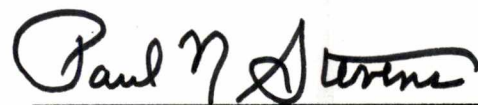


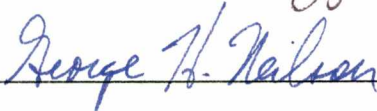
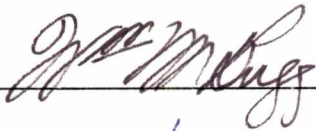
To the Graduate Council:

I am submitting herewith a dissertation written by Antonino Carnevali entitled "An Experimental Investigation of Fast Ion Confinement on the ISX-B Tokamak." I have examined the final copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Physics.

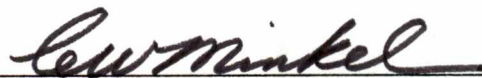


Paul N. Stevens, Major Professor

We have read this dissertation
and recommend its acceptance:



Accepted for the Council:



Vice Provost
and Dean of the Graduate School

**AN EXPERIMENTAL INVESTIGATION OF FAST ION CONFINEMENT
ON THE ISX-B TOKAMAK**

A Dissertation

Presented for the

Doctor of Philosophy

Degree

The University of Tennessee, Knoxville

Antonino Carnevali

June 1985

To the memory of my mother and my grandfather

ACKNOWLEDGMENTS

Many people have contributed to this investigation. First and foremost, I wish to thank Steve Scott for his scientific advice throughout this work, for making sure that I would never stray too far, and for his continuous encouragement. Without his help, this work would have not been accomplished. I also wish to express my gratitude to Paul Stevens, who chaired my doctoral committee and whose undeterred faith in my work supported me throughout this effort. Very special thanks are given to Tommy Thomas and Hutch Neilson for sharing their scientific insights in many enlightening discussions and for their encouragement and support. I want to thank Steve Scott, Paul Stevens, and Hutch Neilson further for carefully reviewing the manuscript. This work has benefited from their constructive suggestions.

I am very grateful to Masanori Murakami for allocating—in an already busy operational schedule—machine time to this experiment. I am also indebted to all the members of the ISX-B group for the reliable operation of the tokamak, the neutral beam injectors, and the plasma diagnostics during many days of late hour work. In addition, I wish to express my appreciation to John Munro for many helpful discussions on the Monte Carlo analysis. Finally, I am thankful to Mike Saltmarsh and Julian Dunlap for their continuous support.

ABSTRACT

An experimental investigation of fast ion confinement was conducted on the ISX-B tokamak at the Oak Ridge National Laboratory to ascertain that the beam ion behavior is properly described by classical processes. Data were collected during tangential injection of H^0 beams (co-, counter-, and co- plus counter-) at power levels up to 1.9 MW in low plasma current ($I_p = 80$ to 215 kA) D^+ discharges. Experimental energy spectra of energetic charge-exchange neutrals along several sightlines in the torus equatorial plane are compared with the predictions of Fokker-Planck and orbit-following Monte Carlo calculations to verify the validity of classical theory. A further tool used in this investigation is the comparison of predicted and experimental beam-plasma neutron emission during injection of beams doped with 3% D^0 . Both the fast neutral spectra and the beam-plasma neutron emission are in close agreement (within factors of ≤ 2) with the calculated values under a variety of plasma parameters, beam parameters, and injection geometries. Furthermore, measured decay rates of the beam-plasma neutron production following beam turn-off show that the beam slowing down—at energies close to the injection energy and in the plasma core—is classical within a 30% uncertainty. These results demonstrate that classical theory describes well the behavior of the beam ions. Moreover, MHD activity is shown not to cause enhanced fast ion losses in the ISX-B. Also, beam additivity experiments indicate that the fast ion density in the plasma volume is proportional to the injected beam power P_b . An unresolved issue is whether the *central* fast ion density is linear with P_b .

In addition, the analysis of charge-exchange spectra is critically evaluated. It is shown that the analysis need be integrated with a knowledge of the orbit topology to correctly interpret the spectra. Cases where the zero banana width, Fokker-Planck calculation is adequate/inadequate to predict fast neutral spectra and the power deposited in the plasma are discussed.

TABLE OF CONTENTS

CHAPTER	PAGE
1. INTRODUCTION	1
2. THE ISX-B TOKAMAK EXPERIMENT	10
2.1 Introduction	10
2.2 The ISX-B	11
2.3 Effects of the Fishbone Instability on Fast Ion Confinement	14
2.4 MHD Activity in ISX-B	17
2.5 Fast Ion Confinement in Z-Mode and L-Mode Discharges	21
3. THEORY OF NEUTRAL BEAM INJECTION. TOPICS IN THE ANALYSIS OF FAST NEUTRAL SPECTRA	25
3.1 Introduction	25
3.2 Deposition	25
3.2.1 The Three Energy Components, $f_0(E)$	26
3.2.2 Ionization Reactions	27
3.2.3 Deposition Profiles, $f_0(R)$	29
3.2.4 Deposition Profiles, $f_0(\zeta)$	32
3.3 Fast Ion Orbits	44
3.3.1 Orbit Types	45
3.3.2 Orbit Loss Regions	50
3.3.3 Tangential vs Perpendicular Injection	53
3.3.4 Sensitivity of the NPA to the Orbit Topology	54

CHAPTER	PAGE
3.4 Collisional Effects	64
3.4.1 Slowing Down	66
3.4.2 Pitch Angle Scattering	69
3.4.3 Energy Diffusion	73
3.4.4 Electric Field Effects	74
3.4.5 Charge Exchange	75
4. THE COMPUTATIONAL CODES	78
4.1 Introduction	78
4.2 Analytical Fast Neutral Spectra (FPP)	80
4.2.1 Spectra During Co-injection at Low I_p	81
4.2.2 Spectra During Counter-injection	83
4.2.3 Counter-moving Particles During Co-injection	85
4.2.4 Co-moving Particles During Counter-injection	87
4.2.5 Spectra During Co-injection at High I_p	89
4.3 Monte Carlo Fast Neutral Spectra (NEWORBX)	89
4.3.1 Calculation of $F_i(R, E, v_{\parallel}/v)$ and $\Phi_0(R, E, R_t)$	91
4.3.2 Tests on the Postprocessor	93
4.3.3 Effects of Varying δt in the Monte Carlo Calculator ...	97
4.3.4 Effects of Varying the Degree of Acceleration	98
4.3.5 Russian Roulette and Particle Splitting	102
5. CO-, COUNTER-, AND BALANCED INJECTION	110
5.1 Introduction	110

CHAPTER	PAGE
5.2 Co-Injection	111
5.2.1 Density Scan	112
5.2.2 Plasma Current Scan	126
5.3 Counter-Injection	138
5.4 Co-, Counter-, and Balanced Injection	143
6. BEAM ADDITIVITY	148
6.1 Introduction	148
6.2 Beam Additivity at High I_p	149
6.3 Beam Additivity at Low I_p	161
7. BEAM-PLASMA NEUTRON EMISSION MEASUREMENTS	166
7.1 Introduction	166
7.2 Theory and Estimate of the Uncertainties	166
7.3 Experimental Measurements of the Slowing-Down Time	173
7.4 Measurements of Beam-Plasma Neutron Yield	179
8. CONCLUSION	187
REFERENCES	193
APPENDIXES	198
APPENDIX A. DESCRIPTION OF THE NEUTRAL PARTICLE ANALYZERS	199

CHAPTER	PAGE
APPENDIX B. MONTE CARLO CALCULATION	
OF F_i AND Φ_0	204
1. Calculation of $F_i(R, E, \zeta)$	204
2. Calculation of $\Phi_0(E, R_t)$	207
APPENDIX C. CALIBRATION OF THE NEUTRON	
DETECTION SYSTEM	210
1. Introduction	210
2. ISX-B Neutron Detection System	212
3. Method of Calibration	212
4. Estimated Accuracy of Neutron-flux Data	217
5. Summary	226
VITA	231

LIST OF TABLES

TABLE	PAGE
2.1 Dimensions and typical plasma and beam parameters on the ISX-B tokamak	13
4.1 Fractional standard deviations for the spectra of Fig. 4.10 with and without Russian roulette and particle splitting	106
5.1 Plasma parameters for sequence 072683 at three time points in the discharge	115
5.2 Power distribution (in kW/1 MW, co-injected) high and low $\bar{n}_e$	124
5.3 Power distribution (in kW/1 MW, co-injected) high and low I_p	132
5.4 Power distribution (in kW/1 MW, counter-injected) high and low I_p	142
5.5 Discharge parameters for the co-, counter-, and balanced injection comparison	143
5.6 Boundary conditions used to calculate $n_0(R)$	145
5.7 Power distribution (in kW/1 MW, injected)	146
7.1 Range of parameters for the comparison of Fig. 7.5	182
C.1 Ratio of count rates, Cf/Am-Be	222
C.2 Estimated uncertainties in the calibration of the neutron detection system	230

LIST OF FIGURES

FIGURE	PAGE
Fig. 2.1 Plan view of the ISX-B experiment	12
Fig. 2.2 Sawtoothing in the ISX-B	18
Fig. 2.3 Fishbone instability detected on the ISX-B	20
Fig. 2.4 Comparison of fast neutral spectra with the predictions of the orbit-following Monte Carlo simulation in <i>L</i> -mode and <i>Z</i> -mode discharges	23
Fig. 3.1 The cross sections for ionization of the injected neutrals as a function of energy (after Sweetman ²⁹)	28
Fig. 3.2 Deposition of the full energy component of a neutral beam on ions, electrons, impurities, and beam ions	30
Fig. 3.3 Deposition of a neutral beam calculated with and without the beam-beam contribution	31
Fig. 3.4 Fast ion birth distribution in $v_{\parallel}/v$ (integrated from $R = 70$ to $R = 120$ cm) at the horizontal midplane	34
Fig. 3.5 Fast ion birth distribution in $v_{\parallel}/v$ at the horizontal midplane in the plasma center (a) and close to the inside edge (b)	36

FIGURE	PAGE
Fig. 3.6 Attenuation integrals computed for escaping charge-exchange neutrals with energy = 10, 20, and 30 keV	39
Fig. 3.7 Neutral density profiles for the edge source	42
Fig. 3.8 The product of background neutral density (n_0) and attenuation integral	43
Fig. 3.9 Poloidal projections of four common orbit types in a tokamak	47
Fig. 3.10 The pinch orbit and neighboring orbits (after Rome and Peng ⁴²)	49
Fig. 3.11 Orbit topology for a 10-keV proton (after Rome, Lyon, and Fowler ³⁹)	51
Fig. 3.12 Orbit topology for a 30-keV proton (after Rome, Lyon, and Fowler ³⁹)	52
Fig. 3.13 Tangential vs perpendicular injection	55
Fig. 3.14 Four representative NPA sightlines superimposed on the orbit topology for a 10-keV proton	57
Fig. 3.15 Comparison of perpendicular fast neutral spectra during co- and counter-injection	58
Fig. 3.16 Neutral flux origination profiles during counter-injection	60
Fig. 3.17 Neutral flux origination profiles during co-injection	61
Fig. 3.18 Effects of the orbit topology on the NPA spectra	63
Fig. 3.19 Co-going fast neutral flux detected during counter-injection .	65

FIGURE	PAGE
Fig. 4.1 Comparison of fast neutral spectra predicted by the Fokker-Planck code FPP with the experimental data during co-injection at low I_p	82
Fig. 4.2 Comparison of FPP with experiment: spectra of counter-moving ions during counter-injection	84
Fig. 4.3 Comparison of FPP with experiment: spectra of counter-moving ions during co-injection	86
Fig. 4.4 Comparison of FPP with experiment: spectra of co-moving ions during counter-injection	88
Fig. 4.5 Comparison of FPP with experiment: co-injection at high I_p	90
Fig. 4.6 Block diagram of the orbit-following Monte Carlo code NEWORBX	92
Fig. 4.7 Test of reliability for the calculation of the fast neutral flux	96
Fig. 4.8 Effects of varying the time step in the orbit-following calculation	99
Fig. 4.9 Effects of varying the degree of acceleration of the collision operator	101
Fig. 4.10 Test of reliability for the Russian roulette and particle splitting schemes	105
Fig. 4.11 Test of reproducibility, using different sets of random numbers in the Monte Carlo calculation	108

FIGURE	PAGE
Fig. 4.12 Tests of reliability for the orbit-following Monte Carlo simulation in cases where orbit effects are important	109
Fig. 5.1 Time histories of plasma parameters for sequence 072683, used for the density scan experiment	113
Fig. 5.2 Deposition profiles of the full-energy and third-energy beam components in high and low density plasmas	114
Fig. 5.3 Fast neutral spectra during co-injection at high and low $\bar{n}_e$	116
Fig. 5.4 Background neutral density profiles calculated assuming low and high wall recycling	121
Fig. 5.5 Time histories of the H_α signals from detectors located in various toroidal sectors	123
Fig. 5.6 Top view of the Monte Carlo beam deposition	125
Fig. 5.7 Effects of enhanced charge-exchange losses on the predicted fast neutral spectra at low $\bar{n}_e$	127
Fig. 5.8 Time histories of plasma parameters for the low and high I_p comparison during co-injection	129
Fig. 5.9 Experimental fast neutral spectra obtained during co-injection at high and low I_p	130
Fig. 5.10 Comparison of experimental and predicted fast neutral spectra during co-injection at high and low I_p	131

FIGURE	PAGE
Fig. 5.11 Effects of a simulated enhancement in pitch angle scattering on the line-integrated fast neutral spectra	135
Fig. 5.12 Effects of a simulated enhancement in pitch angle scattering on the localized fast neutral spectra	136
Fig. 5.13 Time histories of plasma parameters for the low and high I_p comparison during counter-injection	139
Fig. 5.14 Comparison of experimental and predicted fast neutral spectra during counter-injection at high and low I_p	141
Fig. 5.15 Comparison of experimental and predicted fast neutral spectra during co-, counter-, and balanced injection	144
Fig. 6.1 Time histories of plasma parameters for the beam additivity experiment at high I_p	150
Fig. 6.2 Time history of the perpendicular neutral flux at $E \simeq 20$ keV during the beam additivity experiment	152
Fig. 6.3 Experimental line-integrated and localized fast neutral spectra during one- and two-beam injection at high I_p	154
Fig. 6.4 Comparison of experimental spectra with the predictions of the Monte Carlo calculation during one- and two-beam injection	155
Fig. 6.5 Evidence that the DNB current did not change during the discharge	157

FIGURE	PAGE
Fig. 6.6 Time histories of plasma parameters for the beam additivity experiment at low I_p	162
Fig. 6.7 Experimental line-integrated and localized fast neutral spectra during one- and two-beam injection at low I_p	164
Fig. 7.1 Hydrogen and deuterium fast neutral spectra during co-injection of a 1-MW H^0 beam doped with 3% D^0 , at $I_p = 180$ kA	172
Fig. 7.2 Experimental and predicted decay rates of the beam-plasma neutron emission following beam turn-off	175
Fig. 7.3 Comparison of experimental and predicted decay times (τ_N) of the beam-plasma neutron emission for five different plasma discharges	177
Fig. 7.4 The experimental τ_N are compared with the values predicted at the plasma center	180
Fig. 7.5 Comparison of experimental and predicted beam-plasma neutron emission	181
Fig. 7.6 Time histories of the measured neutron emission (beam-plasma plus thermonuclear) during co- and counter-injection of 3% D^0 on a deuterium plasma	184
Fig. 7.7 Time histories of the experimental beam-plasma neutron emission during co- and counter-injection of 3% D^0 on a deuterium plasma	185

FIGURE	PAGE
Fig. A.1 Schematic illustration of the Momentum-Energy Analyzer (MEA)	200
Fig. A.2 The Velocity-Filter neutral particle Analyzer (VFA)	202
Fig. B.1 The geometry for the calculation of Φ_0	208
Fig. C.1 The 19 toroidal positions of the ^{252}Cf neutron source inside the tokamak vessel and the location of the six neutron detectors	214
Fig. C.2 Typical variation of the neutron count rates as the ^{252}Cf neutron source was moved around the vessel	215
Fig. C.3 Effect of scattering and absorption on neutron count rates with the ^{252}Cf neutron source at different toroidal locations	216
Fig. C.4 Effect of approximating a volume source (the plasma) with a line source on the calibration of the neutron detection system	219
Fig. C.5 Energy spectra of the ^{252}Cf and $^{241}\text{Am-Be}$ neutron sources	221
Fig. C.6 Effect of adding new structures around the tokamak on the calibration	224
Fig. C.7 The calibration is not significantly altered by the addition of new structures around the tokamak	225
Fig. C.8 Ratios of raw count rates of two of the neutron detectors over a 13-month period	227

FIGURE	PAGE
Fig. C.9 Time history of the neutron emission during 1% D ⁰ injection	228
Fig. C.10 Time history of the neutron emission during a typical two-beam discharge	229

CHAPTER 1

INTRODUCTION

The worldwide consumption of energy is increasing rapidly. Current projections show that it will increase at an even faster rate in the future. As the available fossil and fissile fuels are limited, new sources of energy are sought. Among these, controlled thermonuclear fusion holds the promise of being practically inexhaustible and economically feasible. Further advantages are that it would contribute very little to atmospheric pollution (as opposed to burning coal) and that it would not produce any long-lived radioactive waste (as opposed to fission).

The fundamental process at play is the fusion of two light nuclei to form a heavier element. The total mass after the reaction is less than the sum of the masses of the reacting elements, and the mass defect is transformed into energy, primarily kinetic energy of the reaction products. One of the possible reactions, for instance, is between deuterium and tritium nuclei:



It is evident that a large amount of energy can be released in fusion events. However, the colliding nuclei must have a high relative velocity to overcome the Coulomb repulsion and come close enough to fuse. Thus, the thermonuclear fuel must be maintained at temperatures on the order of 10^8 K, or equivalently 10 keV. At such temperatures the gas is completely ionized, and it constitutes a plasma. To avoid a rapid cooling of the fuel, it is necessary to contain the

plasma away from material walls. One way of achieving confinement is by means of strong magnetic fields; the charged particles can move freely along the field lines but are constrained to a gyrating motion in the perpendicular direction. Among the different approaches explored in magnetic confinement, machines adopting a toroidal geometry have been particularly successful since they are not affected by the end losses of cylindrical systems, while still keeping a fairly simple coil configuration. One device that exploits the closed field line structure of the toroidal geometry is the tokamak. To gain a deeper understanding of the plasma physics issues and to develop the technologies necessary to design and build a commercial fusion reactor, tokamak experiments have been, and continue to be, the subject of much scientific investigation in controlled fusion research. The research presented in this thesis deals with one particular aspect of tokamak physics, confinement of energetic ions, and was performed on the Impurity Study Experiment (ISX-B) tokamak at Oak Ridge National Laboratory (ORNL).

A simple toroidal magnetic field (B_ϕ) cannot contain a plasma in equilibrium. The field gradient ($B \propto 1/R$) and field curvature cause the positive and negative particles to drift vertically in opposite directions. A vertical electric field $\vec{E}$ is thus generated, which results in an outward $\vec{E} \times \vec{B}$ motion of both ions and electrons and a consequent dumping of the plasma on the outer wall. In a tokamak device, this problem is solved by inducing a toroidal current (I_p) in the plasma. The poloidal magnetic field (B_θ) associated with I_p causes the magnetic field lines to spiral around the torus. Particles following the field lines then drift alternately toward and away from the magnetic axis, with an average drift close to zero, and no net charge separation occurs.

The current induced in the plasma to achieve confinement also heats the plasma through ohmic dissipation. However, as the plasma temperature increases, the electrical resistance of the plasma decreases, and Joule heating becomes less effective. An additional energy source is necessary if further heating of the plasma is desired. Among the schemes devised to provide auxiliary heating to a hot plasma, neutral beam injection continues to be one of the most effective. In this scheme, beams of energetic neutrals are injected into the plasma. Unaffected by the magnetic fields, the neutrals penetrate the plasma along straight paths until they ionize. Once ionized, they form a population of energetic ions, some of which are confined in the plasma. The confined fast ions slow down through Coulomb collisions with the plasma ions and electrons, thus transferring their energy to the plasma.

In early experiments, good agreement was found between theoretical predictions of the increase in central ion temperature following injection [$\Delta T_i(0)$] based on classical beam slowing down and the experimentally measured values.^{1,2} However, one characteristic of those experiments was that the injected beam power (P_b) was low, typically less than the ohmic input power (P_{OH}). Furthermore, a determination of the beam heating efficiency based on measurements of $\Delta T_i(0)$ is affected by the fact that beam injection alters the electron density and temperature and consequently changes the electron-ion heat transfer rates. Subsequently, higher beam power levels were achieved, with $P_b \gg P_{OH}$ becoming a common feature of injection experiments. In some tokamaks (including the ISX-B³), detailed power balance analyses showed that the energy confinement time (defined as the ratio of the total energy content of the plasma ions and electrons to the power deposited in the

plasma) decreases with increasing P_b . At the same time, measurements of plasma magnetic effects were becoming increasingly accurate and widespread, and more efficient methods of magnetic analysis were being developed.⁴ The latter advancements made it possible to obtain a reliable determination of the plasma average kinetic pressure and, therefore, of the total energy (W_T) stored in the plasma. Consequently, the beam heating efficiency came to be characterized by the response of W_T to P_b . It was observed that W_T did not increase linearly with P_b but tended to saturate at high beam powers. More recently, Goldston⁵ and Kaye⁶ have reported scaling results that incorporate data from a number of different tokamaks. They found that the global energy confinement time τ_E^* (defined as W_T/P_b) decreases as P_b is increased ($\tau_E^* \propto P_b^{-\alpha}$, $\alpha \sim 1/2$).

The results of those investigations inspired a new series of experiments to determine whether the beam ion behavior was well understood. It was postulated that the beam power delivered to the plasma was less than calculated, which would explain the nonlinear response of τ_E^* to P_b . As discussed in Chapter 2, a sizable part of the deterioration of τ_E^* could in some tokamaks and in certain regimes be attributed to anomalous beam ion losses. In the ISX-B, preliminary data indicated no evidence of large fast ion losses.³ On the basis of that result, the cause for the τ_E^* degradation was sought elsewhere and, through detailed power balance calculations, was determined to be an increase in the electron thermal diffusivity χ_e .^{3,7} Since the investigation of the confinement in beam-heated discharges developed into one of the major efforts of the ISX-B program, and because of the observation of some anomalous fast ion losses in

other tokamaks,⁸ it became necessary to ascertain definitely whether the confinement of the beam ions in the ISX-B was properly described by classical processes and that the power delivered to the plasma was correctly assessed.

The main objective of this thesis is to investigate experimentally the fast ion behavior in the ISX-B, that is, to determine if (1) the radial profiles of the deposited beam neutrals are as calculated, (2) if the resulting fast ions remain confined and slow down according to theoretical predictions, and (3) if they suffer anomalous losses due to enhanced charge-exchange rates, enhanced pitch angle scattering, or magnetohydrodynamic (MHD) activity. This research was directed mostly to discharges that are thought to be most susceptible to fast ion losses or characterized by a low energy confinement time. For instance, the fast ion guiding center (i.e., the center of the gyromotion) follows orbits whose excursions (δ) scale as I_p^{-1} . Therefore, orbit losses are more likely to occur at low I_p , as δ may be comparable to or larger than the plasma radius (a_p). Also, the direction of injection has a strong influence on the orbit characteristics and on the confinement properties of the injected ions. Although this topic will be discussed in detail in Chapter 3, some important definitions will be introduced presently. "Tangential" and "perpendicular" injection are to be interpreted with reference to the plasma axis. "Quasi-tangential" and "near-perpendicular" are also used, implying injection at small angles from tangential/perpendicular. It is predicted and observed that perpendicular or near-perpendicular injection results in poorer fast ion confinement. With respect to the direction of I_p , injection can be "co-" (in the same direction as) or "counter-" (opposite to). Counter-injected ions are more easily subject to orbit losses than co-injected ions. Of particular interest are experiments in which P_b is increased during the

same plasma discharge while keeping the main plasma parameters approximately constant. This topic will be developed in Chapter 6.

Another objective of this thesis is to critically evaluate the analysis of charge-exchange spectra, which is a standard experimental diagnostic for fast ion measurements. This is done explicitly in Chapter 3, where the theory of neutral beam injection is reviewed, with emphasis being placed on the role played by the various physical processes in determining the charge-exchange neutral flux measurements and where the major uncertainties and approximations affecting the theoretical predictions are identified. The concepts developed in Chapter 3 are subsequently applied to the analysis of charge exchange spectra throughout this work.

The connection between theory and experiment is made mostly through a comparison of the charge-exchange fast neutral spectra with those predicted by computer code modeling of the slowing down and scattering of the fast ions, as well as of the plasma background. Charge-exchange analysis is a well-established technique based on the following process. A small fraction of the beam ions deposited in the plasma will neutralize through charge-exchange collisions with background neutrals. Some of the fast neutrals thus generated escape from the plasma without reionizing and are detected by neutral particle analyzers (NPAs). The NPA separates the incoming neutrals according to mass and energy and yields energy spectra that are representative of the beam ion distribution function and of the plasma conditions. The experimental data were obtained using two NPA, described in Appendix A, which scanned toroidally from near-perpendicular to quasi-tangential in the torus equatorial plane. The neutral particle flux (Φ_0) at several energies could be measured during each

plasma discharge, and complete energy spectra were obtained using data from a "sequence" of essentially identical discharges.

Two existing computer codes, FPP and NEWORBX, were modified for the purpose of providing flexible computational tools for the calculation of charge-exchange spectra—as described in Chapter 4. FPP, which solves the Fokker-Planck equation numerically, was originally written by R. J. Goldston.⁹ It was adapted to the ISX-B experiment by G. H. Neilson of ORNL. FPP provides an expeditious calculation of the fast ion distribution function and the power deposited in the plasma. A major disadvantage of the FPP approach is that the fast ion orbit excursions can be treated only approximately. The orbit-following Monte Carlo code NEWORBX was also written by Goldston, and its description is contained in Ref. 10. This code was subsequently modified by Fowler and Rome¹¹ to account for noncircular magnetic surface geometry. While its computer execution time is long, NEWORBX takes into account the actual fast ion orbits as well as other effects neglected in FPP. A further tool used in this work to verify the validity of classical theory has been the comparison of predicted and experimentally observed beam-plasma neutron emission during injection of energetic deuterons on a deuterium plasma. These measurements—and the corresponding theoretical calculations—are presented in Chapter 7.

In Chapter 2, the ISX-B device and the range of some of its characteristic parameters are described briefly. Its operational regime as compared to other tokamak experiments is discussed. It is shown that the conditions under which anomalous beam losses due to MHD activity were reported on other machines are not present in the ISX-B. Experimental measurements of the effects of

MHD activity on the energetic neutral flux and the beam-plasma neutron emission are presented, which show that no significant fast ion losses can be attributed to this type of phenomena in ISX-B within experimental uncertainty. Also in Chapter 2, after discussing whether large-scale beam losses are expected or detected in ISX-B, the issue of a possible *improvement* in beam ion confinement in impurity-contaminated discharges is investigated. It turns out, in fact, that a linear dependence on $\bar{n}_e$ is introduced in the expression for τ_E^* to describe plasmas doped with small amounts of low-Z impurities (the “Z-mode”¹²), and τ_E^* achieves higher values with respect to similar but clean discharges (the “L-mode”), if $\bar{n}_e$ is high enough. A hypothesis to explain the preceding result was that an enhanced confinement regime for the injected ions is somehow produced in the Z-mode, which, in turn, results in more energy delivered to the plasma and an overall increase in τ_E^* . The experimental evidence presented, however, shows no significant differences in the confinement of the fast ions in L-mode and Z-mode discharges, thus tending to refute the hypothesis.

Chapter 3 reviews some aspects of the theory of neutral beam injection relevant to the analysis of fast neutral spectra. The physical processes discussed are beam deposition, fast ion orbits, slowing down, pitch angle scattering, and charge-exchange rates. In Chapter 4, the characteristic features of the calculation of the fast ion distribution function performed by the analytical code FPP and by the Monte Carlo code NEWORBX are reviewed. A comparison with experimental fast neutral spectra illustrates how the approximate, Fokker-Planck calculation fails to describe some cases of interest. In describing NEWORBX, the emphasis will be on the additions implemented in the code for

the calculation of the fast ion distribution function and of the spectra of the escaping neutrals. The equations used for the calculation are presented in Appendix B.

A detailed comparison of the experimental data with the predictions of the theoretical models, probing the effects of varying the most uncertain input parameters within the range of plausible values, is carried out in Chapters 5-7. Co-, counter-, and balanced injection schemes are compared in Chapter 5, the typical discharge characteristics and plasma parameters are reviewed, and the effects on fast ion behavior are explored. Chapter 6 deals with the question of beam additivity (i.e., determining whether the power transferred to the plasma is proportional to P_b , even if anomalous processes might cause it to be less than the input power). Both low and high I_p discharges are considered. Chapter 7 discusses the analysis of beam-plasma neutron production during injection of H^0 beams doped with 3% D^0 on D^+ plasmas, under a variety of injection geometries and discharge conditions. This provides further information, independent from charge-exchange analysis, on fast ion confinement. Moreover, measured decay times of the beam-target neutron yield in experiments where the doped beam was turned off sharply are compared with those predicted by theory and result in a direct experimental verification of the slowing down process. An extensive calibration of the neutron detection system was performed for this research. Its details and conclusions are reported in Appendix C.

In Chapter 8, the outcome of the investigation is reviewed, and conclusions are drawn. Also, the range of error in the calculated power deposited in the plasma is estimated.

CHAPTER 2

THE ISX-B TOKAMAK EXPERIMENT

2.1 INTRODUCTION

This chapter describes the ISX-B tokamak and its typical operating parameters, probing whether a regime of poor fast ion confinement due to MHD activity might occur in this machine during nondisruptive discharges, as well as testing the hypothesis that an improved beam confinement is responsible for the higher τ_E^* achieved during Z-mode operation. The purpose is to dispose of two miscellaneous topics of interest to the ISX-B program but not to this study.

As mentioned in Chapter 1, anomalous fast ion losses were found responsible in some cases for the apparent deterioration of τ_E^* with increasing P_b . In the Poloidal Divertor Experiment tokamak (PDX, $R_0 = 143$ cm, $a = 43$ cm), for instance, large fluctuations in the energetic neutral flux and in the beam-plasma neutron emission were detected during the MHD activity (fish-bone instability) that accompanies the high-power, near-perpendicular neutral beam injection under certain plasma conditions. Monte Carlo simulations have shown that up to 40% of the beam heating power may be lost due to this instability. Results from several tokamaks in connection with the confinement of the beam ions and the conditions under which anomalous behavior occurred are briefly reviewed. A comparison with the ISX-B operating regime sheds some light on whether large-scale beam losses might be expected in the experiments performed on this machine, and some data are presented to substantiate the conclusions reached.

In connection with the *Z*-mode studies, there is the possibility of an *improvement* in energetic ion confinement in discharges with a somewhat higher level of impurity concentration. That issue is also investigated in this chapter through a comparison of experimental and theoretically predicted fast neutral spectra and beam-plasma neutron production in *Z*-mode and *L*-mode discharges.

Section 2.2 describes the ISX-B configuration—including the relative location of the neutral beam injectors and the neutral particle analyzers—and reviews some typical discharge parameters. In Section 2.3, the regimes in which anomalous fast ion losses were detected in other tokamaks are discussed, and the ISX-B is viewed in this context. Experimental measurements of energetic neutral fluxes and beam-plasma neutron yields collected during ISX-B discharges with some level of MHD activity are presented in Section 2.4. Finally, in Section 2.5, it is shown that the higher τ_E^* attained in *Z*-mode plasmas does not appear to be a consequence of an improved beam ion confinement.

2.2 THE ISX-B

Figure 2.1 shows a plan view of the ISX-B tokamak, the three neutral beam injectors, and the surrounding plasma diagnostics. Details on the machine parameters, objectives, and confinement results are reviewed elsewhere.^{3,13} The tokamak dimensions and the ranges of values for plasma and beam parameters in the experiments performed in connection with this investigation are reported in Table 2.1

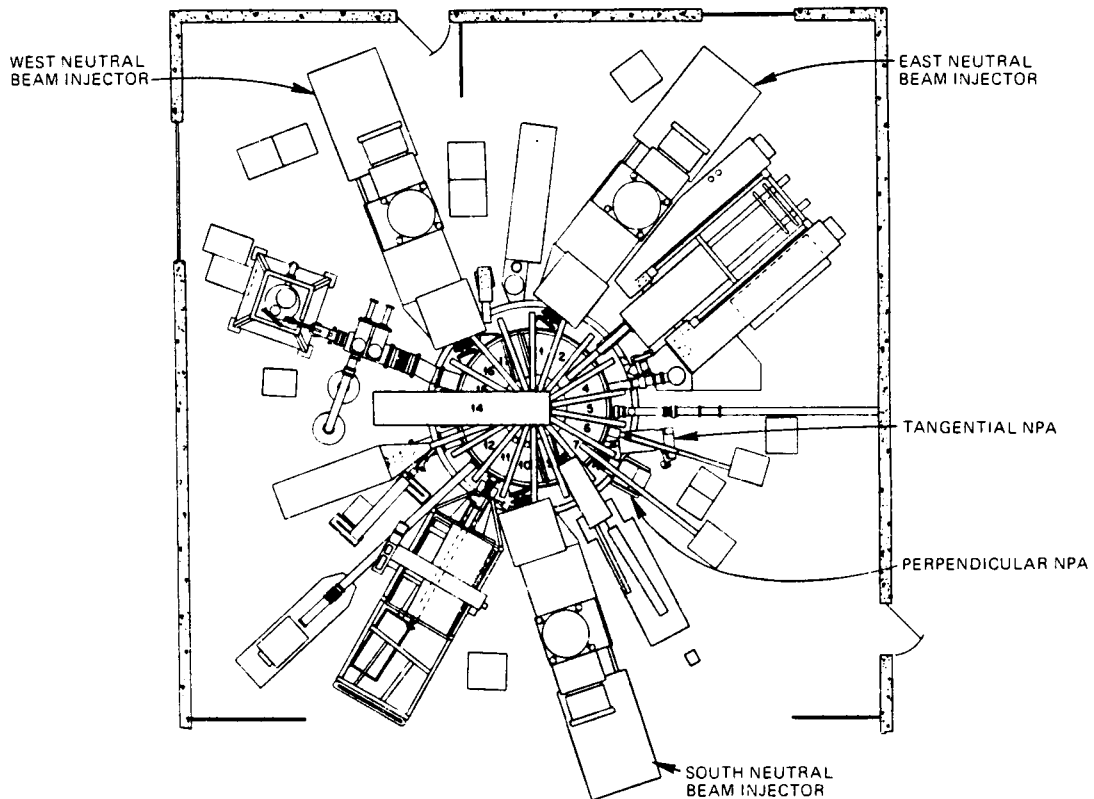


Fig. 2.1. Plan view of the ISX-B experiment. The locations of the three neutral beam injectors and the two neutral particle analyzers are shown. A diagnostic neutral beam was located under the vessel in sector 7 and injected vertically upwards close to the plasma center.

Table 2.1 Dimensions and typical plasma and beam parameters on the ISX-B tokamak

Major radius, R_0	93 cm
Horizontal minor radius, a	27 cm
Plasma ions	D^+
Toroidal magnetic field, B_ϕ	12.3–13.8 kgauss
Plasma current, I_p	80–215 kA
Line-averaged electron density, $\bar{n}_e$	$1.5\text{--}7 \times 10^{13} \text{ cm}^{-3}$
Central electron temperature, $T_e(0)$	$\leq 1000 \text{ eV}$
Central ion temperature, $T_i(0)$	$\leq 1500 \text{ eV}$
Effective Z of plasma, Z_{eff}	$\sim 1\text{--}3$
Discharge duration	$\leq 300 \text{ ms}$
Beam atoms	H^0
Injection tangency radius, R_t	74.5 cm
Fractional energy components, J	$0.41, 0.31, 0.28 \left(E_{\text{inj}}, \frac{E_{\text{inj}}}{2}, \frac{E_{\text{inj}}}{3} \right)$
Beam full energy	19–36 keV
Injected beam power	0.4–1.9 MW

The particular characteristics of individual discharges will be discussed along with the analysis of data. However, from the geometry of the experiment, some general comments of relevance to fast ion studies can be made.

First, because of tangential injection, the path of the neutrals in the plasma is long; consequently, the fraction passing through without ionizing (the "shine through") is small. For the same reason, losses due to resonant charge exchange between injected neutrals and circulating beam ions are minimized. The deposition profile resulting from tangential injection, given the minor radius and the typical plasma densities of the ISX, is peaked on the magnetic axis (i.e., at the plasma center). Another consequence of the injection geometry is that most of the ions are born on well confined, co-passing orbits.

The limiters (TiC-coated graphite, outer mushroom and inner rail) are situated in toroidal sector 14, not far from the location of the beam lines. Therefore, any enhanced release of impurities from the limiter surfaces could have repercussions on the deposition process. Furthermore, since a larger-than-average recycling is expected at the limiter, the background neutral density may be high in that region; thus, a significant portion of the charge-exchange losses may be localized there. As is discussed in Section 3.4, the beam halo itself contributes an additional source of thermal neutrals near this toroidal location. Conversely, the neutral particle analyzers view a plasma region many mean free paths away from the limiters and the beams and, consequently, sample a different $n_0(R)$. So, for instance, the halo contribution to $n_0(R)$ is not included in the calculation of the source term for $\Phi_0(R, E, \zeta)$, although it is retained when calculating the charge-exchange losses.

2.3 EFFECTS OF THE FISHBONE INSTABILITY ON FAST ION CONFINEMENT

The inverse relation of τ_E^* to beam power referred to in Chapter 1 comes from an empirical scaling study of energy confinement in a number of tokamaks.⁵ A wide range analysis of fast ion data, however, seems generally to indicate that the beam ions behave classically. This conclusion was reached, for example, through a detailed analysis of neutron yields in the Princeton Large Torus tokamak¹⁴ (PLT, $R_0 = 130$ cm, $a = 40$ cm) during high-power tangential injection experiments ($P_b \leq 2.5$ MW) and in the Tokamak Fontanay-aux-Roses¹⁵ (TFR, $R_0 = 98$ cm, $a = 20$ cm) in experiments with near-perpendicular injection and $P_b \leq 0.8$ MW using both neutron and fast neutral data.

On the other hand, the presence of fast ion losses larger than calculated has been demonstrated in some cases and is considered likely in others. The best documented evidence was obtained on PDX during discharges with up to 7.2 MW of beam power injected at an angle of 14° from perpendicular (measured at the machine center). Injection at high B_ϕ was shown to produce heating results similar to those obtained on PLT (i.e., indicative of classical processes).¹⁶ Discharges with low B_ϕ and high P_b , however, exhibit a form of MHD instability—which has been named “fishbone instability” due to the characteristic appearance of the Mirnov coil signal—that results in a large loss of beam power (up to 40%) and an apparent saturation of beta with increasing P_b .⁸ The onset of the fishbone instability is empirically characterized by a value of $q\beta_i \geq 0.045$, where q is the safety factor ($q = rB_\phi/RB_\theta$) and β_i is the

volume-averaged beta toroidal (defined as the ratio of the plasma kinetic pressure to the toroidal magnetic field pressure). This instability was identified as an $m = 1, n = 1$ oscillation, where m and n are the poloidal and toroidal mode numbers, and was subsequently described theoretically as a mode destabilized by energetic trapped particles.^{17,18} (See Section 3.3 for a description of trapped orbits.) In these discharges, periodic spikes—well correlated with the Mirnov coil signal—appear in the perpendicular fast neutral flux, corresponding to a flux enhancement by factors of ~ 10 to 100; they are attributed to a direct expulsion of energetic ions from the plasma. Immediately after each burst, both the beam-target neutron yield and the high-energy neutral signal are seen to drop by 20 to 40% relative to their preburst levels, indicating a comparable depletion of the fast ion population. This interpretation is supported by a good match between the experimentally observed modulation and depletion of the neutron and fast neutral signal and the predictions of the Fokker-Planck and Monte Carlo codes in which a periodic loss of energetic perpendicular ions is implemented.

Recently, the PDX has been upgraded to become the Princeton Beta Experiment (PBX) tokamak, with the main objective of studying “bean-shaped” plasmas and achieving higher beta values. As part of the changes, two of the four perpendicular injectors have been reoriented to a tangential direction, and a tangential neutral particle analyzer has been added. Preliminary results¹⁹ show that fast ion losses associated with the fishbone instability are still observable during perpendicular injection into moderately indented, elongated plasmas, but they do not appear during tangential injection into similar discharges.

In experiments performed on the Doublet III tokamak (D-III, $R_0 = 143$ cm, $a = 44$ cm), with injection farther from perpendicular (26° at the machine center) than in PDX, some evidence of beam ion losses due to the fishbone instability has been detected only in H^0 injection, high β_p^* divertor discharges in the form of energetic neutral flux oscillations correlated with the Mirnov loop signal. Fishbones with concomitant fast neutral signal modulation appear only if $\beta_p > 0.016$ and, at the same time, $\beta_t > 0.01$.²⁰

In the case of the ISX-B, however, beam ion losses associated with this instability are not likely to occur for two reasons. The first is that the mode is destabilized by energetic trapped ions, and their population is small in ISX, since the beams are injected at a large angle (51°) from perpendicular, and little pitch angle scattering takes place at high energy due to the low value of E_{critical} in ISX (see Section 3.4). Second, the product $q\beta_t$ assumes values well below 0.045 in most ISX experiments, or, similarly, the high β_p regime is achieved at very low I_p rather than very high beam power, thus resulting in a low β_t . The operation, therefore, remains outside the regime where the fishbone instability is expected in all but very few cases, which do exhibit the fishbone structure on the MHD signal and which are commented upon in Section 2.4.

2.4 MHD ACTIVITY IN ISX-B

In the ISX-B, periodic bursts of fast neutrals with an amplitude $\Delta I/I \sim 2$ are well correlated with the internal disruptions of the $m = 0$, $n = 0$ sawtooth oscillation of frequency ~ 100 Hz. As shown in Fig. 2.2(a), however, the level of the fast neutral signal immediately after each burst is the same as it was

* β_p is defined as the ratio of the plasma average kinetic pressure to the poloidal magnetic field pressure.

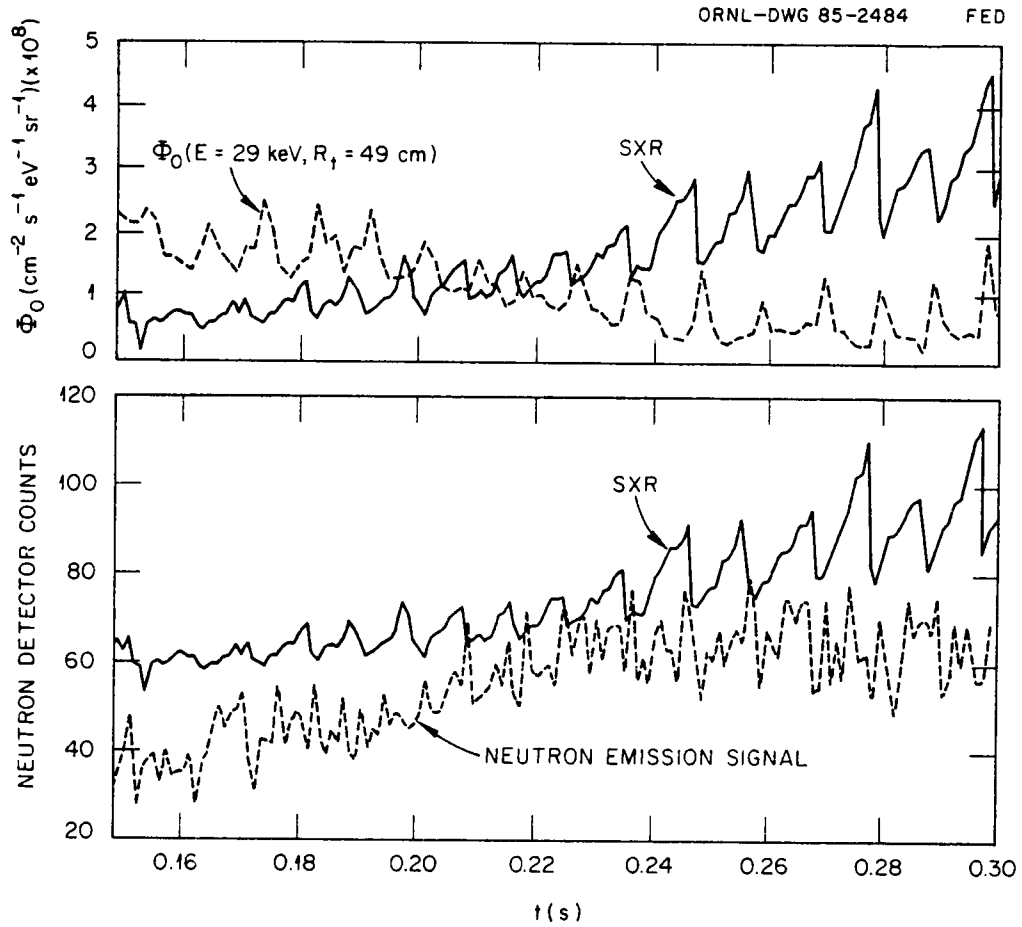


Fig. 2.2. Sawtoothing in the ISX-B. Shot 53119, $B_\phi = 1.38 \text{ T}$, $\bar{n}_e = 4.5 \times 10^{13} \text{ cm}^{-3}$, $I_p = 185 \text{ kA}$, $P_b = 0.9 \text{ MW}$, $E_{\text{inj}} = 30 \text{ keV}$. (a) Spikes in the fast neutral flux are well correlated with the internal disruptions, identified by drops in the soft X-ray emission. (b) No evident correlation is seen with the beam-plasma neutron emission.

before the disruption, indicating that only a redistribution of the energetic ions to a larger average radius—and thus into a region of higher n_0 —takes place, not a direct expulsion from the plasma. (The slow decrease in flux from 150 to 260 ms is a consequence of the increasing plasma density.) This interpretation is corroborated by the absence of correlated fluctuations in the beam-target neutron output in the same discharge, as shown in Fig. 2.2(b). The beam was doped with 3% D^0 , and most of the neutron yield was due to beam-target reactions (total output $\approx 5 \times 10^{10} \text{ s}^{-1}$, thermal output $\approx 0.9 \times 10^{10} \text{ s}^{-1}$). If a significant fraction of the fast ion population were expelled from the plasma during the sawtooth collapse, a periodic decrease in the neutron production, followed by a return to saturation, should be detected. However, no oscillations are seen above the level of the statistical fluctuations ($\sim 15\%$).

Pressure-driven modes (mainly $m = 1, n = 1$) at frequencies of 5 to 25 kHz, similar to the MHD activity observed in PDX at low values of $q\beta_t$, are also present in ISX. However, they have been excluded as a significant cause of the τ_E^* deterioration since a B_ϕ scan at 2 MW of injected beam power—and at constant I_p and $\bar{n}_e$ —produced large changes in the intensity of the MHD activity but left β_p essentially unaltered.²¹ Occasionally, these modes have appeared as repetitive bursts ($\nu \geq 1 \text{ kHz}$) in the soft X-ray and in the Mirnov coil signals, enveloping a higher frequency oscillation ($\nu \sim 20 \text{ kHz}$), an activity typical of the fishbone instability. One such case is illustrated in Fig. 2.3, which shows the Mirnov coil signal and the neutron output (neutron data collected at 5 kHz) in a 10-ms time interval during a discharge that had one of the highest values of $q\beta_t$ achieved in ISX, namely 0.0585 (β_p was 0.011). There is no evidence of dips in the neutron yield correlated with the fishbone events and, con-

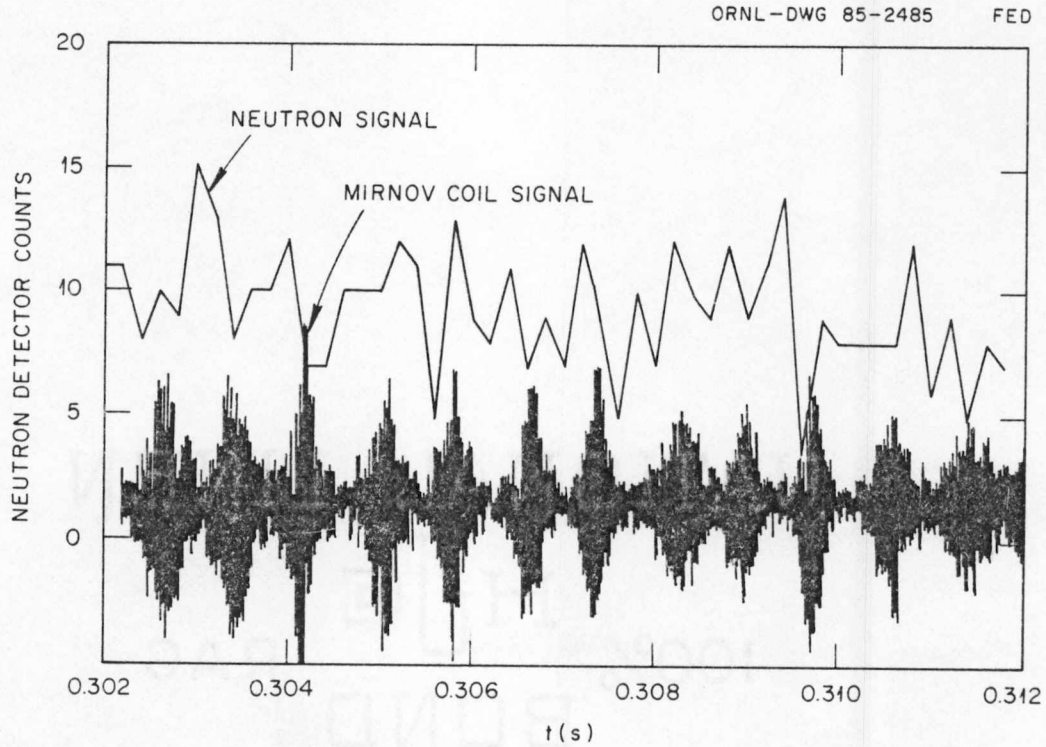


Fig. 2.3. Fishbone instability detected on the ISX-B. The soft X-ray signal along a chord passing through the plasma center (not shown) displayed oscillations well correlated with the Mirnov coil signal. No correlation is seen with the neutron emission (one of the H^0 beams was doped with 1% D^0). The discharge parameters were $B_\phi = 1.38$ T, $I_p = 215$ kA, $\bar{n}_e = 5.8 \times 10^{13}$ cm $^{-3}$, $P_b = 1.8$ MW, $\beta_t = 1.82$ %, $\beta_p = 1.05$ %, $q\beta_t = 0.0585$. The neutron data acquisition rate was 5 kHz.

sequently, no evidence of large fast ion losses associated with the instability. It must be pointed out that beam-target reactions accounted for only $\sim 50\%$ of the neutron emission in that discharge. Because of the poor counting statistics, the loss of a fraction $\leq 45\%$ of the beam ion population could pass undetected. The fast neutral flux measured in this sequence with a data acquisition rate of 10 kHz did not show correlated oscillations above the level of the statistical fluctuations along any sightline, from tangential to perpendicular.

Although no explicit effort was made to make a comprehensive check of all discharges that may have exhibited a fishbone-type instability, none of the fast neutral data collected at 5 and 10 kHz showed fluctuations above the statistical variations—besides the $m = 0$, $n = 0$ sawtooth oscillation—including data gathered during discharges with $q\beta_i > 0.045$. In view of this and the previous considerations, and keeping in mind that the degradation of τ_E^* with beam power is observed even out of the regime where the fishbone instability might occur, it is concluded that the effects of the MHD activity on fast ion confinement can be neglected for the purpose of the present investigation.

2.5 FAST ION CONFINEMENT IN Z-MODE AND L-MODE DISCHARGES

It has been experimentally observed on the ISX-B that the introduction of a small amount of neon into a beam-heated, gettered plasma produces remarkable changes in the discharge characteristics,¹² and in particular it results in an increase of the global energy confinement time by a factor of up to 1.8. This mode of operation has been dubbed the Z-mode, while the L-mode (for Low confinement) is that of a clean, gettered plasma. In this section it is shown that

the higher τ_E^* attained in discharges with neon injection does not appear to be a consequence of an improved fast ion confinement.

As part of the Z-mode investigation, an experiment was performed whereby a sequence of well-gettered plasma shots was repeated with an added puffing of a small quantity of neon. All the external parameters were kept equal in the two sequences, and—at the time when the Thompson scattering profiles were taken—they were $B_\phi = 1.33$ T, $\bar{n}_e = 5.6 \times 10^{13} \text{ cm}^{-3}$, $I_p = 175$ kA, $P_b = 0.98$ MW, and $E_b = 31.2$ keV. (Since the particle confinement time increases when injecting neon, less deuterium was puffed into the vessel, in this case, to reach the same line-averaged density.) A 45% increment in τ_E^* was observed in the Z-mode discharges. Fast neutral spectra along several sightlines were obtained during both sequences, and they were then compared to see if any change could be detected which might lead to an explanation for the higher τ_E^* in terms of a larger beam ion population or an enhanced energy transfer to the plasma. While the tangential spectrum ($R_t = 72$ cm) had remained essentially unaffected, the perpendicular flux (at $R_t = 8.5$ cm) was found to be $\sim 90\%$ higher in the neon injection case, this representing the largest variation among all sightlines. Since this difference might be attributable to additional pitch angle scattering associated with the higher Z_{eff} in the neon sequence (2.0 as opposed to 1.56) and to changes in the T_e and n_e profiles, a meaningful comparison must take these effects into account. This was accomplished by comparing the experimental spectra in each sequence with those predicted by the Monte Carlo and the Fokker-Planck codes, which use as input the Thomson scattering profiles and the inferred Z_{eff} . The results are presented in Fig.

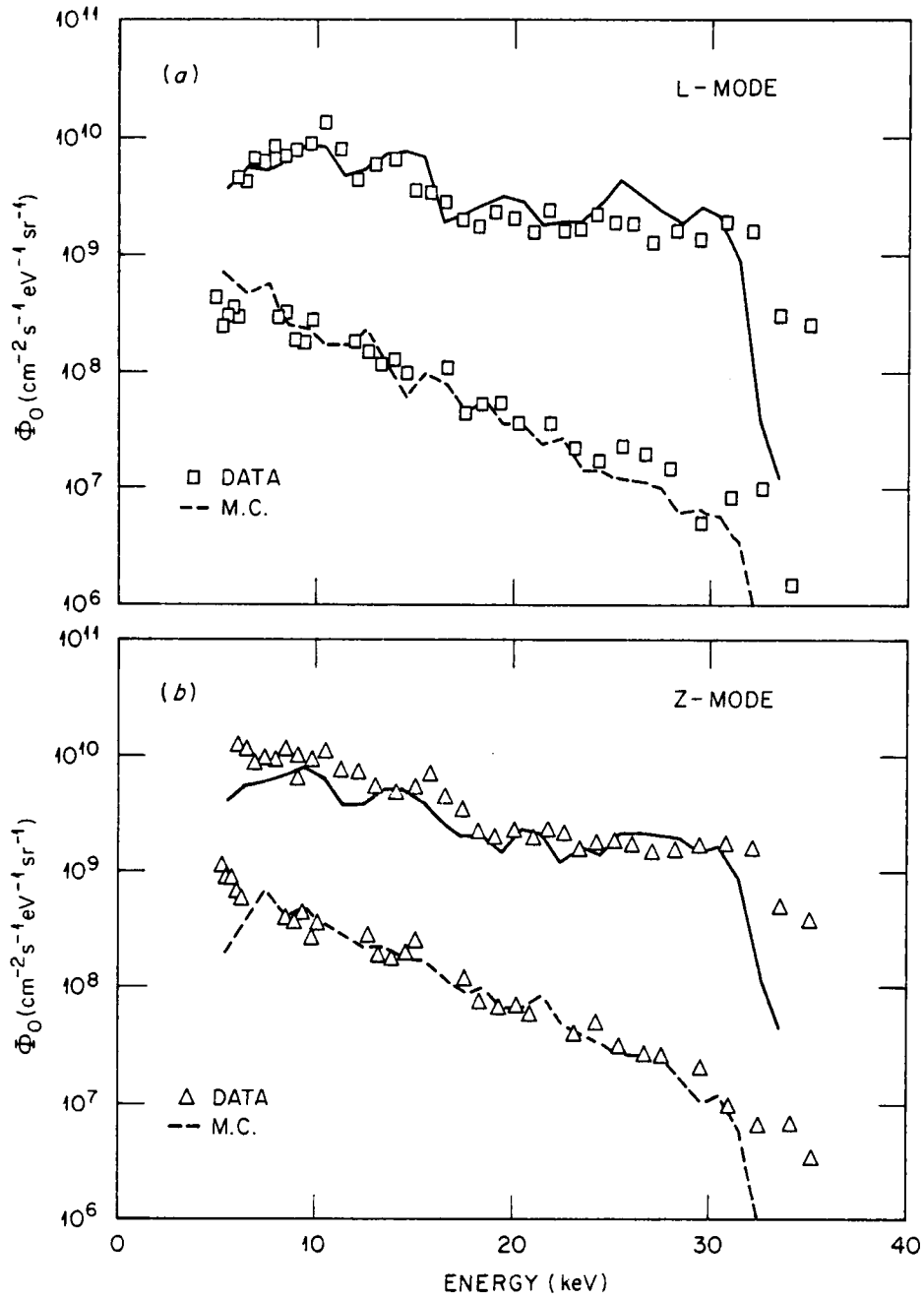


Fig. 2.4. Comparison of fast neutral spectra with the predictions of the orbit-following Monte Carlo simulation in *L*-mode and *Z*-mode discharges. In each plot, the spectrum with higher flux is along the tangential sightline ($R_t = 72$ cm), the other is along the perpendicular sightline ($R_t = 8.5$ cm). Good agreement is observed for both *L*-mode and *Z*-mode.

2.4(a) for the *L*-mode and 2.4(b) for the *Z*-mode. The FPP spectra were in close agreement with the Monte Carlo calculation. Two spectra are displayed for each sequence, corresponding to the viewing chords with $R_t = 72$ and 8.5 cm. The experimental data for the tangential spectra were artificially multiplied by a constant factor of 0.65—in both cases—to improve the match with the predicted magnitude of the flux. The simulation reproduces closely the shapes of the tangential spectra in the two sequences, being only slightly off in the low energy region for the neon case. The data along the perpendicular chord are in good agreement with the theoretical prediction, in shape *and* in magnitude, in both sequences. Thus, it can be concluded that classical processes describe accurately the behavior of the beam ions in the *L*- and *Z*-mode discharges analyzed here. The higher τ_E^* obtained with neon injection, therefore, cannot be attributed to an improved fast ion confinement.

The *Z*-mode is also produced by intrinsic impurities (i.e., without neon puffing) when gettering of the vessel walls is not used. In either case τ_E^* acquires a linear dependence on $\bar{n}_e$ and reaches higher values than in comparable gettered discharges. At the same time, neon injection into an ungettered discharge does not produce any significant enhancement in τ_E^* , nor is it seen to cause any increase in the beam-target neutron output. Accordingly, further evidence that the slowing down process is not anomalous in the *Z*-mode was obtained by comparing the measured decay times in the beam-target neutron yield—following beam turn-off—with the calculated values, in a gettered and an ungettered sequence. In both cases, the theory and experiment were found to be in agreement, within 30% (see Chapter 7), thus confirming that the *Z*-mode results do not appear to be related to anomalies in the confinement or the slowing down of the fast ions.

CHAPTER 3

THEORY OF NEUTRAL BEAM INJECTION. TOPICS IN THE ANALYSIS OF FAST NEUTRAL SPECTRA

3.1 INTRODUCTION

The basic physical processes relevant to neutral beam injection heating of tokamak plasmas are briefly reviewed in this chapter. Emphasis is placed on those topics that are related to the analysis of charge-exchange energy spectra of beam ions. The physical processes of interest are beam deposition, fast ion orbits, slowing down, pitch angle scattering, and charge-exchange rates. The sensitivity of fast neutral flux measurements to various effects resulting from those processes is investigated. The dependence of the measurements on the neutral particle analyzer viewing angle is also explored.

A further purpose of this review is to identify those assumptions in the theory that are questionable and, thus, indicate what type of anomalies might be found. The major approximations used in the analytical and in the simulation codes are also described.

The chapter is divided into three sections: beam deposition, fast ion orbits, and collisional effects.

3.2 DEPOSITION

As injected energetic neutrals penetrate into a plasma, some of them are ionized and form a source of fast ions. Since experimentally the NPA sightlines

lie on the torus equatorial plane, the quantity of interest is the fast ion distribution function as the ions first cross this plane. This may be expressed as a differential distribution $f_0(R, E, \zeta)$, in other words, the birth distribution in major radius (R), energy (E), and pitch angle (ζ , defined as $v_{\parallel}/v$, with $v_{\parallel} = \vec{v} \cdot \hat{J}_p$, where J_p is the toroidal plasma current density). In this section, the beam ion birth distribution and its relationship with the analysis of fast neutral spectra are discussed. The concepts of tangential and perpendicular injection are also developed.

3.2.1 The Three Energy Components, $f_0(E)$

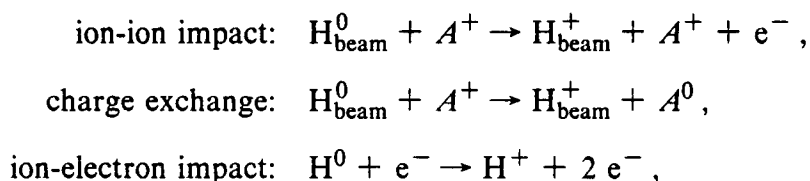
The ion cloud produced by an injector source is a mixture of three species, H^+ , H_2^+ , and H_3^+ . These ions are accelerated up to the injection energy (E_{inj}) by an applied high voltage and are then neutralized in a gas cell so that they may enter the plasma without being affected by the electromagnetic fields. Upon neutralization, H_2 and H_3 separate into their atomic components, giving rise to "currents" of H^0 atoms with energies of $E_{inj}/2$ and $E_{inj}/3$, respectively. Peaks corresponding to these three energies are usually visible in fast neutral spectra along sightlines with tangency radii close to the injection tangency radius. The beam fractional composition in neutral current at E_{inj} , $E_{inj}/2$, and $E_{inj}/3$ entering the ISX-B tokamak was calculated to be 0.41, 0.31, and 0.28 (Ref. 22) from test stand measurements.²³ These measurements are sensitive to the actual operating conditions, and the estimation carries an uncertainty of ~ 10 – 15% . The computational prediction of the fast neutral spectra was not sensitive enough to ascertain the beam fractional composition accurately through comparisons with the experimental data. However, deviations by $\sim 50\%$

from the estimated fractions (e.g., 0.2, 0.4, 0.4) resulted in predicted spectra that were discordant with the experiment.

On the PDX—where the same type of beams is used as on the ISX-B—attempts are being made at determining the beam species fractions by in situ experimental measurements.²⁴ Preliminary results indicate that—as position varies from center to edge—the fractional composition varies along the injector face from 0.45, 0.35, and 0.20 to 0.55, 0.30, and 0.15. An average composition of 0.45, 0.30, and 0.25 in the simulation codes results in good agreement with their experimental spectra.²⁵ The ISX-B data were found consistent with the species mix previously reported; therefore, a uniform fractional composition of 0.41, 0.31, and 0.28 was used in all the simulations for the present work.

3.2.2 Ionization Reactions

The injected neutrals are ionized in the plasma by collisions with electrons, bulk ions, impurity ions, and circulating beam ions. Impact ionization^{26,27} and charge exchange²⁷ are the main processes involved and may be schematically represented by the following:



where A symbolizes either a bulk ion or an impurity or a beam ion.

The cross sections, obtained through empirical fits²⁸ to the data, are shown in Fig. 3.1 (Ref. 29). The combined uncertainties of the experimental data and

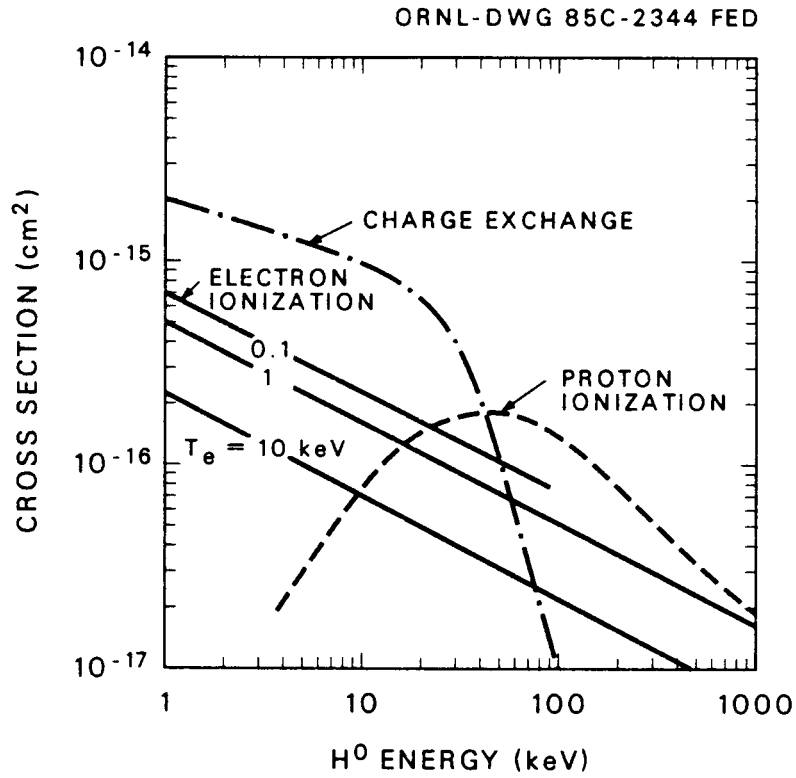


Fig. 3.1. The cross sections for ionization of the injected neutrals as a function of energy (after Sweetman²⁹). In the case of electron ionization, when $v_e > v_0$, $\langle \sigma_e v_e \rangle / v_0$ is shown for a maxwellian electron velocity distribution at temperature T_e .

fit are roughly $\pm 20\%$.³⁰ Charge exchange with background ions dominates the beam deposition in the energy range of the ISX-B experiments ($E_{\text{inj}} \sim 25$ to 35 keV), with ion-ion impact followed by ion-electron impact being of less importance.

3.2.3 Deposition Profiles, $f_0(R)$

All of the ionization reactions presented in Section 3.2.2, with the exception of beam neutral-beam ion reactions, are included in the calculation of the beam deposition in both the Fokker-Planck and the Monte Carlo codes. Since charge exchange and impact ionization on the circulating beam ions are not included in either code, it is necessary to estimate how large an effect is being neglected. The deposition profiles for the full energy component of the beam due to the different processes in a representative ISX-B discharge (0.9-MW co-injection, $\bar{n}_e = 4 \times 10^{13} \text{ cm}^{-3}$, $I_p = 145 \text{ kA}$, $Z_{\text{eff}} = 1.5$) are shown in Fig. 3.2. [The resulting fast ion density $n_{\text{fi}}(r)$ is strongly peaked on axis (at $R \approx 97 \text{ cm}$), a consequence of the smaller volumes of the central regions.] These profiles were obtained by following a single zero-width beamlet "launched" along the centerline of the actual beam with energy $E_{\text{inj}} = 30 \text{ keV}$. The fast ion distribution function used for the calculation of the deposition on the circulating beam ions was that determined by the Monte Carlo simulation. At each spatial step, the cross sections for the beam-beam deposition were calculated at the relative velocities in 30 bins in energy and 20 bins in pitch angle. The corresponding density of circulating beam ions in each R , E , ζ bin was used.

As can be seen from Fig. 3.3, the deposition profiles are affected only slightly by the omission of beam-beam interactions; furthermore, the total

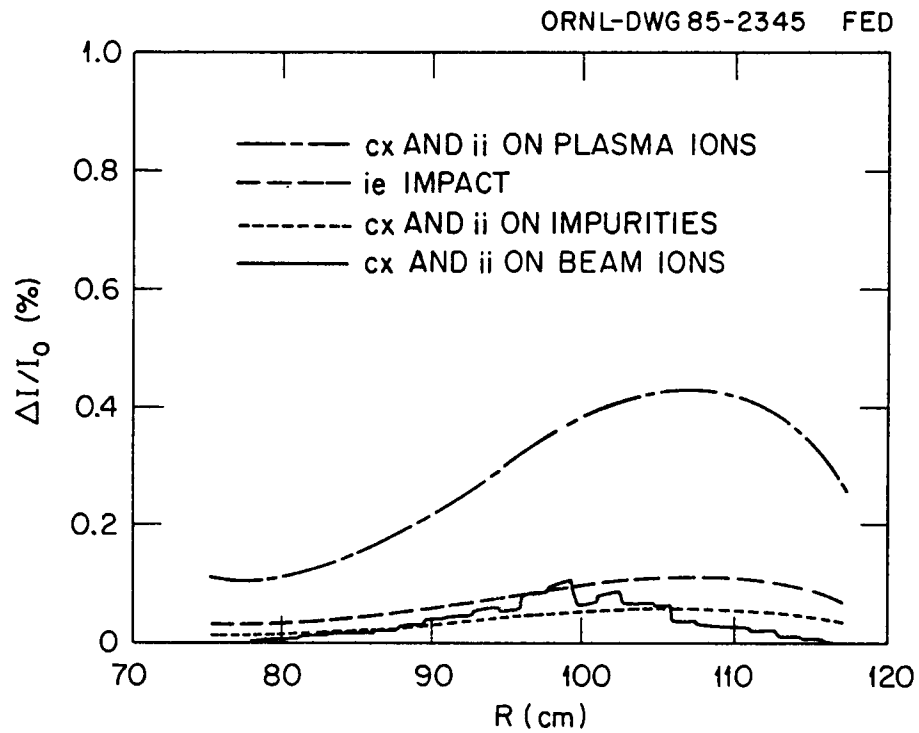


Fig. 3.2. Deposition of the full energy component of a neutral beam on ions, electrons, impurities, and beam ions.

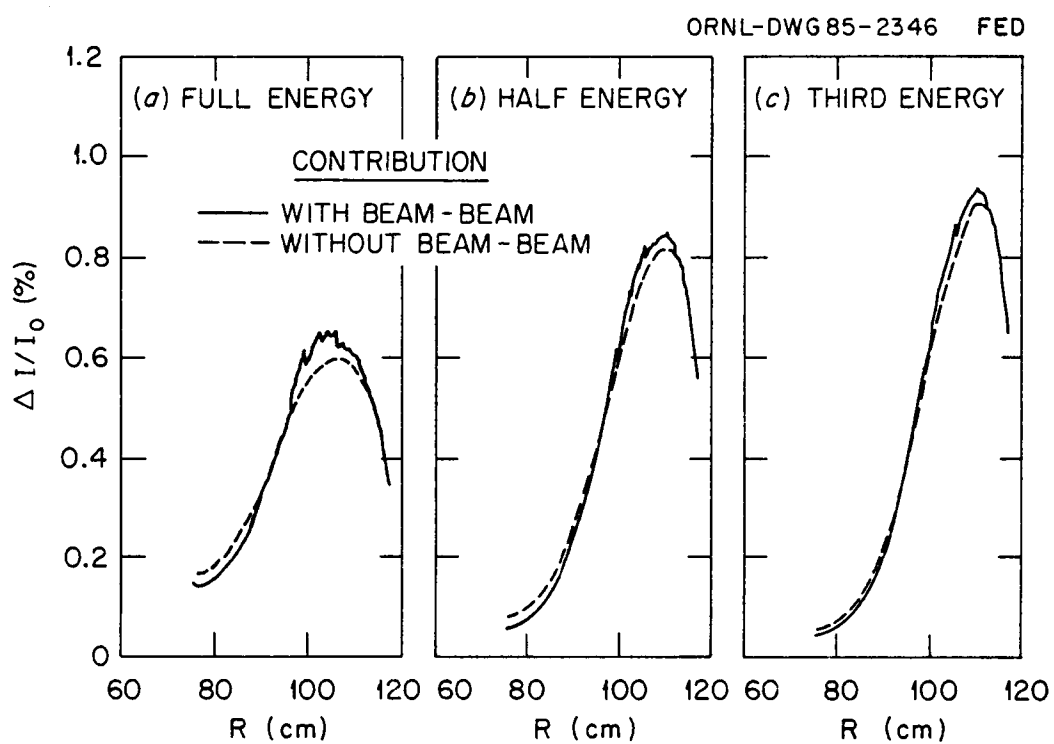


Fig. 3.3. Deposition of a neutral beam calculated with and without the beam-beam contribution.

amount of beam deposited differs only by $\leq 2\%$. This analysis did not take into account a higher-order effect, namely that in charge-exchange events between injected beam neutrals and circulating beam ions in which the primary neutral is deposited, the circulating ion is neutralized and forms a secondary neutral that may reionize somewhere else in the plasma. Since events of this type will be more important at a low relative energy—due to the energy dependence of the cross section—a good portion of these secondary neutrals is expected to have speed and direction close to those of the primary neutral, thus nullifying the deposition event. Thus, the approximation to neglect beam-beam deposition in analyzing typical ISX-B data is acceptable in view of larger uncertainties in the cross sections, although it may not be a negligible process in low $\bar{n}_e$, high P_b experiments.

3.2.4 Deposition Profiles, $f_0(\xi)$

In neutral beam injection heating schemes, it is desirable to deposit most of the beam power close to the plasma center, thereby heating the plasma core to the high temperatures required to achieve efficient fusion rates. If the plasma minor radius is large and the density high and access is limited by toroidal field coils and structure—conditions envisaged for a tokamak fusion reactor—it becomes necessary to increase the energy of the beam neutrals and to inject approximately perpendicular to the toroidal axis for the neutrals to reach the plasma center. However, it is found theoretically and experimentally (see Section 3.3) that high-energy, small pitch angle orbits are poorly confined. Moreover, as described in Section 2.3, large-scale instabilities are seen to take place

during high-power perpendicular injection, with considerable fast ion losses and deleterious effects on the heating efficiency.

The ISX-B relatively small plasma minor radius ($a_p \simeq 27$ cm), moderate densities, and good access allow a beam deposition close to the plasma center with tangential injection (injection at a large angle from perpendicular), the mean free path being $\simeq 45$ cm for a 30-keV H^0 neutral and $\bar{n}_e = 4 \times 10^{13}$ cm^{-3} . Since the neutrals are injected in a direction quasi-tangential to the plasma current, the ensuing fast ions will generally have an initial value of $|v_{\parallel}|/v$ close to unity. If $v_{\parallel} > 0$, the ion is said to be co-moving, and counter-moving if $v_{\parallel} < 0$. Similarly, co- and counter-injection correspond to an initial $v_{\parallel} > 0$ and < 0 , respectively.

Figure 3.4 shows the fast ion birth distribution profiles in pitch angle—at the torus midplane—for both a co- and a counter-injection case, obtained by following the ion orbits only up to the first two midplane crossings in the Monte Carlo simulation. The simulation was performed for a finite-size neutral beam, and scattering on plasma particles was included. Plasma current and line-averaged electron density for the co-injection sequence were $I_p = 180$ kA and $\bar{n}_e = 3.7 \times 10^{13}$ cm^{-3} , and for the counter-injection sequence they were $I_p = 170$ kA and $\bar{n}_e = 3.9 \times 10^{13}$ cm^{-3} . The distribution function has been integrated over the whole range in major radius R , approximately from 70 to 120 cm. It can be seen that as a consequence of the injection geometry very few ions are born with pitch angles detectable by a neutral particle analyzer oriented along sightlines close to perpendicular. Therefore, most of the signal along quasi-perpendicular chords will come from ions that have scattered

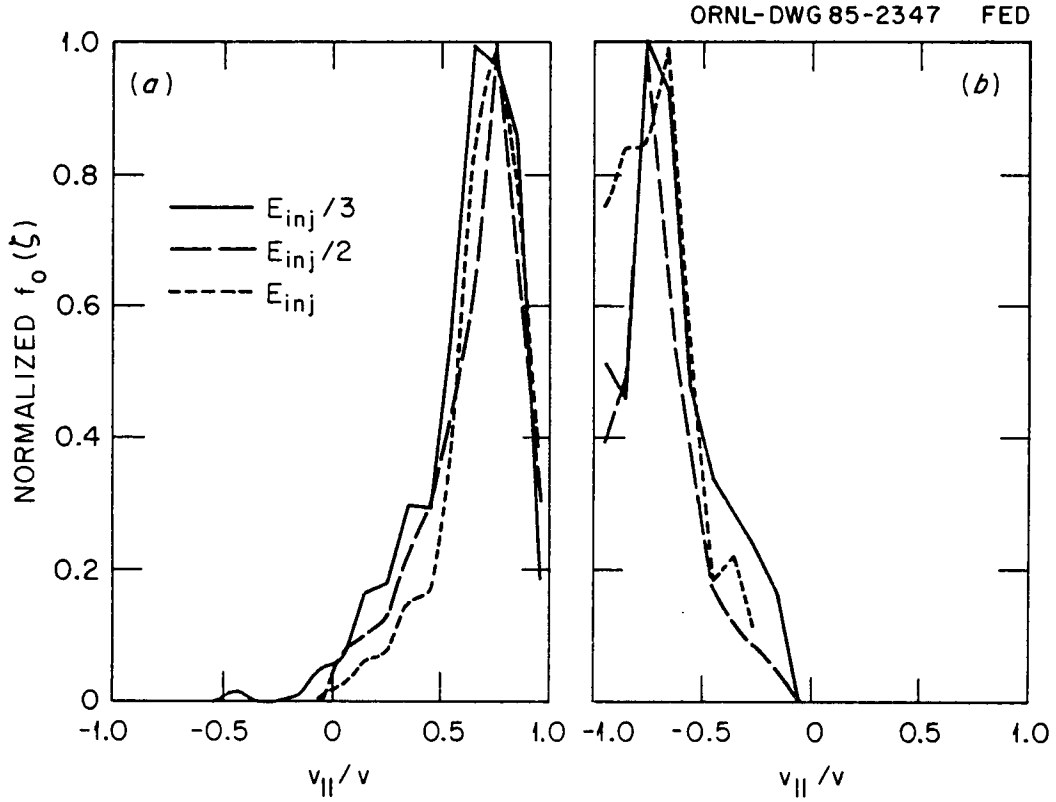


Fig. 3.4. Fast ion birth distribution in $v_{||}/v$ (integrated from $R = 70$ to $R = 120$ cm) at the horizontal midplane. The orbit-following calculation was performed for (a) a co-injection case ($\bar{n}_e = 3.7 \times 10^{13} \text{ cm}^{-3}$, $I_p = 180 \text{ kA}$) and (b) a counter-injection case ($\bar{n}_e = 3.8 \times 10^{13} \text{ cm}^{-3}$, $I_p = 170 \text{ kA}$).

through large angles in velocity space. However, this need not be true for energies close to E_{inj} , as will be considered next.

In Fig. 3.5, injection profiles (co-injection only) are compared for ions born near the plasma center ($90 < R < 100$ cm) and close to the inside edge of the plasma ($75 < R < 85$ cm). The latter profile is broader and centered at a smaller value of $v_{\parallel}/v$. This effect is a consequence of the conservation of magnetic moment μ ($\mu \propto v_{\perp}^2/B$) and energy ($E \propto v_{\perp}^2 + v_{\parallel}^2$) on the orbit time scale, discussed further in Section 3.3. As the ion moves to a smaller R , it encounters a stronger magnetic field B , and—because of μ conservation—its perpendicular velocity $v_{\perp}$ increases, and ζ decreases. As a result, there exists a significant population of fast ions with small initial pitch angles on the inside leg of their orbits. The Monte Carlo simulation, as well as the analytical code, calculates that this population gives rise to most of the charge-exchange signal along sightlines close to perpendicular for $E \approx E_{inj}$. This is perhaps not surprising, considering that very little pitch angle scattering occurs before the ions slow down to energies well below E_{inj} for typical ISX-B parameters (as discussed in Section 3.4), and, therefore, ions born with large $v_{\parallel}$ are very unlikely to contribute to the high-energy portion of the perpendicular spectrum. Ions that do attain a small pitch angle at birth, moreover, do so in a region where they have a relatively high probability to contribute to the fast neutral flux. To show this, it is necessary to digress briefly to clarify which factors determine the sensitivity of the neutral particle analyzer. This also serves the purpose of establishing some of the uncertainties in the charge-exchange measurements presented in this thesis.

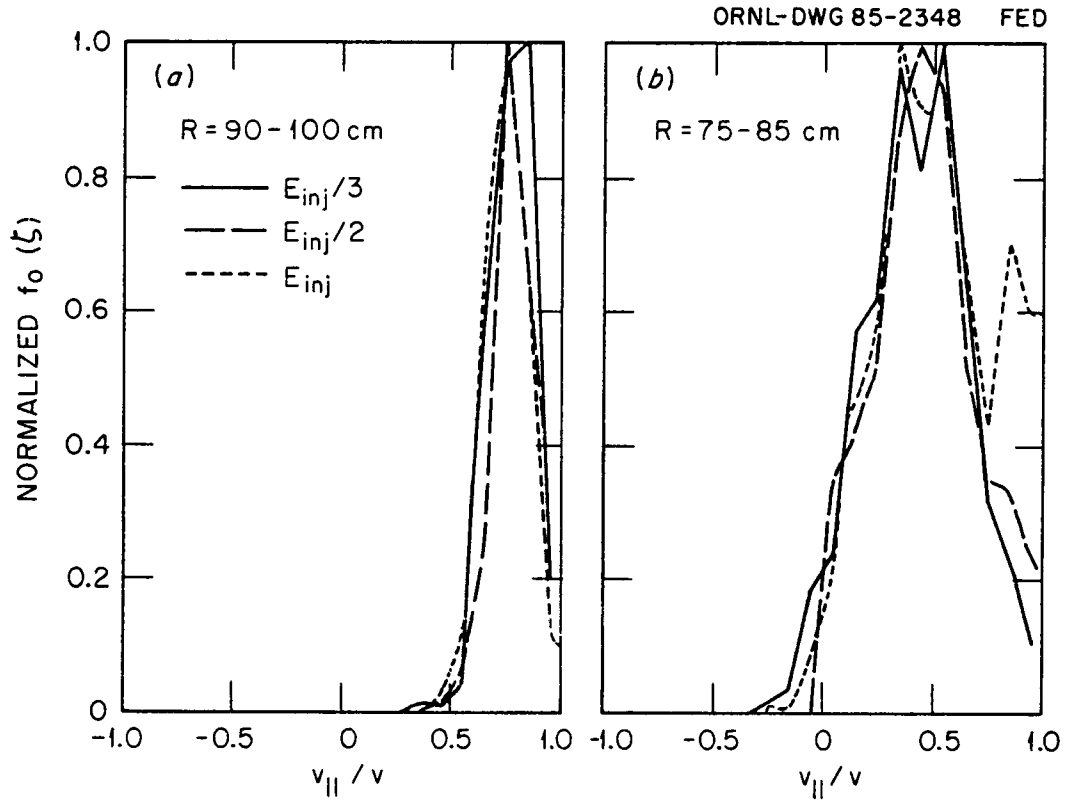


Fig. 3.5. Fast ion birth distribution in $v_{||}/v$ at the horizontal midplane in the plasma center (a) and close to the inside edge (b). This calculation was performed for the same co-injection case shown in Fig. 3.4.

Let $\Phi_0(R, E, R_t)^*$ be the flux of escaping neutrals in the energy range E to $E + \delta E$ originating from charge-exchange events at a location R in the plasma and detected by the neutral particle analyzer oriented along a sightline with tangency radius R_t in the horizontal midplane

$$\Phi_0(R, E, R_t) \propto n_{fi}(R, E, \zeta) n_0(R) \sigma_{cx} v e^{-\int (n\sigma)_{tot} ds}.$$

Here, $n_{fi}(R, E, \zeta)$ is the local density of fast ions with energies between E and $E + \delta E$ and aimed at the detector (i.e., with $\zeta = R_t/R$), $n_0(R)$ is the local background neutral density, σ_{cx} is the charge-exchange cross section evaluated at E , and v is the fast ion velocity. The attenuation integral is performed along the viewing chord from R to the outside edge of the plasma, and $(n\sigma)_{tot}$ is given by

$$(n\sigma)_{tot} = n_e(R) \left[\frac{\langle \sigma_{ie} v_e \rangle}{v} + (\sigma_{ii} + \sigma_{cx}) \left(\frac{n_i}{n_e} + \frac{n_I}{n_e} Z_I^{1.25} \right) \right],$$

with the bulk ion and impurity density fractions being

$$\frac{n_i}{n_e} = \frac{Z_I - Z_{eff}}{Z_I - 1},$$

*See Appendix B. Note that $n_{fi}(R, E, \zeta)$ is the same as $F_i(R, E, \zeta) \delta E \delta \Omega_v$ in the appendix.

and

$$\frac{n_I}{n_e} = \frac{Z_{\text{eff}} - 1}{Z_I(Z_I - 1)} ,$$

where Z_I and Z_{eff} are, respectively, the charge state of the dominant impurity and the effective Z of the plasma.

Computed attenuation integrals are shown in Fig. 3.6 for a low and a high density case ($\bar{n}_e = 2$ and $6 \times 10^{13} \text{ cm}^3$) along quasi-tangential and quasi-perpendicular sightlines at three energies. [Experimental $n_e(R)$ profiles from Thomson scattering diagnostics have been used in the calculations for this and the next figures.] As a way of illustration, it is seen from the figure that >50% of the ions with $E = 30 \text{ keV}$ and $\zeta = R_I/R \simeq 0.12$ that are neutralized close to the inside edge of a low density plasma are expected to reach the outside edge without reionizing.

As mentioned earlier, the uncertainty in the cross sections is $\sim 20\%$, even larger for ionization and charge exchange on impurities. Z_I is determined from spectroscopic measurements, whereas Z_{eff} is obtained, as part of the output of the ZORNOC tokamak data analysis code,³¹ from the measured values of the plasma current and loop voltage, a neoclassical expression for the parallel conductivity, and the assumption of a flat Z_{eff} profile. Uncertainties in the value of Z_{eff} affect not only the inferred bulk ion and impurity density fractions but also the calculation of fast ion scattering. Although it is difficult to place error bars on the deduced value of Z_{eff} , uncertainties of up to factors of 2 are possible. Furthermore, as pointed out by Goldston,⁹ the fast ions may experience a

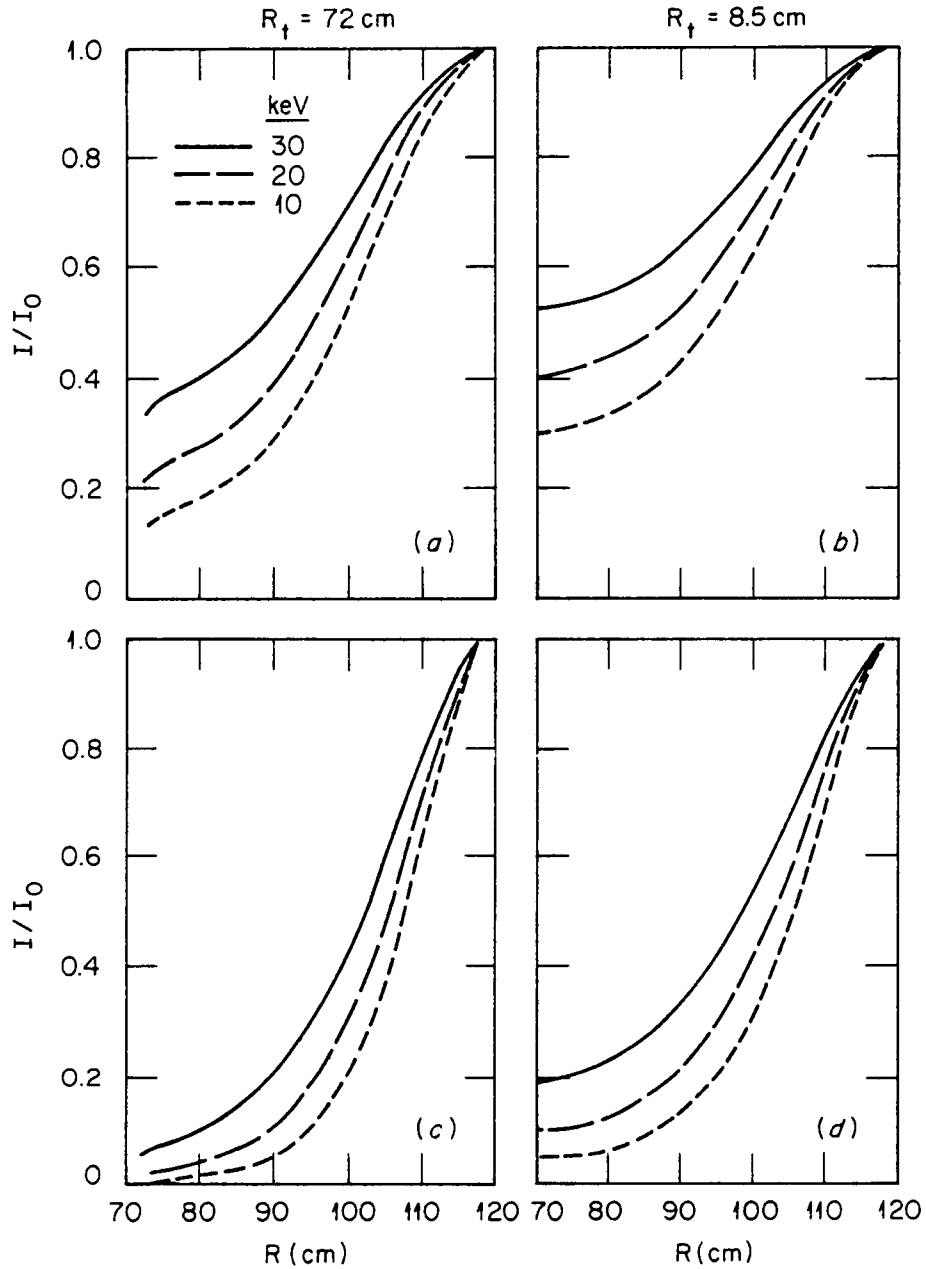


Fig. 3.6. Attenuation integrals computed for escaping charge-exchange neutrals with energy = 10, 20, and 30 keV. Two viewing chords are considered ($R_t = 72$ and 8.5 cm) and low and high plasma densities: (a,b) $\bar{n}_e = 2 \times 10^{13} \text{ cm}^{-3}$; (c,d) $\bar{n}_e = 6 \times 10^{13} \text{ cm}^{-3}$).

higher Z_{eff} than that deduced from resistivity because of their better penetration of the electron clouds of partially stripped impurities. (The fast ion density $n_{\text{fi}}(R, E, \zeta)$ is calculated by analytical and Monte Carlo codes and is the quantity under investigation here.) The last factor that remains to be considered in the expression for Φ is $n_0(R)$, which may well produce the largest uncertainty in the calculated signal for the following reasons. First, $n_0(R)$ is not experimentally measured but is obtained through a transport calculation in cylindrical geometry with axially uniform sources, using the code NEUCG.³² There are three quantities that enter the NEUCG calculation which are not well known: the edge neutral energy E_0 , the ion temperature profile $T_i(R)$, and the wall recycling. The first two determine the neutral penetration and, thus, the profile shape. The other affects the neutral source rate and, consequently, the value of n_0 at the plasma center— $n_0(0)$. The range of plausible values for these quantities may change the resulting Φ_0 by large factors (e.g., factors on the order of 10), as well as affect Φ_0 to varying degrees at different energies and sightlines. In addition, both E_0 and the wall recycling may have large toroidal variations, as discussed by Neilson;³³ therefore, it is not unrealistic to expect $n_0(R)$ at the NPA location to be different from the toroidally averaged $\langle n_0(R) \rangle$, which determines the overall charge-exchange losses. Some preliminary experimental evidence³⁴ has been gathered on the Tokamak Fusion Test Reactor (TFTR) at Princeton, indicating large differences in $n_0(0)$ at toroidal locations close to and far away from the main limiter. A further observation is that $n_0(R)$ is a steep function of R ; thus, it affects the local signal strongly because it may determine

where most of the detected flux originates. Figure 3.7 shows $n_0(R)$ profiles calculated by the NEUCG code for the illustrative low and high $\bar{n}_e$ cases and for two values of E_0 (5 and 100 eV) that roughly encompass the plausible range. The ratio $n_0(a_p)/n_0(0)$ is seen to be $\sim 10^2$ to 10^3 (depending on $\bar{n}_e$) if $E_0 = 5$ eV is assumed and it is reduced by a factor of ~ 10 for $E_0 = 100$ eV. The plots were obtained by assuming a wall recycling of 40%, which is believed to be a typical value in toroidal sectors far from the limiter. Close to the limiter, the recycling is expected to be much higher. A recycling of 90% would shift the profiles upward by a factor of ≈ 6 without changing their shapes. Consequently, the wall recycling affects strongly the charge-exchange losses and the magnitude of Φ_0 but alters only weakly (through the charge-exchange losses) the *shapes* of the fast neutral spectra. Uncertainties in the neutral density *profile*, on the other hand, affect strongly the shapes of the spectra, as well as the charge-exchange losses and the magnitude of the fast neutral flux.

The attenuation integral and $n_0(R)$ have been multiplied together and the result plotted in Fig. 3.8, obtained for a plasma sequence with a value of $\bar{n}_e$ ($4 \times 10^{13} \text{ cm}^{-3}$) that is representative of the data collected for this investigation. As a consequence of the steep profile, the charge-exchange source along the tangential sightline ($R_t = 72 \text{ cm}$) is highly peaked near the outside edge, regardless of energy. The low-energy fast neutral flux originates from that region along the perpendicular sightline as well. However, the perpendicular fast ion population at high energy is very small at the outside edge, resulting in low charge-exchange fluxes. It is evident that, if n_{fi} were the same at the plasma center ($R \approx 97 \text{ cm}$) and at the inside edge (say, $R \approx 75 \text{ cm}$), the

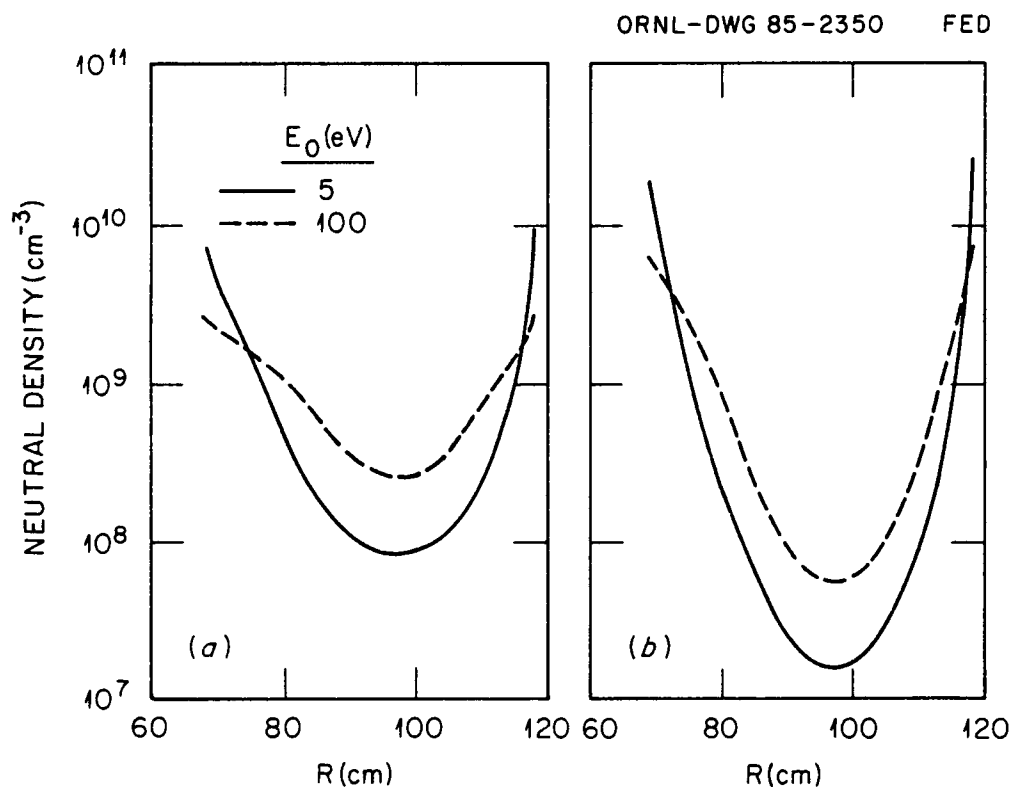


Fig. 3.7. Neutral density profiles for the edge source. The calculations were performed using the one-dimensional cylindrical code NEUCG for (a) $\bar{n}_e = 2 \times 10^{13} \text{ cm}^{-3}$ and (b) $\bar{n}_e = 6 \times 10^{13} \text{ cm}^{-3}$. For each case, the profiles resulting by assuming different edge neutral energies are shown.

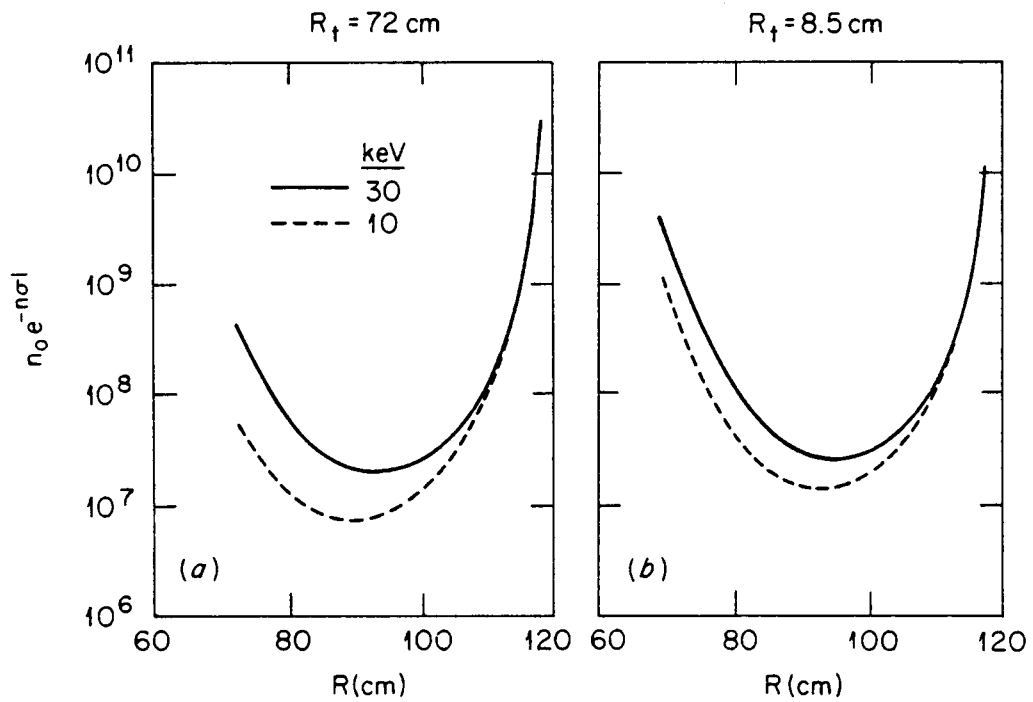


Fig. 3.8. The product of background neutral density (n_0) and attenuation integral. The calculated values along the tangential ($R_t = 72$ cm) and perpendicular ($R_t = 8.5$ cm) sightlines are plotted as a function of major radius R . The line-averaged electron density was $4 \times 10^{13} \text{ cm}^{-3}$.

high-energy perpendicular signal would originate predominantly from the *inside* edge. Referring back to Fig. 3.5 (page 36) and the previous discussion, the fast ion density at $E \approx E_{\text{inj}}$ and small ζ is expected to be *larger* at lower values of R than at the plasma center, reinforcing the conclusion that this signal represents mostly prompt losses of unscattered ions.

3.3 FAST ION ORBITS

Under the restrictions of a collisionless time scale, and assuming slow variations of the electromagnetic fields in time and space with respect to the particle gyromotion, the equations of motion for the fast ions can be obtained in the guiding center approximation.³⁵ With the further assumption that the fields are time-independent, those equations are integrated (numerically) by an orbit-following routine³⁶ in the Monte Carlo code to determine the particle trajectory between collisions.

For the purpose of classifying the orbit types, it proves convenient to introduce some further approximations, that is, toroidal axisymmetry, negligible electric field effects, and magnetic field $|\vec{B}| \approx B_\phi = B_0 R_0 / R$. Nonaxisymmetric effects have been studied on ISX-B,³⁷ and they are negligible for the standard 18 toroidal field coil operation. The velocity of the guiding center then factors into a vertical drift due to the gradient and curvature of $\vec{B}$:

$$\vec{v}_d = \frac{mc}{eBR} \left(v_{\parallel}^2 + \frac{v_{\perp}^2}{2} \right) \hat{y} , \quad (3.1)$$

and a velocity along the field lines

$$\vec{v}_{\text{aff}} = v_{\parallel} \hat{B} ; \quad (3.2)$$

the fast ion orbits can be easily visualized as a competition between these two motions,³⁸ with the energy and magnetic moment conserved.

In Section 3.3.1, the various orbit types will be discussed, and the orbit topology in the torus midplane as a function of R and $v_{\parallel}/v$ (Ref. 39) will be presented. The focus will be on the usefulness of the $(R, v_{\parallel}/v)$ diagrams in interpreting charge-exchange spectra.

3.3.1 Orbit Types

The variables chosen here to describe the guiding center orbits are R , E , and ζ and, specifically, the values they assume at the horizontal midplane (HMP) crossings. Also, the orbits will be characterized by their poloidal projections, that is, their projections on a vertical plane at a fixed toroidal location.

In a tokamak the particles are classified as “passing” or “trapped,” with correspondingly passing and trapped orbits—reviewed by, among others, Kadomtsev and Pogutse⁴⁰ and Stix.⁴¹ The two general categories include several orbit types, some of which will be discussed presently.

A co-passing orbit is one for which $\vec{v} \cdot \hat{J}_p > 0$ everywhere along the trajectory. Its poloidal projection is approximately a circle whose center is displaced outwardly from the axis of the magnetic surface by a distance $\delta \sim \epsilon \rho_p$,^{*} where

^{*}These estimates of δ start losing their validity as δ approaches a_p .

$\epsilon = r/R_0$ and the poloidal gyroradius $\rho_p = mc v/eB_\theta$. A counter-passing orbit, on the other hand, has $\vec{v} \cdot \hat{J}_p < 0$ everywhere and is a circle displaced *inwardly* from the magnetic axis by a distance $\delta \sim \epsilon \rho_p$. An estimate of $\rho_p(a_p)$ for a 30-keV proton in ISX-B yields $\sim 1.6 a_p$, with a corresponding $\delta \sim 0.5 a_p$.

As mentioned earlier, $v_{\parallel}$ decreases as the particle moves to regions of increasing magnetic field strength. If the orbit of a co-passing particle is topologically modified by considering it to have smaller and smaller values of ζ at the outer HMP crossing (ζ_0), for some sufficiently small ζ_0 the particle will reach the inner intersection with the HMP with $v_{\parallel} \simeq 0$. Equations (3.1) and (3.2) show that the motion is then dominated by the vertical drift, so the particle moves straight up until—due to the increasing poloidal field—it acquires an outward motion and an increasing $v_{\parallel}$, completing an orbit that resembles a “D.”

For even smaller values of ζ_0 , the particle will not reach the midplane but will be reflected back with $v_{\parallel} < 0$. The particle then follows a counter-moving path, whose center is shifted inward, until it reaches a symmetric turning point and is again reflected, this time co-moving. This kind of orbit is called a “banana” orbit because of its shape in the poloidal projection and has a width $\delta \sim 2\sqrt{\epsilon}\rho_p$. For a 10-keV proton at $r = a_p/2$, the width would roughly be $\delta \sim 0.7 a_p$. Particles following banana orbits are said to be “trapped” in the magnetic mirror.

Examples of these orbit types are shown in Fig. 3.9, which was obtained by performing the orbit-following Monte Carlo calculation with the collision operator turned off so that the particles would follow the orbits determined by their

ORNL-DWG 85-2352 FED

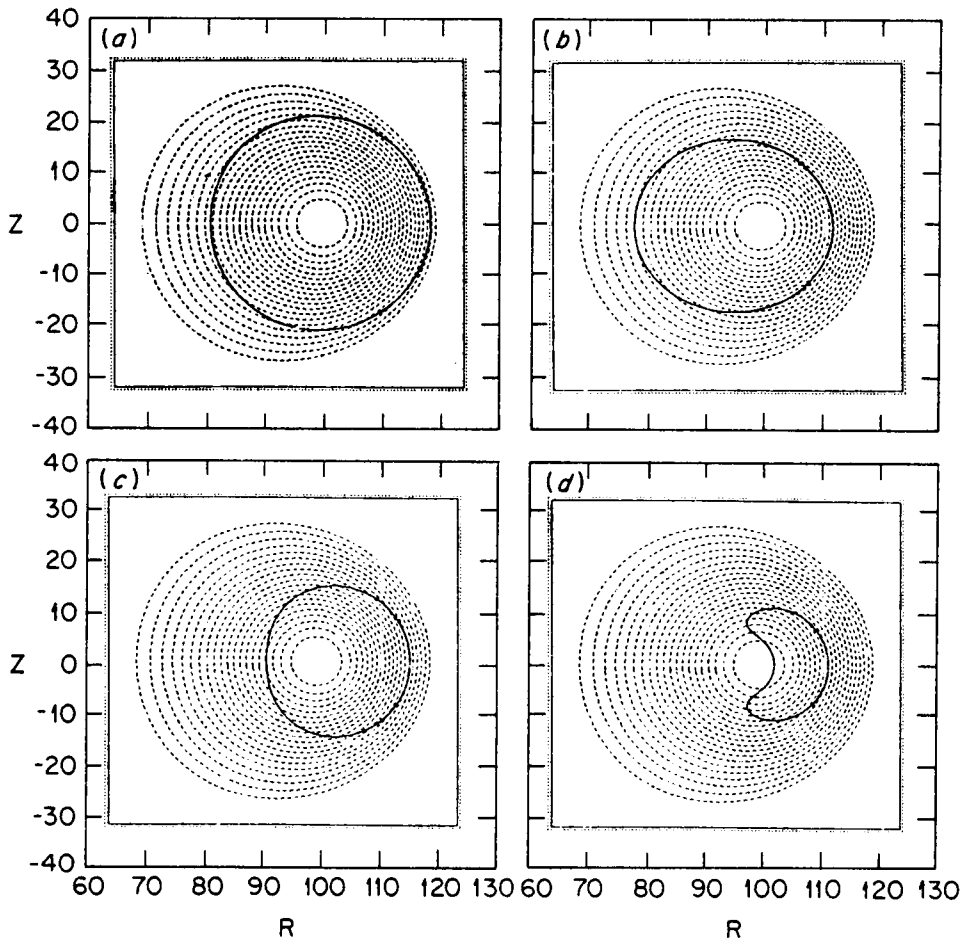


Fig. 3.9. Poloidal projections of four common orbit types in a tokamak; (a) co-passing, (b) counter-passing, (c) D-orbit, (d) banana orbit.

initial conditions. As illustrated by the plots, the particles may deviate considerably from their original flux surfaces (the dashed contours, determined by solving the equilibrium equation) and sample the plasma at different minor radii along their orbits.

Just as the D orbit connects the co-passing and the banana trapping regions, the "pinch" orbit lies on the boundary between the counter-passing and the trapping topologies. (A thorough discussion of pinch orbits and the orbit topology in general is given by Rome and Peng.⁴²) A schematic illustration of a pinch orbit is shown in Fig. 3.10. By a slight variation of its coordinates (R, E, ζ) , the pinch orbit can scatter into a large-width banana or kidney orbit, with $v_{\parallel} > 0$ on the outer leg, or into a counter-passing orbit, as shown in the figure.

To point out some of the approximations used in the analytical code (FPP), it may be noted here that FPP assigns each particle at the time of deposition to a radial shell between two adjacent concentric flux surfaces of circular cross section, at an average minor radius among those sampled by the orbit, and does not allow for radial transport; that is, the particle does all its slowing down and scattering while remaining in the same shell. The banana orbits are treated in the zero-width approximation, that is, at the turning points the particle is reflected back along the same path followed while co-moving. Thus, the trapping region is symmetric in $v_{\parallel}$, $v_{\perp}$ space about the $v_{\perp}$ axis, with the trapping boundary given by $|v_{\perp}/v| \geq (1 - 2r/R)^{1/2}$ from E and μ conservation. Writing the expression for the trapping boundary as $|v_{\parallel}/v| \leq (2r/R)^{1/2}$, it is seen that a particle with $v_{\parallel} \approx 0$ is considered in FPP to be deeply trapped, though it

ORNL-DWG 85-2353 FED

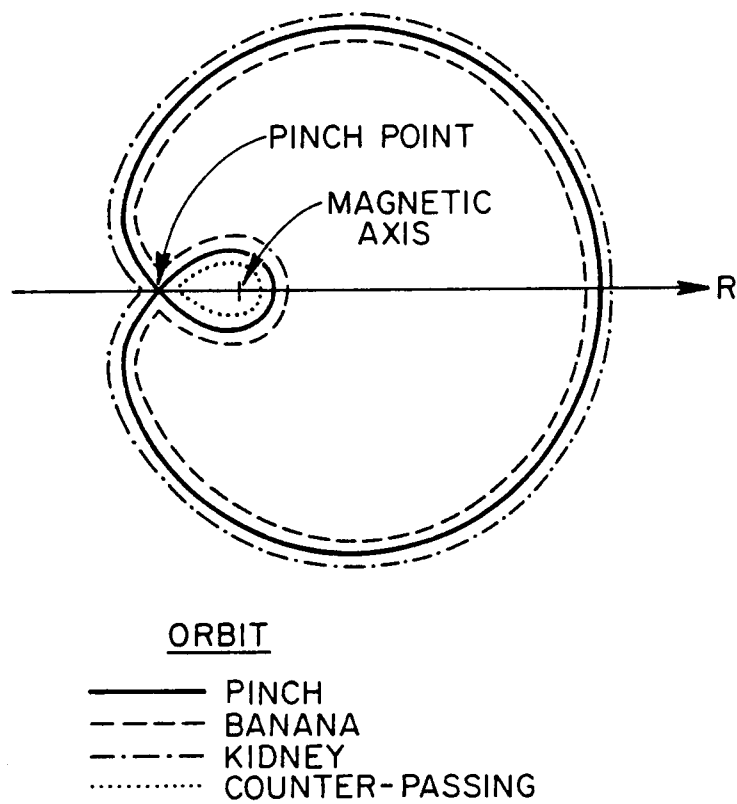


Fig. 3.10. The pinch orbit and neighboring orbits (after Rome and Peng⁴²).

actually is at the boundary of the trapping region (e.g., the D orbits). Furthermore, no pinch orbits are treated in the FPP code, and this will have dramatic effects on the predicted fast neutral spectra along viewing sightlines sensitive to this class of orbits, as discussed later.

3.3.2 Orbit Loss Regions

An important feature of the orbit topology is the boundaries of the loss regions: an orbit crossing the HMP in one of these regions takes the particle outside the plasma, and the particle is considered lost.*

Figure 3.11 depicts the topology for a 10-keV proton in a plasma equilibrium that represents in a qualitative fashion much of the ISX-B data. A loss region for co-passing ions is seen at the inner edge of the plasma; these ions will exit the plasma on the outside because the centers of their orbits are shifted outward from the axes of the magnetic surfaces. Similarly, counter-passing particles close to the outer edge of the plasma will follow orbits out of the plasma on the inside. Pinch orbits, counter X-type stagnation orbits (a deformation of the pinch orbit), large-width and outer bananas, and large-width kidney orbits make up the remaining boundaries of the loss regions.

The topology for a 30-keV proton is shown in Fig. 3.12, which prompts two immediate observations: a larger space of the $R, v_{\parallel}/v$ diagram is occupied by the loss region at higher energies, and the co- and counter-halves of the space are now disconnected, so, for example, counter-passing particles can no longer achieve $v_{\parallel} \geq 0$ through small-angle scattering.

*The particle must actually hit the vessel wall, or a limiter, to be lost. However, this is not taken into account in the computational codes used for the present investigation.

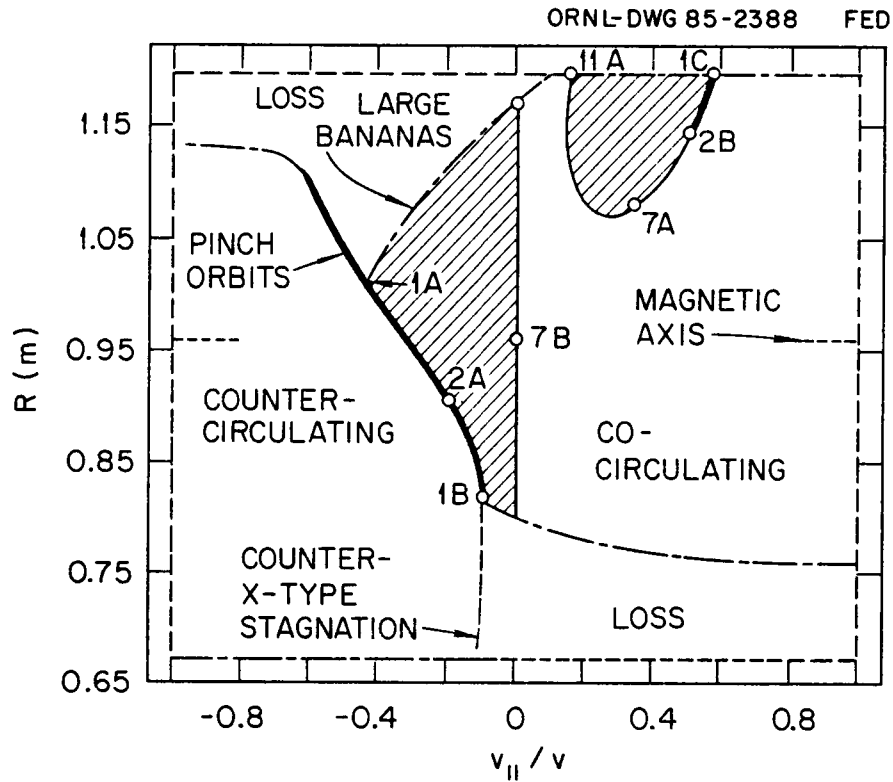


Fig. 3.11. Orbit topology for a 10-keV proton (after Rome, Lyon, and Fowler³⁹). Shaded areas represent trapping regions. A low β (0.3% volume-averaged), low current ($I_p = 110$ kA) equilibrium was used for the calculation.

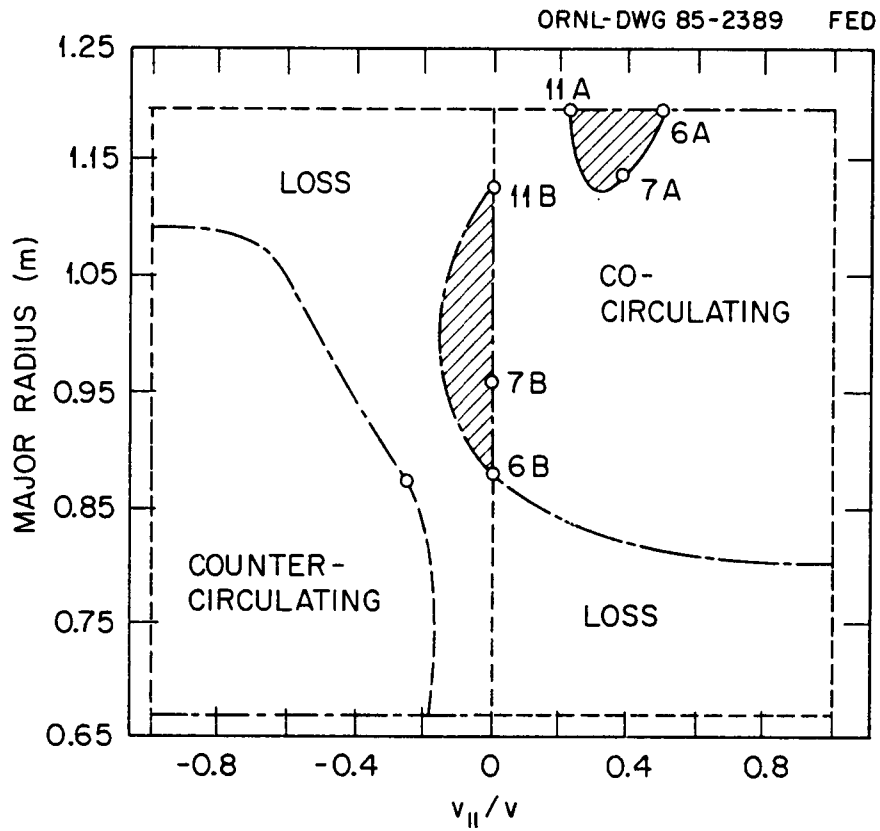


Fig. 3.12. Orbit topology for a 30-keV proton (after Rome, Lyon, and Fowler³⁹). The calculation is for the same equilibrium as in Fig. 3.11.

As is discussed in Chapter 4, the loss regions are properly implemented in the Monte Carlo code, whereas in the FPP code they are retained in an approximate manner for counter-injection only (except at deposition, as noted). The rationale for the FPP treatment of the loss regions is that co-injected ions must scatter through a large portion of the trapping region before reaching the loss boundary, and it would be inconsistent to account for a large banana-width effect in a zero-width approximation. For counter-injection in FPP, the loss region is the trapping region at energies $\geq E_{\text{loss}}(r)$, where $E_{\text{loss}}(r)$ is the energy that results in a banana width $\delta = a_p - r$. In the approximate treatment of the orbits, the pitch angle at the trapping boundary is independent of energy. As a result, the fraction of fast ions trapped during counter-injection is underestimated (except at low E). Thus, FPP may tend to underestimate the orbit losses during counter-injection as well as co-injection.

3.3.3 Tangential vs Perpendicular Injection

As pointed out in Section 3.2, energetic, perpendicular ions (i.e., those having a small $|v_{\parallel}/v|$) are not well confined. It is evident, by looking at Fig. 3.12, that only a small region of the $R, v_{\parallel}/v$ space is occupied by confined orbits for this class of ions. Furthermore, the trapped ions will pass near the plasma edge on the co-moving portions of their orbits and will, therefore, have a fairly large chance to charge exchange and escape from the plasma due to the high background neutral density. The co-passing ions will also have large orbit widths since the drift velocity dominates their motion, resulting in wide deviations from the flux surfaces. Thus, they may be lost through charge exchange. Those confined perpendicular ions that are not lost to charge exchange may still scatter in phase and real space into the nearby orbit loss regions.

In perpendicular injection schemes, the ions are *born* not too far from the loss regions, and direct orbit and charge-exchange losses may be a significant fraction of the total injected power. Perpendicular injection in the counter-direction results in very large prompt orbit losses. With tangential injection, on the other hand, most of the ions are born on well-confined orbits, and they need to scatter more before they reach the loss region.

An experimental illustration of these two different confinement regimes is presented in Fig. 3.13. Fast neutral spectra at $R_i \approx R_i(\text{inj})$ are shown for a typical ISX-B tangential co-injection case [Fig. 3.13(a)] and for the diagnostic neutral beam (DNB) counter-injected perpendicularly [Fig. 3.13(b)]. Qualitatively, there is a substantial difference between the two spectra. The tangential spectrum is rather smooth, showing only small peaks at the three beam energy components. The fast ions are well confined as they slow down and, thus, contribute to the signal at all energies. The DNB spectrum, on the other hand, displays marked peaks at the injected components.* In this case, the ions are quickly lost from the plasma; therefore, the spectrum is depleted at energies below the injection energies.

3.3.4 Sensitivity of the NPA to the Orbit Topology

A few observations have already been made regarding orbit effects on the fast ion distribution function and on the sensitivity of the NPA to the orbit topology. Here, some additional viewpoints are presented, illustrated by specific examples. This will provide information on what classes of orbits contribute most strongly to the CX signal along the different sightlines, what the spatial

*The DNB working gas was deuterium, but a small hydrogen contamination from the beamline walls produced HD₂ and HD molecules, which gave rise to the D⁰ peaks at $E \approx 10$ and 16 keV, respectively.

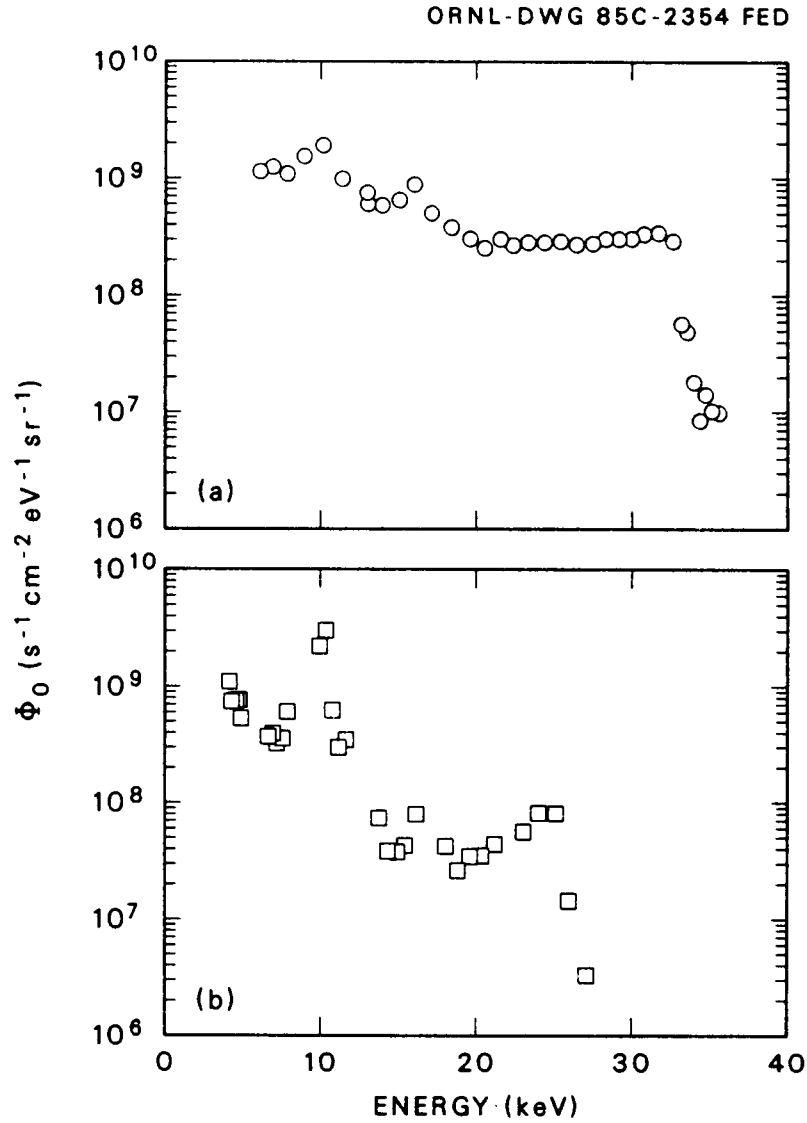


Fig. 3.13. Tangential vs perpendicular injection. Fast neutral spectra at $R_t \approx R_t(\text{injection})$ for (a) a typical ISX-B tangential co-injection case and (b) the DNB counter-injected perpendicularly. $E_{\text{inj}} \approx 31.5$ and 24 keV for (a) and (b), respectively.

origination profile of the signal is, and for what cases is the approximate, analytical treatment inadequate for predicting NPA spectra. Such information is vital to a good understanding of CX spectra, and the fast neutral spectrum calculator developed for this thesis performs this type of analysis in a consistent way.

The equation for an NPA sightline viewing in the equatorial plane with tangency radius R_t , in the $R, v_{\parallel}/v$ space, is $v_{\parallel}/v = \pm R_t/R$, obtained from simple geometry (“ $\pm$,” depending on whether the analyzer is viewing co- or counter-moving particles). The same equation applies to the beam centerline, with $R_t = 74.5$ cm for ISX-B and “ $\pm$ ” indicating co- or counter-injection. Representative tangential and perpendicular NPA viewing chords are shown in Fig. 3.14, superimposed on the orbit topology for a 10-keV proton. A simple observation is that no signal is expected from the inner region of the torus along sightlines with $R_t > 0$ nor from the outer region along sightlines with $R_t < 0$. Another immediate conclusion is that both tangential and perpendicular “positive” chords sample solely co-passing ions. In contrast, as noted previously, the zero-width calculation leads to the result that the perpendicular signal comes almost entirely from trapped particles.

The importance of referring to the orbit diagrams in interpreting charge-exchange spectra to infer fast ion confinement is perhaps best illustrated by a comparison of perpendicular spectra during co- and counter-injection. Figure 3.15 shows the experimental spectra at $R_t = +8.5$ cm and $R_t = -8.5$ cm, during injection at $R_t = +74.5$ cm and $R_t = -74.5$ cm, respectively, with plasma and beam parameters for the two sequences kept as nearly the same as

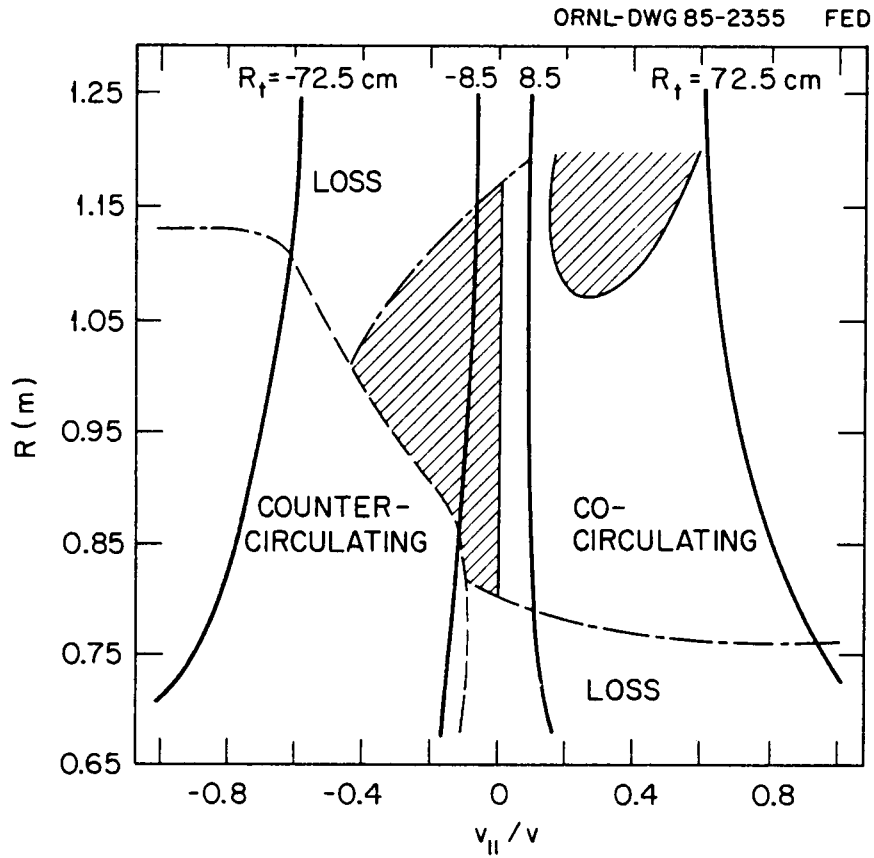


Fig. 3.14. Four representative NPA sightlines superimposed on the orbit topology for a 10-keV proton.

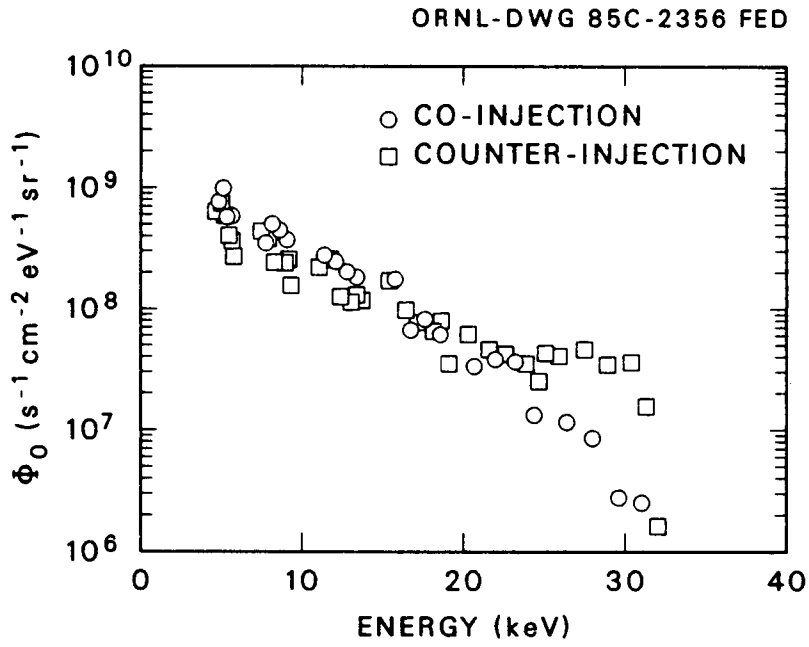


Fig. 3.15. Comparison of perpendicular fast neutral spectra during co- and counter-injection. The main parameters of the discharge were (co-/counter-): $\bar{n}_e = 3.8/3.9 \times 10^{13} cm^{-3}$, $I_p = 144/145$ kA, $B_\phi = 1.21/1.21$ T, $P_b = 0.92/0.89$ MW.

possible. It is seen that the high-energy portion of the counter-injection spectrum is larger than the corresponding co-injection signal. However, concluding from this that counter-injected ions are better confined or that the background neutral density in counter-injection sequences is higher would be erroneous. The observed effect is instead a consequence of the asymmetry of the orbit topology. Both signals are due to prompt losses of particles that ionize close to the outside edge of the plasma and achieve a small value of $v_{\parallel}/v$ at the inside crossing. The difference is that in the counter case this inside crossing can be very close to the plasma periphery (precluded by the loss region in the co-case); thus, the signal originates from a region of higher background neutral density.

One significant result of the Monte Carlo simulation is that the largest part of the fast neutral flux for *all* sightlines with $-72 < R_t < -8$ cm, during tangential counter-injection, comes from a region close to the plasma edge on the *inside* of the torus, as shown in Fig. 3.16; this is a consequence of the strong dependence of Φ_0 on $n_0(R)$. By contrast, the co-moving signal detected during tangential co-injection originates from the outer few centimeters of the plasma along tangential chords, mostly from a wide band around the magnetic axis for sightlines with smaller tangency radii (Fig. 3.17). In this case, the prediction is explained by the fact that the injected ions need only small pitch angle scatter to be viewed along sightlines with $R_t \approx R_i$ (injection). Thus, prompt losses of ions deposited close to the outside edge of the plasma—again, in a region of high n_0 —contribute to the largest portion of the signal. On the other hand, ions born on the outside would require a large angle scatter to be detected along perpendicular chords, and this is much more likely to happen at the plasma center than at the periphery since the ratio of the scattering time to

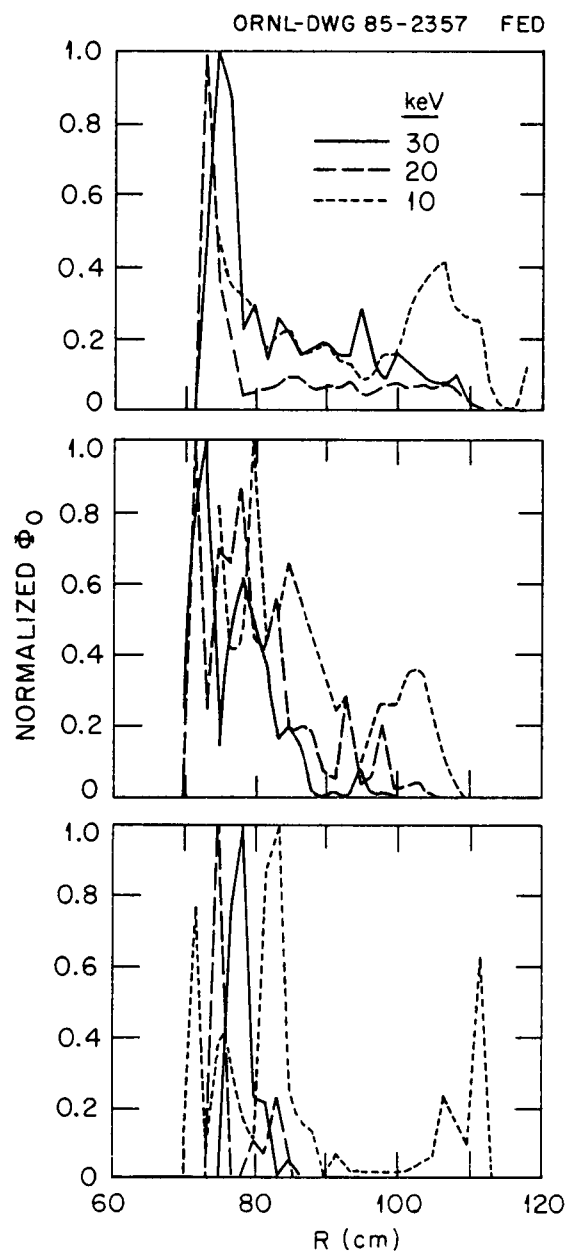


Fig. 3.16. Neutral flux origination profiles during counter-injection. Top: $R_t = -72$ cm; center: $R_t = -42$ cm; bottom: $R_t = -8.5$ cm. Plasma parameters were $\bar{n}_e = 3.7 \times 10^{13} \text{ cm}^{-3}$, $I_p = 110$ kA, $B_\phi = 1.23$ T. The plasma edge is at $R \approx 68$ cm.

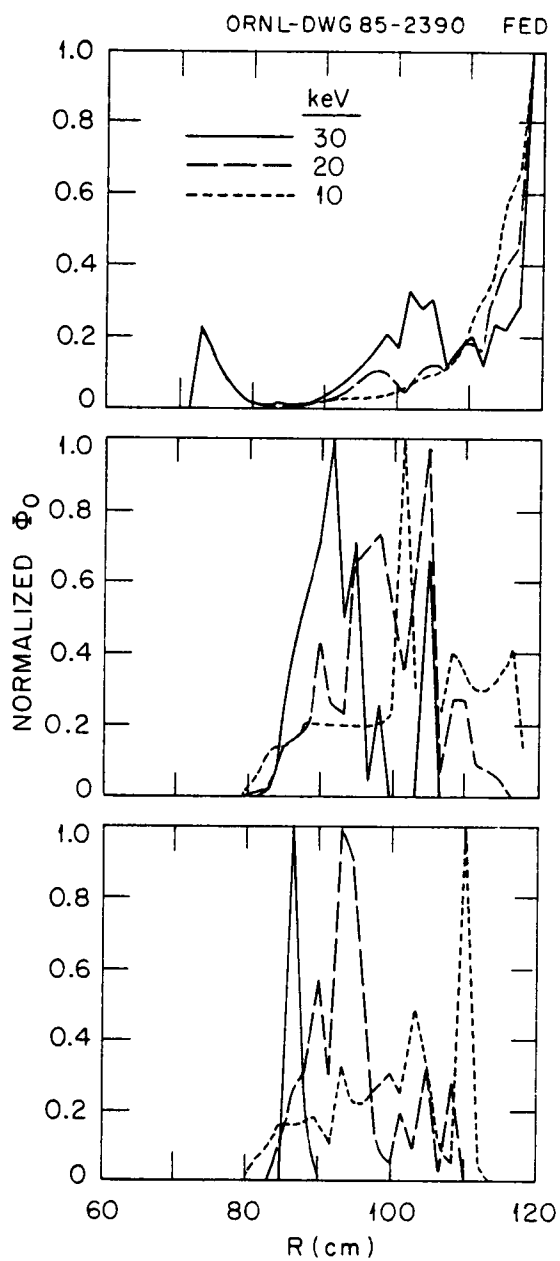


Fig. 3.17. Neutral flux origination profiles during co-injection. Top: $R_i = 72$ cm; center: $R_i = 42$ cm; bottom: $R_i = 8.5$ cm. Plasma parameters were $\bar{n}_e = 3.7 \times 10^{13} \text{ cm}^{-3}$, $I_p = 96 \text{ kA}$, $B_\phi = 1.34 \text{ T}$. The plasma edge is at $R \approx 120 \text{ cm}$.

the slowing-down time is much smaller at the center, as discussed in Section 3.4. Moreover, the initial pitch angle attained at the inner HMP crossing is smaller than that at the outer HMP crossing so less scattering is necessary.

Another illustration of how sensitive the NPA signal can be to the orbit topology is depicted in Fig. 3.18. The simulated fast neutral spectra in a counter-injection sequence at three perpendicular sightlines are plotted together. The tangency radii of the viewing chords are -10 , -8.5 , and -6 cm. The spectra at $R_t = -10$ cm and $R_t = -8.5$ cm are almost indistinguishable from each other, but looking in a slightly more perpendicular direction ($R_t = -6$ cm), a large drop in the detected signal is observed. The interpretation of this result is quite simple, referring back to Figs. 3.12 and 3.14 (pages 52 and 57): these sightlines pass very close to the boundary of the loss region at small values of R (from which most of the signal arises), and the discontinuity in Φ_0 is a consequence of the viewing chord crossing this boundary. The perpendicular analyzer [momentum energy analyzer (MEA)] could not be oriented to view sightlines with $|R_t| < 8.5$ cm, but the same effect was noted experimentally by comparing the spectra at $R_t = -8.5$ cm during counter-injection at different plasma currents (Chapter 5). A large decrease in the high-energy signal was detected when I_p was lowered from 145 kA to 110 kA, and this is interpreted as the loss region boundary crossing the fixed viewing chord.

A more general verification of the orbit topology comes from an experiment in which the beam was counter-injected ($R_t = -74.5$ cm), whereas the analyzers were oriented to look at co-moving ions and scanned toroidally from $R_t = 8.5$ cm to $R_t = 87$ cm. (A similar experiment was first performed at

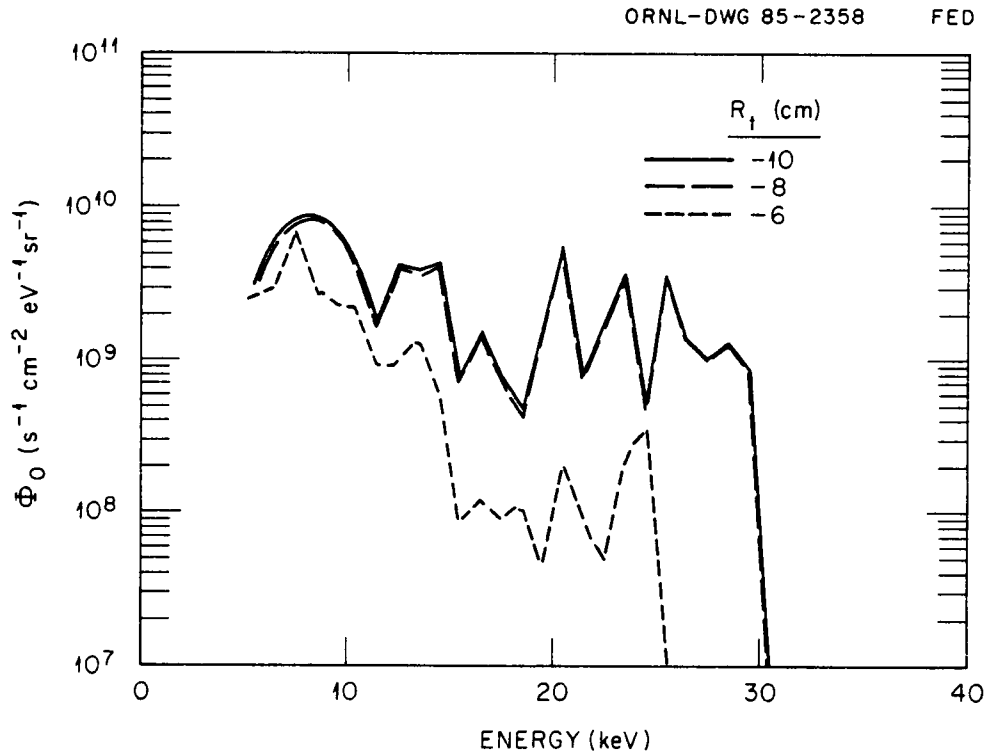


Fig. 3.18. Effects of the orbit topology on the NPA spectra. The orbit-following Monte Carlo simulation along three neighboring sightlines is shown for a counter-injection case. The spectrum is depleted when the viewing chord ($R_t = -6$ cm) crosses the loss region boundary.

Princeton on the PLT tokamak.⁴³⁾ To be detected, the ions must have their velocity vector changed from antiparallel to parallel to $\hat{J}_p$. This “reflected” flux, according to the orbit picture (and under the basic assumption of the Fokker-Planck theory that scattering by a large angle is due to multiple small-angle collisions), comes entirely from ions that have scattered through the trapping region and from ions following pinch orbits and fat bananas, and it is characterized by a peak at quasi-tangential sightlines detecting ions on pinch orbits. The experimental flux as a function of tangency radius at three energies, together with the corresponding curves calculated by the Monte Carlo code, is shown in Fig. 3.19. The simulation properly reproduces the shapes of the experimental curves, as well as the magnitude of the flux at the low and medium energies, where the statistical quality is better, thus confirming the validity of the orbit theory. By contrast, it will be shown in Chapter 4 that the zero-banana-width approximation of the FPP code results in the fast neutral flux being higher at the more perpendicular sightlines, contrary to the experiment.

3.4 COLLISIONAL EFFECTS

The statistical description of the fast ion population is contained in the differential distribution function $f(\vec{x}, \vec{v}, t)$. The time evolution of f , as the fast ions deliver their energy to the plasma, is described by the Boltzmann equation. This is averaged over the ion gyromotion to yield the following “drift-kinetic” equation:

$$\frac{df}{dt} = \frac{\partial f}{\partial t} + \vec{v} \cdot \vec{\nabla}_r f + \frac{Ze}{m} \vec{E} \cdot \vec{\nabla}_v f = \left. \frac{\partial f}{\partial t} \right|_{\text{collisions}} + S - L, \quad (3.3)$$

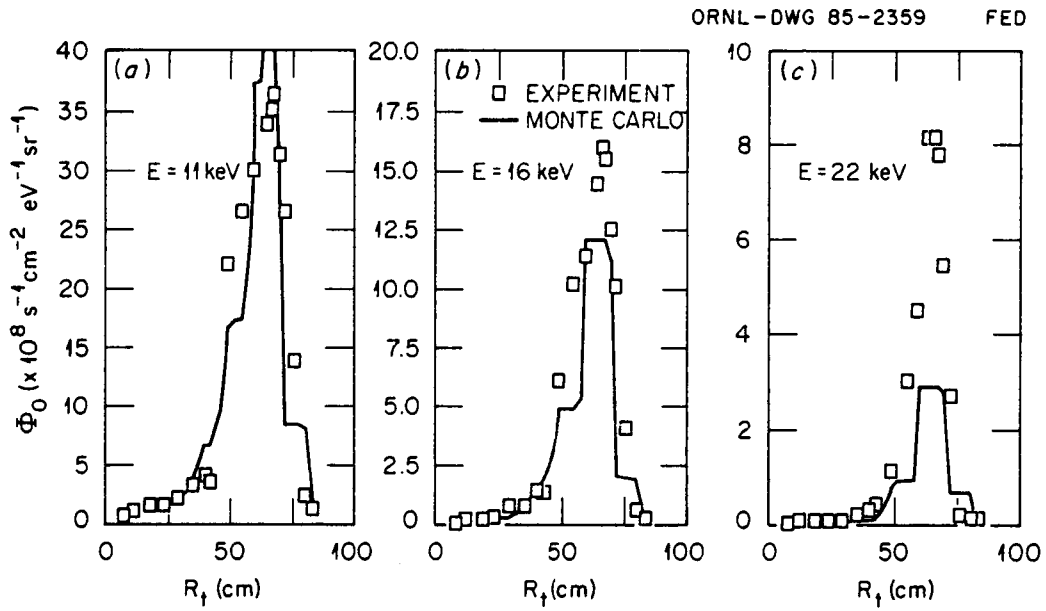


Fig. 3.19. Co-going fast neutral flux detected during counter-injection. The flux is plotted as a function of the tangency radius of the viewing chord and at three energies. The orbit-following Monte Carlo simulation is in good agreement with the experiment (the discrepancy in flux magnitude at high energy is partly attributable to poor statistics).

where S represents the beam ion source rate, L is the loss rate (unconfined orbits and charge exchange), v is the velocity of the guiding center, E is the macroscopic electric field, and the change due to collisions with the background particles is given by the Fokker-Planck operator derived by Rosenbluth, MacDonald, and Judd.⁴⁴

The term $\vec{v} \cdot \vec{\nabla}_r f$ gives the rate of change of f as a function of the spatial coordinates and—in the Monte Carlo code—is treated by the orbit integration. The other terms, governing the slowing down, scattering, energy diffusion, and charge exchange, are discussed in this section (to first order in T_e/E_{beam}), and their relevance to plasma heating, ISX-B parameters, and NPA spectra is considered.

As a general premise, it is worth noting that the following operators are “bounce averaged” along the first orbit in the analytical treatment, whereas they are calculated locally by the orbit-following Monte Carlo code.

3.4.1 Slowing Down

The fast ions slow down through drag on electrons, bulk ions, and impurities, and the corresponding rate of change in f —for $v_i < v \ll v_e$ —is given by⁴⁵

$$\frac{\partial f}{\partial t} = \frac{1}{\tau_{se} v^2} \left\{ \frac{\partial}{\partial v} [(v^3 + v_c^3) f] + \frac{\partial}{\partial v} \left[\left(\frac{v^2 T_e}{m} + \frac{v_c^3 T_i}{m v} \right) \frac{\partial f}{\partial v} \right] \right\}, \quad (3.4)$$

where terms containing v_c^3 represent collisions with ions and the others represent collisions with electrons. The following definitions apply:

$$\tau_{se} = \frac{3mm_e v_e^3}{16\sqrt{\pi} Z^2 e^4 n_e \ln \Lambda_e} ,$$

the Spitzer slowing-down time on electrons, m , Z , and v are the beam ion mass, charge number, and speed, v_e and v_i are the electron and ion thermal speeds, and

$$v_c = \left[\frac{3\sqrt{\pi}}{4} \frac{m_e}{m_i} [Z] \right]^{1/3} v_e , \quad \text{with } [Z] = \frac{\sum_j n_j Z_j^2 \frac{m_i}{m_j} \ln \Lambda_j}{n_e \ln \Lambda_e} ,$$

where $\ln \Lambda [\equiv \ln(b_{\max}/b_{\min})]$ is the logarithm appearing in the Coulomb scattering cross section⁴⁶ and has a value of ~ 16 for ISX parameters. The average rate of change of the velocity is

$$\left\langle \frac{\partial \mathbf{v}}{\partial t} \right\rangle = \frac{\int \mathbf{v} \frac{\partial f}{\partial t} d^3 \mathbf{v}}{\int f d^3 \mathbf{v}} . \quad (3.5)$$

Using $d^3v = 4\pi v^2 dv$, letting $f = \delta(v - v_0)$, and integrating by parts, the following equation is easily obtained:

$$\left\langle \frac{\partial v}{\partial t} \right\rangle = -\frac{v}{\tau_{se}} \left[\left(1 - \frac{T_e}{E} \right) + \frac{v_c^3}{v^3} \left(1 + \frac{T_i}{2E} \right) \right]. \quad (3.6)$$

Note that the term T_e/E tends to reduce the slowing-down rate. However, this term is small with respect to the zero-order terms. To zero order in T/E , Eq. (3.6) becomes

$$\left\langle \frac{\partial v}{\partial t} \right\rangle = -\frac{v}{\tau_{se}} \left[1 + \left(\frac{v_c}{v} \right)^3 \right]. \quad (3.7)$$

As before, the first term is due to electron friction, and the second term is due to ion friction. The critical velocity v_c is the velocity at which the fast ions slow down (and deliver their energy) at equal rates on ions and electrons. For $v > v_c$, electron drag is dominant, and for $v < v_c$, ion drag becomes more important. Since the critical energy $E_c (= 1/2 mv_c^2)$ is proportional to the electron temperature T_e , it follows that higher values of T_e result in more beam power deposition to the ions. In ISX-B, $E_c \leq 10$ keV typically, whereas $E_{inj} \approx 30$ keV; thus, most of the beam power is delivered directly to the electron population, as opposed to other tokamaks—PLT, for example—which have higher values of T_e and are, therefore, characterized by a more direct power input to the ions. It may also be noted that, for the operating parameters of the ISX-B,

the occurrence of non-prompt losses would reduce the power going into the ion channel proportionately more than that going into the electron channel.

3.4.2 Pitch Angle Scattering

The rate of change of f due to pitch angle scattering on the background plasma is described by the expression⁴⁵

$$\frac{\partial f}{\partial t} = \frac{v_c^3 m_i \langle Z \rangle}{2\tau_{se} m[Z]} \frac{1}{v^3} \frac{\partial}{\partial \zeta} \left[(1 - \zeta^2) \frac{\partial f}{\partial \zeta} \right], \quad (3.8)$$

where

$$\langle Z \rangle = \frac{\sum_j n_j Z_j^2 \ln \Lambda_j}{n_e \ln \Lambda_e}, \quad \zeta = \frac{v_{\parallel}}{v},$$

and m_i is the mass of the bulk ion population.

Equation (3.8) may be considered as a competition between a frictional term $(\partial f / \partial \zeta)$, which tends to bring f to the average value $\zeta = 0$, and a diffusive term $(\partial^2 f / \partial \zeta^2)$, which tends to make f isotropic in pitch angle.

The average rate of change of ζ due to collisions is

$$\left\langle \frac{\partial \zeta}{\partial t} \right\rangle = \frac{\int \zeta \frac{\partial f}{\partial t} d\zeta}{\int f d\zeta} = -\frac{m_i \langle Z \rangle}{m \tau_{se} [Z]} \frac{v_c^3}{v^3} \zeta. \quad (3.9)$$

At energies $E \gg E_c$, very little pitch angle scattering takes place, since collisions with electrons are dominant. This explains the low signal detected in the high-energy portion of perpendicular spectra, which comes from the small population of beam ions born with a small pitch angle, which need not scatter much to be detected.

The average change in ζ that a fast ion undergoes as it slows down can be estimated from Eq. (3.9), with “ dt ” expressed as a function of dv , using Eq. (3.7):

$$\frac{\partial \zeta}{\zeta} = C \left\{ \frac{\left(\frac{v_c}{v} \right)^3 dv}{v \left[1 + \left(\frac{v_c}{v} \right)^3 \right]} \right\},$$

where $C = m_i \langle Z \rangle / m[Z]$.

Integrating from an initial state i to a final state f ,

$$\ln \left(\frac{\zeta_f}{\zeta_i} \right) = C \left\{ \int_i^f \frac{dv}{v} - \int_i^f \frac{dv}{v \left[1 + \left(\frac{v_c}{v} \right)^3 \right]} \right\}.$$

Evaluation of the second integral on the right side leads to the following result:

$$\ln \left(\frac{\zeta_f}{\zeta_i} \right) = C \left[\ln \left(\frac{v_f}{v_i} \right) - \frac{1}{3} \ln \left(\frac{v_f^3 + v_c^3}{v_i^3 + v_c^3} \right) \right],$$

or

$$\frac{\zeta_f}{\zeta_i} = \left[\frac{v_f^3 (v_i^3 + v_c^3)}{v_i^3 (v_f^3 + v_c^3)} \right]^{\frac{m_i \langle Z \rangle}{m[Z]}}. \quad (3.10)$$

Now, $\langle Z \rangle$ is almost equivalently Z_{eff} , and $[Z] \sim 1$, even for $\langle Z \rangle \sim 10$. Also, for the typical ISX-B injection experiment, $m_i = 2$ AMU, and $m = 1$ AMU; thus, converting from velocity space to energy space, Eq. (3.10) becomes

$$\frac{\zeta_f}{\zeta_i} \simeq \left[\frac{E_f^{3/2} (E_i^{3/2} + E_c^{3/2})}{E_i^{3/2} (E_f^{3/2} + E_c^{3/2})} \right]^{\frac{2}{3} Z_{\text{eff}}}. \quad (3.11)$$

Evaluating Eq. (3.11) with $E_c = 10$ keV, $E_i = 30$ keV, $E_f = 20$ keV, and $Z_{\text{eff}} = 1$ results in $\zeta_f/\zeta_i \simeq 0.92$. So the pitch angle changes on the average by only 8% while the fast ions slow down from 30 to 20 keV. A $Z_{\text{eff}} = 3$ would result in a 22% change in ζ for the same values of E_c , E_i , and E_f .

At energies closer to the critical energy, collisions with bulk ions become increasingly more important; consequently, larger changes in ζ occur. Considering, for instance, $E_i = 20$ keV and $E_f = 10$ keV, $\Delta\zeta/\zeta$ turns out to be 23% for $Z_{\text{eff}} = 1$ and 54% for $Z_{\text{eff}} = 3$.

A scattering time τ_{scatt} is defined as

$$\tau_{\text{scatt}} \equiv \frac{\zeta}{\partial\zeta/\partial t},$$

and results in

$$\tau_{\text{scatt}} \cong \frac{\tau_{se}}{2 Z_{\text{eff}}} \frac{E^{3/2}}{E_c^{3/2}} \propto \frac{\tau_{se}}{Z_{\text{eff}}} \frac{E^{3/2}}{T_e^{3/2}} .$$

Similarly, defining a slowing down time τ_{slow} by

$$\tau_{\text{slow}} \equiv \frac{v}{-\partial v / \partial t}$$

yields $\tau_{\text{slow}} = \tau_{se}$ (for $v \gg v_c$). Thus, the ratio of scattering time to slowing-down time is

$$\frac{\tau_{\text{scatt}}}{\tau_{\text{slow}}} \propto \frac{1}{Z_{\text{eff}}} \left(\frac{E}{T_e} \right)^{3/2}$$

and assumes the smallest value at the plasma center, where T_e is the highest.

It must be pointed out that collisions of beam ions with other beam ions are not taken into account by these calculations. For this work, an estimate of beam-beam scattering with respect to beam-plasma scattering was obtained by comparing the 90° scattering times for the two processes. As for the estimate of beam-beam deposition, the fast ion distribution function calculated by the Monte Carlo code was used in the computation. Since the scattering cross section is proportional to v_{rel}^{-4} , the calculation was performed for an ion with a pitch angle matching the peak of the distribution function to maximize the neglected effect. The ratio of fast ion density (summed over ζ and E) to bulk

ion density at the plasma center was ~ 0.1 . The beam-beam 90° scattering time was found to be longer by factors ≥ 10 (depending on r) than the corresponding beam-plasma scattering time; therefore, it was concluded that neglecting beam-beam collisions would not introduce a significant error. Experimental results were consistent with this conclusion when comparing the separation of fast neutral spectra along different sightlines at low and high $\bar{n}_e$. If beam-beam scattering were not negligible, then its effects would be comparatively stronger in a lower density plasma, and the resulting spectra at different R_t would be closer together. There was, however, no clear evidence of this effect, and, in fact, the spectra were generally farther apart at low $\bar{n}_e$, in support of the assumption that collisions with plasma particles are dominant.

3.4.3 Energy Diffusion

As the fast ions slow down, the average velocity of the distribution function decreases. At the same time, diffusion in velocity space occurs. The corresponding "spreading" of the distribution function is described (to first order in δt) by

$$\langle (\delta v)^2 \rangle = \left[\left\langle \frac{\partial v^2}{\partial t} \right\rangle - 2v \left\langle \frac{\partial v}{\partial t} \right\rangle \right] \delta t .$$

The term $\left\langle \frac{\partial v}{\partial t} \right\rangle$ is given by Eq. (3.6). The term $\left\langle \frac{\partial v^2}{\partial t} \right\rangle$ is obtained in the same way and is given by

$$\left\langle \frac{\partial v^2}{\partial t} \right\rangle = \frac{1}{\tau_{se}} \left(-2v^2 - \frac{2v_c^3}{v} + \frac{6T_e}{m} \right) .$$

Combining the two results yields

$$\langle (\delta v)^2 \rangle = \frac{1}{\tau_{se}} \left(\frac{2T_e}{m} + \frac{2T_i v_c^3}{m v^3} \right) \delta t, \quad (3.12)$$

with the two terms representing speed diffusion on electrons and ions, respectively. Again, for $E \gg E_c$, the second term is negligible with respect to the first one. Also, by comparing the electron terms for drag and diffusion (i.e., $\delta v^2/v^2$ vs $\delta v/v$), it is found that the diffusion term is smaller by a factor T_e/E , so the slowing-down rate is faster than the speed diffusion rate.

Proceeding similarly, the following expression for the diffusion in pitch angle is obtained:

$$\langle (\delta \zeta)^2 \rangle = \frac{v_c^3}{v^3} \frac{m_i \langle Z \rangle}{\tau_{se} m [Z]} (1 - \zeta^2) \delta t. \quad (3.13)$$

As the distribution function moves toward the average value $\zeta = 0$, the spread becomes larger and tends to make f isotropic in pitch angle.

3.4.4 Electric Field Effects

The $\vec{F} \cdot \vec{\nabla}_v f$ term in the Boltzmann equation represents the effects of macroscopic (or collective) forces, with only the $\vec{E} \cdot \vec{\nabla}_v f$ part retained in the guiding center approximation. A further simplification is made by considering only the toroidal component E^* of the electric field, where $E^* = E_\phi(1 - Z_{\text{beam}}/Z_{\text{eff}})$, which takes into account a lowering of E_ϕ due to the electron drift.

This term may be expanded to give

$$\frac{\partial f}{\partial t} = \frac{ZeE^*}{m} \left[\frac{(1 - \zeta^2)}{v} \frac{\partial f}{\partial \zeta} + \zeta \frac{\partial f}{\partial v} \right].$$

Thus, the electric field affects the fast ion distribution function f in speed and in pitch angle, with the coefficients given by

$$\frac{\partial v}{\partial t} = \frac{ZeE^* \zeta}{m} \quad \text{and} \quad \frac{\partial \zeta}{\partial t} = \frac{1 - \zeta^2}{v} \frac{ZeE^*}{m}.$$

These effects are not always negligible when compared to the corresponding collisional results, and they are included in the computational codes. The acceleration of ions with $\zeta \approx 1$ due to the electric field can be ~ 10 to 20% of the acceleration due to Coulomb collisions. Also, the electric field tends to decrease the slowing-down rate of co-moving ions and to increase it for counter-moving ions and, consequently, affects the shapes of co- and counter-spectra differently. The rate of change of the pitch angle due to the electric field becomes larger than the corresponding collisional term as ζ approaches zero—since the collisional term is directly proportional to ζ , while the electric field term is proportional to $1 - \zeta^2$.

3.4.5 Charge Exchange

The loss rate term in Eq. (3.3) comprises prompt and non-prompt orbit losses and charge-exchange neutrals that escape the plasma without reionizing. (Reionization is allowed in the Monte Carlo simulation but not in the analytical

code.) Since only quiescent plasmas are considered here, and since the magnetic field ripple is small in ISX-B, MHD and ripple losses are not included in the present investigation. The treatment of orbit losses in the Monte Carlo and the analytical codes has already been discussed in Section 3.3. Attention is now given to charge-exchange losses. The charge-exchange operator is simply⁴⁵

$$\frac{\partial f}{\partial t} = -\frac{f}{\tau_{cx}}, \quad (3.14)$$

where $\tau_{cx} = 1/n_0\sigma_{cx}v$ is the charge-exchange time. The conditions when charge-exchange losses become important can be found by solving Eq. (3.14) from an initial state i to a final state f using Eq. (3.7) for " dt ." The result is

$$\left. \frac{\Delta f}{f} \right|_{cx} = \left[\frac{v_i^3 + v_c^3}{v_f^3 + v_c^3} \right]^{-\tau_{slow}/3\tau_{cx}} - 1.$$

Thus, the effect of charge exchange on the distribution function is determined by the ratio $\tau_{slow}/3\tau_{cx}$; for $\tau_{cx} \gg \tau_{slow}/3$, the effect is small, though it becomes increasingly important as a smaller τ_{cx} is considered. Since

$$\frac{\tau_{cx}}{\tau_{slow}} \propto \frac{n_e}{n_0 T_e^{3/2}},$$

charge-exchange effects are quite significant at the plasma periphery due to the high neutral density.

As will be discussed in Chapter 5, charge-exchange losses of fast ions affect the power balance more strongly in low density discharges, where a large

source of "halo" neutrals—peaked at the plasma center—is produced at deposition by injected beam atoms undergoing charge-exchange reactions with the bulk ions. Also, at low densities, a relatively large fraction of the neutrals produced at the wall penetrate to the plasma center. Furthermore, in the ISX-B experiment, the small plasma radius and generally low values of plasma current give rise to fast ion orbit excursions into the outer region of the plasma ($\epsilon\rho_p/a_p \sim 1$). Therefore, charge-exchange losses may constitute a non-negligible fraction of the input power at low $\bar{n}_e$. For this reason, and because of the experimental uncertainties in $n_0(R)$, these losses are a potentially significant source of error in determining heating efficiencies and fast ion confinement. This source of error is more important in the FPP code since beam ions are assigned at birth to average shells among those sampled by their first orbits, therefore missing the largest chance of charge exchanging at the outermost points of the orbits.

CHAPTER 4

THE COMPUTATIONAL CODES

4.1 INTRODUCTION

The deterministic Fokker-Planck code (FPP) and the Monte Carlo code (NEWORBX) used for this thesis are described elsewhere;^{9,10} therefore, they are not described in any detail here. However, since comparisons of experimental NPA spectra with those calculated by the two codes are central to this investigation, it is necessary to probe the reliability of the computational tools in predicting fast neutral spectra. One of the major shortcomings of the FPP code is the approximate treatment of the fast ion orbit excursions. The advantage of the FPP method over the orbit-following Monte Carlo simulation is that the computer execution time is much shorter. Therefore, it is of interest to establish in what cases the FPP approach adequately predicts the fast neutral spectra. This will be done in this chapter. Furthermore, the beam power delivered to the plasma ions and electrons in the energy analysis performed in ZORNOC is calculated by a Fokker-Planck routine similar to FPP. Thus, it is important to determine to what extent the approximate treatment of the orbits affects the calculated power deposited in the plasma. This issue will be investigated in Chapters 5 and 8 by comparing the beam power distribution calculated by the FPP and NEWORBX codes under a variety of plasma parameters and beam injection schemes.

Both codes use the electron density and temperature profiles [$n_e(R)$, $T_e(R)$] determined experimentally by Thomson scattering diagnostics. The FPP

code solves the drift-kinetic equation numerically with bounce-averaged operators (i.e., averaged along the orbit). The code takes into account the fact that a trapped ion spends more time close to the banana tip, where its parallel velocity vanishes; this weighting is necessary since the scattering operator is not constant along the orbit because ζ changes with R . The magnetic surface geometry is approximated by concentric circles. The orbits are treated in the zero-width approximation, with loss regions for counter-injection only (except for prompt losses at deposition, which are accounted for in the case of co-injection also). Due to the improper treatment of the orbits, this approach may lead to inaccurate conclusions when applied to viewing sightlines that are affected strongly by the orbit topology.

The NEWORBX code makes use of Monte Carlo methods to simulate the fast ion behavior, using the magnetic surface geometry (noncircular, nonconcentric surfaces) obtained through a solution of the Grad-Shafranov equation that is consistent with experimental measurements. The guiding center equations of motion are solved to first order in ϵ ($\epsilon \equiv \rho_g/L$, where ρ_g is the radius of gyration around the magnetic field line and L is the characteristic distance over which the fields change), resulting in a good representation of the actual fast ion orbits. Because realistic flux surfaces and fast ion orbits are used, the Monte Carlo approach produces an accurate calculation of the fast ion distribution function and the expected fast neutral spectra. The long computer execution time and the poor statistics for sightlines viewing away from the injection angle have been the two main limitations encountered with the Monte Carlo approach in this research. Russian roulette and particle splitting schemes were implemented in the calculation of the fast ion distribution function to improve

the statistical quality of the Monte Carlo estimates and thereby to obtain smooth simulated spectra of perpendicularly scattered ions.

In Section 4.2, the limitations of FPP are discussed, using several examples. Cases in which the calculation performs well are also included. Additions made to the Monte Carlo code to estimate fast neutral spectra are described in Section 4.3. Tests performed on the modified programs, parameters and statistics for typical runs, analysis of localized spectra with the DNB, Russian roulette and splitting schemes, and examples of the code output are also presented.

4.2 ANALYTICAL FAST NEUTRAL SPECTRA (FPP)

Many of the approximations that enter the analytical calculation have already been discussed in Chapter 3 and in the introduction to this chapter. To summarize, they are circular, concentric flux surfaces; bounce-averaged deposition and slowing down; zero-width orbits; approximate loss region for counter-injection (none for co-injection); no radial diffusion; reionization of charge-exchange neutrals neglected; and charge-exchange rates calculated away from their maxima. In addition, other approximations (which are used in NEWORBX as well) include the neglect of beam-beam interactions and the simplified treatment of the plasma edge, and the general assumptions intrinsic to the Fokker-Planck approach (e.g., that effects due to large angle collisions are negligible).

It would be difficult to provide a quantitative assessment of the cumulative effects of the previous approximations on the predicted spectra, but it is possible to show and explain qualitatively—on the basis of the improper treatment of

the orbits—the failure of the FPP prediction for certain cases. This will be accomplished for four examples through comparisons of experimental data and through referring to the orbit topology. In addition, an example is presented which demonstrates that FPP can adequately reproduce the experimental spectra in cases where orbit effects are less important. For all the examples, the absolute magnitude of the flux, as well as the shapes of the spectra can be compared, since no arbitrary normalization constants have been employed.

4.2.1 Spectra During Co-injection at Low I_p

The low I_p regime is important for two reasons. First, it provides a test of the fast ion theory in cases where orbit effects are expected to be significant. Second, one of the major efforts of the ISX-B program was the investigation of the energy confinement at high β_p , and these studies were conducted at relatively low values of I_p .

Experimental NPA spectra at $R_t = 42$ cm and $R_t = 8.5$ cm are shown in Fig. 4.1, together with the FPP prediction for the same two sightlines. These spectra were obtained during a low plasma current sequence ($I_p = 98$ kA) with resulting large orbit widths ($\epsilon\rho_p/a_p \approx 0.8$ for a 30-keV proton at the plasma edge). The theoretical and experimental spectra are in fairly good agreement at $R_t = 42$ cm, but they differ by large factors for the more perpendicular chord, especially at higher energies. It was pointed out earlier that the high-energy perpendicular flux comes mostly from charge-exchange events at the inside legs of orbits that start at the outer edge of the plasma. There are two effects that may cause FPP to overestimate this flux, both effects allowing the signal to originate from a region of higher n_0 (i.e., closer to the inside edge of the torus).

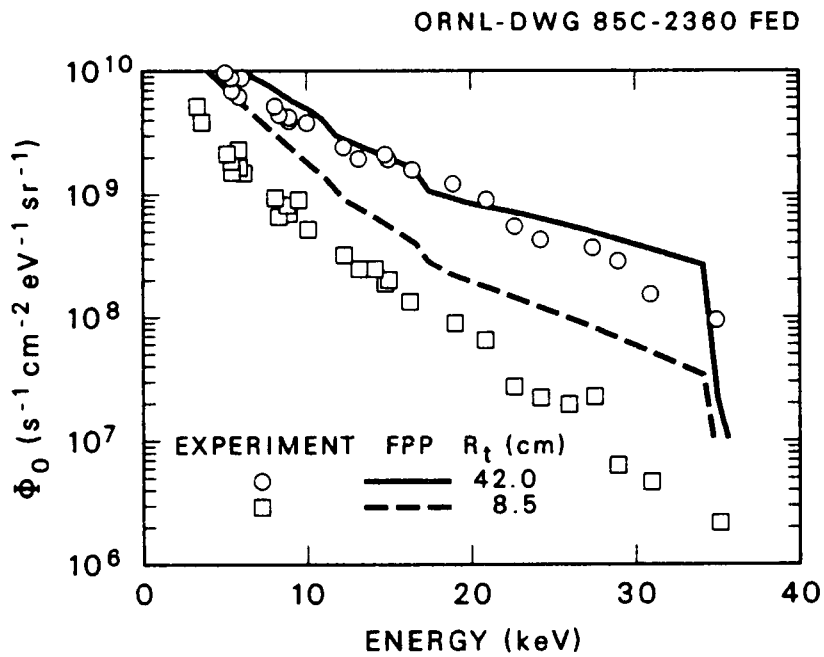


Fig. 4.1. Comparison of fast neutral spectra predicted by the Fokker-Planck code FPP with the experimental data during co-injection at low I_p . $I_p = 98$ kA, and $\epsilon\rho_p/a_p \sim 0.8$ for a 30-keV proton at the plasma edge.

First, co-passing orbits in FPP are taken to be circles regardless of the initial pitch angle. However, in the case under consideration, the detected signal originates from ions whose orbits deviate from circles and start resembling Ds. Consequently, the code calculates the inner crossing of the HMP to be closer to the plasma edge on the inside. Second, since the particles are deposited in an average radial shell, they are artificially shifted to a smaller R for co-injection. In addition, these orbits are close to the loss region boundary and may easily scatter into unconfined paths, whereas FPP does not include loss regions for co-injection after deposition and will, therefore, overestimate the calculated signal.

The effects previously described also play a role at lower energies, with the zero banana-width approximation and the absence of loss regions during the slowing down probably of more direct bearing because the signal originates from a wider radial band and is closer to the plasma center.

Thus, in this extreme—yet important—case, neglecting the actual orbit excursions and the loss regions results in a gross overestimation of the perpendicular flux. Although the conclusion cannot be drawn that the power delivered to the plasma is also grossly overestimated, it is nonetheless clear that the analytical code is not suitable for predicting perpendicular fast neutral spectra during co-injection at low I_p .

4.2.2 Spectra During Counter-injection

Figure 4.2 shows a similar comparison for a counter-injected sequence, with $I_p = 145$ KA. The tangency radii for the two sightlines are $R_t =$

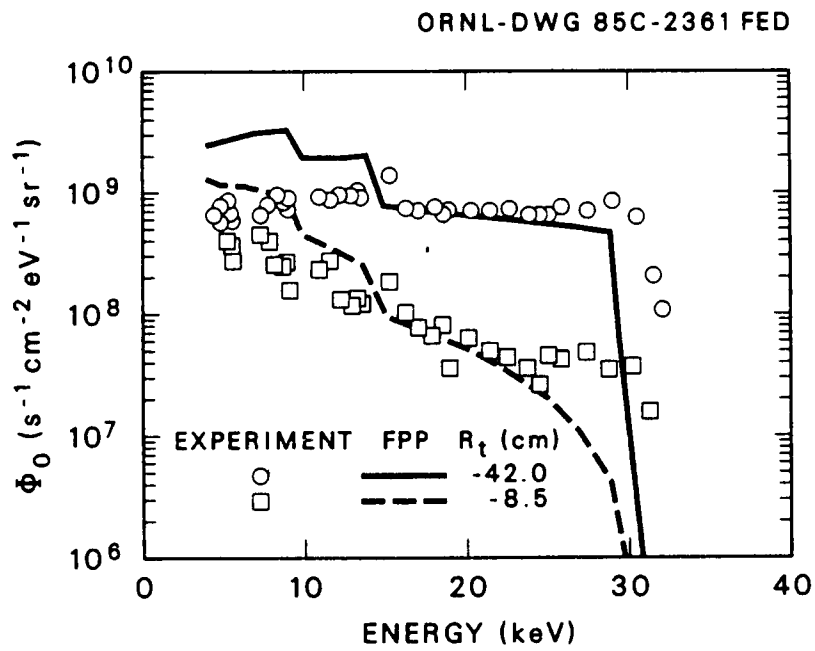


Fig. 4.2. Comparison of FPP with experiment: spectra of counter-moving ions during counter-injection.

-42 cm and $R_t = -8.5$ cm. As shown in Fig. 3.16 (page 60), the largest portion of the counter-moving flux to an NPA during counter-injection comes from the inner HMP crossing along all chords. In FPP the averaged deposition for counter-injection is at a *larger* R , in a region of lower n_0 on the inside of the torus; thus, the calculated signal will be underestimated. This is especially evident along the $R_t = -8.5$ cm sightline, but it may be a strong effect even along tangential chords. At lower energies, this effect is not only less important but may be more than compensated for by an underestimation of the scattering into the loss region, so the analytical code predicts a flux larger than the experimental one. A similar comparison at $I_p = 170$ kA showed the Fokker-Planck prediction to be in fairly good agreement with the experimental data along the $R_t = -42$ cm. The agreement along the perpendicular chord, however, improved only slightly with respect to the lower current case. Therefore, FPP is not adequate to analyze fast neutral spectra in counter-injected sequences at low I_p , even along sightlines far from perpendicular. At high I_p , FPP reproduces adequately the fast neutral spectra along sightlines far from perpendicular.

4.2.3 Counter-moving Particles During Co-injection

The NPA spectra at $R_t = -42$ cm and $R_t = -8.5$ cm during injection at $R_t = +74.5$ cm are shown in Fig. 4.3. It is evident that the calculated results do not reproduce the experimental data. The discrepancies may be interpreted with the help of Fig. 3.14 (page 57). The $R_t = -42$ cm chord looks straight into the loss region; FPP does not include the loss region for co-injection and, therefore, will overestimate the flux along this sightline. Also, at

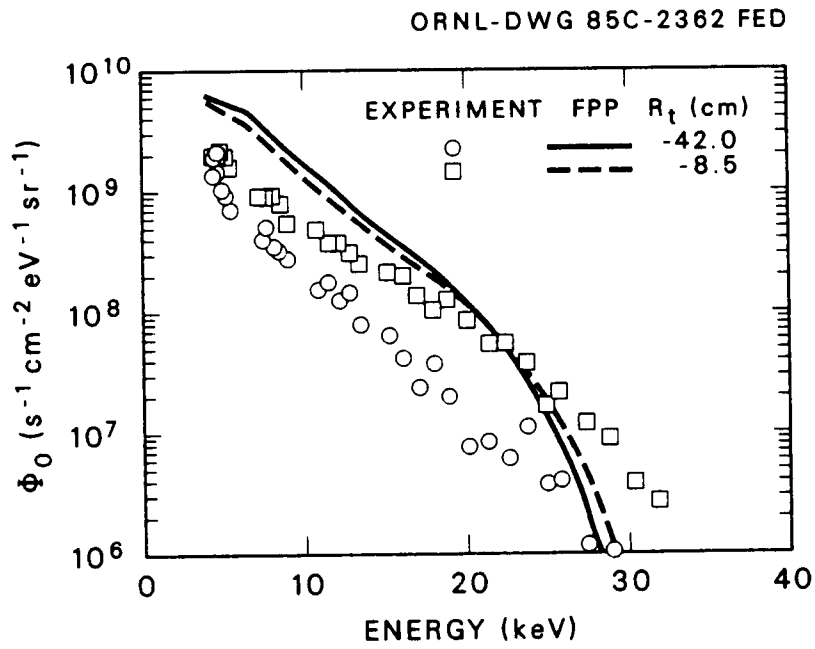


Fig. 4.3. Comparison of FPP with experiment: spectra of counter-moving ions during co-injection.

low energies a relatively large fraction of the fast ions becomes trapped; this fraction is in fact overestimated in the FPP treatment for co-injection. Consequently, because of the symmetric trapping region in FPP, a large population of counter-moving ions is generated, which, in turn, results in an overestimation of the escaping neutral flux along "negative" sightlines. On the other hand, the more perpendicular chord is not influenced as strongly by the orbit topology at low energies, so the disagreement is less pronounced in that regime. At high energies, but below the energy at which the co- and counter- regions of the R , $v_{\parallel}/v$ space disconnect, a significant portion of the experimental flux may come from ions that are born on, or close to, pinch orbits at the outer plasma periphery and for which the next crossing is near the line of sight at $R_t = -8.5$ cm. This would explain why FPP underestimates the high-energy flux along the perpendicular chord.

4.2.4 Co-moving Particles During Counter-injection

This particular geometry has already been discussed in Section 3.3 in connection with pinch orbits and the sensitivity of an NPA to the orbit topology. It was shown there that NEWORBX accurately predicts the resulting fast neutral fluxes at several energies and along a large number of viewing chords from tangential to perpendicular. The FPP calculation, on the other hand, results in spectra which have a trend opposite to that of the experimental data, as illustrated by Fig. 4.4. The more tangential the sightline, the lower the predicted signal, whereas the experimental data display the largest flux at the most tangential chord, which is the closest to the co-moving leg of the pinch

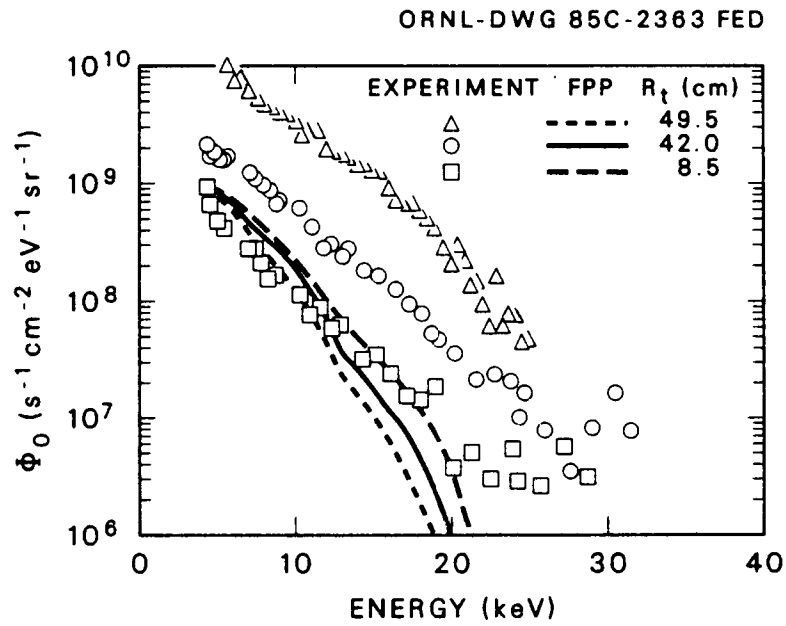


Fig. 4.4. Comparison of FPP with experiment: spectra of co-moving ions during counter-injection.

orbit boundary. The discrepancy for the $R_t = 49$ cm chord at $E = 20$ keV is by a factor of ~ 300 .

In conclusion, FPP should not be used to calculate the spectra of escaping fast neutrals in any case where large-width orbit effects are significant.

4.2.5 Spectra During Co-injection at High I_p

In contrast, FPP does produce spectra that are in good agreement with the experimental data (and with the Monte Carlo calculation) when applied to discharges and viewing geometries that are not strongly affected by the occurrence of finite-width orbits. One such a case is exemplified by charge-exchange spectra of co-moving ions during tangential co-injection into a high I_p plasma. This is shown in Fig. 4.5 for a sequence with $I_p = 180$ kA and a corresponding $\epsilon\rho_p/a_p \sim 0.4$ for a 30-keV proton at the plasma boundary. Therefore, Fokker-Planck codes appear to be quite suitable to predict fast neutral spectra in tokamaks with tangential co-injection and $\epsilon\rho_p/a_p \ll 1$.

4.3 MONTE CARLO FAST NEUTRAL SPECTRA (NEWORBX)

In view of the apparent limitations of the FPP code, a Monte Carlo estimation routine for the fast neutral spectra was developed and implemented into the already existing code NEWORBX. This was necessary, for example, to properly compare co- and counter-injection schemes, as well as to correctly treat low I_p cases. Since the Monte Carlo calculation will be the fundamental tool used in this thesis to investigate fast ion confinement, a detailed description of its implementation and some tests of reliability are presented in the following sections.

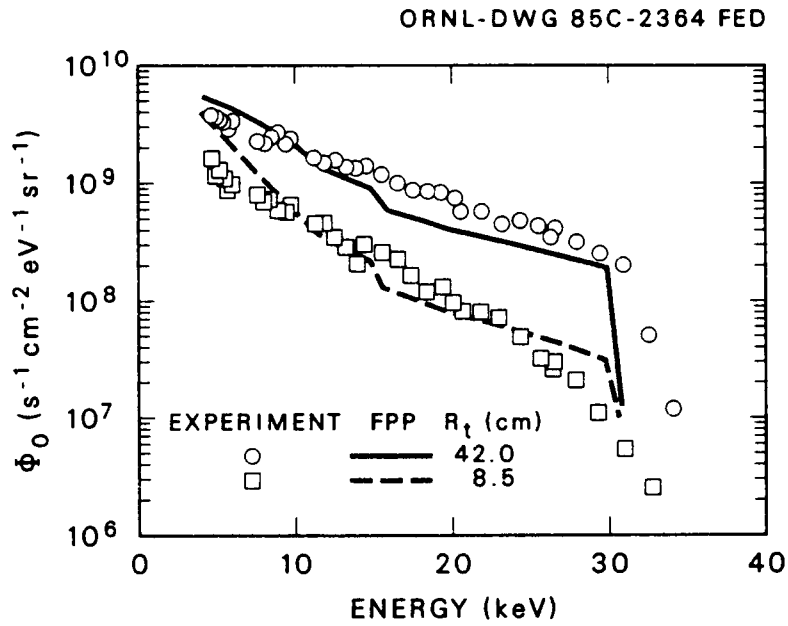


Fig. 4.5. Comparison of FPP with experiment: co-injection at high I_p . This comparison is similar to that of Fig. 4.1, but here $I_p = 180$ kA and $\epsilon\rho_p/a_p \sim 0.4$ for a 30-keV proton at the plasma edge.

4.3.1 Calculation of $F_i(R, E, v_{\parallel}/v)$ and $\Phi_0(R, E, R_t)$

The block diagram displayed in Fig. 4.6 illustrates how the Monte Carlo simulation and associated estimations are carried out. The thicker lines and heavily framed boxes indicate those parts that have been added for the calculation of the fast ion distribution function, $F_i(R, E, v_{\parallel}/v)$.

Rather than calculating the spectra as a direct output of the code, it was deemed more advantageous to proceed in the following manner: each time the particle orbit crosses the torus midplane (the plane scanned by the charge-exchange analyzers), the parameters necessary to determine $F_i(R, E, v_{\parallel}/v)^*$ are stored in an array, and when the particle is lost or thermalizes, the array is written out into an output file (FIn), and the next particle is started. After the Monte Carlo run is over, a postprocessor calculates F_i , as well as the fast neutral spectra. This procedure allows for more flexibility in the analysis because of the following:

1. The same Monte Carlo run can be analyzed by varying the sizes of the R , E , and $v_{\parallel}/v$ bins to suit different statistical requirements.
2. The individual particle histories may be recalled; for example, if a spike were present on a smooth spectrum, the particle(s) causing it may be studied.
3. New features may be developed and added to the postprocessor to analyze an existing output file without having to run the Monte Carlo code again.
4. It is straightforward to extract subsets of F_i to obtain, for example, the trapped particle contribution to a particular spectrum, or the perpendicular

*See Appendix B for details.

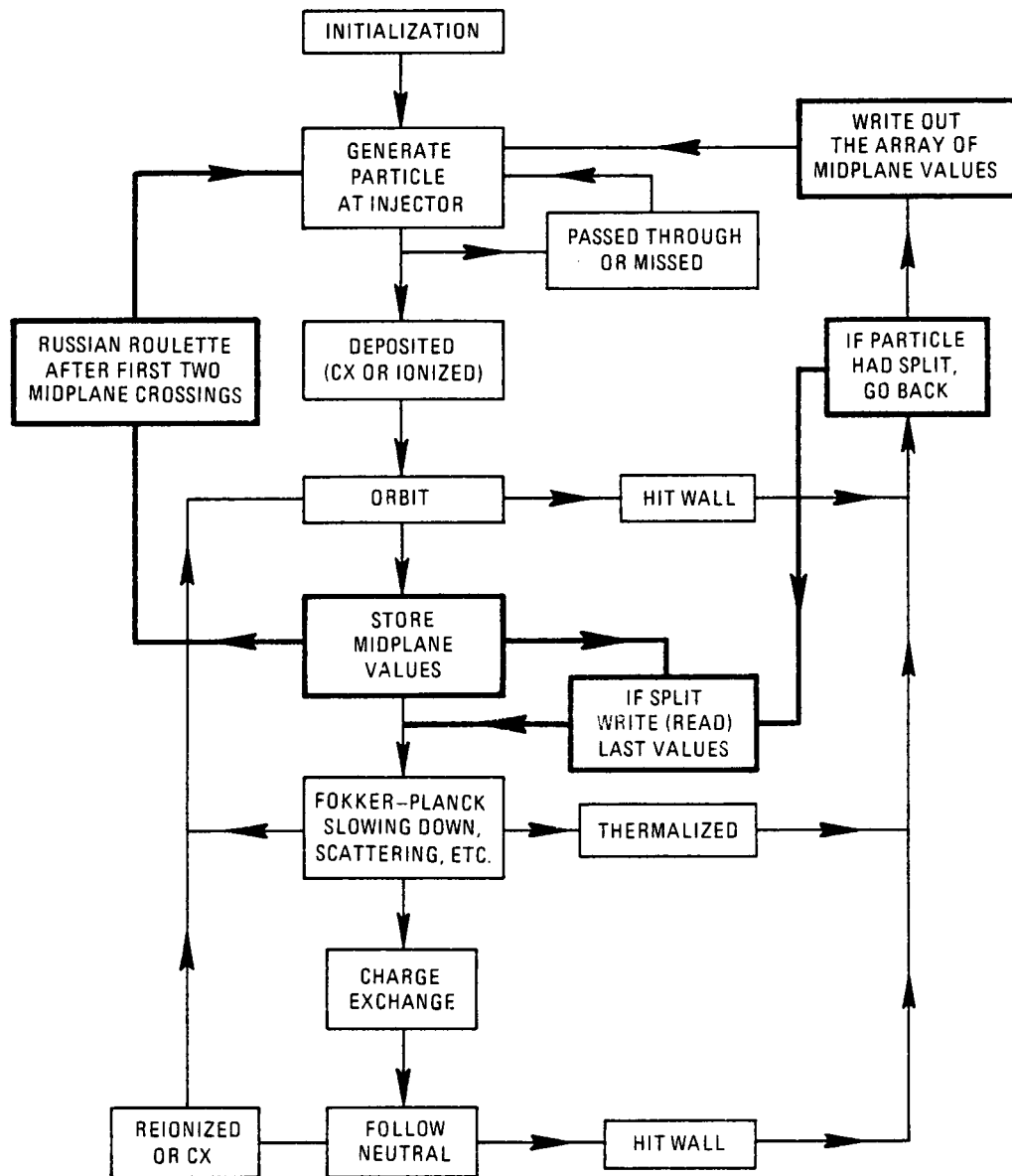


Fig. 4.6. Block diagram of the orbit-following Monte Carlo code NEWORBX. The features added for the calculation of the fast ion distribution function are shown.

flux due to particles that were born on orbits with large values of $v_{\parallel}/v$, etc. This capability may be used as a learning tool to understand the slowing down and scattering of fast ions and as a guide in interpreting the charge-exchange spectra.

5. The same F_i may be coupled with different (plausible) background neutral density profiles to better match the experimental spectra. (The profile used for the calculation of the charge-exchange losses in the Monte Carlo simulation is a toroidal average, thus not necessarily the same as the local profile in front of the spectrum analyzers, as discussed in Section 3.2.)
6. The flux along any number of viewing chords may easily be obtained by running the postprocessor repetitively.

The major drawback of this procedure is that large output files are generated; correspondingly, large amounts of disk space are required to store the files and to load and execute the programs.

4.3.2 Tests on the Postprocessor

NEWORBX creates, in addition to the original output (mostly the power deposition as a function of radius), a set of files containing information collected at all HMP crossings. A postprocessor (POSPRO) then reads these files and, given a chosen number of R , E , and ζ intervals, calculates $F_i(R, E, v_{\parallel}/v)$, together with several other quantities of interest (e.g., the contribution to F_i due to trapped orbits and the number of particles that produce the fast neutral signal at each energy).

A second postprocessor (MCCXA) then integrates along an NPA sightline to obtain the calculated neutral flux $\Phi_0(E, R_i)$. MCCXA also calculates the flux origination profiles (i.e., the contribution of each region ΔR to the expected flux) by following the chosen chords into the plasma and solving the equation given at the end of Appendix B at each spatial step. If the analysis of localized spectra is chosen—that is, the DNB on minus DNB off flux—then $n_0(R)$ is replaced by the fraction of DNB neutrals calculated to reach the HMP without ionizing. Experimentally, the DNB enhances the H^0 flux from the main beams by adding a source of D^0 neutrals in a small region ($r \sim 6$ cm) close to the magnetic axis. Subtracting the H^0 flux measured with the DNB off from that measured with the DNB on (at the same energy setting) yields the flux originating from charge-exchange events between fast ions in the plasma core and DNB neutrals reaching the HMP. In the calculation the relative velocity between the beam ion and the DNB neutral is used, and σ_{cx} is likewise corrected. A flat, parabolic, or triangular profile for the DNB intensity, as well as different fractional energy components, may be assumed.

A simple test for the calculation was readily available since NEWORBX can be run with the collision operator—as well as the electric field and the charge-exchange operators—turned off. When this is done, the particles move along the orbits determined only by their initial conditions. Several such particles at different energies, some on co-passing orbits and some trapped, were started in NEWORBX; the quantities calculated by the postprocessors were then compared with the orbit plots and were found to be in agreement with the values of R , E , ζ , etc., observed at the various HMP crossings. Other simple tests, such as the calculation of F_i from a prepared set of midplane crossings or

the calculation of Φ_0 from a prepared F_i , also performed satisfactorily. The sizes of the R , E , and ζ bins were varied independently during calculations performed on the same FIn's files to ascertain that the results would remain the same. No changes occurred when varying the E and ζ bins, aside from an expected alteration of the statistical fluctuations. If, however, the size of the R bin was made too large ($\Delta R \geq 4$ cm), then the calculated neutral flux was seen to change significantly, especially if at the same time a large integration step was used ($\Delta s \sim 1$ cm) in MCCXA; this was caused by deviations in the interpolated value of $n_0(R)$. To avoid this problem, the size of the radial bin was kept at ~ 1 cm, while Δs was set at 0.1 cm.

The NEWORBX calculations were first tested by comparing the predicted and experimental fluxes, along several sightlines, at $E \simeq E_{inj}$, for a co-injection sequence at high I_p (190 kA). Since collisional effects and orbit losses are minimized by the chosen constraints, a good agreement could be expected in this case if the simulation were performing properly. The results for three MEA chords are shown in Fig. 4.7. The lines correspond to the experimental values of Φ_0 at $E = 31$ keV (E_{inj} was 32 keV), while the symbols represent the fluxes predicted by the Monte Carlo simulation, as a function of the total number of particles followed (only the full energy component of the beam was launched). The prediction reproduces the data fairly closely if enough particles are launched, the maximum deviation being $\sim 30\%$ for the sightline with $R_t = 8.5$ cm, thus lending excellent overall credibility to the calculation. Further, the comparison shows that a large number of particles must be launched to eliminate gross statistical errors in the calculated perpendicular flux. For the example presented, ~ 4000 particles in the full energy component of the beam are

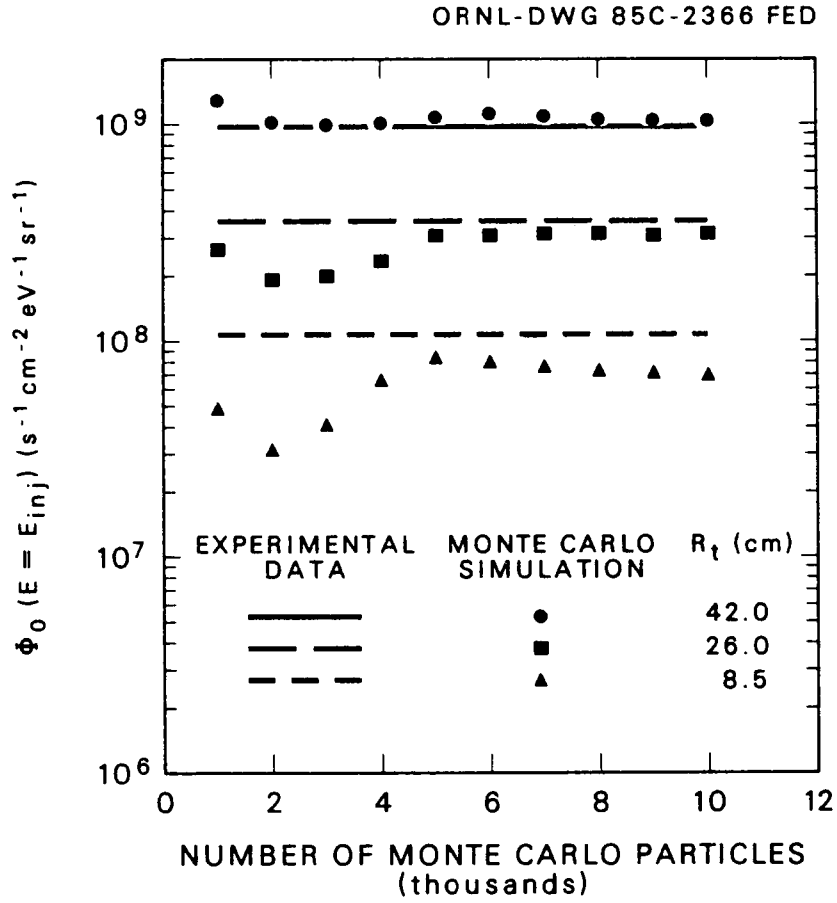


Fig. 4.7. Test of reliability for the calculation of the fast neutral flux. The flux at $E \approx E_{inj}$ predicted by the Monte Carlo simulation—at three NPA sightlines—is compared with the experimental data.

required to reach the asymptotic value at $R_t = 8.5$ cm and $E = E_{\text{inj}}$. Since the full energy component of the beam constitutes 41% of the beam current, a total of $\sim 10,000$ particles is needed to obtain a reliable and complete perpendicular spectrum.

4.3.3 Effects of Varying δt in the Monte Carlo Calculator

It has been pointed out by Goldston¹⁰ that if the time step used to integrate the equations of motion is too long, the orbits are not followed correctly, and the first detectable effect is the shrinking of co-passing orbits toward $r = 0$. The time step chosen for the Monte Carlo analyses presented in this thesis ($\delta t \approx 0.7 \times 10^{-7}$ s for a 20-keV H_1 ion) is consistent with the guideline suggested by Goldston in scaling to different tokamaks.¹⁰ Nonetheless, it was deemed necessary to verify that the orbits are followed properly and that the calculated fast ion distribution function does not change when compared to that obtained using a smaller time step. It must be pointed out that, although an integration time step is used in this discussion, an integration *length* is actually specified by the user—as a fraction of the central circumference. Typically, the integration length was chosen $= 2\pi R_0/40$, corresponding to 14.6 cm and $\delta t \approx 0.7 \times 10^{-7}$ s for a 20-keV proton.

As a first test, the Fokker-Planck collision operator was turned off so that, in the absence of numerical errors the ions should remain on their original orbits. No alterations in the trajectories were observed when switching from $\delta t = 0.2 \times 10^{-7}$ s to $\delta t = 0.7 \times 10^{-7}$ s. In neither case did the particles deviate from their original paths. An identical run with a time step *longer* by a factor of 4 ($\delta t = 2.8 \times 10^{-7}$ s), on the other hand, showed clearly the shrinking of

co-passing orbits, as illustrated in Fig. 4.8. In comparing the values of the particle parameters stored at each midplane crossing for the $F_i(R, E, v_{\parallel}/v)$ calculation obtained with $\delta t = 0.2 \times 10^{-7}$ and 0.7×10^{-7} s, no significant differences were noted, except for small ($\leq 0.5\%$) variations due to the fact that the parameters were calculated at a slightly larger distance from the horizontal midplane with the longer time step.

A second test consisted of two complete runs with the collision operator turned on, one with the standard δt , the other with the smaller δt , as before. The same initial conditions were used in both cases, including a 3000-particle birth distribution. The fast ion distribution function and the fast neutral energy spectra along several sightlines were found to be essentially the same to within statistical variations. It was thus concluded that the chosen integration time step would not produce numerical errors in the prediction of the fast neutral spectra.

4.3.4 Effects of Varying the Degree of Acceleration

A common way of shortening Monte Carlo run times without appreciably changing the results of the calculation is to enhance the effects of the Fokker-Planck collision operator with respect to the orbital motion of the beam ions. This should not affect the radial transport process of the fast ions since the diffusion coefficient in the banana regime (low collisionality plasma) is proportional to the collision frequency (ν). A word of caution is offered by Goldston¹⁰—not to increase ν so much that radial transport occurs in the plateau regime where the diffusion coefficient is no longer proportional to ν . In

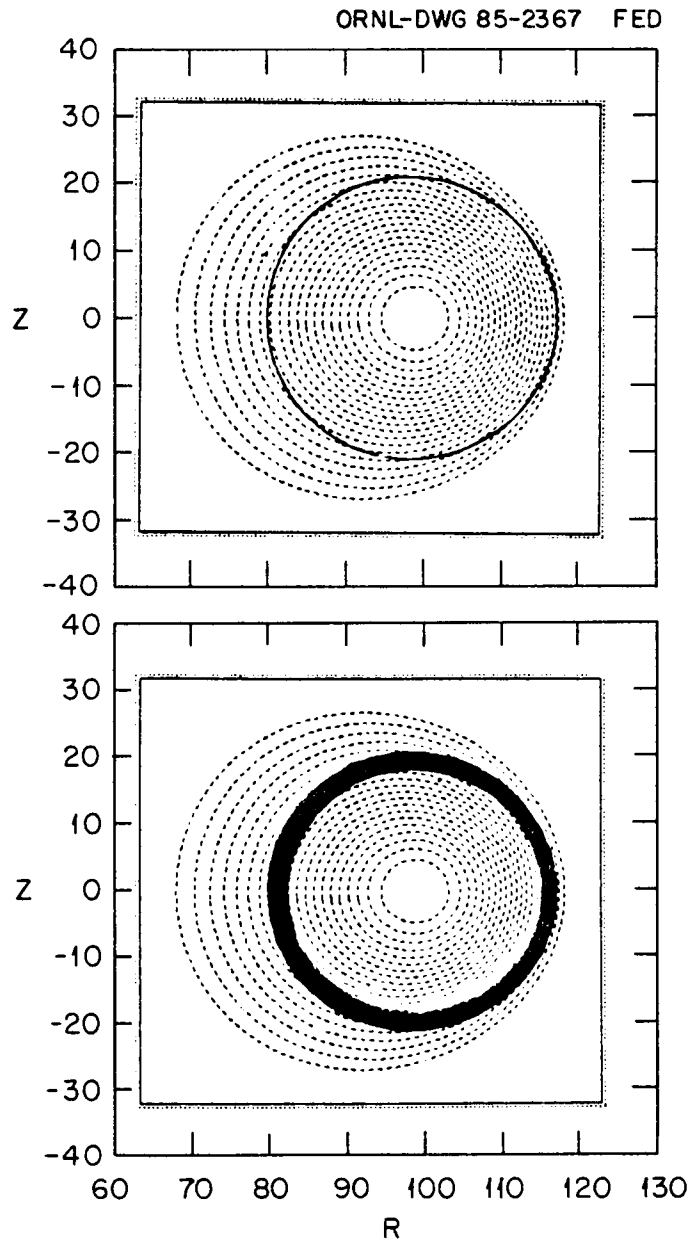


Fig. 4.8. Effects of varying the time step in the orbit-following calculation. Poloidal projections of simulated co-passing orbits were obtained with the collision operator turned off. Top: $\delta t = 0.7 \times 10^{-7}$ s; bottom: $\delta t = 2.8 \times 10^{-7}$ s. An artificial shrinking of the orbit is observed with the longer time step.

counter-injection cases, too strong an acceleration is expected to produce an artificial improvement of the beam ion confinement because originally counter-moving particles may become deeply trapped without passing through barely trapped pinch orbits and fat bananas, which would carry them outside the plasma.

The code updates the degree of acceleration at each midplane crossing to maintain the largest of $\langle |\Delta(v_{\parallel}/v)| \rangle$ and $\langle |\Delta v/v| \rangle$ during the previous half of the poloidal orbit equal to $1/\text{GOOCON}$, where GOOCON is a user-specified acceleration constant. The artificial acceleration increases as GOOCON decreases. To estimate the effects of varying the degree of acceleration on the fast ion density distribution and on the charge-exchange fast neutral spectra, runs with $\text{GOOCON} = 20$ and 40 were compared for both a co-injection and a counter-injection case. The fast neutral spectra calculated for the co-injection case showed no statistically significant differences, whereas the perpendicular flux during counter-injection was predicted to be somewhat higher ($\sim 50\%$) when GOOCON was set equal to 20 .

As a check, the distribution functions at high energy ($E = 27$ keV) and small pitch angle ($-0.4 \leq \zeta \leq 0$)—sensitive to pinch orbit losses—obtained from runs with $\text{GOOCON} = 20$ and 40 , were compared for the counter-case [Fig. 4.9(b)]. A large depletion in F_i was seen for $90 \leq R \leq 95$ cm, that is, in the neighborhood of the pinch orbit boundary when GOOCON was set equal to 40 but not when the larger acceleration ($\text{GOOCON} = 20$) was used. At the same time, the distribution function at $E = 27$ keV and $-1 \leq \zeta \leq -0.7$ was unperturbed by the change in the degree of acceleration, as shown in Fig. 4.9(a). Furthermore, a similar run performed with $\text{GOOCON} = 80$ produced

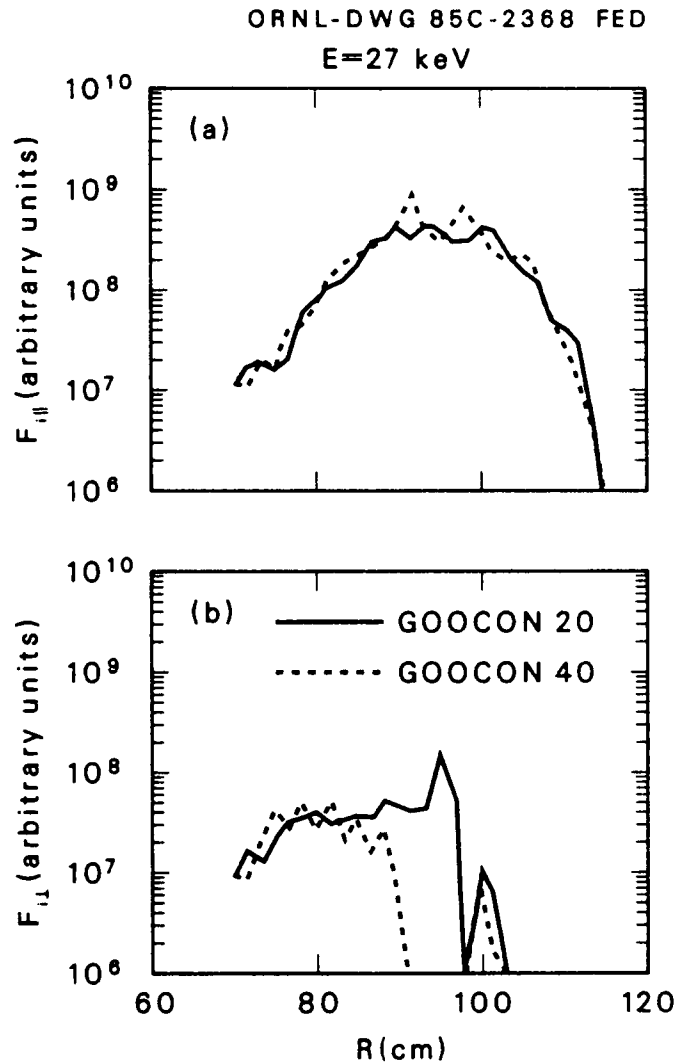


Fig. 4.9. Effects of varying the degree of acceleration of the collision operator. Tangential ($F_{i||}$) and perpendicular ($F_{i\perp}$) fast ion distribution functions were calculated for a counter-injection case. An artificial improvement of the confinement of perpendicular ions is observed with the higher degree of acceleration (GOOCON = 20).

results essentially indistinguishable from those obtained with $\text{GOOCON} = 40$. This assured that $\text{GOOCON} = 40$ was large enough to properly simulate counter-injection discharges.

It was concluded that an artificial improvement in the confinement of counter-injected ions—as they scatter into the trapping region—was produced by the code when ν was made too large. Consequently, all the analyses of counter-injection sequences were performed with $\text{GOOCON} = 40$, while a value of 20 was used for the co-injection cases.

4.3.5 Russian Roulette and Particle Splitting

It was found that the Monte Carlo calculation converges quickly, and with a relatively small variance, to a final value for the tangential flux, but a much larger number of particles is required to achieve an acceptable statistical quality for the flux along the most perpendicular chord. A redistribution of the statistics was thus needed, and this was achieved by implementing Russian roulette and particle splitting schemes in NEWORBX.

Since the ratio of the number of particles contributing to the high-energy perpendicular flux to those contributing to the tangential flux is quite small, and in view of the fact that the high-energy, perpendicularly moving ions are easily lost from the plasma—due to their proximity to the orbit loss region—a Russian roulette scheme is needed that strongly favor those particles that have a small pitch angle at birth to obtain smooth perpendicular spectra. However, this procedure would introduce a large variance into the calculation of the tangential spectra because few particles having large weights would produce most of that signal. Furthermore, the calculation of the perpendicular flux at

lower energies would also suffer from a strong Russian roulette on those ions with large pitch angles at birth because it turns out that this flux comes almost entirely from particles that originally have $v_{\parallel}/v > 0.5$ and scatter in velocity space as they slow down. To avoid errors associated with the elimination of contributing particles, a mild Russian roulette was adopted for most of the runs, with a stronger one reserved for a few special applications.

The method chosen for eliminating some tangentially moving ions in favor of perpendicular ones is very simple. Three variables are assigned values in an input list, two cut-off values of $|v_{\parallel}/v|$ (ZETA1 and ZETA2) and a minimum survival probability ALFA (≤ 1). After the first two midplane crossings, the minimum value of $|v_{\parallel}/v|$ on the orbit (i.e., at the inside crossing) is tested against ZETA1 and ZETA2. If $|v_{\parallel}/v|_{\min} \leq \text{ZETA1}$, the survival probability (P) is 1; if $|v_{\parallel}/v|_{\min} \geq \text{ZETA2}$, then P is set equal to ALFA. Otherwise, P is a linear function of pitch angle, with values between 1 and ALFA. A random number η_i is cast, and if $P < \eta_i$, the particle is eliminated; otherwise, it survives with its weight increased by a factor $1/P$. In most of the analyses, ZETA1 = 0.3, ZETA2 = 0.45, and ALFA = 0.2 were used.

For the purpose of calculating fast neutral spectra, it was found convenient not to keep those particles that are lost without crossing the HMP and those ions that cross the HMP once, but out of the NPA viewing angle. Of course, these ions were added to the total number of particles run. Furthermore, it is worth mentioning that none of these methods devised to improve the statistics in the calculation of the fast neutral spectra was used when calculating the power delivered to the plasma, the power losses, and the beam-target neutron

yield. The statistical quality of these calculations could, in fact, be adversely affected by those schemes.

To further reduce the variance in the simulated perpendicular spectra, particle splitting techniques were also implemented. A function P similar to that used for the Russian roulette was adopted, with $ZETA1 = 0.2$ and $ZETA2 = 0.25$ typically and $ALFA = 0$. At each crossing, the current value of $|v_{\parallel}/v|$ is tested for splitting: if $P \geq \eta_j$, then the particle weight is divided by two, and its position, energy, new weight, etc., are stored, to be used—after the parent particle finally thermalizes or is lost from the plasma—as starting parameters for a daughter particle.

To avoid excessive splitting at low energies, where many particles already contribute to the perpendicular flux, an input list variable $ELOW$ was introduced so that no further splitting would occur below $ELOW$. Since following particles with very low weights would be inefficient timewise, a minimum weight $WMIN$ was also entered in the input list. $WMIN$ was usually set equal to 0.1, that is, one-tenth of the starting weight. The code keeps track of the weights as a particle splits. The sum of the final weights was always found to equal the weight acquired by the original particle after the Russian roulette, thus assuring that the weight was being conserved by the splitting process.

As a final check, a comparison of predicted fast neutral spectra obtained with and without Russian roulette and particle splitting was carried out to make sure that the end results of the simulation would not change and to measure the improvement in statistics. Figure 4.10 displays the resulting spectra, plotted for the $R_t = +72$ -, $+42$ -, and $+8.5$ -cm chords. The beams were co-injected ($R_t = +74.5$ cm), and the plasma current was 96 kA.

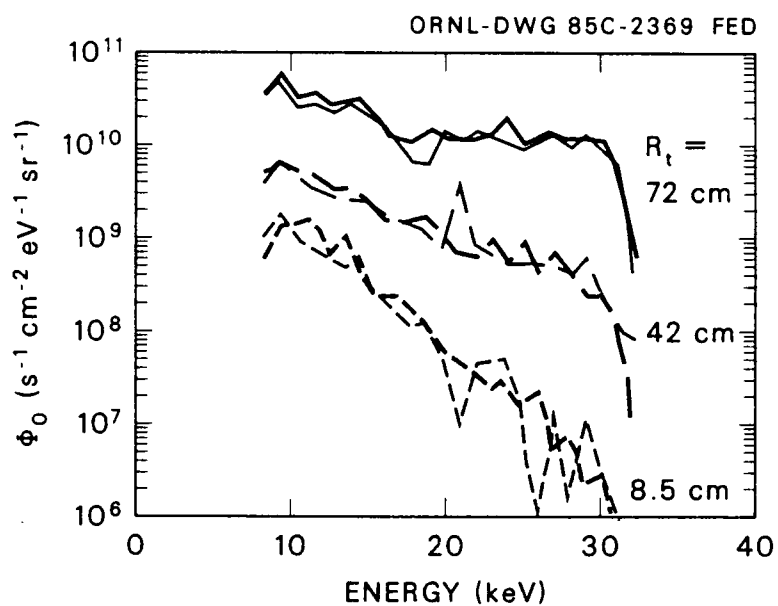


Fig. 4.10. Test of reliability for the Russian roulette and particle splitting schemes. The Monte Carlo-simulated spectra from a straight run and from one with Russian roulette and particle splitting (thicker lines) are compared.

The spectra calculated using Russian roulette and splitting do not differ from those obtained in the straight run, except for the high energy portion of the perpendicular spectrum being smoother. Three thousand particles were launched in the standard case, with the same number allowed to survive the Russian roulette (~ 7200 were started). In an attempt to make a quantitative comparison of the statistics, average fractional standard deviations for each sightline separately were calculated from the three 1000-particle partial results, and they are shown in Table 4.1.

Table 4.1 Fractional standard deviations for the spectra of Fig. 4.10 with and without Russian roulette and particle splitting

R_t (cm)	σ^a (%)	σ^b (%)
72	30	23
42	33	38
8.5	84	59

^aWithout Russian roulette and particle splitting.

^bWith Russian roulette and particle splitting.

As may be inferred from Fig. 4.10, the largest improvement in the statistics occurred for the perpendicular spectrum in the region from 20 to 30 keV.

The CDC-7600 CPU time increased from 86 to 130 min when using Russian roulette and splitting so that ~ 4600 particles should have been launched in the straight simulation to make a fair comparison. It may be noted that the large increase in execution time is mostly due to particle splitting—since more

particles are followed—while Russian roulette has a negligible effect on the execution time. There are two points to consider. The first is that this was one of the earliest calculations performed, and it was not optimized (ZETA2 for splitting, for example, was set equal to 0.35, whereas the $R_t = 8.5$ -cm sightline sees ions with $\zeta \leq 0.2$; thus, some unnecessary splitting took place). The second point is that the main goal of that comparison was to ensure that the implementation of the Russian roulette and splitting would not introduce spurious effects, whereas these schemes could be more effective in the analysis of sequences with peculiar geometries, for example, counter-spectra during co-injection or co-spectra during counter-injection. The 3000-particle simulation with Russian roulette and splitting was repeated, using different sets of random numbers, to further test the reproducibility of the calculation. As illustrated by Fig. 4.11(a), the two runs produced nearly the same spectra at all tangency radii. In Fig. 4.11(b), the composite spectra are shown, with the average fractional standard deviations for the three chords calculated to be 17, 19, and 33%.

Finally, to test the reliability of the orbit-following Monte Carlo estimations in cases where orbit effects are important, the predicted spectra were compared with the experimental data for the cases displayed in Figs. 4.3 (page 86) and 4.4 (page 88). It was shown earlier that the improper treatment of the orbits results in large discrepancies between the FPP predictions and the experimental spectra for those special viewing geometries. By contrast, the NEWORBX estimation is in fairly close agreement with the experiment in both cases, as illustrated in Fig. 4.12. Consequently, a high level of confidence may be assigned to the orbit-following Monte Carlo calculation of the fast ion distribution function and the fast neutral spectra.

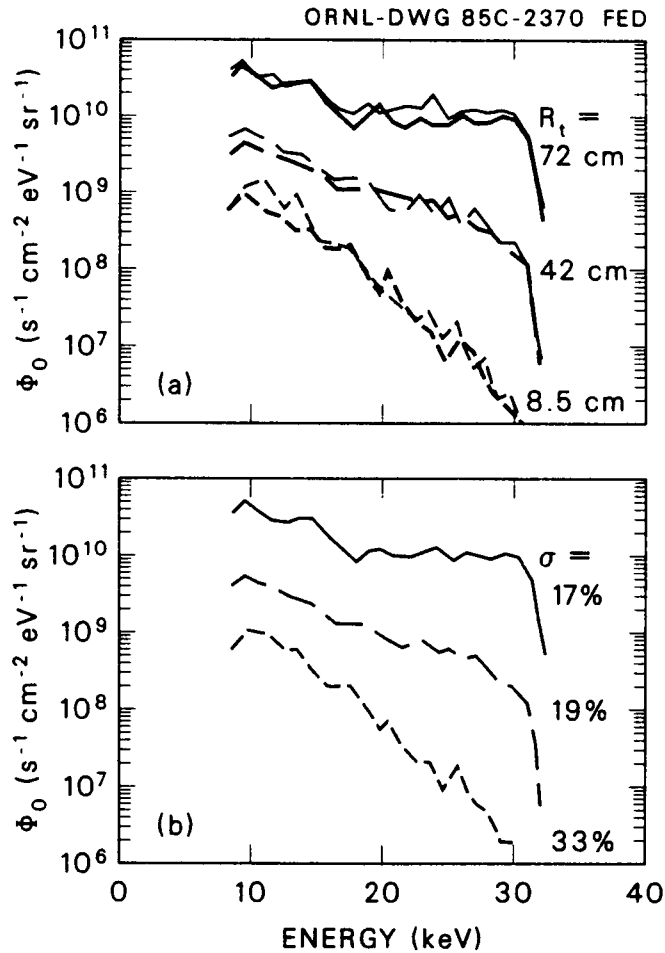


Fig. 4.11. Test of reproducibility, using different sets of random numbers in the Monte Carlo calculation. Approximately 8000 particles were started in each of the two runs shown in (a). The averages of the two runs are shown in (b), together with the fractional standard deviations for the three sightlines.

ORNL-DWG 85C-2576 FED

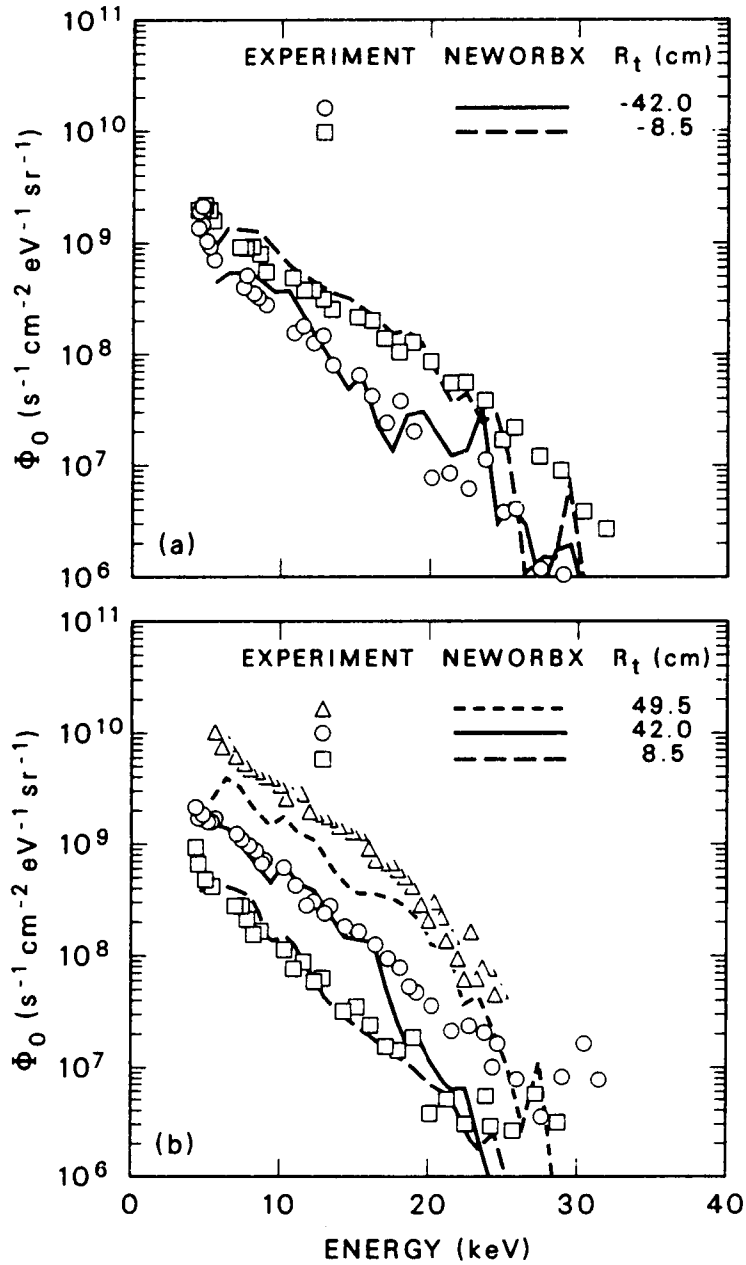


Fig. 4.12. Tests of reliability for the orbit-following Monte Carlo simulation in cases where orbit effects are important. The simulation is compared in (a) with the same experimental data shown in Fig. 4.3 and in (b) with the data shown in Fig. 4.4.

CHAPTER 5

CO-, COUNTER-, AND BALANCED INJECTION

5.1 INTRODUCTION

This chapter presents a comparison of experimental fast ion data collected on the ISX-B with the corresponding predictions of the theoretical model. The purpose is to assess the level of understanding of beam injection physics under a variety of beam and plasma conditions. A further objective is to determine the range of uncertainty in the calculated beam power deposited into the plasma in the ISX-B.

As discussed previously, the heating neutral beams in the ISX-B were injected quasi-tangentially, either in the same direction as the toroidal component of $\hat{J}_p$ (co-injection) or opposite to it (counter-injection). The two injection schemes resulted in marked differences in the plasma characteristics and in fast ion confinement. In this chapter, the typical features of co- and counter-injected discharges are first reviewed, then fast ion confinement and the resulting plasma heating are discussed. The analysis is carried out through a comparison of the experimental and calculated fast neutral spectra obtained for some illustrative ISX-B cases. In matching the predictions of the computational code with the experimental data, $n_0(R)$ and Z_{eff} will be varied within their ranges of uncertainty. A comparison of the resulting simulations with the experimental spectra will provide an estimate of the uncertainties in the charge-exchange losses, in orbit losses due to enhanced pitch angle scattering, and in the power delivered to the plasma.

A consequence of unidirectional injection (either co- or counter-) is that momentum is imparted from the beam ions to the plasma; as a result, a toroidal velocity v_ϕ is generated, and plasma potential and transport rates are expected to change from their ohmic values.^{47,48} Effects induced by plasma rotation were considered as a possible cause of the τ_E^* deterioration with increasing beam power. To investigate this possibility, a third beam line—pointing opposite to the first two—was added to the ISX-B in 1982 to control momentum input independently of energy input. Although subsequent experiments excluded v_ϕ as a cause for the τ_E^* degradation,⁴⁹ noticeable differences (in qualitative agreement with theoretical predictions) were indeed observed in the values of v_ϕ , plasma potential, and particle transport rates between co-, counter-, and balanced injection (concurrent co- and counter-injection at similar power levels).^{50,51} To explore whether rotational effects might affect to any significant extent the confinement of the beam ions, fast neutral spectra obtained during balanced injection are also analyzed.

Section 5.2 deals with co-injection, probing how well the theory predicts the spectra of escaping fast neutrals in discharges with different $\bar{n}_e$ and I_p . Section 5.3 carries out the same investigation for counter-injected discharges. Finally, co-, counter-, and balanced injection in similar discharges and at the same total power level are compared in Section 5.4.

5.2 CO-INJECTION

Co-injection in the ISX-B produced well-behaved discharges in both getter and ungettered plasmas over a wide range of parameters. Injected powers

of up to 2.5 MW, line-averaged densities up to $1.8 \times 10^{14} \text{ cm}^{-3}$, and I_p ranging from 60 to 220 kA were obtained with a typical discharge duration of ~ 200 ms after injection.

In this section, the experimental fast neutral spectra collected during typical ISX-B co-injected discharges are matched with the predictions of the Monte Carlo code NEWORBX. A high- and a low-density case is considered first and high and low I_p sequences next.

5.2.1 Density Scan

As part of the investigation of the high τ_E^* regime, several nongettered, high-density experiments were performed on the ISX-B. In one of these experiments (072683), Thomson scattering profiles were taken at the time when the highest $\bar{n}_e$ was attained and also at two earlier time points in the discharge, before and during strong gas puffing. Thus, the experiment provides an opportunity to compare the experimental and predicted fast neutral spectra at low, medium, and high $\bar{n}_e$. Time histories of the main plasma parameters are shown in Fig. 5.1, and their values at the three laser times are presented in Table 5.1. The deposition profiles (cm^{-3}) of the full-energy and third-energy beam components are shown in Fig. 5.2—as calculated by the NEWORBX code for the high and low density cases. The profiles differ only slightly at the injection energy, but a significant broadening is observed for the low energy component at the higher plasma density. Fast neutral spectra along several viewing chords were obtained. The spectra along four sightlines from tangential to perpendicular are compared with the respective Monte Carlo simulations using the electron density and temperature profiles and plasma parameters measured or inferred (e.g., Z_{eff}) at 180 and 280 ms.

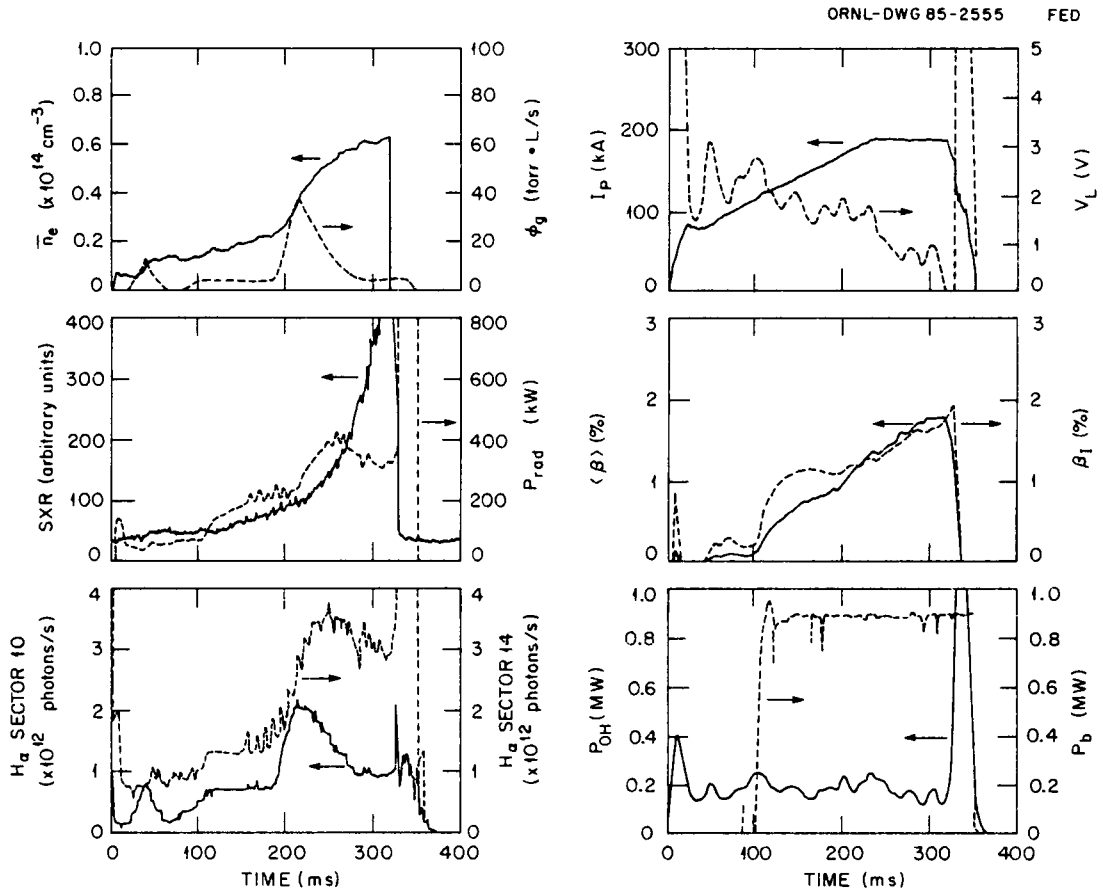


Fig. 5.1. Time histories of plasma parameters for sequence 072683, used for the density scan experiment. Thomson scattering profiles were taken at 180, 220, and 280 ms.

ORNL-DWG 85-2556 FED

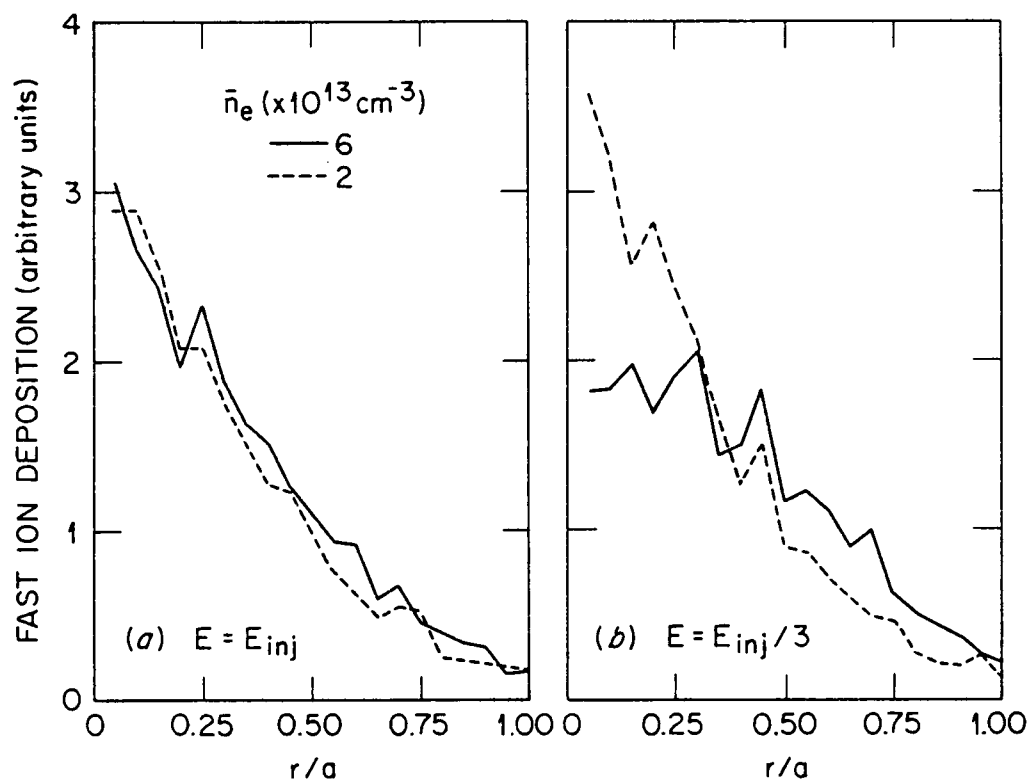


Fig. 5.2. Deposition profiles of the full-energy and third-energy beam components in high and low density plasmas. The beam co-injected hydrogen at $E_{inj} = 32 \text{ keV}$.

**Table 5.1 Plasma parameters for sequence 072683
at three time points in the discharge**

Parameters	Time point		
	180 ms	220 ms	280 ms
$\bar{n}_e$ (10^{13} cm^{-3})	2.27	4.14	5.96
I_p (kA)	158	181	186
B_ϕ (kGauss)	13.4	13.4	13.4
P_b (MW)	0.90	0.90	0.90
$T_e(0)$ (eV)	1021	883	907
$T_i(0)$ (eV)	1323	1131	1080
$n_e(0)$ (10^{13} cm^{-3})	3.37	4.76	7.84
Z_{eff}	2.63	2.05	1.79

In Fig. 5.3(a), the predicted spectra are compared with the data for the high $\bar{n}_e$ case ($\bar{n}_e = 6 \times 10^{13} \text{ cm}^{-3}$). A wall recycling coefficient (R) of 0.4 was used to determine n_0 for the calculation of both the charge-exchange losses and the magnitude of the fast neutral flux. In steady state, the edge source of neutrals is given by

$$\frac{N}{\tau_p} = \frac{\Phi_g}{1 - R} ,$$

where Φ_g is the rate at which the gas is puffed into the vessel and τ_p is the particle confinement time. Thus, a wall recycling coefficient of 0.4 corresponds to a particle source rate equal to 1.67 times the gas puff rate. The edge neutral temperature $E_0(a)$ was assumed to be 5 eV. As discussed in Appendix A, the tangential NPA [the Velocity-Filter Analyzer (VFA), $R_t = 49.5$ to 87 cm] was operated with stripping-cell pressures different from the value used during

ORNL-DWG 85C-2554 FED

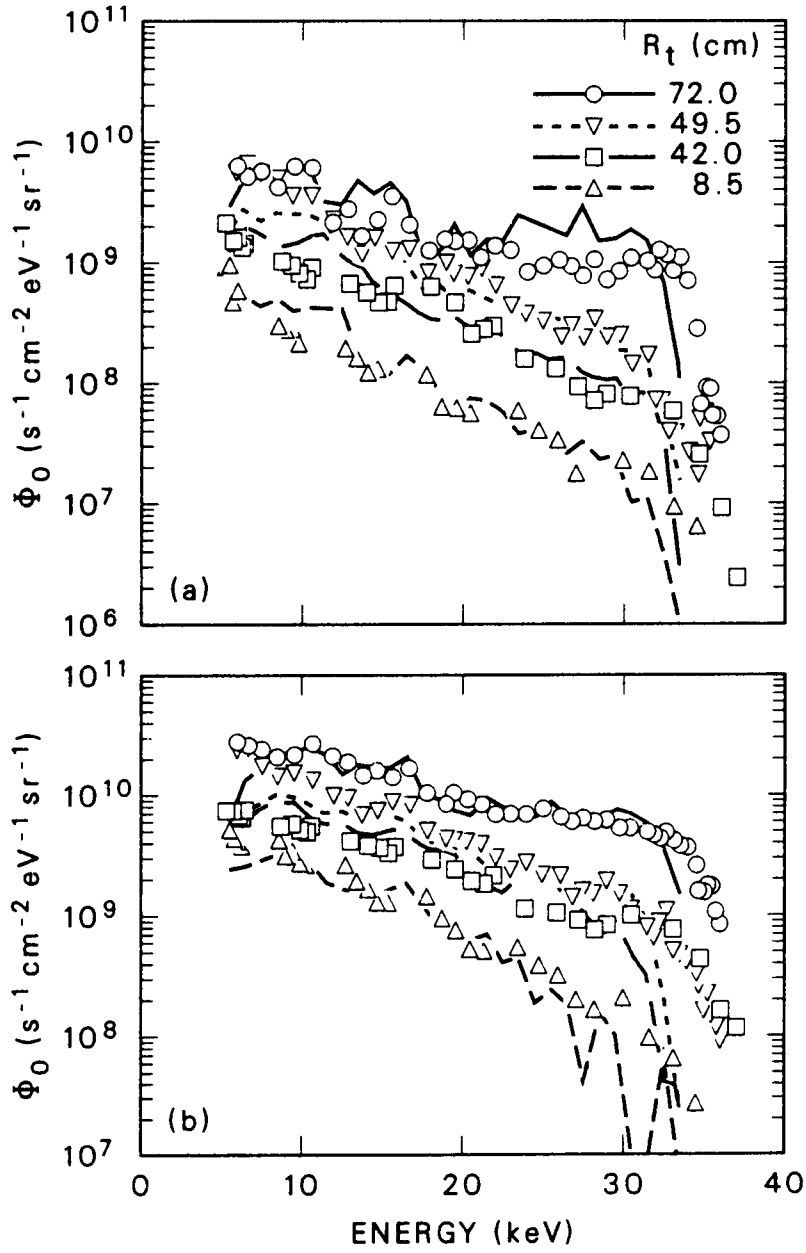


Fig. 5.3. Fast neutral spectra during co-injection at high and low $\bar{n}_e$. The spectra are compared with the Monte Carlo predictions at (a) $\bar{n}_e = 6 \times 10^{13} \text{cm}^{-3}$ and (b) $\bar{n}_e = 2 \times 10^{13} \text{cm}^{-3}$.

the calibration. An appropriate correction was applied to all the data collected with this analyzer. For this particular comparison, the experimental VFA data were artificially reduced by a factor of 0.75 after the adjustment for the gas cell efficiency. This correction is within the error bars, considering that (1) a post mortem analysis showed that the gas flow rate was monitored with an uncertainty of $\pm 40\%$ and (2) the edge neutral source may be somewhat different at the Momentum-Energy Analyzer (MEA) and VFA locations. The shapes and separation of the different spectra are well represented by the simulation. Furthermore, the code correctly predicts the magnitude of the flux detected by the perpendicular NPA (the MEA, $R_t = 42$ to 8.5 cm), which was operated at the calibrated gas cell pressure. The larger widths of the high energy tail ($E > E_{inj}$) are due mostly to the resolution of the analyzers; $\Delta E/E$ is $\geq 5\%$, corresponding to $\Delta E \geq 1.5$ keV at $E = 30$ keV. Furthermore, the statistics for the Monte Carlo calculation are poor for energies greater than the injection energy. It is conceivable that this energy region is undersampled and that launching a very large number of particles would result in wider high energy tails. For energies between E_{inj} and $E_{inj}/2$, the tangential flux is lower than predicted. This feature is not always observed and is attributed to the overall uncertainties in the experimental measurements and in the simulations. In some cases—although not in this particular instance—an artificially lower flux to the VFA was a consequence of the channeltron detectors counting near saturation. This was observed occasionally in the tangential spectrum at the higher energies and at $E_{inj}/2$ and $E_{inj}/3$, where the highest count rates were reached.

The low energy portion of the spectrum along the $R_t = 49.5$ -cm sightline is steeper than the Monte Carlo prediction; this appeared to be typical of co-injected discharges.* Attempts were made to reproduce this feature in the Monte Carlo simulations by varying $n_0(R)$, Z_{eff} , or by artificially enhancing the scattering coefficient at large minor radii—where an increase in the impurity concentration takes place during co-injection.^{50,52} Some improvement in matching the $R_t = 49.5$ -cm spectra was produced by a variation of parameters; however, this could be achieved only at the expense of worsening the match along the other viewing chords. On the other hand, data taken along the neighboring $R_t = 42$ -cm sightline with the more reliable MEA are in good agreement with the Monte Carlo simulation. In view of this, and considering that global uncertainties of up to factors of ~ 2 affect the theoretical calculation, the present study could not resolve this discrepancy. However, two effects may be mentioned that would reduce the discrepancy somewhat. The first is of an experimental nature. As discussed in Appendix A, the VFA was used without the mass discrimination capability when collecting fast neutral data. Thus, neutrals from plasma deuterons, as well as those from beam hydrogen atoms, were collected. At energies $E \leq 10$ keV, the thermal flux associated with the plasma deuterons was estimated to be $\sim 10\%$ of the total flux. Including this correction would lower the low energy VFA data by approximately that amount. The other effect comes from the Monte Carlo simulation. To shorten

*Counter-injection spectra did not seem to display this behavior. However, there is generally much scatter in the counter-injection data at $R_t = 49.5$ cm, and it is not possible to make a definitive statement on this issue.

the computer times, the Monte Carlo calculations were stopped when the particles slowed down to $E \sim 4.5$ to 5 keV. Because of energy diffusion and acceleration by the toroidal electric field, some particles with $E \leq 4.5$ keV could gain energy and contribute to the fast ion population at $E \geq 5$ keV. Consequently, the altered simulation tends to slightly underestimate the low energy portion of the spectra (along all sightlines). Under these conditions, the Monte Carlo calculations do not faithfully mimic the physical system.

In subsequent comparisons (after the density scan), only spectra along the $R_t = 72$ -, 42-, and 8.5-cm viewing chords will be shown—for clarity. It is necessary to keep in mind that the VFA data are characterized by a lower level of confidence than the MEA data for the following reasons. The VFA was operated at a gas cell pressure significantly lower than that used for the calibration. Although it is reasonable to assume that the stripping efficiency of the gas cell is linear in pressure, the gas flow rates were measured only to an accuracy of $\pm 40\%$. Moreover, since the count rates varied widely depending on the particular plasma and beam parameters, the gas cell pressure was adjusted from experiment to experiment. For these reasons, the absolute magnitude of the VFA fast neutral flux should be regarded as a free parameter. As for the shapes and relative separation of spectra along different VFA sightlines, there are two points to reiterate. First, the $R_t = 72$ -cm flux in some energy ranges was occasionally lowered by saturation of the detectors. This is not an insurmountable problem since the occurrence could be recognized and the extent of its effects could be estimated. Second, the spectra along the $R_t = 49.5$ -cm chord are discordant with both the theoretical prediction and the neighboring MEA sightline. Since it was not possible to determine the causes of this

behavior, all the fast neutral data collected with the VFA are to be used with caution.

Next, the sensitivities of both the charge-exchange losses and the fast neutral spectra to the background neutral density profile $n_0(R)$ were tested. The Monte Carlo simulation for the high $\bar{n}_e$ case was performed assuming $R = 0.8$ and $E_0(a) = 100$ eV when calculating $n_0(R)$ for the charge-exchange losses. Those values were chosen to maximize the charge-exchange losses while still maintaining R and $E_0(a)$ within plausible magnitudes. The change in the neutral density profile is displayed in Fig. 5.4. Both the wall source and the beam halo contribute to $n_0(R)$. The calculated charge exchange losses increased by a factor of ≈ 4 , but, since they constituted only 2.2% of the injected power with the original $n_0(R)$, they remained $< 10\%$ of the total power even in the high recycling case. Consequently, the larger charge-exchange losses did not produce any detectable change in the fast neutral spectra when the original profile [i.e., with $R = 0.4$, $E_0(a) = 5$ eV] was used to calculate Φ_0 . If $R \gg 0.4$ and/or $E_0(a) \gg 5$ eV were assumed to calculate Φ_0 , the predicted flux would become increasingly higher and incompatible with the experimental data. The agreement between experimental data and Monte Carlo simulation could be maintained if $E_0(a) \gg 5$ eV were assumed together with a vanishingly low recycling coefficient. However, since recycling is *the source* of higher energy neutrals, the two assumptions would be physically inconsistent.

In Fig. 5.3(b) experimental and simulated spectra are compared for the low $\bar{n}_e$ case. The sightlines are the same as those shown in Fig. 5.3(a). Again, the VFA data were artificially reduced by a factor of 0.75. For the charge-exchange losses, $R = 0.4$ and $E_0(a) = 5$ eV were used. However, an edge

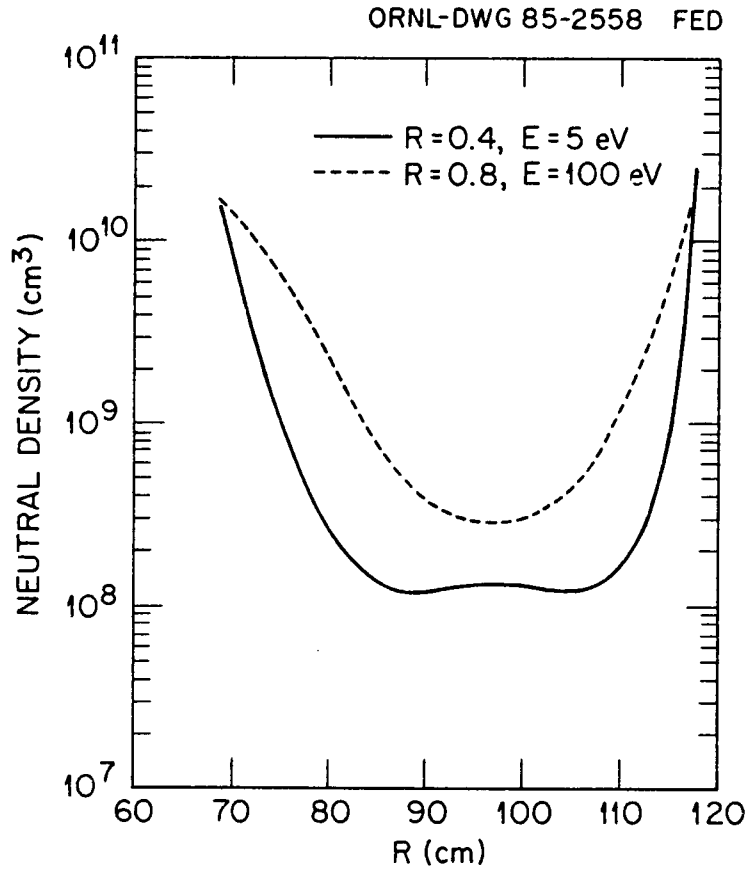


Fig. 5.4. Background neutral density profiles calculated assuming low and high wall recycling. The same beam-halo contribution is included in both profiles; $\bar{n}_e = 6 \times 10^{13} \text{ cm}^{-3}$, and $P_b = 0.9 \text{ MW}$.

source rate *smaller* than the gas puff rate (i.e., $0.9 \Phi_g$) had to be assumed at the NPA location to match the experimental flux in magnitude. The gas puff valve was located in toroidal sector 10, ~ 1 m away from the NPA ports located in sectors 6 and 7. If the wall recycling is low, a multiplier <1 on Φ_g is expected at locations some distance away from the gas valve. Figure 5.5 shows the time histories of the H_α signals (proportional to the edge neutral density) in various toroidal sectors. A comparison of these signals in conjunction with the Φ_g plot of Fig. 5.1 (page 113) indicates that (1) recycling is the dominant source of neutrals close to the limiter (located in sector 14) but decreases rapidly away from the limiter, (2) the source due to the gas puff decreases away from sector 10, and (3) the recycling appears to be weaker at early times in the discharge than during the high-density portion. In view of the preceding considerations, a gas puff multiplier <1 at the location of the NPA ports is plausible. At the intermediate density of $4 \times 10^{13} \text{ cm}^{-3}$ —during the strong gas puffing—good agreement between experimental and predicted spectra was obtained assuming a Φ_g multiplier of 1.1, that is, intermediate between that of the high and low $\bar{n}_e$ cases.

Even with the experimental flux differing in magnitude by a factor of $\simeq 8$ between the high and the low $\bar{n}_e$ discharges, the Monte Carlo simulation satisfactorily predicts the fast neutral spectra along all sightlines in both cases. A breakdown of the injected beam power for the high and low $\bar{n}_e$ discharges—as calculated by the NEWORBX code—is shown in Table 5.2. The powers quoted in parentheses were calculated by the ZORNOC code—using an approximate, analytical solution of the Fokker Planck equation—and are those used in the

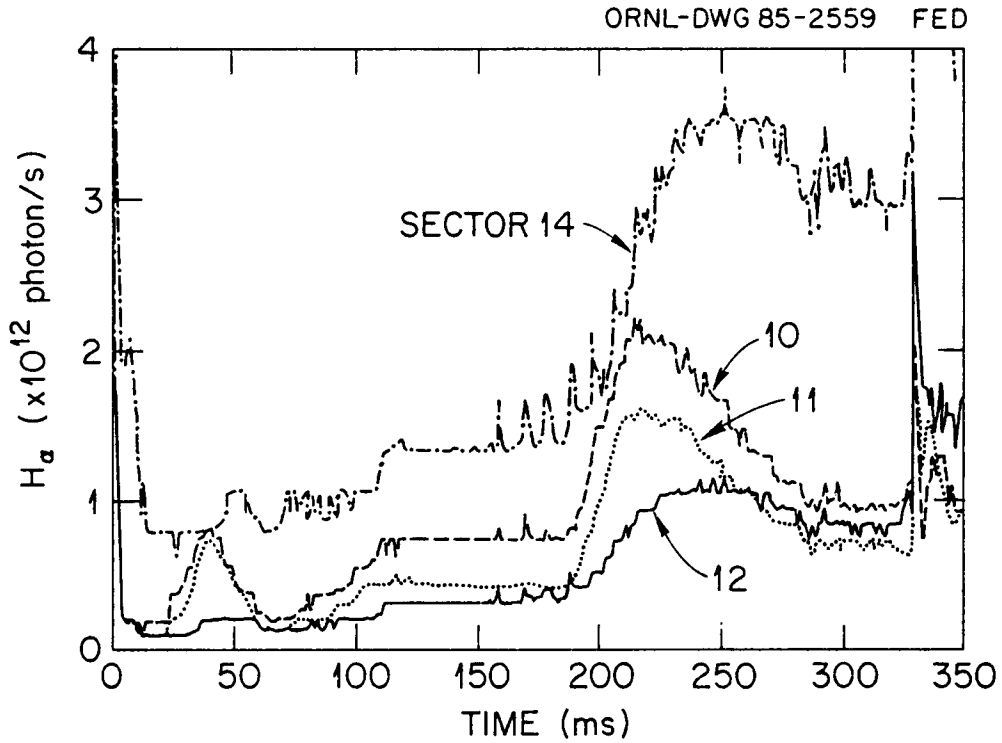


Fig. 5.5. Time histories of the H_{α} signals from detectors located in various toroidal sectors. The gas puff valve was in sector 10, the limiters in sector 14, and the NPA in sectors 6 and 7. The plasma sequence is 072683.

**Table 5.2 Power distribution (in kW/1 MW, co-injected)
high and low $\bar{n}_e$**

	$\bar{n}_e = 6 \times 10^{13} \text{ cm}^{-3}$	$\bar{n}_e = 2 \times 10^{13} \text{ cm}^{-3}$
P_{be}	554 (616)	444 (461)
P_{bi}	337 (312)	236 (184)
P_{cx}	22 (56)	125 (179)
Shine through	8	107
Total orbit losses	38	93
Prompt orbit losses	25	75
Nonprompt orbit losses	13	18
P_{OH}	-13	-52
P_{therm}	54	47

transport calculation. They are close to the values calculated by the orbit-following Monte Carlo code—except for the charge-exchange losses, which are predicted to be significantly higher since reionization of the escaping neutrals is not taken into account. For the low $\bar{n}_e$ case, the shine through and the charge-exchange losses are much larger than for the high $\bar{n}_e$ case, where they are of negligible magnitude. Also, prompt orbit losses are significantly larger. (In NEWORBX, prompt orbit losses are defined as those of ions that exit the plasma before the fifth horizontal midplane crossing.) This is because more neutrals are deposited close to the inside edge of the torus—in the loss region for co-injection [see Figs. 5.6 and 3.12 (page 52)].

To determine the extent of possible charge-exchange losses in the low $\bar{n}_e$ case, the simulation was repeated with $R = 0.95$ and $E_0(a) = 100 \text{ eV}$ for the calculation of the losses. Note that $R = 0.95$ is a plausible value at the limiter but is expected to be an overestimation when used as a toroidal average. With

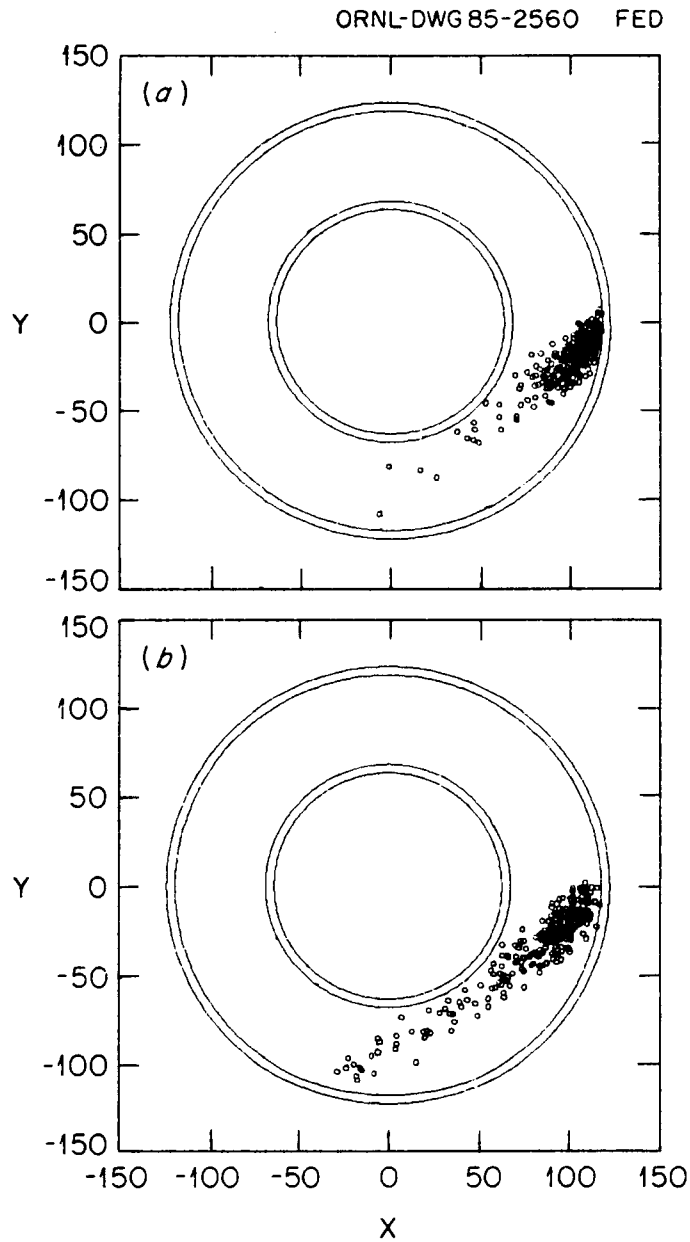


Fig. 5.6. Top view of the Monte Carlo beam deposition. The high $\bar{n}_e$ case is shown in (a) and the low $\bar{n}_e$ case in (b).

these boundary conditions, the predicted spectra are clearly in disagreement with the experimental data, as shown in Fig. 5.7(a). The calculated charge-exchange losses constituted 66.8% of the injected power. The calculation was then performed with $R = 0.8$ and $E_0(a) = 100$ eV, and the resulting spectra are presented in Fig. 5.7(b). The agreement between the simulation and the experiment appears to have worsened from that of Fig. 5.3(b). A more realistic upper limit to the charge-exchange losses for the low $\bar{n}_e$ sequence could be set using $R = 0.6$ and $E_0(a) = 50$ eV. Under these conditions, the predicted spectra would not be inconsistent with the experimental data within the uncertainties. The power lost to charge exchange assuming $R = 0.6$ and $E_0(a) = 50$ eV is 256 kW/1 MW injected. This is 43% higher than the value obtained in ZORNOC, but the power delivered to the plasma decreases by only $\sim 12\%$. As for the high $\bar{n}_e$ sequence, the largest plausible R may be higher than 0.6—considering the H_α signals at the two time points. However, in that case the charge-exchange losses are only a small fraction of the injected power, even for $R = 0.8$ and $E_0 = 100$ eV, as discussed previously. It is also important to note that the upper limit to the charge-exchange losses for the high $\bar{n}_e$ case only slightly exceeds the value calculated by ZORNOC and used in the transport analysis.

5.2.2 Plasma Current Scan

For the investigation of fast ion confinement, low I_p discharges are of interest because orbit displacements from the magnetic surfaces are maximized

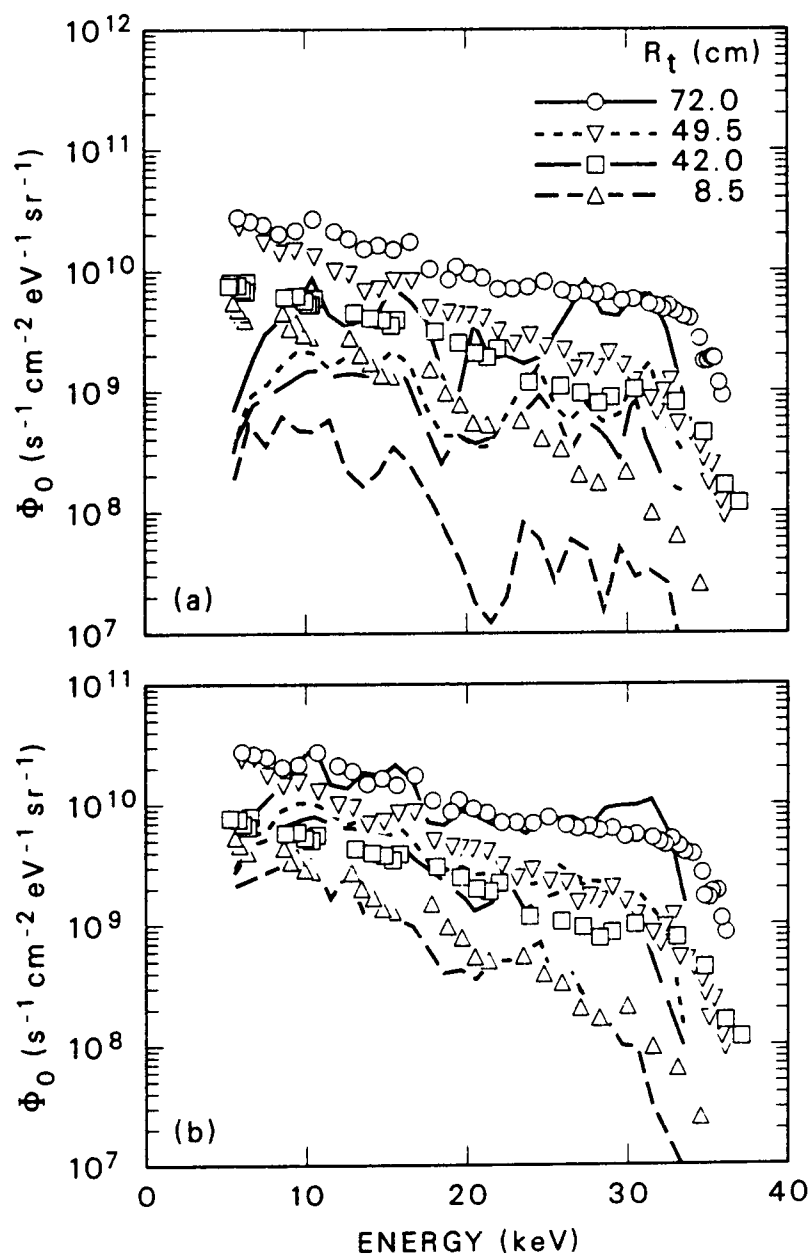


Fig. 5.7. Effects of enhanced charge-exchange losses on the predicted fast neutral spectra at low $\bar{n}_e$. A Φ_g multiplier = 20 and $E_0(a) = 100$ eV were assumed to calculate $n_0(R)$ for the charge-exchange losses in case (a). The corresponding values for case (b) are $5 \times \Phi_g$ and $E_0(a) = 100$ eV. To calculate the flux to the NPA, a Φ_g multiplier = 0.9 and $E_0(a) = 5$ eV were used in both cases.

and large orbit losses are expected. More generally, the discharge characteristics vary strongly with I_p , and it is interesting to probe whether the theoretical prediction of the fast ion behavior describes equally well both low and high I_p cases. To mention some of the differences between the two regimes, low I_p discharges have lower τ_E^* , higher β_p , lower $T_e(0)$ and $T_i(0)$, and more peaked profiles. The MHD activity is also typically different. Fast neutral spectra obtained during low and high I_p (gettered, co-injected) discharges will now be compared with the corresponding Monte Carlo predictions. An effort was made to keep the external plasma parameters as nearly the same as possible between the two sequences. The time histories of some of the discharge characteristics are displayed in Fig. 5.8. The Thomson scattering profiles were taken at 190 ms. The experimental spectra for the two cases are shown in Fig. 5.9, superimposed on one another to display the changes occurred when I_p was varied.

The spectra for the high I_p case are compared with the Monte Carlo simulation in Fig. 5.10(a). No corrections were applied to the experimental flux along the $R_t = 72$ -cm chord besides that for the stripping-cell efficiency. $R = 0.4$ and $E_0(a) = 5$ eV were used to calculate $n_0(R)$ for both the charge-exchange losses and Φ_0 . The simulation is in excellent agreement with the experimental data. The corresponding comparison for the low I_p case is shown in Fig. 5.10(b). Again, no further adjustment was applied to the VFA data. Here, too, R was set $= 0.4$ and $E_0(a) = 5$ eV for both $n_0(R)$ profiles. The Monte Carlo simulation correctly predicts that the tangential spectrum is unaffected by the change in I_p . The fast neutral signal along the tangential sightline is produced by co-passing ions that circulate between the outer edge of

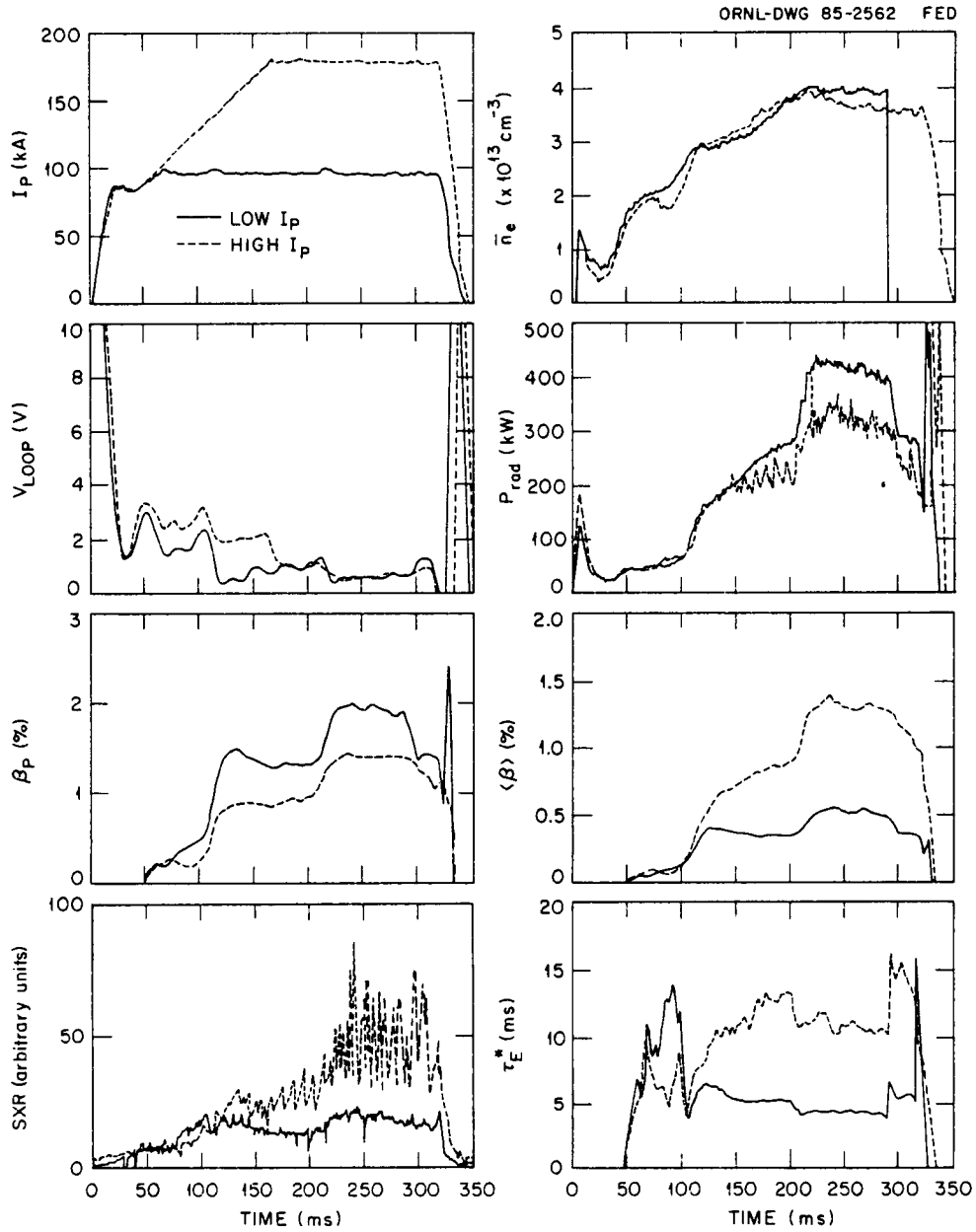


Fig. 5.8. Time histories of plasma parameters for the low and high I_p comparison during co-injection. Thomson scattering profiles were taken at 190 ms. $B_\phi = 1.38$ T for both sequences, and $P_b = 0.92$ and 0.85 MW for the low and high I_p cases, respectively.

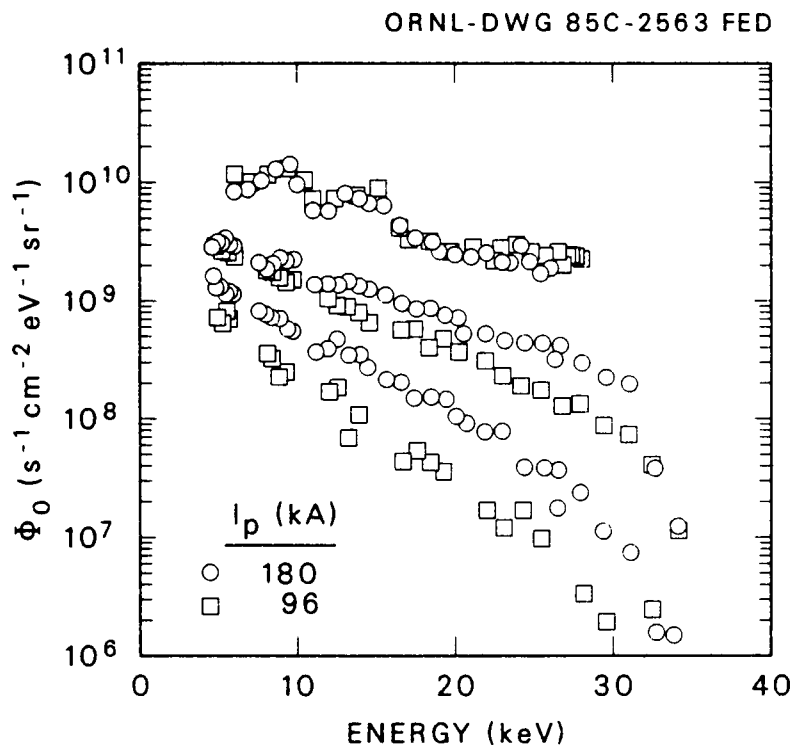


Fig. 5.9. Experimental fast neutral spectra obtained during co-injection at high and low I_p . The other external plasma parameters were the same for the two sequences. The tangency radii of the viewing chords are—from top to bottom— $R_t = 72, 42$, and 8.5 cm. At low I_p , enhanced orbit losses of ions with $v_{\parallel}/v \ll 1$ are evidenced by the flux depletion along the perpendicular and quasi-perpendicular sightlines.

ORNL-DWG 85C-2564 FED

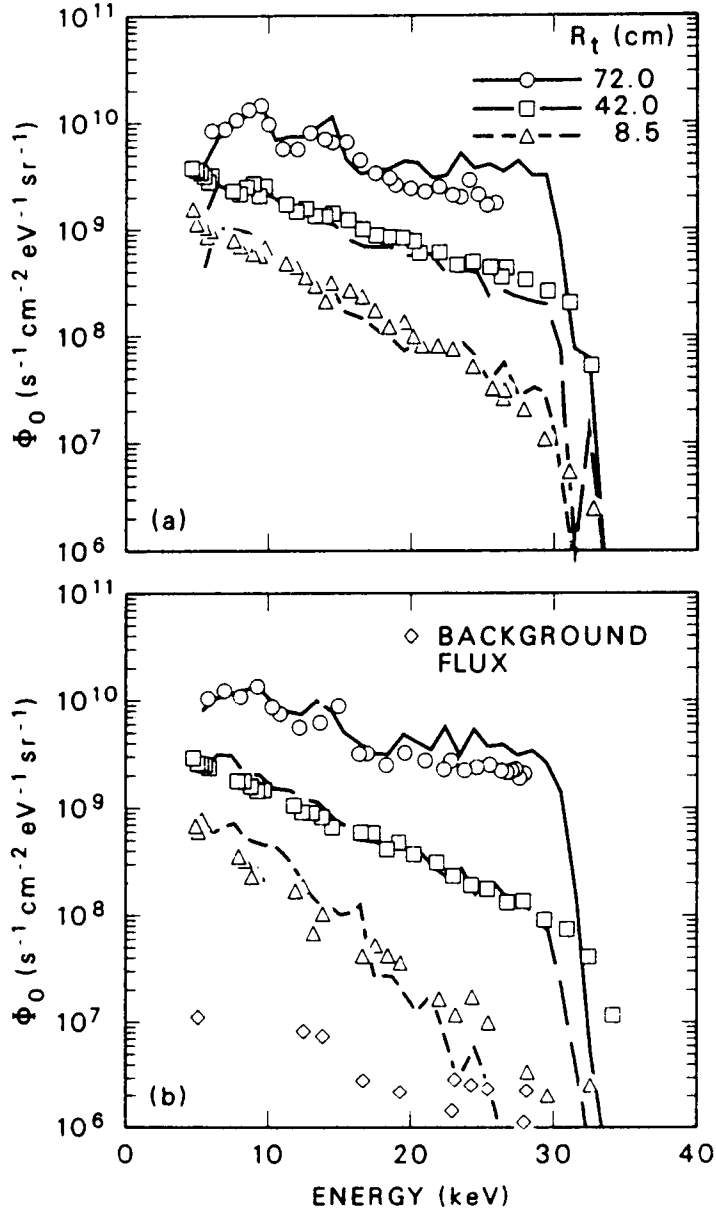


Fig. 5.10. Comparison of experimental and predicted fast neutral spectra during co-injection at high and low I_p . (a) $I_p = 180$ kA, and (b) $I_p = 96$ kA.

the torus and the plasma center. These orbits are far from the loss region and remain relatively unaffected by the lower I_p . Experimentally, the increased orbit losses at low I_p are reflected in the lower fast neutral flux along the more perpendicular viewing chords, especially in the high energy portion of the spectra. This is well reproduced by the Monte Carlo simulation. The fact that the experimental flux at high energy and along the most perpendicular sightline is higher than predicted is partly a consequence of the low signal-to-noise ratio. Also, the statistical uncertainty is significant for both the experimental data and the Monte Carlo simulation in that region.

The power delivered to the plasma and power losses for the two I_p values are presented in Table 5.3. It can be seen that orbit losses amount to <10% of the injected power even for the low I_p case. However, the high energy perpendicular NPA signal is affected strongly by the increased prompt losses because the largest portion of that signal originates from ions born at the outer edge of

**Table 5.3. Power distribution (in kW/1 MW, co-injected)
high and low I_p**

	$I_p = 180$ kA	$I_p = 96$ kA
P_{be}	576 (618)	609 (707)
P_{bi}	283 (266)	212 (196)
P_{cx}	44 (91)	41 (59)
Shine through	20	33
Total orbit losses	35	81
Prompt orbit losses	28	79
Nonprompt orbit losses	7	2
P_{OH}	0	-1
P_{therm}	42	25

the plasma and crossing the horizontal midplane close to the boundary of the loss region on the inside of the magnetic axis. By contrast, the enhanced orbit losses at low $\bar{n}_e$ discussed previously do not deplete the high energy perpendicular spectrum since they affect ions born at the *inner* edge of the plasma with a pitch angle close to unity. These ions do not contribute to the perpendicular spectrum.

The fraction of the total power deposited in the plasma at low I_p is only slightly lower than in the high I_p case—82% as opposed to 86%. A somewhat larger fraction of the deposited power goes to the electrons at low I_p —74% vs 67%. This is a consequence of the lower T_e and correspondingly lower E_{critical} . The radially averaged electron temperatures were 258 and 364 eV for the $I_p = 96$ and 180 kA, respectively. The larger amount of power that “thermalizes” (i.e., beam ions that reach the bulk ion temperature) in the $I_p = 180$ kA sequence is an indicator of the better confinement properties of high I_p discharges.

A comparison with the powers calculated in ZORNOC shows a significant difference in the power delivered to the electrons in the low I_p case. The ZORNOC value is 16% higher, mostly a consequence of the imperfect treatment of the orbits.

The simulations for these two plasma sequences were also performed with larger values of Z_{eff} to test the sensitivity of the calculated spectra to that parameter as well as modeling anomalous pitch angle scattering. This also established that the power deposited in the plasma in typical ISX-B discharges would not be significantly altered by a postulated enhancement in pitch angle

scattering that yield spectra consistent with the experimental measurements. The experimental spectra for both the high and low I_p sequences are compared in Fig. 5.11 with Monte Carlo simulations in which $Z_{\text{eff}} = 7$ was adopted (the value inferred in ZORNOC from plasma resistivity was ≈ 1). At the higher Z_{eff} , the predicted flux decreased along the tangential sightline and increased along viewing chords away from tangential. To match the experimental spectra at high/low I_p , Φ_g multipliers of 1.3/1.0 were used, and the VFA data were artificially lowered by factors of 0.7/0.6. It is evident that the shapes and relative separation of the calculated spectra are not very sensitive to variations in Z_{eff} since even this large value of Z_{eff} did not alter the prediction significantly. Due to the relatively low average values of T_e —and, therefore, of E_c —the slowing-down process was dominated in ISX-B by collisions with electrons. Consequently—as discussed in Chapter 3—pitch angle scattering effects were weak, except perhaps in the central region of the plasma, where E_c assumed the highest values.

In view of this, the spectra localized to the plasma center (DNB on–DNB off) are expected to be more sensitive than the line-integrated spectra to changes in Z_{eff} . The localized spectra obtained during the low I_p sequence along quasi-tangential and perpendicular sightlines (intercepting the DNB centerline) are compared in Fig. 5.12 with the predictions of the NEWORBX code using $Z_{\text{eff}} = 1.1, 3.0$, and 7.0 . In calculating Φ_0 , the number of DNB neutrals that reach the HMP was determined from the measured ion current and voltage, an estimated neutralization efficiency of $\sim 90\%$, an assumed flat intensity profile over the 6-cm radius, and the calculation of the attenuation using the measured value of the line-averaged plasma density. The DNB fractional

ORNL-DWG 85C-2565 FED

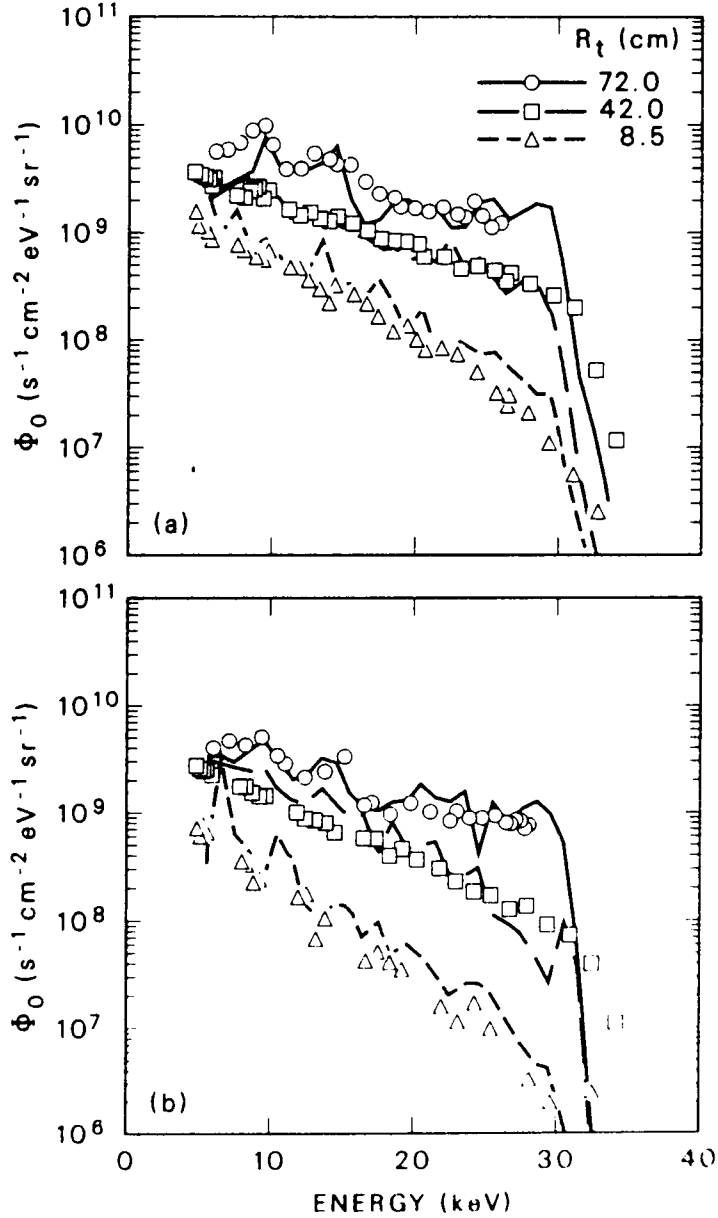


Fig. 5.11. Effects of a simulated enhancement in pitch angle scattering on the line-integrated fast neutral spectra. The line-integrated experimental spectra at (a) $I_p = 180$ kA and (b) $I_p = 96$ kA are compared with Monte Carlo simulations in which $Z_{\text{eff}} = 7$ was assumed.

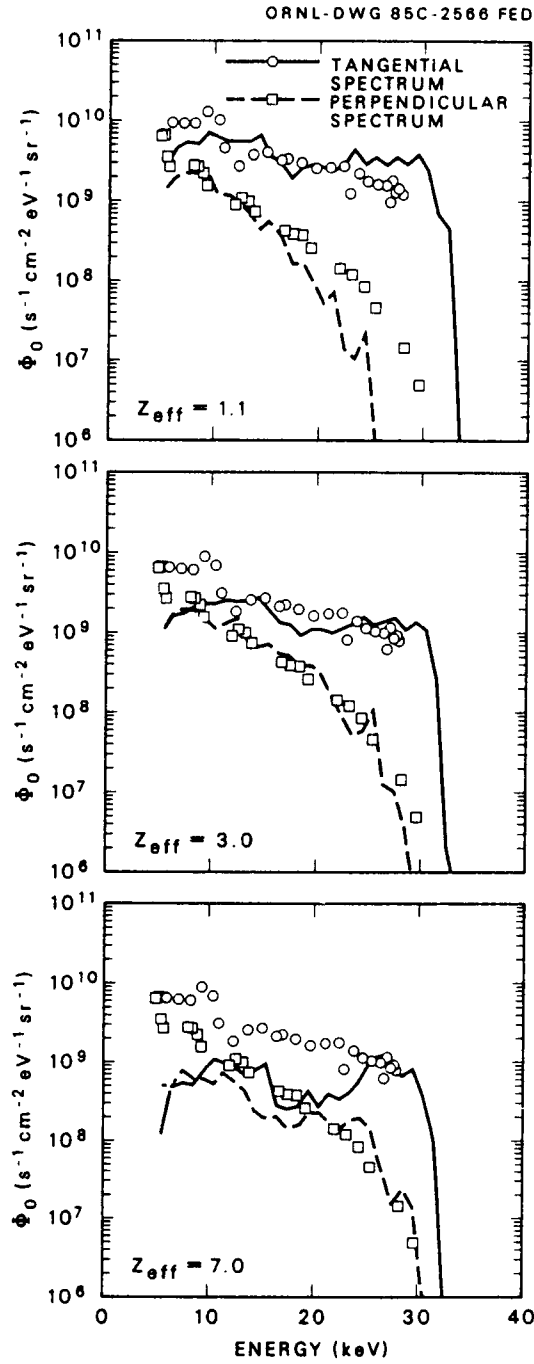


Fig. 5.12. Effects of a simulated enhancement in pitch angle scattering on the localized fast neutral spectra. The localized experimental spectra at $I_p = 96$ kA are compared with Monte Carlo simulations using different values of Z_{eff} .

composition at E_{inj} , $E_{inj}/2$, and $E_{inj}/3$ was assumed to be 0.4, 0.3, and 0.3. Different fractions produced only minor changes in the computed Φ_0 . The VFA experimental data were artificially lowered by a factor of 0.7 (corresponding approximately to the largest estimated error in the stripping-cell pressure) for the high Z_{eff} cases, whereas they were not altered for the $Z_{eff} = 1.1$ case. The simulation that used $Z_{eff} = 7$ is clearly in disagreement with the experimental data. Thus, the analysis of fast neutral spectra establishes that a (postulated) strongly anomalous pitch angle scattering is discordant with the experimental evidence. However, no definitive conclusions can be drawn from the comparisons with $Z_{eff} = 1.1$ and 3. The tangential spectrum is in closer agreement with the data if $Z_{eff} = 1.1$ (the value deduced from resistivity) is adopted, whereas the experimental perpendicular spectrum is reproduced by the simulation if $Z_{eff} = 3$ is assumed. Experimentally, the flux enhancement with the DNB on was by factors of ~ 6 along the perpendicular chord and ~ 2 along the tangential chord. The tangential spectrum has a lower degree of reliability than the perpendicular spectrum because it was obtained as differences between pairs of numbers of approximately the same magnitude. Thus, the comparison of Fig. 5.12 would seem to favor a value of $Z_{eff} \approx 3$. However, the intensity profile of the DNB could be taken to be triangular in shape, with a radius $r = 10$ cm, and $n_0(r) = n_0(0)/10$. These values would not be inconsistent with measurements of the FWHM of the enhanced (i.e., with the DNB on) thermal flux obtained during toroidal scans around the DNB location. With these parameters for the DNB, the high energy portion of the perpendicular spectrum is predicted to be higher since the perpendicular fast ion population at smaller major radii can contribute to the signal. A Z_{eff} of ~ 2 is expected to produce

good agreement with the experiment if the DNB intensity profile is assumed to be triangular.

It is interesting to note that the calculated power delivered to the plasma varies little with even large changes in Z_{eff} . For co-injection discharges, the larger non-prompt orbit losses at high Z_{eff} may be more than compensated for by reduced shine-through and prompt orbit losses and by the larger amount of power extracted from the toroidal electric field. For the counter-injection case at high I_p discussed in the next section, a value of $Z_{\text{eff}} = 4$ —instead of the ZORNOC value of 1.9—results in lowering P_{be} by 8%, P_{bi} by 19%, and the total power deposited in the plasma by 11%.

5.3 COUNTER-INJECTION

Counter-injected discharges in the ISX-B always disrupted within ≤ 50 ms from the beginning of injection. They were characterized by high levels of impurity accumulation in the plasma core, high radiated powers, and low electron and ion temperatures. These discharges were typically run at low beam power, medium densities, and medium to high plasma currents. Gettering was also required.

Two experiments were specifically dedicated for the investigation of beam ion confinement during counter-injection, one at $I_p = 170$ kA, and the other at $I_p = 110$ kA. These experiments were performed consecutively on the same day. Discharge characteristics for the two sequences are displayed in Fig. 5.13. The laser times were 215 ms for the high I_p case and 190 ms for the low I_p . B_ϕ (≈ 12.3 kGauss), $\bar{n}_e$ ($\approx 3.8 \times 10^{13} \text{ cm}^{-3}$), P_b (≈ 0.50 MW), and E_{inj} (≈ 28.8

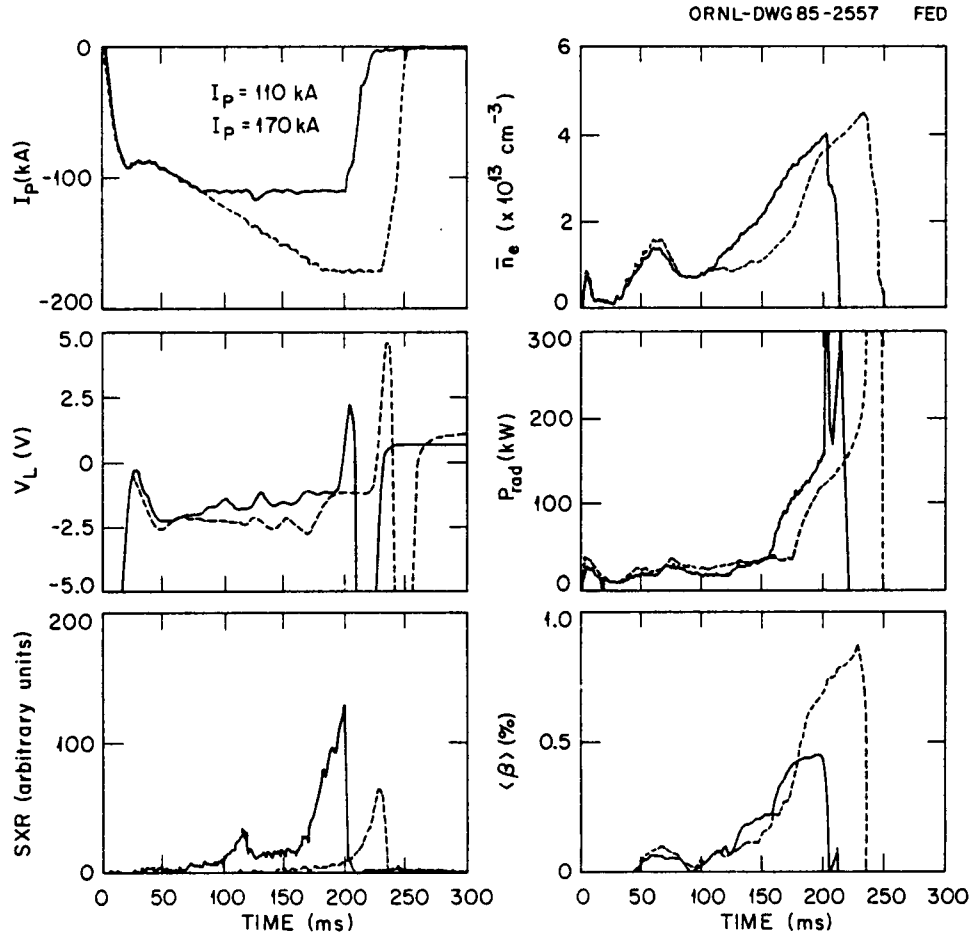


Fig. 5.13. Time histories of plasma parameters for the low and high I_p comparison during counter-injection. Thomson scattering profiles were taken at 190 and 215 ms, respectively.

keV) were approximately the same for both sequences at corresponding laser times. The comparison of the Monte Carlo simulation with the experimental spectra is shown in Fig. 5.14(a) for the high I_p and in Fig. 5.14(b) for the low I_p case. The VFA flux was artificially lowered by 40% in both comparisons. The background neutral density profiles used to calculate the charge-exchange losses were determined assuming $E_0(a) = 10$ eV and a Φ_g multiplier of 2.5. In the calculation of the fast neutral flux to the NPA, on the other hand, $E_0(a)$ was assumed to be 5 eV and the Φ_g multiplier 0.55 for the $I_p = 170$ kA case and 0.4 for the $I_p = 110$ kA case. The different values for the Φ_g multiplier are not inconsistent with differences in the H_α traces. Good agreement is observed between the predicted and the experimental spectra. Comparing the experimental spectra obtained during co-injection with those obtained during counter-injection, the latter are seen to have a flatter appearance. This difference is reproduced closely by the Monte Carlo simulation and is, therefore, explainable in terms of classical processes. The larger orbit losses and the shorter slowing-down times in counter-injection discharges reduce the fast ion population at energies away from E_{inj} , thus lowering the resulting fast neutral flux. It may also be noted that the code properly predicts the large decrease in the high energy perpendicular flux along the $R_t = -8.5$ -cm chord (counter-injection, low I_p). As discussed in Chapter 3, the depletion is caused by the loss region boundary crossing the perpendicular sightline at the lowest I_p setting. (The spectrum taken during a counter-injection experiment at $I_p = 145$ kA—discussed in the next section—did not show any severe depletion.)

The calculated powers for the high and low I_p counter-injected cases are summarized in Table 5.4. Orbit losses account for a considerable portion of the

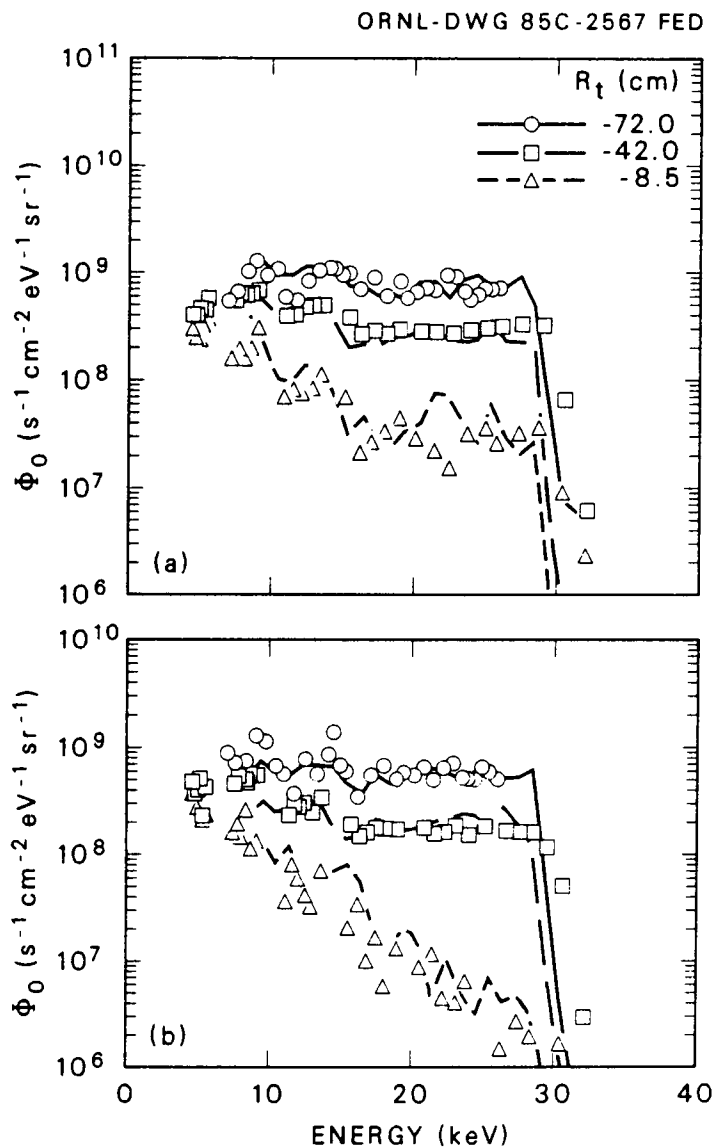


Fig. 5.14. Comparison of experimental and predicted fast neutral spectra during counter-injection at high and low I_p . (a) $I_p = 170$ kA, and (b) $I_p = 110$ kA. Injection was at $R_t = -74.5$ cm.

**Table 5.4. Power distribution (in kW/1 MW, counter-injected)
high and low I_p**

	$I_p = 170$ kA	$I_p = 110$ kA
P_{be}	435 (491)	422 (528)
P_{bi}	190 (207)	143 (165)
P_{cx}	66 (101)	48 (87)
Shine through	33	28
Total orbit losses	244	339
Prompt orbit losses	174	238
Nonprompt orbit losses	70	101
P_{OH}	15	10
P_{therm}	17	10

injected power during counter-injection, especially at the lower I_p setting—34% of the total power. In this case, where orbit effects are most important, ZORNOC overestimates the power delivered to the electron population by 25% and the total power deposited in the plasma by 23%. There is one point to clarify. The beam deposition is calculated in ZORNOC by Monte Carlo techniques.⁵³ The calculation can be performed with or without bounce averaging over the first orbit. If bounce averaging is chosen, the ions are followed on their initial orbits (only a half of the first poloidal orbit is followed because of up and down symmetry) and first orbit losses are correctly estimated. However, ions that scatter promptly into unconfined orbits are not properly treated, and, therefore, prompt losses may be underestimated with respect to the NEWORBX calculation. If the bounce averaging is not chosen, the ions are not followed on their initial orbits, and, consequently, first orbit losses may also be underestimated. Most of the ZORNOC analyses were performed with bounce-averaged deposition, but the two counter-injection cases presented in this section were analyzed

without bounce averaging. It is conceivable that the ZORNOC calculation of the power deposited in the plasma would be in closer agreement with the NEWORBX estimation if bounce averaging at deposition were used.

5.4 CO-, COUNTER-, AND BALANCED INJECTION

In this section, three plasmas are compared. They all had approximately the same external parameters, with the exception of the direction of injection. In one case the beam was injected in the co-direction, in another in the counter-direction, and in the third case two beams of equal power were injected, one co- and one counter-, with the total power being the same as that of the single beam in the other two experiments. Discharge parameters for the three sequences at the respective laser times are tabulated in Table 5.5.

The comparison of predicted and experimental fast neutral spectra for the three cases is shown in Fig. 5.15. The VFA data were artificially multiplied by factors of 0.7, 1.65, and 0.55 for the co-, counter-, and balanced sequences,

Table 5.5. Discharge parameters for the co-, counter-, and balanced injection comparison

	Co-	Counter-	Balanced
$\bar{n}_e$ (10^{13} cm^{-3})	3.83	3.87	4.0
I_p (kA)	144	145	149
B_ϕ (kGauss)	12.1	12.1	12.2
P_b (MW)	0.92	0.89	0.97
$T_e(0)$ (eV)	869	596	660
$T_i(0)$ (eV)	690	450	600
$n_e(0)$ (10^{13} cm^{-3})	5.27	4.89	4.87
Z_{eff}	1.1	1.1	1.3

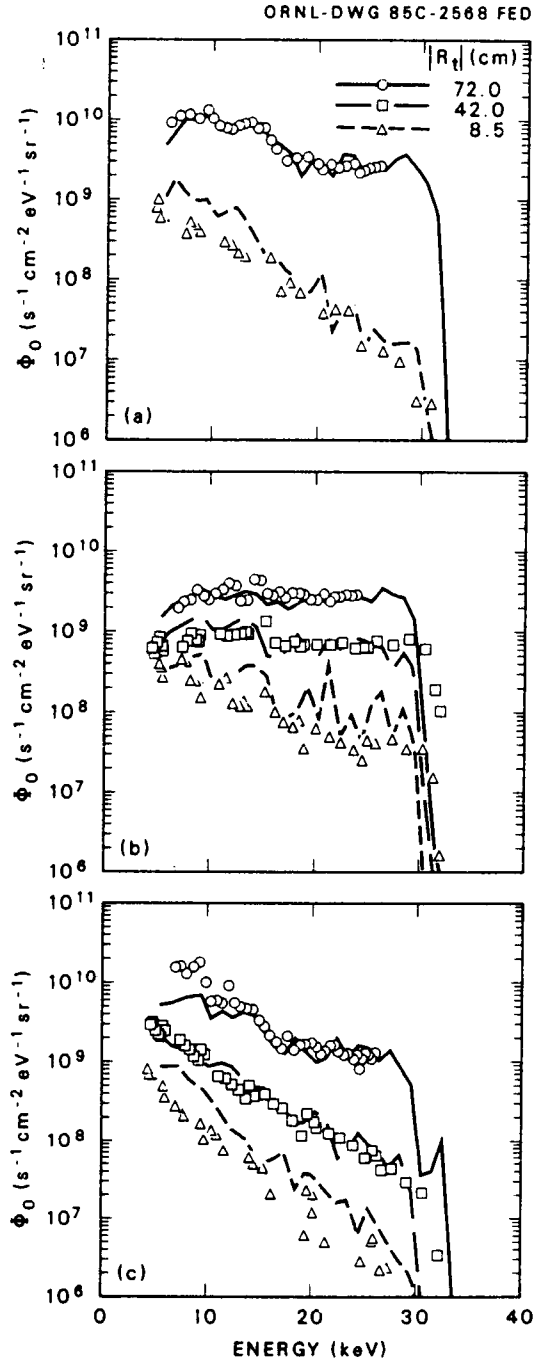


Fig. 5.15. Comparison of experimental and predicted fast neutral spectra during co-, counter-, and balanced injection: (a) co-injection, (b) counter-injection, and (c) balanced injection.

respectively. The boundary conditions assumed in the NEUCG code to evaluate $n_0(R)$ for the three cases are summarized in Table 5.6, with the first values used for the charge-exchange losses and the second values for the Φ_0 calculation. The Monte Carlo simulation satisfactorily reproduces the spectra under the different injection schemes. Perhaps the most serious anomalies occur in the perpendicular spectrum and in the low energy portion of the tangential spectrum for the balanced injection sequence. The experimental flux along the perpendicular sightline is lower than predicted by a factor of ≥ 2 ; the discrepancy could not be resolved. The same discrepancy existed during the co-injection part of the discharge as well. The co-beam was injected at 100 ms, followed by the counter-beam at 200 ms. Thomson scattering profiles were obtained at 180 ms and at 230 ms. A comparison of experimental and simulated spectra at 180 ms also showed the predicted flux larger by a factor of ~ 2 . Thus, the discrepancy cannot be attributed to the particular injection scheme. The low energy flux along the $R_t = 72$ -cm sightline may have a strong contribution from the counter-beam due to particles that follow pinch orbits and large bananas. As discussed in Chapter 3, this flux is sensitive to small inaccuracies in $n_0(R)$ at the plasma edge, in the orbit topology, and in the tangency radius of the viewing chord. Furthermore, the approximate treatment of the limiter edge in computing the orbit losses in NEWORBX may reduce the population of ions that

Table 5.6. Boundary conditions used to calculate $n_0(R)$

	Co-	Counter-	Balanced
Φ_g multiplier	1.67, 1.67	2.5, 1.0	1.67, 0.83
$E_0(a)$ (eV)	5, 5	10, 5	5, 5

travel close to the plasma boundary. As a result, the fast neutral flux sensitive to this class of ions will be artificially low.

The distributions of the injected power for the three sequences are shown in Table 5.7. The ZORNOC prediction is in fairly close agreement with the NEWORBX calculation—except, again, for overestimating the charge-exchange losses. Slightly more power goes to the electrons than to the ions in ZORNOC with respect to the Monte Carlo simulation.

A result common to both codes is that the total power delivered to the plasma is approximately the same in co-injected and balanced discharges. Relatively more power goes to the ions in the co-injected sequence due to the higher T_e .

Comparing co- and counter-injection, both the Fokker-Planck and the Monte Carlo calculations predict a sizable decrease in the power deposited in the plasma during counter-injection. NEWORBX calculates this to be 24%

Table 5.7. Power distribution (in kW/1 MW, injected)

	Co-	Counter-	Balanced
P_{be}	540 (586)	449 (482)	556 (612)
P_{bi}	265 (210)	163 (161)	218 (196)
P_{cx}	65 (168)	79 (126)	37 (83)
Shine through	27	7	32
Total orbit losses	72	290	135
Prompt orbit losses	61	247	112
Nonprompt orbit losses	11	43	23
P_{OH}	0	0	0
P_{therm}	31	12	22
Power to plasma	805 (796)	612 (643)	774 (808)

lower than for co-injection, whereas the ZORNOC result is a 19% decrease. P_{be} goes down by 17% (18%) and P_{bi} by 38% (23%). As a consequence of the inadequate treatment of nonprompt orbit losses in the deterministic approach, the reduction in P_{bi} for counter-injection is underestimated in ZORNOC. This results in the observed smaller decrease in the total power delivered to the plasma.

CHAPTER 6

BEAM ADDITIVITY

6.1 INTRODUCTION

This chapter deals with whether the density of the fast ions confined in the plasma is proportional to the injected beam power in the ISX-B. To attest that this is not a pedantic pursuit, it may be noted that nonadditivity has been reported by the GA group in limiter discharges on the D-III tokamak.^{54,55} Two experiments were performed on ISX-B to test beam additivity, with the following setup. The west beam was co-injected at 100 ms (H^0 , 30 keV, 850 kW), and the east beam was co-injected at 200 ms (H^0 , 30 keV, 800 kW). The line-averaged electron density ($3.8 \times 10^{13} \text{ cm}^{-3}$) and the plasma current were kept approximately constant from 180 ms on. Two sets of discharges were executed, one at $I_p = 96 \text{ kA}$ and the other at $I_p = 180 \text{ kA}$. The diagnostic neutral beam (DNB parameters D^0 and $E_{inj} \sim 25 \text{ keV}$) were used in some of the shots to localize the fast H^0 flux measurements to the plasma center: Φ_0 (DNB on) $- \Phi_0$ (DNB off) = Φ_0 (from center). Line-integrated, as well as localized spectra, were compared at 190 and 280 ms, during injection of one and two beams, respectively. Since Φ_0 is proportional to the fast ion density, this experiment provides a fairly direct test of beam additivity when other parameters that influence the detected signal are not significantly altered by the injection of subsequent beams. However, changes that occurred in the profiles were included in the analyses to provide a more reliable interpretation of the data. To gather further information from these experiments, the west beam was

doped with deuterium so that the beam-plasma neutron emission could be monitored during the discharge.

Section 6.2 presents results obtained in the high I_p sequence. The results at low I_p are discussed briefly in Section 6.3. They do not differ significantly from those at high I_p .

6.2 BEAM ADDITIVITY AT HIGH I_p

Time histories of the plasma parameters for the beam additivity experiment at high I_p are shown in Fig. 6.1. The Thomson scattering profiles for the one-beam sequence were taken at 190 ms and the profiles for the two-beam sequence at 280 ms. I_p and $\bar{n}_e$ were held approximately constant from $t = 180$ ms on, and B_ϕ was 13.9 kGauss. The first beam was turned off sharply at 286 ms, and the discharges lasted until ~ 320 ms. It was then possible to compare fast ion data taken during injection of one beam, two beams, and one beam again—while keeping the external characteristics of the discharge unchanged.

The passive, line-integrated fast neutral flux went up by factors of ≥ 2 along all viewing chords as the second beam was added to the first [an enhancement by a factor larger than 2 is possible because of changes induced by the second beam in the $T_e(R)$ and $n_0(R)$ profiles]. Spectra were also obtained using the DNB to localize the measurement to the plasma center. The MEA sightline intercepts the DNB centerline at $R_t \approx 8.5$ cm, and the VFA intercepts it at $R_t \approx 67$ cm. The enhancement in the H^0 flux when the DNB was on was by factors of ~ 3 along the perpendicular chord and ≤ 2 along the tangential chord. The enhancement is larger at $R_t = 8.5$ cm because the extra

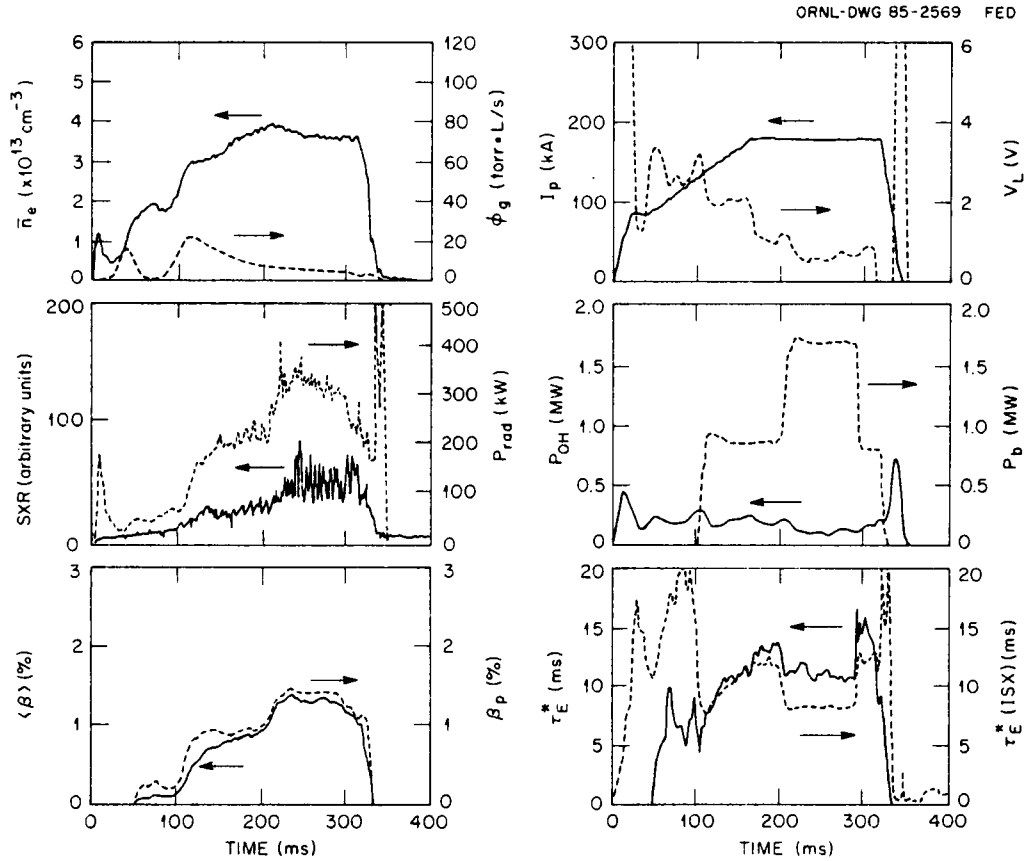


Fig. 6.1. Time histories of plasma parameters for the beam additivity experiment at high I_p . Thomson scattering profiles were obtained at 190 and 280 ms. The first beam was turned off at 286 ms.

source of neutrals is added where most of the (passive) perpendicular flux originates. In support of this interpretation, it may be noted that the increase in the perpendicular flux with the DNB on was by a factor of ~ 6 in the low I_p sequence, where orbit losses weight the signal more strongly to the center. Also, the DNB produced almost no flux enhancement in counter-injection sequences, since most of the signal originates from the inner edge of the plasma. To establish that the DNB does not perturb the plasma conditions locally, fluxes with the DNB on and off along sightlines that do not view the DNB cross section ($R_t = 87$ and 49 cm) were compared. No significant differences were observed, and it was thus concluded that the measurement is not altered by the DNB, except for localizing the charge-exchange emission along certain sightlines, as discussed previously.

In contrast to the passive, line-integrated flux measurements, the localized flux showed hardly any increase following injection of the second heating beam, as illustrated by the data presented in Fig. 6.2. The line-integrated fast neutral flux along the perpendicular sightline in one particular energy channel is plotted as a function of time at the top of the figure. The signal becomes visible shortly after injection of the first beam, and it increases by a factor of ~ 2.7 with the second beam. After turn-off of the west beam line, the flux is clearly reduced. The time history of the localized flux along the same viewing chord and at approximately the same energy is shown at the bottom of the figure. The signal begins to appear at 120 ms—the time of injection of the DNB. Because this is a DNB on minus DNB off measurement, a signal is expected *only* when the DNB is on. No substantial increase in flux is observed when the second beam is injected, nor is any change detected when the first beam is turned off.

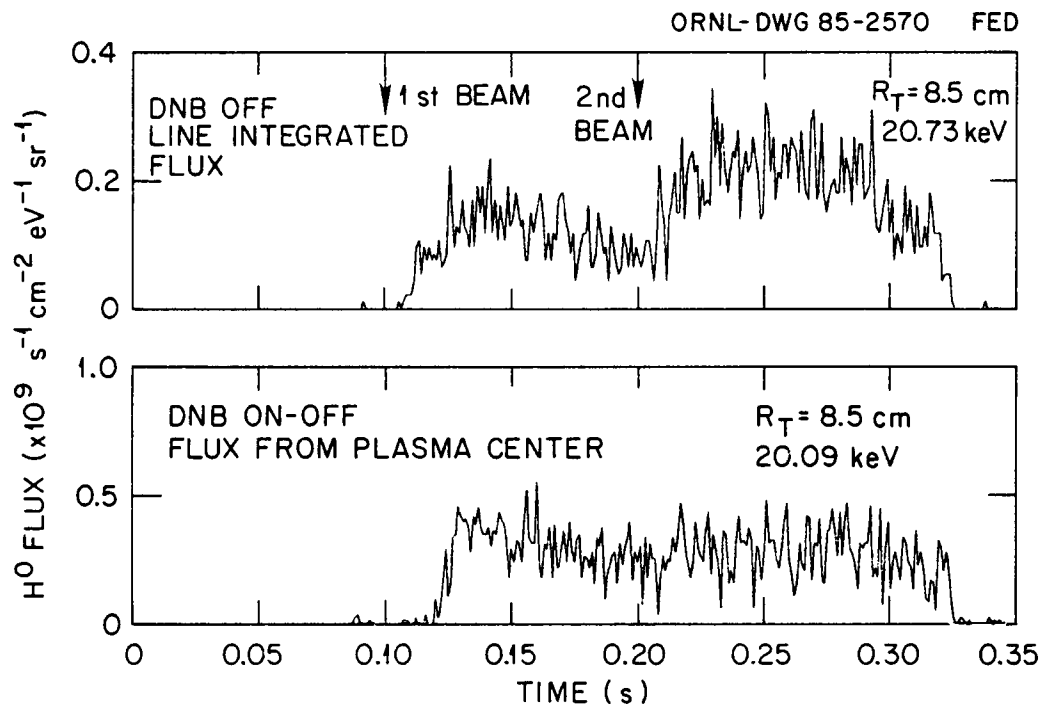


Fig. 6.2. Time history of the perpendicular neutral flux at $E \approx 20 \text{ keV}$ during the beam additivity experiment. The line-integrated flux increased when the second beam was injected, whereas the flux from the plasma center did not.

Although other energy channels (especially higher energies) did show some enhancement in the localized flux with the injection of the second beam, the enhancement was not so conspicuous as that observed in the passive measurements.

A more conclusive comparison can be made by matching the flux in several energy channels at two properly chosen time points. Figure 6.3 shows the energy spectra taken along several NPA sightlines at 190 and 280 ms. The VFA data were corrected for stripping cell efficiency only. Injecting two beams of equal power—while holding the external plasma parameters constant—produced line-integrated fast neutral fluxes at least twice as large as those observed when only one beam was injected. This suggests that the fast ion density is indeed proportional to P_b . However, the neutral flux originating from the plasma center—at all energies—increased only slightly, if at all.

The question arises whether these results might be a consequence of changes in the plasma profiles. To test this hypothesis, the experimental spectra were compared with the predictions of the computational codes, where changes in $T_e(R)$, $n_e(R)$, and $n_0(R)$ are taken into account. As shown in Fig. 6.4 (a and c), the Monte Carlo prediction of the line-integrated spectra is in very good agreement with the experiment at both time points. A wall recycling coefficient of 0.4 and $E_0(a) = 5$ eV were assumed to calculate $n_0(R)$ for the charge-exchange losses as well as the flux to the NPA. Although the localized spectra are reproduced with a lower degree of accuracy (b and d), it is clear that the localized flux during two-beam injection is predicted to be a factor of ~ 3 higher than during one beam only, contrary to the experimental evidence.

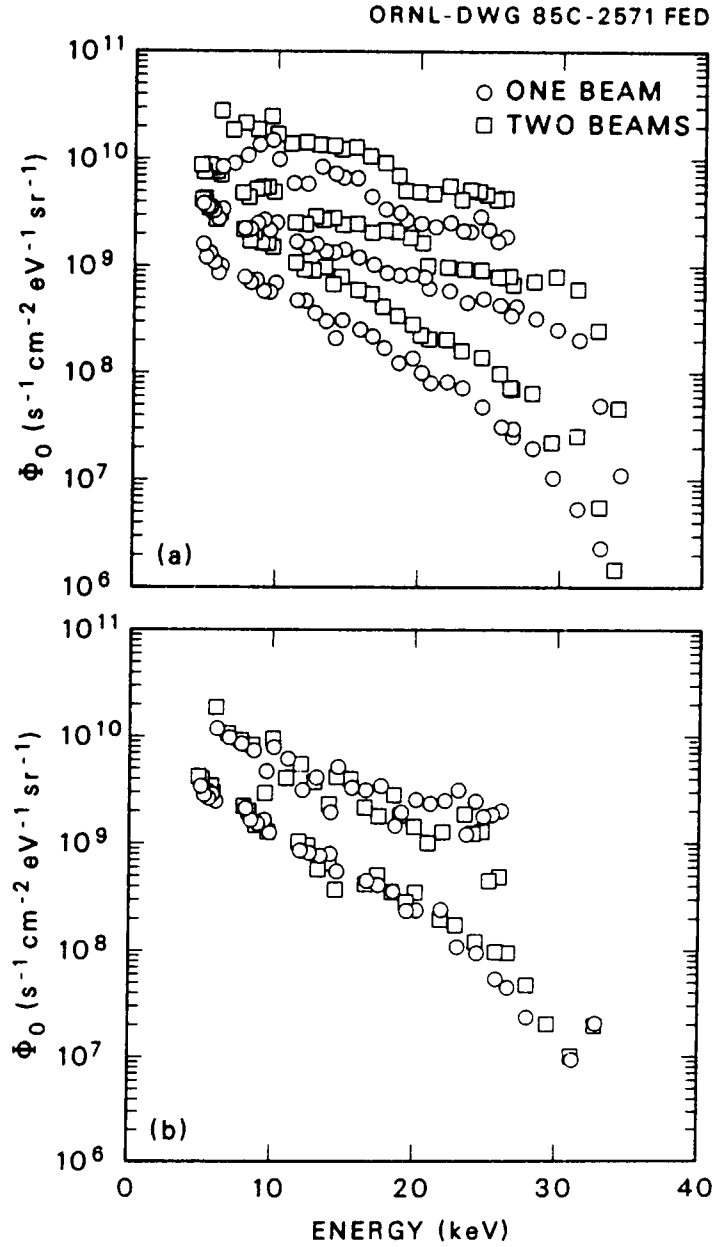


Fig. 6.3. Experimental line-integrated and localized fast neutral spectra during one- and two-beam injection at high I_p . (a) Line-integrated spectra at $R_t = 72, 42$, and 8.5 cm (from top to bottom). (b) Localized spectra at $R_t = 67$ (top) and 8.5 cm (bottom).

ORNL-DWG 85C-2572 FED

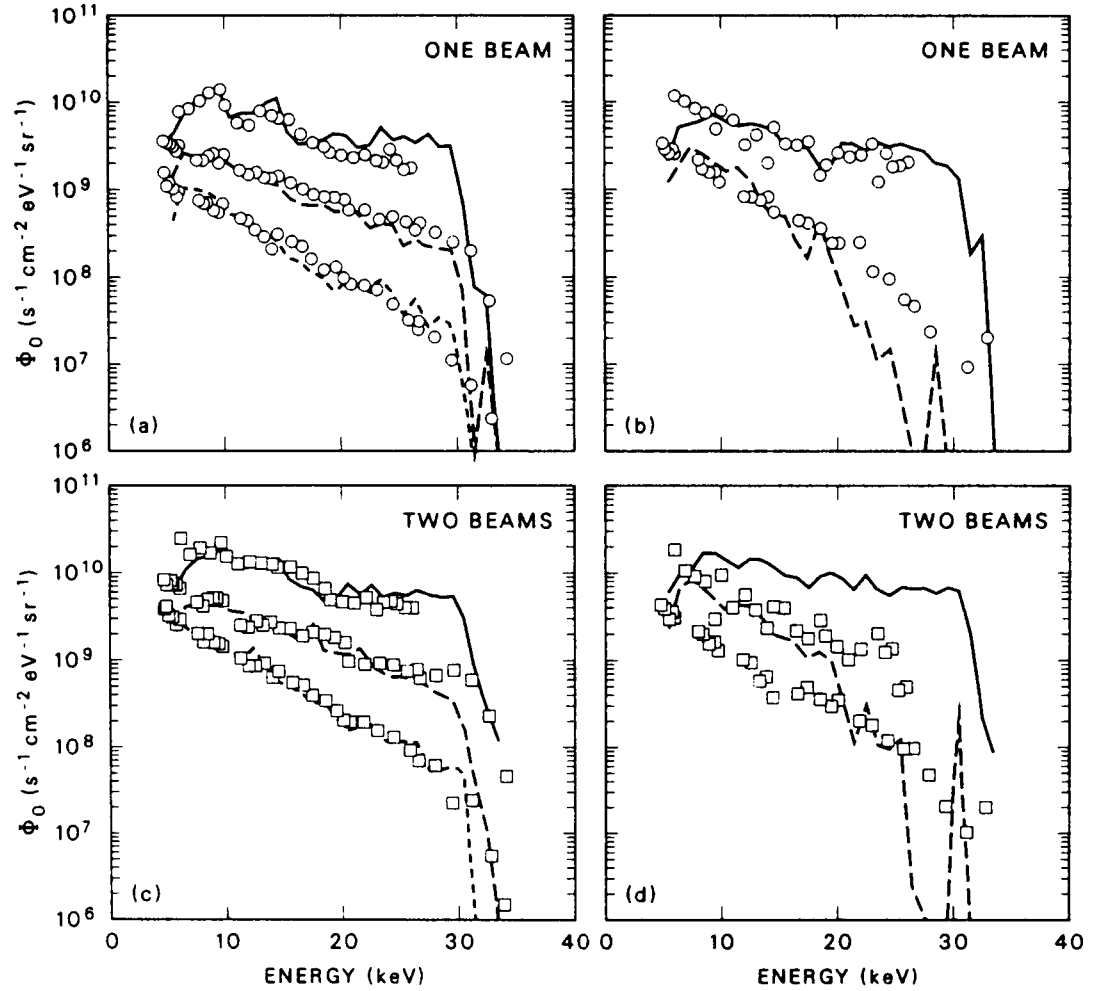


Fig. 6.4. Comparison of experimental spectra with the predictions of the Monte Carlo calculation during one- and two-beam injection. (a) and (c) Line-integrated spectra at $R_t = 72, 42$, and 8.5 cm. (b) and (d) Localized spectra at $R_t = 67$ and 8.5 cm.

The FPP code produced results in close agreement with the Monte Carlo calculation. Therefore, the lack of flux enhancement in the localized spectra cannot be explained on account of changes in the profiles at high P_b .

The possibility that the DNB current might have decreased by a factor of ≥ 2 from 190 to 280 ms need also be investigated. In Fig. 6.5, two sets of evidence are presented that show that the DNB current did not decline during the discharge—within a 25% uncertainty. At the top of the figure, the spectra of fast deuterons from the DNB itself* are compared at 190 and 280 ms. The flux is the same within the scatter. At the bottom of the figure, the localized H^0 spectra at 190 ms are compared with those obtained at 315 ms, when the discharge had approximately resumed the configuration it had at 190 ms (the passive, line-integrated spectra at 315 ms were within 10% of the spectra at 190 ms). The localized flux appears to be only slightly lower at the later time, setting the limit to a possible decrease in the DNB efficiency to $\leq 25\%$.

Two other possible flaws in the data collected with the DNB on were investigated. One was that the flux might have been dominated by the signal originating from the DNB ions themselves. In fact, although the DNB was fueled for these experiments with deuterium gas to avoid contamination of the H^0 spectra, it did remain polluted with hydrogen even after several days of operation. This was evidenced by peaks in its spectrum at D^0 energies corresponding to HD_2 , HD , and H_2D molecules at the ion source. Since the DNB ions were injected with pitch angles that made them readily visible along

*These spectra were actually taken during the $I_p = 96$ kA sequence. The spectra for the high I_p sequence are beset by multiple peaks, which render the comparison less straightforward, although they lead to the same conclusions.

ORNL-DWG 85C-2573 FED

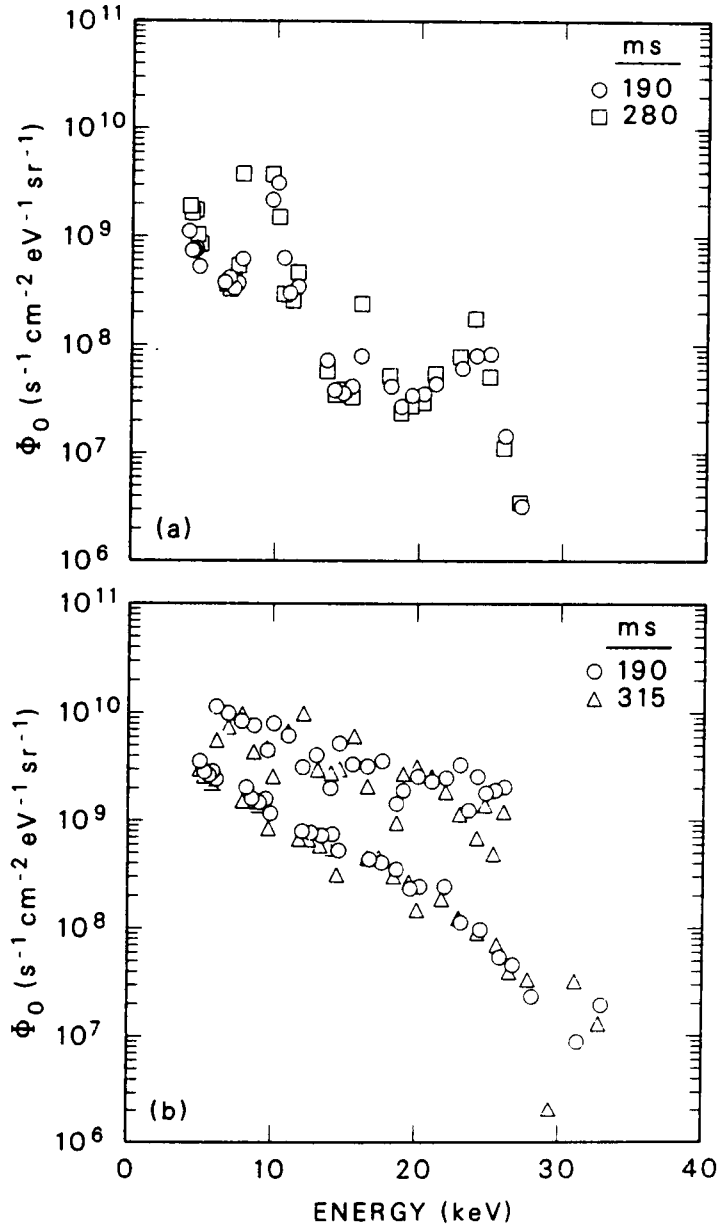


Fig. 6.5. Evidence that the DNB current did not change during the discharge. (a) Spectra of deuterons from the DNB at 190 and 280 ms ($R_t = 8.5$ cm). (b) Localized H^0 spectra during one-beam injection at 190 and 315 ms ($R_t = 67$ and 8.5 cm).

the perpendicular chord, it is this sightline that would be mostly affected by the spurious signal. From a combined analysis of deuterium and hydrogen spectra, it was estimated that the signal from the DNB constituted $\sim 30\%$ of the total H^0 flux at the DNB injection energy. However, the DNB fast ion population decreased rapidly away from the injection energy due to large orbit losses. The overall DNB contribution to the H^0 flux was estimated to be $\leq 10\%$ and was neglected in the analysis. The other possibility is that the channeltron detectors might have reached counting saturation with the DNB on. Above a certain level, the gain of a channeltron detector decreases with increasing incident input flux.⁵⁶ At high count rates, the mean output pulse level may become smaller than the threshold voltage of the discriminator, and the output count rate is no longer proportional to the incident flux. The count rates for the perpendicular flux were found to be in the linear range at all times during the discharge, and, therefore, the perpendicular spectrum was not affected by count losses. However, the count rates along the tangential sightline were high enough during the one beam phase that a further increase following the injection of the second beam would have shifted them into the nonlinear regime. The tangential flux with the DNB on may have been reduced by an estimated 10 to 30% at low energies during the two-beam phase, while the high energy flux was affected more strongly—by an indeterminable amount. It need be pointed out that the count rates during the passive measurements were either in or close to the linear range at all energy settings, all sightlines, and all times in the discharge. The same is true for the measurements obtained with the DNB on during the one-beam phase. Thus, only the signal obtained along the tangential sightline

with the DNB on during the two-beam phase may have suffered from saturation effects. Consequently, the localized tangential flux measured at 280 ms (DNB on—DNB off) would be reduced by a larger percentage than the fractional reduction in count rates due to saturation. This effect would intensify if the flux enhancement due to the DNB were not large—as was the case for the tangential sightline. This is the most likely reason why the high energy, localized, tangential flux appears to be actually lower when two beams instead of one were injected, and it could also account for the lack of enhancement in the localized tangential flux at low energies. However, it is reiterated that the perpendicular spectrum was not affected by counting losses.

Thus, even with the above caveats, it appears that the central fast ion density did not increase by a proportional amount when the second beam was added to the first. At the same time, the total number of beam ions in the plasma volume did apparently increase by a factor of ≈ 2 , as can be deduced from the analysis of the line-integrated spectra. Therefore, it would appear that either some anomalous deposition process may have prevented the second beam from reaching the plasma center or a redistribution of the fast ions to a larger average radius may have taken place at the higher beam power.

The second beam penetrated the plasma at a toroidal location close to the limiters. It is then conceivable that its deposition might have been affected by the higher concentration of impurities expected from recycling and sputtering. Two Monte Carlo simulations of the two-beam injection sequence were performed to investigate the effects of anomalous deposition on the resulting fast neutral spectra. In the first one, the local mean free paths (λ) were artificially decreased by a factor of 2 throughout the plasma. In the other, λ was decreased

by a factor of 5 in the outermost 4 of the 20 radial shells. In both cases, the localized flux was predicted to be lower than in the straight simulations (except at $E \approx E_{\text{inj}}$ along the perpendicular chord), but only by ~ 15 to 20%. As a consequence of the enhanced deposition in the outer region of the torus, the high energy portion of the localized perpendicular spectrum was shifted up by a factor of ≥ 2 , thus becoming closer to the experimental data. However, the line-integrated, high energy, perpendicular flux also increased (by $\geq 50\%$), in this case worsening the agreement with the experimental data. Since even these large changes in the deposition process could not account for the lack of enhancement in the localized flux with the second heating beam, it seems unlikely that the experimental results could be explained on the basis of anomalous beam deposition.

The first beam was doped with 3% D^0 for this experiment. It will be shown in Chapter 7 that the beam-plasma neutron emission comes predominantly from the plasma core. Thus, measurements of this emission can provide additional evidence that might substantiate one of the two hypotheses proposed above. The beam-plasma neutron yield was measured to be 3.0×10^{10} neutrons/s at 190 ms and 2.1×10^{10} neutrons/s at 280 ms. The NEWORBX code predicts, instead, an increase from 2.3×10^{10} to 3.1×10^{10} neutrons/s at the same time points. As will be discussed in Chapter 7, the uncertainties in the calculated beam-target neutron production are fairly large. However, since the calculations are performed here on the same discharge and at the same plasma density, the discordance between the experimental data and the Monte Carlo predictions may be significant. A caveat to this conclusion is that the central deuterium target density n_D may decrease considerably upon injection of the

second beam, if $\bar{n}_e$ is constant. In the Monte Carlo calculation, the n_D dilution due to H^0 injection was assumed to be by factors of 0.85 and 0.75 for the one- and two-beam phases, respectively. (A further constant correction by a factor of 0.85 was applied in both cases due to hydrogen desorption from the walls and limiters.) Although a larger reduction in target density was assumed for the two-beam case, the actual n_D dilution is not well known. With this caveat in mind, the experimentally measured decrease in the emission seems to favor the interpretation that the beam ions spread away from the plasma center after injection of the second beam.

To roughly estimate the size of the displacement that would account for the experimental observations, calculations were performed with the FPP code in which the radii of the guiding center orbits were artificially increased at deposition. A radial increment of 2.5 cm applied to the fast ion orbits in the two-beam phase resulted in localized spectra that were essentially the same as during the one-beam phase. At the same time, the predicted line-integrated spectra were not significantly altered from those obtained in the nominal calculation. The beam-plasma neutron emission was predicted to increase from 3.5×10^{10} to 4.2×10^{10} neutrons/s in the straight runs, whereas it remained at 3.5×10^{10} neutrons/s if the 2.5-cm orbit shift was postulated.

6.3 BEAM ADDITIVITY AT LOW I_p

Discharge characteristics for the beam additivity experiment at low I_p are displayed in Fig. 6.6. Thomson scattering profiles were taken at 190 and 280 ms. The first beam—doped with 1% D^0 —was turned off at 290 ms.

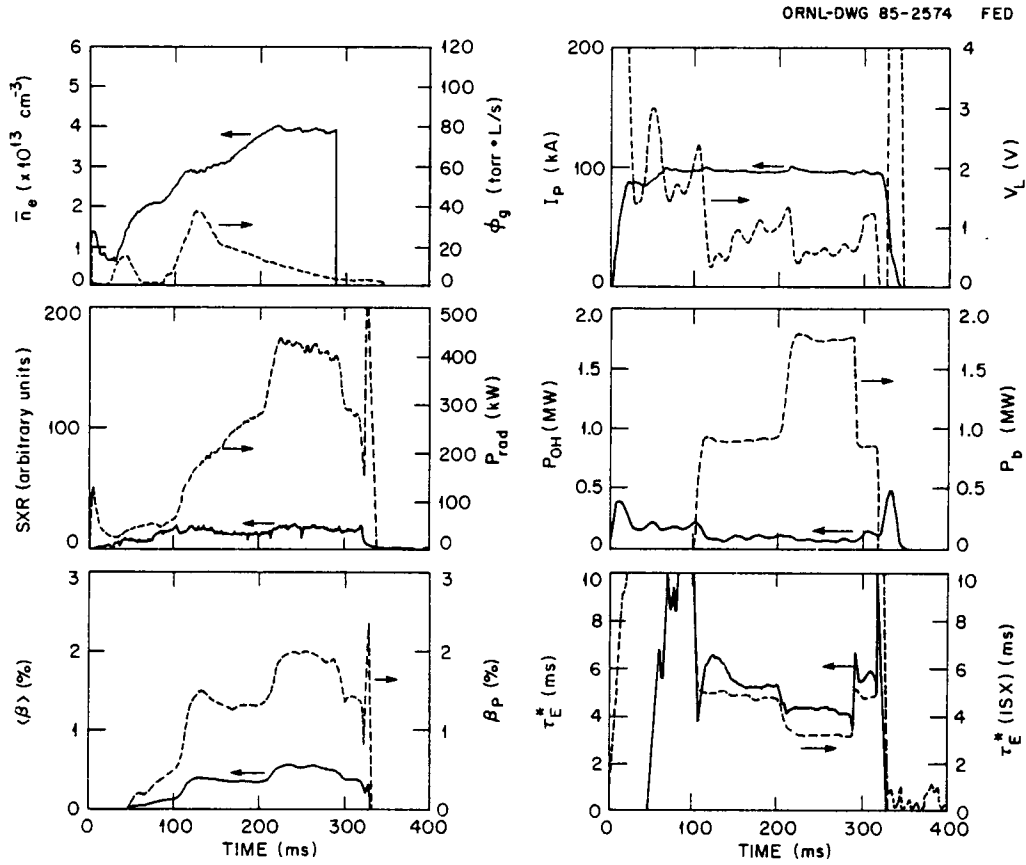


Fig. 6.6. Time histories of plasma parameters for the beam additivity experiment at low I_p . Thomson scattering profiles were taken at 190 and 280 ms. The first beam was turned off at 290 ms.

A comparison of the experimental spectra obtained during the one- and two-beam phases is presented in Fig. 6.7. As in the high I_p sequence, the line-integrated flux shows at all energies and sightlines a definitive enhancement with the injection of the second beam. The spectra are well represented by Monte Carlo simulations if wall recycling coefficients of 0.4 and 0.7 are assumed at 190 and 280 ms, respectively. The larger R needed for the match at 280 ms is consistent with evidence from the H_α monitors that the recycling increased strongly after the second beam was injected. Once again, no substantial enhancement in the localized flux was observed (only the more reliable, perpendicular spectrum is shown). At the same time, the Monte Carlo simulation predicts an increase in the localized flux by factors of ≥ 2 at low energies and ≥ 3 at high energies. As an aside, it may be noted that the high and low I_p experiments were performed two months apart from each other. This eliminates the chance of a peculiar behavior (of the DNB, for instance) during one particular experiment.

The beam-plasma neutron output was lower during the two-beam phase than in the one-beam phase. The emission was measured to be 1.1×10^{10} neutrons/s at 190 ms and 0.73×10^{10} neutrons/s at 280 ms. The NEWORBX code predicts a neutron output of $0.5 \times 10^{10} \text{ s}^{-1}$ at both time points. Considering that the uncertainty in the absolute value of the experimental measurement is of $\pm 25\%$ and that larger uncertainties (e.g., in the n_D dilution) affect the calculated value, no definitive conclusions can be drawn from this comparison. By the same token, however, the results are not inconsistent with a hypothesized spreading of the beam ions away from the central region of the plasma at the higher beam power.

ORNL-DWG 85C-2675 FED

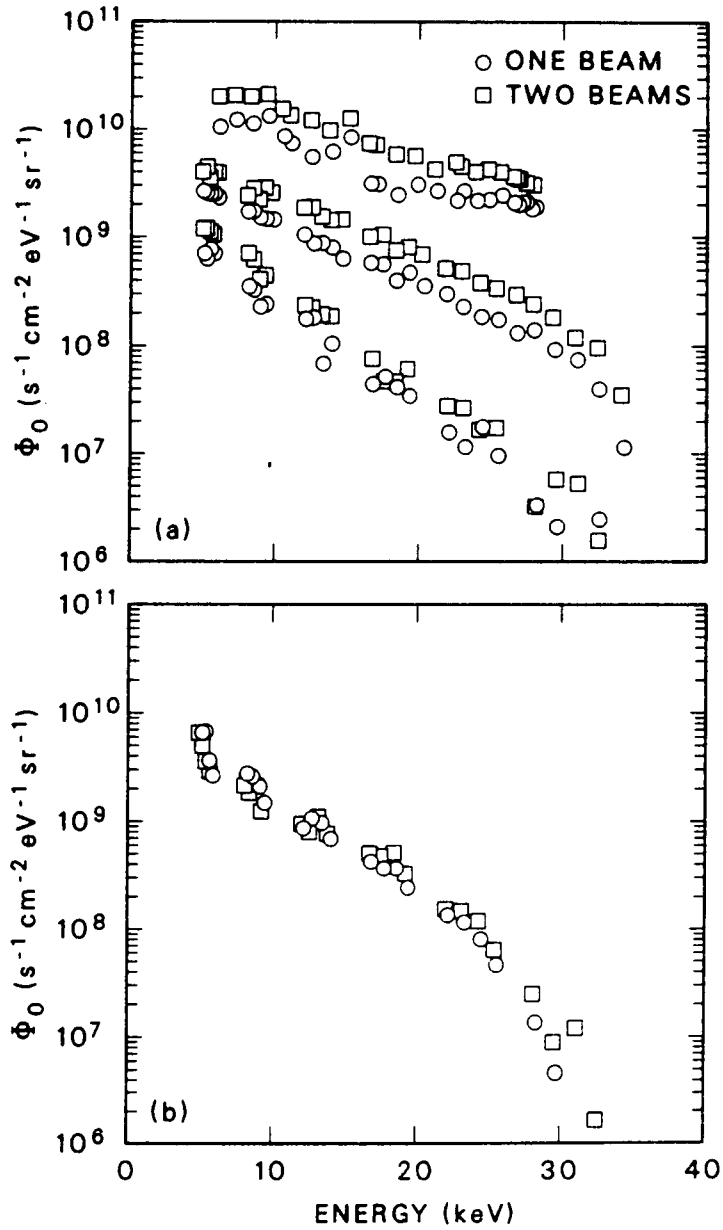


Fig. 6.7. Experimental line-integrated and localized fast neutral spectra during one- and two-beam injection at low I_p . (a) Line-integrated spectra at $R_t = 72, 42$, and 8.5 cm. (b) Localized spectra at $R_t = 8.5$ cm.

In summary, the analysis of the two-beam additivity experiments indicates that the number of beam ions confined in the plasma volume was proportional to the injected power in the ISX-B. However, some experimental evidence from the localized spectra and from measurements of the beam-target neutron emission suggests that the fast ion density in the plasma core might not have increased proportionally to P_b . Since similar results were obtained at low and high I_p , the event would not likely depend on the plasma current or on the particular type of MHD activity. A postulated spread of the fast ions away from the plasma center by displacements of the order of 2 to 3 cm would account for the apparent discrepancy between theory and experiment. Under this assumption, the total power delivered to the plasma would remain essentially the same, while the power deposition profile would peak a few centimeters away from the center. In view of the experimental uncertainties involved and because of the limited set of data available, the issue was not resolved in the present study.

CHAPTER 7

BEAM-PLASMA NEUTRON EMISSION MEASUREMENTS

7.1 INTRODUCTION

A well-established method for investigating the confinement of the beam ions, in addition to the analysis of fast neutral spectra, is the measurement of beam-plasma neutron emission.^{14,15,57,58} The experimental measurements are compared with computations based on classical beam capture and slowing down, thus testing whether classical processes govern the behavior of the energetic particles. The comparison is sensitive to the deposition profile of the full energy component of the beam and to the first stages of the slowing down of full energy ions circulating in the plasma core. It is, therefore, on these specific processes that information is obtained.

A brief review of the pertinent theory is presented in Section 7.2, together with simple estimates of the uncertainties involved. Theoretical decay rates of the neutron emission following a sharp beam turn-off are compared with experimental data in Section 7.3 to verify the slowing-down rates. Finally, in Section 7.4 the predicted neutron emission is compared with the measured yield under a variety of plasma conditions, injection geometries, and beam power levels.

7.2 THEORY AND ESTIMATE OF THE UNCERTAINTIES

When injecting a deuterium beam on a cold D^+ plasma, the beam-target neutron reaction rate (I) is obtained by integrating the local contribution over the plasma volume and in energy space from $E = 0$ to $E = E_{inj}$:

$$I = \int \int f_D(\vec{x}, E) n_D(\vec{x}) \sigma_{DD}(E) v dE d^3\vec{x} \quad \text{neutrons/s} , \quad (7.1)$$

where

$f_D(\vec{x}, E) dE$ = density of slowing-down beam deuterons with
energies between E and $E + dE$ (cm^{-3}),

$n_D(\vec{x})$ = plasma deuteron density (cm^{-3}),

$\sigma_{DD}(E)$ = cross section for $D(D, n)^3\text{He}$ reaction (cm^2),

v = beam deuteron speed (cm/s).

A close fit to the D-D fusion cross section is given by⁵⁹

$$\sigma_{DD}(E) = \frac{2.2 \times 10^{-22} e^{-47.88/\sqrt{E}}}{E} \quad (\text{cm}^2) ,$$

where E is in keV. The nonzero plasma temperature can be taken into account to a very good approximation by evaluating $\sigma_{DD}(E)$ and v at a cross-section weighted average energy E_{rel} (Ref. 14):

$$E_{\text{rel}} = \left[E^3 + \left(\frac{3}{2} T_i \right)^3 + 6 E^2 \left(\frac{3}{2} T_i \right) + E \left(\frac{3}{2} T_i \right)^2 \right]^{1/3} ,$$

where T_i is the plasma ion temperature.

One effect that must be included in the calculation of beam-plasma neutron production is the toroidal rotation of the plasma. Momentum is imparted from the beams to the plasma and results—during unidirectional injection—in a

toroidal rotation of the plasma in the direction of injection. The central rotation velocity is determined through measurements of the Doppler shift of the radiation from fully stripped oxygen that charge exchange with beam atoms.⁶⁰ The rotation velocity in ISX-B was $\sim 1 \times 10^7$ cm/s, and it was found to depend only weakly on P_b , $\bar{n}_e$, and I_p in ungettered, co-injected discharges.⁶¹ Since the plasma rotates in the same direction as the beam, the relative velocity between the plasma and the beam deuterons is reduced, and the reaction rate is lowered. In fact, the relative velocity is approximately given by

$$v_{\text{rel}} \approx v - v_{\text{rot}} \cos\theta ,$$

where $\cos\theta$ is the pitch angle of the beam ions. Referring to Fig. 3.5 (page 36), the average value of $\cos\theta$ for fast ions born in the plasma center is seen to be ≈ 0.75 . For a 30-keV beam and the typical rotation velocity in ISX-B, the effective reaction rate is $\sim 75\%$ of the reaction rate calculated for a stationary plasma, and the correction becomes $\sim 70\%$ at $E = 23$ keV.⁶² The calculated value of I —for unidirectional injection—was multiplied by a factor of 0.75 to account for the effect of plasma rotation.

Although both FPP and NEWORBX calculate I by performing the integrations implied in Eq. (7.1), it is useful to consider a simplified version of the problem for the purpose of estimating the uncertainties. Since the D-D fusion reactivity (σv) decreases rapidly with decreasing relative energy, most of the neutron output is produced by beam ions with energies close to E_{inj} . For instance, by the time an ion injected with $E_{\text{inj}} = 30$ keV has slowed down to the energy $E_N \approx 23$ keV, the reactivity has decreased by a factor of $1/e$.

Furthermore, the beam-plasma neutron emission is localized to the central region of the plasma because the emission is proportional to the product of the slowing-down time ($\propto T_e^{3/2}/n_e$) and the deuterium target density ($\sim n_e$). This product is strongly weighted on axis because of the T_e dependence. Letting N_D be the number of beam deuterons in the central region of the plasma with energies between E_{inj} and E_N and letting n_D be the average central density of the plasma deuterons, the reaction rate is then roughly

$$I \sim N_D n_D \sigma_{DD} v \quad (\text{neutrons/s}) .$$

The various quantities in this expression will now be examined one at a time to establish the uncertainties involved in the calculation.

The combined uncertainty in the fusion cross section and in the evaluation of σv at $E = E_{rel}$ instead of averaging $\langle \sigma v \rangle$ over a Maxwellian distribution of the plasma ions is on the order of ~ 10 to 15%. The target density n_D is determined from Thomson scattering measurements of $n_e(R)$ and the calculated dilution due to impurities (inferred from Z_{eff} and Z_I) and due to beam hydrogen (in these experiments the beams injected 97% H^0 and 3% D^0). Although the beam ion density upon injection is typically much smaller (by factors ≥ 10) than the plasma density, a considerable fraction of the central ion density is constituted by fast ions that are confined until they slow down to thermal energies. This is a consequence of the beam ion hydrogen source being peaked at the center, whereas the deuterium source (gas puff and recycling) is at the outside of the plasma. Time-dependent modeling calculations⁶³ result in thermal

H/D concentrations in the range from 20 to 50% towards the end of typical ISX-B discharges.⁶⁴ These calculations are affected by large uncertainties in the transport coefficients and also by the fact that a steady state is not reached on the time scale of the experiment. The values that were used in the Monte Carlo simulations for the target dilution due to beam hydrogen ranged from 10 to 30%, depending on P_b and $\bar{n}_e$. Furthermore, a comparison of thermal ($E = 0.5 - 2$ keV) H^0 and D^0 fluxes measured by the NPA during the ohmic phase of several discharges showed that $n_D/(n_D + n_H)$ was typically 0.85 before beam injection. This is attributed to desorption of hydrogen accumulated on the walls during previous discharges and during beam conditioning, and an appropriate correction is included in the calculation of the target density. The total uncertainty in the value of n_D is expected to be on the order of $\geq 30\%$. Neglecting orbit and charge-exchange losses, the number of beam deuterons contributing to I is given by

$$N_D = \dot{N}_{OD} \xi \tau_N$$

where

$\dot{N}_{OD}$ = full energy neutral deuterium injection rate,

ξ = fraction of full energy deuterons captured in the plasma core,

τ_N = time to slow down from E_{inj} to E_N .

The decay time τ_N is a function of the peak values of T_e and n_e , measured experimentally by the Thomson scattering diagnostic; it has been verified in

beam turn-off experiments with a resulting uncertainty of $\leq 30\%$ (see Section 7.3).

The injection rate of the full energy component of H^0 is determined directly from P_b and E_{inj} , which are known with fair accuracy, and from the beam fractional composition that carries an uncertainty of ~ 10 to 15% , as discussed in Section 3.2. Due to the different focusing and neutralization efficiencies for hydrogen and deuterium in the injector source, the D^0/H^0 ratio is not the same as the D/H ratio at the beam source. In fact, the D^0/H^0 ratio at the full injection energy of 30 keV is estimated to be $\sim 80\%$ of the D/H ratio at the source.³⁷ Thus, for a 3% deuterium working gas, the beam D^0/H^0 ratio is $\sim 2.5\%$. Hydrogen and deuterium fast neutral spectra were obtained along the same viewing chord ($R_t = 42\text{ cm}$) and during the same plasma sequence, using the mass-discriminating capabilities of the MEA. The spectra, together with the corresponding Monte Carlo prediction, are shown in Fig. 7.1. The ratio of the experimental D^0 and H^0 fluxes is seen to be ≈ 0.025 . Since the data were taken during a co-injection sequence at high I_p , the larger orbit widths for D^+ with respect to H^+ are not expected to produce significant differences in the spectra along that sightline. Thus, the observed D^0/H^0 ratio confirms the expected value of 2.5% . The orbit-following Monte Carlo simulation (which assumed $D^0/H^0 = 2.5\%$) is in fairly good agreement with the experimental results, although it would not be inconsistent with a somewhat lower concentration of D^0 , indicating a residual uncertainty of $\leq 30\%$ in D^0/H^0 .

The fraction of beam deposited in the central region of the plasma ξ is determined by $n_e(R)$, by the ionization and charge-exchange cross sections, and

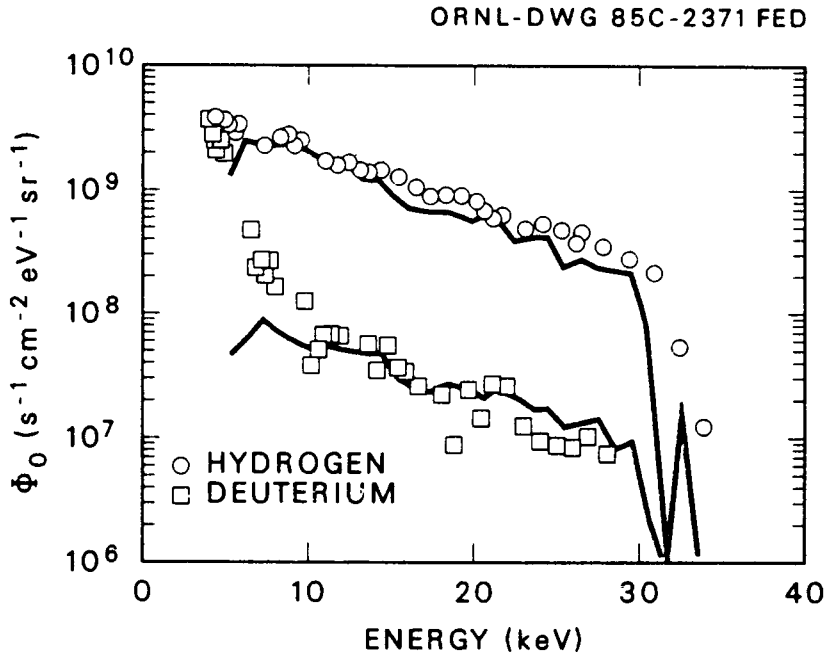


Fig. 7.1. Hydrogen and deuterium fast neutral spectra during co-injection of a 1-MW H^0 beam doped with 3% D^0 , at $I_p = 180$ kA. Both spectra were taken along the $R_t = 42$ -cm sightline. The continuous lines are the corresponding predictions of the Monte Carlo simulation.

by the impurity concentration and charge state. Since the probability of ionizing in a given interval ΔR is given by $1 - \exp[-(n\sigma)_{\text{tot}}\Delta R]$, and $(n\sigma)_{\text{tot}}\Delta R \ll 1$, the uncertainty in the deposition profile is on the order of the uncertainty in the local value of $(n\sigma)_{\text{tot}}$, which is $\sim 25\%$.

Although somewhat crude, the estimates outlined above clearly indicate that a global uncertainty of $>50\%$ should be ascribed to the calculated value of I . Finally, the estimated range of uncertainty in the experimental measurement of the neutron emission is approximately $\pm 25\%$, as discussed in Appendix C.

7.3 EXPERIMENTAL MEASUREMENTS OF THE SLOWING-DOWN TIME

This section presents results of experiments aimed at verifying that the beam ions slow down according to classical theory (i.e., through Coulomb collisions with the plasma particles). The FPP prediction of the decay time in the beam-plasma neutron emission following a sharp beam turn-off is compared with the experimentally measured value for several different discharges. It will be shown that good agreement is found—within the experimental uncertainty of $\sim 30\%$ —between theory and experiment and, therefore, that the slowing-down process is classical. It is important to realize that most of the uncertainties discussed in the previous section apply only to absolute measurements of the neutron yield and, thus, do not affect this comparison. In fact, only the uncertainties in σ_{DD} and in the measured values of $T_e(R)$ and $n_e(R)$ need be retained in the calculated value of τ_N .

On ISX-B, the beam doped with deuterium was turned off immediately after the time at which the Thomson scattering profiles were taken. The profiles

were then used for the FPP calculation of the decay rate of the neutron emission. The discharges lasted typically ≥ 10 ms after the beam turn-off. The thermonuclear neutron yield—to be subtracted from the total emission to obtain the beam-plasma contribution—was measured at the laser time while injecting pure H^0 beams in similar discharges, and it was assumed to remain constant during the decay time τ_N . The assumption is reasonable since the beam ions will continue to transfer energy to the plasma deuterons—directly and through the electron population—for a time $\geq \tau_N$ after turn-off. Evidence collected during one of these experiments, in fact, confirmed that the assumption is correct. The thermonuclear emission was monitored after turn-off of one of two 100% H^0 beams, and it was seen to remain constant for $\sim 1 \tau_N$, decreasing by only $\sim 20\%$ in a time $2 \tau_N$.

Figure 7.2 shows a typical comparison of experimental and predicted decay rates in the beam-plasma neutron production. One single beam ($P_b = 0.84$ MW, $E_{inj} = 31$ keV) was co-injected into a gettered discharge. The turn-off time was set at 281.5 ms (signaled also by a noise spike in the neutron detector count rate). The Thomson scattering profiles were taken at 280 ms. Plasma parameters for this sequence were $I_p = 187$ kA, $\bar{n}_e = 6.3 \times 10^{13} \text{ cm}^{-3}$, $T_e(0) = 664$ eV, $Z_{eff} = 1.6$. The neutron emission is seen to decay exponentially with a time constant $\tau_N \approx 1.8$ ms, 20% larger than the predicted value of ≈ 1.5 ms.

Four more beam turn-off experiments were performed. Out of the total of five, three were two-beam sequences with only the doped beam being turned off. One of the five was an ungettered sequence, two were well gettered, and

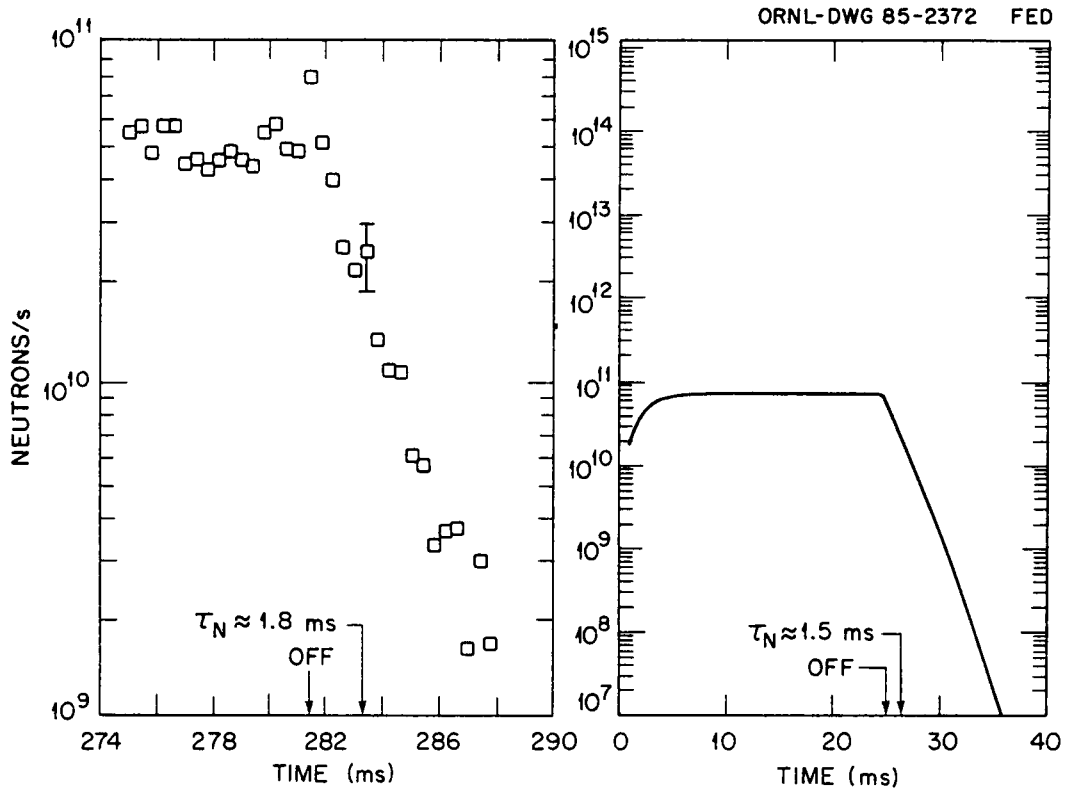


Fig. 7.2. Experimental and predicted decay rates of the beam-plasma neutron emission following beam turn-off. Experimental data are shown on the left, and the corresponding Fokker-Planck prediction is shown on the right.

the remaining two were nominally gettered but exhibited characteristics typical of ungettered discharges. Plasma currents ranged from 96 to 190 kA, $\bar{n}_e$ from 3.7×10^{13} to $6.3 \times 10^{13} \text{ cm}^{-3}$, while $B_\phi = 1.4 \text{ T}$ for all five. Figure 7.3 shows the resulting experimental and predicted (by FPP) values of τ_N for the five sequences. The good agreement between FPP and the data indicates that classical theory describes well the initial slowing down of the beam ions. However, it must be reiterated that this comparison would not be sensitive to anomalous processes in later stages of the slowing down, that is, for $E \ll E_{\text{inj}}$.

The decay time τ_N can be related to the slowing-down time τ_s in the following way. Expressed as a function of energy, Eq. (3.7) becomes

$$\frac{dE}{dt} = - \frac{2E}{\tau_{se}} \left[1 + \left(\frac{E_c}{E} \right)^{3/2} \right]. \quad (7.2)$$

Using Eq. (7.2), τ_N is found to be

$$\tau_N = \frac{\tau_{se}}{3} \ln \left[\frac{E_{\text{inj}}^{3/2} + E_c^{3/2}}{E_N^{3/2} + E_c^{3/2}} \right]. \quad (7.3)$$

For the typical ISX-B parameters, then,

$$\tau_N \sim \frac{\tau_{se}}{14}, \text{ and } \tau_{se} \sim 25 \text{ to } 30 \text{ ms (for injected deuterons).}$$

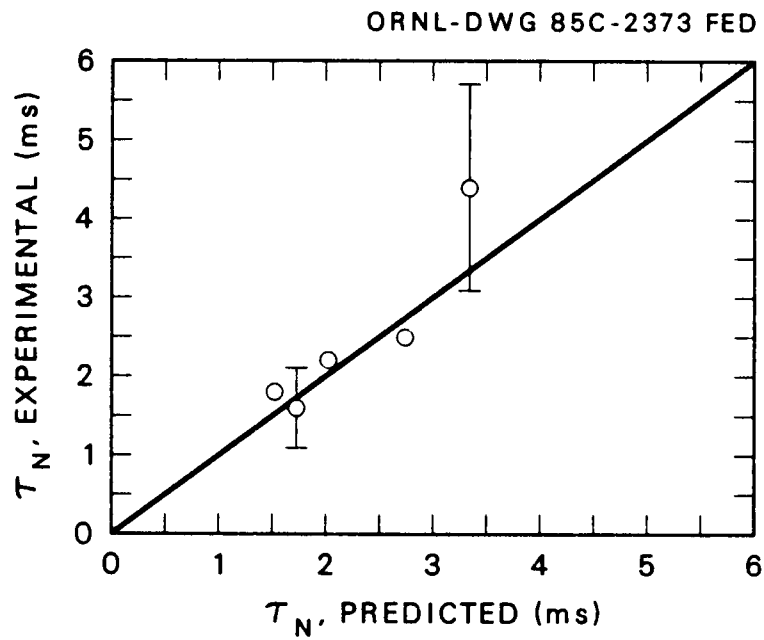


Fig. 7.3. Comparison of experimental and predicted decay times (τ_N) of the beam-plasma neutron emission for five different plasma discharges. The Thomson scattering radial profiles of T_e and n_e were used in the calculation.

Letting τ_s be the total slowing-down time on electrons *and* ions, the fast ion velocity decays exponentially with a time constant τ_s :

$$v = v_0 e^{-t/\tau_s} , \quad (7.4)$$

where

$$\frac{1}{\tau_s} = \frac{1}{\tau_{se}} + \frac{1}{\tau_{si}} . \quad (7.5)$$

The slowing-down time on ions— τ_{si} —can be written as a function of τ_{se} and the instantaneous fast ion energy E , using the expressions given by Spitzer:⁶⁵

$$\tau_{si} \approx 0.0062 \left(\frac{E}{T_e} \right)^{3/2} \tau_{se} . \quad (7.6)$$

The time required to slow down from E to $E - \delta E$ is, from Eq. (7.4),

$$\delta t(E) = \frac{\ln(E) - \ln(E - \delta E)}{2} \tau_s(E) . \quad (7.7)$$

The total slowing-down time is found by integrating Eq. (7.7) from v_{inj} to v_{inj}/e , with $\tau_s(E)$ given by Eqs. (7.5) and (7.6). The result is $\tau_s \approx 8$ ms, and, consequently, $\tau_N \sim \tau_s/4$. Calculations performed on PLT produced similar results, with τ_s/τ_N in the range from 2.5 to 5 for that tokamak.¹⁴

As a final point, to further establish that the neutron decay rate is dominated by the slowing down in the plasma core, the experimental τ_N is compared in Fig. 7.4 with τ_N obtained from Eq. (7.3), using *central values* for T_e and n_e in calculating τ_{se} . It can be seen that the agreement with the data is almost as good as that achieved by the full FPP calculation (Fig. 7.3), which follows the slowing down of the beam in the whole plasma volume.

7.4 MEASUREMENTS OF BEAM-PLASMA NEUTRON YIELD

In this section, measurements of beam-plasma neutron yields are considered. First, a global comparison is presented between the set of all the ISX-B data and the corresponding predictions of the Monte Carlo code. Then, attention is given to an experiment in which this type of measurement was used as a tool to compare fast ion confinement in co- and counter-injected discharges.

The experimental measurements of the neutron emission collected under a variety of conditions are matched in Fig. 7.5 with the values predicted by NEWORBX. The thermonuclear yield has been subtracted from the experimental data (and it has not been included in the Monte Carlo calculation) so that each point in the plot represents the beam-plasma neutron intensity for a particular plasma sequence. The circles refer to data taken during co-injected discharges, and the squares to discharges with balanced injection. In all cases when two beams were injected, only one beam was doped with 3% D⁰, the other being 100% H⁰. Due to the large ratio of target density to fast ion density, beam-beam reactions can be neglected. For all points in the plot except one, the doped beam was co-injected. In one of the balanced injection sequences, the

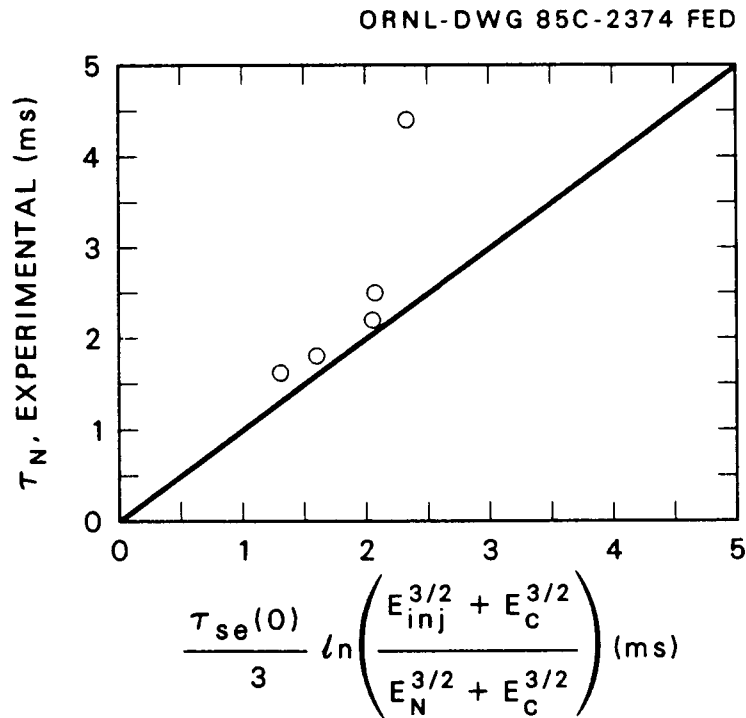


Fig. 7.4. The experimental τ_N are compared with the values predicted at the plasma center (same data set as that of Fig. 7.3). The predicted values of τ_N , here, were obtained using the central values of T_e and n_e and Eq. (7.3).

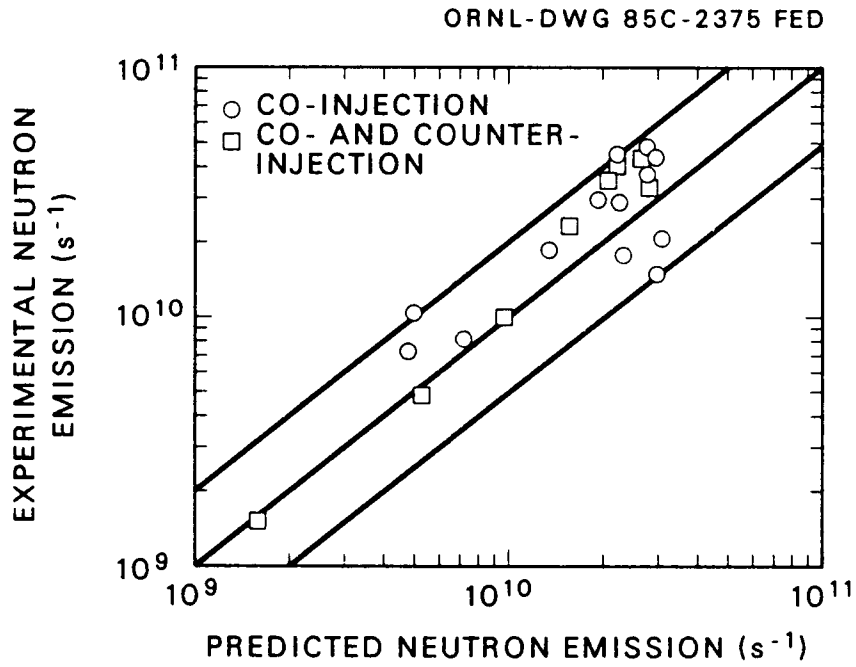


Fig. 7.5. Comparison of experimental and predicted beam-plasma neutron emission. The central solid line corresponds to one-to-one agreement, while the other two lines represent a discrepancy by a factor of 2.

doped beam was alternately the co- and the counter-beam. That particular experiment allowed a comparison of the confinement of co- and counter-injected ions, and the results will be presented at the end of this section. All the corrections discussed in Section 7.2 have been applied to the calculated values. However, no correction for plasma rotation was applied to the balanced injection cases since these have a negligible rotation velocity.^{61,62} The range in plasma and beam parameters encompassed by this comparison is displayed in Table 7.1.

Table 7.1 Range of parameters for the comparison of Fig. 7.5

Line-averaged electron density	$1.4 \times 10^{13} < \bar{n}_e < 7 \times 10^{13} \text{ cm}^{-3}$
Plasma current	$96 < I_p < 190 \text{ kA}$
Toroidal magnetic field	$1.2 < B_\phi < 1.4 \text{ T}$
Central electron temperature	$630 < T_e(0) < 950 \text{ eV}$
Central ion temperature	$530 < T_i < 1330 \text{ eV}$
Injected beam power	$0.46 < P_b < 1.8 \text{ MW}$
Beam energy	$18.4 < E_{\text{inj}} < 31.2 \text{ keV}$

Theory and experiment are seen to agree within a factor of ≤ 2 . The large number of variables that enter the theoretical calculation, and the uncertainties associated with them, may account for a discrepancy of that magnitude. Therefore, the Fokker-Planck theory accounts well—within the error bars—for the confinement and initial slowing down of the beam ions in the plasma core. No significant dependence of the relative agreement between theory and experiment on P_b , I_p , $\bar{n}_e$, or the injection geometry was detected. On the other hand, the paucity of the data does not warrant any definitive conclusion on this point.

As mentioned previously, one experiment consisted of injecting 3% deuterium first in the co-beam and then in the counter-beam during the same (balanced) sequence. The measured neutron emission for the two cases (beam-plasma plus thermonuclear) is shown in Fig. 7.6. The co-beam was injected at 100 ms, and the counter-beam at 200 ms. With 3% D^0 in the first beam, the neutron output is seen to rise sharply and then remain constant until the counter-beam comes in, at which time the intensity increases by a factor of ~ 2 in ~ 30 ms, probably due to a combination of several effects. First, the toroidal plasma rotation is quenched in about that time scale.^{61,62} Second, the central electron temperature may have increased with the second beam (it was not measured during the one-beam phase), thus making τ_N larger. Last, the density was being ramped up strongly with increased gas puffing from $2.3 \times 10^{13} \text{ cm}^{-3}$ at 190 ms up to $4.7 \times 10^{13} \text{ cm}^{-3}$ at 230 ms and to $6.4 \times 10^{13} \text{ cm}^{-3}$ at 270 ms. The higher density would result in lower charge-exchange losses from the plasma core and a lower deuterium target dilution. With the 3% D^0 bottle placed on the second beam, the neutron emission stays relatively low until 200 ms, due to thermonuclear reactions only. When the doped, counter-injected beam comes in, the intensity shoots up to a level close to, but somewhat lower than, that detected when the co-beam was injecting deuterium. The second beam injects in a direction opposite to the plasma rotation (until the rotation is stopped), which should result in a higher reactivity in the very first stage of injection. However, the enhancement is calculated to be on the order of $\sim 25\%$, which is obscured by the experimental uncertainty in the measurement. The beam-plasma neutron production rate (total minus estimated thermonuclear) is shown in Fig. 7.7. The neutron output for the counter-beam is on the average

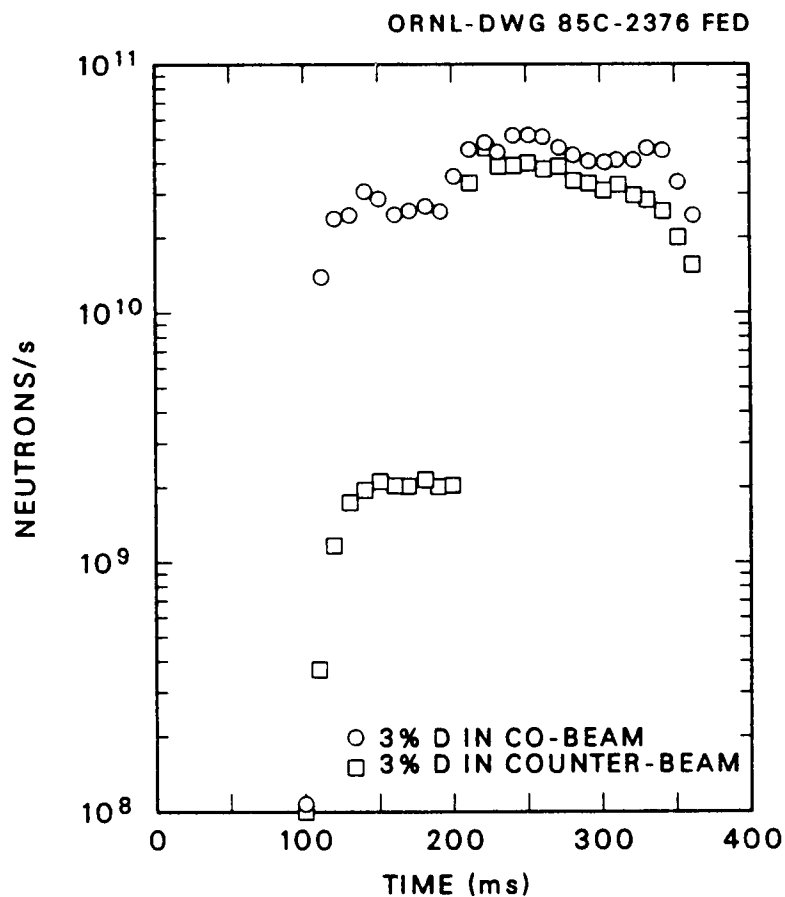


Fig. 7.6. Time histories of the measured neutron emission (beam-plasma plus thermonuclear) during co- and counter-injection of 3% D^0 on a deuterium plasma. The co-beam was injected at 100 ms, and the counter-beam at 200 ms. At the time when the Thomson scattering profiles were taken (300 ms), the discharge parameters were $B_\phi = 1.37$ T, $\bar{n}_e = 6.7 \times 10^{13} \text{ cm}^{-3}$, $I_p = 195$ kA, $P_b = 0.91 + 0.79$ MW, $E_{inj} = 29.7$ and 32.1 keV.

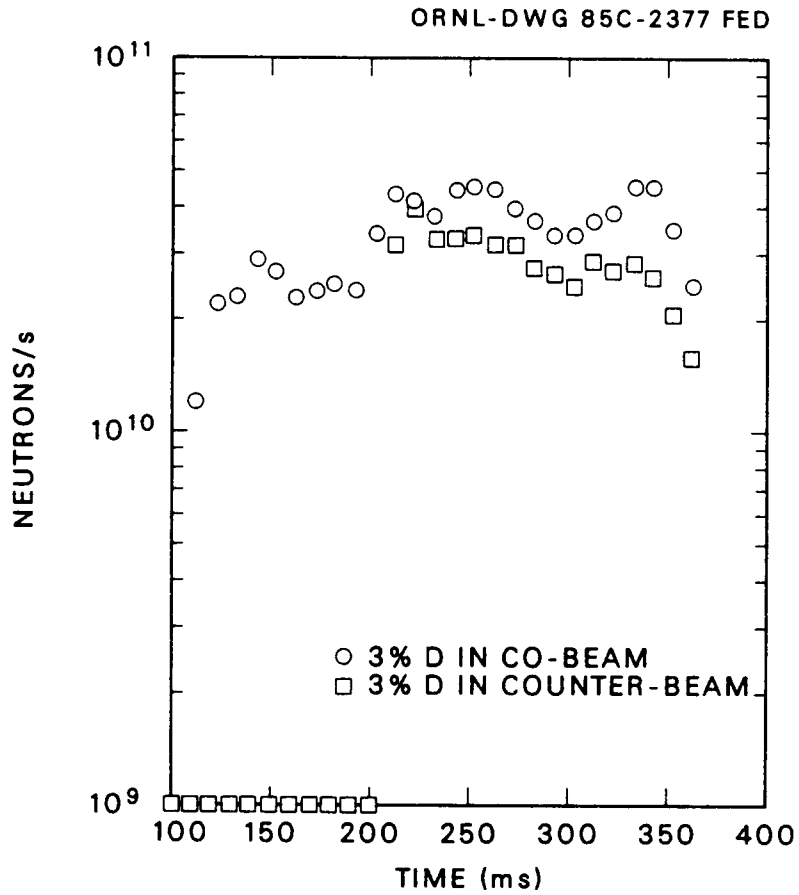


Fig. 7.7. Time histories of the experimental beam-plasma neutron emission during co- and counter-injection of 3% D^0 on a deuterium plasma. The predicted values at 300 ms are 2.8 and 1.56×10^{10} neutron/s for the co- and counter-case, respectively.

$\sim 25\%$ lower than for the co-beam. Two corrections must be included. One is for the lower beam current, by a factor of 1.25, in the counter-case. The other accounts for the different reactivities due to the fact that the counter-beam was injected at a higher voltage. This correction yields a factor of 0.74, which tends to cancel out the first correction. The conclusion is that the beam-plasma neutron emission for counter-injection is $\geq 25\%$ lower than for co-injection (under the same conditions), implying a similar difference in fast ion confinement for the two injection geometries. It must be emphasized that this result was obtained at a high plasma current ($I_p = 195 \text{ kA}$) and that the experiment is indicative of the confinement of the most energetic beam deuterons captured in the plasma core. Larger orbit losses for counter-injection (with respect to co-injection) at lower I_p and over the whole (R, ζ) space may result in a somewhat larger difference in confinement. The ratio of the neutron emission for the two cases, at 300 ms, is 1.53 (after the corrections for beam current and energy). The Monte Carlo calculation could not be performed on this particular sequence because not enough data were taken with the Thomson scattering diagnostic to provide reliable T_e and n_e profiles. However, the same sequence was repeated a month later, and profiles of good quality were obtained. Using those, the Monte Carlo code predicted a ratio of 1.79, which is in substantial agreement with the experiment. Simulations were also performed for H^0 beams. In this case, the orbit losses were calculated to increase by a factor of ~ 10 —from 3.3 to 34% of P_b —when changing from co- to counter-injection. At the same time, the total power delivered to the plasma (ions and electrons) was calculated to decrease by 32%, from 93 to 63% of P_b . The largest decrease occurred for P_{bi} , which went down from 30 to 16% of the injected power.

CHAPTER 8

CONCLUSION

An experimental investigation of fast ion confinement in the ISX-B tokamak has been presented in this thesis. In this chapter, the results obtained will be reviewed and conclusions will be drawn.

Charge-exchange analysis of fast neutral spectra is a well-established diagnostic technique to infer fast ion confinement. Typically, the experimental data are compared with the predictions of Fokker-Planck and Monte Carlo solutions of the drift-kinetic equation to assess whether the beam ions behave classically or are subject to anomalous processes. The present work has shown that the analysis need be integrated with the orbit topology picture to correctly interpret the spectra. Examples have been given of cases in which the deterministic, approximate treatment fails to adequately describe the experimental data. The type of experiments for which the deterministic calculation produces satisfactory results was also discussed. In view of the limitations of the deterministic approach, a Monte Carlo calculator of the beam ion distribution function and of fast neutral spectra was developed and implemented in the code NEWORBX for this research. Russian roulette and particle splitting schemes were used to obtain smooth spectra at viewing angles far from the direction of injection. The Monte Carlo simulation follows the actual orbit excursions of the energetic particles and properly mimics the physical system in the absence of anomalous processes. The sensitivity of fast neutral flux measurements to various effects resulting from beam deposition, slowing down, scattering, and charge-exchange rates was also investigated.

Data were collected encompassing a range of plasma and beam parameters under different injection geometries. Cases considered explicitly were high and low $\bar{n}_e$, high and low I_p for both co- and counter-injection, and high and low P_b during co-injection. A comparison of co-, counter-, and balanced injection was also presented. The experimental fast neutral spectra displayed marked differences depending on the discharge characteristics. Yet the Monte Carlo simulation reproduced the experimental data in all cases (with the exception of the localized spectra during high power injection). The close agreement between theory and experiment under a variety of conditions demonstrates that the fast ion behavior in ISX-B is well described by classical processes. Furthermore, the fact that the simulation predicts equally well the spectra in co-, counter-, and balanced injection discharges indicates that plasma rotation and plasma potential did not affect strongly the slowing-down process. Measurements of beam-plasma neutron emission, also obtained under a range of parameters, support the conclusion that the beam ion behavior is classical in ISX-B. The measured yields and the Monte Carlo predictions were found to match within factors of ≤ 2 . It was argued that an uncertainty of this magnitude may be expected due to the large number of variables that affect the calculated values.

The agreement between experimental and predicted beam-target neutron output suggests that the beam deposition profiles are calculated correctly. This conclusion is reinforced by the discrepancy introduced in the simulated perpendicular fast neutral spectrum when the mean free paths were artificially decreased by a factor of 2.

Measured decay rates of the beam-plasma neutron production following beam turn-off showed that the beam slowing down is classical within a 30%

uncertainty, at least at energies close to E_{inj} and in the plasma core. That the slowing down is classical may also be inferred from the good agreement between the experimental and predicted fast neutral spectra in both co- and counter-injection discharges, where the slowing down is altered by differences in T_e and in the effects of the toroidal electric field.

An important result of this work has been the demonstration that the MHD activity did not cause enhanced fast ion losses in the ISX-B. During sawtooth discharges, fluctuations in the fast neutral flux correlated with the internal disruptions were detected. However, these oscillations are attributable to a redistribution of the fast ions to a larger average radius and not to a direct expulsion from the plasma. Even in the presence of a fishbone-type instability, no correlated fast ion losses were observed. This result is thought to be a consequence of the near-tangential injection in the ISX.

Monte Carlo simulations were also used to assess the extent of postulated charge-exchange losses that still yield fast neutral spectra consistent with the experimental data. It was found that for a high $\bar{n}_e$ case ($\sim 6 \times 10^{13} \text{ cm}^{-3}$) the enhanced charge-exchange losses would have a negligible effect on the power deposition. For the low $\bar{n}_e$ case considered ($2 \times 10^{13} \text{ cm}^{-3}$), on the other hand, they were 43% higher than calculated in the ZORNOC code. However, the corresponding decrease in the power delivered to the plasma was only about 12%.

The effects of a postulated enhancement in pitch angle scattering were similarly studied by varying the Z_{eff} used in the simulation. It was established that an enhanced pitch angle scattering modeled as $Z_{eff} = 7$ is untenable

because it produces localized spectra that are discordant with the experimental data. Due to the relatively low T_e in the ISX, the shapes of the spectra are dominated by the slowing-down process rather than pitch angle scattering. For this reason, the method was not sensitive enough to closely estimate Z_{eff} . It appears that values of Z_{eff} somewhat higher than those used in ZORNOC—that is, in the range 1 to 3 and perhaps higher in counter-injected discharges—are possible. However, the higher Z_{eff} would have negligible effects on the calculated power deposited in the plasma during co-injection, while it would lower it only by small amounts ($\leq 10\%$) in counter-injection cases.

No deviations from classical behavior were detected when comparing fast ion data collected during gettered and ungettered discharges. Specifically, the increase in energy confinement time obtained during Z-mode operation does not appear to be a consequence of an improved fast ion confinement.

The subject of beam additivity was investigated at both high and low I_p in medium density discharges ($3.8 \times 10^{13} \text{ cm}^{-3}$). The experiments verified that the density of the fast ions confined in the plasma volume is indeed proportional to the injected beam power. However, some evidence was reported that suggests that the fast ion density in the plasma core might be less than linear with P_b . The data available were not conclusive and, thus, the issue could not be resolved. It is deemed of some importance that this issue be explored further in other tokamaks.

The calculated beam power distribution was compared for high and low $\bar{n}_e$ cases, for high and low I_p cases during co- and counter-injection, and for the co-/counter-/balanced injection comparison. Here, a brief summary will be

presented contrasting co- and counter-injection schemes. Four co- and four counter-injection cases were analyzed for which the discharge parameters were similar enough to allow a one-to-one comparison. Six of these were discussed in Chapter 5, namely the co-sequences at $I_p = 96, 145,$ and 180 kA, and the counter-sequences at $I_p = 110, 145,$ and 170 kA. The last two cases correspond to the co-/counter comparison (at $I_p = 195$ kA) presented in Chapter 7. Roughly averaging over the four pairs, the following conclusions can be drawn. In changing from co- to counter-injection, the fraction of the injected beam power lost to bad orbits increases from 5 to 10% to 25 to 35%. On the average, the power delivered to the plasma decreases by $\sim 30\%$, from 0.85 to $0.6 P_b$. The power deposited in the ion population decreases somewhat more than the power deposited in the electrons. The largest deterioration in confinement occurs at the lowest I_p and at the highest $\bar{n}_e$.

Finally, in comparing the power distributions calculated in ZORNOC—and used in the transport calculations—with the more reliable results obtained from the Monte Carlo simulations, the following observations can be made. For co-injection sequences at $I_p \geq 145$ kA, ZORNOC calculates the power deposited in the plasma within 2% of the Monte Carlo simulation in all cases. For the co-injection sequence at $I_p = 96$ kA, this power was overestimated by 10%. The ZORNOC calculation also results in more power going into the electron channel, overestimating this by an average of $\approx 8\%$ for $I_p \geq 145$ kA and by $\approx 15\%$ for the low I_p case. For counter-injection sequences at $I_p \geq 145$ kA, ZORNOC overestimates the power delivered to the plasma by $\sim 10\%$. At $I_p = 110$ kA, the overestimation is by $\sim 20\%$. The largest

discrepancies take place at low I_p ($\sim 20\%$) and at high $\bar{n}_e$ (14%), where the losses of counter-injected ions become more significant.

REFERENCES

REFERENCES

1. L. A. Berry et al., "Neutral Beam Injection Experiments in ORMAK," in *Plasma Physics and Controlled Nuclear Fusion Research 1*, 113 (1974).
2. K. Bol et al., "Neutral Beam Heating in the Adiabatic Toroidal Compressor," in *Plasma Physics and Controlled Nuclear Fusion Research 1*, 77 (1974).
3. D. W. Swain, M. Murakami, et al., *Nucl. Fusion* **21**(11), 1409 (1981).
4. D. W. Swain and G. H. Neilson, *Nucl. Fusion* **22**(8), 1015 (1982).
5. R. J. Goldston, *Energy Confinement Scaling in Tokamaks*, Princeton Plasma Physics Laboratory Report PPPL-2060, Princeton, N.J. (1984).
6. S. M. Kaye and R. J. Goldston, *Global Energy Confinement Scaling for Neutral-Beam Heated Tokamaks*, Princeton Plasma Physics Laboratory Report PPPL-2157, Princeton, N.J. (1984).
7. M. Murakami et al., *Plasma Physics and Controlled Nuclear Fusion Research 1*, 57 (1983).
8. K. McGuire et al., *Phys. Rev. Lett.* **50**(12), 891 (1983).
9. R. J. Goldston, "Fast Ion Diagnostics Experiments on ATC: Radially Resolved Measurements of q , Z_{eff} , $T_{\parallel}$, and $T_{\perp}$," Ph.D. Thesis, Princeton Plasma Physics Laboratory, Princeton, N.J. (1977).
10. R. J. Goldston et al., *J. Comp. Phys.* **43**, 61 (1981).
11. R. H. Fowler and J. A. Rome, *Bull. Am. Phys. Soc.* **25**(8), 849 (1980).
12. E. A. Lazarus et al., *Nucl. Fusion* **25**(2), 135 (1985).
13. P. H. Edmonds et al., "High Beta Results in ISX-B with Intense Neutral Beam Injection," in *Proceedings of the Third International Symposium on Heating in Toroidal Plasmas*, Grenoble (1982).
14. J. D. Strachan et al., *Nucl. Fusion* **21**(1), 67 (1981).
15. TFR Group, *Nucl. Fusion* **23**(4), 425 (1983).
16. D. Johnson et al., *High Beta Experiments with Neutral Beam Injection on PDX*, Princeton Plasma Physics Laboratory Report PPPL-1964, Princeton, N.J. (1983).
17. R. B. White et al., *Phys. Fluids* **26**(10), 2958 (1983).
18. L. Chen, R. B. White, and M. N. Rosenbluth, *Phys. Rev. Lett.* **52**(13), 1122 (1984).

19. R. Kaita et al., "Beam Ion Thermalization Measurements During Neutral Injection in Indented PBX Plasmas," *Bull. Am. Phys. Soc.* **29**(8), 1218 (1984).
20. E. J. Strait et al., "Fast Ion Loss Due to Fishbone Oscillations in Doublet III," *Bull. Am. Phys. Soc.* **29**(8), 1364 (1984).
21. J. L. Dunlap et al., *Phys. Rev. Lett.* **48**(8), 538 (1982).
22. W. L. Gardner, Oak Ridge National Laboratory, private communication.
23. C. C. Tsai et al., *J. Nucl. Mater.* **111 & 112**, 153 (1982).
24. H. W. Kugel et al., *Bull. Am. Phys. Soc.* **27**, 1049 (1982).
25. R. Kaita et al., Princeton Plasma Physics Laboratory Report PPPL-2156, Princeton, N.J. (1984); also to be published in *Nucl. Fusion*.
26. M. Gryzinski, *Atomic Collision Processes*, London Conference, 226 (1963).
27. R. L. Freeman and E. M. Jones, "Atomic Collision Processes in Plasma Physics Experiments," Culham Laboratory Report CLM-R 137 (1974).
28. A. C. Riviere, *Nucl. Fusion* **11**, 364 (1971).
29. D. R. Sweetman, *Nucl. Fusion* **13**, 157 (1973).
30. C. F. Barnett et al., *Atomic Data for Controlled Fusion Research*, Oak Ridge National Laboratory Report ORNL-5206 and ORNL-5207 (1977).
31. R. M. Wieland et al., *Nucl. Fusion* **23**(4), 447 (1983).
32. K. H. Burrell, *J. Comp. Phys.* **27**, 88 (1978).
33. G. H. Neilson, *Charge Exchange Measurements of Ion Behavior in the ISX Tokamak*, Oak Ridge National Laboratory Report ORNL/TM-7333 (1980).
34. S. D. Scott, "Analysis of Charge-Exchange Ion Temperature Measurements on TFTR," *Bull. Am. Phys. Soc.* **29**(8), 1303 (1984).
35. T. G. Northrop, *The Adiabatic Motion of Charged Particles* (Wiley, New York, 1963).
36. R. H. Fowler, D. K. Lee, P. W. Gaffney, and J. A. Rome, *FLOC—Field Line and Orbit Code for the Study of Ripple Beam Injection into Tokamaks*, Oak Ridge National Laboratory Report ORNL/TM-6293 (1978).

37. S. D. Scott, "An Experimental Investigation of Magnetic Field Ripple Effects on Tokamak Plasmas," Ph.D. Thesis, Massachusetts Institute of Technology (1982).
38. D. G. McAlees, *Alpha Particle Energetics and Neutral Beam Heating in Tokamak Plasmas*, Oak Ridge National Laboratory Report ORNL/TM-4661 (1974).
39. J. A. Rome, J. F. Lyon, and R. H. Fowler, *Using a Constants-of-Motion Space to Clarify Measurements Involving Energetic Ion Orbits in Tokamaks*, Oak Ridge National Laboratory Report ORNL/TM-7913 (1981).
40. B. B. Kadomtsev and O. P. Pogutse, Nucl. Fusion **11**, 67 (1971).
41. T. H. Stix, Plasma Phys. **14**, 367 (1972).
42. J. A. Rome and Y-K. M. Peng, *The Topology of Tokamak Orbits*, Oak Ridge National Laboratory Report ORNL/TM-6352 (1978).
43. R. Kaita, R. J. Goldston, and J. P. Bussac, Nucl. Fusion **8**, 953 (1981).
44. M. N. Rosenbluth, W. M. MacDonald, and D. L. Judd, Phys. Rev. **107**(1), 1 (1957).
45. J. G. Cordey and W. G. F. Core, Phys. Fluids **17**(8), 1626 (1974).
46. N. A. Krall and A. W. Trivelpiece, *Principles of Plasma Physics*, (McGraw-Hill Book Company, 1973).
47. W. M. Stacey and D. J. Sigmar, Nucl. Fusion **19**, 1665 (1979).
48. K. H. Burrell, T. Ohkawa, and S. K. Wong, Phys. Rev. Lett. **47**, 511 (1981).
49. M. Murakami et al., "Confinement of Beam-Heated Discharges in ISX-B," in *Proceedings of the Tenth International Conference on Plasma Physics and Controlled Nuclear Fusion Research*, London, UK (1984).
50. R. C. Isler et al., Nucl. Fusion **23**(8), 1017 (1983).
51. A. J. Wootton et al., "Balanced Beam Injection on ISX-B," in *Proceedings of the Fourth International Symposium on Heating in Toroidal Plasmas*, Rome, Italy (1984).
52. E. C. Crume, Jr., *Simulation of Inertial and Beam-driven Effects on Impurities in Tokamak Plasmas*, Oak Ridge National Laboratory Report ORNL/TM-8699 (1983).

53. R. H. Fowler et al., *NFREYA—A Monte Carlo Beam Deposition Code for Noncircular Tokamak Plasmas*, Oak Ridge National Laboratory Report ORNL/TM-6845 (1979).
54. C. J. Armentrout et al., "Comparison of Fast Ion Flux at Intermediate Energies for H and L Mode Discharges in Doublet III," *Bull. Am. Phys. Soc.* **28**(8), 1122 (1983).
55. J. Lohr et al., "Parallel Neutral Flux Measurements on Doublet III," *Bull. Am. Phys. Soc.* **28**(8), 1122 (1983).
56. C. H. Petley, "Channel Electron Multipliers," UDC 621.383.81, Mullard Industrial Electronics Division.
57. H. P. Furth, in *Controlled Fusion and Plasma Physics* (Proc. 6th Europ. Conf., Moscow) **2**, 51 (1973).
58. J. D. Strachan et al., *Studies of Energetic Ion Confinement During Fishbone Events in PDX*, Princeton Plasma Physics Laboratory Report PPPL-2165, Princeton, N.J. (1984).
59. G. H. Miley, H. Towner, and N. Ivich, "Fusion Cross Sections and Reactivities," University of Illinois Report COO-2218-17, Urbana, Ill. (1974).
60. R. C. Isler and L. E. Murray, *Appl. Phys. Lett.* **42**(4), 355 (1983).
61. R. C. Isler, *Bull. Am. Phys. Soc.* **28**(8), 1053 (1983).
62. S. D. Scott, *Bull. Am. Phys. Soc.* **28**(8), 1111 (1983).
63. H. C. Howe, Oak Ridge National Laboratory Report ORNL/TM-9537 (1985).
64. H. C. Howe, private communication.
65. L. Spitzer, Jr., *Physics of Fully Ionized Gases* (Interscience Publishers, Inc., New York, 1956).

APPENDIXES

APPENDIX A

DESCRIPTION OF THE NEUTRAL PARTICLE ANALYZERS

Two mass-discriminating neutral particle analyzers, the Momentum-Energy Analyzer (MEA) and the Velocity-Filter Analyzer (VFA), were used to collect the experimental data presented in this thesis. Since they are described elsewhere,^{33,37} only their main features and capabilities are reviewed here.

In both instruments, the fast neutrals escaping from the plasma are collimated by a series of small apertures into a stripping cell—filled with D_2 at a constant pressure of several microns—in which a fraction of them is ionized. The ions are then allowed to pass through a region of electric and magnetic fields, where they are sorted according to mass and energy. The two analyzers scan horizontally along the ISX midplane, the MEA from $R_t = 8$ cm to $R_t = 42$ cm and the VFA from $R_t = 49$ cm to $R_t = 97$ cm. (R_t is the tangency major radius of the viewing chord.) Both have an energy range that extends from ~ 0.5 to 40 keV, although most of the VFA data were limited to a maximum of ~ 28 keV due to damage sustained in one of its channeltron detectors. The data acquisition system allowed for fast data collection up to 10 kHz.

The MEA was developed, calibrated, and implemented on ISX by G. H. Neilson.³³ A schematic illustration of this analyzer is shown in Fig. A.1. In measurements, the gas cell pressure was kept constant at $\approx 8.7 \mu$ —the same pressure used for the calibration. A perpendicular static magnetic field is employed to separate the incoming particles according to their momenta, and a set of seven curved plate electrostatic energy analyzers are used to sort them by

ORNL / DWG / FED - 77477R

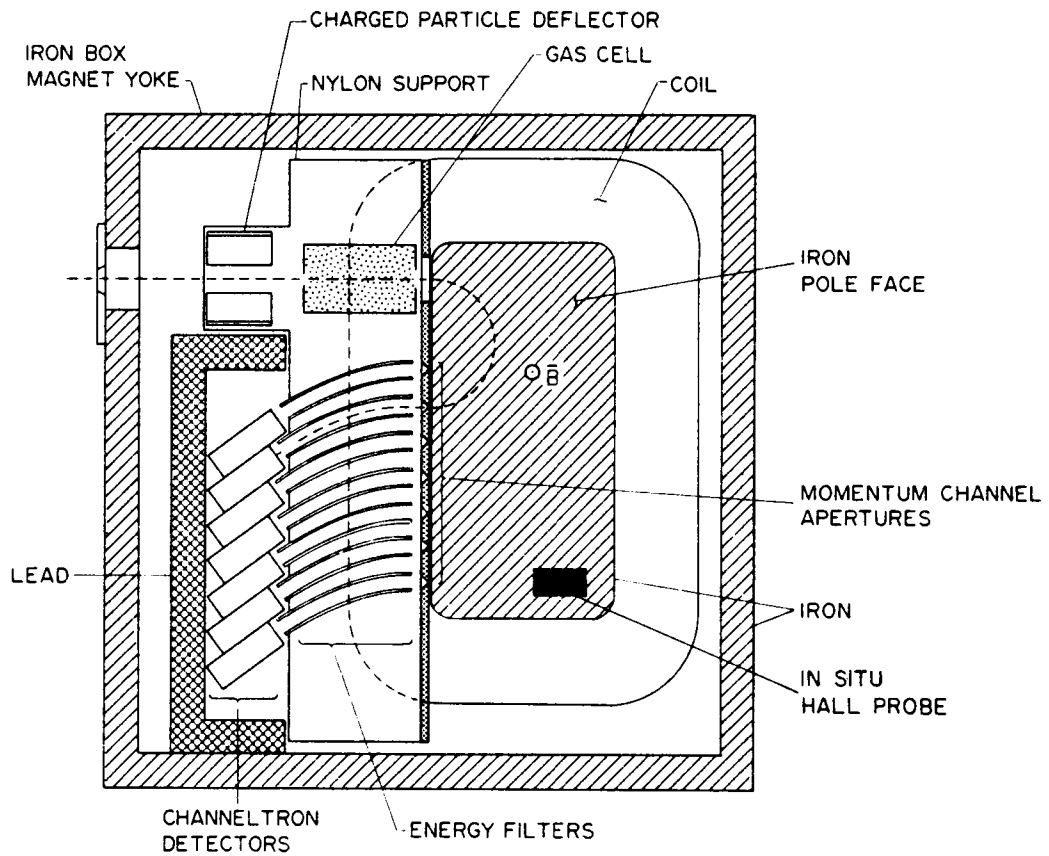


Fig. A.1. Schematic illustration of the Momentum-Energy Analyzer (MEA).

energy. Only ions of the chosen species (i.e., H_1 or D_1), at seven different energies, are passed by the B and E filters during each tokamak discharge. These particles are then detected by channel electron multipliers (channeltrons) operated in a pulse-counting mode. The voltage and current settings are varied between discharges so that other energies and/or atomic species may be viewed. The energy resolution is $\approx 5\%$, and the mass rejection ratio is ≈ 100 . (That is, with the instrument set to measure the H^0 flux and a mixture of H^0 and D^0 impinging on it, $\sim 1\%$ of the deuterons would escape the mass discrimination and would produce counts.)

The VFA, designed and calibrated by J. T. Mihalcz and S. D. Scott,³⁷ achieves mass and energy discrimination by first filtering the ions in velocity as they pass through an $E \times B$ region, then in energy by means of a four-channel parallel plate electrostatic analyzer. The VFA is shown in Fig. A.2. When measuring fast neutral fluxes, the VFA stripping cell was supplied with gas flow rates $\leq 0.1 \text{ cm}^3 \cdot \text{A}/\text{min}$, whereas the calibration was performed with a flow rate of $1.0 \text{ cm}^3 \cdot \text{A}/\text{min}$ (providing a calculated pressure of $\approx 3.8 \mu$). The lower pressure setting was necessary to avoid saturating the channeltrons when the analyzer was oriented along chords near the direction of beam injection. For the given gas cell dimensions and pressures and the incoming particle energies, the detection efficiency varies approximately linearly with gas flow rate. Accordingly, the data collected with the VFA were multiplied by the ratio of the gas flow rate used for the calibration to that used for the individual measurements. By stepping the voltages applied to the velocity filter and to the electrostatic energy analyzer every millisecond or so during a tokamak discharge, data at several energies per channel can be acquired. The data for this research were

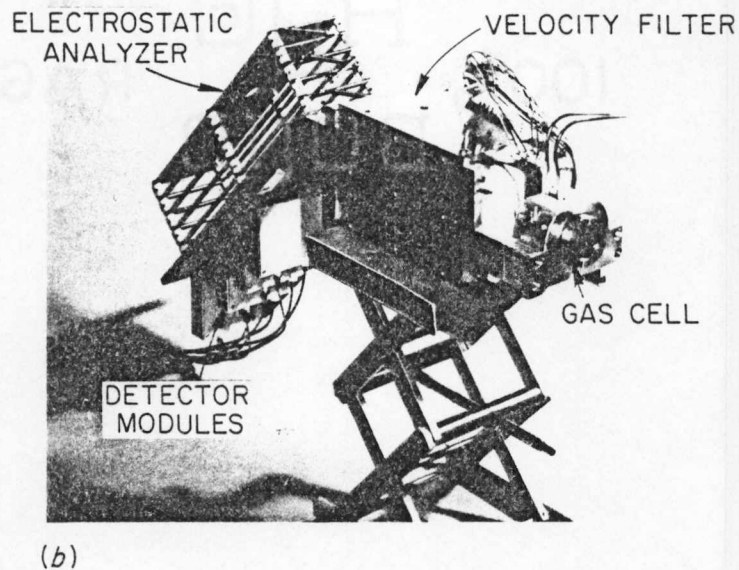
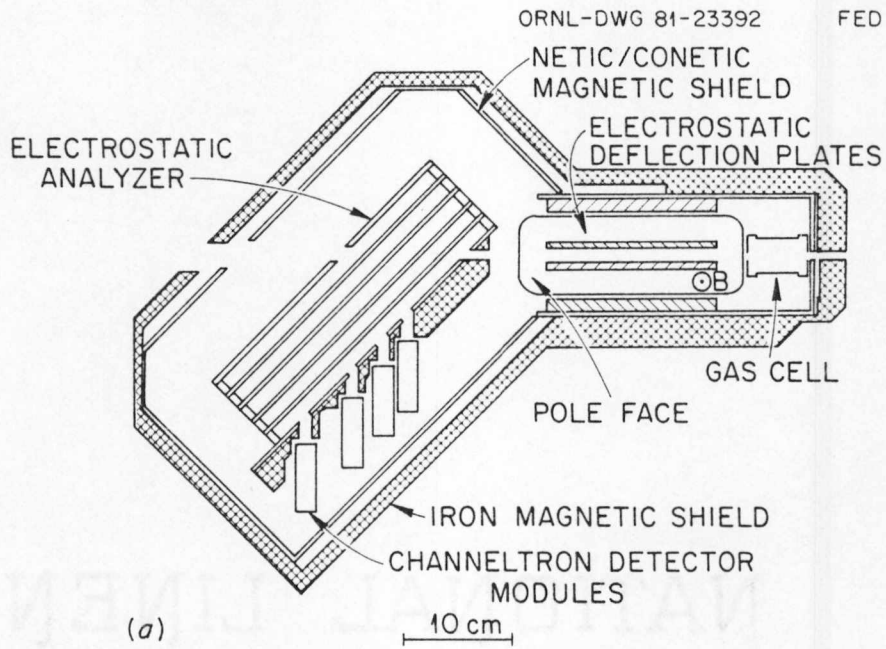


Fig. A.2. The Velocity-Filter neutral particle Analyzer (VFA).

collected with the velocity filter turned off, that is, without mass discrimination. Since spectra of injected H^0 were obtained with the VFA at energies greater than or equal to several times the plasma deuterium temperature, no mass discrimination was necessary. In this configuration the analyzer measures the flux at four energies simultaneously and can yield a fairly continuous energy spectrum in one single plasma discharge. However, because of an unresolved discrepancy between the four channels, this capability was not used, and the spectra were obtained using one channel only.

APPENDIX B

MONTE CARLO CALCULATION OF F_i AND Φ_0

In this appendix the Monte Carlo calculation of the beam ion distribution function $F_i(R, E, v_{\parallel}/v)$ and the fast neutral flux density $\Phi_0(E)$ is reviewed.

1. Calculation of $F_i(R, E, \zeta)$

Let $F_i(V, E, \zeta) \delta V \delta E \delta \Omega_v$ be the number of ions in an elemental volume, where δV is the volume element in real space and $\delta \Omega_v$ is the elemental solid angle in velocity space, subtended by ζ in $\delta \zeta$ ($\zeta \equiv v_{\parallel}/v$). In steady state the distribution function can be expressed as

$$F_i(V, E, \zeta) \delta V \delta E \delta \Omega_v = \dot{n}(V, E, \zeta) \tau ,$$

where $\dot{n}$ is the beam particle input rate and τ is the ion residence time in the volume. If one considers F_i on the horizontal midplane (HMP), τ can be written as

$$\tau = \sum_{\text{cross}} \delta t(V, E, \zeta) ,$$

where the summation is performed over the HMP crossings, and where $\delta t(V, E, \zeta)$ is the individual time step during which the ion is in the particular bin.

Let N_l be the number of launched Monte Carlo particles. The corresponding residence time, averaged over the N_l particles, is

$$\langle \tau \rangle = \frac{1}{N_l} \sum_{i=1}^{N_l} \sum_{\text{cross}} \delta t(V, E, \xi) W ,$$

where W is the weight, or the number of particles represented by each Monte Carlo particle. $W = 1$ for each particle at the start, but its value may change during the slowing down due to the Russian roulette and particle splitting schemes. As discussed in Section 4.3, the slowing-down process in the Monte Carlo calculation is accelerated to a varying degree with respect to the orbital motion, the acceleration factor ($\equiv G$) being updated at each HMP crossing. Since the acceleration technique increases the slowing down rate by a factor G , but does not affect the probability distribution, the calculated time spent in the bin is artificially reduced by the same factor G . To compensate for this, δt must be replaced by $\delta t \cdot G$, and F_i then becomes

$$F_i(V, E, \xi) \delta V \delta E \delta \Omega_v = \frac{\dot{N}}{N_l} \sum_{i=1}^{N_l} \sum_{\text{cross}} \delta t(V, E, \xi) G W ,$$

where $\dot{N}$ is the total injection rate of ions in the plasma. Now, δt is the time spent in some small space interval δs near $z = 0$ ($\hat{z}$ being the perpendicular to the HMP), or

$$\delta t = \frac{\delta s}{\dot{z}} .$$

Not retaining the toroidal resolution, the real space volume element can be written as

$$\delta V = 2\pi R \delta R \delta s .$$

Also, with $v_{\perp}$ free to take any direction in a plane perpendicular to $v_{\parallel}$, there is a simple relation between $\delta\Omega_v$ and $\delta\zeta$. In fact, from simple geometry and the equation $\zeta = v_{\parallel}/v$,

$$\delta\Omega_v = 2\pi\delta\zeta ,$$

and F_i , therefore, becomes

$$F_i(R, E, \zeta) \delta R \delta E \delta \zeta = \frac{\dot{N}}{4\pi^2 N_l} \sum_{i=1}^{N_l} \sum_{\text{cross}} \frac{WG}{R\dot{z}} . \quad (\text{B.1})$$

The number of Monte Carlo particles is a user-defined parameter, and $\dot{N}$ is determined by the known beam power, energy, and fractional composition. At each crossing, the values of R , E , ζ , W , G , $\dot{z}$ (plus the particle number and the orbit type) are stored. A postprocessor then calculates $F_i(R, E, \zeta)$ according to Eq. (B.1), given a chosen set of δR , δE , and $\delta \zeta$.

2. Calculation of $\Phi_0(E, R_t)$

The local fast ion density, per cubic centimeter, in a given bin is given by

$$F_i(R, E, \zeta) \delta E \delta \Omega_v = \frac{\dot{N}_{<\tau>}}{\delta V} .$$

The number of fast neutrals escaping the plasma from R in δR , with energy E in δE and pitch angle ζ in $\delta \zeta$, per cubic centimeter and per second, is obtained by multiplying the fast ion density by the local neutralization rate and by the escape probability (or attenuation integral) P :

$$\delta \dot{N}_o(R, E, \zeta) = F_i(R, E, \zeta) \delta E \delta \Omega_v n_o(R) \sigma_{cx}(v) v P(s, E) ,$$

where s is the distance to the NPA along the viewing chord.

In measurements, E is determined by the analyzer settings and ζ by the geometry ($\zeta = R_t/R$), so that for a particular choice of E and R_t ,

$$\delta \dot{N}_o \left(R, E_j, \frac{R_t}{R} \right) = F_i \left(R, E_j, \frac{R_t}{R} \right) \delta E \delta \Omega_v n_o(R) \sigma_{cx}(v_j) v_j P(s, E_j) .$$

Referring to Fig. B.1, the total number of neutrals escaping the plasma per second from the elemental space volume δV located at R , with energy E in δE , along the NPA viewing chord, is

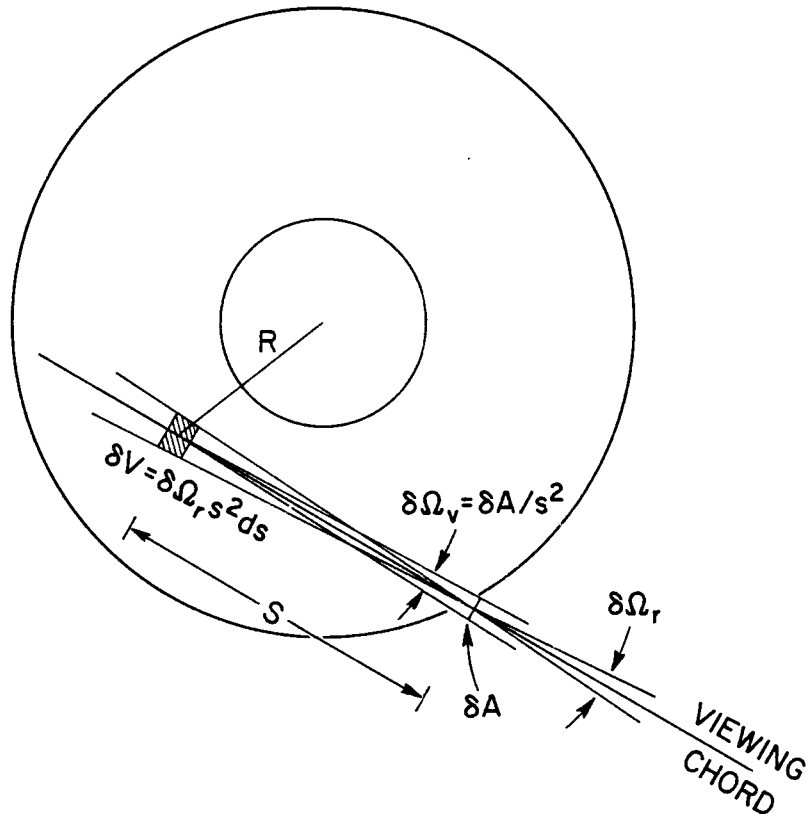


Fig. B.1. The geometry for the calculation of Φ_0 .

$$\delta\Phi_o(R, E_j, R_t) \equiv \delta\dot{N}_o \delta V = \delta\dot{N}_o \left(R, E_j, \frac{R_t}{R} \right) \delta\Omega_r s^2 \delta s .$$

Considering an arbitrary surface δA outside the plasma, $\delta\Omega_v$ is given by

$$\delta\Omega_v = \frac{\delta A}{s^2} ,$$

so

$$\delta\Phi_o(R, E_j, R_t) = F_i \left(R, E_j, \frac{R_t}{R} \right) \delta E \delta A \delta\Omega_r \delta s n_o(R) \sigma_{cx}(v_j) v_j P(s, E_j)$$

can be written as the total number of fast neutrals escaping per second through δA . Integrating along the sightline,

$$\Phi_o(E_j, R_t) = \delta E \delta A \delta\Omega_r \int_{\text{chord}} F_i \left(R, E_j, \frac{R_t}{R} \right) n_o(R) \sigma_{cx}(v_j) v_j P(s, E_j) ds ,$$

with units of particles per second. The neutral flux density, in units of $\text{cm}^{-2} \text{sec}^{-1} \text{eV}^{-1} \text{sr}^{-1}$, to be compared with the experimental analysis is, thus,

$$\Phi_o(E_j, R_t) = \int_{\text{chord}} F_i \left(R, E_j, \frac{R_t}{R} \right) n_o(R) \sigma_{cx}(v_j) v_j P(s, E_j) ds ,$$

where $F_i(R, E_j, R_t/R)$ is as calculated previously and the integration is replaced by a summation in small steps of length δs in the actual computer calculation.

APPENDIX C

CALIBRATION OF THE NEUTRON DETECTION SYSTEM

This appendix describes the neutron detection system and its calibration on the ISX-B. Neutron flux measurements are a common diagnostics for determining the plasma ion temperature, but if the heating-beam working gas contains a known quantity of deuterium, they can also be used to infer fast ion confinement. For the latter purpose, it is essential to obtain a good estimate of the uncertainty in the measurement. A description of the method of calibration and an assessment of the uncertainties involved are presented here.

1. Introduction

The neutron emission from fusion reactions in ISX-B is due to



The reaction rate is a strong function of the deuterons' energy, $\sigma(E) \sim \exp(-47/\sqrt{E})/E$. When the reaction rate is averaged over a Maxwellian ion velocity distribution, the total neutron production rate is a strong function of the ion temperature, $\langle\sigma v\rangle \sim \exp(-18.76/T_i^{1/3})/T_i^{2/3}$. The emission rate per unit volume is $R = n_d^2 \langle\sigma v\rangle/2$. Thus, in ohmic plasmas or in H^0 beam-heated plasmas, the ion temperature can be determined relatively accurately even if the neutron flux is measured with modest accuracy. (For example, the inferred ion

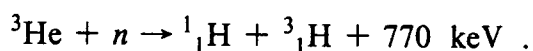
temperature varies as $R^{1/6}$ at $T_i = 850$ eV.) The accuracy of the ion temperature calculated from the neutron output is limited more by the uncertainty in n_d and by deviations from a Maxwellian velocity distribution (most neutrons are produced by deuterons with several times the thermal energies, e.g., $E/T_i = 6$ at $T_i = 1$ keV) than by errors in the neutron flux measurement.

Another possible application of neutron flux measurements is in the investigation of fast ion confinement. A 30-keV neutral H^0 beam doped with 3% deuterium produces approximately four times as many neutrons (through beam-plasma collisions) than does the background plasma. Roughly speaking, the beam-plasma neutron production rate is proportional to the fraction of full-energy deuterons that survive the first orbit and proportional to the fast ion slowing-down time. The measured neutron yield can be compared with detailed Fokker-Planck calculations and with Monte Carlo guiding center orbit calculations to assess whether the beam ions behave classically.

It is important to note that (unlike the T_i measurements) modest statistical or calibration errors in the neutron system would affect the conclusions regarding fast ion confinement. For this reason, a careful calibration of the ISX-B neutron detection system was performed, using a radioactive source (^{252}Cf) placed at many locations within the ISX-B vacuum vessel. Additional experiments were performed to gauge the magnitude of unavoidable errors, such as the difference between the D-D neutron energy and the energy spectrum of the ^{252}Cf source, in the calibration procedure. The result is that the accuracy of the neutron flux measurements in ISX-B is approximately $\pm 25\%$.

2. ISX-B Neutron Detection System

The neutron detection system on ISX-B consisted of four ^3He and two ^{235}U detectors. The former are filled with ^3He gas and make use of the reaction



The ionization produced as the protons and tritons are brought to rest is multiplied by a strong electric field and is used to produce a current pulse that is then amplified and counted. The detectors are contained in moderator cans (paraffin) to take advantage of the larger reaction cross section at lower neutron energies.

The ^{235}U detectors work in a similar manner, the major difference being that the ionizing agents are fission fragments with very high energies (50 to 100 MeV), thus making this type of detector less susceptible to high-energy-photon background since the amount of ionization produced by the fission fragments is much larger than that produced by photons, giving rise to a larger signal. They saturate (i.e., subject to unaccountable counting losses) at a count rate of $10^6/\text{s}$. The ^3He , on the other hand, saturate at 5×10^4 counts/s, but have the advantage of being more sensitive to low neutron fluxes. The six detectors were located at different toroidal locations around the tokamak.

3. Method of Calibration

To calibrate the neutron detection system, a ^{252}Cf neutron source was used. The uncertainty in source strength was determined by calculating the

expected dose at 1 m (due to fast neutrons) and comparing this with a direct measurement. Calculations based on the known neutron output in 1976 (NBS calibration) yielded an expected dose of 22.9 millirems/h, whereas the experimental value was measured with an ORNL fast-neutron survey meter to be 22 millirems/h. The discrepancy is about 4%.

The source was placed at 19 toroidal positions inside the vessel (close to the axis at $r = 0$), as shown in Fig. C.1, which also displays the location of the neutron detectors. The count rates of the six detectors were measured and then plotted as a function of the toroidal source position; the statistical errors in the count rates were $\sim 2\%$ for the ^3He detectors and $\sim 6\%$ for the ^{235}U . The toroidal coordinate Φ is defined with respect to the toroidal location of the iron core outer leg, also illustrated in Fig. C.1. Figure C.2 displays a typical plot. Notice that the maximum count rate is approximately seven times the minimum count rate and approximately twice the toroidally averaged count rate.

The toroidal variation of count rate arises from the variation of source-to-detector distance with Φ and also from the varying neutron attenuation between source and detector. The minimum count rate (for all detectors) occurs when one of the iron core legs lies between the source and detector. From the fact that these curves are fairly smooth, we deduce that scattering and absorption are primarily due to the vessel itself—and especially to the toroidal field coils—rather than to localized individual structures. Upon multiplying out the distance-squared factor, the effect of scattering and absorption may be seen, as illustrated in Fig. C.3. The magnitude of the scattering effect—as given by the ratio of maximum to minimum rate—is of the order of

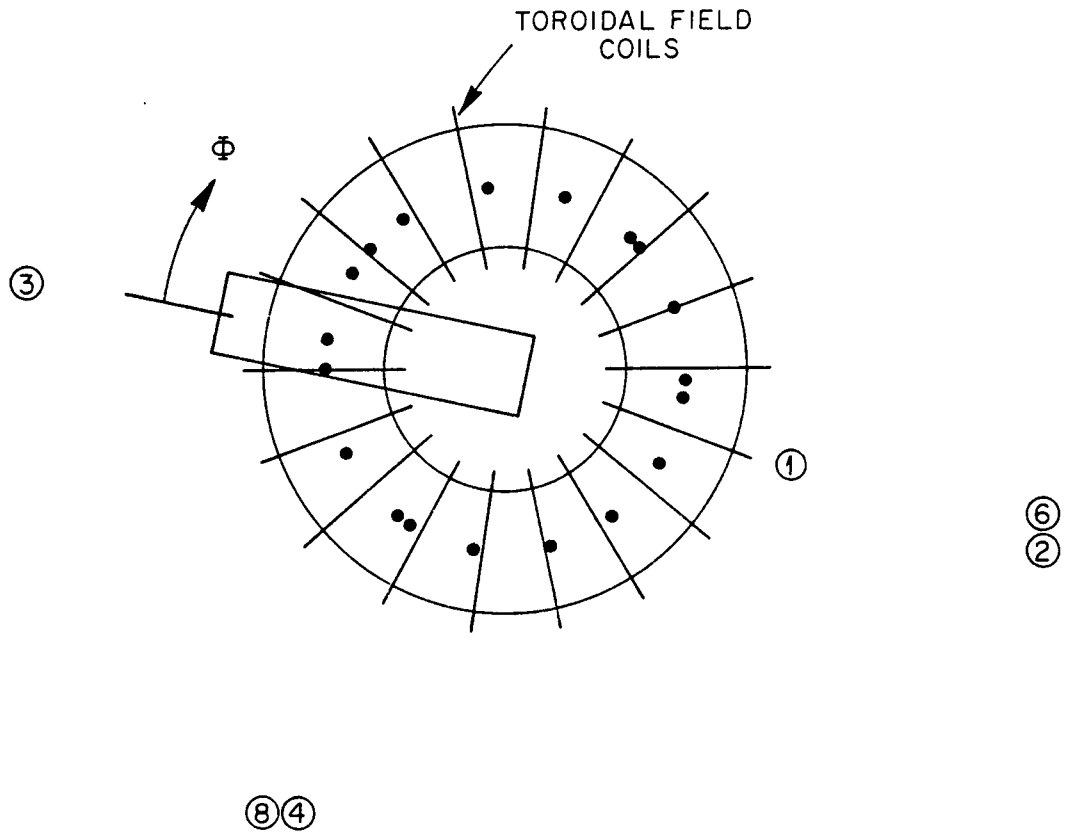


Fig. C.1. The 19 toroidal positions of the ^{252}Cf neutron source inside the tokamak vessel and the location of the six neutron detectors. Detector 1 was located on the floor; all the others were located on the walls. Also shown is the toroidal coordinate Φ .

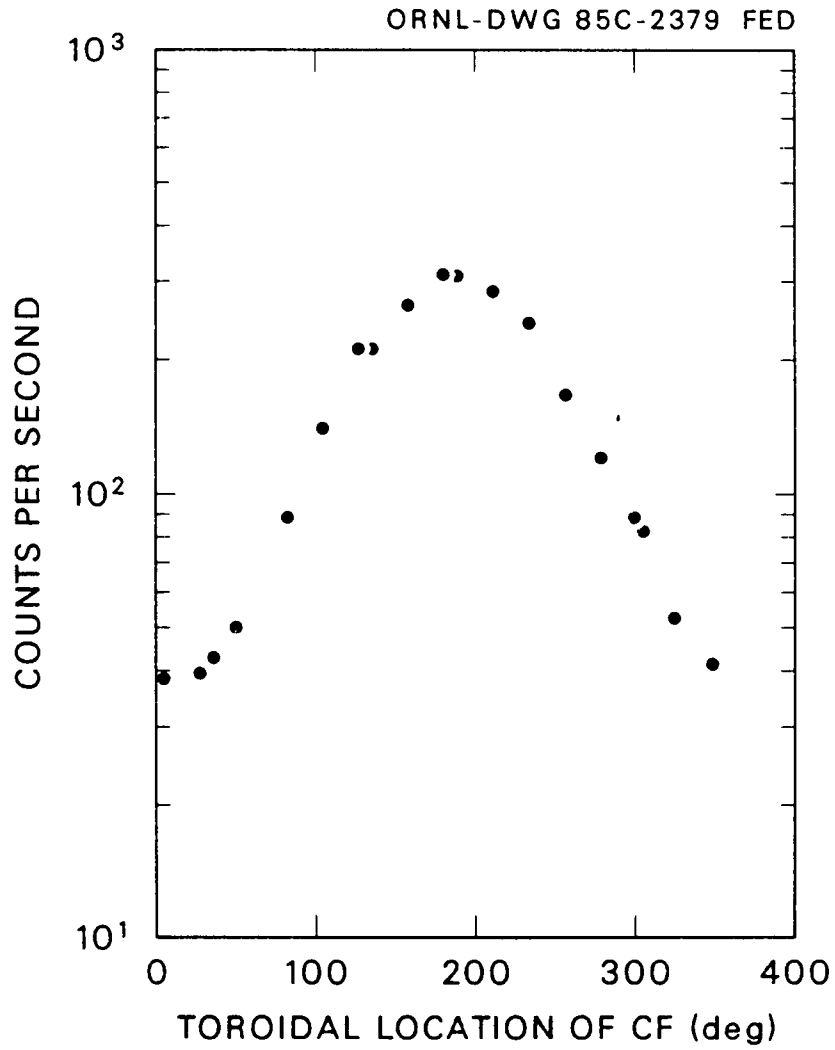


Fig. C.2. Typical variation of the neutron count rates as the ^{252}Cf neutron source was moved around the vessel. Plotted are data from detector 1.

ORNL-DWG 85C-2380 FED

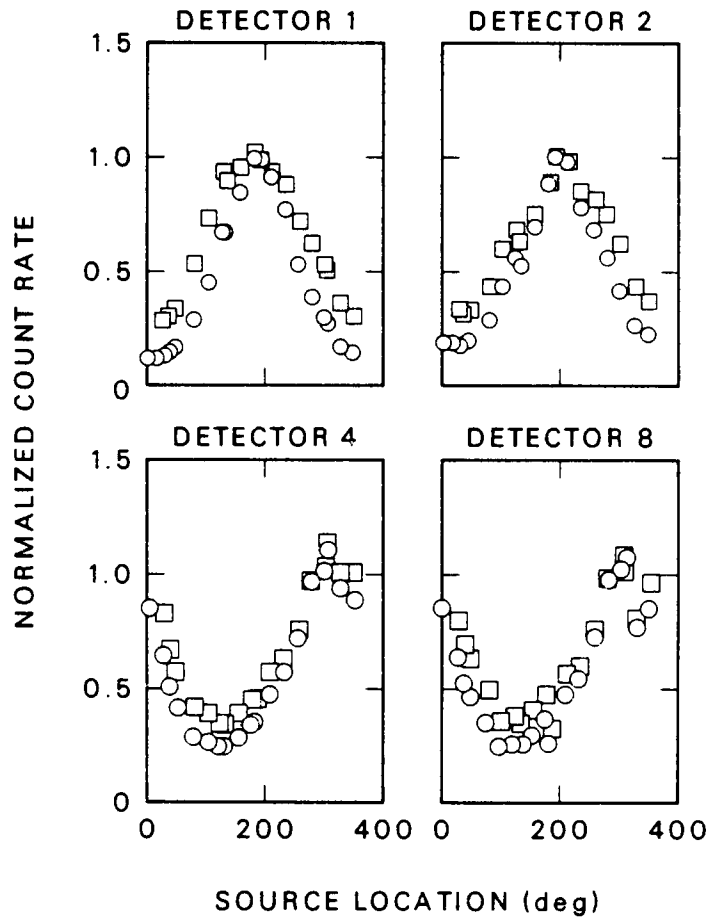


Fig. C.3. Effect of scattering and absorption on neutron count rates with the ^{252}Cf neutron source at different toroidal locations. Circles are raw count rates. Squares are count rates multiplied by the square of the distance between source and detectors.

three for all detectors. Notice that the normalized curves of detector No. 4 (^3He) and No. 8 (^{235}U) have the same toroidal variation. These detectors were positioned adjacent to one another.

4. Estimated Accuracy of Neutron-flux Data

Several additional experiments were performed to determine the sensitivity of the calibration factors to certain unavoidable approximations and errors in the calibration procedure. In addition, old ISX-B neutron flux measurements were reviewed to assess the overall reliability of the neutron detection system. The following topics were investigated:

1. source strength,
2. line source approximated by a discrete set of points,
3. volume source (plasma) approximated by a line source,
4. differences in neutron energy spectra,
5. discrimination against high energy photons,
6. new structures added around tokamak, and
7. fluctuations in detection efficiency and statistical spread.

The uncertainty in source strength was—as discussed previously—about 4%. Since the calculated rather than the measured value was used, the magnitude of the neutron emission from the plasma could be overestimated by that amount.

The calibration factor for each detector was taken to be the known source strength (neutron per second) divided by the average of the measured count

rates at the 19 discrete toroidal source locations. A more accurate line-integrated calibration could be performed by moving the source continuously through the vacuum vessel. The "discrete approximation" to the line integral would introduce a significant error only if the measured count rate fluctuates rapidly as the source is moved toroidally through the vacuum vessel. Such would be the case, for example, if a few strong neutron absorbers were constructed about the tokamak; then the count rate would decrease dramatically when an absorber lay between the source and the detector. But, in fact, the measured count rates varied quite smoothly with toroidal angle, as shown in Fig. C.3. Thus, it was concluded that the "discrete approximation" introduced only a negligible error in the calibration.

To investigate the uncertainty in approximating a volume source with a line source, a comparison was run of rate vs Φ with the source at $r = 0$ and displaced ~ 8 in. (outwardly and up) from $r = 0$. Twelve source positions were used for this comparison. The resulting plots for four detectors are shown in Fig. C.4. Although some particular points differ by as much as 40%, upon averaging toroidally the two curves differ by

- 8% for detector 1,
- +10% for detector 2,
- +2% for detector 4,
- +10% for detector 6, and
- 0% for detector 8.

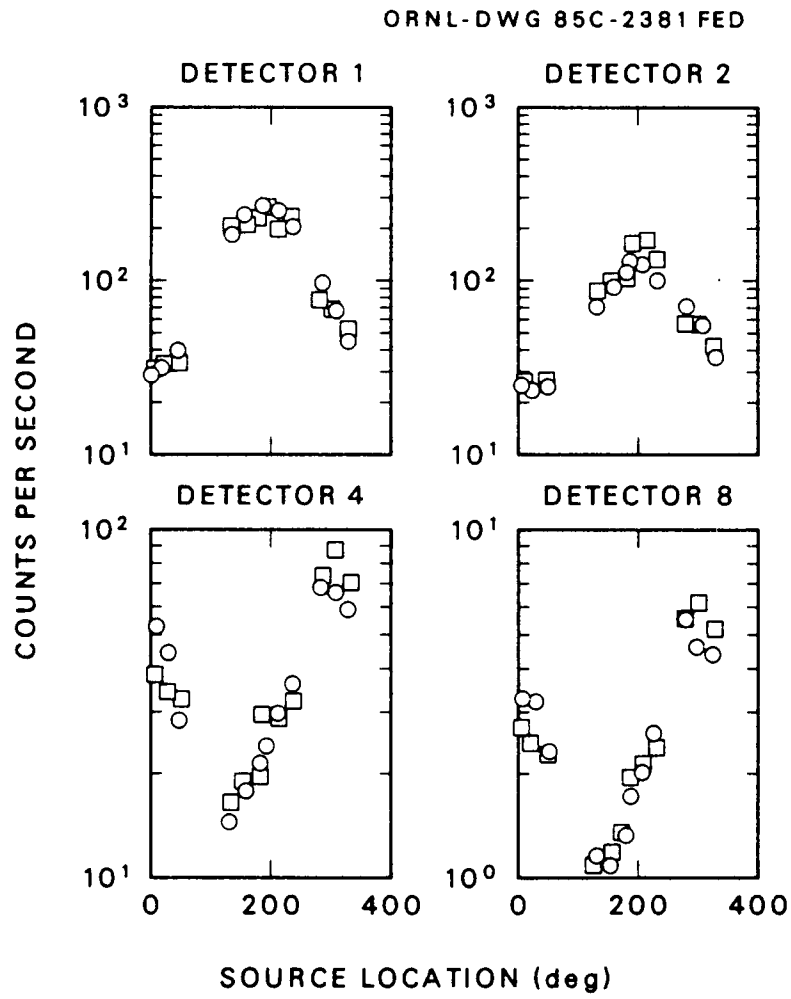


Fig. C.4. Effect of approximating a volume source (the plasma) with a line source on the calibration of the neutron detection system.

(The effect of increased or decreased source to detector distance is small and has been neglected; it would make the quoted errors slightly smaller.) Thus, it does not make a significant difference, on the average, whether a (line) neutron source is on the central circumference or on a circumference displaced by a distance of the order of the plasma radius. The result implies that only a small uncertainty was introduced in the calibration by approximating a volume source with a line source. This uncertainty was crudely estimated to be $\leq 10\%$.

Another potential uncertainty arises from the different energy spectra of the ^{252}Cf neutron source and the actual D-D fusion neutrons; both the intrinsic detection efficiency and the scattering/absorption of neutrons between source and detector depend on neutron energy. The neutron emission from the deuterium plasma is nearly monoenergetic at $E = 2.45$ MeV, whereas that from the ^{252}Cf has a somewhat broad spectrum (FWHM ~ 2.5 MeV), though it is peaked close to the D-D neutron energy. Figure C.5 shows the spectrum of the neutrons emitted from the ^{252}Cf and, also, the spectrum of the neutron output from $^{241}\text{Am-Be}$; the latter is broader and is peaked at higher energy (≈ 4 MeV, as opposed to 1.7 MeV for Cf).

A comparison was run using the Cf and the Am-Be sources: these were put, in turn, at nine different locations close to the tokamak. Some of the locations were chosen so that there would be no structures between source and detectors, thus minimizing scattering/absorption and allowing the study of the energy dependence of the detection efficiency alone. In other locations the effect of scattering/absorption was maximized by placing the source on the floor directly opposite to some of the detectors (placed on the walls), with the

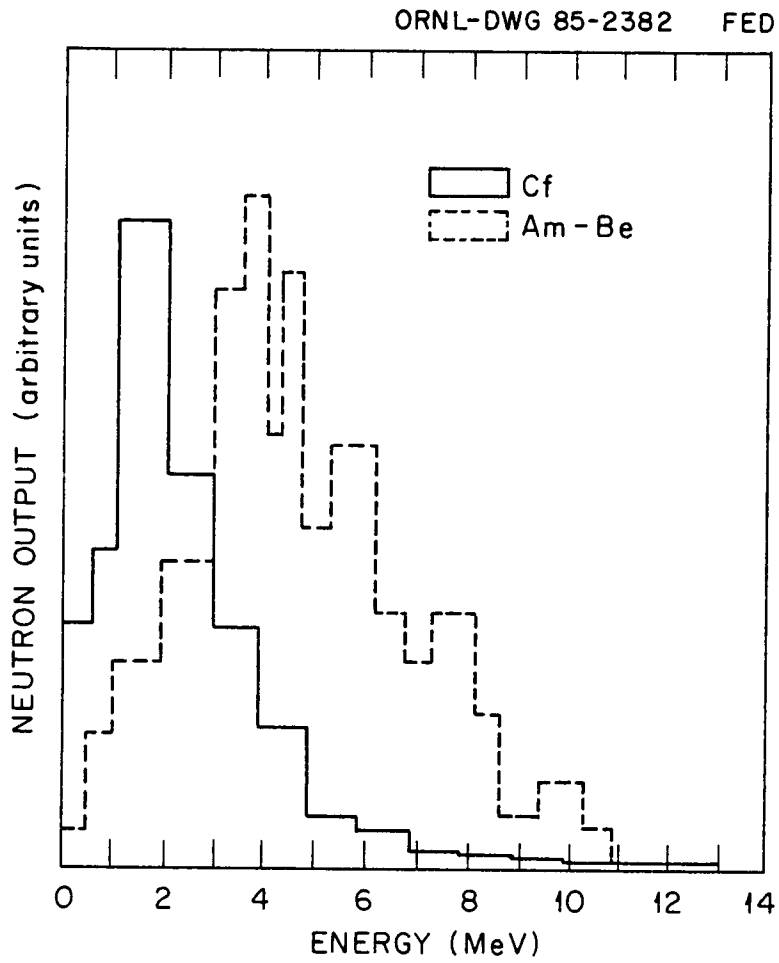


Fig. C.5. Energy spectra of the ^{252}Cf and $^{241}\text{Am-Be}$ neutron sources.

tokamak and other structures between them. Calibrated values of neutron outputs from the two sources yield a ratio of

$$\frac{\text{Cf}}{\text{Am-Be}} = 5.51 .$$

The experimental setup was such that detectors No. 2 and No. 4 would produce the most reliable data, which are shown in Table C.1.

Table C.1 Ratio of count rates, Cf/Am-Be

Detector (number)	Source at location of scattering	
	minimum	maximum
2	5.08	6.16
4	5.39	6.03

Notice that the energy dependence of detection efficiency seems to favor neutrons of higher energy, whereas the scattering from structures is favorable to those of lower energy, the two effects thus tending to cancel each other out. The average of all experimental data (nine locations, five detectors) was 6.06, with a 9% standard deviation; this value is 10% larger than the calibrated value of 5.51. Considering that the difference between Cf and fusion neutrons is less than the difference between Cf and Am-Be, a calibration uncertainty of $\sim 5\%$ due to the energy spectrum of the ^{252}Cf source was assessed.

To obtain a rough estimate for the discrimination of the ^3He detectors against high energy photons, a γ source (^{60}Co) was placed in front of one of

the detectors. The calculated flux of photons (of energy ~ 1 MeV) through the detector was $\sim 1 \times 10^6/\text{s}$. No signal above the background level was detected. Since the sensitivity of the measurement was $\sim 0.05/\text{s}$, it was concluded that the discrimination of the ^3He detectors against γ s is $> 2 \times 10^7$.

A crude, conservative estimate of the background count rates during plasma shots was obtained from hydrogen discharges, ohmic and neutral beam heated (H on H), for which the neutron production should be negligible. When the typical low hard-X-ray signal was present, the inferred "neutron" production was ohmic: $\sim 10^6/\text{s}$ and NBI: $\sim 10^7/\text{s}$. These values are a factor of about 100 less than the typical count rates with deuterium plasma; therefore, an overestimation of the neutron flux by $\sim 1\%$ is expected. (A significantly higher background rate is detected, though, in the presence of large X-ray signals generated in electron runaway discharges.)

The extent to which the calibration factors are affected by new structures added around the tokamak was also investigated. Figure C.6 shows a comparison of the data obtained during a calibration performed on October 10, 1981, and those obtained on August 24, 1982, after the south beam line was installed. A large effect related to absorption and scattering from the south beam line would have shown as a localized "bump" between the two curves for detector No. 8, which was located on the south wall. From Fig. C.6 it is evident that the localized effect is in no case larger than 20 to 30% (at $\Phi = 190$ to 240°) and is quite possibly less than that. Moreover, the toroidally averaged effect is $\leq 10\%$. A further indication that the new structure did not significantly change the calibration is seen in Fig. C.7, which shows the time history of the neutron

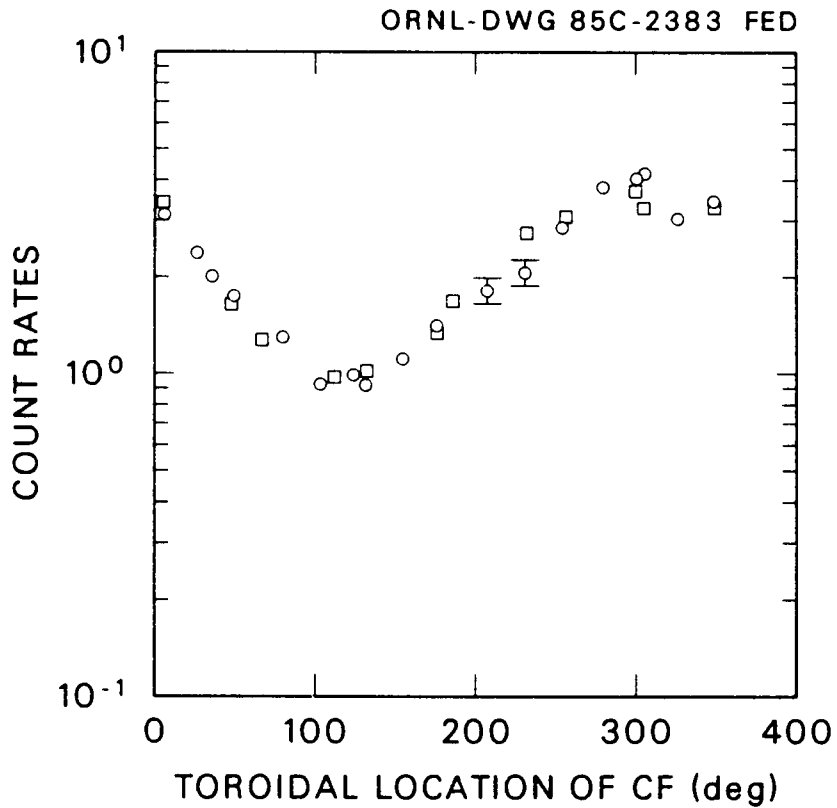


Fig. C.6. Effect of adding new structures around the tokamak on the calibration. Squares are neutron count rates for detector 8 during the calibration performed on 10/81, before installation of the south beam injector. Circles are the corresponding data on 8/82, after installation of the south beam injector.

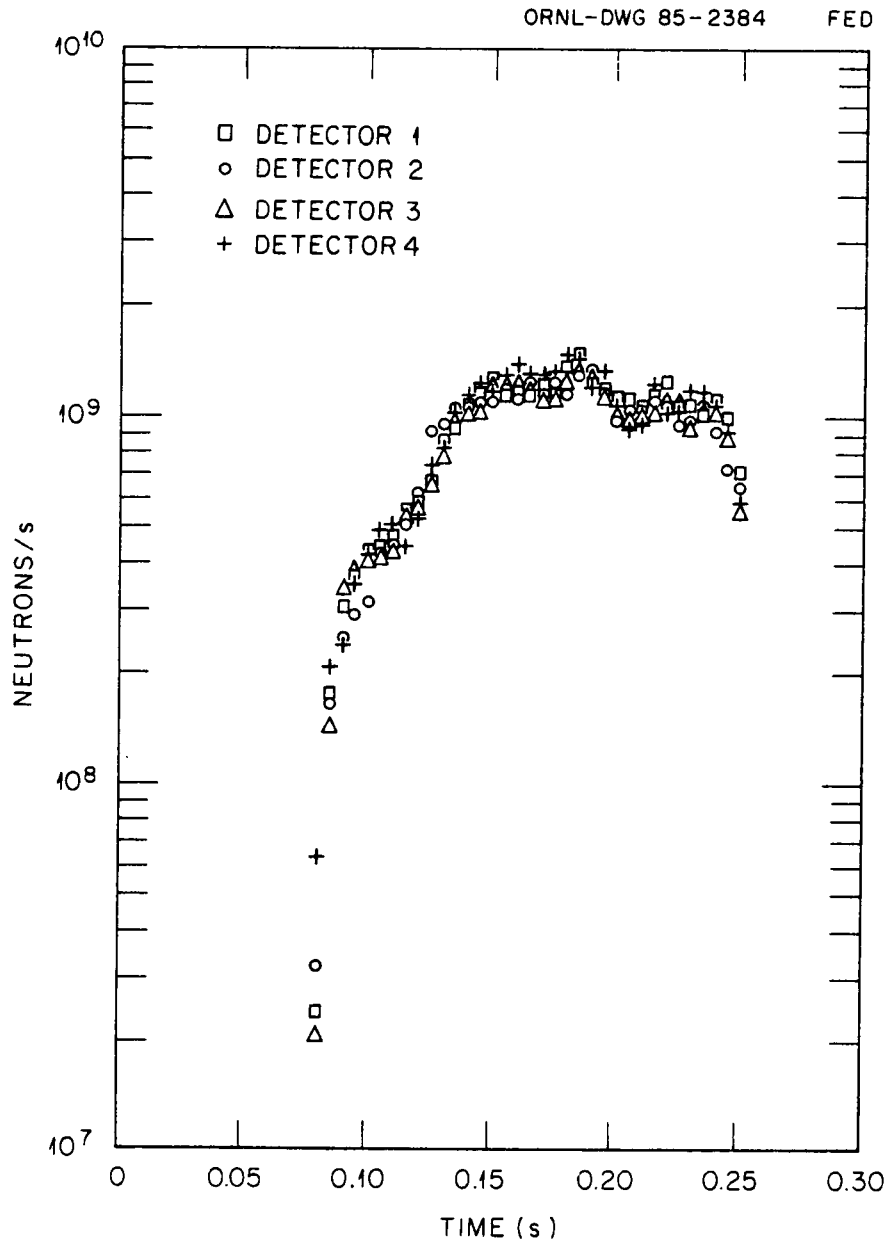


Fig. C.7. The calibration is not significantly altered by the addition of new structures around the tokamak. Data collected before installation of the south beam injector were analyzed with the calibration factors obtained after the installation of the large, localized structure. Good agreement among neutron detectors at different toroidal locations is still observed.

emission in a sequence run on October 11, 1981 but analyzed with the calibration factors obtained on August 24, 1982; the plots show good agreement among the detectors.

Uncertainties due to fluctuations in detection efficiency (e.g., due to faulty electronics) and statistical spread were finally considered. Figure C.8 shows how the ratio of the raw count rates (i.e., not multiplied by any calibration factor) of detectors No. 2 and No. 3 stayed the same—within a 9% standard deviation—over a period of 13 months. (Notice that this includes also the effect of added structures.) Similar plots showed that the detection efficiency of detector No. 4 was varying widely during the same 13-month period; detector No. 4 was, therefore, taken as less reliable during that period. Excluding detector No. 4, the calibration factors changed by an average of 12% from October 1981 to August 1982. Figures C.9 and C.10 display the time history of the neutron emission in sequence 073121 (NBI, 1% D^0) and sequence 073021 (2 beams, H^0), using the appropriate calibration factors of August 1982. The spread in inferred neutron production among the neutron detectors about the average is ~ 15 to 20%.

5. Summary

A recapitulation of the estimated uncertainties is presented in Table C.2.

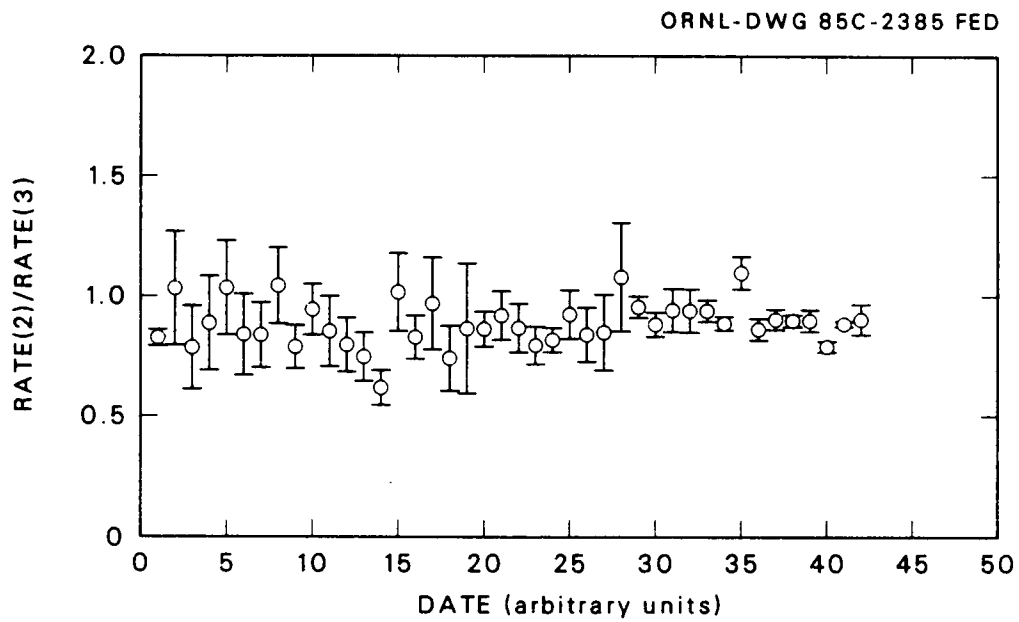


Fig. C.8. Ratios of raw count rates of two of the neutron detectors over a 13-month period.

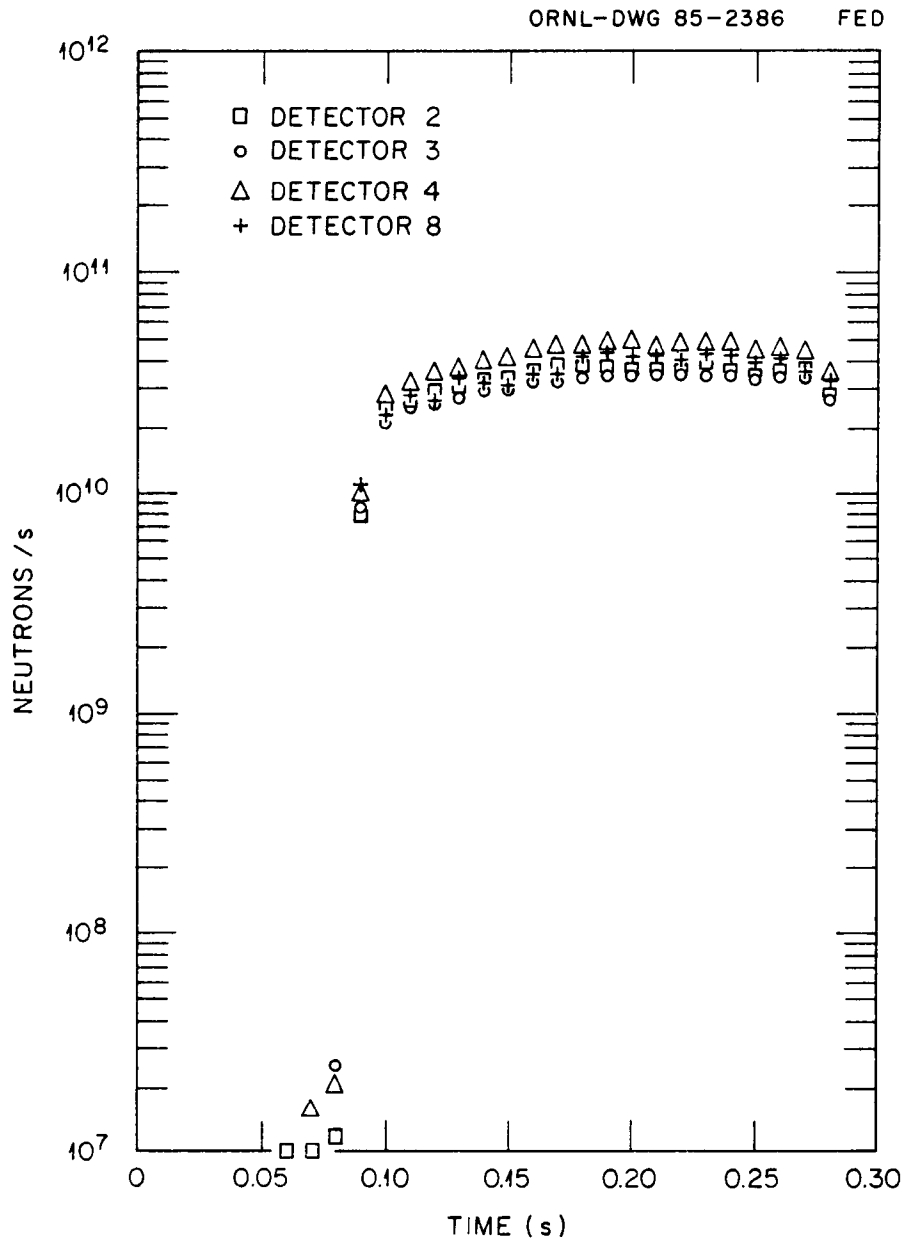


Fig. C.9. Time history of the neutron emission during 1% D^0 injection.

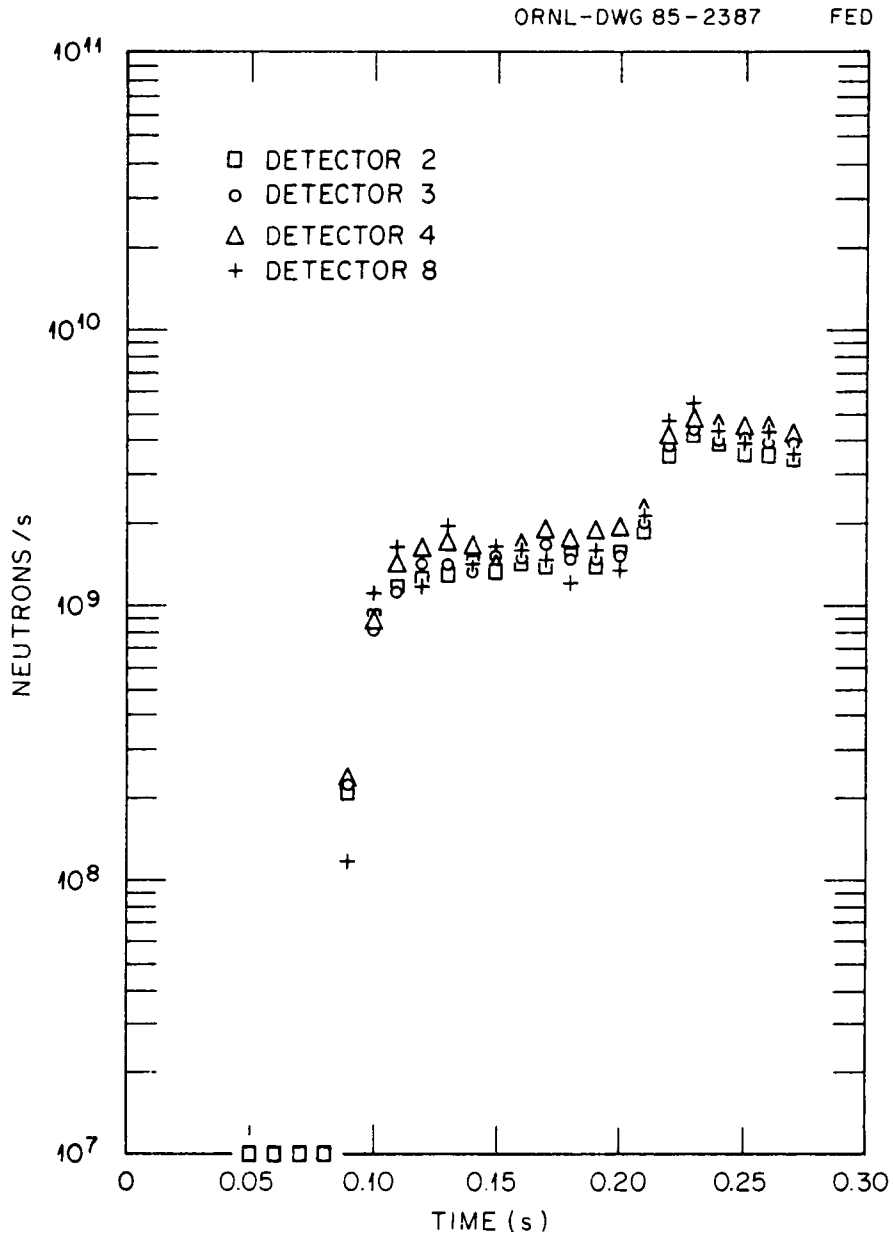


Fig. C.10. Time history of the neutron emission during a typical two-beam discharge.

**Table C.2 Estimated uncertainties in the calibration
of the neutron detection system**

Cause	Uncertainty (%)
Due to source strength	+4
Due to discrete locations	0
Due to line vs volume	± 10
Due to different energy spectra	± 5 (possibly, -5)
Due to X-ray background	+1
Due to new structures + fluctuations	± 12
Due to data spread	± 15

An averaged estimate of the global uncertainty is $\pm 25\%$.

VITA

The author was born in Rome, Italy, on May 11, 1951. There he attended the Liceo Classico, where he studied latin and greek literature and made his own Plautus's words—*homo sum, humani nihil a me alienum puto*. In 1975 he moved to New York City, where he graduated from Hunter College, CUNY, with a BA cum laude in physics. He received the Ph.D. in physics from The University of Tennessee at Knoxville in 1985. In September 1978 he was married to the lovely Lisandra Cosme of Toa Alta, PR.