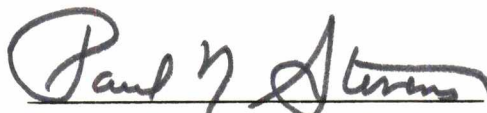


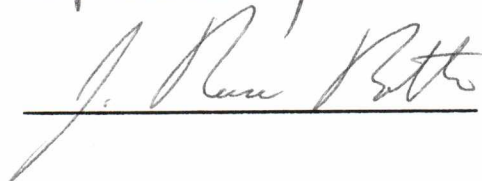
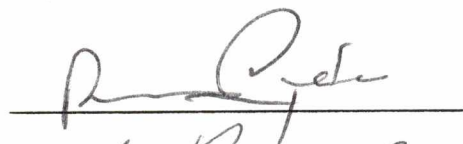
To the Graduate Council:

I am submitting herewith a dissertation written by Arthur Louis Qualls entitled "Pellet Fueling Experiments on the Advanced Toroidal Facility." 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 Nuclear Engineering.



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

**PELLET FUELING EXPERIMENTS ON
THE ADVANCED TOROIDAL FACILITY**

A Dissertation
Presented for the
Doctor of Philosophy
Degree
University of Tennessee, Knoxville

Arthur Louis Qualls

December 1991

Acknowledgments

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stability analyses for the measured profiles.

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Abstract

The experimental results of pellet injection into electron cyclotron resonance heated (ECH) stellarator plasmas on the Advanced Toroidal Facility are presented. The research focused on two main topics: (1) pellet ablation and pellet particle deposition, and (2) plasma thermal collapse and recovery induced by pellet injection.

The fueling efficiency of pellet injection, defined as the ratio of the number of atoms in the pellet before it enters the plasma to the number of electrons added to the plasma, was estimated to be 73%. The rate of D_{α} emission from the pellet ablation process was shown to be independent of the mass of the pellet, and the intensity of the emission coupled with the calculated position of the pellet in the plasma was not indicative of the measured particle deposition.

The injection of a properly sized pellet was shown to lead to a reproducible response in which the plasma stored energy collapses. As it recovers, the plasma density remains higher than the pre-pellet density and the central electron temperature increases. This is followed by a relaxation of the density back to the pre-pellet value. The relaxation of the density back to the pre-pellet value occurs in two stages. First, the density profile broadens and then the temperature profile broadens. The evolution of the pressure profile in the plasma is consistent with the hypothesis that the broadening of the density profile is due to unfavorable pressure gradients that occur in the plasma as the stored energy recovers. The actual loss of particles is due to the establishment of a new equilibrium between the particle confinement time and the amount of edge recycling that occurs as the temperature increases in the edge region of the plasma.

Table of Contents

I.	INTRODUCTION	1
	Pellet Ablation, Particle Deposition and D_α Emission	3
	Plasma Response to Pellet Injection	5
	System Description	6
	The Advanced Toroidal Facility	6
	The Pellet Injection System	21
II.	PARTICLE DEPOSITION AND D_α EMISSION	37
	Density Measurements as a Function of Pellet Mass	37
	Fueling Efficiency of Pellet Injection	41
	D_α Emission Studies	43
	Measurement of D_α Emission	44
	Comparison of D_α Emission to Pellet Mass	45
	D_α Emission as an Indication of Particle Deposition	48
	Description of the D_α Emission Traces	49
	Dependence of D_α Emission on Pellet Size	52
	Dependence of D_α on Target Plasma Density	53
	Emission Beyond the Magnetic Axis of the Plasma	58
	Effect of Magnetic Configuration on D_α Emission	62
	Effect of Heating Power on D_α Emission	67
	Summary	68

III. PLASMA RESPONSE TO PELLETT INJECTION	73
Response of the Plasmas to Pellet Injection	73
Energy Confinement After Pellet Injection	80
The Pellet-Induced Collapse and Recovery	88
Reproducibility of the Pellet-Induced Collapse and Recovery . .	91
Timing of the Density Relaxation	92
Effect of Gas Fueling on the Response to Pellet Injection	95
Multiple Pellet Injection Experiments	95
Effect of Altering the Magnetic Configuration	100
Summary	102
IV. DISCUSSION OF THE COLLAPSE AND RECOVERY	104
Onset of the Thermal Collapse	104
Recovery of the Stored Energy	111
Density Relaxation	113
ECE in the Edge Region of the Plasma	114
Magnetic Fluctuation Measurements	117
Pressure Gradient Stability Analysis	119
Summary	130
V. SUMMARY AND CONCLUSIONS	132
Summary of D_{α} Emission Experiments	132
Summary of the Plasma Response to Pellet Injection	134
REFERENCES	137
VITA	141

List of Figures

1.1	Schematic showing the magnetic coils on the ATF.	8
1.2	Cross section of the theoretical flux surfaces corresponding to $\rho = .1, .2, \dots, 1$ for ATF plasmas in the standard configuration at $\phi \approx 11^\circ$. The solid line represents the approximate path of the pellets in the plasma.	9
1.3	Theoretical flux surfaces at the $\phi = 11^\circ$ location for ATF plasma with $f_m = -.13$. The solid line represents the approximate path of the pellets in the plasma.	10
1.4	Theoretical flux surfaces at the $\phi = 11^\circ$ location for ATF plasma with $f_m = +.13$. The solid line represents the approximate path of the pellets in the plasma.	11
1.5	Schematic showing the major components of the Advanced Toroidal Facility.	15
1.6	Path of the 2-mm interferometer in a ATF Plasma with the standard configuration.	16
1.7	Possible chordal measurements available from the FIR interferometer.	17
1.8	Electron density profile for shot 12935, based on the inversion of FIR interferometer data. The peakedness of the electron density profile typically increases after pellet injection.	18
1.9	The diagnostic waveforms of a typical ECH heated, 1-Tesla, ATF discharge with a pellet injected at $t \approx .257$ (shot 16539).	22

1.10	Schematic showing the main components of the ATF pellet injection system.	23
1.11	Schematic of the gun component of the ATF pellet injection system.	25
1.12	Schematic of a gun barrel of the ATF pellet injector.	26
1.13	Assembly drawing showing the spool piece, a barrel isolation valve, and a flexible bellows of the ATF pellet injection system.	28
1.14	Schematic showing the first and second stage of guide tubes intersecting the microwave mass detector.	32
1.15	Output of the MWMD system as a typical pellet passes through the cavity.	34
1.16	Plot of the vessel pressure rise due to pellet injection versus the change in the microwave mass detector system output.	35
2.1	The expected change in a line-integrated density measurement passing through the center of a circular cross section, toroidal plasma with $a = 27$ cm and $R = 210$ cm, as a function of pellet penetration for a pellet containing 2.66×10^{19} atoms.	38
2.2	Change in the 2-mm $\bar{n}_e \ell$ at the time of injection versus the measured number of atoms in the pellet.	39
2.3	Change in the output of the 2-mm interferometer at the time of pellet injection plotted against the change in the output of a central channel of the FIR interferometer.	41
2.4	The output of a central channel and an edge channel of the FIR interferometer for a typical shot with pellet injection.	42
2.5	Change in the output of an edge channel of the FIR interferometer at the time of injection versus the number of atoms in the pellet. .	43

2.6	Estimated number of particles added to the plasma at the time of injection versus the measured number of atoms in the pellet.	44
2.7	The detected D_α emission as a function of pellet position in major radius for shot 16539.	46
2.8	The D_α emission as a function of pellet position in major radius that has been corrected to compensate for the decreasing distance from the pellet to the detector during the ablation process for shot 16539. The emission is assumed to be from a point source at the calculated pellet position.	47
2.9	Area under D_α trace (Volt-S) versus the number of atoms in the pellet for shots in a pellet mass scan.	48
2.10	D_α emission traces for shots 16544, 16548, 16537, 16538 and 16540. The emission of the smaller pellets are similar to those of larger pellets until the emission begins to reduce due to diminishing pellet size.	51
2.11	D_α trace for two pellets. The pellet injected in shot 16540 contained over twice the number of atoms as did the pellet injected in shot 16548.	54
2.12	D_α trace for shot 16539 plotted over the theoretical flux surfaces corresponding to $\rho = .1, .2, \dots, 1$ for ATF plasmas in the standard configuration at $\phi = 11^\circ$	55
2.13	D_α traces for pellets injected into plasmas with increasing densities. The peak in the emission that occurs as the pellet enters the plasma is observed to decrease with increasing target plasma density. . . .	57

2.14	D_α emission traces for pellets injected into two plasmas with the standard magnetic configuration. The plasma during shot 17939, had a higher pre-pellet density and a more optimal magnetic field strength for the absorption of the ECH power than it did during shot 16538.	59
2.15	D_α trace for shot 16538 plotted over the theoretical flux surfaces corresponding to $\rho = .1, .2, \dots, 1$ for ATF plasmas in the standard configuration at $\phi = 11^\circ$. The emission after the pellet crosses the magnetic axis of the plasma remains substantial.	61
2.16	D_α emission traces for pellets injected into plasmas with prolate magnetic configurations.	64
2.17	D_α trace for shot 18767 plotted over the theoretical flux surfaces corresponding to $\rho = .1, .2, \dots, 1$ for plasmas with the prolate magnetic configuration at $\phi = 11^\circ$	65
2.18	D_α emission traces for pellets injected into plasmas heated with gyrotron #1 and #2 (18771), heated with gyrotron #1 only (18798), and with gyrotron #2 only (18804).	69
2.19	D_α emission traces for pellets injected into plasmas heated with gyrotron #1 only (18811), with gyrotron #2 only (18839), and with both gyrotrons at a higher density (18771).	70
3.1	Diagnostic waveforms for shot 16543. The pellet entered the plasma at $t \approx .257$ s, and made only small perturbation in the plasma parameters.	75
3.2	Diagnostic waveforms for shot 16542.	76
3.3	Diagnostic waveforms for shot 16546.	78

3.4	Diagnostic waveforms for shot 16548. The stored energy increased due to the injection of the pellet.	79
3.5	Diagnostic waveforms for shot 16544. The stored energy increased at the time of injection, but eventually suffered a thermal collapse.	81
3.6	Diagnostic waveforms for shot 16549. A thermal collapse occurred almost immediately after pellet injection.	82
3.7	Diagnostic waveforms for shot 16553. The injection of the pellet caused a complete collapse of the plasma stored energy. The plasma did not recover from the collapse.	83
3.8	Diagnostic waveforms for shot 18849. The density increased due to an increased gas puff.	85
3.9	Diagnostic waveforms for shot 18770. The stored energy increased due to the injection of the pellet. The stored energy increased from approximately .7 kJ to 1.4 kJ.	86
3.10	Stored energy plotted against 2-mm $\bar{n}_e \ell$ for shots 18849 and 18770. There is a modest enhancement of the stored energy for the pellet fueled case.	87
3.11	Diagnostic waveforms for shot 12935. The four times of interest are indicated for shots that underwent a pellet-induced collapse and recovery.	90
3.12	The 2-mm $\bar{n}_e \ell$ at the times of interest for shots 12936 through 12944.	91
3.13	Plot of the 2-mm $\bar{n}_e \ell$ signals for a series of shots that underwent pellet-induced collapse and recovery. This demonstrates the reproducibility of the response. There is an offset between each shot of $10 \times 10^{14} \text{ cm}^{-2}$	92

3.14	Value of the 2-mm $\bar{n}_e \ell$ at the time of interest for shots with a large range of pellet sizes. The density just before the density relaxation is independent of the size of the pellet.	93
3.15	2-mm $\bar{n}_e \ell$ signals for several shots in a pellet mass scan. There is an offset between each shot of $10 \times 10^{14} \text{ cm}^{-2}$	94
3.16	Comparison of the values of the 2-mm $\bar{n}_e \ell$ at the times of interest for a series of shots with increased gas puffing after pellet injection, to those with reduced gas puff.	96
3.17	2-mm $\bar{n}_e \ell$ signals for a series of shots in which the second pellet arrived at various times during the recovery from the pellet induced-collapse of the first pellet. There is an offset between each shot of $10 \times 10^{14} \text{ cm}^{-2}$	97
3.18	D_α emission for shot 17951. The emission is typical of that observed for a 1-Tesla, ECH heated, ATF plasma.	98
3.19	D_α emission for a series of pellets that were injected at various stages of the pellet-induced collapse and recovery. The emission in the edge region of the plasma is higher for the pellets that were injected after the density began to return the pre-pellet value. . . .	99
3.20	Diagnostic waveforms for a shot that underwent pellet-induced collapse and recovery with an oblate magnetic configuration.	101
4.1	The electron density profile inferred from the FIR interferometer data for shot 16544. The density profile is slowly varying after pellet injection.	105
4.2	Output of ECH leakage detector, 2-mm $\bar{n}_e \ell$, and stored energy for shot 16546	107

4.3	Output of ECH leakage detector, 2-mm $\bar{n}_e \ell$, and stored energy for shot 16548	108
4.4	Output of ECH leakage detector, 2-mm $\bar{n}_e \ell$, and stored energy for shot 16544	109
4.5	Output of ECH leakage detector, 2-mm $\bar{n}_e \ell$, and stored energy for shot 16549	110
4.6	Electron density profile at the beginning of the recovery of the stored energy for three shots (16534, 16539, 16540) with reduced gas fueling during the pellet-induced collapse and recovery, and one shot with increased edge fueling (16550).	112
4.7	Temperature profile for shot 17902 at 1 ms intervals, just before and after the density relaxation, as inferred from the ECE diagnostic. .	115
4.8	Electron density profile at various times for shot 17902.	116
4.9	Fluctuation data taken from a Mirnov coil located at the plasma edge for shot 16550. The data has been filtered to show various bandwidths. The amplitude of the fluctuations returns to the pre-pellet levels as the density begins to return to the pre-pellet value. .	118
4.10	The electron density profiles just before the density relaxes for four shots with the standard configuration (shots 16534, 16539, 16540, and 16550).	122
4.11	Electron temperature profiles before the density relaxes for four shots with the standard configuration (shots 16534, 16539, 16540, and 16550).	123

4.12	Pressure profile at 10 ms intervals during the pellet-induced collapse and recovery for shot 17902 (standard magnetic configuration). The peakedness of the profile increases as the plasma stored energy recovers.	125
4.13	Electron pressure profiles before the density relaxes for shots with the standard magnetic configuration (shots 16534, 16539, 16540 (reduced gas puff) and shot 16550 (increased gas puff)).	126
4.14	Pressure profile just before the density relaxes for shot 17902 (standard magnetic configuration) and shot 19248 (oblate magnetic configuration).	128

CHAPTER I

INTRODUCTION

Research in magnetic confinement of plasmas for the production of fusion power has lead to the development of two predominant toroidal concepts: the tokamak and the stellarator. To date, large tokamaks have been able to create and sustain plasmas with higher temperatures and densities, however recent advances in the performance of stellarators coupled with their potential to operate in steady state, have made the stellarator an attractive confinement concept.

Gas fueling from the edge is the primary method of fueling all major magnetic confinement devices currently in operation. Pressurized gas is connected to a servo-control valve and released at the inside wall of the vacuum vessel. The valve can be pre-programmed to provide a desired flow rate or can be used in a feedback loop to maintain a set plasma density. This method has the advantage of being easy to implement and operate; however, it has the disadvantage of fueling the plasma from the edge.

In 1954, Spitzer et al. developed the figure eight stellarator concept.²⁸ In this conceptual design, a magnetic divertor was incorporated to remove ash and impurities. Spitzer reasoned that with edge fueling, it would be difficult to get new fuel far enough into the plasma so that most of it would make it past the magnetic fields of the divertor. Experiments have shown that edge fueling typically results in only about 20% of the particles actually being absorbed into the plasma. To get around this problem, he proposed the high-speed injection of frozen fuel pellets deep into the plasma core.

The development of devices that form and accelerate small pellets of frozen hydrogenic fuel was begun in the early 1970's and pellet injection experiments have been performed on many magnetic confinement experiments since the mid-1970's. The majority of experiments have been performed on tokamaks. The first pellet fueling experiments on a tokamak were done on the Oak Ridge Tokamak at Oak Ridge National Laboratory in 1976.⁹ Detailed reviews of the results of pellet fueling experiments into tokamaks have been published in the literature.^{20,14}

Gas fueling is still the primary method of fueling and there are many areas of pellet fueling that have not been fully addressed. Research is continuing to develop an understanding of the physics involved in the processes of pellet ablation, pellet particle deposition, and plasma response to pellet fueling.

Pellet injection experiments into ECH heated plasmas have been ongoing on the Advanced Toroidal Facility (ATF) since May 1989. The purpose of this dissertation is to describe these experiments and to assess their bearing on the important topics of pellet fueling of stellarator plasmas.

Pellet injection experiments have been carried out on two other stellarators: Wendelstein VII-A, and Heliotron-E. The ATF differs from these devices in several respects. The ATF has a smaller aspect ratio ($A = R/\bar{a} \approx 7$) than Wendelstein VII-A ($A \approx 10$) and Heliotron-E ($A \approx 11$), and a larger plasma volume (3.0 m³ compared to 1.6 to 1.7 m³). On Wendelstein VII-A, shearless configurations with low rotational transform and a magnetic well were studied.³⁰ On Heliotron-E a high-shear, high-transform configuration with a magnetic well is being studied.³¹ The ATF occupies an intermediate position.¹⁸

The main objective of the pellet injection experiments on Wendelstein VII-A and Heliotron-E was to increase the target plasma density for neutral beam injection, however pellet ablation studies were performed in ohmically heated, ECH heated, and neutral beam heated plasmas on Wendelstein VII-A.⁶ In ECH heated

plasmas, the electron temperature and density were comparable to those achieved on the ATF. Small pellets ($N_p \approx 8 \times 10^{18}$ atoms) penetrated approximately 10 cm, just to the plasma axis, and the resulting fueling efficiency was approximately 30%. The poor fueling efficiency was attributed to enhanced pellet ablation from non-thermal electrons in the edge region of the plasma.

Pellet injection experiments on Heliotron-E have attempted to optimize the plasma parameters obtainable with pellet injection by modulating neutral beam power at the time of injection. It was found that injecting pellets at a reduced level of NBI power and increasing the power afterwards lead to increased pellet penetration which provided improved plasma parameters than attained with injection into constant high NBI power²⁹.

Pellet Ablation, Particle Deposition and D α Emission

As the pellet passes through the plasma its surface is ablated, and neutral atoms from the pellet surface form a shield that attenuates the incoming plasma particles thereby extending the pellet's lifetime and its penetration into the plasma. The cloud surrounding a hydrogen pellet is a mixture of diatomic hydrogen, atomic hydrogen, protons, and electrons. Ionization of the atoms in the cloud from impact ionization by plasma electrons, and to a lesser extent by ions, is the method by which the pellet fuels the plasma. During the ablation process, a Balmer- α line corresponding to the transition between the upper quantum state $n=3$ and the lower state $n=2$ results from the de-excitation of a percentage of the hydrogenic isotopes. This photon emission is denoted H_α for hydrogen and D_α for deuterium.

It was demonstrated by Foster et al. ⁸ that the ratios of cross-sections for ionizing and photon emission events of hydrogen are approximately constant over

the energy range of electrons in plasmas of fusion interest, and it was suggested that the Balmer- α emission could be used as a measure of the rate of pellet ablation. Milora et al.²² experimentally determined that one H_α photon is emitted for approximately every 46 hydrogen atoms ionized.

The duration of the D_α emission coupled with the measured velocity of the pellet has been used to determine the penetration of the pellet into the plasma and the intensity of the emission has been used as an indication of the relative amount of pellet ablation as a function of pellet position in the plasma. The assumption was that the percentage of D_α photons emitted per atom ionized was a constant over the lifetime of the pellet, and as the ablated particles were ionized they become constrained to the flux surface closest to the point of ionization. Therefore, if the measured intensity of the emission could be determined as a function of pellet position in the plasma, it would provide an indication of the particle deposition due to pellet injection.

The validity of the duration of the D_α emission as an indication of the pellet penetration has been verified through work done on the JET Tokamak by L.R. Baylor.² However, less understood is the relationship among D_α emission, pellet ablation, and particle deposition. Thomas examined the expected change in line-integrated density measurements based on the relative intensity of the H_α emission during the ablation process on the ISX-B Tokamak¹³ and found that the observed change was in agreement within the experimental uncertainty of the diagnostics. These results were obtained with NBI, which produced deflections in the trajectories of the pellets, causing them to miss the center of the plasma by an estimated 6 cm.

It is difficult to obtain direct measurements of the properties of the pellet and the ablation cloud in the plasma. The D_α emission is the only readily available diagnostic information from the ablation process and it is therefore important to

understand the implications of the detected emission. The D_α emissions from pellets injected into a variety of ATF plasmas have been measured and analyzed. The characteristics of the emissions, the effect of changing plasma conditions on it, and how these observations relate to the issues of pellet ablation theory are addressed in chapter 2. Whether the total emission during the ablation process is indicative of the total number of particles ablated, and whether the relative intensity of the emission signal is an accurate indication of the actual particle deposition in the plasma during the ablation process are also addressed.

Plasma Response to Pellet Injection

ATF plasmas often experience thermal collapses in which the density remains constant, or even increases, as the temperature profile of the plasma narrows and eventually collapses. It has been discovered that the injection of a properly sized pellet will lead to a thermal collapse of the plasma. The pellet-induced collapse has been shown to be reproducible, which permits the thermal collapse to be studied systematically. After the thermal collapse, the plasma temperature and stored energy recover, and during the recovery the plasma undergoes a period of increased stored energy and density, which is followed by a rapid relaxation of the plasma density back to the pre-pellet value. This response has been observed for different fueling and heating schemes and for different magnetic configurations. The thermal collapse induced by pellet injection, the subsequent recovery of the plasma stored energy, and the resulting density relaxation have been studied, and the results of these experiments are presented in chapters 3 and 4. Summary and conclusions of this dissertation are presented in chapter 5.

System Description

The Advanced Toroidal Facility

The ATF is the largest stellarator currently in operation. A stellarator is a toroidal confinement device used to create and sustain plasmas of fusion interest. In a toroidal confinement device, toroidal and poloidal magnetic fields are required to confine the plasma. The superposition of the poloidal magnetic field and the toroidal magnetic field results in a helical magnetic field, in which field lines rotate about the minor axis of the plasma as they are followed about the major axis. The ATF is an $l=2$ torsatron type of stellarator. On the ATF, both the toroidal and poloidal magnetic fields are produced by currents flowing in the same direction in two sets of external helical coils. The field lines roughly follow the turning of the helical field coils, which produce 12, 30° field periods ($m=12$), for one complete toroidal rotation. The helical field coils are capable of producing a magnetic field strength of up to 2 Tesla.

The twisting of the field lines is called the rotational transform (ι), and due to it a field line will map out a surface as it is followed around the major axis. If the field line closes upon itself after a finite number of toroidal passes, it is said to map out a rational flux surface, otherwise it will map out an irrational flux surface. As a given magnetic line encircles the torus, it passes through alternating regions of favorable and unfavorable magnetic field line curvature. If the average curvature is favorable, the configuration is said to have a magnetic well.¹⁰ The ATF has a variable magnetic well depth of up to 7%.

The rotational transform of the ATF in the standard magnetic configuration varies from about .3 in the center to about .9 at the edge. The change in the direction of the magnetic field between flux surfaces due to the varying rotational transform is called magnetic shear, Θ , and is related to the rotational transform

by the following expression:

$$\Theta = r^2(d\epsilon/dr)/2\pi r_0. \quad (1.1)$$

Magnetic shear and the depth of the magnetic well play important roles in the stability properties of the plasma.

The shape of the helical field coils on the ATF allow for extensive access to the plasma for heating, fueling, and diagnostic devices. There are 24 upper and lower square ports (.35 m x .35 m), and a line passing through the origin of the major radius of the ATF and two corners of these ports is defined as the $\phi = 0^\circ$ location of a toroidal field period. There are 12 circular ports (.2-m diameter) located on the inside wall of the vacuum vessel, and 12 large, outer ports (.9 m x .6 m), both centered at $\phi = 15^\circ$.

In addition to the basic helical windings, there are three pairs of axisymmetric coils. These coils, the inner, outer and mid-vertical field coils (VF) allow control of the magnetic well, through the dipole moment, and the central rotational transform, through the quadrupole moment. Changes in these parameters can be expressed as linear combinations of currents in the inner, outer, and mid-VF coils. A schematic showing the major components of the ATF is shown in Figure 1.1.

The three main parameters that determine plasma characteristics for an ATF plasma are the magnetic geometry, the plasma heating, and the fueling scheme. For the pellet injection experiments the magnetic field strength was limited to 1 Tesla; however, pellets were injected into plasmas having three different magnetic configurations at this field strength. The heating source for these pellet injection experiments was electron cyclotron resonance heating (ECH). The fueling of the plasma before pellet injection is controlled by the gas fueling system and the amount of edge recycling from the vacuum vessel wall.

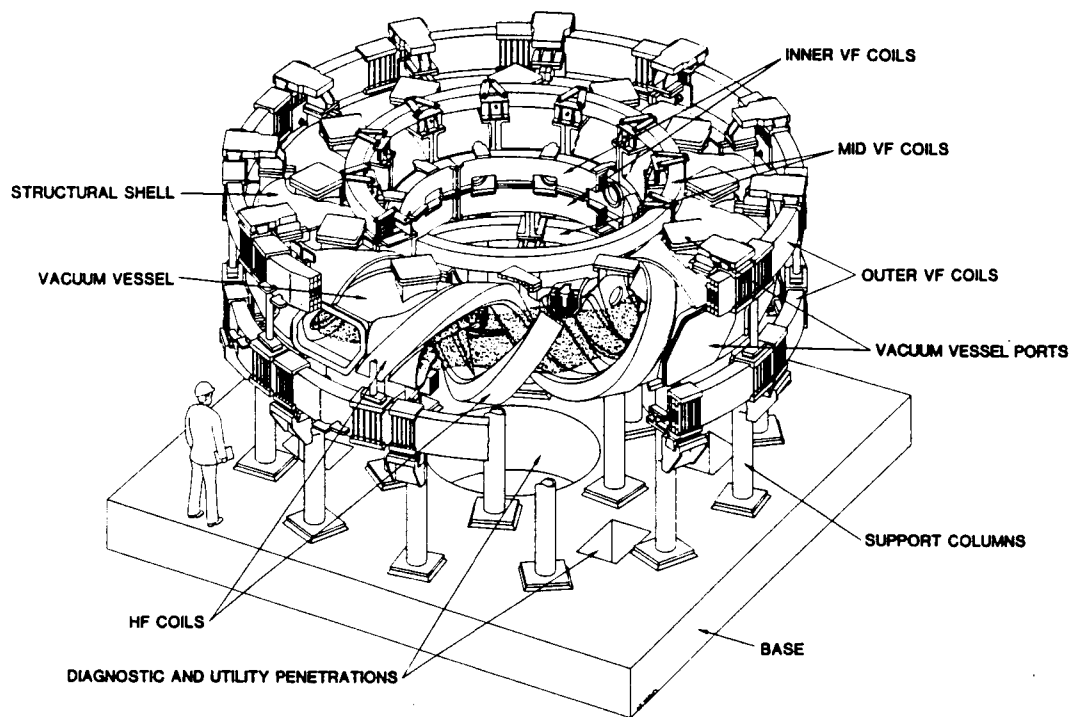


Figure 1.1: Schematic showing the magnetic coils on the ATF.

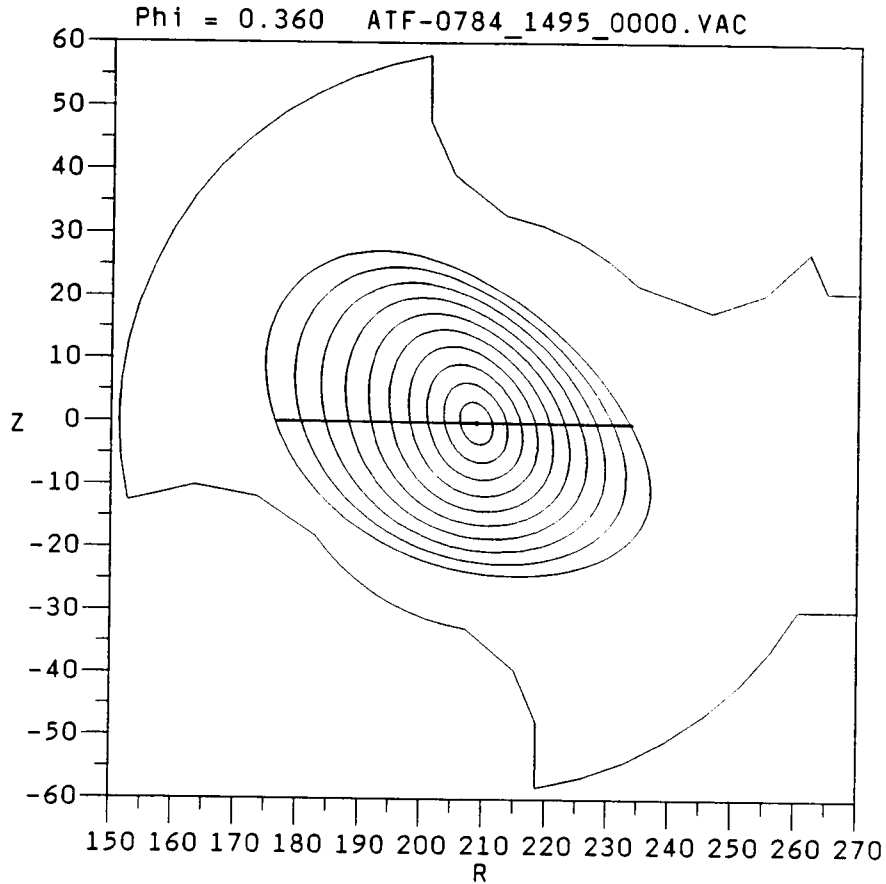


Figure 1.2: Cross section of the theoretical flux surfaces corresponding to $\rho = .1, .2, \dots, 1$ for ATF plasmas in the standard configuration at $\phi \approx 11^\circ$. The solid line represents the approximate path of the pellets in the plasma.

Magnetic Configuration Control on the ATF In its standard operating configuration, the ATF plasma has a major radius of 2.1 m, a minor radius of .3 m, and a total plasma volume of approximately 3 m³. Figure 1.2 shows the theoretical magnetic flux surfaces corresponding to $\rho = .1, .2, \dots, 1$, where ρ is the square-root of the normalized toroidal flux, at $\phi \approx 11^\circ$ for the standard magnetic configuration, which corresponds to the approximate location where the pellets enter the plasma.

By varying the currents in the VF coils, the dipole moment and the quadrupole moment of the magnetic configuration can be varied. In a dipole

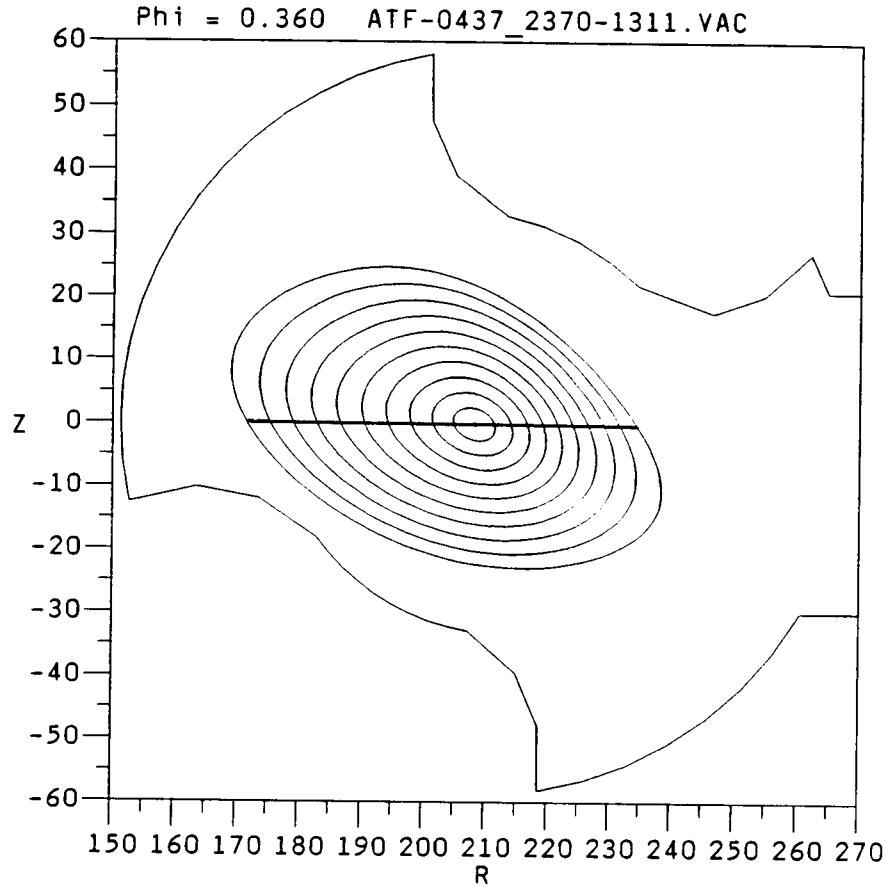


Figure 1.3: Theoretical flux surfaces at the $\phi = 11^\circ$ location for ATF plasma with $f_m = -.13$. The solid line represents the approximate path of the pellets in the plasma.

moment scan, the magnetic axis of the plasma is shifted in or out from its standard location. There were no pellet injection experiments in which the dipole moment was varied. In a quadrupole moment scan, the current of the mid-VF coil is changed while the magnetic axis position is fixed. The variation in the ratio of the ampere-turns in the mid-VF coil to the helical field coil, f_m , causes a change in the plasma shape from horizontally elongated or, oblate ($f_m < 0$), to vertically elongated, or prolate ($f_m > 0$).

Pellet injection experiments were performed at values of $f_m = 0$ and $\pm .13$. The flux surfaces at the $\phi \approx 11^\circ$ location for $f_m = \pm .13$ are shown in Figures 1.3

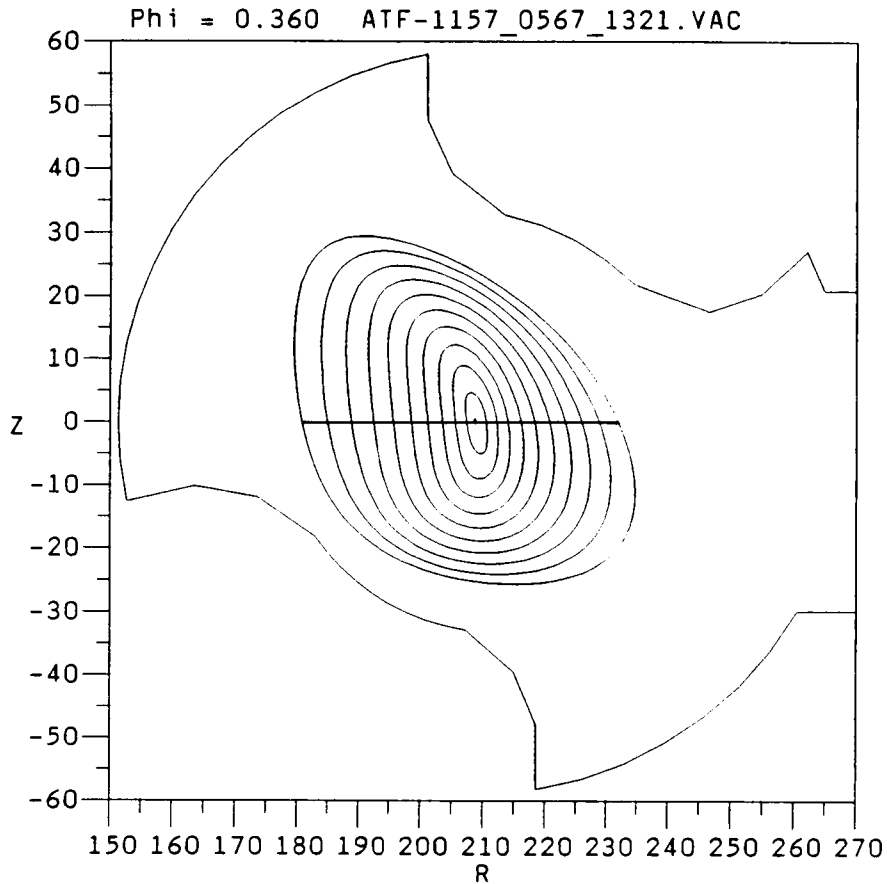


Figure 1.4: Theoretical flux surfaces at the $\phi = 11^\circ$ location for ATF plasma with $f_m = +.13$. The solid line represents the approximate path of the pellets in the plasma.

and 1.4.

ECH Heating Capabilities The ATF has two gyrotrons that can provide a total of 400 kW of electron cyclotron resonance heating.⁵ ECH power is absorbed by electrons with the same gyrofrequency as the power frequency, and is then transferred to the other electrons and the ions through scattering interactions. The transfer of energy to the ions is inefficient due to the large difference in the masses of the electron and the ions.

In each of these systems, microwave power is generated at 53.2 GHz. At

this frequency, the power can be used for pulsed operation in the ordinary mode at the fundamental resonance (1.9 Tesla) and for steady state operation in the extraordinary mode at the second-harmonic resonance (.95 Tesla). The cutoff density at the maximum field of 1.9 Tesla is limited to $n_e \lesssim 3 \times 10^{14} \text{ m}^{-3}$ and $n_e \lesssim 1.7 \times 10^{13} \text{ m}^{-3}$ for a field strength of .95 Tesla.

The two beams are launched into the plasma through top ports #10 and #12 of vacuum vessel. The port for gyrotron #2 is located approximately one and a half field periods from the point where the pellet enters the plasma, and the port for gyrotron #1 is displaced an additional field period beyond that. Plasma electron temperatures of about 1 KeV and ion temperatures of 0.2-0.3 KeV are typical for ATF operation with ECH as the only heat source.

Plasma Fueling Fueling of the ATF plasma can be described in terms of particle sources. The total fueling Φ_t is the sum of the fueling from the gas puff, Φ_{gp} , neutral beams, Φ_{nb} , those particles recycled from surfaces in the vacuum vessel, Φ_e , and by pellet injection, Φ_p ,

$$\Phi_t = \Phi_{gp} + \Phi_e + \Phi_{nb} + \Phi_p. \quad (1.2)$$

For the pellet injection experiments described in this work, there was no neutral beam operation. The primary method of controlling the plasma density is by gas fueling from the edge, which is commonly called gas puffing. The amount of fresh working gas injected at the edge of the plasma is controlled by a servo-control valve connected to a pressurized source. The flow rate of the gas can be pre-programmed or can be used in a feedback control loop to maintain a set density. Combinations of gas puffs from three independent systems are available.

An important feature of ATF operation is wall conditioning. Edge fueling due to the recycling of particles from the vessel wall is a significant factor in

determining the plasma density and impurity level. During the initial operation of the ATF, the plasma suffered from a collapse of the stored energy that was related to the cleanliness of the vacuum vessel wall. Baking and discharge cleaning were used to clean the walls, and allowed 1 Tesla discharges to remain stable for up to one second. However, baking and discharge cleaning were not adequate to prevent thermal collapse of neutral beam heated plasmas. In order to mitigate the collapse, the vacuum vessel was conditioned through a sequence of gas-discharge cleaning, baking, and gettering. Initial gettering cycles used two chromium getters to cover approximate 30% of the vessel wall. The number of getter balls was increased to 4 to provide approximately 60% coverage, and eventually, six titanium getters were used to cover approximately 80% of the interior surfaces of the vacuum vessel.⁷

Typically, the vessel is gettered every morning before operation. As shots are taken, the amount of recycling from the wall increases. To compensate for this, the amount of gas from the gas puff system must be reduced to provide consistent plasma density. Eventually the gas puff will have to be turned off, and density control below the density produced by edge recycling is not possible. If the edge fueling due to recycling becomes too large, the vessel can be gettered again.

Pellet Injector Location The pellet injector is mounted on the horizontal midplane of the plasma, at approximately 11° along a toroidal field period (30° is one complete field period) at an angle of 5° from perpendicular to a line tangent to the vessel at the location where the injection line and the vessel intersect. Pellets enter the plasma at $\phi \approx 11^\circ$, and if they completely penetrate the plasma, they will exit at $\phi \approx 15^\circ$. The trajectory of the pellet depends upon the barrel from which it was fired due to the convergence of the injection lines. However the point of convergence for the barrels is at the magnetic axis of the

plasma, and since most of the pellets injected penetrate to about this point, any displacement from the centerline of the injection line will be neglected. Most of the pellets were injected from barrel #3, which has a line of flight lying within the horizontal mid-plane of the plasma, and any displacement from this plane will be neglected in the determination of the pellet trajectory in the plasma. The major components for the heating, diagnosing, and fueling ATF plasmas are shown in Figure 1.5.

Plasma Diagnostics The plasma diagnostics that are most critical to pellet fueling experiments are the Far-Infrared (FIR) Interferometer, the 2-mm interferometer, the electron cyclotron emission (ECE) diagnostic, the Thomson scattering diagnostic, the Mirnov coils for measuring magnetic fluctuations, and the coils for measuring the stored energy of the plasma.

2-mm Interferometer and the Far Infrared Interferometer There are two interferometry systems that provide continuous line-integrated electron density measurements of the plasma throughout the discharge. In interferometry, the phase change experienced by a coherent microwave beam passing through the plasma is measured. The phase change is proportional to the line integral of the electron density along the chord.

The 2-mm interferometer operates at 140 GHz, and has a maximum operational density limit of $n_e \approx 2.4 \times 10^{14} \text{ cm}^{-3}$. The system can follow a maximum rate of change of line-integrated density of $\bar{n}_e \ell / dt \approx 1.0 \times 10^{15} \text{ cm}^{-2} / \text{ms}$. It views the plasma along the horizontal midplane at $\phi = 15^\circ$. The chordal path is represented by the solid line in Figure 1.6, which shows the theoretical flux surfaces for the ATF in the standard configuration at the $\phi = 15^\circ$ position. The assessment of the line-integrated density based on the measurement from the 2-mm inter-

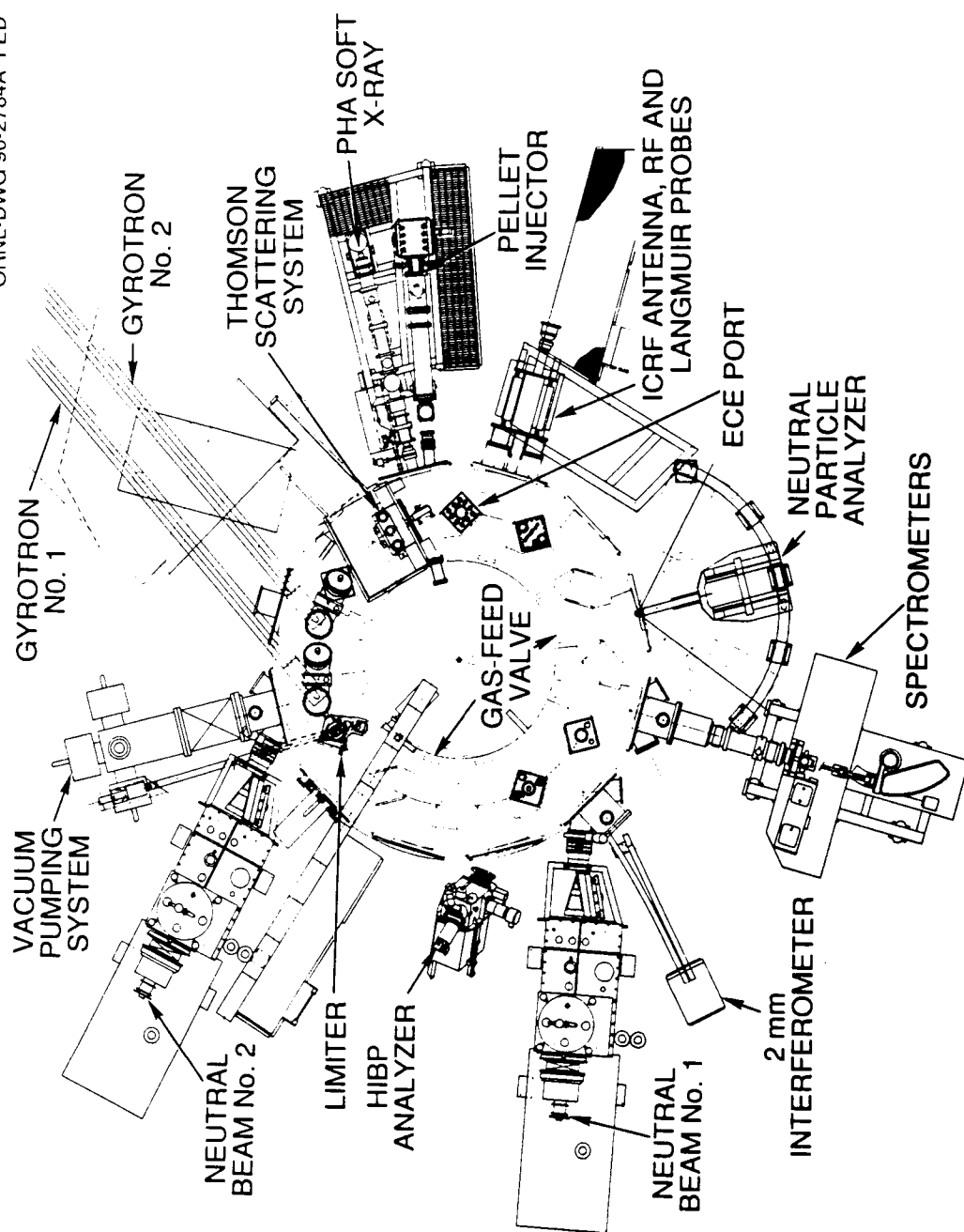


Figure 1.5: Schematic showing the major components of the Advanced Toroidal Facility.

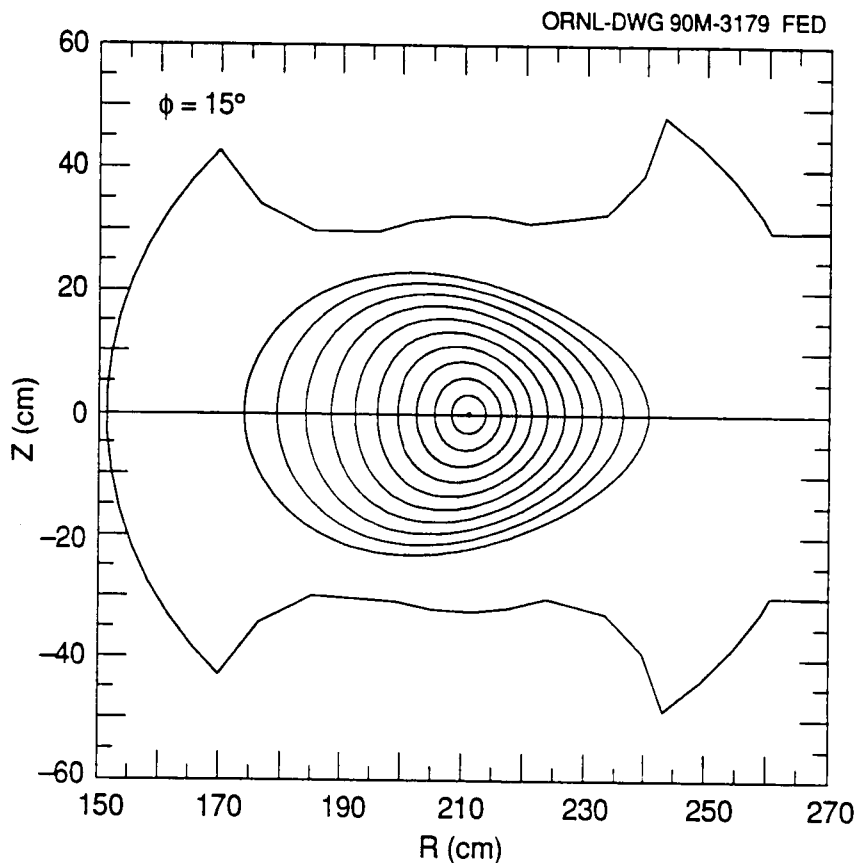


Figure 1.6: Path of the 2-mm interferometer in a ATF Plasma with the standard configuration.

ferometer must be adjusted for different chordal lengths whenever the magnetic geometry, and thus the shape of the plasma is altered. The chord length of the 2-mm interferometer for the plasmas in the standard configuration is 66 cm. For the oblate configuration ($f_m = -.13$) the chord length is 74.6 cm, and for the prolate configuration ($f_m = +.13$) the chord length is 57.2 cm.

The Far Infrared Interferometer is a 15 vertical chord system based on a pair of optically pumped difluoromethane lasers operating at a wavelength of $214 \mu\text{m}$.¹⁹ The chords pass vertically through the plasma at $\phi = 0^\circ$. The possible chordal measurements for this diagnostic are shown in Figure 1.7 along with the

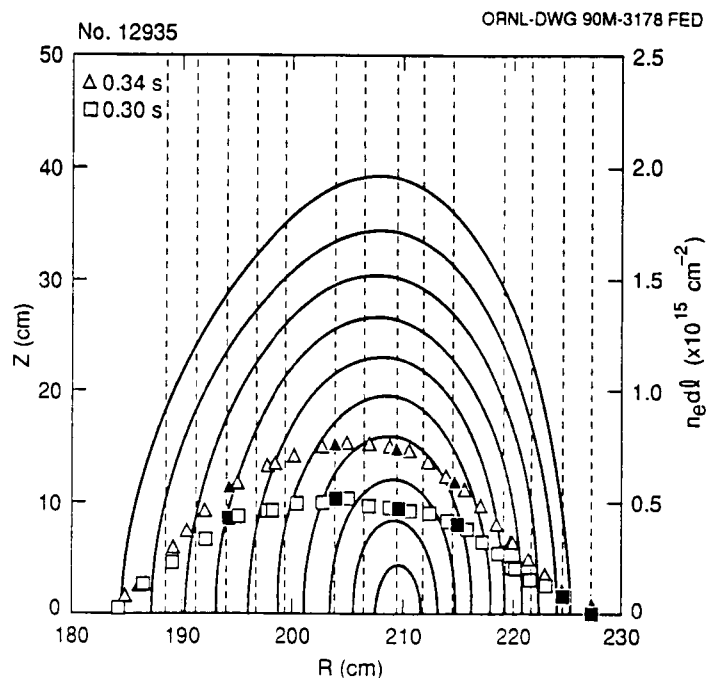


Figure 1.7: Possible chordal measurements available from the FIR interferometer.

flux surface geometry at the $\phi = 0^\circ$ location.

An inversion technique has been developed³ which provides a determination of the electron density profile throughout a shot from the line-integrated density measurements of the FIR interferometer. The electron density profile throughout a typical pellet fueled shot (12935) is shown in Figure 1.8.

Electron Cyclotron Emission As a result of the gyromotion of electrons about field lines of a confining magnetic field, electron cyclotron emission (ECE) occurs at the electron cyclotron frequency, ω_{ce} , and its harmonics, which is proportional to the strength of the magnetic field. On the ATF a superheterodyne, filter bank, microwave radiometer is used to detect ECE emission.⁴ The magnetic field strength is usually a monotonic function of radial position, therefore the fre-

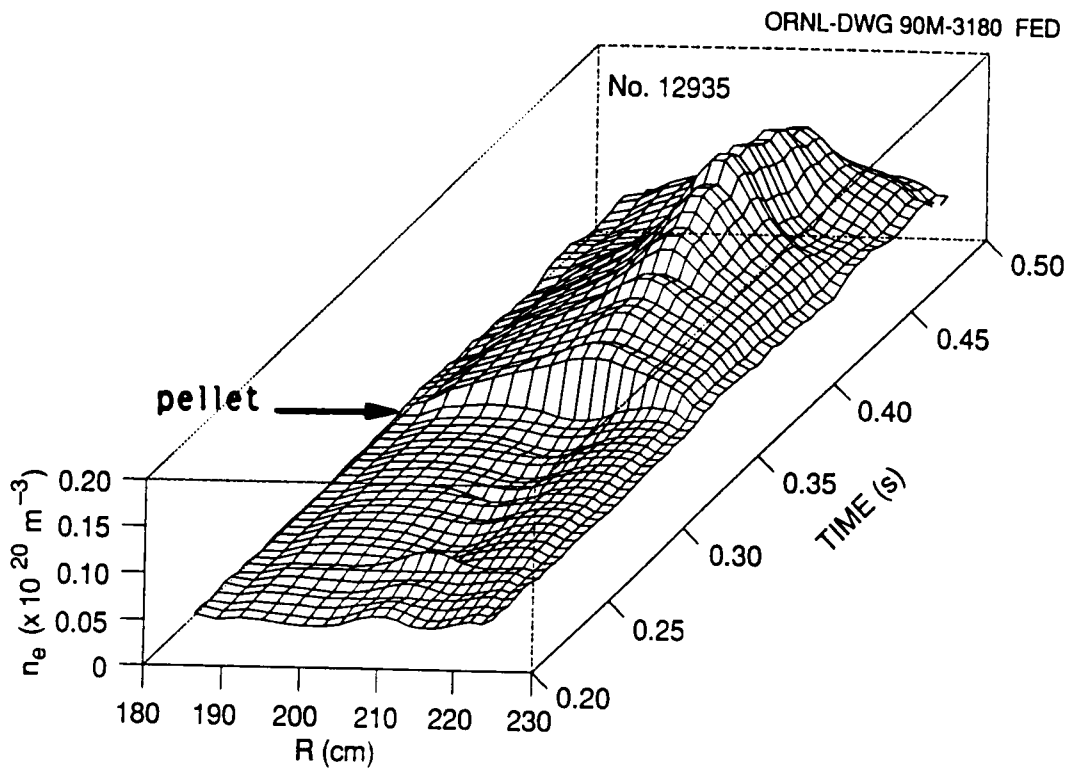


Figure 1.8: Electron density profile for shot 12935, based on the inversion of FIR interferometer data. The peakedness of the electron density profile typically increases after pellet injection.

quency of the emission, and the layer in which it is generated are uniquely related to each other.

In plasmas of fusion interest, measurement of the optically thick ordinary mode emission at the fundamental cyclotron frequency or the extraordinary mode emission at the second-harmonic can provide a direct determination of the electron temperature. However the cutoff densities are low for these frequencies and the third-harmonic emission is used to determine the electron temperature in 1-Tesla, ATF plasmas.

A small percentage of non-thermal electrons can produce emission levels that dominate the emission spectrum, making it difficult to correctly interpret the data. When a pellet is injected into the plasma, the energy of the non-thermal electrons are reduced by the ablation process, and this permits the evolution of the electron temperature profile to be accurately determined during the period of high density following pellet injection. The absolute error in the temperature determined by this method is on the order of 20%, due to uncertainty in absolute calibration. The error based on the signal to noise ratio of the diagnostic is small however and the difference in the temperature on a shot-to-shot basis is accurately depicted by the diagnostic.

Thomson Scattering A two-dimensional Thomson scattering system is used to measure electron temperature and density profiles at one time during an ATF shot.¹⁵ In this system, light from a 25-J ruby laser is passed vertically through the plasma at $\phi = 0^\circ$. Free electrons in the plasma are accelerated by the electric field of the laser beam. The acceleration of the charged particles causes them to emit radiation, which can then be detected as scattered light.

For the light source involved and the plasma conditions of the ATF, the scattering is dominated by individual electrons. The amount of scattered light is

indicative of the electron density and the width of the scattered spectrum, due to Doppler shift, is indicative of the electron temperature.

Stored Energy Measurement There are two systems used on the ATF to measure the plasma stored energy: the saddle loop and the diamagnetic loop. The value of the plasma stored energy as measured by the two systems are typically in good agreement, however the measurement associated with the saddle loop has less noise and the stored energy as measured by this diagnostic will be used throughout this work.

Mirnov Coils There are six Mirnov coils located within the vacuum vessel at various locations toroidally, either on the top or the bottom of the plasma, which are used to measure magnetic fluctuations at the edge region of the plasma. The amplitudes of these fluctuations are indicative of the level of plasma activity, and the coherence between the fluctuations is indicative of the type of instability.

Typical ATF operation During typical ATF operation the current in the helical field begins to ramp up at $t = -1$ s, which creates a population of free electrons in a working gas, usually hydrogen or deuterium. The plasma is formed by application of the ECH to the working gas in the vacuum vessel at $t=0$. The optimum pressure of the working gas for breakdown to occur is 5×10^{-5} torr. Under ECH heating, the plasma will attain quasi-steady state operation within about 100 ms. The End-of-Event (EOE) occurs when all the heating sources are turned off, after which the magnetic field is ramped down.

The typical diagnostic waveforms that will be used to describe the plasmas discussed throughout this dissertation are presented in Figure 1.9. The shot presented (shot 16539) is a typical shot with pellet injection. The top plot shows the

outputs of the 2-mm interferometer (solid line) in units of cm^{-2} , and the stored energy in units of kJ, as measured by the saddle loop (dashed line). The emission from a central channel of the ECE diagnostic (channel #12) is represented by the solid line in the second graph from the top, in units of volts. The dashed line in this graph represents the emission of an ECE channel that is viewing further out toward the edge of the plasma (channel #2), and its units are also volts. The power outputs of the two gyrotron systems in kW are shown in the third graph from the top. The output for gyrotron #1 is represented by the solid line and that for gyrotron #2 is represented by the dashed line. The solid line in the bottom graph represents the amount of gas fueling during the shot in torr-l/s from the gas injection system.

The Pellet Injection System

Pellet Injector The pellet injection system consists of the pellet injector and the pellet injection line. Figure 1.10 shows an assembly drawing of the pellet injection system relative to the ATF. The gun consists of five main components: (1) the vacuum box, (2) the two liquid-helium-cooled copper blocks, (3) the eight barrel assemblies, (4) the valves required to operate each barrel, and (5) the interface spool piece assembly. The gun component of the injector is shown in Figure 1.11.

The pellet injector is based on the pipe-gun concept, which produces hydrogen pellets or deuterium pellets by direct condensation in the barrels.²⁷ The vacuum box is fabricated from 1.9-cm-thick aluminum plates welded together into a frame to support the top, rear, right and left side plates, and the interface spool piece. The rear plate supports the feed gas and propellant valves required to operate each barrel. The top plate contains the feedthroughs required for the liquid helium to enter and exit the vacuum box. This liquid helium cools two copper

Shot #16539

1 Tesla

Standard Configuration

Gyrotron #1 & #2

Line-averaged density at time of injection: $3.9 \times 10^{12} \text{ cm}^{-3}$

Number of atoms in pellet: 3.8×10^{19}

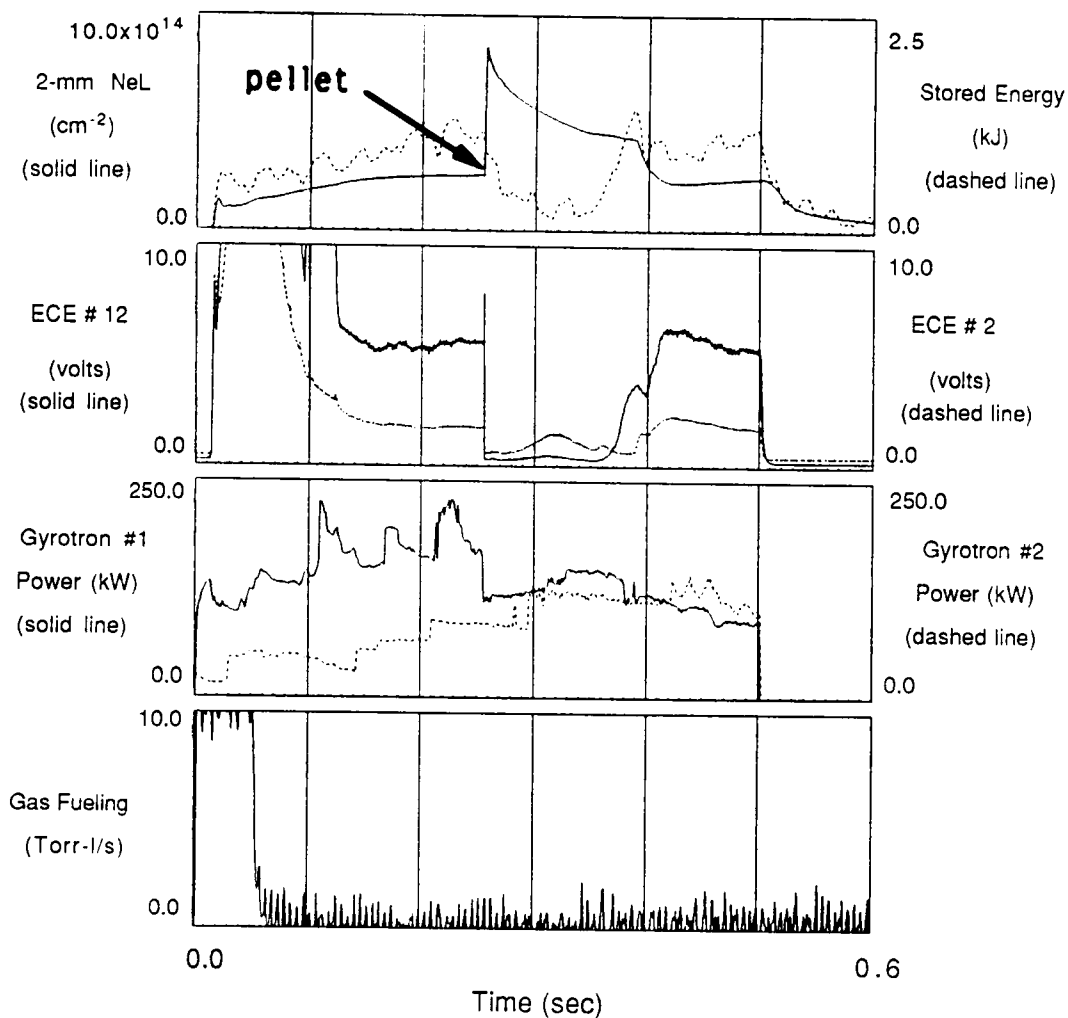


Figure 1.9: The diagnostic waveforms of a typical ECH heated, 1-Tesla, ATF discharge with a pellet injected at $t \approx .257$ (shot 16539).

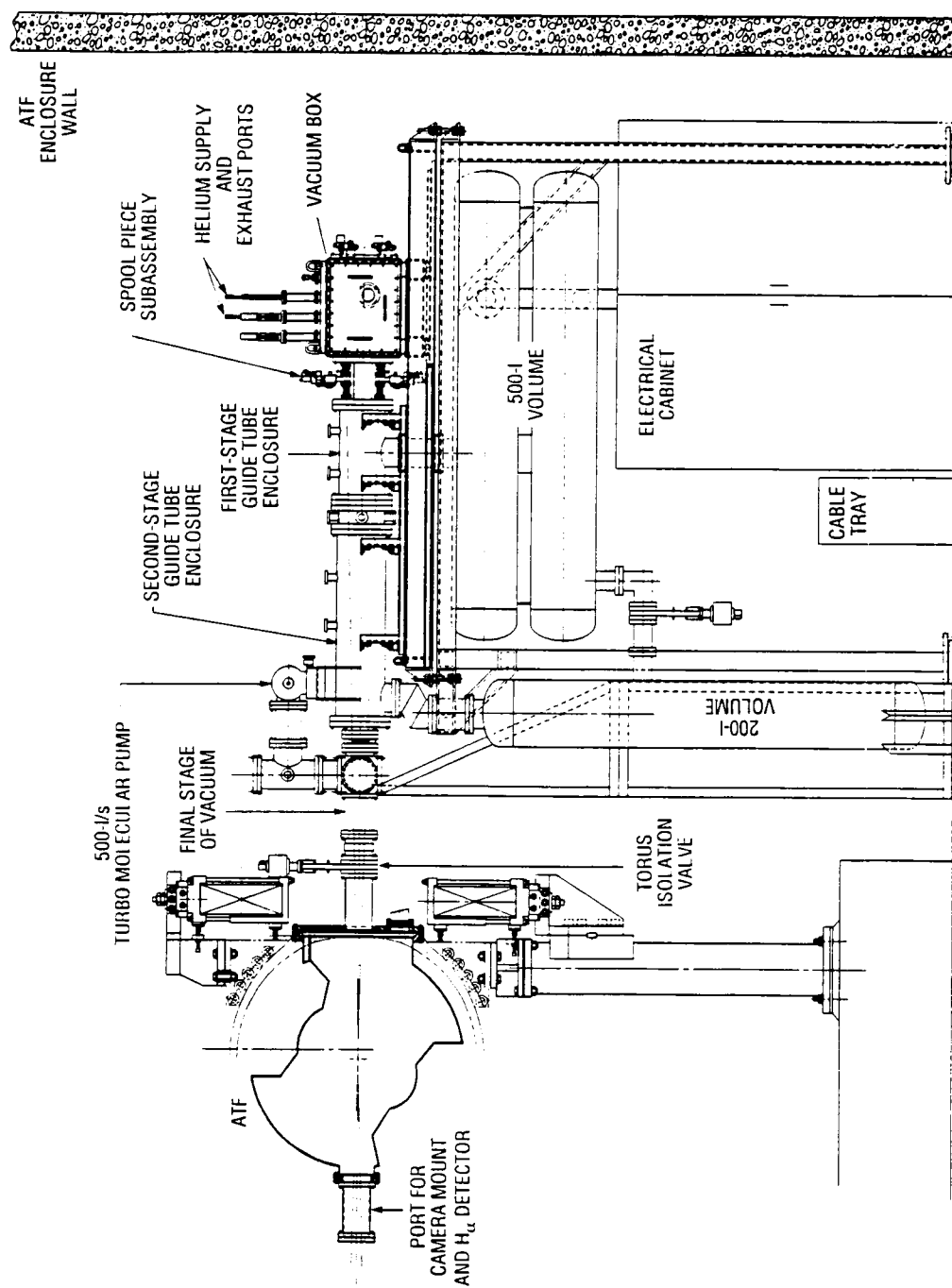


Figure 1.10: Schematic showing the main components of ATF pellet injection system.

blocks to the cryogenic temperatures required to form the pellets. The vacuum box is maintained at below 10^{-5} torr to provide thermal insulation for the copper blocks. The main and auxiliary copper blocks are fabricated from oxygen-free, high-conductivity copper with 4.82-mm-deep channels machined into each block.

The main block is maintained at 8°K for the production of hydrogen pellets and 9°K for deuterium. The auxiliary block is cooled by the exhaust from the main block and is typically operated in the range of 16° to 30°K. There are eight barrel assemblies mounted concentrically around the main cooling block.

The barrels are made of stainless steel tubing and have an overall length of 40.34 cm. Inside diameters of the barrel tubing on the injector are 0.79, 0.99, 1.09, 1.37, 1.57, and 1.80 mm. A VCR fitting is brazed to the breech end of the barrel to serve as a coupling to a fast propellant valve. A copper disk is silver-soldered 10.31 cm from the breech end of the barrel and is captured in a T-shaped bracket that is bolted to the main cooling block. Indium foil is used in the disk-to-bracket joint to provide good thermal contact. The disk cools the outside of a section of barrel, and hydrogen gas or deuterium gas in contact with this point inside the barrel condenses and forms a pellet. A warming collar is bracketed to copper sleeves on the barrel. The warming brackets are thermally linked to the auxiliary block by copper straps. This establishes a temperature gradient along the barrel that helps control the aspect ratio of the pellet. The muzzle end of the barrel is silver-soldered to an alignment collar which is captured in a photo-diagnostic piece that is part of the interface spool piece assembly. A gun barrel is shown in Figure 1.12.

The pellets are fired by the application of room temperature, high pressure hydrogen gas to the rear of the pellet. The pellet is sheared from the walls of the barrel and accelerated out the end of the barrel by the expanding propellant gas.

The focal point of the barrels is determined by the converging angle of

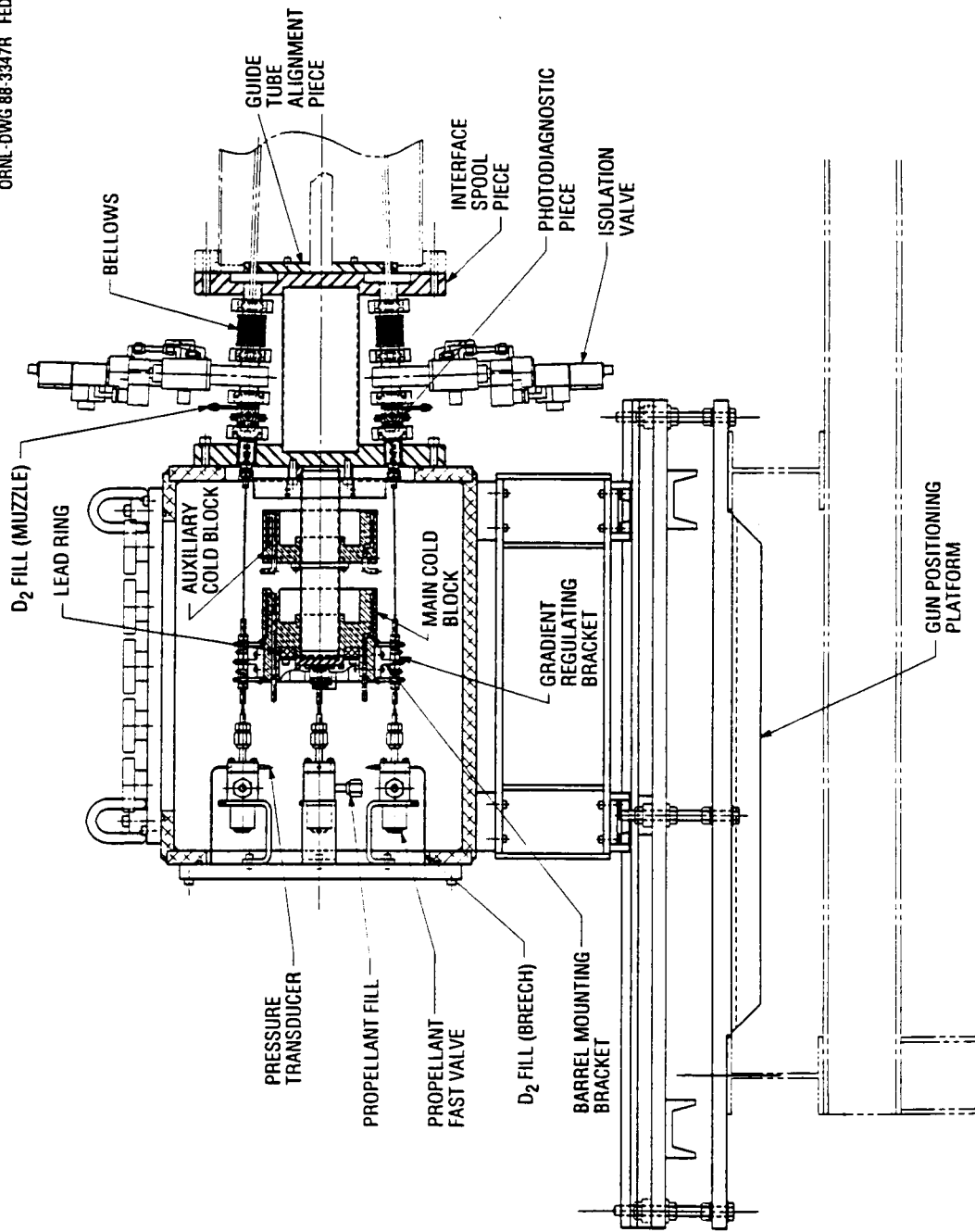


Figure 1.11: Schematic of the gun component of the ATF pellet injection system.

GUN BARREL ASSEMBLY

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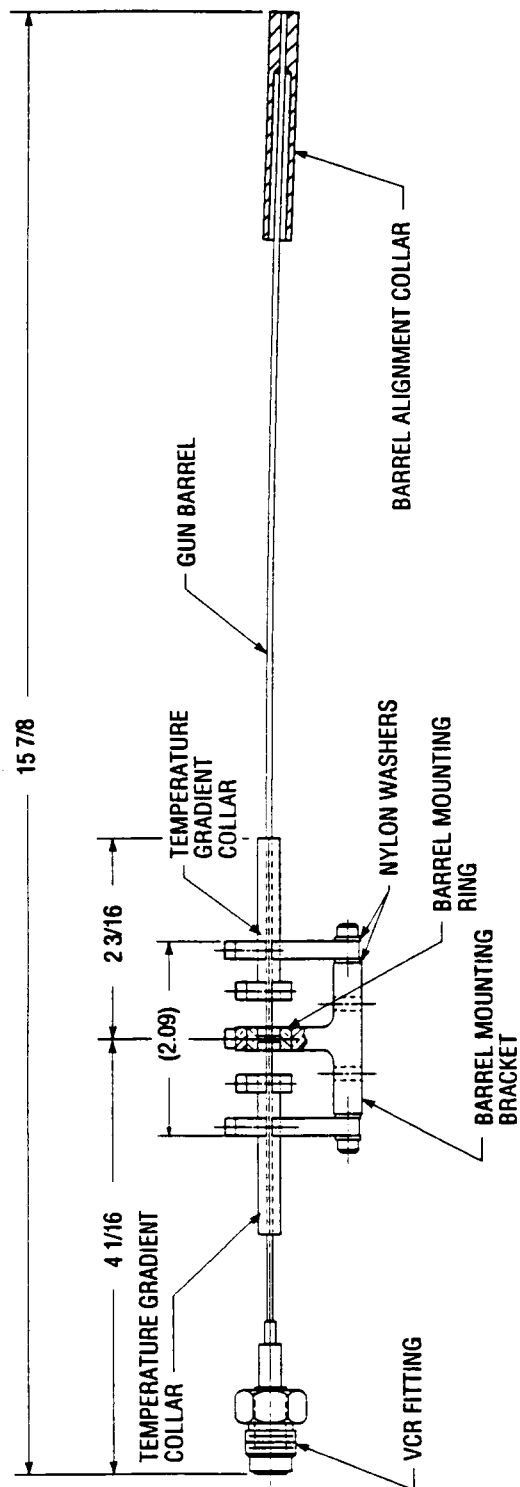


Figure 1.12: Schematic of a gun barrel of the ATF pellet injector.

the spool piece. Quick-Flange stubs are welded into precision holes machined in the upstream and downstream end plates of the spool piece. Mounted between the stubs are photo-diagnostic pieces, barrel isolation valves and flexible bellows, as shown in Figure 1.13. The isolation valves isolate the barrels from the vacuum system during a pellet formation sequence. The precision alignment of the stub flanges, together with the close tolerance fit of the photo-diagnostic piece and the isolation valve, results in the accurate pointing of the gun barrels. The focal point of the injector is 3.42 m from the downstream edge of the spool piece and is on the centerline of the ATF plasma.

Injection Line The pellet injection line consists of two guide tube stages, a 500-liter volume, a 200-liter volume, a final stage of vacuum, and the pumps used to maintain the vacuum conditions of the injection line.²⁵ Each guide tube stage consists of a vacuum enclosure and an array of eight converging guide tubes. The enclosure for the first stage of guide tubes is made of two 33.65-cm O.D. Conflat flanges welded to a section of 25.4-cm O.D. stainless steel tubing with a 0.42-mm wall thickness. The first stage guide tube enclosure is 50.8-cm long. The guide tubes in the first stage are 0.953-cm O.D. stainless steel tubes with 2.26-mm wall thickness. The tubes are held in place on the upstream side by the centering collars in the O-ring seal between the barrel isolation valve and the flexible bellows. Gas vent slots machined into the centering collars allow the propellant gas to pass into the guide tube assembly enclosure. The guide tubes are held in place by mounting brackets that are bolted over holes machined into the enclosure flange. The convergence angle of the guide tubes is the same as the convergence angle of the pellets as they exit the barrels.

As a pellet exits the first stage of guide tubes, it passes through a diagnostic station and enters the second stage of guide tubes. Outside diameters of

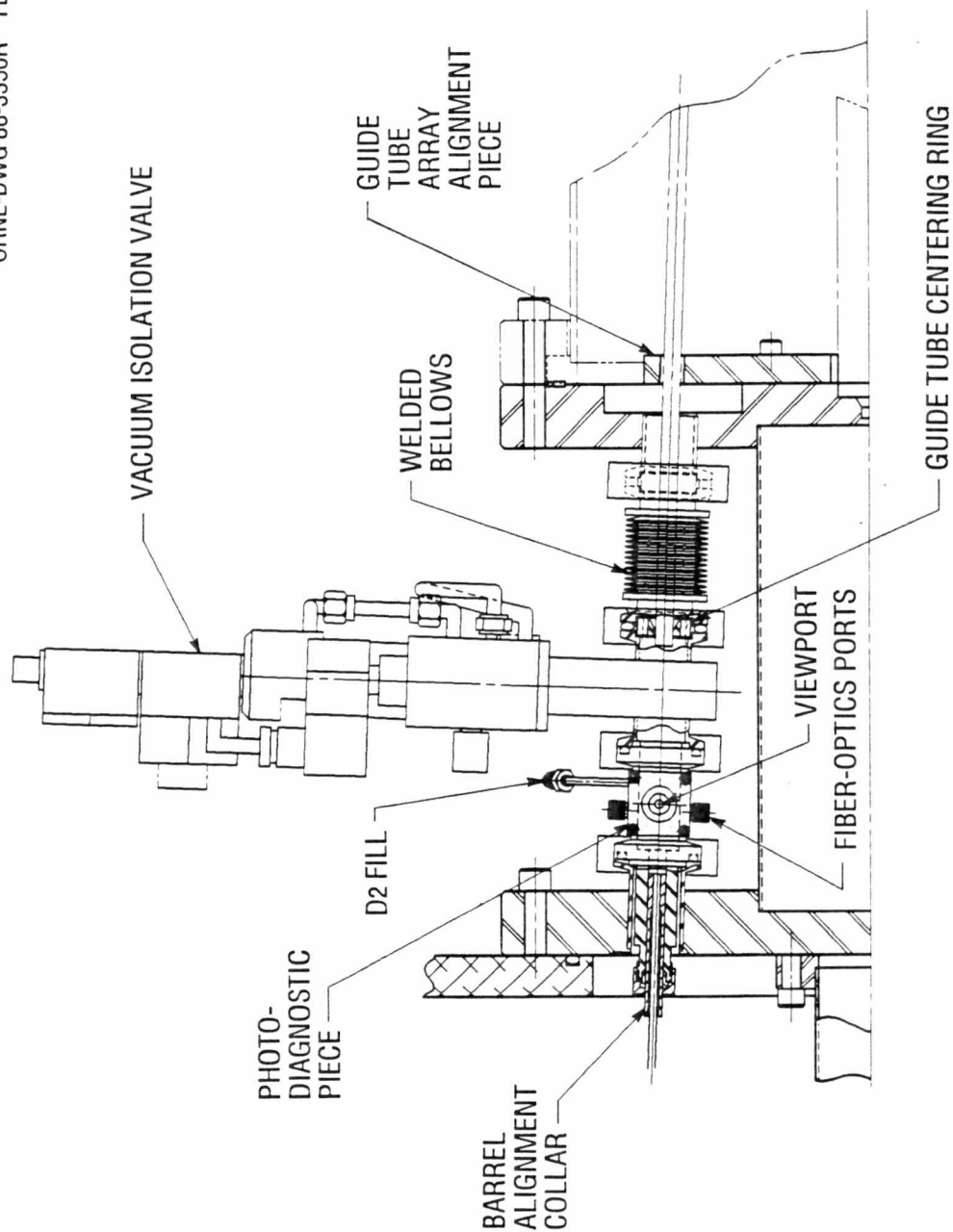


Figure 1.13: Assembly drawing showing the spool piece, a barrel isolation valve, and a flexible bellows of the ATF pellet injection system.

the guide tubes in the second stage are 1.27 cm, and the wall thicknesses are 1.25 mm. The convergence angle is the same as that of the first stage of guide tubes. The vacuum enclosure for the second stage is essentially the same as that of the first stage except that it is 101.6-cm long.

There are two ballast volumes between the guide tube stages and a 1000 l/s Roots pump. The volumes are designed to limit the amount of propellant gas that is injected into the torus during a pellet firing sequence. Two 250-liter tanks are mounted under the guide tube enclosures and are coupled to form one 500-liter volume, which is connected to the first stage guide tube enclosure by a 15.2-cm port. A 200-liter tank is connected to the second stage guide tube enclosure and the lower 250-liter tank. Propellant gas enters the first stage guide tube enclosure through the slots machined in the guide tube centering rings. The large impedance of the propellant gas down the guide tubes causes the majority of the gas to enter the 500-liter volume, where it is pumped out by the Roots pump. The gas that propagates down the guide tubes experiences the same effect in the second stage guide tube enclosure.

The final stage of vacuum extends from an isolation valve at the downstream end of the second stage enclosure to the 6-in. inlet port of the torus. There is a torus isolation valve in this stage which remains open during ATF operation with pellet injection. A 500 l/s turbo-molecular pump is used to maintain a pressure of approximately 10^{-8} torr in this stage of vacuum. The ballast tanks coupled with the closing of the isolation valve at the end of the second stage of guide tubes after a shot sequence, and the pumping of the final stage of vacuum prevent any appreciable amounts of propellant gas from entering the torus.

Pellet Diagnostics Two opposing 1-mm fiber optic lines are positioned so that a pellet exiting the barrel will interrupt the beam of light passing between

them. The detection of this interruption is used to trigger a miniature nitrogen-pumped dye laser module that provides back lighting for a CCD video camera, the output of which is recorded on a video recorder. The freeze frame capability of the recorder is used to produce a still image of the pellet as it exits the barrel. This image can be photographed and used as a qualitative indication of the aspect ratio of the pellet.

Located between the two stages of guide tubes is a second diagnostic station. As the pellet exits the first set of guide tubes, it interrupts the beams from a second group of light gates. The detection of this interruption, along with that of the first set of light gates, is used to determine the velocity of the pellet. The pellet then passes through a microwave mass detector. The detector is a toroidal cavity with entrance and exit holes machined so that the pellets will pass through the cavity as they pass from the first stage of guide tubes to the second.

A D_{α} light detector is located on an inside view port, directly across from the entrance of the injection line. The output of this sensor is used to determine the penetration of the pellet into the plasma and to provide a second estimate of the pellet mass (if all of the pellet is ablated in the plasma).

Calibration of the Pellet Mass Detection System The density of frozen deuterium is .203 gm/cm³. The volume of a cylindrical pellet 1-mm in length and 1-mm in diameter is 7.85×10^{-4} cm³. A deuterium pellet of this size is comprised of approximately 5×10^{19} atoms. In a pipe-gun type injector, some of the pellet will remain on the barrel wall, or will be eroded away by the propellant gas, which reduces the effective radius of the pellet. If a pellet's radius is 90% of the barrel radius, then the volume of the pellet would be reduced by about 20%. This would result in approximately 4×10^{19} atoms contained in a pellet with an aspect ratio of 1 from a 1-mm barrel. Also, in a pipe-gun type injector, the aspect

ratio of a pellet, which is defined as the ratio of the length of the pellet to its diameter, can be altered from less than one to greater than three. The number of the particles in the pellet varies linearly with the aspect ratio.

Because of the pellet erosion and varying aspect ratio, it is difficult to determine the actual pellet mass in a pipe gun type of injector. Traditional methods, such as supply gas inventory and photography, are not sufficiently accurate and are usually difficult to interpret. The technique used on this injector for determining the mass of a pellet is to measure the change in power transmitted through a microwave cavity as the pellet passes through the cavity.

The cavity is located in the second diagnostic station, between the first and second stage of guide tubes. At that location, the eight guide tubes form a circular pattern with a diameter of 15.43 cm and a single toroidal cavity is used to monitor all eight barrels. Figure 1.14 is a schematic showing how the cavity intersects the flight path of the pellets between the first stage and second stage of guide tubes.

A microwave detector diode monitors the power transmitted through the cavity in a frequency discriminator configuration. A dielectric pellet passing through the cavity decreases the resonant frequency of the cavity, which in turn reduces the transmitted power. The microwave circuit used to measure the mass of the pellets consists of a 10.35-GHz dielectric resonance oscillator source, two attenuator pads, a Schottky barrier detector diode, and a low noise amplifier. Coupling to the cavity is achieved with a coaxial-to-waveguide adapter and an iris coupling hole (0.655 cm diam). Two such holes are located 180° apart toroidally, as shown in Figure 1.14. The microwave source is detuned from the TEM_{081} cavity resonance such that the cavity transmission is approximately 70% of that at the resonance center. For the region of the resonance curve that corresponds to 55-85% of the maximum transmission at the resonance center, the variation in cavity

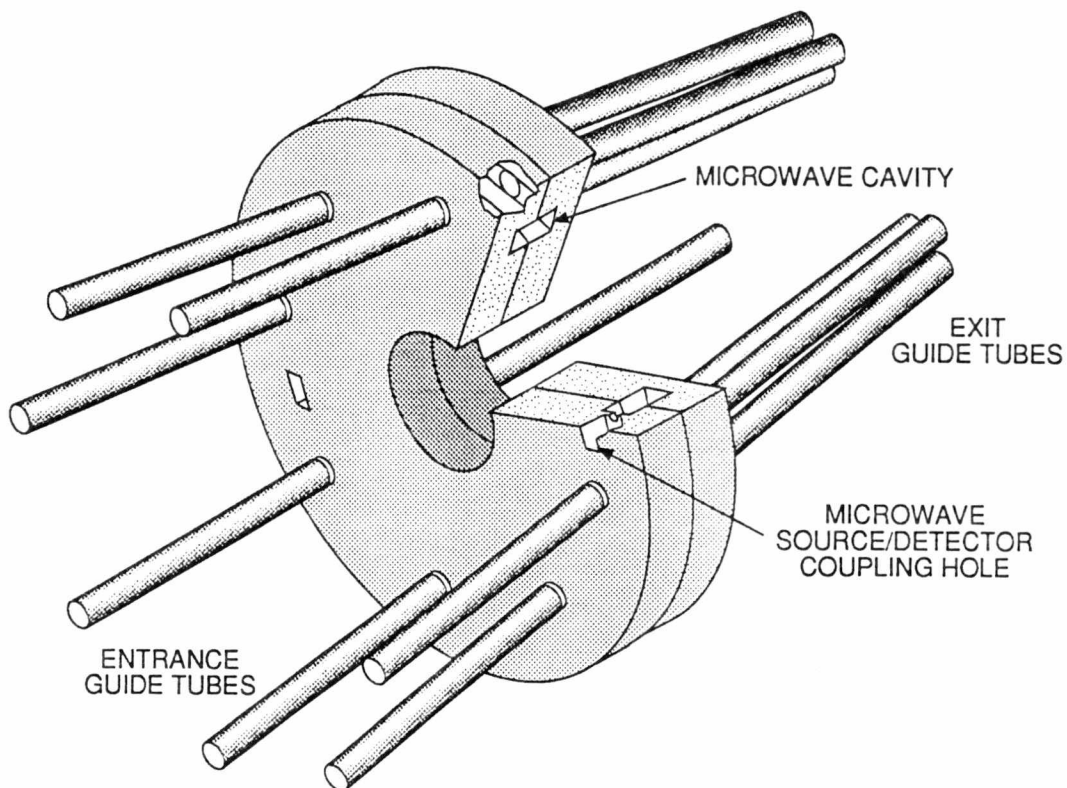


Figure 1.14: Schematic showing the first and second stage of guide tubes intersecting the microwave mass detector.

transmission is nearly linear with frequency. The microwave circuit then acts as a frequency discriminator whose output voltage is nearly linear with changes in the cavity resonance frequency, such as those that occur when a dielectric pellet passes through the cavity.

The TEM_{081} cavity resonance is designed to provide identical sensitivity at each of the eight pairs of exit/entrance holes. For this cavity mode, the electric field, E , is in the radial direction and is given by

$$E_R = E_o(R_o/R) \cos(n\theta) \cos(2\pi z/L), \quad (1.3)$$

with $R_o=77.11$ mm, $n=8$, and $L=16.05$ mm. The distance from the cavity mid-

plane is denoted by z . The shift in the resonance frequency, δF , is proportional to the mass of the pellet, M_p , and the local energy density of the electric field at the location of the pellet and is given by

$$\delta F = M_p (R_o/R)^2 \cos^2(n\theta) \cos^2(2\pi z/L). \quad (1.4)$$

As a pellet traverses the cavity, the change in power transmitted through the cavity is expected to vary with position as $\cos^2(n\theta)$. Because of the spatial variation in the electric field energy density of the cavity mode and the large diameter of the entrance/exit holes, the response of the cavity will vary depending on the displacement of the pellet path from the axis of the holes. For the estimated smallest possible pellets (.7-mm-diam.) the maximum possible displacement of the pellet path is 2.3 mm. This is based on the 5.0-mm inside diameter of the first stage of guide tubes, a 1.5° half-angle of divergence from the barrel, and a free flight distance of 3 cm from the end of the first stage of guide tubes to the center of the cavity. For a toroidal displacement from the axis of the entrance/exit holes, d , the transmitted power is expected to vary as $\cos^2(8d/R_o)$, resulting in a 5.6% reduction for the maximum displacement of 2.3 mm. For the same displacement in the radial direction, the transmitted power is expected to vary as $[R_o/(R_o \pm d)]^2$, resulting in a maximum $\pm 6\%$ variation in the sensitivity.

The output signal of the microwave detector is digitized by a CAMAC-based data acquisition system at 500 KHz. Typical pellet velocities for the injector range from 800 to 1200 m/s, and the in-cavity flight distance is approximately 16 mm. With a sampling rate of 500 KHz, there will about eight sample points for the typical pellet's time of flight through the cavity. The maximum possible error due to the missing of the peak voltage by the digitizer at a sampling rate of 500 KHz, for a pellet velocity of 1000 m/s, is about 3%. This value is mildly dependent on the velocity of the pellet, but the effect is negligible over the range of velocities possible with this injector.

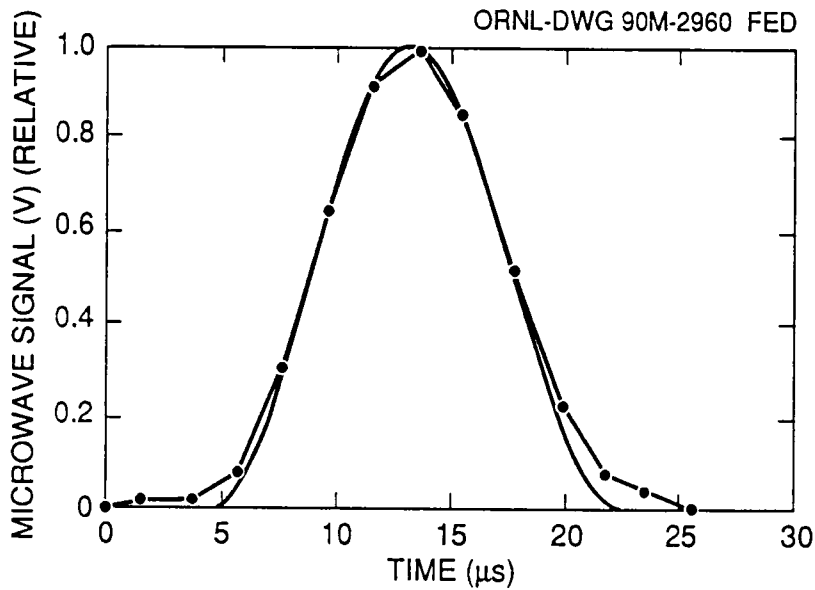


Figure 1.15: Output of the MWMD system as a typical pellet passes through the cavity.

The actual data points for the output of the microwave mass detection system (MWMD) system as a typical pellet passes through the cavity are shown in Figure 1.15. The velocity of this pellet was approximately 1060 m/s. The solid line is a fitted curve using the functional dependence of Equation 1.4 and the data points above the midpoint. An excellent fit is obtained above the 40% level. Below this level the experimental data are wider than the fit. This is accounted for by the perturbation of the electric field when it penetrates the entrance/exit holes. The asymmetry in this widening is indicative of the response time of the microwave detector.

The mass measurement system must be calibrated¹⁷ in order to determine the pellet mass for the observed change in power transmitted through the cavity. To do this, a series of pellets was injected into the ATF vacuum vessel without plasma operation and a high sensitivity capacitance manometer was used to measure

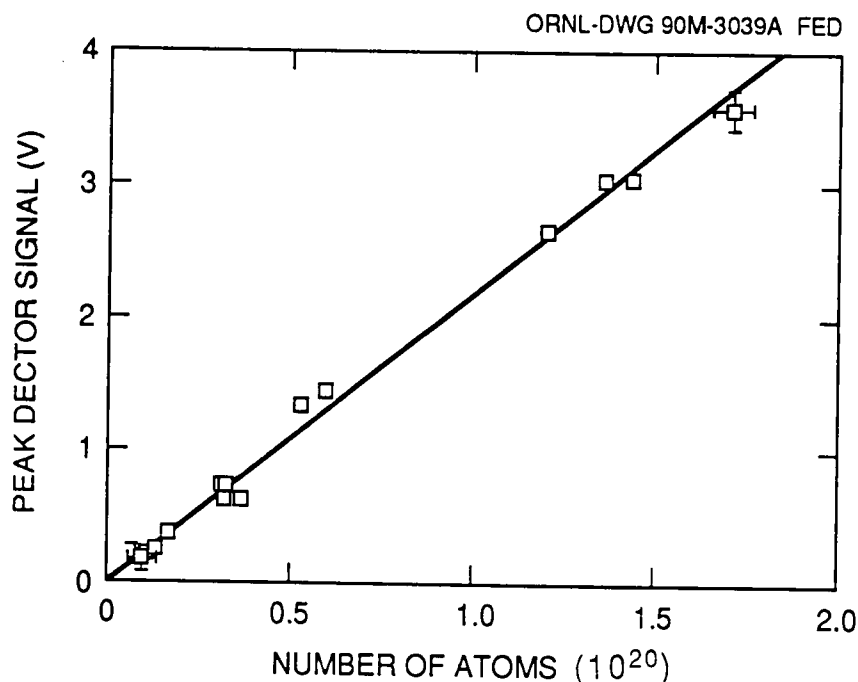


Figure 1.16: Plot of the vessel pressure rise due to pellet injection versus the change in the microwave mass detector system output.

the pressure increase in the vessel due to the injected pellet. The number of particles required to produce the observed pressure increase was determined using the known volume of the vacuum vessel.

The calibration was made using 14 pellet sizes ranging in the number of atoms contained from $N_p \approx .1 \times 10^{19}$ to $N_p \approx 1.9 \times 10^{19}$. The detected number of atoms is plotted in Figure 1.16 against the change in the output voltage of the microwave mass detector. The error bars associated with the uncertainties of the pellet detection system and the vessel pressure measurement are shown for the largest and smallest pellets.

The results indicate that a change in transmitted power of 1 volt corresponded to 6.0×10^{19} atoms. Due to an interference problem with the 53.2-GHz

ECH source, a filter was placed in line after the calibration was performed. This reduced the output signal by 27%, which resulted in a calibration factor of 4.4×10^{19} atoms/volt.

CHAPTER II

PARTICLE DEPOSITION AND D_α EMISSION

Density Measurements as a Function of Pellet Mass

Pellet particle deposition is an important aspect of pellet injection, because the ability to preferentially deposit fresh fuel in a plasma could allow for control of the density profile. The ATF is equipped with a multi-channel FIR interferometry system, which provides up to 7 line-integrated electron density measurements continuously throughout a discharge. This permits the effects of pellet particle deposition to be measured.

Because the volumes contained within nested flux surfaces decrease toward the magnetic axis of the plasma, pellet penetration to the center of the plasma is expected to produce a sharply peaked plasma density profile. A number of particles deposited in a flux volume close to the center of the plasma will produce a larger change in the average density than the same number of particles deposited in a larger flux volume located closer to the edge of the plasma. Therefore, the change in the measured line-integrated density resulting from pellet injection is dependent on both the actual number of particles contained in a pellet and on where the particles are deposited within the plasma. Figure 2.1 shows the expected change in a line-integrated electron density measurement for a chord which passes through the center of a hypothetical set of concentric, toroidal, circular flux surfaces centered at a major radius of $R = 2.1$ m, with a minor

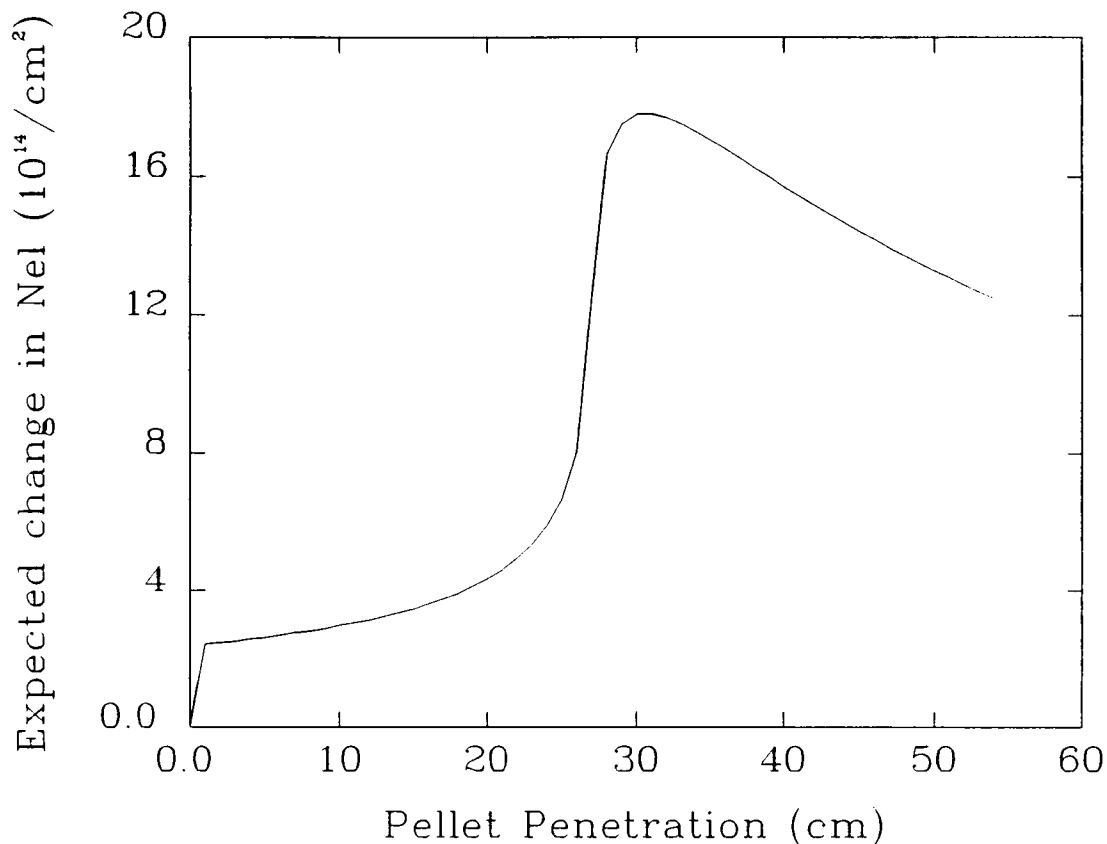


Figure 2.1: The expected change in a line-integrated density measurement passing through the center of a circular cross section, toroidal plasma with $a = 27$ cm and $R = 210$ cm, as a function of pellet penetration for a pellet containing 2.66×10^{19} atoms.

radius $a = .27$ m, and with 1-cm difference in radius between each successive surface, if a total of 2.66×10^{19} electrons were evenly distributed over the flux volumes that the pellet encountered as it penetrated the plasma. Because the volumes contained within the flux tubes decrease towards the magnetic axis of the plasma, the change in line-integrated density measurements is strongly coupled to the penetration depth of the pellet. The maximum density increase is expected for a pellet that penetrates 31 cm into the plasma, if the pellet deposition rate is constant and inversely proportional to the penetration depth of the pellet.

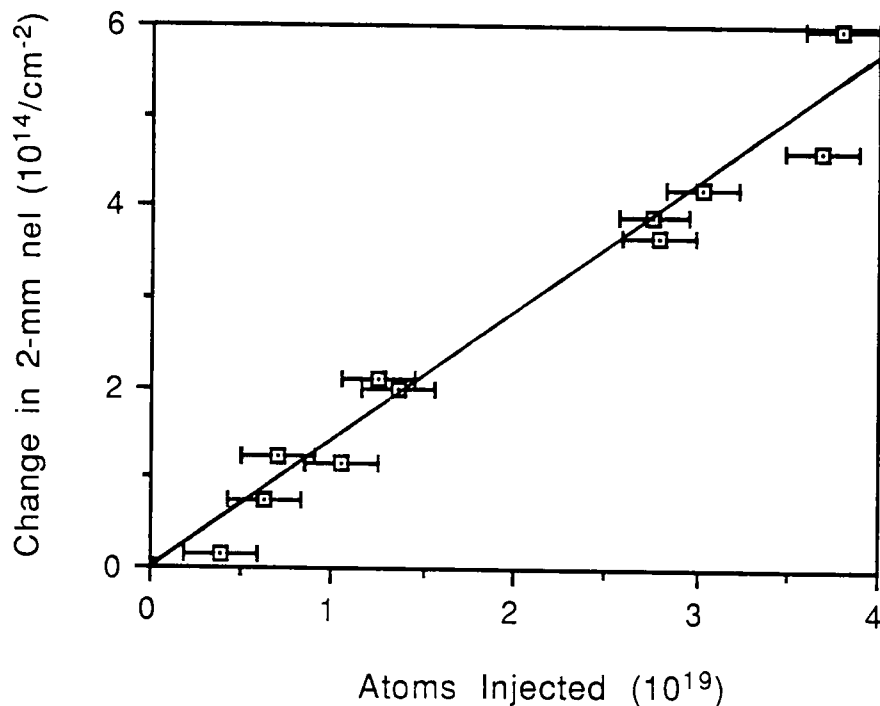


Figure 2.2: Change in the 2-mm $\bar{n}_e \ell$ at the time of injection versus the measured number of atoms in the pellet.

The change in the line-integrated electron density of the plasma measured by the 2-mm interferometer is plotted in Figure 2.2 against the measured number of atoms injected into 1-Tesla, ECH heated plasmas. The pellets ranged in size from $N_p \approx .38 \times 10^{19}$ to $N_p \approx 4.6 \times 10^{19}$ atoms. A fit to the data is shown on the plot. The relationship is linear within the experimental uncertainty of the MWMD system. For shot 16539 ($N_p \approx 3.8 \times 10^{19}$ atoms) the change was $6.0 \times 10^{14} \text{cm}^{-2}$.

Based on the nearly linear relationship between the line-integrated density measurements and the mass of the pellet, the pellet particles appear to be evenly distributed over the plasma volume. It is possible that a particle deposition profile effect in the central region of the plasma occurs, but it is dissipated before the

2-mm interferometer can respond to the change in density. It is also possible that the density in the central region of the plasma may exceed the operational range of the diagnostic for a few milliseconds after pellet injection causing the density to be underestimated. The maximum rate of density change that the 2-mm interferometer can follow is $1.0 \times 10^{15} \text{ cm}^{-2}/\text{ms}$, and it will experience a cutoff effect at a local density of $n_e \approx 2.4 \times 10^{14} \text{ cm}^{-3}$. The FIR interferometer has the capability to measure densities of up to $2.4 \times 10^{16} \text{ cm}^{-3}$, which is much higher than the values expected with pellet injection. The change in the line-integrated density measured by a channel of the FIR interferometer which passes close to the center of the plasma is plotted against the change in the line-integrated density as measured by the 2-mm interferometer in Figure 2.3. The agreement between the two signals is linear over the entire range of pellet sizes, which implies that the density does not reach the critical density for the 2-mm interferometer even for the injection of large pellets. The output of the interferometry systems is proportional to the length of their chordal path through the plasma. For these data, the path length for the 2-mm interferometer and the FIR interferometer was approximately 66 cm and 72 cm respectively. This accounts for the larger change in the line-integrated density measured by the FIR interferometer.

Figure 2.4 shows the output of channel #12 and channel #6 for a typical shot in the pellet mass scan. The change in the output of the FIR interferometer channel #12 is plotted in Figure 2.5 against the number of atoms contained in the pellet for several shots in the pellet mass scan. The change in the line-integrated density from an edge channel increases approximately linearly with increasing pellet mass.

Typically, the density will increase proportionally to the mass of the pellet in both the central and edge regions of the plasma at the time of injection. The increased density in the edge region is lost soon after injection but the central

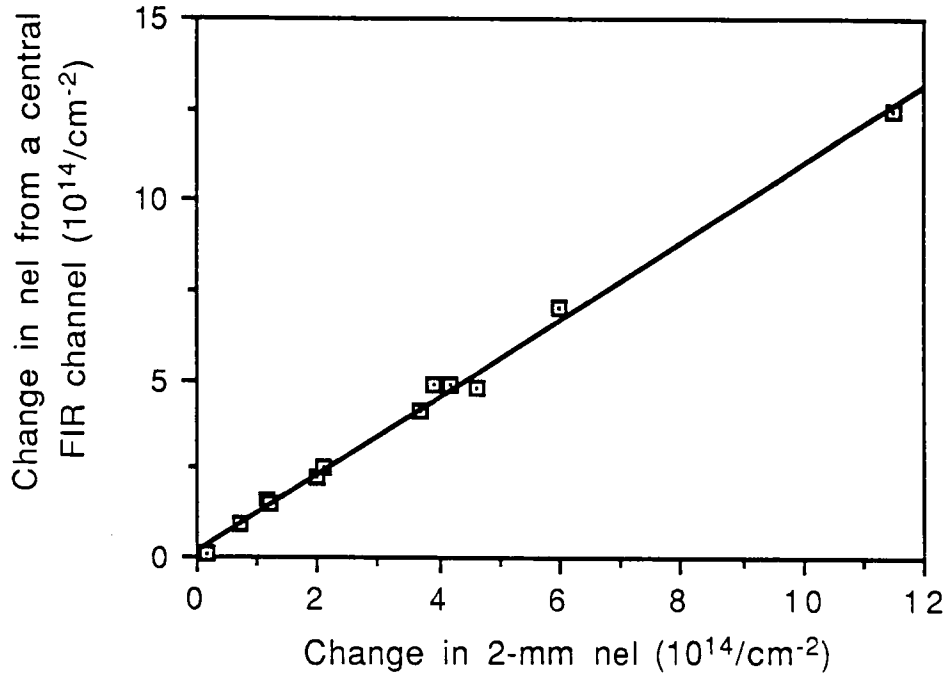


Figure 2.3: Change in the output of the 2-mm interferometer at the time of pellet injection plotted against the change in the output of a central channel of the FIR interferometer.

density remains high. This produces a peaked density profile after pellet injection. However, at the time of injection the shape of the density profile is not drastically altered. The overall local density is increased uniformly.

Fueling Efficiency of Pellet Injection

The particle deposition profile effect has been shown to be small. By neglecting it, an estimation of the number of electrons added to the plasma by pellet injection can be obtained and compared to the measured number of atoms in the pellet before injection, which is defined as the fueling efficiency of pellet injection. The change in the output of the 2-mm interferometer is plotted against the measured number of atoms in the pellet in Figure 2.6 for 55 shots. Based on a fit to the data, assuming no particle deposition profile effect, the chord length

Shot #16539

1 Tesla

Standard Configuration

Gyrotron #1 & #2

2mm Nel at time of injection: $2.6 \times 10^{14} \text{ cm}^{-2}$

Number of atoms in pellet: 3.8×10^{19}

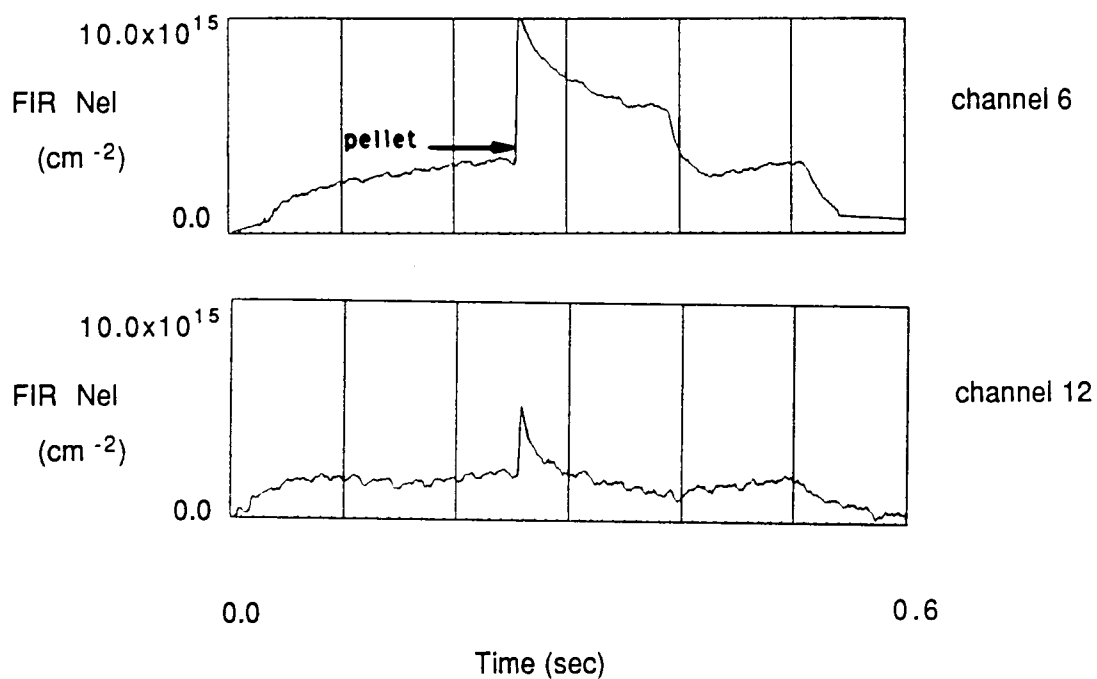


Figure 2.4: The output of a central channel and an edge channel of the FIR interferometer for a typical shot with pellet injection.

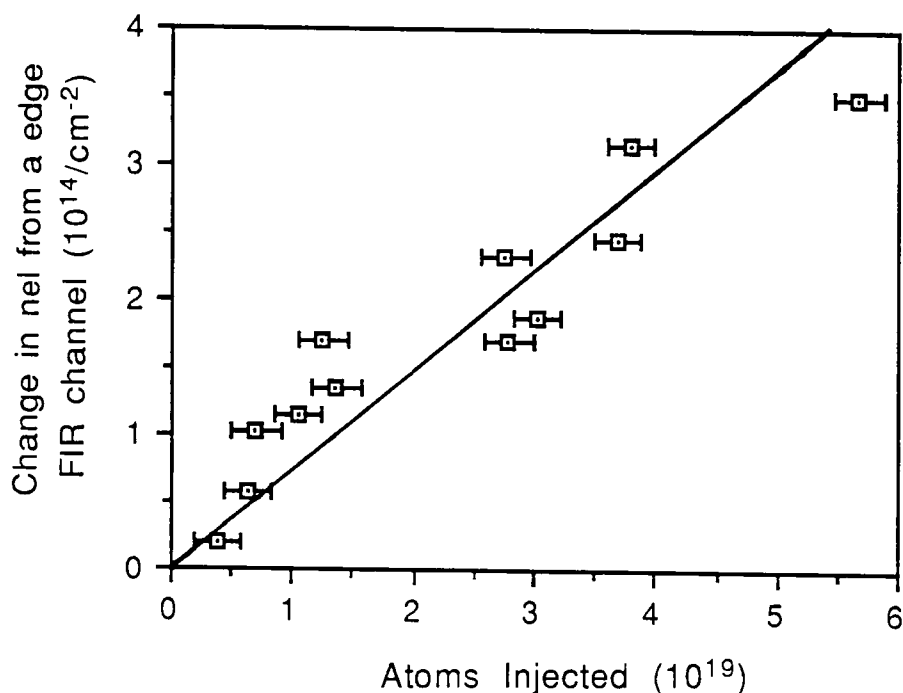


Figure 2.5: Change in the output of an edge channel of the FIR interferometer at the time of injection versus the number of atoms in the pellet.

of the 2-mm interferometer to be .66 m, and the overall plasma volume to be 3.0 m^3 , the fueling efficiency of pellet injection is approximately 73% for ATF, ECH, 1-Tesla plasmas.

D_α Emission Studies

In pellet injection experiments on other devices ^{8 21 13}, the relative intensity of the D_α emission was assumed to be indicative of the rate of pellet particle ionization during the ablation process. If the charged particles were constrained to the flux surfaces where they were initially created, and the number of photons emitted per atom ionized remained constant over the lifetime of the pellet, then the intensity of the D_α emission would be indicative of the pellet particle depo-

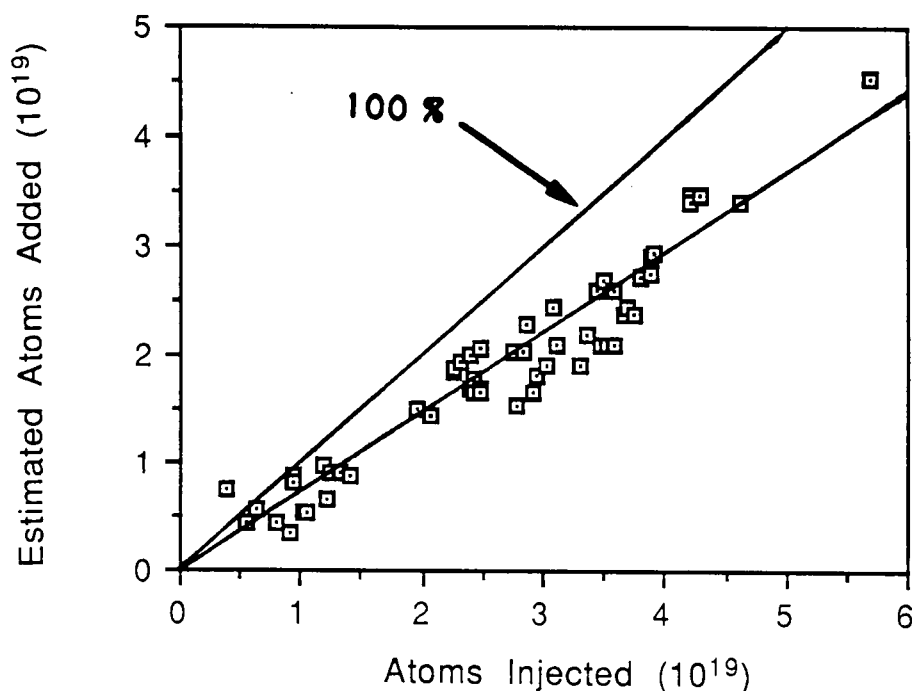


Figure 2.6: Estimated number of particles added to the plasma at the time of injection versus the measured number of atoms in the pellet.

sition. In this section, the measured D_{α} emission from the pellets injected into ATF plasmas will be discussed.

Measurement of D_{α} Emission

A view port is located on the inside of the vacuum vessel, directly along the centerline and at the same mid-plane location as the pellet injection line. A UDT PIN D photosensitive diode, with a narrow bandwidth filter centered at 656 nm with a FWHM of 10 ± 2 nm, is mounted on the view port such that the flight paths of the pellets are within its field of view as they penetrate the plasma. The diode output is amplified by a UDT-201a broad band amplifier, which has a maximum frequency response of .5 MHz, and digitized at a 500 KHz rate using the CAMAC-based data acquisition system. A typical D_{α} emission trace for a pellet

that penetrates to about the magnetic axis of the plasma is shown in Figure 2.7 (shot 16539).

The data must be corrected to compensate for the decreasing distance from the pellet (assumed to be a point source) to the detector over the pellet's lifetime in the plasma. Based on extensive measurements of the distance between the two light gates used to measure the pellet's velocity and the distance from the second light gate to a reference point on the vacuum vessel, the position of the pellet in the plasma as a function of time and the distance from the pellet to the D_α detector is determined. The raw data are corrected by division of the square of the distance from the pellet to the detector. Figure 2.8 shows the corrected D_α emission trace as a function of pellet position in major radius for shot 16539. Throughout this body of work, reference to the detected D_α emission will refer to the corrected signal. It is the relative value of this type of signal that has been assumed to be indicative of the rate of pellet ablation in previous pellet injection experiments.

The D_α emission from shot 16539 is rather typical of that observed for the pellet sizes which are of usual interest for injection into a 1-Tesla, ECH, ATF plasma. The volume-averaged density of the plasma at the time of injection was $\langle \bar{n}_e \rangle \approx 3.9 \times 10^{12} \text{ cm}^{-3}$. The D_α emission began at $R \approx 2.35 \text{ m}$ and increased to its maximum level at $R \approx 2.26 \text{ m}$. The emission level decreased at $R \approx 2.24 \text{ m}$ and remained essentially constant as the pellet approached the center of the plasma. Eventually the pellet became prohibitively small and the emission decreased and terminated.

Comparison of D_α Emission to Pellet Mass

The D_α emission traces from the pellets injected during the pellet mass scan that was used to illustrate the particle deposition profile effect due to pellet

Shot #16539

1 Tesla

Standard Configuration

Gyrotron #1 & #2

Line-averaged density at time of injection: $3.9 \times 10^{12} \text{ cm}^{-3}$

Number of atoms in pellet: 3.8×10^{19}

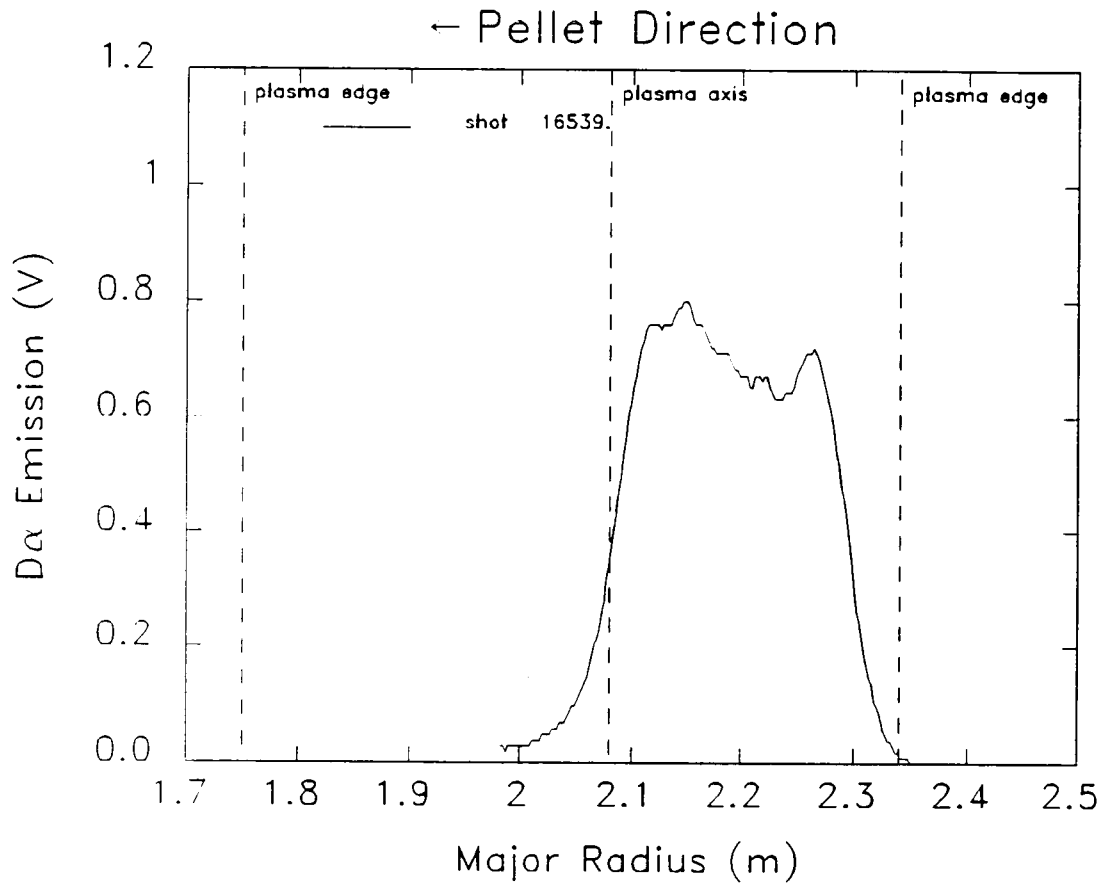


Figure 2.7: The detected $D\alpha$ emission as a function of pellet position in major radius for shot 16539.

Shot #16539

1 Tesla

Standard Configuration

Gyrotron #1 & #2

Line-averaged density at time of injection: $3.9 \times 10^{12} \text{ cm}^{-3}$

Number of atoms in pellet: 3.8×10^{19}

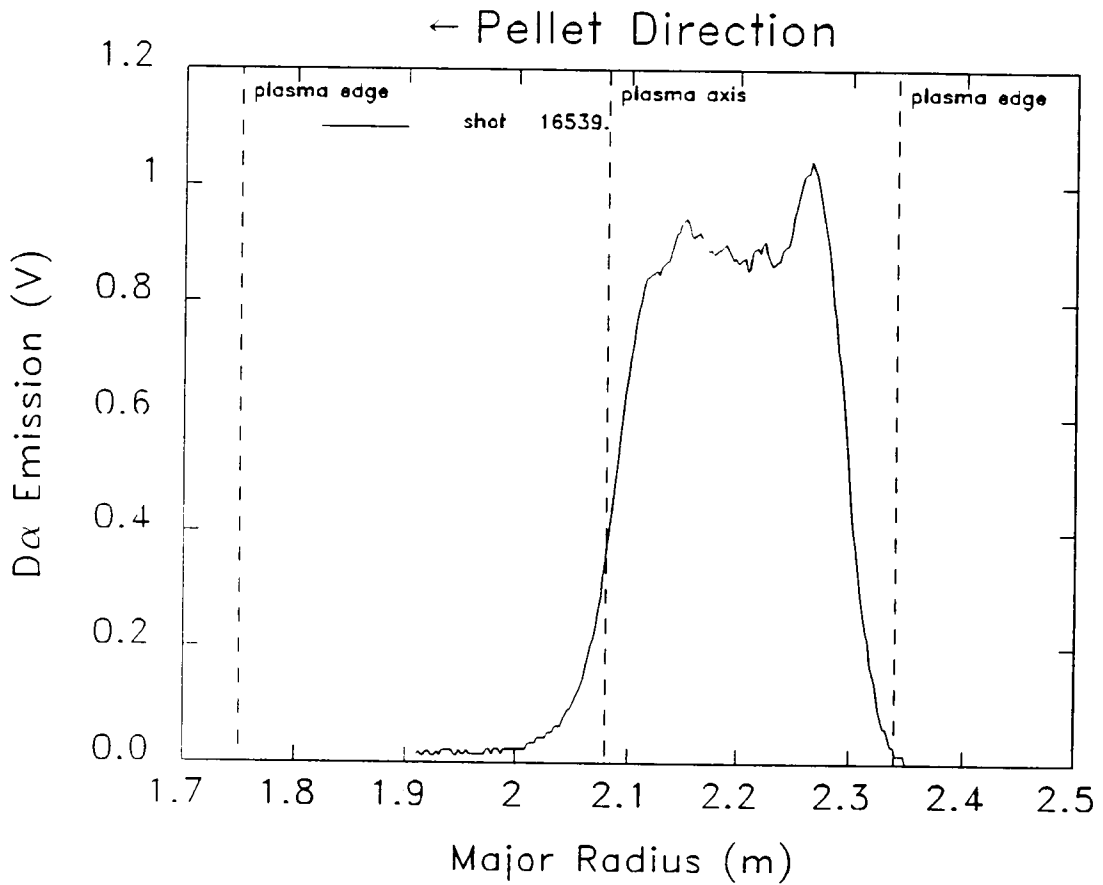


Figure 2.8: The D α emission as a function of pellet position in major radius that has been corrected to compensate for the decreasing distance from the pellet to the detector during the ablation process for shot 16539. The emission is assumed to be from a point source at the calculated pellet position.

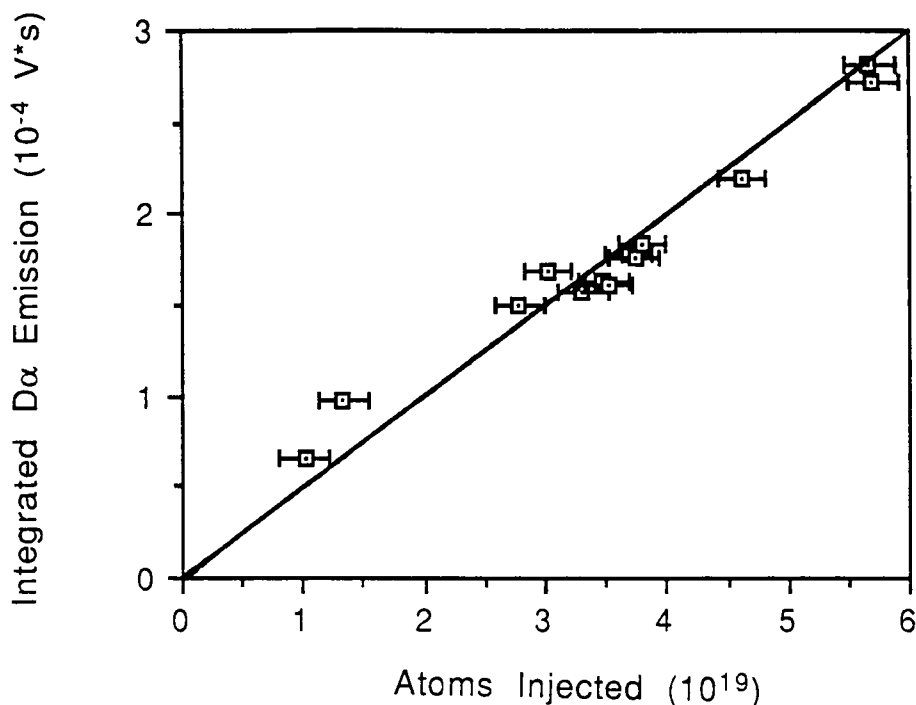


Figure 2.9: Area under D_α trace (Volt-S) versus the number of atoms in the pellet for shots in a pellet mass scan.

injection have been numerically integrated, and the area under the traces is plotted against the number of atoms in the pellets in Figure 2.9. A fit to the data is shown on the plot, and the relationship between the area under the D_α trace and the mass of the pellet is linear within the experimental uncertainty of the measurements. This demonstrates that the total D_α emission from the pellet ablation process is proportional to the number of atoms injected within the experimental error.

D_α Emission as an Indication of Particle Deposition

At this point, a statement can be made about the ability of the relative intensity of the D_α emission to indicate particle deposition. It was demonstrated that the particles added due to pellet injection were essentially evenly distributed over the entire plasma volume and the shape of the density profile was not drasti-

cally altered at the time of injection. Except for the peak that is observed as the pellet enters the plasma, the D_α trace for shot 16539 was almost constant over the entire pellet lifetime. Figure 2.8 shows the D_α trace for shot 16539 ($N_p \approx 3.8 \times 10^{19}$ atoms). The shape of the trace is a good first order approximation to a square wave, which would correspond to an approximately constant ablation rate. This pellet penetrated 31 cm into the plasma. If the fueling efficiency is taken to be 73%, then the total number of electrons deposited in the plasma would be approximately 2.66×10^{19} .

The expected change in the line-integrated density measurement for this number of electrons and a penetration depth of 31 cm was approximately $1.8 \times 10^{15} \text{ cm}^{-2}$, with a path length of 57 cm. The pellet injected during shot 16539 produced a change in the 2-mm $\bar{n}_e \ell$ of approximately $5.8 \times 10^{14} \text{ cm}^{-2}$. The observed change was more than a factor of 3 lower than the expected change, and was approximately that which would be measured if the 2.66×10^{19} atoms were evenly distributed over the plasma volume, instead of being localized to flux surfaces.

The emission intensity is independent of the pellet mass but the density in the edge region of the plasma increases with increasing pellet mass. Also, the expected changes in the density measurements based on the relative intensity of the emission do not agree with the measured changes. It can be concluded that while the D_α emission is proportional to the total number of atoms ionized in these plasmas, the intensity and the location of the emission do not provide an accurate indication of the measurable particle deposition from the pellet ablation process.

Description of the D_α Emission Traces

Figure 2.10 shows the D_α emission as a function of pellet position for several shots in the mass scan. The pellet injected during shot 16548 ($N_p \approx$

2.8×10^{19} atoms) was so small that the ablation began to decrease immediately due to the effect of decreasing pellet size, however the peak in the emission which is centered at $R \approx 2.26$ m was present. In shot 16544 ($N_p \approx 3.8 \times 10^{19}$ atoms), the ablation level remained high well into the central region of the plasma. As the pellet reached the axis of the machine ($R \approx 2.09$ m), the ablation began to decrease due to decreasing pellet size.

In shot 16537 ($N_p \approx 4.6 \times 10^{19}$ atoms), the emission appears to have begun a typical decrease due to the effect of decreasing pellet size. However, as the pellet passed $R \approx 2.08$ m, there was a distinct discontinuity in the emission intensity and the rate of decline of the D_α emission decreased. This can be seen more clearly in the case of large pellets that penetrate beyond the magnetic axis of the plasma, for example shots 16538 and 16540.

For these plasma conditions, there appears to be a region ranging from $R \approx 2.13$ m to $R \approx 2.08$ m in which the D_α emission intensity decreases. The reduction in detected D_α emission cannot be attributed to decreasing pellet size, because it is independent of the size of the pellet at the location at which it occurs. Therefore, it must be due to a reduction in the ablating potential of the plasma.

Beyond this region, if enough of the pellet remains, the emission level stops decreasing, and as can be seen from the D_α trace of shot 16540, can again become constant at approximately 2/3 of the value detected on the outer half of the plasma. The pellet continues to ablate until the decreasing pellet size becomes a limiting factor and the emission goes to zero.

There are several features of these D_α traces that are of interest. (1) There does not appear to be a pellet size dependence on the D_α emission intensity, which is contrary to present pellet ablation theory. (2) The peak in the emission that occurs as the pellet enters the plasma indicates that a substantial rate of ablation at the plasma edge occurs. Typical traces from the injection of pellets

Shot #16548 Number of atoms in pellet: 2.8×10^{19}
 Shot #16544 Number of atoms in pellet: 3.8×10^{19}
 Shot #16537 Number of atoms in pellet: 4.6×10^{19}
 Shot #16538 Number of atoms in pellet: 5.4×10^{19}
 Shot #16540 Number of atoms in pellet: 5.7×10^{19}
 1 Tesla
 Standard Configuration
 Gyrotron #1 & #2
 Line-averaged density at time of injection: $3.9 \times 10^{12} \text{ cm}^{-3}$

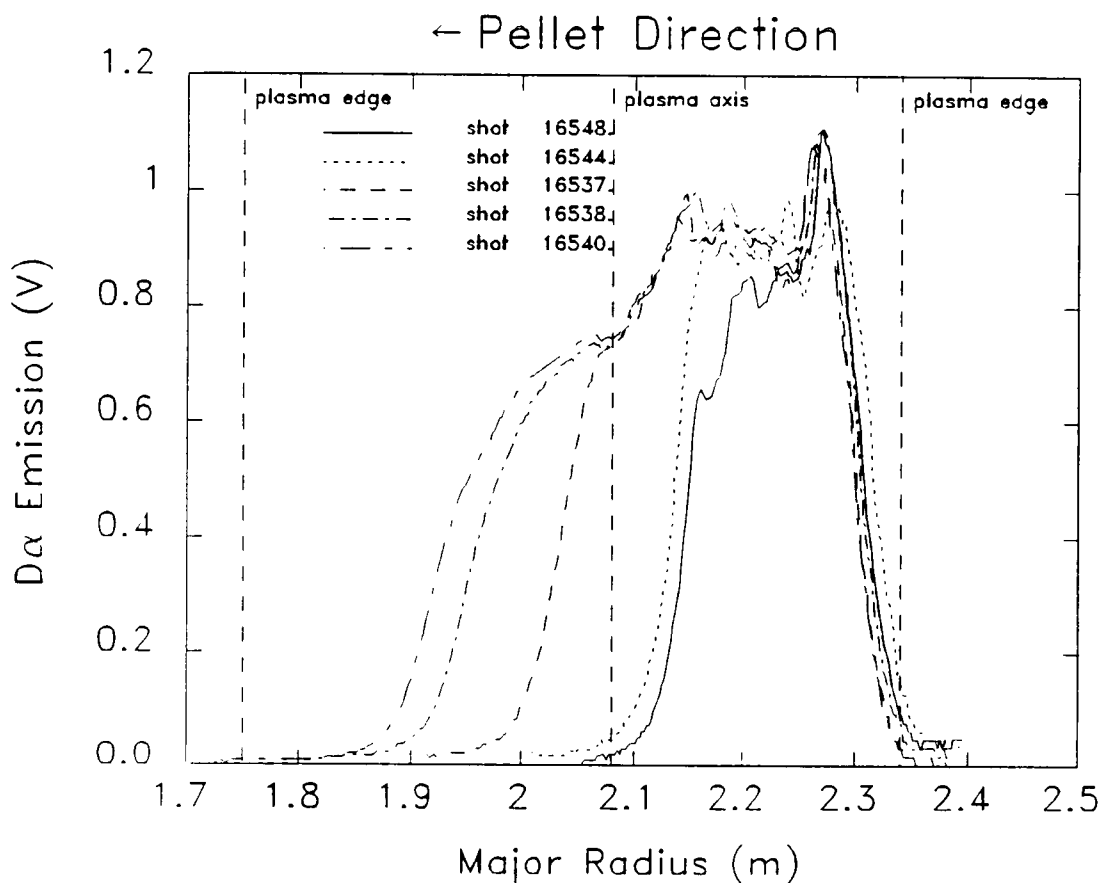


Figure 2.10: D_α emission traces for shots 16544, 16548, 16537, 16538 and 16540. The emission of the smaller pellets are similar to those of larger pellets until the emission begins to reduce due to diminishing pellet size.

into tokamaks differ in that the emission rises more gradually at the plasma edge and increases towards the central region of the plasma. (3) Also in contrast to the emission traces observed on tokamaks, is the significant amount of emission that occurs beyond the magnetic axis of the plasma. In a tokamak, when the pellet passes beyond the magnetic axis of the plasma, the D_α emission typically reduces to a near zero value and the pellet will usually penetrate the entire plasma column. These features of the D_α trace for 1-Tesla, ECH heated plasmas in the standard magnetic configuration will be discussed in the remainder of this section. The rest of the chapter will describe the effects on the emission traces of altering the heating source and the magnetic configuration of the plasma.

Dependence of D_α Emission on Pellet Size

An empirical scaling law has been derived by Parks and Turnbull²⁴ for the pellet ablation rate of hydrogenic pellets, G , in plasmas that are similar in density and temperature to those produced in the ATF and is given by

$$G = 4\pi r_p^2 n_s \dot{r}_p \quad (\text{atoms/s}) \quad (2.1)$$

where

$$\dot{r}_p = 8.94 \times 10^{14} r_p^{-2/3} n_{eo}^{1/3} T_{eo}^{1.64} n_s^{-1} \quad (\text{cm/s}) \quad (2.2)$$

is the rate of change of the equivalent spherical pellet radius of the pellet, n_s is the density of solid hydrogen (atoms/cm^3) $\approx 5.2 \times 10^{22}$, n_{eo} is the local electron number density in cm^{-3} , and T_{eo} is the local electron temperature in eV.

The Neutral Gas Shielding (NGS) model of pellet ablation and the empirical scaling laws that have been derived from pellet ablation experiments, like equation 2.1, predict an ablation rate dependence on the pellet size of $r_p^{1.33}$. For a spherical pellet with a radius of .5 mm, a pellet with twice the number of

atoms would have a radius of approximately .63 mm. The ablation rate of the larger pellet is predicted to be approximately 36% higher in similar plasma conditions. However, the emission traces for the pellets injected into these plasmas were found to be independent of the pellet size. The emission traces of the larger pellets closely overlay that of the smaller pellets until the emission from the smaller pellets begins to decrease due to diminishing pellet size. This implies that the effective pellet radius does not affect the emission rate in these plasmas, except when the pellet has been almost completely ablated. The pellet injected during shot 16540 ($N_p \approx 5.7 \times 10^{19}$ atoms) contained over twice the number of atoms as did the pellet injected during shot 16548 ($N_p \approx 2.8 \times 10^{19}$ atoms), however the initial levels of the D_α emission were almost identical, as shown in Figure 2.11.

Dependence of D_α on Target Plasma Density

An interesting feature of the D_α emission for the 1-Tesla, ECH plasmas is the peak that is observed as the pellet enters the plasma. For shots 16534-16550, this peak is centered at $R \approx 2.26$ m, and ends at $R \approx 2.24$ m. Figure 2.12 shows the flux surfaces corresponding to $\rho = 0, .1, .2, \dots, 1$ for the standard configuration at $\phi = 11^\circ$, which is approximately the location where the pellet enters the plasma. The D_α trace for shot 16539 is overlaid on the plot. The flux surface corresponding to $\rho = 1$ at the mid-plane of the vacuum vessel closely corresponds to $R = 2.35$ m, which is the calculated location of the pellet when the D_α emission begins. The peak in the emission is centered at $R \approx 2.26$ m, which corresponds to the $\rho \approx .7$.

The pellet ablation rate in an ECH heated plasma is thought to be determined by three main factors: the density of the plasma, the temperature of the electrons, and the size of the pellet. However, a small number of non-thermal electrons can produce significant ablation.⁶ The D_α emission for these plasmas has

Shot #16548 Number of atoms in pellet: 2.8×10^{19}
 Shot #16540 Number of atoms in pellet: 5.7×10^{19}
 1 Tesla
 Standard Configuration
 Gyrotron #1 & #2
 Line-averaged density at time of injection: $3.9 \times 10^{12} \text{ cm}^{-3}$

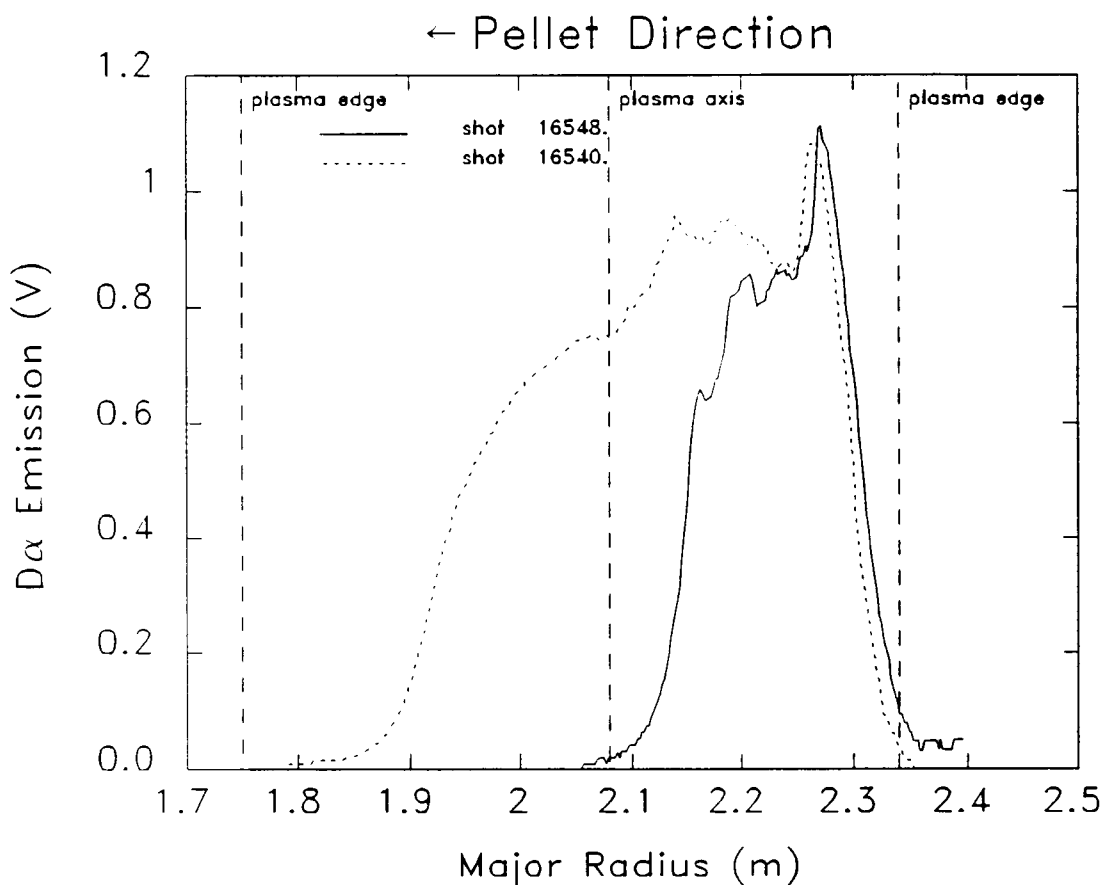


Figure 2.11: D_α trace for two pellets. The pellet injected in shot 16540 contained over twice the number of atoms as did the pellet injected in shot 16548.

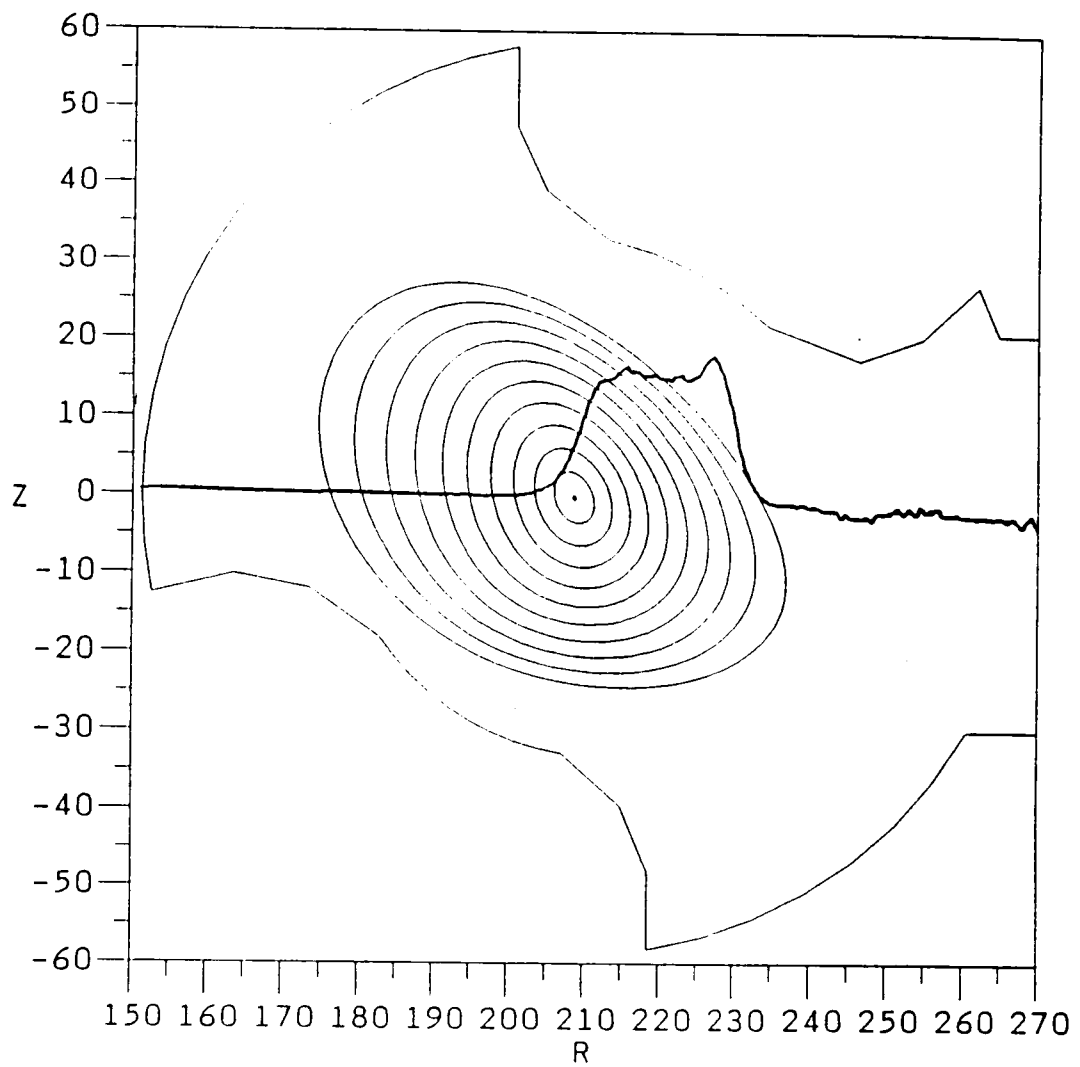


Figure 2.12: D_α trace for shot 16539 plotted over the theoretical flux surfaces corresponding to $\rho = .1, .2, \dots, 1$ for ATF plasmas in the standard configuration at $\phi = 11^\circ$.

been shown to be independent of the size of the pellet, and therefore the observed peak is due to either a region of increased plasma density or temperature. A series of pellets was injected into target plasmas ranging in volume average density from $\langle \bar{n}_e \rangle \approx 3.5 \times 10^{12} \text{ cm}^{-3}$ to $\langle \bar{n}_e \rangle \approx 12.5 \times 10^{12} \text{ cm}^{-3}$ in order to determine the effect of increasing plasma density on the D_α emission. The D_α traces for several of these shots are overlaid in Figure 2.13.

In shot 13403 ($\langle n_e \rangle \approx 5.3 \times 10^{12} \text{ cm}^{-3}$) the initial peak in the ablation is observed. As the target density increases, (13404, ($\langle n_e \rangle \approx 6.0 \times 10^{12} \text{ cm}^{-3}$), the peak disappears. For shot 13405, ($\langle n_e \rangle \approx 6.5 \times 10^{12} \text{ cm}^{-3}$) the intensity from the ablation process as the pellet enters the plasma was decreased substantially.

As the density of the target plasma decreases, the detected D_α emission from the ablation process at the edge of the plasma increases. Therefore, the peak in the emission that is detected as the pellet enters the plasma is not due to increased density. The peak has been shown to be independent of pellet size, therefore it must be due to a region of increased electron temperature or a population of non-thermal electrons. Measurements of the plasma electron temperature by the Thomson scattering diagnostic do not show evidence of increased thermal electron temperature in this region of the plasma and the ECE from $\rho > .7$ is dominated by non-thermal emission for the low density target plasmas. Therefore, it is probable that the increased emission is due to a population of non-thermal electrons.

The non-thermal electrons in this region of the plasma may explain the lack of pellet mass dependence on pellet ablation in the edge region of the plasma. If the ablation in this region is dominated by a non-thermal electron population, then only a limited number of these electrons would be available for ablation. The peak in the ablation that occurs as the pellet enters the plasma was observed to decrease with increasing plasma density. This is possibly a result of an increase in

Shot #13403

Line-averaged density at time of injection: $5.3 \times 10^{12} \text{ cm}^{-3}$

Shot #13404

Line-averaged density at time of injection: $6.0 \times 10^{12} \text{ cm}^{-3}$

Shot #13405

Line-averaged density at time of injection: $6.5 \times 10^{12} \text{ cm}^{-3}$

1 Tesla

Standard Configuration

Gyrotron #1 & #2

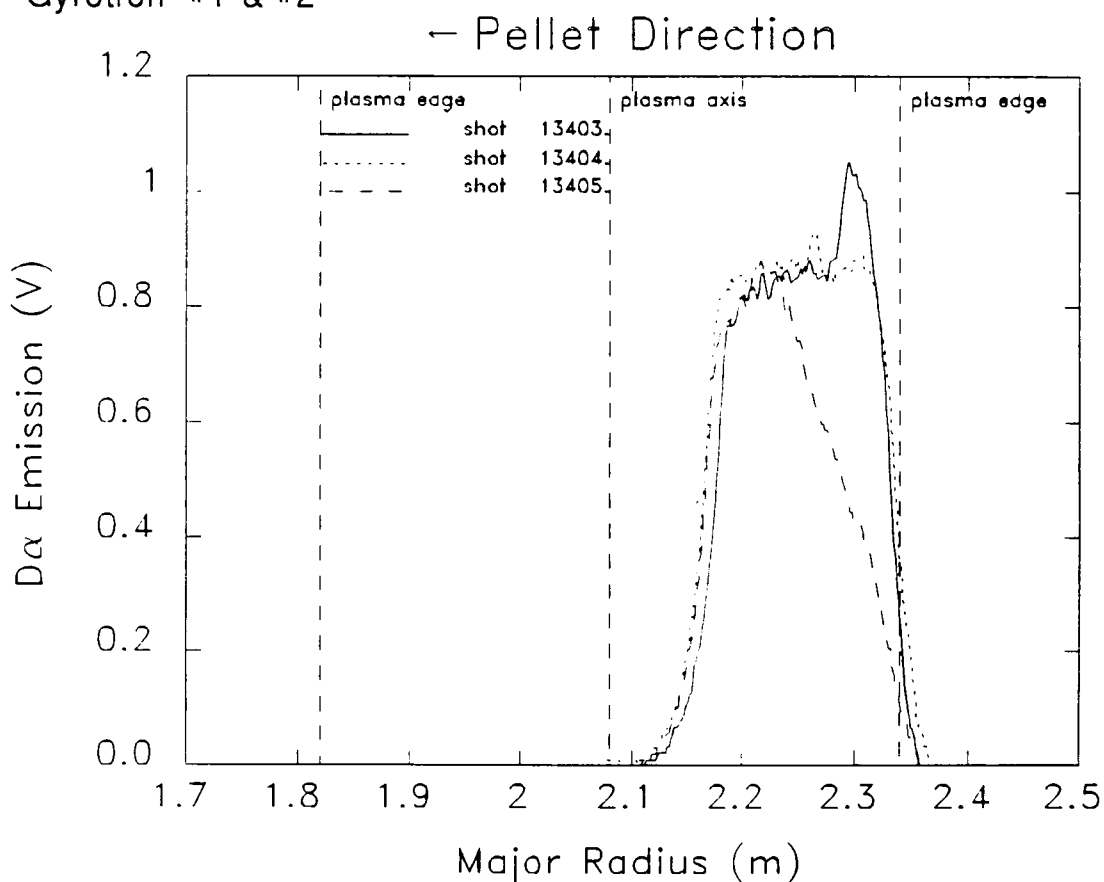


Figure 2.13: D_α traces for pellets injected into plasmas with increasing densities. The peak in the emission that occurs as the pellet enters the plasma is observed to decrease with increasing target plasma density.

the plasma collisionality which would reduce the number of non-thermal electrons in the plasma.

The characteristics of the peak in the D_α emission at the edge of the plasma are also affected by the value of magnetic field strength (B_o) of the plasma. The optimal magnetic field strength for the absorption of the second-harmonic ECH heating is $B_o \approx .96$ Tesla. When the field is reduced from the optimal value, the second-harmonic resonance surface moves away from the launching beam, reducing the first-pass absorption.²³ For shot 17939 the magnetic field strength was $B_o = .962$ Tesla, and for shot 16538 the magnetic field strength was $B_o = .942$ Tesla. The D_α emission traces for these shots are overlaid in Figure 2.14. Even though the volume-averaged electron density was higher for shot 17939, the peak in the emission trace was sharper for this shot than that of shot 16549, which had the less optimal magnetic field strength for ECH power absorption. The region of reduced D_α emission is also present for the case with the more optimal magnetic field strength for ECH absorption. This suggests a correlation between the ECH absorption and the existence of the peak in the D_α emission in the edge region of the plasma. This further supports the conclusion that the peak in the D_α emission is due to a population of non-thermal electrons.

Emission Beyond the Magnetic Axis of the Plasma

For the plasmas with the standard magnetic configuration there is a region ranging from $R \approx 208$ cm to $R \approx 213$ cm where the D_α emission is reduced compared to that on the outer portion of the plasma. This reduction in emission is independent of pellet size, and must therefore be due to a reduction in the ablating potential of the plasma. This effect may be a result of the magnetic confinement of the plasma in nested toroidal flux volumes. As the pellet approaches the magnetic

Shot #16538 Atoms: 5.4×10^{19}

Line-averaged density at time of injection: $3.9 \times 10^{12} \text{ cm}^{-3}$

Shot #17939 Atoms: 5.4×10^{19}

Line-averaged density at time of injection: $4.2 \times 10^{12} \text{ cm}^{-3}$

Standard Configuration

1 Tesla

Gyrotron #1 & #2

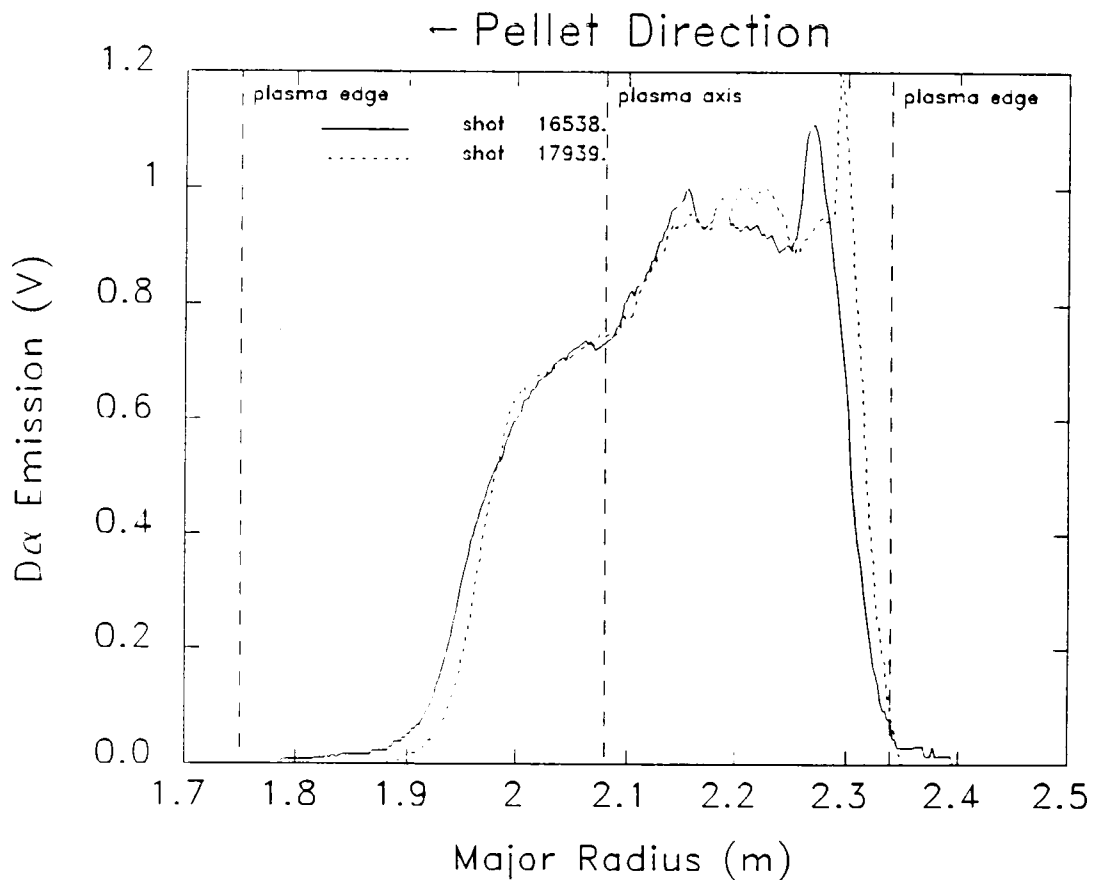


Figure 2.14: D_α emission traces for pellets injected into two plasmas with the standard magnetic configuration. The plasma during shot 17939, had a higher pre-pellet density and a more optimal magnetic field strength for the absorption of the ECH power than it did during shot 16538.

axis of the plasma, it encounters smaller flux volumes which have fewer particles and therefore less ablating potential. The interesting feature of the D_α traces for the large pellets injected in shots 16537, 16538, 16540, and 17939 is that after the pellet passed this region, the decrease in the emission is temporarily checked and then it remains substantial over the inner half of the plasma column. This observed behavior is significant because of how it differs from that in a tokamak.

D_α emission due to pellet ablation in tokamaks has been observed to drop to near zero values after the pellet crossed the magnetic axis of the plasma. This reduction has traditionally been explained using the rotational transform of the magnetic field lines, which causes the pellet to interact with the same particles on the inner half of the plasma column that were responsible for the ablation on the outer half of the plasma column. The particles on the inside of the plasma column would then have reduced temperatures and therefore less ablating potential. In this case however, the D_α emission can remain close to the level observed before the pellet crossed the axis. The D_α trace for a large pellet (shot 16538) is shown along with the flux surfaces at the $\phi \approx 11^\circ$ location in the standard configuration in Figure 2.15.

If the particles responsible for the ablation on the inside half of the plasma column are the same particles that were responsible for pellet ablation on the outer half of the plasma column, then the energy used to ablate the pellet on the inner half of the plasma column could have been used to ablate more of the pellet as it initially entered the plasma. If the cooling effect due to the rotational transform of the particles does occur, then either the particles were not drastically cooled by their first interaction with the pellet and its associated ablation cloud, or the pellet is interacting with a different population of particles after it crosses the axis - this could only be a population of trapped electrons on other field lines than ordinarily encountered.

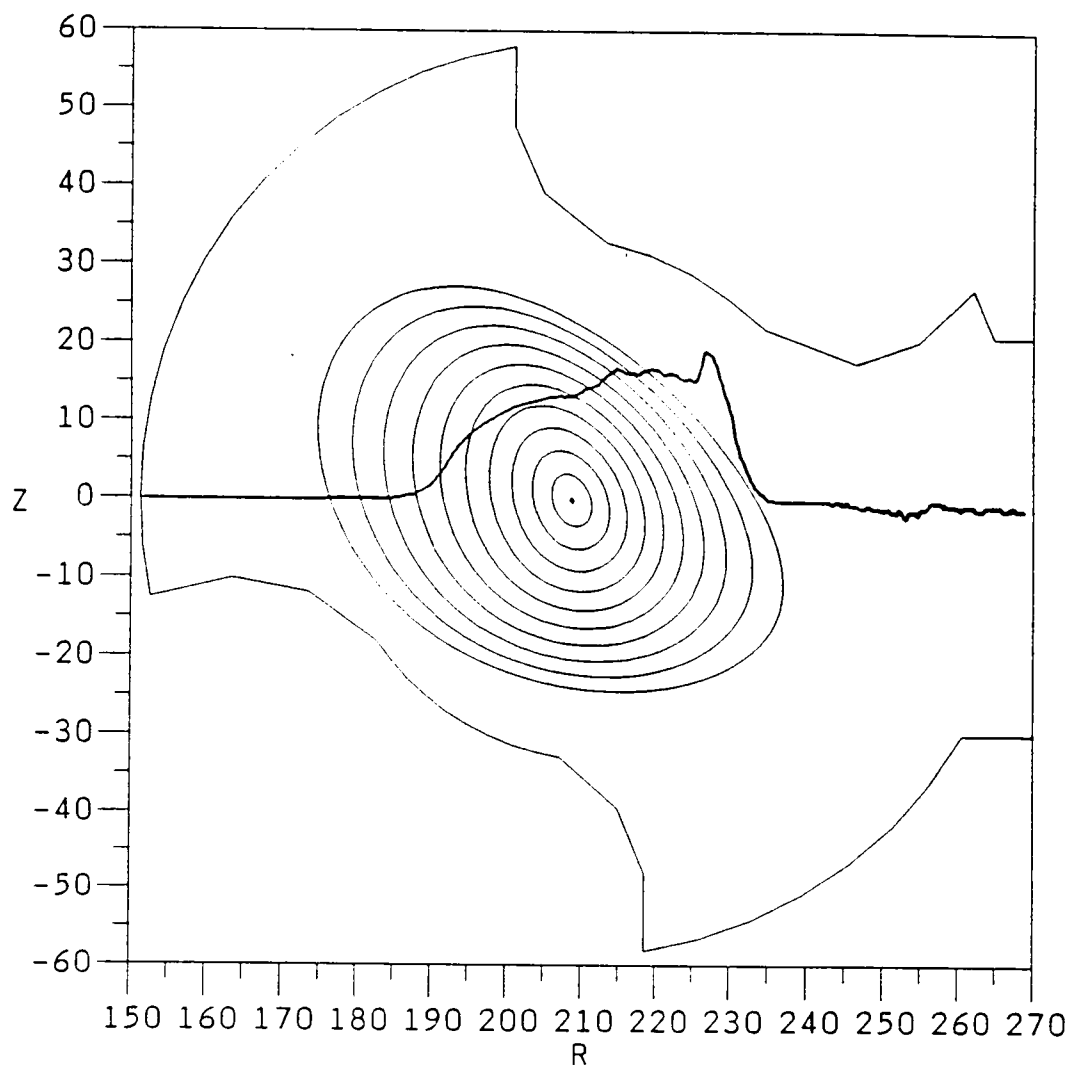


Figure 2.15: D_α trace for shot 16538 plotted over the theoretical flux surfaces corresponding to $\rho = .1, .2, \dots, 1$ for ATF plasmas in the standard configuration at $\phi = 11^\circ$. The emission after the pellet crosses the magnetic axis of the plasma remains substantial.

The trapped particle fraction is dependent on the magnetic ripple (ϵ_h) of the device, which for the ATF varies from $\epsilon_h \approx .004$ on axis to $\epsilon_h \approx .395$ at the plasma edge. The orbits of trapped particle fractions are such that no particles exist only on the inner half of the plasma column. Therefore, this population of particles is not a likely candidate to explain the significant amount of emission that is observed as the pellet crosses the center of the plasma. The most probable conclusion for the substantial ablation that occurs after the pellet crosses the axis of the plasma is that the passing electrons do not lose all of their ablating potential as they interact with the pellet cloud on the outer half of the plasma column.

If the passing electrons did not expend all of their energy ablating the pellet on the outer half of the plasma column, then why is there a lack of a pellet mass dependence on the pellet ablation? It is possible that a mass flow rate limitation from the pellet surface limits the ablation rate.

Effect of Magnetic Configuration on D_α Emission

By altering the ratio of the current in the helical coils to the current in the mid-VF coils, the shape of the magnetic structure of the plasma can be altered. When the plasma is shaped such that at $\phi = 0^\circ$ it appears to be vertically elongated, it is said to be prolate. A pellet mass scan similar to that done in the standard configuration was done for a plasma with a prolate magnetic configuration. As in the standard configuration case, the D_α emission was not dependent on the pellet mass as the pellet entered the plasma, and the peak in emission at the edge region of the plasma tended to decrease as the target plasma density increased. The interesting feature of the emission traces for the shots with the prolate configuration was that the emission level increased as the pellets approached the center of the plasma, and for some pellets, a large spike in the emission level

was detected just before the plasma reached the magnetic axis of the plasma.

Pellets injected into shots 18767, 18768, 18769, 18779, and 18780 were observed to have a spike in the D_α emission. The pre-pellet line-integrated electron densities for shots 18779 and 18780 were $\langle \bar{n}_e \rangle \approx 4.5 \times 10^{12} \text{ cm}^{-3}$. For shots with a similar pre-pellet density in the standard magnetic configuration, the ablation was not observed to increase drastically towards the center. Shots 18767, 18768, and 18769 had low pre-pellet density ($\langle \bar{n}_e \rangle \approx 3.2 \times 10^{12} \text{ cm}^{-3}$) and low stored energy (.6 KJ). The pellet injected in shots 18767, 18768, and 18780 contained 2.1×10^{19} , 1.6×10^{19} and 3.4×10^{19} atoms respectively. Figure 2.16 shows the D_α traces for these shots. The peak value of the detected D_α emission at the center of the plasma for shot 18780 is over 2 volts. In the other large pellet cases the value is between 1.2 and 1.4 volts.

The D_α trace for a large pellet (shot 18767) is shown along with the flux surfaces at the $\phi \approx 11^\circ$ location in the prolate configuration in Figure 2.17. Experimental measurements of the electron temperature profile for plasmas with this magnetic configuration do not indicate that a region with increased electron temperature exists. While it is possible that the emission is due to a population of non-thermal electrons, its cause is unknown. This does however shed some light on an earlier point of interest. There does not appear to be a mass flow limitation from the pellet surface for those pellets which had a large increase in emission as they approached the center of the plasma, and it is not likely that there would be a mass flow limitation at any other location in the plasma or for a plasma with a different magnetic configuration. Therefore the lack of a pellet mass dependence on the ablation in the edge region of the plasma is not due to a mass flow limitation from the pellet surface, and must be due to a limit in the ablating potential of the plasma.

It is perhaps surprising that the ablation emission remains significant after

Shot 18767 Gyrotron #1 & #2

Shot 18768 Gyrotron #1 & #2

Line-averaged density at the time of injection: $3.2 \times 10^{12} \text{ cm}^{-3}$

Shot 18780 Gyrotron #1 & #2

Line-averaged density at the time of injection: $4.5 \times 10^{12} \text{ cm}^{-3}$

1 Tesla

Prolate Configuration

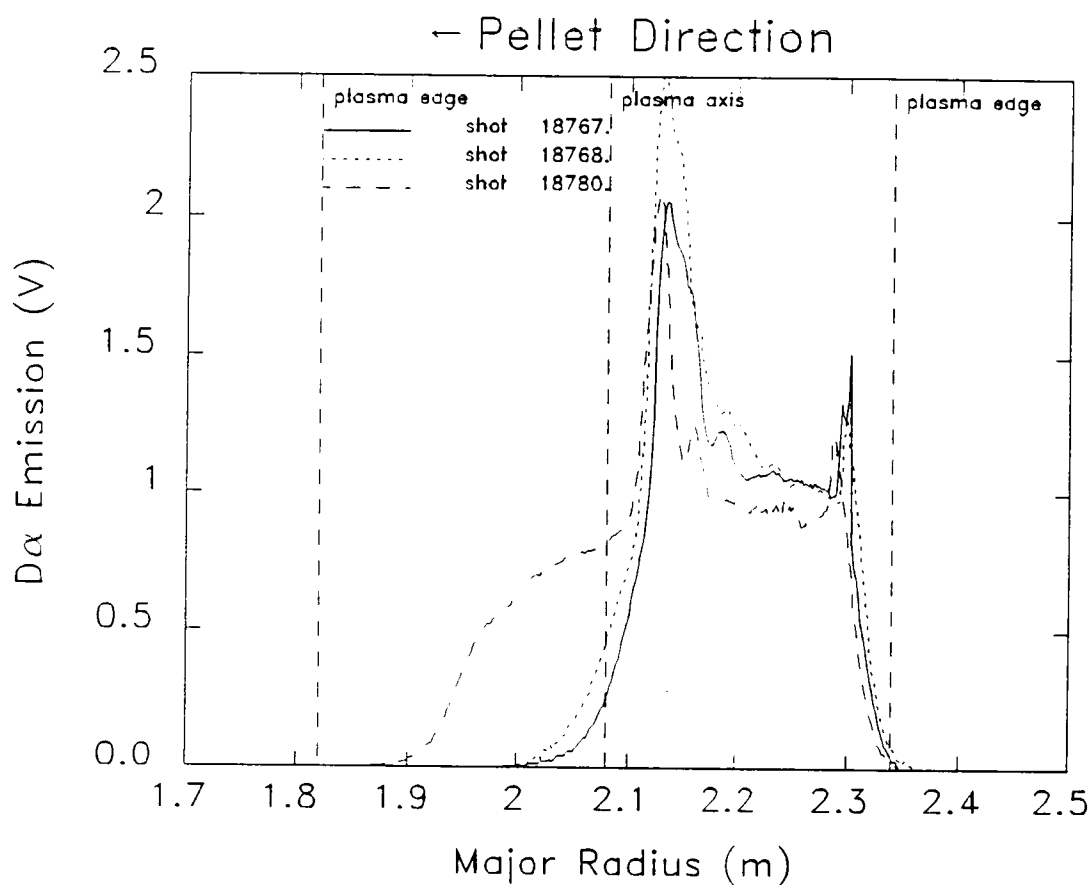


Figure 2.16: D_α emission traces for pellets injected into plasmas with prolate magnetic configurations.

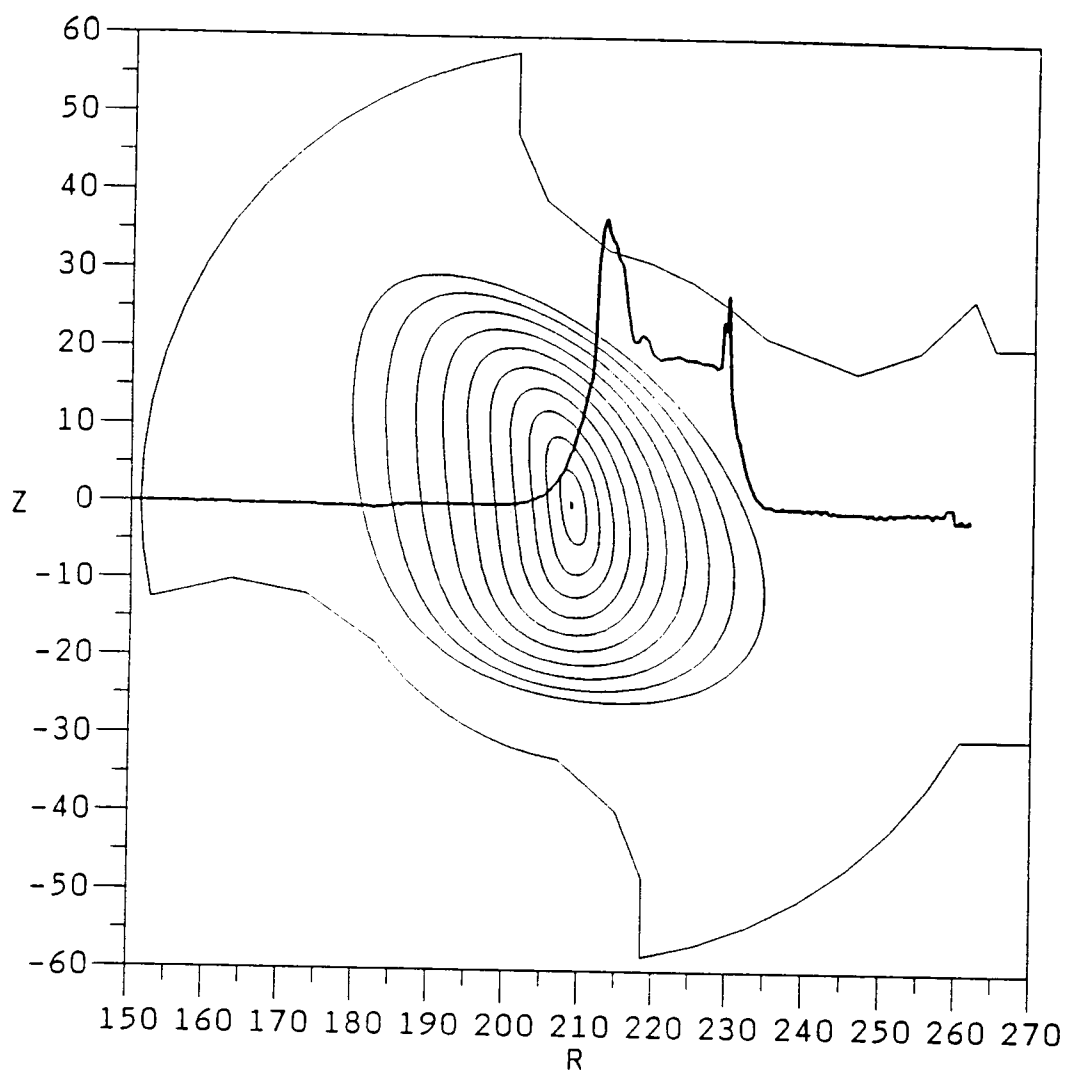


Figure 2.17: D_α trace for shot 18767 plotted over the theoretical flux surfaces corresponding to $\rho = .1, .2, \dots, 1$ for plasmas with the prolate magnetic configuration at $\phi = 11^\circ$.

the pellet crosses the magnetic axis of the plasma, even though the ablating potential of the outer half of the plasma column appears to have been already reached and there does not appear to be a mass flow rate limitation from the surface of the pellet.

It is probable that the pellet and its associated ablation cloud extract only a small fraction of the electron energy available on a flux surface as it passes. If a pellet with a diameter of 1 mm and an ablation cloud with a thickness equal to the pellet diameter had a velocity of 1000 m/s, it would travel the distance of its total width in 3 μ s.

If a pellet extracts energy from the flux surface only at the point of interaction, then the energy extracted can be approximately expressed as the ratio of the total width of the pellet and ablation cloud to the poloidal circumference of the flux surface. For a surface with an average minor radius of 10 cm, the poloidal circumference is about 60 cm. A pellet and ablation cloud of 3 mm would extract only .5% of the available energy for ablation on that surface if it interacted with it for one instant. However, the relatively slow velocity of the pellet causes it to remain on a surface for approximately 3 μ s. A 1 Kev electron has a velocity of approximately 2×10^7 m/s. For a major radius of 2 m, such an electron would make one toroidal pass every .6 μ s. Electrons of this energy would make approximately 5 toroidal passes in the time it takes the pellet to cross a flux surface. Thus, approximately five times the energy extracted in an instantaneous interaction between the flux surface and the pellet ablation cloud would be extracted for a pellet moving at 1000 m/s. However, the total energy extracted is still only about 2.5% of the total available energy.

As the pellet passes a region, it will leave in its path a cold, dense plasma that will then spread out over the flux surface. The interaction of the remnants of the pellet ablation cloud and the electrons on the flux surface is an unknown.

If the deposited particles interact with the electrons on a time scale that is faster than the time that it takes the pellet to cross the axis and reach the surface on the inner half of the plasma column the ablative potential could be reduced substantially.

The energy extracted as the pellet interacts with a flux surface is small compared to the total energy available for ablation and this may explain why the pellet experiences substantial ablation after it crosses the magnetic axis of the plasma. However, this argument should also be valid for tokamaks. It is clear that the emission from pellets that cross the magnetic axis in tokamaks is significantly different from that observed in ATF plasmas.

The lack of a pellet mass dependence on the emission intensity can possibly be explained in using these arguments. If the total width of the pellet and the associated ablation cloud is not strongly dependent on the pellet radius, then the fraction of a flux surface taken up by a pellet would be invariant and the energy extracted for pellet ablation would be independent of the pellet radius. More sophisticated diagnostics would be required to measure the actual width of the pellet ablation cloud in order to address this issue.

Effect of Heating Power on D_α Emission

For the plasmas discussed in this work, the heating source was one or both of the two 200-kW gyrotron systems. The absorption of the heating power from these systems is dependent on the local plasma density, temperature, and magnetic field strength of the plasma. Experiments were performed using the three possible combinations of gyrotrons to determine the effect it would have on pellet ablation. It should be noted that all of the shots discussed in this section had a prolate magnetic configuration.

The D_α traces for shots 18771, 18798, and 18804 are shown in Figure 2.18. The plasma was heated with gyrotrons #1 and #2 in shot 18771, with gyrotron #1 in shot 18798, and with gyrotron #2 in shot 18804. The $\bar{n}_e \approx 3.4 \times 10^{12} \text{ cm}^{-3}$ for shot 18771 and $\bar{n}_e \approx 4.5 \times 10^{12} \text{ cm}^{-3}$ for shots 18804 and 18798 at the time of injection. The emission traces for the two shots heated with one gyrotron are similar in form to each other, indicating that the ablation is independent of which gyrotron is used to heat the plasma. These traces increase much more gradually at the edge of the plasma than for the case in which the plasma is heated by both gyrotrons. A peak in the emission is observed for the one-gyrotron cases, however it is shifted in closer to the center of the plasma than that for the 2-gyrotron cases. Although the emission increases more rapidly at the edge with the use of both gyrotrons, the emission level in the central region of the plasma is only about 10% higher than that observed when the plasma is heated with only one gyrotron.

Figure 2.19 shows the D_α traces from two pellets that were injected into plasmas at a lower density. Shot 18839 was heated by gyrotron #2 and shot 18811 was heated by gyrotron #1. The emission traces for these shots are essentially identical until the emission in shot 18811 begins to decrease due to decreasing pellet size. The emission traces from the pellets injected into the low density plasmas that were heated by only one gyrotron are similar to those from the pellet injected into the higher density plasmas heated with both gyrotrons. It is apparent that the shape of the emission trace is a strong function of the plasma density, which affects the absorption of the ECH power.

Summary

There are several observations which can be made concerning pellet ablation and particle deposition in ATF plasmas. These stellarator plasmas are of

Shot 18771 Gyrotron #1 & #2

Line-averaged density at the time of injection: $3.4 \times 10^{12} \text{ cm}^{-3}$

Shot 18798 Gyrotron #1

Shot 18804 Gyrotron #2

Line-averaged density at the time of injection: $4.5 \times 10^{12} \text{ cm}^{-3}$

1 Tesla

Prolate Configuration

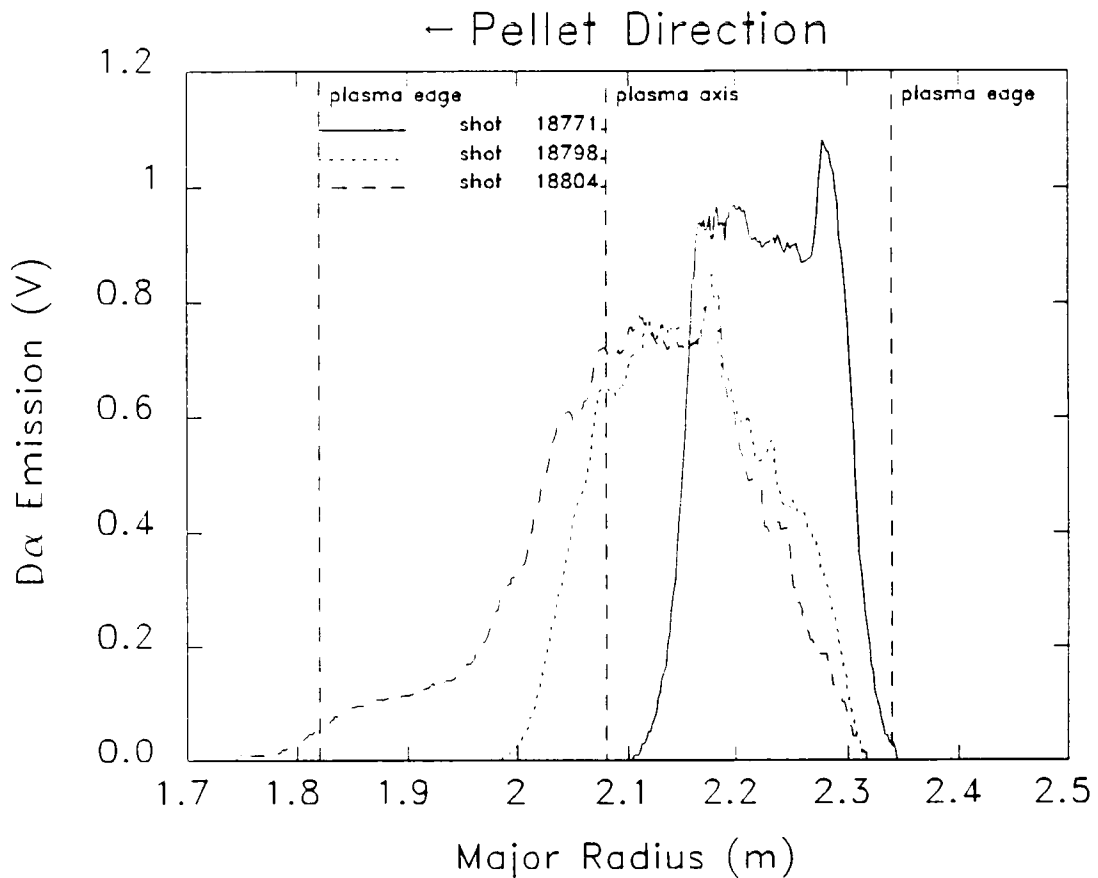


Figure 2.18: D_{α} emission traces for pellets injected into plasmas heated with gyrotron #1 and #2 (18771), heated with gyrotron #1 only (18798), and with gyrotron #2 only (18804).

Shot 18811 Gyrotron #1

Shot 18839 Gyrotron #2

Line-averaged density at the time of injection: $2.8 \times 10^{12} \text{ cm}^{-3}$

Shot 18771 Gyrotron #1 & #2

Line-averaged density at the time of injection: $3.4 \times 10^{12} \text{ cm}^{-3}$

1 Tesla

Prolate Configuration

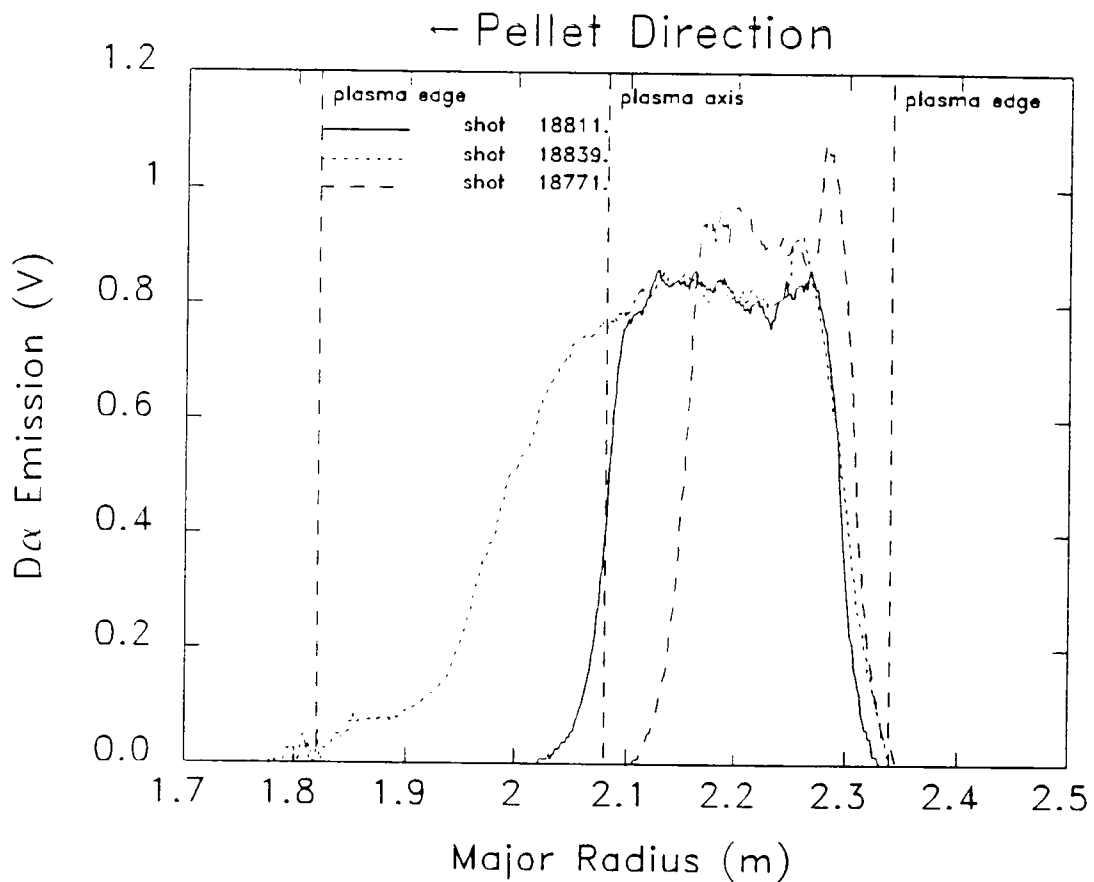


Figure 2.19: D_α emission traces for pellets injected into plasmas heated with gyrotron #1 only (18811), with gyrotron #2 only (18839), and with both gyrotrons at a higher density (18771).

comparable volume to those of small tokamaks and the results differ in several respects. Based on the estimation of the total number of particles in the plasma immediately before and after pellet injection, the pellet fueling efficiency is approximately 73% for ATF, ECH heated, 1-Tesla plasmas. There is little change in the density profile shape due to pellet injection. The particles are essentially evenly distributed over the entire plasma volume.

The rate of D_α emission is independent of pellet size in these plasmas, until the pellet becomes very small. This contradicts the empirical scaling laws that have been developed to relate pellet ablation to pellet and plasma parameters. This is not due to a mass flow limitation from the surface of the pellet, and is probably due to a limitation on the ablation potential of the plasma which changes with different operating conditions.

There is no detectable dependence on the emission traces produced from pellet injection based on which gyrotron is used to heat the plasma. However, the use of both gyrotron systems to heat the plasma results in a 10% increase in D_α emission intensity from the central region of the plasma. Although the gyrotrons appear to heat the central region of the plasma when used independently, heating the plasma with both systems produces an identical level of D_α emission when the pellets are in the edge region as when they are in the central region. This effect is also observed for pellets injected into very low density plasmas that are heated with only one gyrotron.

A peak in the D_α emission occurs at $\rho \approx .7$, and is observed for plasmas that were heated with both gyrotrons in each magnetic configuration into which pellets have been injected. This peak decreases with increasing target plasma density and as the magnetic field strength is reduced from that which is optimal for the absorption of the ECH power. This peak is thought to be due to ablation from non-thermal electrons.

The D_α emission intensity remains significant after the pellet crosses the magnetic axis of the plasma. This sustained emission cannot be attributed to a population of helically trapped electrons whose orbits are such that they do not interact with the pellet as it penetrates the outer half of the plasma. This is in contrast to the results of pellet injection experiments involving tokamaks, in which pellets that cross the axis tend to ablate very little on the inside half of the plasma and usually completely penetrate the plasma column.

Plasmas with a prolate configuration appear to have a region of enhanced ablation potential ranging from $\rho \approx .4$ to the magnetic axis of the plasma. The actual cause of this enhanced ablation is unknown, however the existence of this enhanced emission eliminates the possibility of a mass flow limitation being the cause of the lack of D_α emission dependence in the edge region of the plasma.

CHAPTER III

PLASMA RESPONSE TO PELLET INJECTION

The purpose of this chapter is to characterize the response of 1-Tesla, ECH heated, ATF plasmas to pellet injection. The characterization of the plasma response is made from observations of experiments beginning May 31, 1990, and continuing through May 30, 1991. The magnetic configuration for all of the shots discussed was the standard configuration at a magnetic field strength of 1 Tesla and heating provided by two gyrotrons unless otherwise noted. The working gas of the plasmas and the pellets were either hydrogen or deuterium. It was found that the plasma response is independent of the isotope used.

Response of the Plasmas to Pellet Injection

The dominant factor affecting the plasma response to pellet injection is the density of the plasma after pellet injection. Shots from the pellet mass scan discussed in chapter 2, will be used to characterize the response of the plasma in terms of the size of the pellet injected. The density of the target plasma was consistent for each shot in the sequence, therefore the density after pellet injection was dependent only on the mass of the pellet.

Figure 3.1 shows the line-integrated electron density as measured by the 2-mm interferometer, the stored energy, the input ECH power, the ECE from the central region of the plasma, the ECE from the edge region of the plasma, and

the gas puff used to fuel the plasma, for a shot with a small pellet (16543).

The volume-averaged electron density before injection for these shots was $\langle \bar{n}_e \rangle \approx 3.9 \times 10^{12} \text{ cm}^{-3}$, and the stored energy was approximately 1.5 kJ at the time of injection. The gas puff for these shots was held constant at approximately 6 torr-l/s until the time of injection, at which point it was ramped to zero at $t \approx .5 \text{ s}$. The pellet was fired at $t \approx .250 \text{ s}$ and reached the plasma at $t \approx .257 \text{ s}$.

For shot 16543, the pellet ($N_p \approx 0.4 \times 10^{19}$ atoms) was too small to produce a noticeable change in the ECE or the measured stored energy. A small increase in the output of the 2-mm interferometer was observed at $t \approx .257 \text{ s}$.

Figure 3.2 shows the diagnostic waveforms for shot 16542 ($N_p \approx 0.6 \times 10^{19}$ atoms). The increase in the line-integrated electron density was approximately 47% of the pre-pellet value, and the stored energy of the plasma showed no response to the injection of the pellet. A noticeable drop in the level of the ECE can be observed at the time of injection, but the signal returned to the pre-pellet value within 40 ms.

Figure 3.3 shows the diagnostic waveforms for shot 16546 ($N_p \approx 1.01 \times 10^{19}$ atoms). The line-integrated electron density increased by approximately 70% of the pre-pellet value at the time of injection, and instead of immediately relaxing to the pre-pellet value, it assumed an intermediate value at which it remained steady. The stored energy increased at the time of injection for this case, and then decreased as the density eventually returned to its pre-pellet value. The response of the ECE was roughly inversely proportional to that of the density measurement. The emission level dropped quickly at the time of injection and then recovered to an intermediate value. At this point, the plasma had increased stored energy and density, and reduced temperature. At $t \approx .277 \text{ s}$, the line-integrated electron density began to decrease and the ECE increased, as the plasma traded off density

Shot #16543

1 Tesla

Standard Configuration

Gyrotron #1 & #2

Line-averaged density at time of injection: $3.9 \times 10^{12} \text{ cm}^{-3}$

Number of atoms in pellet: 0.4×10^{19}

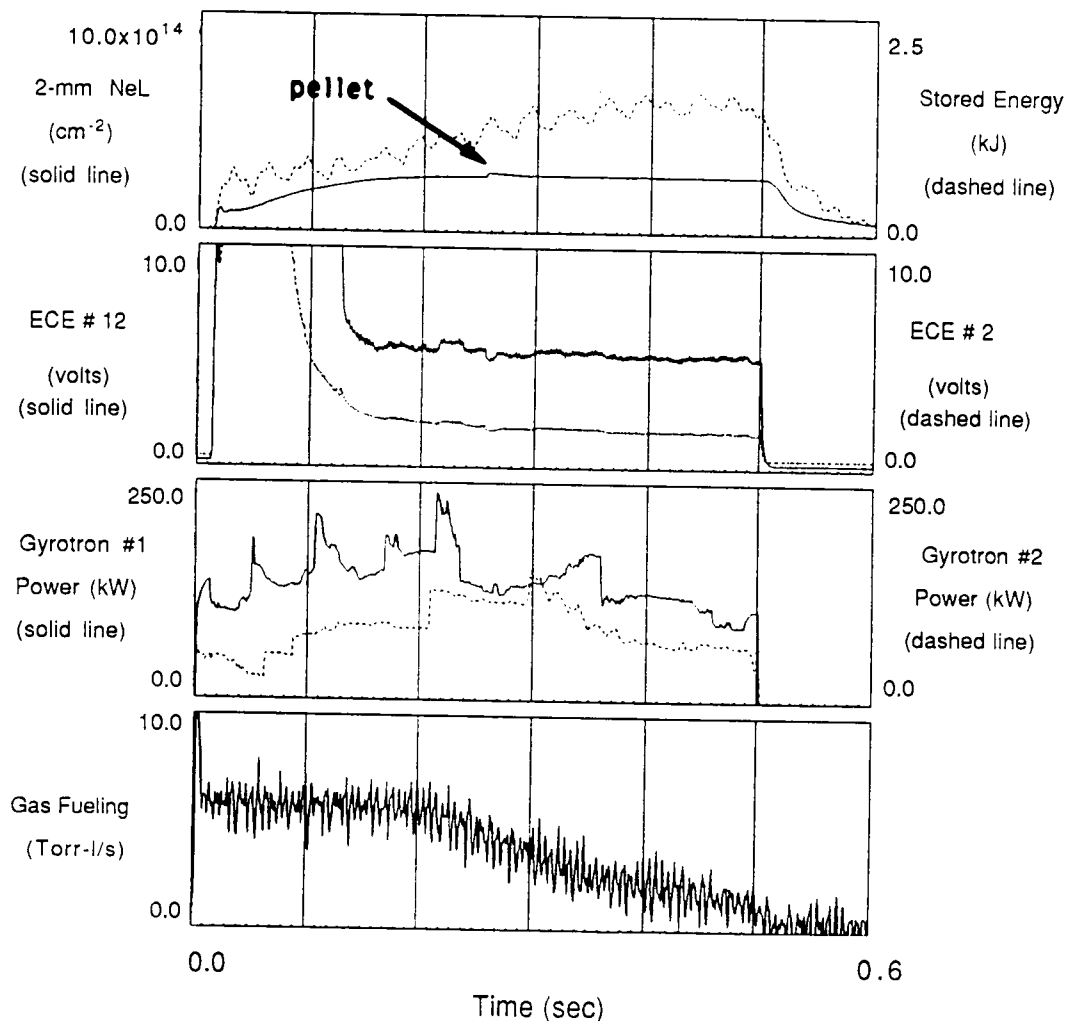


Figure 3.1: Diagnostic waveforms for shot 16543. The pellet entered the plasma at $t \approx .257 \text{ s}$, and made only small perturbation in the plasma parameters.

Shot #16542

1 Tesla

Standard Configuration

Gyrotron #1 & #2

Line-averaged density at time of injection: $3.9 \times 10^{12} \text{ cm}^{-3}$

Number of atoms in pellet: 0.6×10^{19}

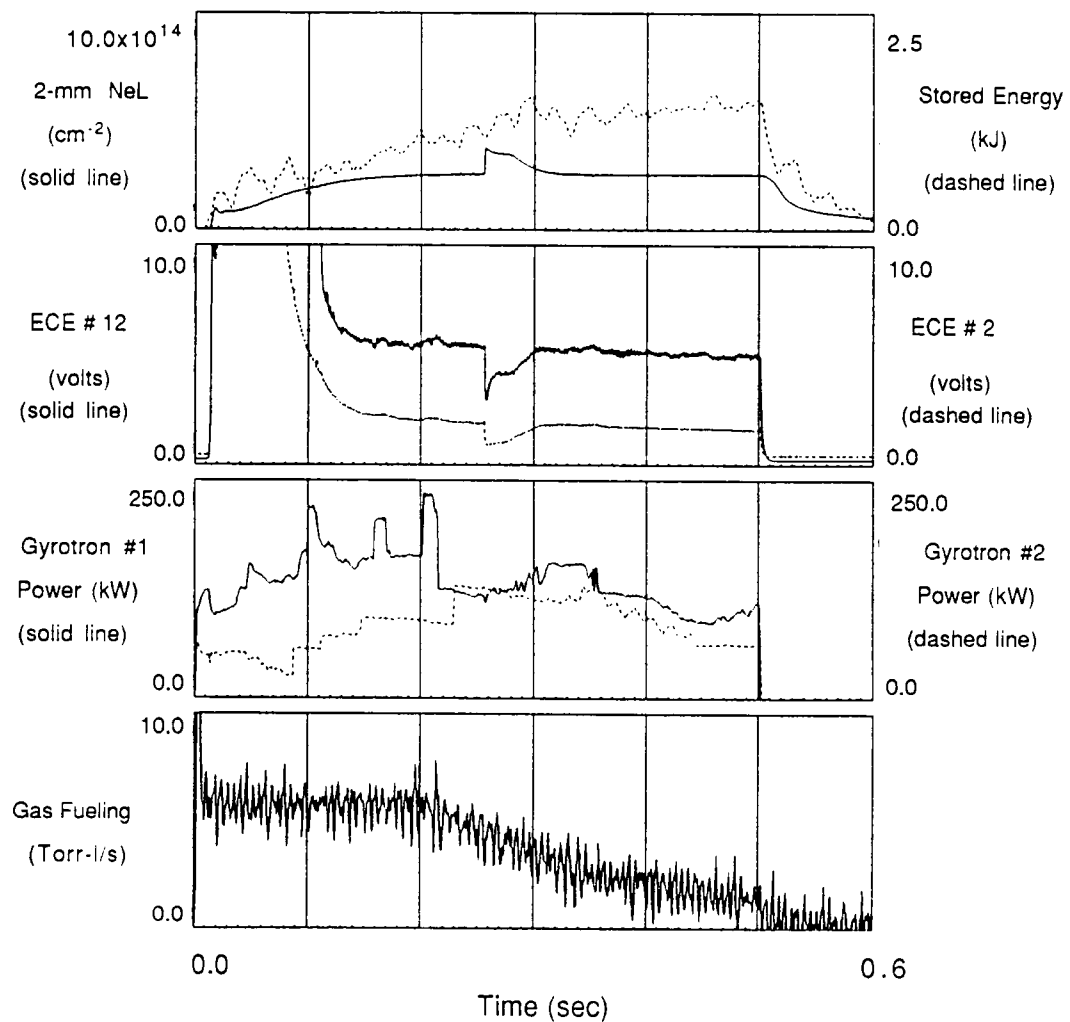


Figure 3.2: Diagnostic waveforms for shot 16542.

for temperature. The plasma had returned to the pre-pellet parameters at $t \approx .348$ s.

Figure 3.4 shows the diagnostic waveforms for shot 16548 ($N_p \approx 2.8 \times 10^{19}$ atoms). The line-integrated electron density after injection was approximately 2.3 times that of the pre-pellet value. Again, the stored energy increased at the time of injection, however for this shot, the density continued to increase after injection. For the smaller pellets, the density after the pellet was injected was the peak density for the shot. The density reached a level where it remained constant for a period of approximately 70 ms, until the end of the shot. The ECE intensity at the edge region of the plasma was reduced to a near zero level immediately after injection and never recovered. The ECE from the central region of the plasma decreased to a value of approximately 1/4 of the pre-pellet value. The emission remained at or below this value until the end of the shot. At this time the plasma had increased stored energy and density, but very low temperature.

The injection of the pellet in shot 16548 seems to have brought the plasma to the edge of an operational boundary for these target plasma conditions. This can be seen more clearly by examining the plasma response to the injection of a larger pellet. Figure 3.5 shows the diagnostic waveforms for shot 16544 ($N_p \approx 3.0 \times 10^{19}$ atoms). The plasma density response was similar to that for 16548, however the stored energy experienced a collapse and recovery in shot 16544. It is likely that the stored energy was beginning to collapse in shot 16548, but the end of the shot arrived before the collapse could fully evolve. In shot 16544, the ECE was significantly reduced at the time of injection, and gradually decreased in both the edge and central region. The signal remained constant until $t \approx .36$ s, at which point it decreased to a near zero value, corresponding to a drop in the stored energy. The stored energy dropped to near the pre-pellet value and remained there for approximately 50 ms. At $t \approx .465$ s, the ECE in the central

Shot #16546

1 Tesla

Standard Configuration

Gyrotron #1 & #2

Line-averaged density at time of injection: $3.9 \times 10^{12} \text{ cm}^{-3}$

Number of atoms in pellet: 1.0×10^{19}

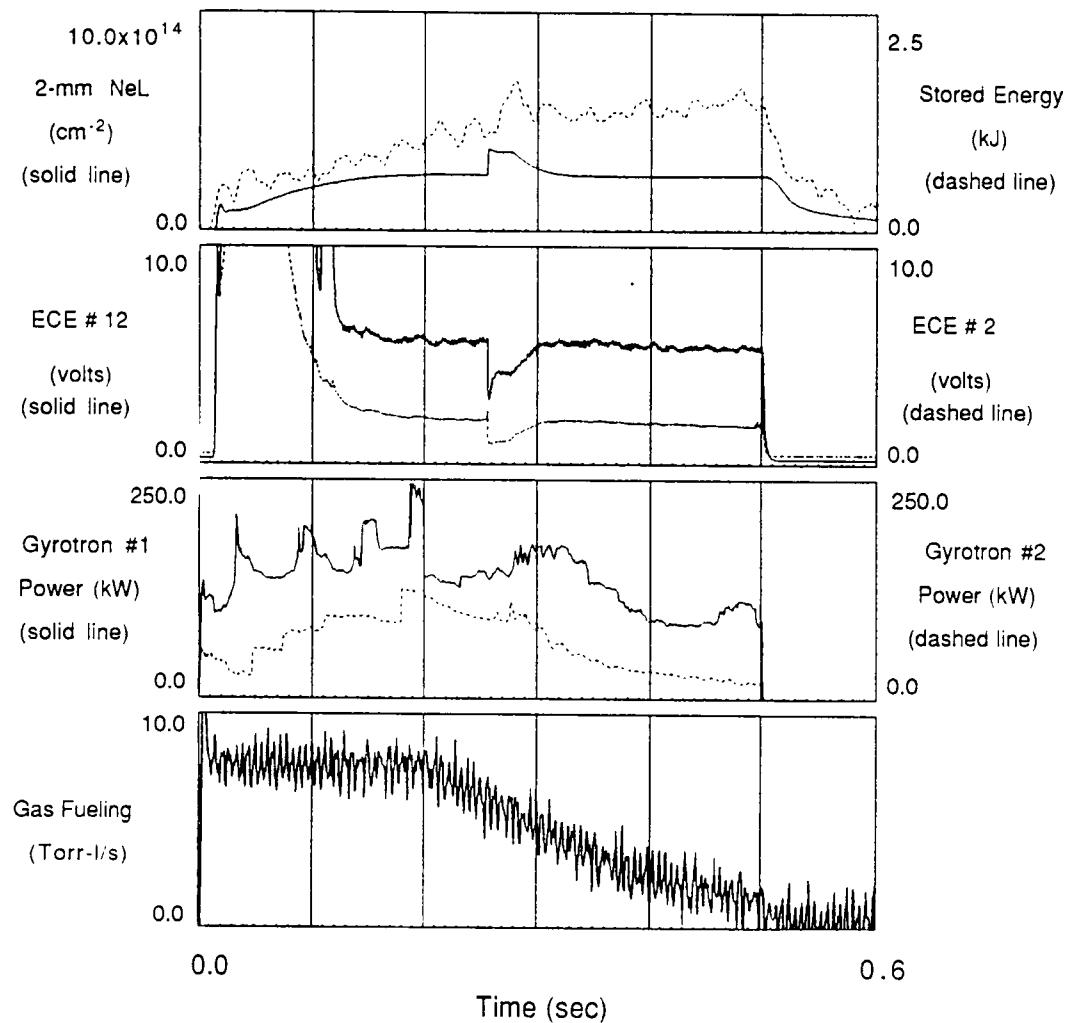


Figure 3.3: Diagnostic waveforms for shot 16546.

Shot #16548

1 Tesla

Standard Configuration

Gyrotron #1 & #2

Line-averaged density at time of injection: $3.9 \times 10^{12} \text{ cm}^{-3}$

Number of atoms in pellet: 2.8×10^{19}

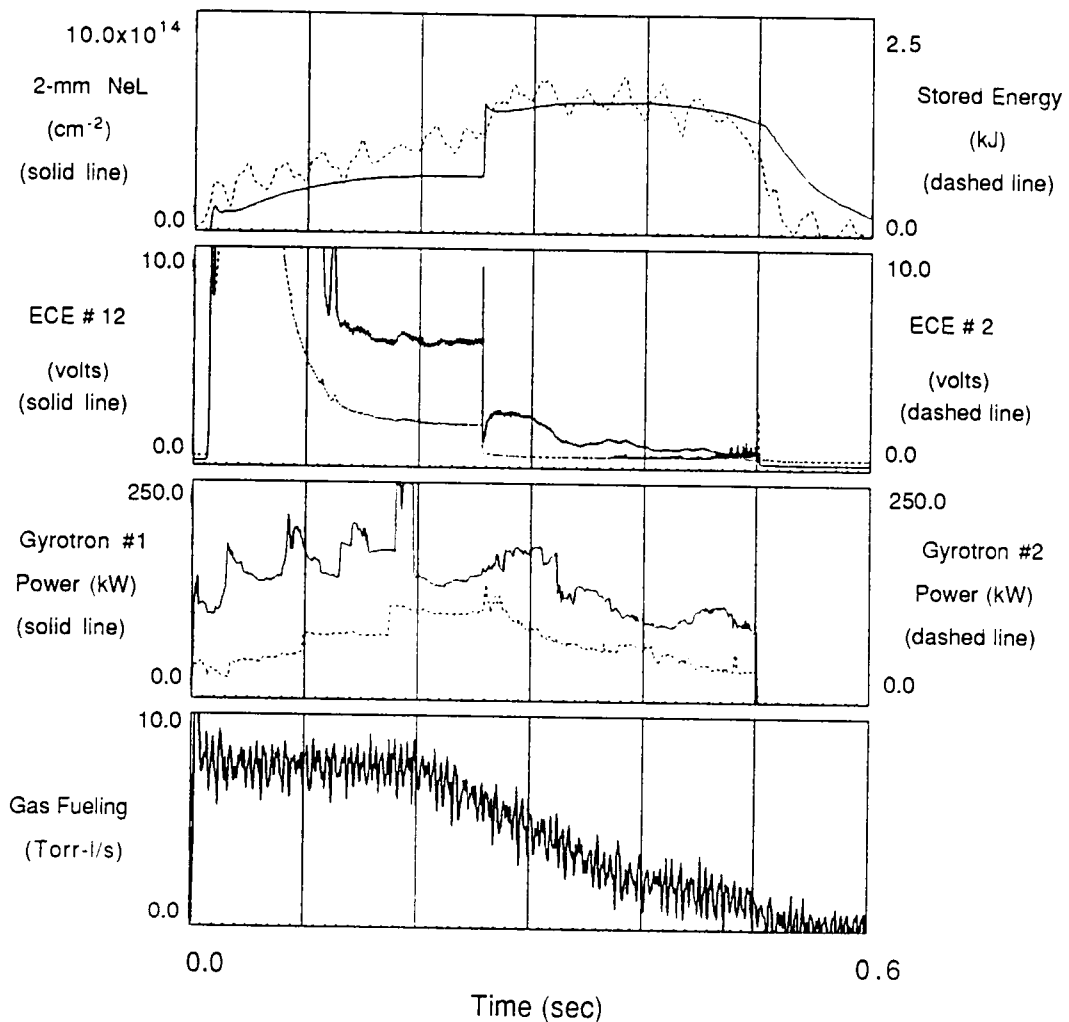


Figure 3.4: Diagnostic waveforms for shot 16548. The stored energy increased due to the injection of the pellet.

region began to recover, as did the stored energy. The density at this point was slowly varying.

At $t \approx .48$ s the emission level in channel #2, which detects emission from the region of the plasma corresponding to $\rho \approx .7$, increased sharply. Corresponding to the time of the recovery of the edge emission, there was a rapid decrease of the plasma density and the stored energy peaked and began to decrease. The end of the shot occurred just as the density was returning to the pre-pellet value and the ECE had recovered to approximately 1/2 of the pre-pellet value.

If the pellet mass is increased, a reproducible response to pellet injection is observed. Figure 3.6 shows the response for shot 16549 ($N_p \approx 3.7 \times 10^{19}$ atoms). The stored energy began to drop immediately after injection, and the ECE level was immediately reduced to a near zero level in both the central and edge regions of the plasma. The density decayed slowly after injection until the beginning of the recovery of the ECE in the central region. At $t \approx .42$ s, the ECE recovered in the edge region, and at that time the density decayed back to the pre-pellet value. The stored energy peaked and returned to approximately the pre-pellet value.

If the pellet is made large enough, the plasma will undergo a complete thermal collapse from which it will not recover before the end of the discharge. An example of this is shot 16553 ($N_p \approx 16 \times 10^{19}$ atoms). The diagnostic waveforms for shot 16553 are shown in Figure 3.7.

Energy Confinement After Pellet Injection

The beneficial effects of pellet injection on the energy confinement of the plasma can be observed during shots in which the stored energy increased immediately after pellet injection. The top graph in Figure 3.8 shows a plot of the $\bar{n}_e \ell$ and the stored energy for shot 18849. The stored energy increased with increasing

Shot #16544

1 Tesla

Standard Configuration

Gyrotron #1 & #2

Line-averaged density at time of injection: $3.9 \times 10^{12} \text{ cm}^{-3}$

Number of atoms in pellet: 3.0×10^{19}

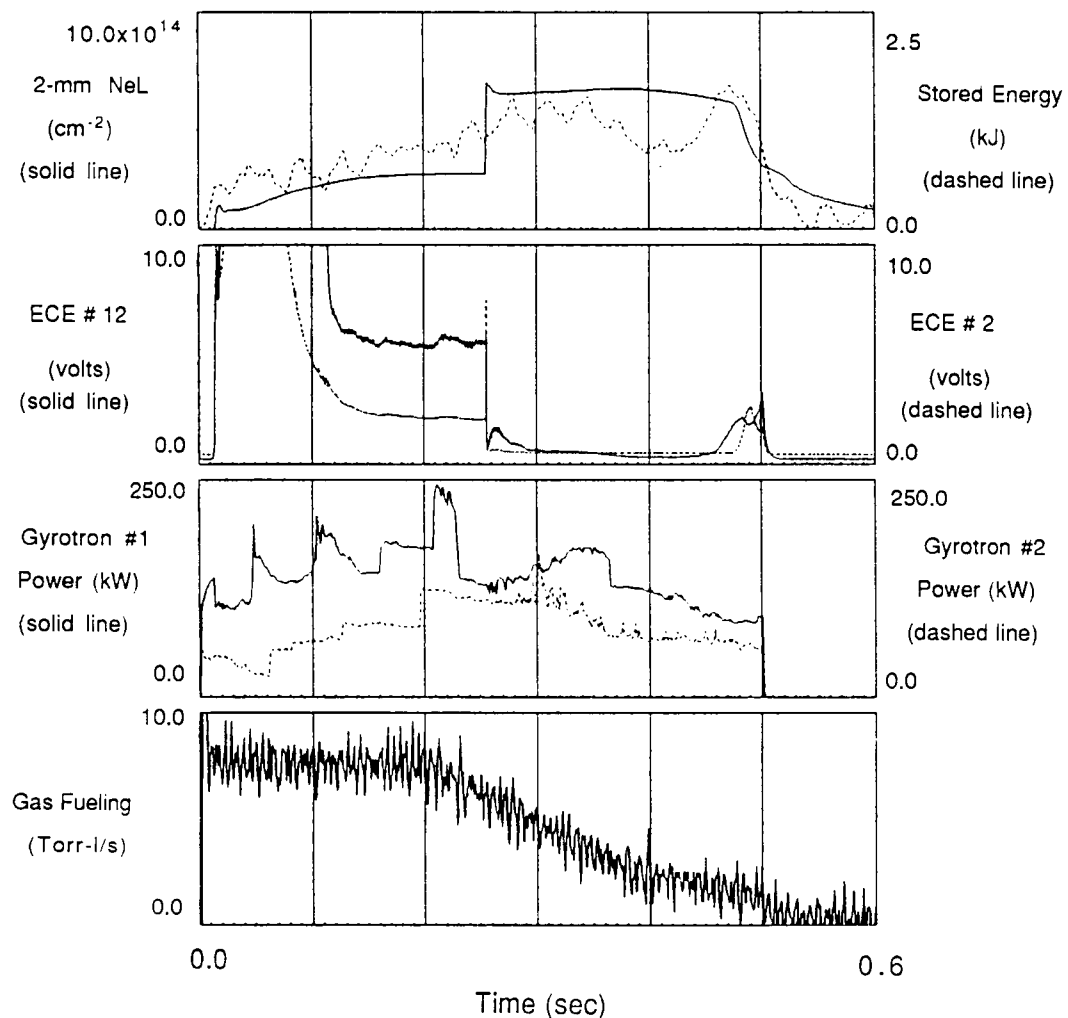


Figure 3.5: Diagnostic waveforms for shot 16544. The stored energy increased at the time of injection, but eventually suffered a thermal collapse.

Shot #16549

1 Tesla

Standard Configuration

Gyrotron #1 & #2

Line-averaged density at time of injection: $3.9 \times 10^{12} \text{ cm}^{-3}$

Number of atoms in pellet: 3.7×10^{19}

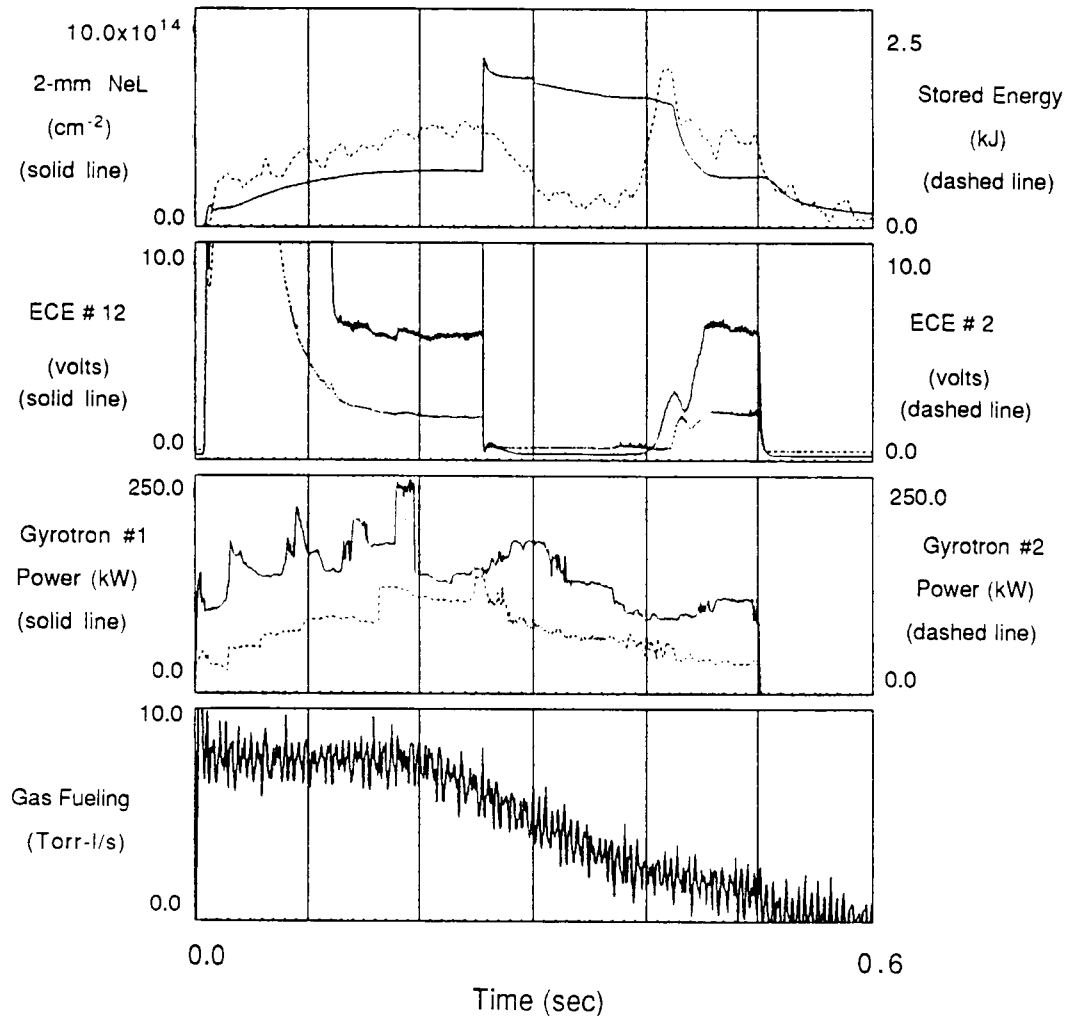


Figure 3.6: Diagnostic waveforms for shot 16549. A thermal collapse occurred almost immediately after pellet injection.

Shot #16553

1 Tesla

Standard Configuration

Gyrotron #1 & #2

Line-averaged density at time of injection: $3.9 \times 10^{12} \text{ cm}^{-3}$

Number of atoms in pellet: 16×10^{19}

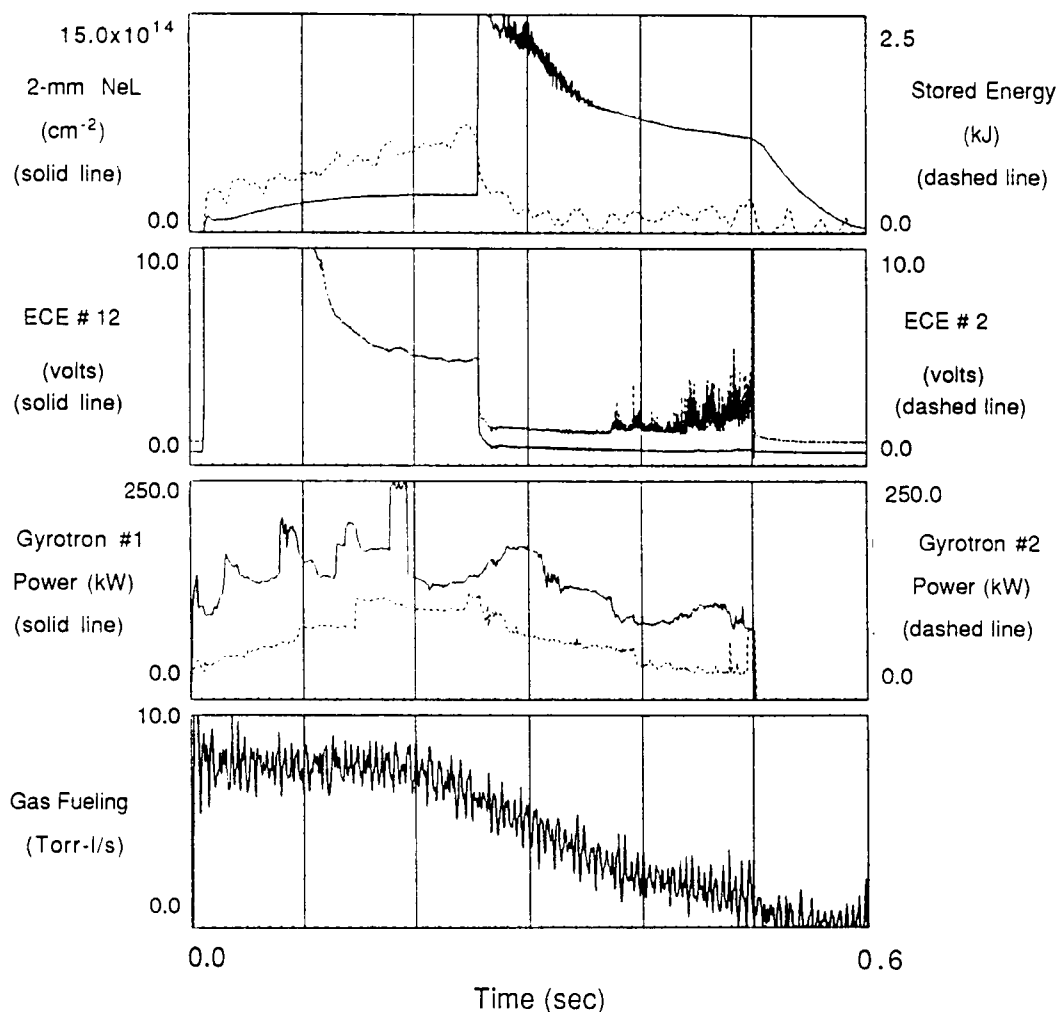


Figure 3.7: Diagnostic waveforms for shot 16553. The injection of the pellet caused a complete collapse of the plasma stored energy. The plasma did not recover from the collapse.

density due an increased gas puff (signal not available). The diagnostic waveforms are shown in Figures 3.9 for shot 18770. In this case a pellet ($N_p \approx 1.25 \times 10^{19}$ atoms) was injected, and the stored energy increased after injection. For shot 18770, when $\bar{n}_e \ell \approx 5.5 \times 10^{14} \text{ cm}^{-2}$, the corresponding stored energy was 1.4 kJ. For shot 18849, when $\bar{n}_e \ell \approx 5.5 \times 10^{14} \text{ cm}^{-2}$, the corresponding stored energy was 1.1 kJ. The stored energy is plotted as a function of the density for the two shots in Figure 3.10.

It is important to note that the value of the $\bar{n}_e \ell$ is a function of the shape of the density profile, and based on the inversion of the FIR interferometer data. The density profile usually becomes more peaked following pellet injection, as can be seen in Figure 1.8. For two identically shaped plasmas with the same value of a line-integrated density measurement through the center of the plasma, the plasma with the most peaked profile actually has fewer total particles. Therefore, the increase in stored energy for the same value of $\bar{n}_e \ell$ for shot 18770 is not due to an overall increase in the total number of particles in the plasma, rather it is due to a density profile effect.

As the density profile relaxed to a broader profile in shot 18770, the enhancement of the stored energy due to the profile effect dissipated. For this shot the density did not evolve to the pre-pellet value before the end of the shot discharge, however it can be seen in Figure 3.10 that the pre-pellet dependence of the stored energy on the density was returning as the $\bar{n}_e \ell$ decreased.

The energy confinement time of the plasma τ_E can be expressed as

$$\tau_E = W/(P - dW/dt), \quad (3.1)$$

where W is the stored energy and P is the power input into the plasma. Based on the measured stored energy before the injection of the pellet (.7 kJ) and at the peak in the stored energy (1.4 kJ) in shot 18770, the energy confinement time

Shot #18849
 1 Tesla
 Prolate Configuration
 Gyrotron #1 & #2

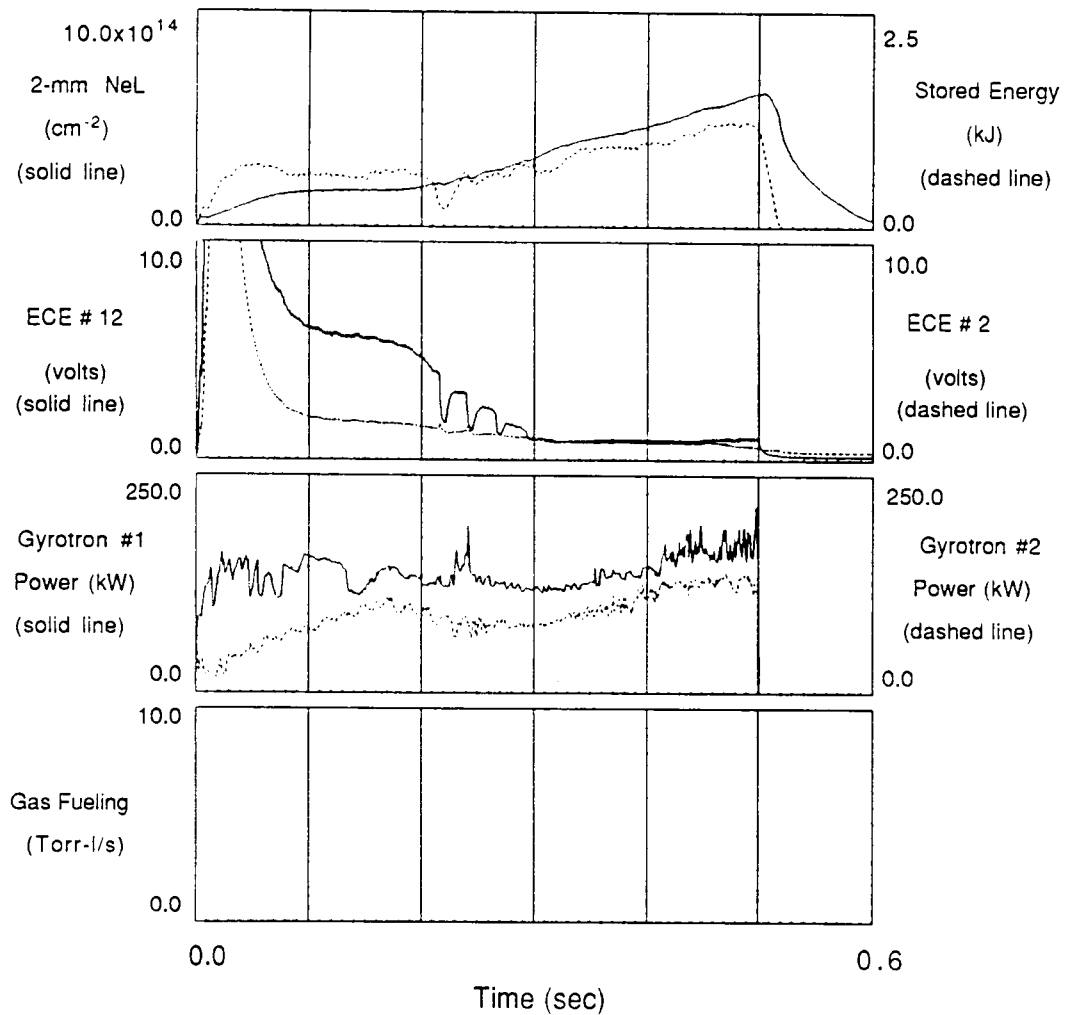


Figure 3.8: Diagnostic waveforms for shot 18849. The density increased due to an increased gas puff.

Shot #18870

1 Tesla

Prolate Configuration

Gyrotron #1 & #2

Line-averaged density at time of injection: $3.5 \times 10^{12} \text{ cm}^{-3}$

Number of atoms in pellet: 2.5×10^{19}

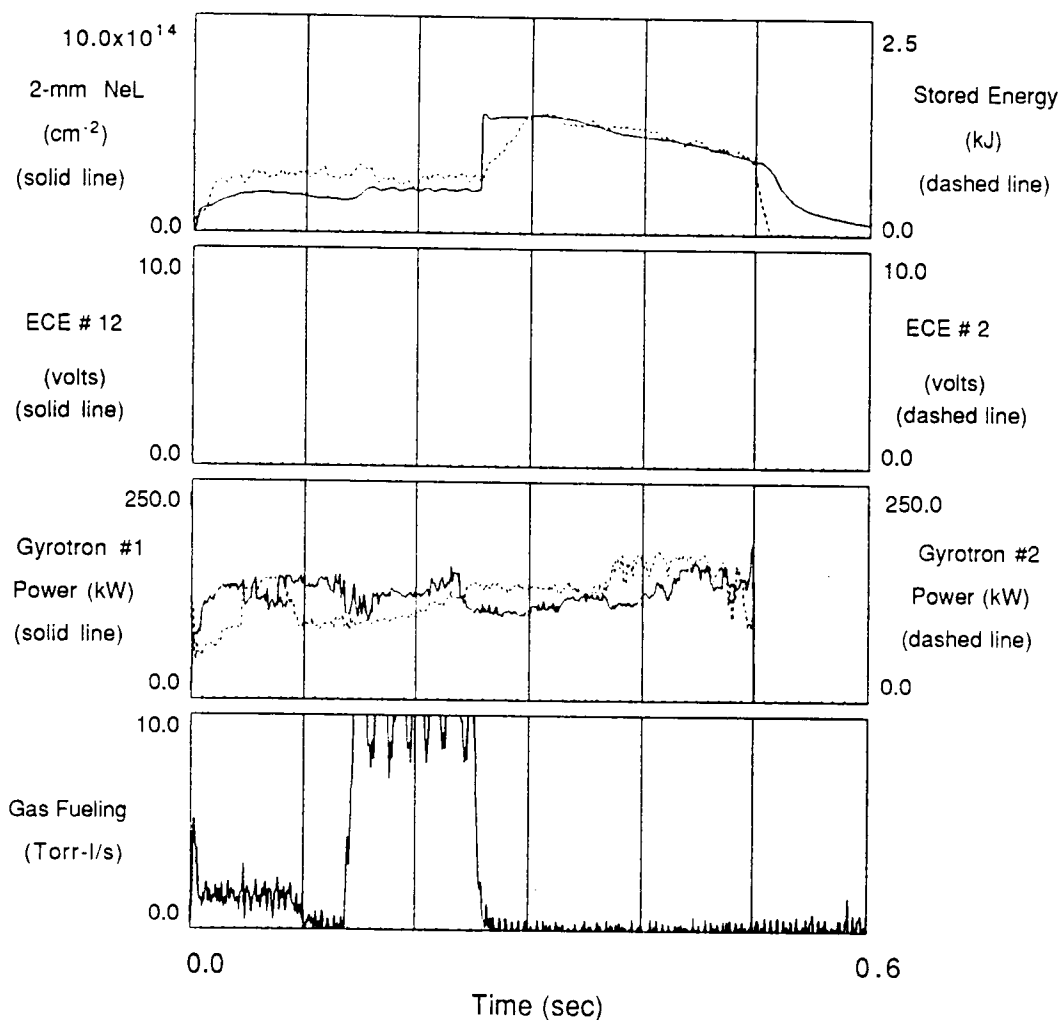


Figure 3.9: Diagnostic waveforms for shot 18770. The stored energy increased due to the injection of the pellet. The stored energy increased from approximately .7 kJ to 1.4 kJ.

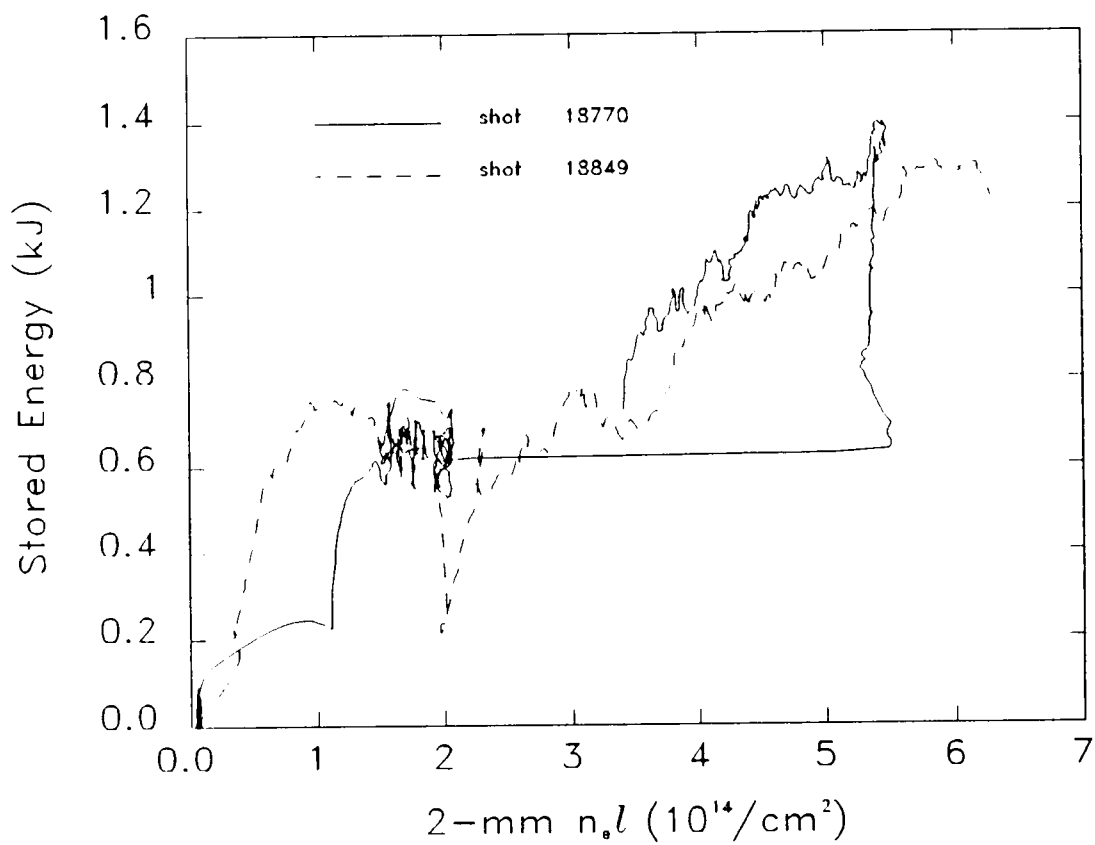


Figure 3.10: Stored energy plotted against 2-mm $\bar{n}_e l$ for shots 18849 and 18770. There is a modest enhancement of the stored energy for the pellet fueled case.

of the plasma improves by a factor of approximately 2 due to the injection of the pellet. Some statistical information for the shots with this response to pellet injection is presented in Table I.

Table I
Information about Plasmas with Increased Stored Energy
due to Pellet Injection

Average $\langle n_e \rangle$ before injection	$4.2 \times 10^{12} \text{ cm}^{-3}$
Average $\langle n_e \rangle$ after injection	$7.8 \times 10^{12} \text{ cm}^{-3}$
Minimum $\langle n_e \rangle$ after injection	$6.6 \times 10^{12} \text{ cm}^{-3}$
Maximum $\langle n_e \rangle$ after injection	$11.8 \times 10^{12} \text{ cm}^{-3}$
Average W before injection	1.02 kJ
Average W at peak value during recovery	1.54 kJ
Average duration of response	129 ms

The Pellet-Induced Collapse and Recovery

Thermal collapses of ATF discharges have been related to vacuum vessel wall conditioning. Steps to mitigate thermal collapses and produce higher density discharges that last longer have been successful, however the mechanics of the thermal collapse have not yet been fully understood. It has been found that pellet injection can instigate a thermal collapse in a reproducible manner, which permits systematic study of the collapse, recovery, and subsequent density relaxation. The behavior of the pellet-induced collapse and recovery has been examined and it is

characterized based on the observations of 61 shots. The effect of changing the operating conditions of the ATF on the response will also be discussed.

The values of the stored energy and the 2-mm $\bar{n}_e \ell$, at four times of interest during 61 shots that underwent the pellet-induced collapse and recovery have been examined. The times of interest are (1) just before pellet injection, (2) just after pellet injection, (3) just before the density begins to relax, and (4) after the plasma has returned to the pre-pellet condition. These times of interest are marked for shot 12935 in Figure 3.11. Information describing the average characteristics of these 61 shots is listed in Table II.

Table II
Information about Pellet-Induced Collapse and Recovery
Standard Configuration

Average $\langle n_e \rangle$ before injection	$4.4 \times 10^{12} \text{ cm}^{-3}$
Average $\langle n_e \rangle$ after injection	$10.7 \times 10^{12} \text{ cm}^{-3}$
Minimum $\langle n_e \rangle$ after injection	$6.4 \times 10^{12} \text{ cm}^{-3}$
Maximum $\langle n_e \rangle$ after injection	$19.7 \times 10^{12} \text{ cm}^{-3}$
Average W before injection	1.25 kJ
Average W at peak value during recovery	1.56 kJ
Average duration of response	175 ms

All of these 61 shots had the standard magnetic configuration and were heated with both gyrotrons. It should be noted that a variety of gas fueling schemes, which affect the density before injection and the evolution of the pellet-induced collapse and recovery are represented in these shots.

Shot #12935

1 Tesla

Standard Configuration

Gyrotron #1 & #2

Line-averaged density at time of injection: $6.1 \times 10^{12} \text{ cm}^{-3}$

Number of atoms in pellet: NA

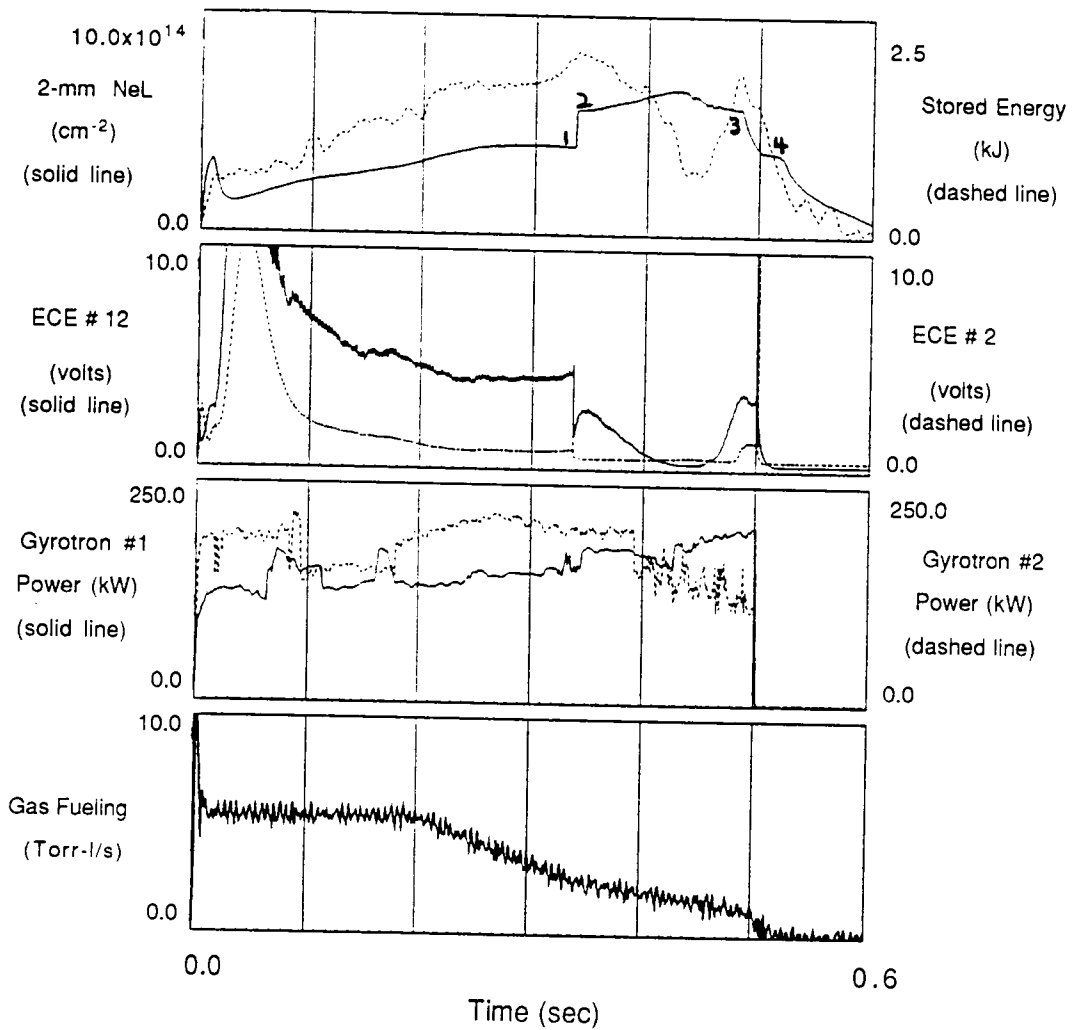


Figure 3.11: Diagnostic waveforms for shot 12935. The four times of interest are indicated for shots that underwent a pellet-induced collapse and recovery.

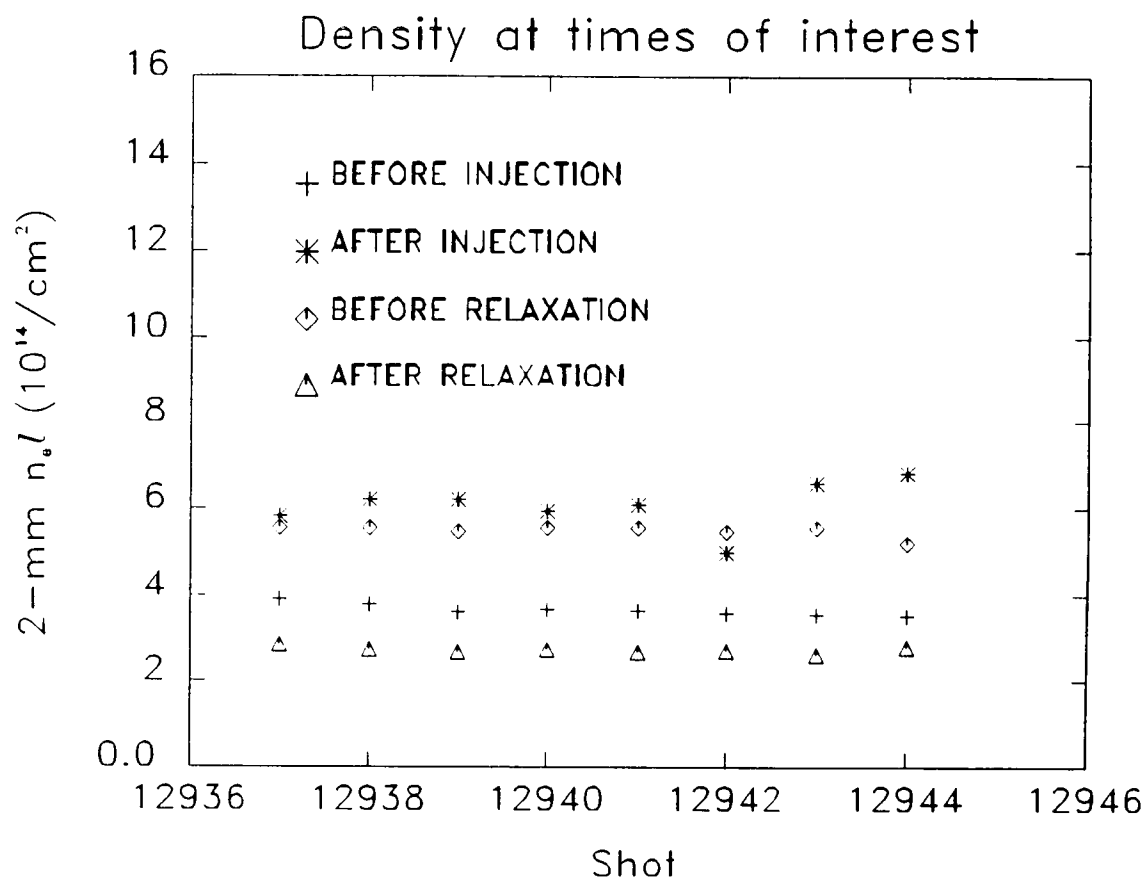


Figure 3.12: The 2-mm $\bar{n}_e l$ at the times of interest for shots 12936 through 12944.

Reproducibility of the Pellet-Induced Collapse and Recovery

A sequence of shots was taken to determine the reproducibility of the pellet-induced collapse and recovery. Shot 12935 is representative of the target plasmas used in shots 12936-12944. The pellets injected during this series of shots were formed under similar conditions and their masses do not vary widely. Figure 3.12 shows the value of the 2-mm $\bar{n}_e l$ at the times of interest for shots 12936-12944.

Although the density increase due to the injection of the pellet varied slightly, the density evolved to a consistent ($\langle \bar{n}_e \rangle \approx 9.1 \times 10^{12} \text{ cm}^{-3}$) value before

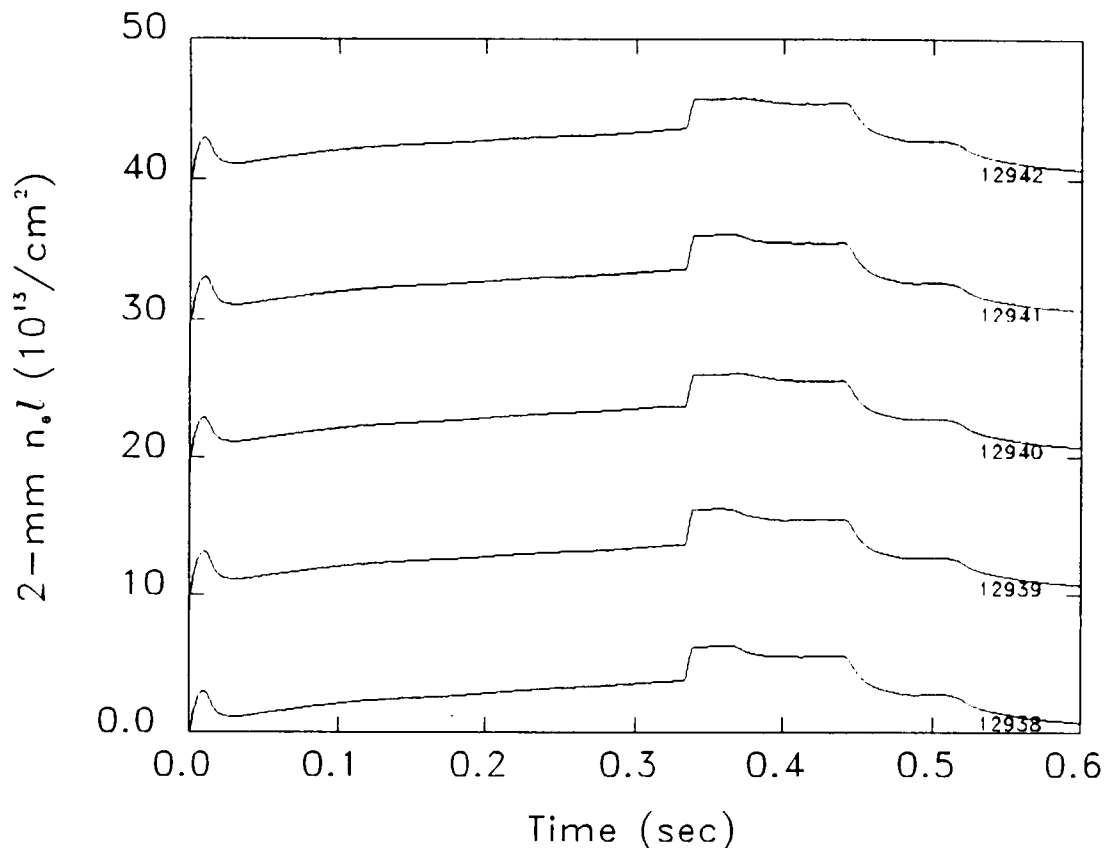


Figure 3.13: Plot of the 2-mm $\bar{n}_e l$ signals for a series of shots that underwent pellet-induced collapse and recovery. This demonstrates the reproducibility of the response. There is an offset between each shot of $10 \times 10^{14} \text{ cm}^{-2}$.

it relaxed back to approximately the pre-pellet value ($\langle \bar{n}_e \rangle \approx 4.5 \times 10^{12} \text{ cm}^{-3}$).

Figure 3.13 shows the 2-mm $\bar{n}_e l$ signal for shots 12938 through 12942 - overall, the response is very reproducible.

Timing of the Density Relaxation

Once the pellet mass is increased to the point where the thermal collapse occurs, an increase in the pellet mass will not alter the characteristics of the recovery of the plasma, however it will delay it. Figure 3.14 shows the values of the 2-mm $\bar{n}_e l$ at the times of interest for the shots in a pellet mass scan experiment that underwent the pellet-induced collapse and recovery. Figure 3.15 shows the 2-mm $\bar{n}_e l$ for several of the shots in this series. The change in the $\bar{n}_e l$ produced by

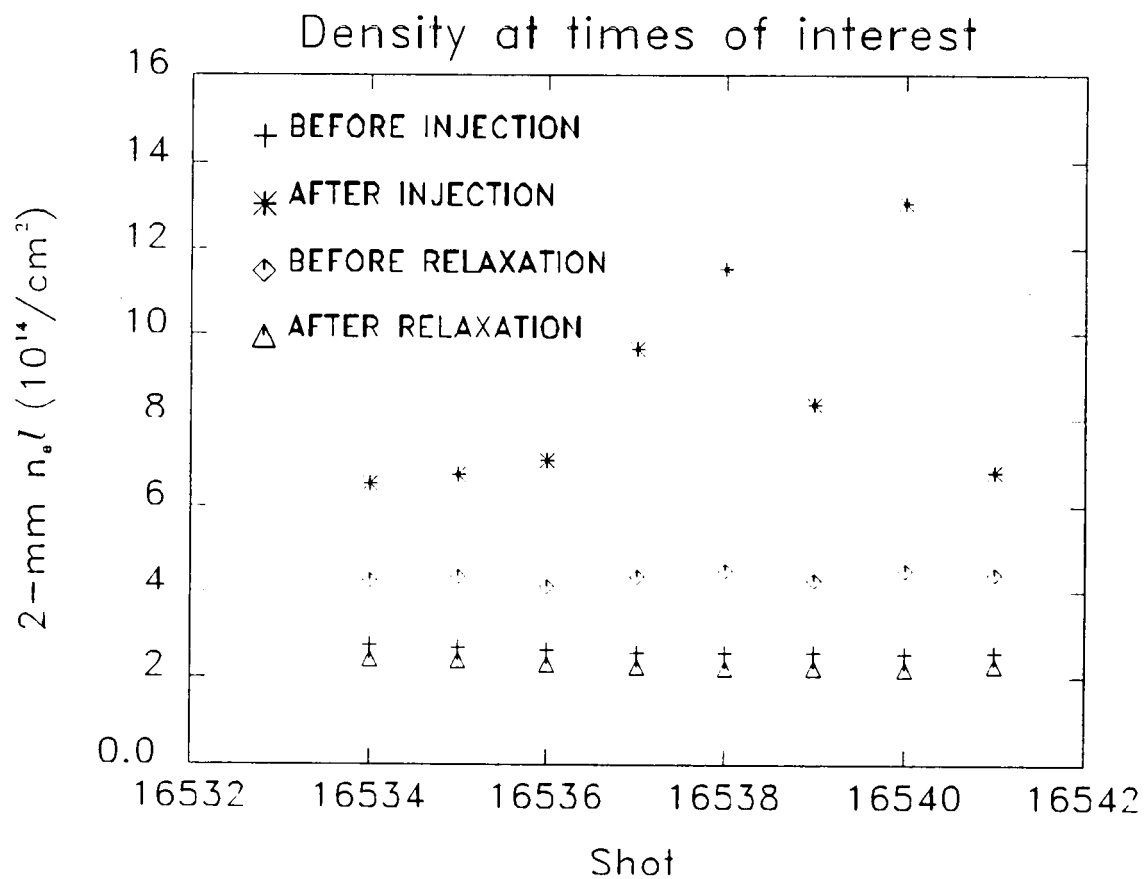


Figure 3.14: Value of the 2-mm $\bar{n}_e \ell$ at the time of interest for shots with a large range of pellet sizes. The density just before the density relaxation is independent of the size of the pellet.

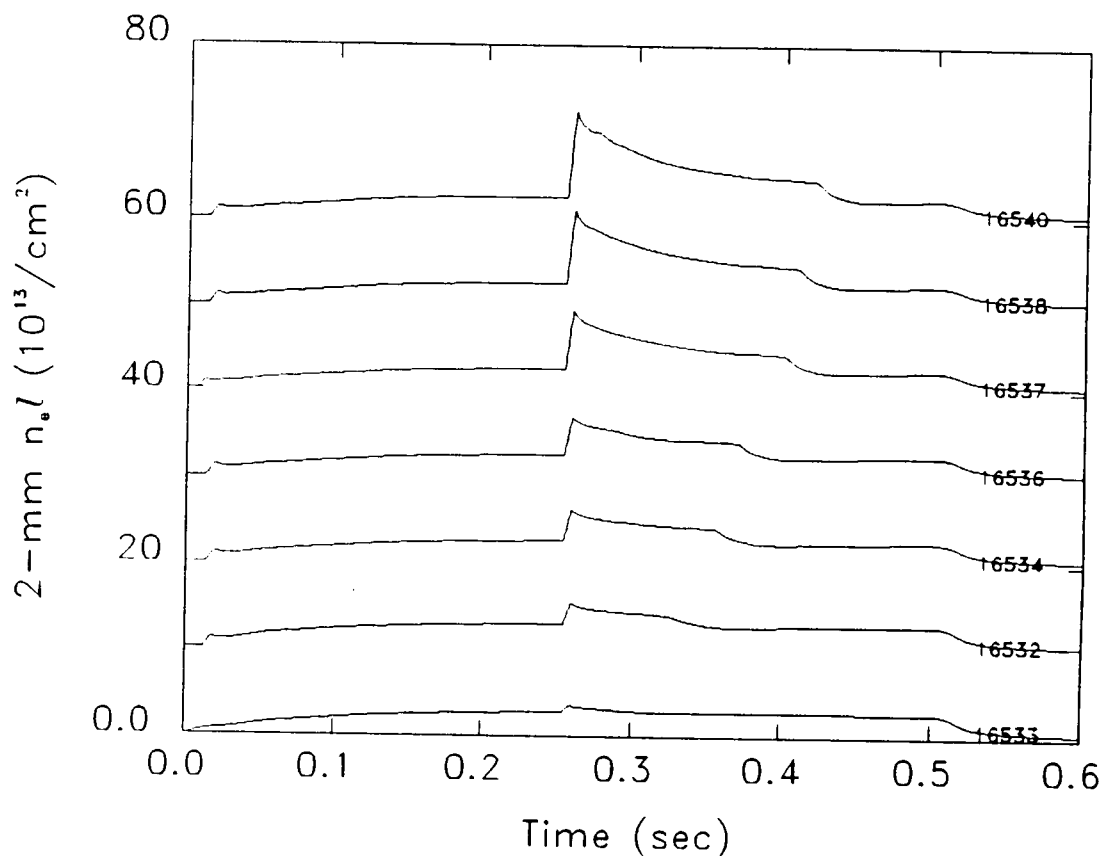


Figure 3.15: 2-mm $\bar{n}_e l$ signals for several shots in a pellet mass scan. There is an offset between each shot of $10 \times 10^{14} \text{ cm}^{-2}$.

the pellet varied by over a factor of 2, but the value of the density when it began to relax was independent of the size of the pellet, as was the density to which the plasma eventually decayed. What does change as a result of increased pellet size is the duration of time from the injection of the pellet to the beginning of the density relaxation. This can be seen graphically in Figure 3.15. This suggests that a plasma that suffers a collapse due to pellet injection will undergo a similar recovery regardless of pellet size. It appears to take the plasma longer to evolve to a condition where the recovery can begin if more mass is added to the plasma by the injection of a larger pellet. If the heating, gas fueling, and the magnetic configuration of the plasma are consistent, then the recovery from pellet-induced

collapse will also be consistent.

Effect of Gas Fueling on the Response to Pellet Injection

The pellet-induced collapse and recovery was produced in two series of plasmas with different levels of gas fueling during the response. Figure 1.9 shows the gas puff used for the reduced edge fueling case and Figure 3.1 shows the gas puff used for the increased edge fueling case. The gas puff was reduced to a near zero value at $t \approx .05$ s in one series and it was ramped down from 6 torr-l/s at the time of injection to zero at $t \approx .5$ s for the other series. Shots 16542 through 16553 had increased edge fueling. Figure 3.16 shows a plot of the 2-mm $\bar{n}_e \ell$ at the four times of interest for both series of shots. The value of the density when it began to relax was higher for the plasmas with the additional gas fueling after injection, but the density of the plasma after the density relaxation was approximately the same for the two cases.

Multiple Pellet Injection Experiments

The transition from the period of recovery where the density is steady, or slowly varying, to the period of rapid density loss occurs suddenly. An experiment was performed to help characterize the evolution of this transition by injecting a second pellet into the plasma at various stages of the recovery from the thermal collapse and measuring the ablating capabilities of the plasma. Measurement of the D_α emission from the second pellets provides an indication of the ablating potential of the plasma, and thus the local electron temperature at the corresponding pellet position. Figure 3.17 shows the 2-mm $\bar{n}_e \ell$ signals for several of the two pellet shots.

Figure 3.18 shows the D_α emission of the first pellet for a typical shot in

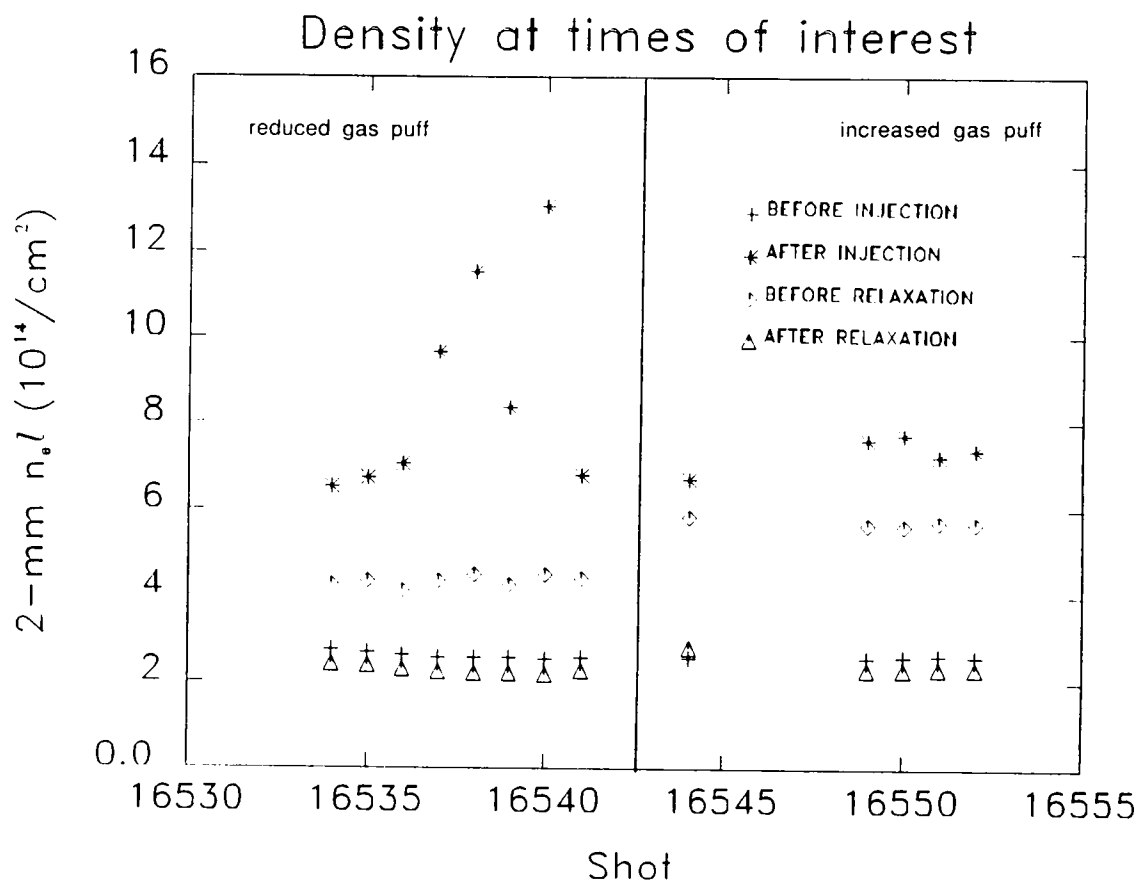


Figure 3.16: Comparison of the values of the 2-mm $\bar{n}_e l$ at the times of interest for a series of shots with increased gas puffing after pellet injection, to those with reduced gas puff.

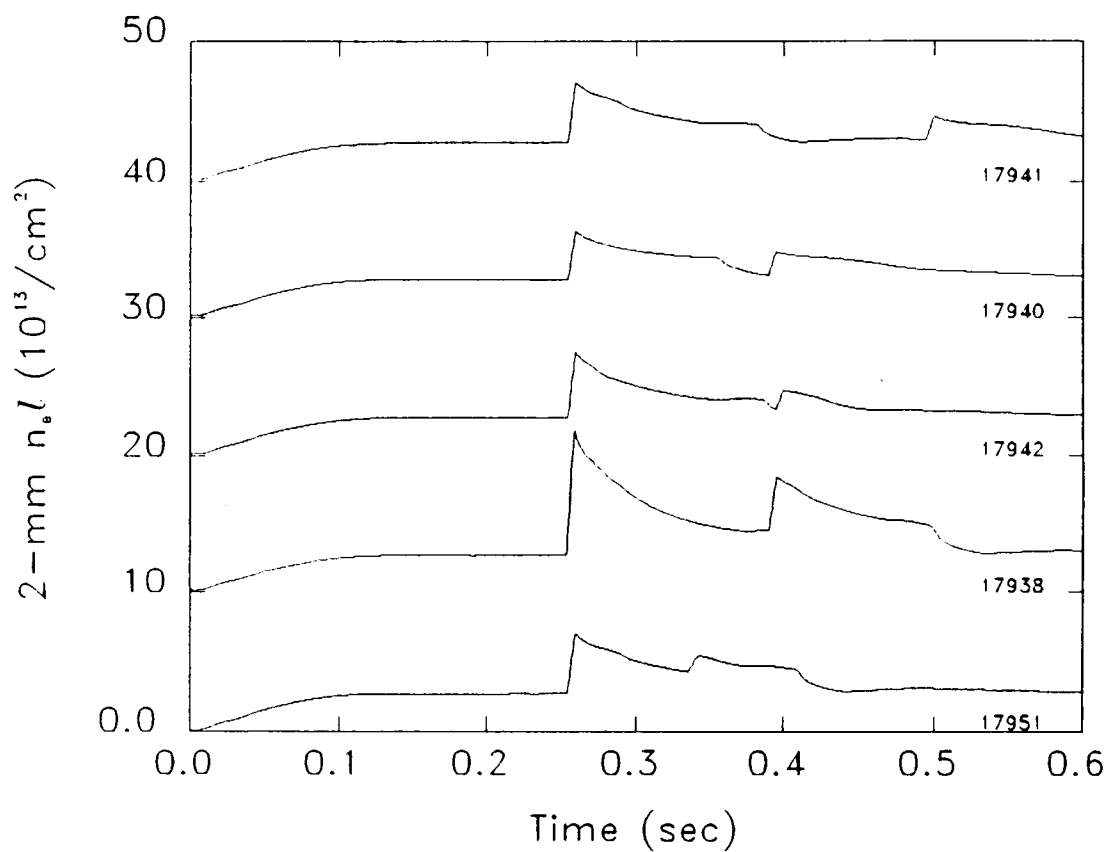


Figure 3.17: 2-mm $\bar{n}_e l$ signals for a series of shots in which the second pellet arrived at various times during the recovery from the pellet induced-collapse of the first pellet. There is an offset between each shot of $10 \times 10^{14} \text{ cm}^{-2}$.

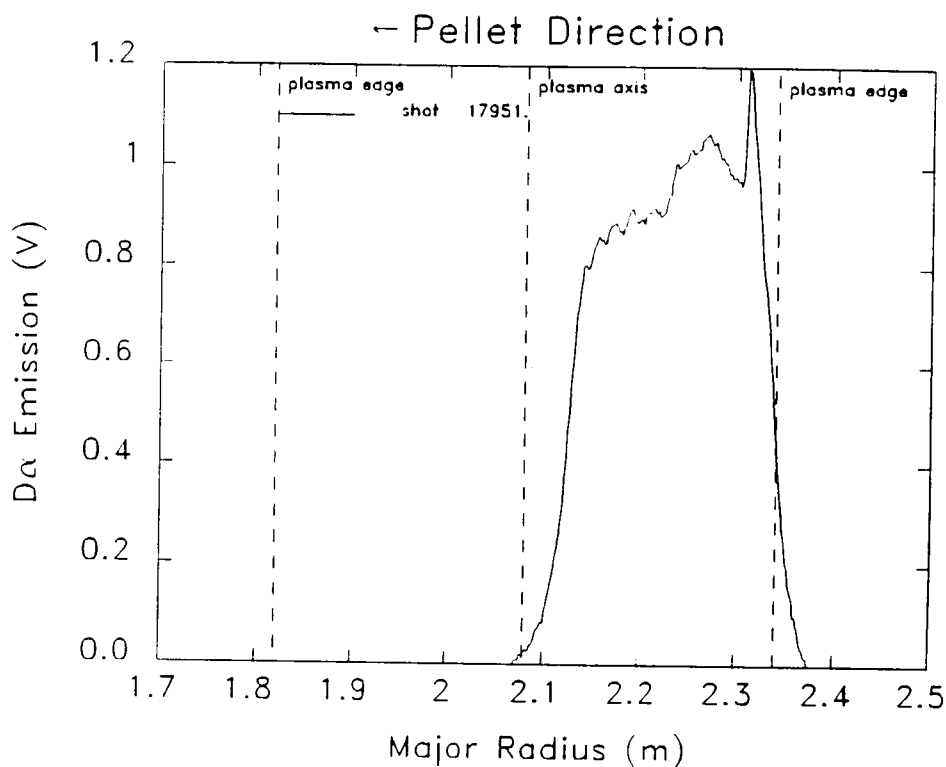


Figure 3.18: D_{α} emission for shot 17951. The emission is typical of that observed for a 1-Tesla, ECH heated, ATF plasma.

the sequence (shot 17951). The emission is typical of that observed for a 1-Tesla, ECH, ATF plasma. After an initial peak in the emission at the plasma edge, the D_{α} emission dropped to an average value of approximately .9 volts, and remained steady until the end of the pellet lifetime, which occurred near the center of the plasma.

Figure 3.19 shows the measured D_{α} emission from several of the second pellets. The plasma had very little ablating potential at the edge of the plasma during the period of the recovery before the ECE from the edge region of the

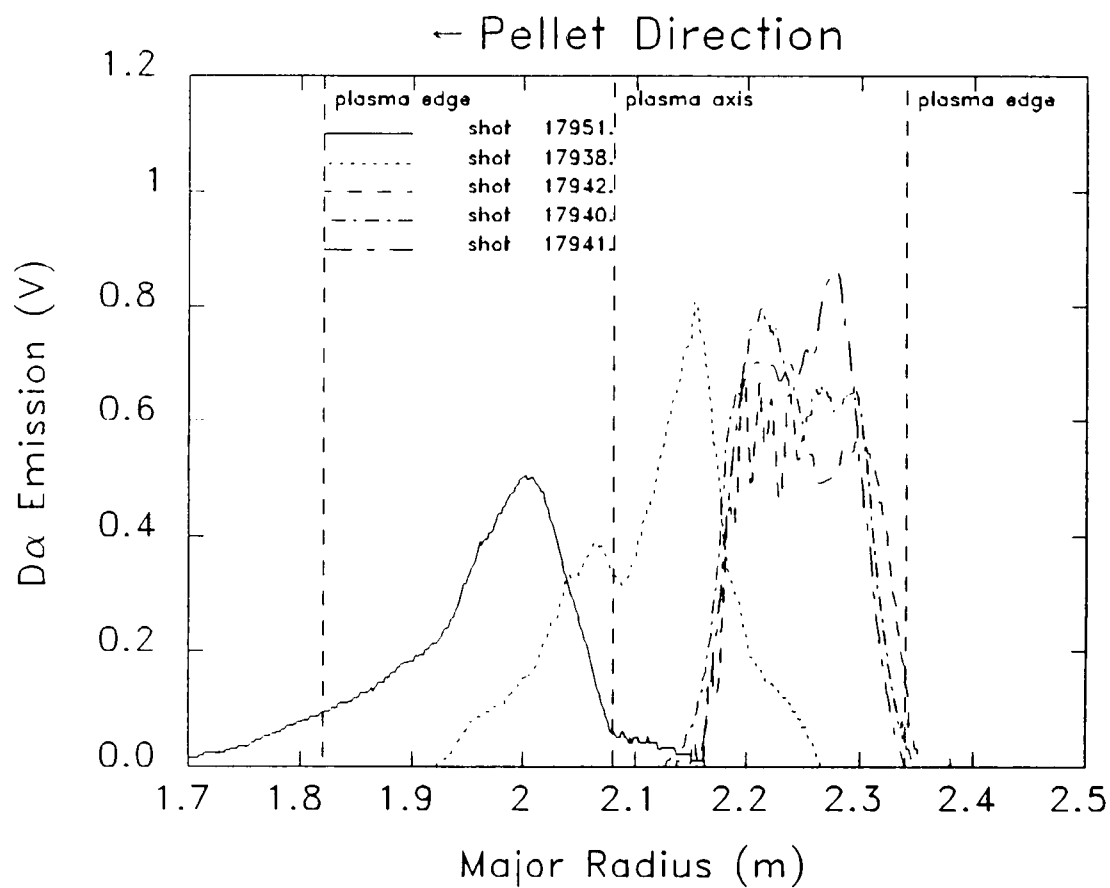


Figure 3.19: D_{α} emission for a series of pellets that were injected at various stages of the pellet-induced collapse and recovery. The emission in the edge region of the plasma is higher for the pellets that were injected after the density began to return the pre-pellet value.

plasma recovered (shot 17951). The peak of the emission is shifted to $R \approx 2$ m.

The D_α emission from pellets arriving before the density began to relax differ significantly from those in which the pellets arrived after. In shot 17942, the second pellet arrived just after the density began to return to the pre-pellet value. The emission from the pellet in the edge region of the plasma has increased to almost equal that of the central region, and the leading edge of the emission is now clearly defined at 2.35 m. A short time later in the evolution, the peak in the edge region has increased (shot 17949) and eventually the emission from the second pellet became similar to that of the first.

Effect of Altering the Magnetic Configuration

The pellet-induced collapse and recovery was reproduced in plasmas that had an oblate magnetic configuration, and the diagnostic waveforms for a typical shot that underwent the pellet-induced collapse and recovery with this configuration are shown in Figure 3.20. Table III lists the same information for these shots that is provided in Table II for plasmas with the standard configuration.

The most notable differences between the response for the standard and the oblate configurations are that the stored energy is higher on average at the peak of the recovery than at the time of injection for the standard configuration and lower for the oblate case, and the value of the density when it begins to relax is much closer to the pre-pellet density for the prolate configuration than for the standard configuration. Although the stored energy is lower during the thermal recovery than at the time of injection for the oblate case, the stored energy at the time of the recovery for this case is slightly higher on average than that of the standard configuration case.

Shot #19248

1 Tesla

Oblate Configuration

Gyrotron #1 & #2

Line-averaged density at time of injection: $4.7 \times 10^{12} \text{ cm}^{-3}$

Number of atoms in pellet: 3.5×10^{19}

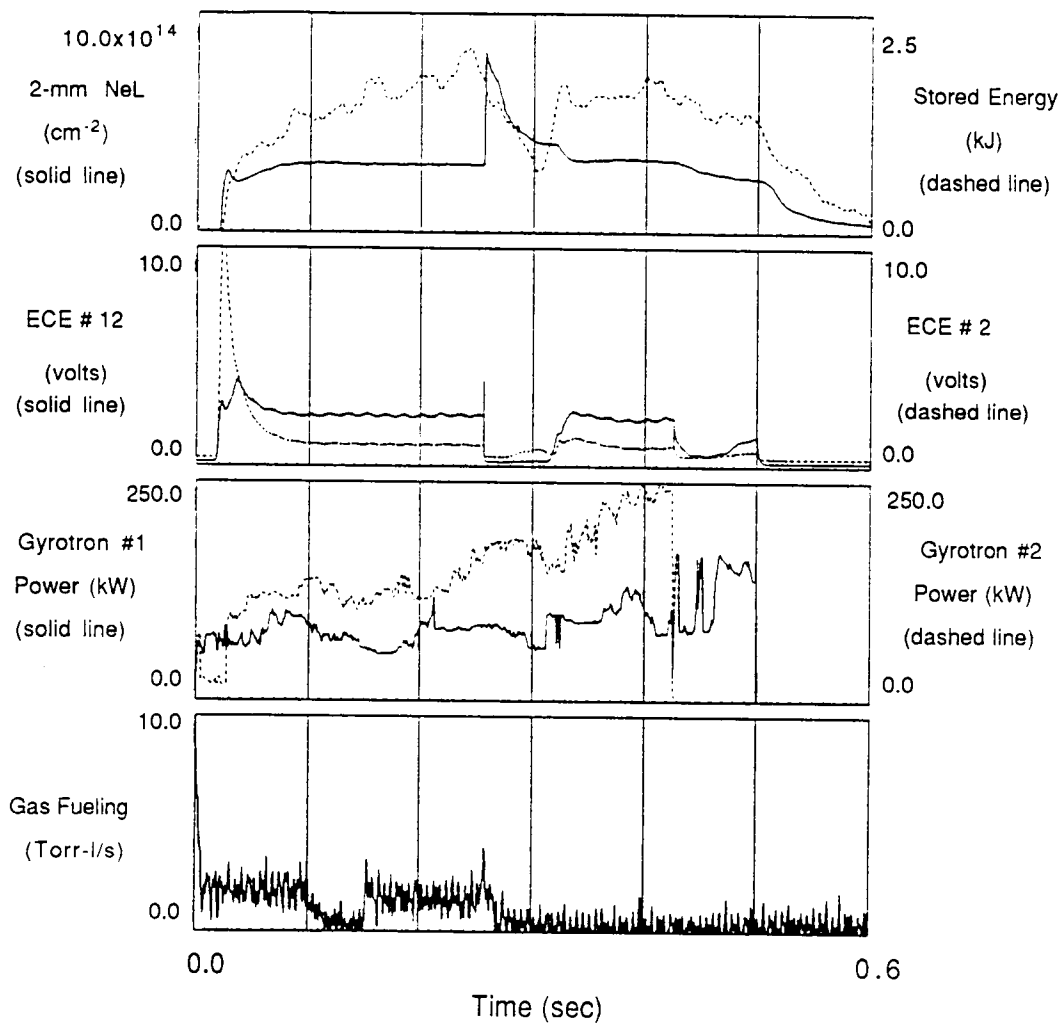


Figure 3.20: Diagnostic waveforms for a shot that underwent pellet-induced collapse and recovery with an oblate magnetic configuration.

Table III
Information about Pellet-Induced Collapse and Recovery
Oblate Configuration

Average $\langle n_e \rangle$ before injection	$4.1 \times 10^{12} \text{ cm}^{-3}$
Average $\langle n_e \rangle$ after injection	$9.6 \times 10^{12} \text{ cm}^{-3}$
Minimum $\langle n_e \rangle$ after injection	$7.8 \times 10^{12} \text{ cm}^{-3}$
Maximum $\langle n_e \rangle$ after injection	$14.7 \times 10^{12} \text{ cm}^{-3}$
Average W before injection	1.87 kJ
Average W at peak value during recovery	1.65 kJ
Average duration of response	85 ms

Summary

Small pellets that do not produce a substantial decrease in the ECE from the plasma usually produce no effect that lasts for more than 10-20 ms. The particles that are added to the plasma due to pellet injection are quickly lost. As larger pellets are injected, the decrease in the electron temperature at the time of injection becomes more substantial and the added particles remain in the plasma for a longer period before being lost. This is typically accompanied by an increase in the stored energy of the plasma. It was found that the stored energy after pellet injection was greater than that of plasmas with similar densities that were fueled by gas puffing only.

Increasing the pellet size above that which produced an increase in the stored energy of the plasma at the time of injection leads to a thermal collapse of the plasma. Upon the recovery of the stored energy, the density begins to

relax which results in the loss of particles added to the plasma due to pellet injection. The pellet-induced collapse and recovery can be described in terms of four distinctive phases: (1) pellet injection and temperature collapse, (2) high density and low temperature, (3) recovering temperature and stored energy, and (4) temperature recovery in the edge region of the plasma and density relaxation.

The pellet-induced collapse and recovery was shown to be reproducible, which permits systematic study of the thermal collapse and subsequent recovery in ATF plasmas. The injection of larger pellets does not alter the recovery from the collapse, however it does delay it. Additional gas puffing during the pellet-induced collapse and recovery results in a higher line-integrated density before the density begins to relax.

The pellet-induced collapse and recovery was reproduced in plasmas that had an oblate magnetic configuration. The two major differences in the response for the oblate configuration and the standard configuration was that the stored energy at the time of the density relaxation was higher than the pre-pellet value for the standard case, and lower for the oblate case, and the density of the plasma before it began to relax was much closer to the pre-pellet density for the oblate configuration than for the standard configuration.

CHAPTER IV

DISCUSSION OF THE COLLAPSE AND RECOVERY

In the previous chapter, the response of the plasma to pellet injection was described, and the pellet-induced collapse and recovery was characterized in detail. Data from the plasma diagnostic systems have been analyzed and the resulting conclusions as to why the plasma undergoes a thermal collapse, and why it recovers as it does, will be presented in this chapter.

Onset of the Thermal Collapse

The occurrence of the pellet-induced thermal collapse was shown to be a function of the density of the plasma after pellet injection. There are conditions where the injection of a pellet will lead to an increase in the value of the stored energy. This increase is a modest improvement over the stored energy achieved by gas fueling alone.

As the pellet is made larger the increase in the density and the resulting decrease in the electron temperature become greater, but it is not necessarily the injection of the pellet that produces the thermal collapse. In shot 16544, the pellet was injected at $t = .257$ s, but the collapse in the stored energy did not occur until $t = .354$ s. In this case, the pellet was not large enough to cause the immediate collapse of the stored energy, however the evolution of the plasma after the arrival of the pellet caused the plasma to undergo a thermal collapse. It has

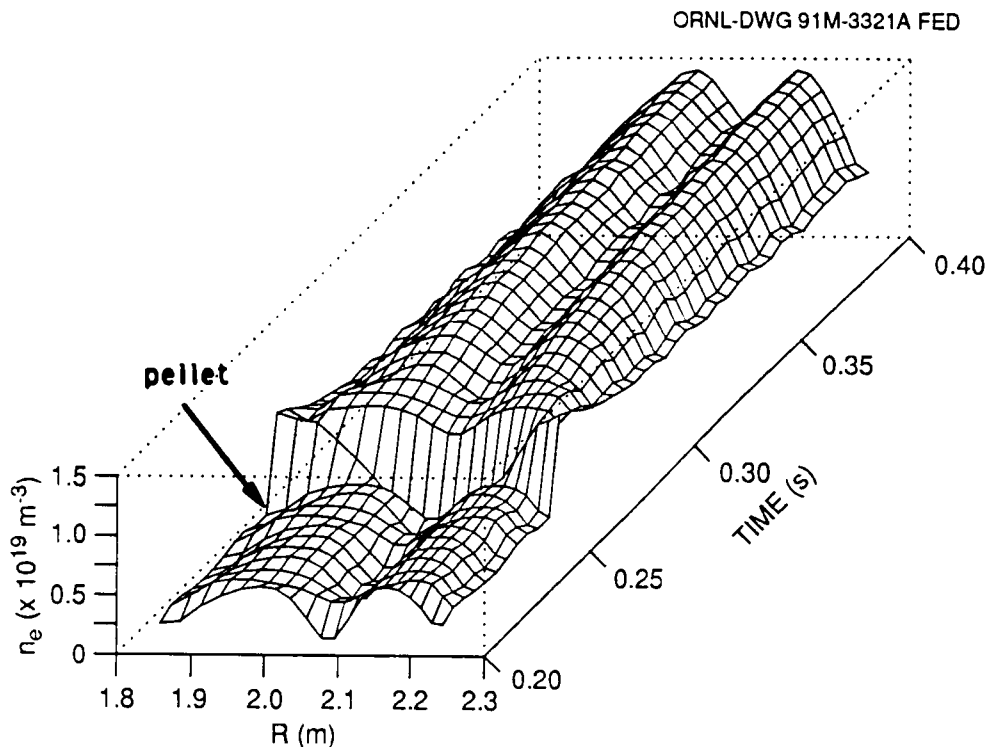


Figure 4.1: The electron density profile inferred from the FIR interferometer data for shot 16544. The density profile is slowly varying after pellet injection.

been suggested that a power imbalance occurs that causes the temperature profile of the plasma to narrow and eventually collapse.¹²

Figure 4.1 shows the electron density profile inferred from the FIR interferometer data throughout shot 16544. The electron density profile was slowly varying after pellet injection and before the thermal collapse. Figure 3.5 shows the typical diagnostic waveforms for shot 16544. As the pellet entered the plasma, the edge ECE was reduced to a near zero value and the central channel is reduced to about 1/4 of its original value. The central emission slowly decayed to a near zero value as the density slowly increased. The initial increase of the plasma density due to the injection of the pellet did not cause the collapse in the stored energy.

The temperature decreased slowly after pellet injection, but the reduction occurred over many energy confinement times, which is on the order of 5 ms. This implies that the ECH power was being absorbed by the plasma. The plasma in this case was only slightly out of power balance, which resulted in a steady loss of plasma temperature which has been shown to propagate from the edge region towards the central region.

If a pellet is large enough, the decrease in the stored energy occurs immediately after pellet injection. This is because of an increased power imbalance due to the increased density caused by the larger pellets. Evidence of this effect can be seen by plotting the ECH power detected from a power leakage detector that is viewing the plasma through an inside port. The leakage detector provides a measure of the amount of unabsorbed ECH power that passes through the port.

The $\bar{n}_e \ell$, the stored energy, and the detected power leaking out of the vessel for a series of shots that had increasing pellet size are shown in Figures 4.2 through 4.5. The change in leakage due to pellet injection is not detectable in shot 16546. The level of the leakage signal increased slightly for shot 16548. In this shot, the stored energy increased at the time of injection and remained high throughout the duration of the shot. In shot 16544, the pellet did not cause an immediate drop in the stored energy, but eventually the stored energy did collapse. The leakage in this case increased substantially over that of shot 16548. The injection of the pellet in shot 16549 caused the stored energy to decrease immediately. The leakage signal increased substantially at the time of injection for this shot and it was higher than that for shot 16544. The leakage began to decrease as the stored energy began to recover. The coupling of the ECH power to the plasma was improving. As the density returned to the pre-pellet value, the leakage decreased to its pre-pellet value. This suggests that the power imbalance is due to an increase in the amount of reflection of the ECH power.

Shot #16546

1 Tesla

Standard Configuration

Gyrotron #1 & #2

Line-averaged density at time of injection: $3.9 \times 10^{12} \text{ cm}^{-3}$

Number of atoms in pellet: 1.0×10^{19}

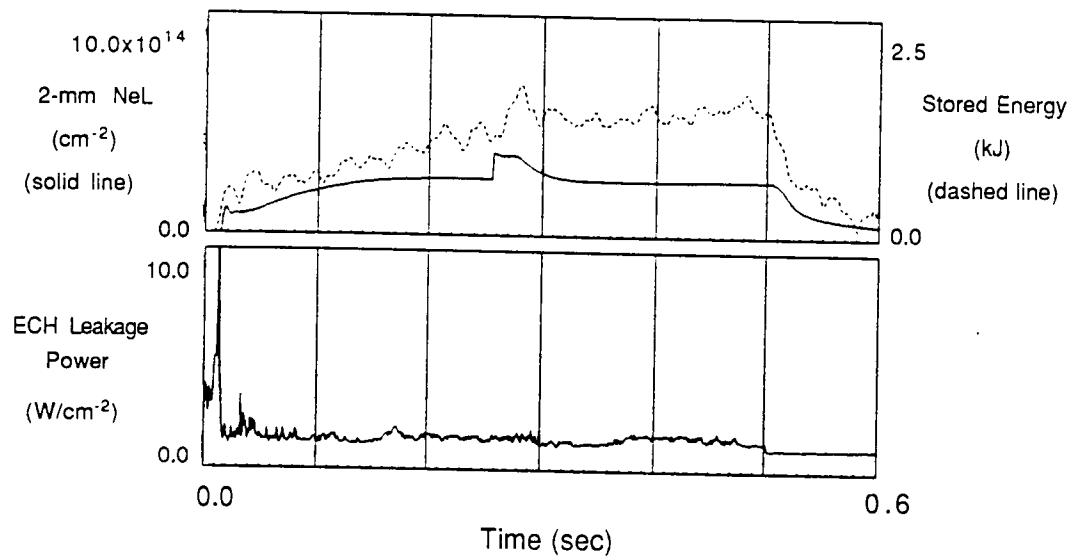


Figure 4.2: Output of ECH leakage detector, 2-mm $\bar{n}_e \ell$, and stored energy for shot 16546

Shot #16548

1 Tesla

Standard Configuration

Gyrotron #1 & #2

Line-averaged density at time of injection: $3.9 \times 10^{12} \text{ cm}^{-3}$

Number of atoms in pellet: 2.8×10^{19}

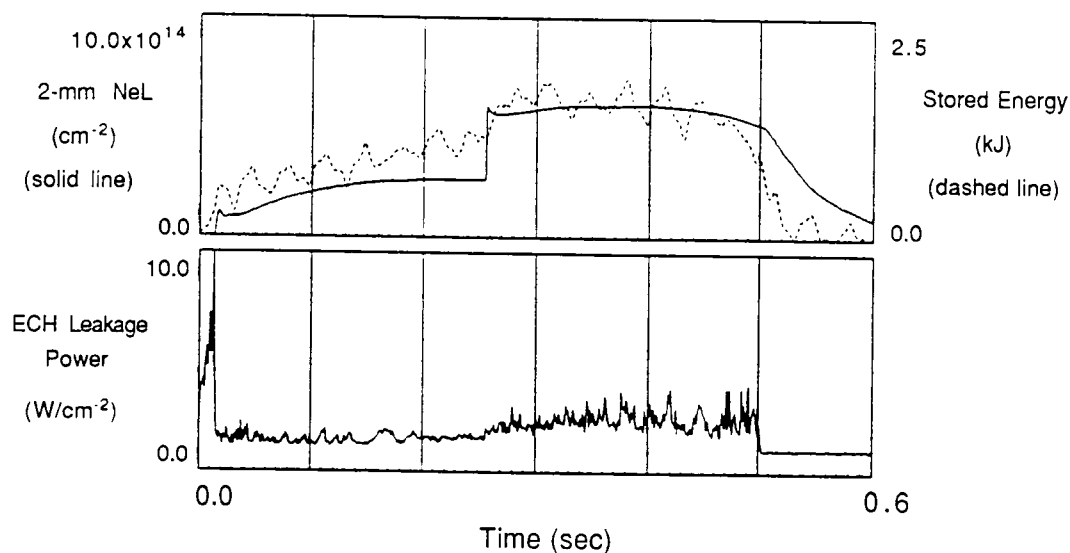


Figure 4.3: Output of ECH leakage detector, 2-mm $\bar{n}_e \ell$, and stored energy for shot 16548

Shot #16544

1 Tesla

Standard Configuration

Gyrotron #1 & #2

Line-averaged density at time of injection: $3.9 \times 10^{12} \text{ cm}^{-3}$

Number of atoms in pellet: 3.0×10^{19}

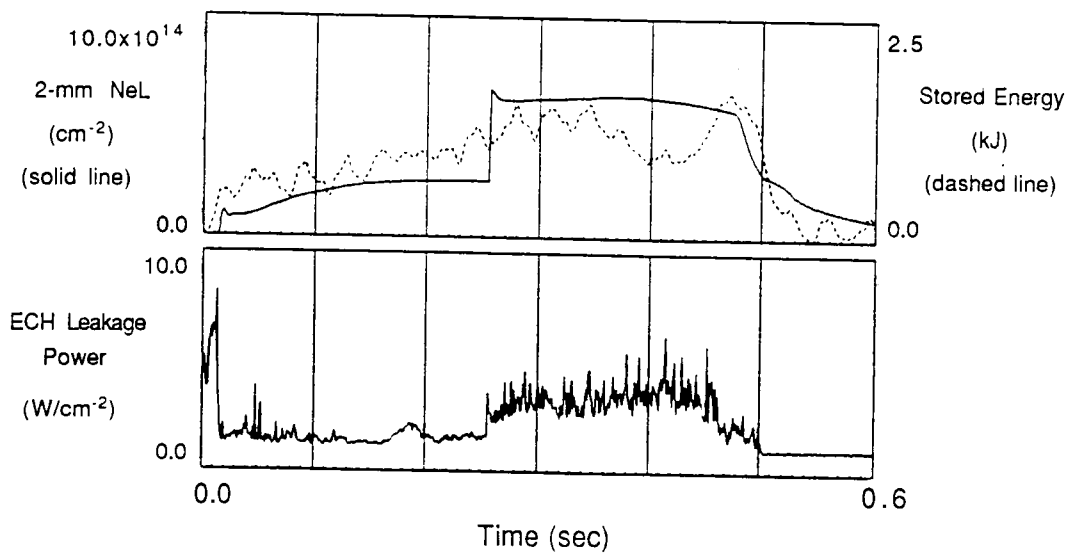


Figure 4.4: Output of ECH leakage detector, 2-mm $\bar{n}_e \ell$, and stored energy for shot 16544

Shot #16549

1 Tesla

Standard Configuration

Gyrotron #1 & #2

Line-averaged density at time of injection: $3.9 \times 10^{12} \text{ cm}^{-3}$

Number of atoms in pellet: 3.7×10^{19}

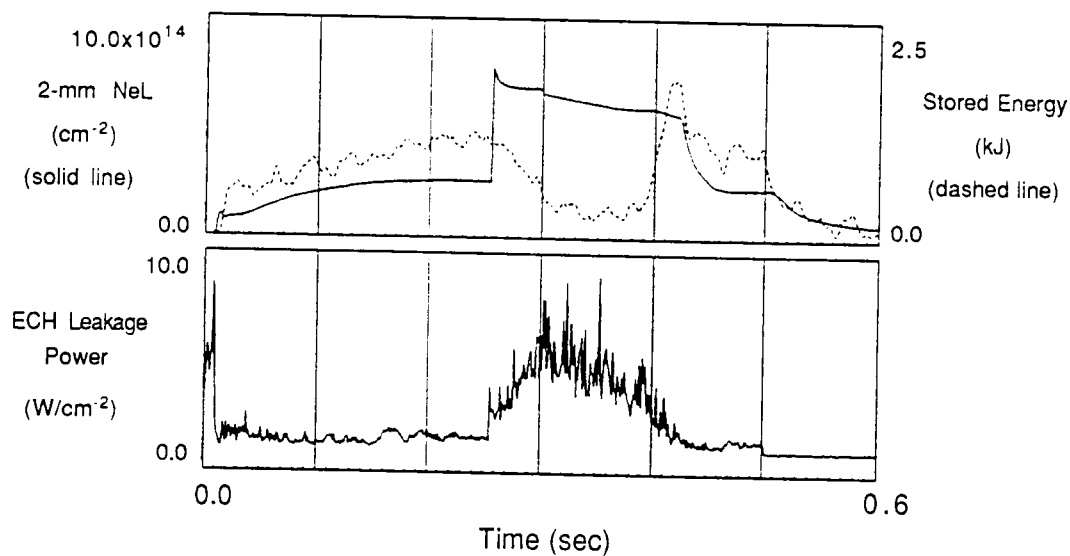


Figure 4.5: Output of ECH leakage detector, 2-mm $\bar{n}_e \ell$, and stored energy for shot 16549

Recovery of the Stored Energy

It has been demonstrated that the increased density due to pellet injection results in reduced absorption of the ECH power, and this leads to the thermal collapse. Also, the injection of larger pellets delays the recovery of the stored energy but otherwise does not seriously alter its characteristics. This suggests that the plasma must evolve to a particular plasma condition before the recovery can begin. The larger the density increase due to the injection of the pellet, the longer the time that it takes for the plasma to purge the excess particles that must be lost before the ECH heating can effectively couple to the plasma, producing a positive power balance, and allowing the recovery to begin.

Increasing the gas fueling after the time of injection caused the density to increase at the beginning of the recovery of the stored energy, which implies that the overall density of the plasma is not crucial to the recovery. Rather, the local density of the plasma at a particular plasma location may have to drop below some critical value before the plasma will begin to recover.

Figure 4.6 shows the electron density profiles as a function of ρ at the beginning of the recovery of the stored energy for three shots that had the reduced gas puff during the pellet-induced collapse and recovery (shot 16534, 16539, and 16540) and one shot that had increased gas puff during the pellet-induced collapse and recovery (shot 16550). The density profile of the three shots that had similar gas puffs are in good agreement when the stored energy began to recover, but the shot with increased gas fueling maintained a higher density in the central region of the plasma. This implies that the central plasma density is not the crucial factor determining when the stored energy will begin to recover, however it is very probable that an upper limit does exist on the central plasma density in order for the recovery to begin. The absolute uncertainty associated with the

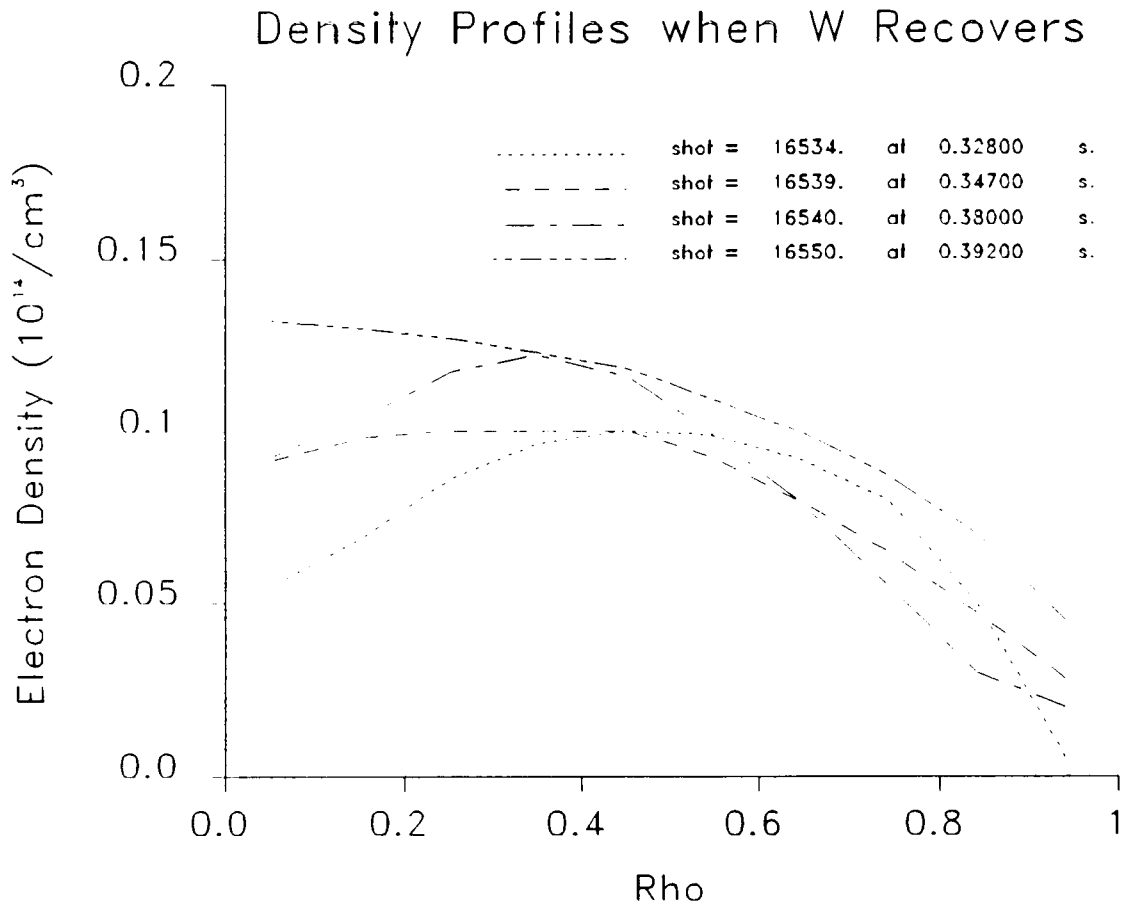


Figure 4.6: Electron density profile at the beginning of the recovery of the stored energy for three shots (16534, 16539, 16540) with reduced gas fueling during the pellet-induced collapse and recovery, and one shot with increased edge fueling (16550).

density profile as determined by the inversion of the FIR interferometer data is on the order of 20%. This makes it difficult to make a more definitive determination of the value of the density below which the plasma will begin to recover or its corresponding location.

Density Relaxation

If the response of the plasma to the injection of a pellet was simply a function of the coupling of the ECH power to the plasma, then one would expect that as the stored energy began to recover, the density would gradually decay to the pre-pellet value. This occurs only for the cases in which the stored energy did not collapse after pellet injection. If the stored energy does collapse, then during the recovery the density will evolve to a consistent value which are dependent on the level of edge fueling and magnetic configuration. As the pellet is made larger, the drop in the stored energy becomes larger, and upon the recovery, the discontinuity in the 2-mm $\bar{n}_e \ell$ signal which results from the relaxation of the density back to the pre-pellet value becomes more distinctive. This can be seen graphically in Figure 3.15.

As the plasma re-heats from the central region of the plasma towards the edge region, the stored energy peaks and the density begins to decrease. At some point during the recovery of the stored energy there is a transition from events that occur on a slow time scale to those that occur much more rapidly.

It would obviously be beneficial if the plasma could sustain the increased stored energy and density. The cause of the transition from a period of good particle confinement to a period of enhanced particle loss needs to be better understood. If the cause of the density relaxation back to the pre-pellet radius can be determined, then ways to avert the density decay can possibly be developed

which may allow plasmas with high stored energy and high density to survive for longer periods of time. The characteristics of the density relaxation and the possibility that the relaxation is a result of unfavorable pressure gradients in the plasma has been examined and the results are presented in the remainder of this chapter.

ECE in the Edge Region of the Plasma

It was shown that the peak in the D_α emission that occurred when the pellet was at $\rho \approx .7$ was independent of the size of the pellet. Experiments where a second pellet was injected into different stages of the pellet-induced collapse and recovery demonstrated that increased D_α emission at the edge of the plasma occurs only after the ECE in the edge region has recovered. It was also shown that the D_α emission that is detected when the pellet passes through this region of the plasma decreases with increasing plasma density.

Figure 4.7 shows the temperature profiles for shot 17902 as inferred from the ECE diagnostic at intervals of 1 ms just before and after the density relaxation, which occurred at $t = .383$ s. The inferred temperature in the region of the plasma corresponding to $\rho > .7$ began to increase between $t = .382$ s and $t = .383$ s. The evidence suggests that the increase is due to emissions from non-thermal electrons.

The non-thermal electrons that appear as the density relaxation begins must either be transported to the edge region from the central region of the plasma, or the electrons that are already at this location must be driven to non-thermal energies by the ECH heating. The electron density profiles at various times throughout shot 17902 are shown in Figure 4.8. For this shot, the density profile began to relax from its most peaked shape at $t \approx .35$ s, which is approximately 33 ms before the edge ECE is observed to increase. This illustrates that

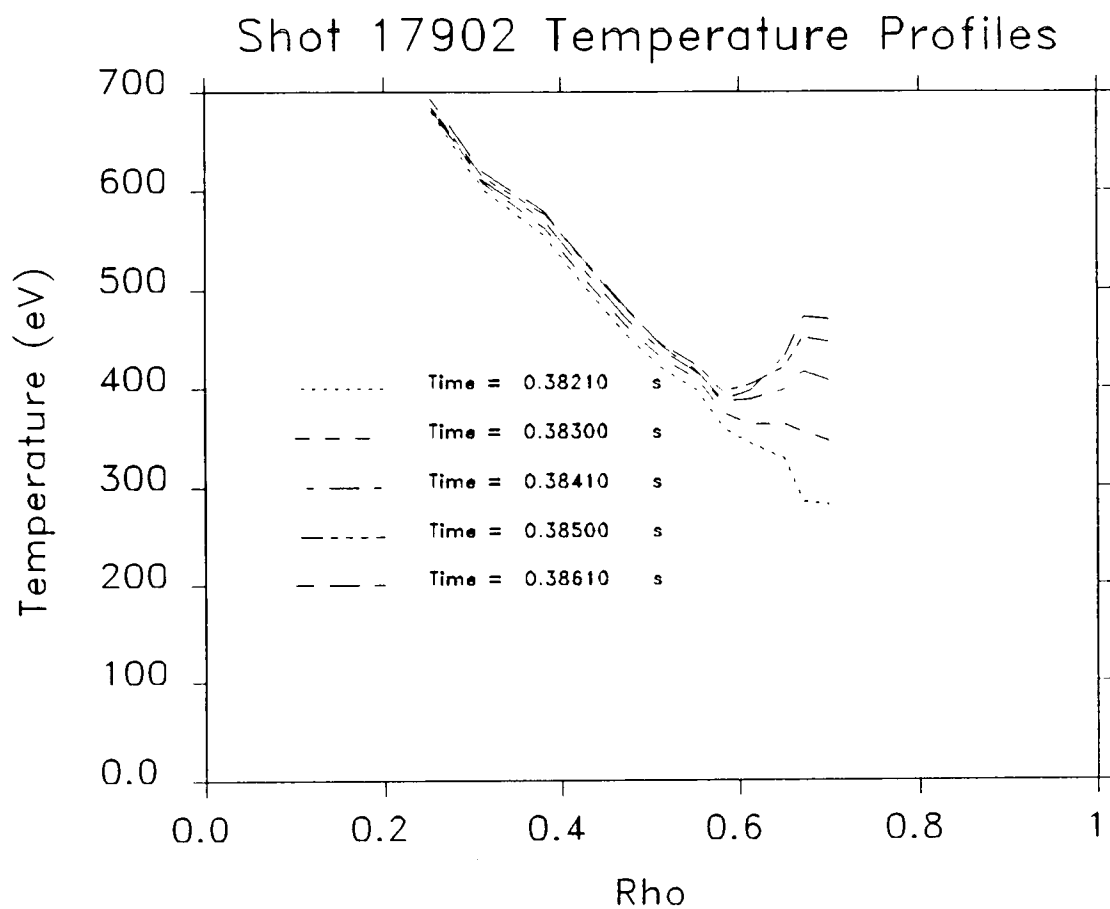


Figure 4.7: Temperature profile for shot 17902 at 1 ms intervals, just before and after the density relaxation, as inferred from the ECE diagnostic.

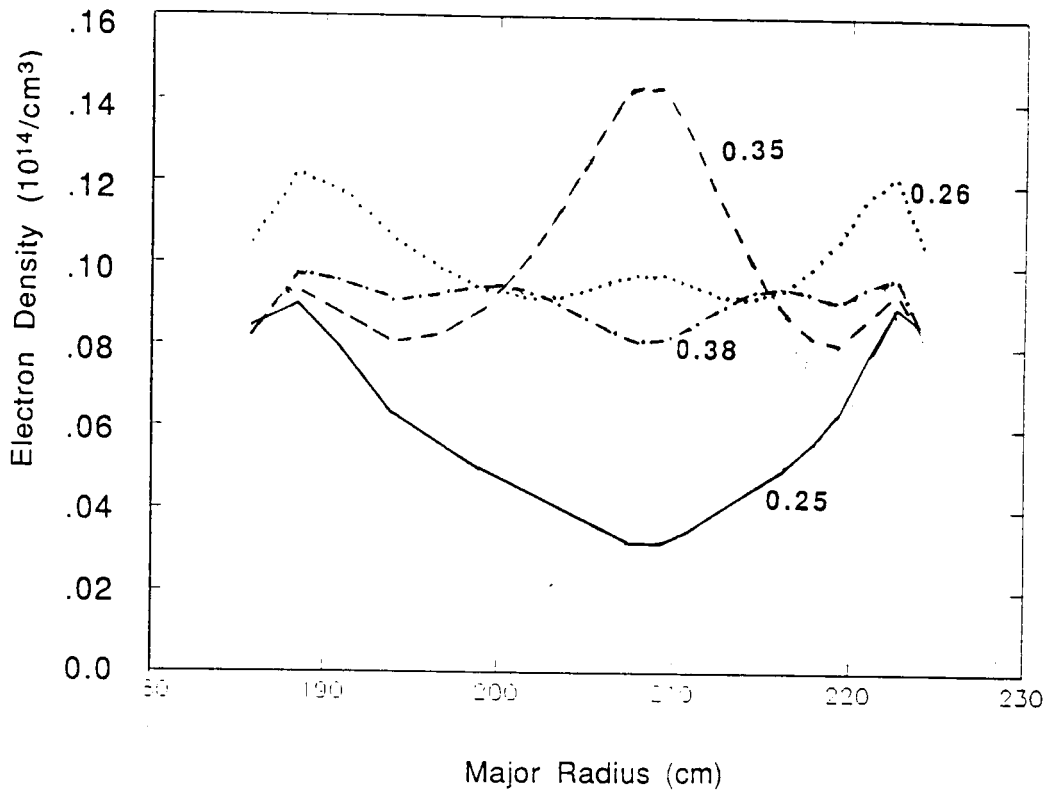


Figure 4.8: Electron density profile at various times for shot 17902.

the density relaxation consists of two components. First the peakedness of the density profile begins to relax while the average plasma density is slowly varying. Then the total number of particles in the plasma begins to decrease.

At the time of the increase in the ECE in the edge region, the density profile has already relaxed substantially. The increased ECE is not due to the transport of more energetic electrons from the central region of the plasma, because if were the increase would occur as the density profile relaxes. The recovery of the ECE in the edge region of the plasma is not due to particle transport that occurs as the density profile relaxes. Therefore, it is probably the result of the formation of a new population of non-thermal electrons.

Magnetic Fluctuation Measurements

Measurements of the magnetic fluctuations at the edge of the plasma by the Mirnov coils, which are located ≈ 30 cm outside the plasma and oriented approximately poloidally, indicate that a burst of activity corresponds to the beginning of the density relaxation. Figure 4.9 shows processed data from a coil for shot 16550. The data are broken up into 6 bandwidths. The top graph in the plot shows the 2-mm $\bar{n}_e \ell$ data. The burst of activity occurred at $t \approx .430$ s. This behavior is typical of that observed for plasmas which underwent the pellet-induced collapse and recovery. The amplitudes of the magnetic fluctuations return to the pre-pellet value. Coherence analysis of the signals from poloidally and toroidally displaced coils does not indicate strong global coherence during these bursts of activity, which suggests that the activity is not due to macroscopic instabilities in the plasma.

It has been established that the pellet ablation in the edge region is significantly reduced before the ECE emission in the edge region of the plasma recovers. Also, the increased amplitude of the magnetic fluctuations cannot be attributed to increased levels of plasma instability. The evidence supports the conclusion that the effective minor radius of the plasma is reduced after pellet injection due to a narrowed temperature profile.

The particle balance can be expressed as

$$dN_e/dt = \Phi_e + R(N_e/\tau_p) - N_e/\tau_p \quad (\text{s}^{-1}), \quad (4.1)$$

where N_e is the total number of electrons, Φ_e is the source from gas fueling and recycling from the wall, R is the recycling coefficient, and τ_p is the particle confinement time. In equilibrium, $(dN_e/dt=0)$, equation 4.1 becomes

$$N_e = (\Phi_e \tau_p)/(1 - R). \quad (4.2)$$

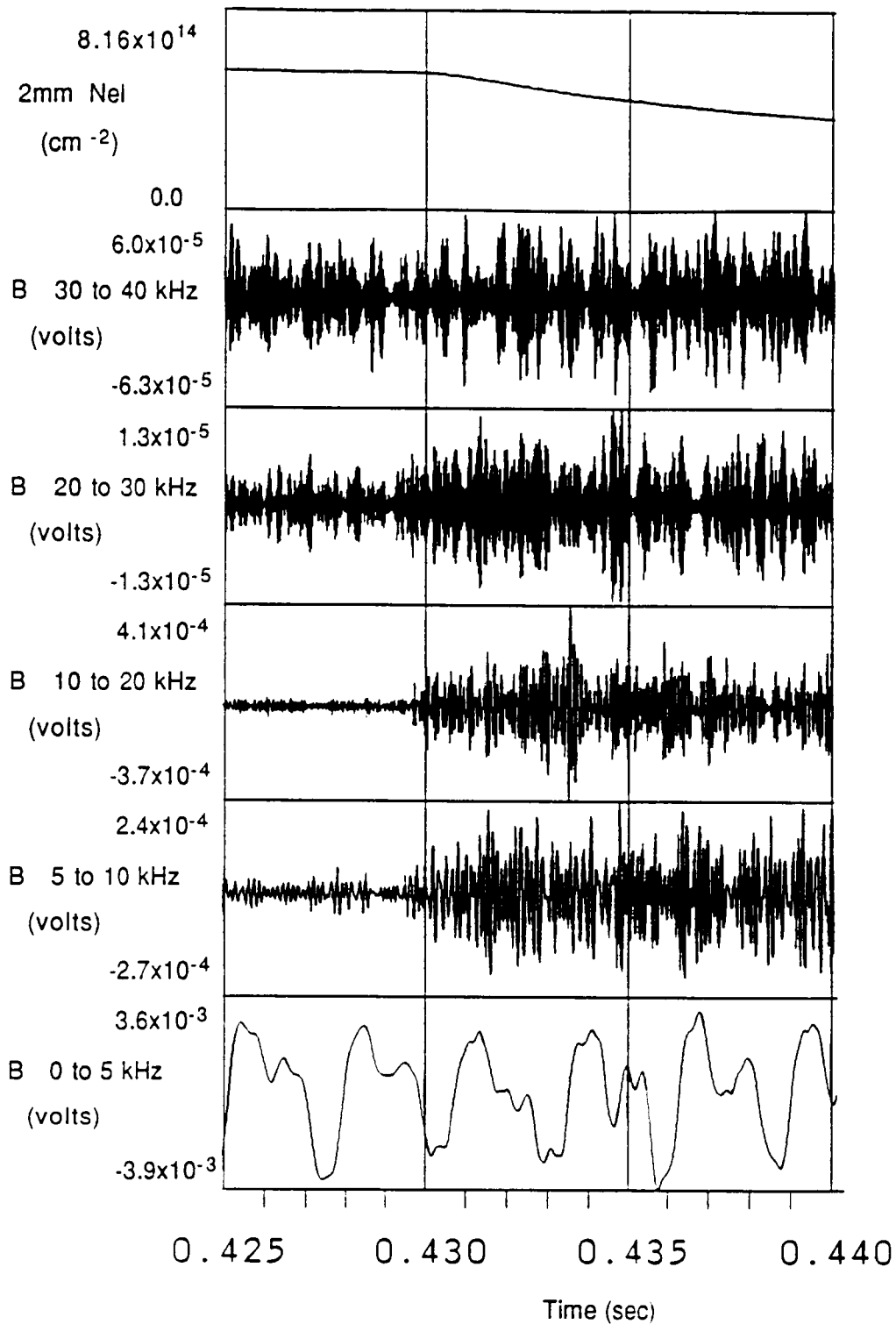


Figure 4.9: Fluctuation data taken from a Mirnov coil located at the plasma edge for shot 16550. The data has been filtered to show various bandwidths. The amplitude of the fluctuations returns to the pre-pellet levels as the density begins to return to the pre-pellet value.

Thus, N_e is controlled by a balance between the particle confinement time of the plasma and the amount of edge recycling when the plasma is in equilibrium.

When the profile expands back to its pre-pellet value, the increased heat flux to the vessel walls increases the amount of edge recycling. The particle confinement properties of the plasma probably change as well and a new equilibrium is reached based on the new values of these properties. The result is a reduction in N_e .

The burst of activity detected by the Mirnov coils is most likely caused by the expansion of the electron temperature profile, which moves high temperature plasma closer to the coils, resulting in a larger amplitude of the detected fluctuation level.

Pressure Gradient Stability Analysis

The Bohr-Van Leeuwen theorem predicts that as plasmas deplete their reservoirs of free energy, their energy density gradient perpendicular to the magnetic field lines becomes smaller, and its radial profile flattened.²⁶ The broadening of the density profile may be a manifestation of this phenomenon. In this case, the reservoir of free energy is the pressure gradient from the central to the edge region of the plasma.

Instabilities driven by unfavorable pressure gradients within the plasma are a possible candidate for the mechanism which triggers the density relaxation after the plasma has recovered from the pellet-induced collapse and recovery.

Magnetohydrodynamic (MHD) instabilities can be classified according to their driving source. A given mode is either pressure driven or current driven. Current-driven modes are caused by the parallel current in a plasma, and in a stellarator, the parallel current can be controlled to near zero values, thus es-

entially eliminating current-driven modes as sources of plasma instability. The ideal MHD model is the most basic model for describing the macroscopic equilibrium and stability properties of a plasma. This model describes how magnetic, inertial, and pressure forces interact within an ideal perfectly conducting plasma. The addition of plasma resistivity allows field lines, which are frozen on surfaces of constant pressure in the ideal MHD model, to break and reconnect. The addition of such non-ideal effects can allow for the development of slower, weaker instabilities, which can also lead to enhanced transport.¹⁰

Density profiles observed in ECH heated stellarator plasmas have often been observed to be flat, and in some cases hollow, and a general analysis of the stationary particle and energy balance equations suggests that plasma instabilities driven by unfavorable pressure profiles in the plasma are possible causes of the anomalous transport that result in these plasmas.¹⁶ In stellarators, based on analysis of 2-D equilibria, the dominant instabilities are interchange modes that occur when there is a sufficient pressure gradient on a surface of rational ι that lies in a region of unfavorable average curvature, or magnetic hill.¹¹ The plasma pressure has a natural tendency to expand outward, balanced by the restraining effect of the magnetic field. In an interchange perturbation, two flux tubes at different radii "interchange", which leads to a system with lower potential energy and thus instability.¹⁰

On Heliotron-E, it was demonstrated that when a significant pressure gradient existed near the $\iota = 1$ location, which lies in a magnetic hill, sawtooth oscillations are detected on the soft x-ray detectors and the Mirnov coils. These instabilities are thought to limit the achievable β in Heliotron-E plasmas.³²

In the plasmas that undergo the pellet-induced collapse and recovery, the density profile is more peaked after pellet injection and the electron temperature is increasing in the central regions of the plasma during the re-heat from the thermal

collapse. With a peaked density profile and increasing central temperature, the pressure profile of the plasma is becoming more peaked during the recovery. It is possible that the pressure gradient from the central to the edge region of the plasma increases such that the magnetic configuration is no longer stable to the modes driven by it. This may lead to enhanced transport which relaxes the density profile. As the density gradient decreases, the remaining pressure gradient relaxes and the plasma again becomes stable. In the next section, the possibility that the density relaxation is due to unfavorable pressure gradients in the plasma will be discussed.

Electron Pressure Profile Analysis

Effect of altering edge fueling The electron density profiles just before the density begins to relax as determined by the inversion of FIR interferometer data for shots 16534, 16539, 16540, and 16550 are shown in Figure 4.10. The shots that had increased gas puff during the thermal collapse and recovery had a higher overall density when the density began to relax. This is expected because the 2-mm $\bar{n}_e \ell$ was higher before the relaxation for the shots with increased gas puff. The density relaxation is independent of the plasma density profile, but the profile does evolve consistently for similar operating conditions.

The measured electron temperature profiles for these shots at the corresponding times are shown in Figure 4.11. The profiles for the shots with the reduced gas puff show excellent agreement among themselves, and are higher than the temperature profile for the shot that had the higher density. This would be expected if the pressure gradient is the factor which causes the plasma to expand and drives the enhanced particle transport.

By multiplying the local electron density by the local electron tempera-

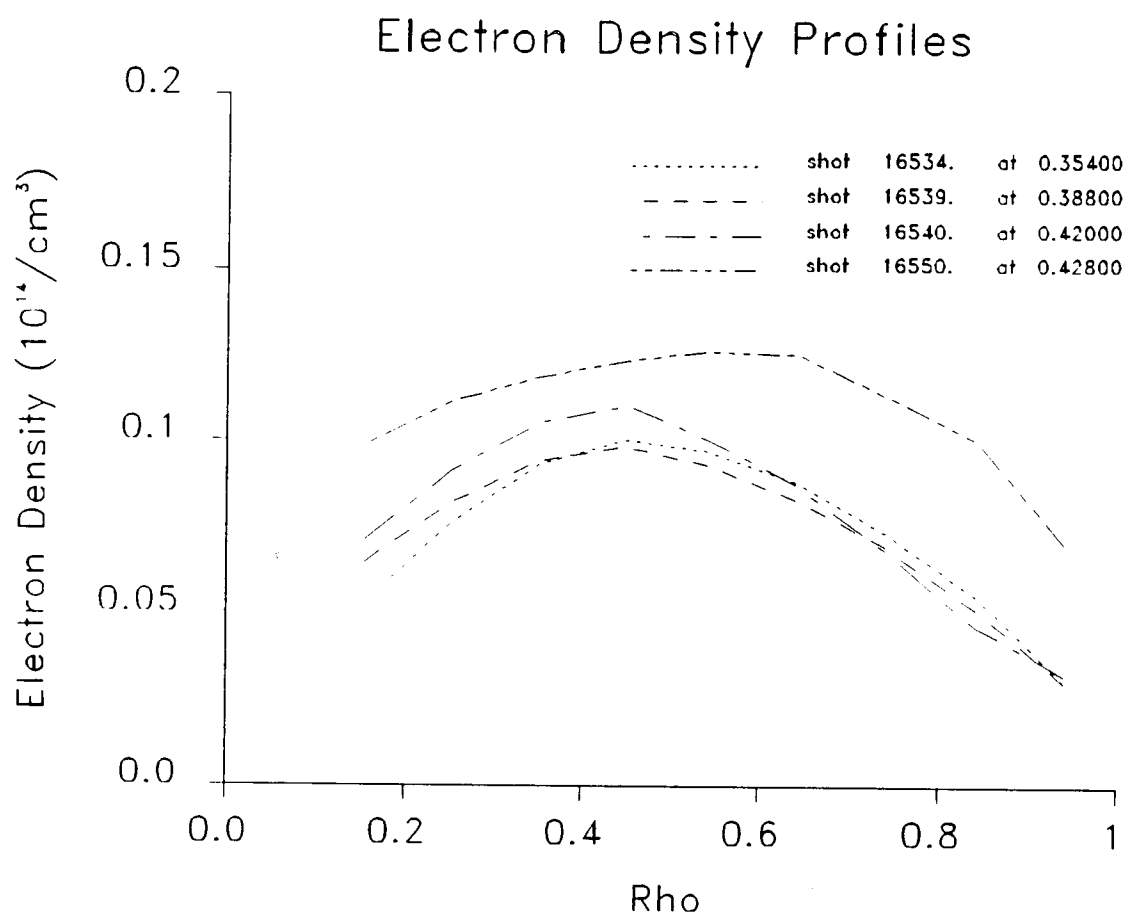


Figure 4.10: The electron density profiles just before the density relaxes for four shots with the standard configuration (shots 16534, 16539, 16540, and 16550).

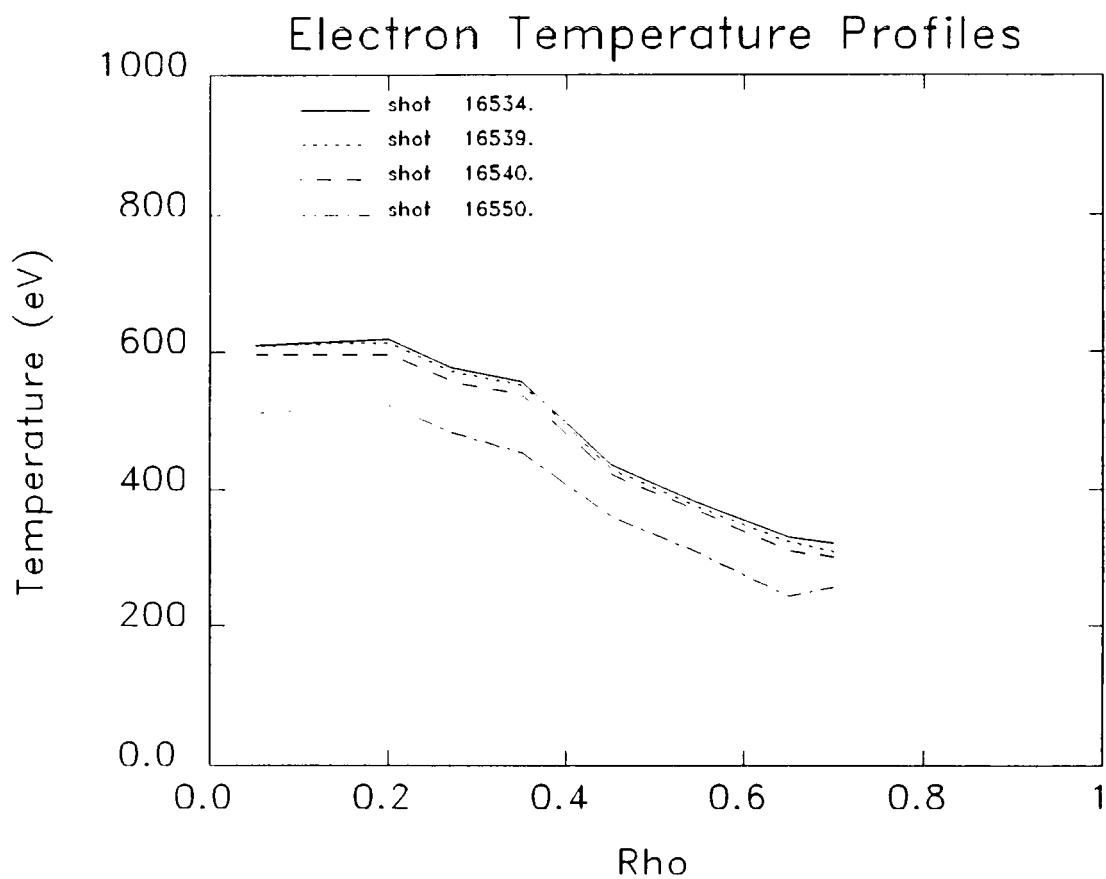


Figure 4.11: Electron temperature profiles before the density relaxes for four shots with the standard configuration (shots 16534, 16539, 16540, and 16550).

ture, the pressure profiles (neglecting the pressure due to the ions, which is small) can be generated. These pressure profiles are valid from $\rho \geq .2$. The measured central electron temperature based on the ECE diagnostic is typically less than that determined by the Thomson Scattering diagnostic by as much as 200 eV. However, from $\rho \geq .2$ the values of the temperature based on the measurements of the two systems are in good agreement. The uncertainty associated with the measured pressure profiles are on the order of 30%, however the trends in the data on a shot to shot basis are credible.

Pressure profile evolution during shot 17902 The pressure profile for shot 17902 has been determined at 10-ms intervals during the pellet-induced collapse and recovery and is shown in Figure 4.12. The pressure gradient from the central region to the edge of the plasma increased as the stored energy increased. After the time of the decrease in the line-averaged electron density measurements ($t \approx .383s$) the pressure gradient began to decrease and returned to the pre-pellet value.

Pressure profile before the density relaxation The inferred pressure profiles for shots 16534, 16539, 16540 and 16550 just before the density relaxation are shown in Figure 4.13. The profiles for plasmas with the same magnetic configuration but different levels of edge fueling during the response are in agreement within the experimental uncertainty of the measurement for $\rho \gtrsim .4$.

Pressure profile for shots with different magnetic configurations

Pressure-gradient-driven instability is associated with the flow of current perpendicular to the magnetic axis and the threshold for the stabilization of these modes is dependent on the properties of the confining magnetic field. The two

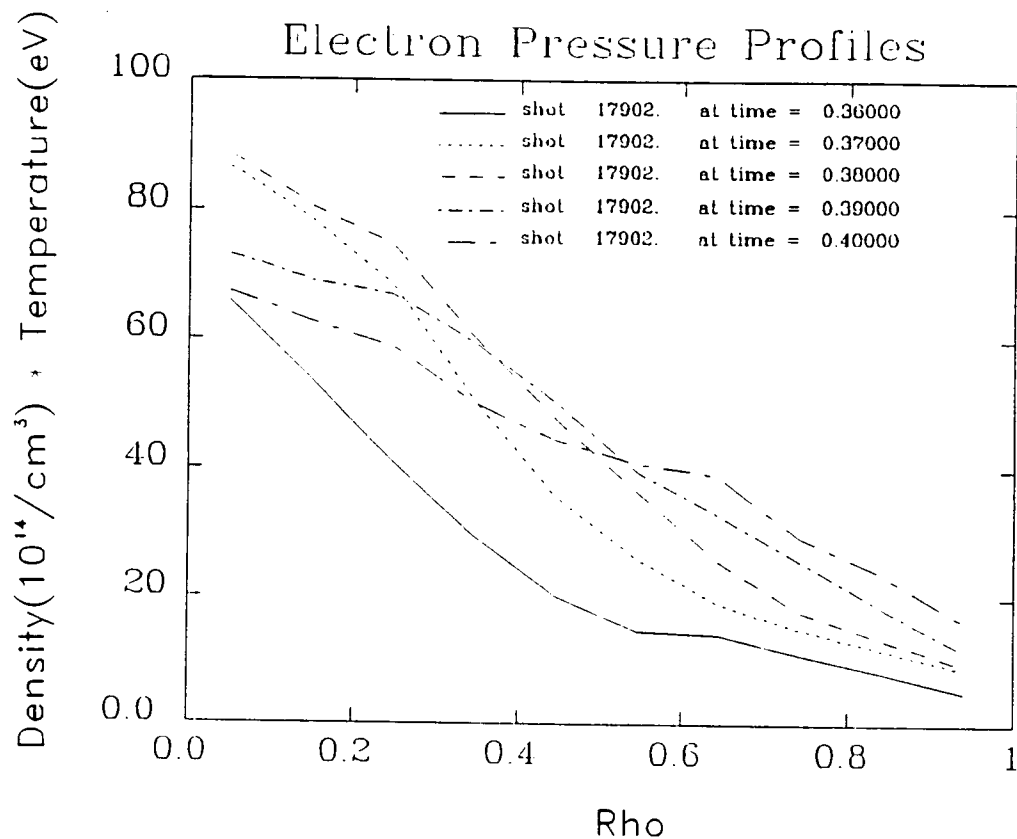


Figure 4.12: Pressure profile at 10 ms intervals during the pellet-induced collapse and recovery for shot 17902 (standard magnetic configuration). The peakedness of the profile increases as the plasma stored energy recovers.

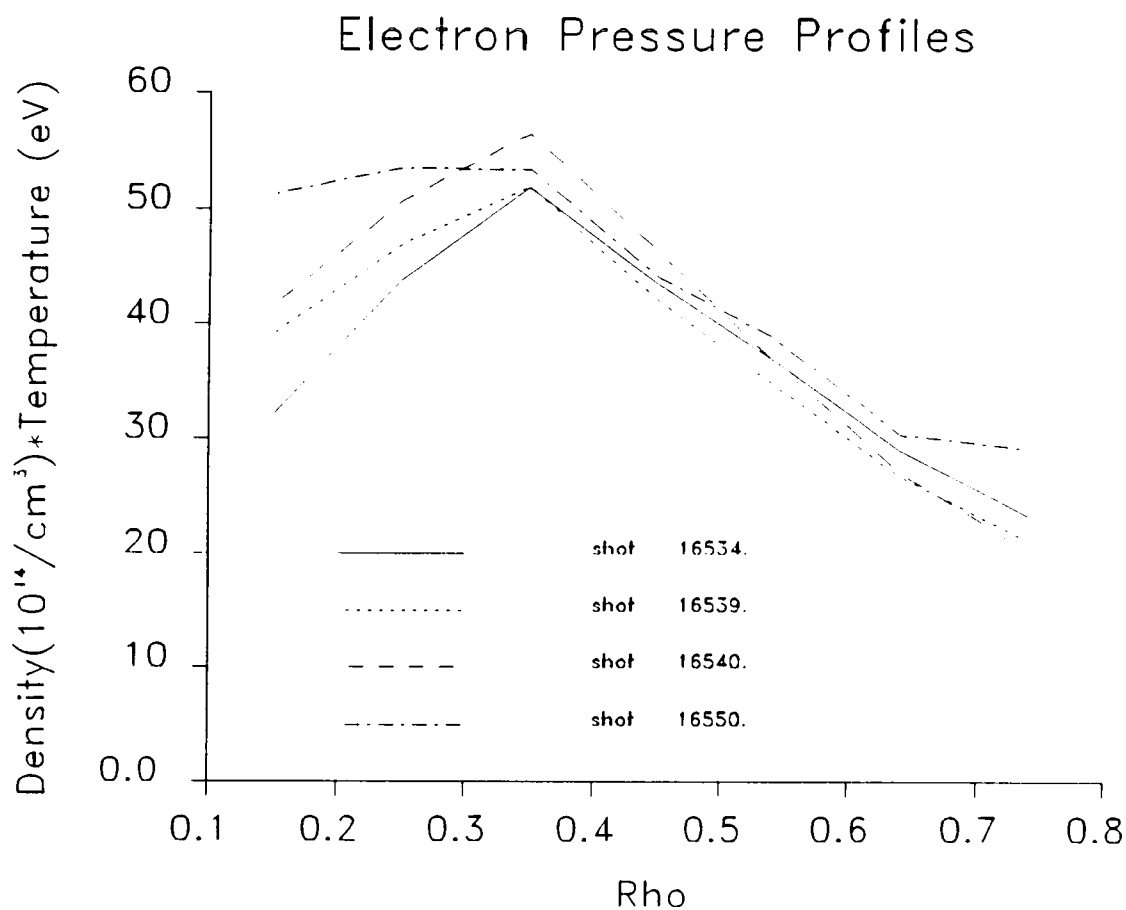


Figure 4.13: Electron pressure profiles before the density relaxes for shots with the standard magnetic configuration (shots 16534, 16539, 16540 (reduced gas puff) and shot 16550 (increased gas puff)).

important parameters describing the confining magnetic field are the shear, which is related to the rotational transform, and the magnetic well. On the ATF, there are three pairs of axisymmetric windings in addition to the basic helical windings. These additional windings allow control of the magnetic well, the rotational transform, and the magnetic shear, which can be effective in stabilizing pressure-gradient-driven interchange instabilities. If the pressure gradient is sufficiently small compared to the shear, then interchange modes can be stabilized.¹⁰

By deepening the magnetic well, more of the field line curvature becomes favorable and the plasma becomes more stable to interchange modes. If an unfavorable pressure gradient is driving instabilities that causes the density relaxation to occur, then altering the magnetic geometry of the ATF should change the plasma's susceptibility to the onset of the instability and the pressure profiles at which the plasma becomes unstable should also change. Figure 4.14 shows the pressure profile immediately before the expansion of the plasma for a shot with an oblate configuration (shot 19248) and a shot with the standard configuration (shot 17920). The pressure gradient at the time of the density relaxation was lower for the shot with the oblate configuration.

Stability Analysis A stability analysis of the plasma based on the measured pressure profiles and the corresponding magnetic configuration was performed based on the solution of the MHD equations for localized perturbations using the full 3-D equilibria.¹ In the analysis, stability criteria using both the ideal and the resistive MHD models were examined. It was found that no violations of ideal MHD stability criteria were expected for the measured pressure profile in either the standard or the oblate configuration at the beginning of the density relaxation. The analysis was also performed for the most peaked pressure profile that was measured during shot 17902. Again, no violations of ideal MHD stability

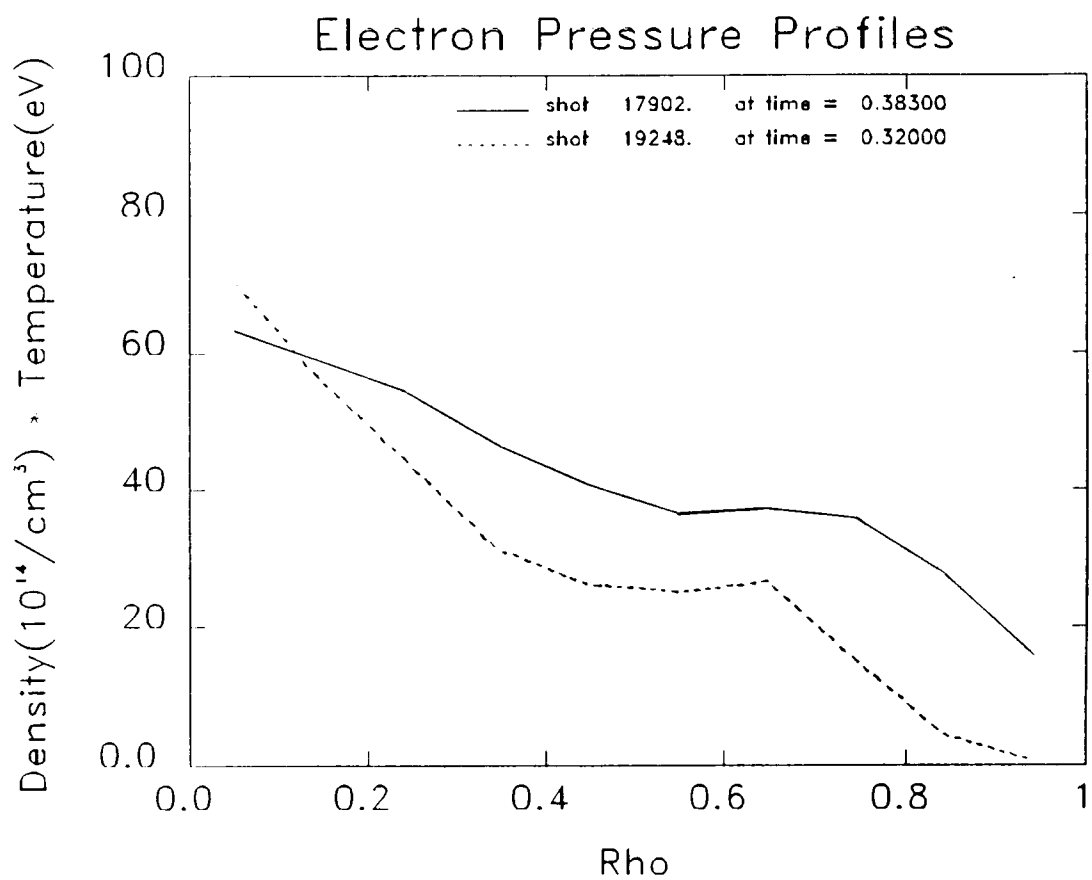


Figure 4.14: Pressure profile just before the density relaxes for shot 17902 (standard magnetic configuration) and shot 19248 (oblate magnetic configuration).

criteria were found.

Resistive interchange instabilities were predicted for all of analyzed pressure profiles. The growth rates for these instabilities are small, and are essentially the same as those observed with gas fueling only.

It has been shown that the pressure gradients before the density profile begins to broaden are higher than those observed under normal edge fueling conditions and that the pressure profile returns to the pre-pellet value as the plasma density decreases. Also, the pressure profile evolves consistently for shots with the same magnetic configuration, and changing the magnetic configuration effects the evolution of the pressure profile before the density relaxation.

The behavior of the pressure profile is consistent with the hypothesis that pressure-gradient-driven instability is responsible for the plasma's inability to simultaneously maintain peaked temperature and density profiles. If resistive pressure gradient instability does limit the peakedness of the density profile in ATF plasmas, then it is probable that they are responsible for the broadening of the density profile that occurs during the recovery from the pellet-induced collapse and recovery. However, the role that pressure-gradient-driven instabilities play in determining the density profiles in ATF plasmas under normal operating conditions is not well understood. Before it can be conclusively argued that pressure-gradient-driven instability is responsible for the broadening of the density profiles during the recovery from the thermal collapse, a better understanding of their role under normal operating conditions must be developed.

Summary

The following is a description of what the experimental evidence suggests happens during the pellet-induced collapse and recovery. After the initial increase in the plasma density due to pellet injection, the temperature in the edge region of the plasma decreases to a near zero value. The plasma is cold and dense in this outer region. A power imbalance occurs due to poor coupling of the ECH power to the plasma because of the increased density, which causes the temperature profile of the plasma to narrow and decrease in magnitude. As the temperature in the central region of the plasma decreases, the stored energy experiences a thermal collapse. During this time, the electron density profile becomes more peaked. The stored energy continues to decrease until the power balance achieves equilibrium. It will remain in this state until the density decreases enough to permit improved coupling of the ECH power. Once the ECH is absorbed more effectively, the overall power balance becomes positive and the stored energy begins to recover. The energy and particle confinement properties of the plasma are excellent during the recovery of the stored energy. Soon after this, the temperature increases in the edge region of the plasma and the number of particles in the plasma begins to decrease. The stored energy of the plasma then begins to decrease due to the loss of particles from the central region of the plasma.

The evolution of the plasma pressure profile during the recovery from the thermal collapse suggests that the broadening of the density profile which occurs before the loss of plasma particles may be controlled by resistive pressure gradient instability in the plasma. The sudden increase in the edge ECE and the amplitude of the fluctuations measured by the magnetic loops at the plasma edge indicate that the plasma temperature profile broadens, which triggers the loss of plasma particles. This conclusion is supported by the D_α emission detected from

the pellets that were injected at various times during the re-heat. The pellets that were injected after the density began to decrease, experienced significant ablation in the edge regions of the plasma as compared to those injected before. The actual loss of particles from the plasma is the result of a new equilibrium that is established between the particle confinement time and the amount of edge recycling as the profiles broaden and increase the heat flux to the vacuum vessel wall. It is the combination of these two effects which controls the evolution of the plasma back to the pre-pellet parameters after a pellet-induced thermal collapse and recovery.

CHAPTER V

SUMMARY AND CONCLUSIONS

This work describes pellet injection experiments into stellarator plasmas that are comparable in size to that of small tokamaks. The experiments focused on two major areas of study: pellet ablation and plasma response to pellet injection.

Summary of D_α Emission Experiments

There are several interesting features of the D_α emission from pellets injected into ATF plasmas. It was shown that the rate of D_α emission was independent of the size of the pellet, which contradicts the prevailing pellet ablation theories and the pellet ablation scaling laws derived from pellet ablation experiments on tokamaks. Also in contrast to the results of pellet ablation experiments performed on tokamaks, is the significant level of D_α emission observed after the pellet has crossed the magnetic axis of the plasma. In tokamaks, if a pellet penetrates beyond the magnetic axis of the plasma, it typically penetrates the entire plasma column, due to reduced ablation experienced on the inside half of the plasma. It is not clear why there is an apparent limit to the pellet ablation that occurs on the outer half of the plasma column when significant pellet ablation occurs after the pellet crosses the magnetic axis of the plasma.

It was shown that a peak in the D_α emission which is centered at $R \approx 2.26$ m was independent of the size of the pellet. Results from the experiments where a second pellet was injected into different stages of the pellet-induced collapse

and recovery indicate that the increased D_α emission at the edge of the plasma occurs only after the ECE in the edge region has increased. A population of non-thermal electrons in the edge region of the plasma ($\rho \approx .7$ to $\rho \approx 1$) is thought to be responsible for the increased ECE emission which is necessary in order to observe the high emission rates at the plasma edge. Also, the emission peak decreases with increasing target plasma density and the peak disappears if the density is increased sufficiently. This happens because the plasma density and the collisionality increase and the number of electrons that can be driven to non-thermal energies decreases.

For ATF plasmas in the standard configuration, there is a region with reduced ablating potential which ranges from $R \approx 2.13$ m to $R \approx 2.08$ m. The reduction in D_α emission from this region is observed for plasmas with and without the optimal magnetic field strength for ECH absorption. For plasmas with the prolate magnetic configuration, a region corresponding to approximately the same location produces ablation rates significantly higher than that observed as the pellet enters the plasma. This enhanced emission eliminates the possibility of a mass flow limitation rate from the surface of the pellet as the cause of the lack of a pellet mass dependence on the ablation rate. It also suggests that the absorption of the ECH power is substantially different for the two different magnetic configurations.

The expected change in the line-integrated density measurements based on the relative intensity of D_α emission at the corresponding pellet position were not observed. Based on the observed changes in the electron density diagnostics, it was concluded that the pellet particles are evenly distributed over the entire plasma volume.

The emission from pellets injected into plasmas heated by either gyrotron is virtually indistinguishable from that observed when the plasma is heated by

the other. The amount of emission observed when the plasma was heated by both of the gyrotron systems was much higher in the edge region of the plasma, but the level of emission in the central region was only about 10% higher than that observed for the single gyrotron cases. Neither of the gyrotrons provide much ablative potential in the edge region, but the combined effect of the two systems produces a sharp rise in the ablation emission at $R \approx 2.35$ m, and a peak in the ablation emission at $R \approx 2.26$ m. This type of emission is also observed from pellets injected into very low density plasmas heated with only one gyrotron.

The area of study that can benefit most from future pellet ablation studies is that of ECH absorption. The emission detected from the injection of large pellets could allow for more extensive studies of the effects of the plasma magnetic configuration, magnetic field strength, and plasma density on the absorption of ECH power.

Summary of the Plasma Response to Pellet Injection

The injection of a properly sized pellet has been shown to produce an increase in the stored energy and hence the confinement of the plasma. It was also shown that pellet fueling provides a moderate improvement in the stored energy over that produced at similar densities with gas fueling alone. If the pellet is large enough, it can cause the plasma to undergo a thermal collapse. Thermal collapse in ATF plasmas has been related to the local electron power balance, but the overall behavior is not well understood. The injection of a properly sized pellet has been shown to produce a reproducible thermal collapse, which has permitted the collapse to be studied systematically.

The thermal collapse has been shown to be related to an overall power imbalance in the plasma, which is due to a density cutoff effect for the ECH power.

The severity of the imbalance is related to the density of the plasma after injection. A small pellet may cause the collapse to occur several particle confinement times after injection due to density increases after injection. In these cases, the plasma is only slightly out of power balance and the majority of the ECH power is being absorbed in the plasma. A large pellet can cause the collapse to occur almost immediately after injection.

Upon the recovery of the stored energy, the plasma undergoes a density collapse. It was shown that the characteristics of the recovery were not altered by increased pellet size. The injection of larger pellets increased the period of time from the injection of the pellet to the beginning of the recovery of the stored energy. This was attributed to the density being required to drop below a critical value before a positive electron power balance can be achieved. It is difficult to make inferences about the required density and the exact location of the critical region due to the large uncertainty associated with the density profile as inferred from the FIR interferometer data. It can be said that the beginning of the recovery of the stored energy is independent of the overall plasma density, specifically the density in the central region of the plasma.

During the recovery from the thermal collapse, the density profile is slowly varying. At some point in the recovery, the particles added by pellet injection are lost from the plasma, and the plasma returns to its pre-pellet condition.

The relaxation of the density back to the pre-pellet value occurs in two stages. First, the density profile broadens and then the temperature profile broadens. The evolution of the pressure profile in the plasma is consistent with the hypothesis that the broadening of the density profile is due to unfavorable pressure gradients that occur in the plasma as the stored energy recovers, and may be a manifestation of the Bohr-Van Leeuwen theorem, which predicts that the product of the temperature and density profiles along the radius should be constant. If

resistive pressure-gradient-driven instability is responsible for the broad density profiles typically observed in ATF plasmas, then it is probable that they are responsible for the relaxation of the density back to the pre-pellet value. A better understanding of the role played by pressure-gradient-driven instabilities in these plasma is needed before this can be determined conclusively. The actual loss of particles is due to the establishment of a new equilibrium between the particle confinement time and the amount of edge recycling that occurs as the temperature increases in the edge region of the plasma.

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VITA

Arthur Louis Qualls was born on September 12, 1963, and has been in school almost ever since. His parents fondly called him 'Little Disaster' and strongly encouraged him to pursue a career in nuclear science, which he did.

He entered graduate school at the University of Tennessee, Knoxville, in June 1986. At the time he was very young and very dumb. He is no longer very young, and although he has learned a considerable amount in the past few years, the experience has only served to demonstrate how much there is to learn. After graduation he plans to learn as much as he can.

His motto has always been "Fight for the underdog", and he seems to spend an awful lot of time fighting for himself. He has other mottos (wear glasses if you need 'em), but they are really just good rules to live by.

As you can probably tell, he doesn't go in for this sort of thing and he will probably have to write a serious one of these things one day - but not today.