

To the Graduate Council:

I am submitting herewith a dissertation written by William Harry Casson entitled "Far-Infrared Scattering on ELMO Bumpy Torus and Impurity Study Experiments." I have examined the final copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Physics.

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FAR-INFRARED SCATTERING ON ELMO BUMPY TORUS
AND IMPURITY STUDY EXPERIMENTS

A Dissertation
Presented for the
Doctor of Philosophy
Degree
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William Harry Casson

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This work is gratefully dedicated
to my parents
for starting the whole thing.

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ABSTRACT

A far-infrared (FIR) laser scattering diagnostic was installed on the ELMO Bumpy Torus (EBT) experiment to measure density waves and fluctuations. The system was tested and calibrated using a TPX plastic Bragg acoustic cell and was shown to be fully functional. Only low signal levels were observed during most plasma conditions including fast and slow wave ion cyclotron heating (ICH) experiments. It was demonstrated that the level of fluctuations in EBT-S was much lower than in EBT-I. Also penetration of ICH driven waves into the plasma core was evidenced. Pulsed experiments provided evidence of an instability, probably related to the rapid increase in ECH power, that had a remarkably short lifetime.

Unresolved forward scattering of FIR radiation was accomplished on the Impurity Study Experiment (ISX) by spectrum analyzing the output signals from the FIR interferometer system. MHD instabilities and fluctuation levels were observed in agreement with other plasma diagnostics.

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CHAPTER 1

INTRODUCTION

1-1 Background

During the past fifteen years significant and steady progress has been made towards realizing the utilization of fusion energy for production of electrical power. Longer confinement times, higher densities, and higher temperatures have been achieved through a program costing billions of dollars and involving thousands of researchers. The achievement, in a single plasma, of a confinement time and density that exceeded the Lawson criterion was accomplished recently by a team at MIT and represents a major milestone in fusion energy research. However significant these accomplishments are, they do not represent the only important goals of fusion energy research in this country. Essential to the design and operation of a fusion powered electrical plant is an in-depth understanding of the physics involved in the plasma core. Since plasma processes are also observed in other fields of physics research such as cosmology and solid state physics, then plasma research is intimately tied to our understanding of the universe and the advancement of our technology.

Like all fields of physics research, plasma physics can be divided into two categories, theory and experiment. Experimental plasma physics can be further divided into the study of plasma processes and plasma diagnostics, although the division is less clear-cut. Plasma diagnostics involve many fields of physics research and technological

development, and they frequently advance a field of research unrelated to plasma physics. Because it is not possible to advance our understanding of plasma processes without accurate and reliable information about the interior of the plasma, a major portion of fusion research is directed towards diagnostics.

Most of the effort at Oak Ridge National Laboratory (ORNL) during the last several years has been divided between the two major plasma confinement devices: the Impurities Studies Experiment (ISX) and the Elmo Bumpy Torus Experiment (EBT). As part of the overall diagnostics effort, several studies of density fluctuations in both experiments have been conducted. The information obtained, however, has been limited. The purpose of this thesis project has been to develop improved methods for the observation and measurement of density fluctuations and to evaluate the information obtained in terms of the overall current understanding of the plasmas studied. Section 1-2 describes the importance of density fluctuations and how they are measured.

1-2 Fluctuations and Their Measurement

A plasma at equilibrium loses energy at a rate that is partially determined by the level of fluctuations. Fluctuations of density and electric field both contribute to anomalous diffusion. Diffusion can be reduced by increasing the magnetic field, but even though diffusion losses due to binary collisions are reduced proportional to $1/B^2$, collective losses and diffusion due to fluctuations are reduced only at a rate of $1/B$.²² An understanding of the fluctuations level and their

spatial distribution is therefore an important step in resolving questions of particle and energy transport, and in improving confinement in plasma devices. The characteristics of the fluctuations are described completely by the dielectric permittivity tensor. Inversely, a complete measurement of the fluctuations is sufficient to determine the dielectric permittivity tensor. This leads to an understanding of the energy dissipation via the fluctuation-dissipation theorem.³⁵ To reach this level of understanding, concurrent measurements of the density fluctuations and the potential fluctuations must be made for all spatial locations, and the phase between the two fluctuations measured. Currently this is beyond the state of the art of nonperturbing plasma diagnostics. However, independent measurements of density fluctuations and electric fluctuations are now becoming possible by use of long wavelength lasers and heavy-ion beam probes. The measurement of density fluctuations can result in indications of the stability of the plasma. In total equilibrium the fluctuation level will most likely be too low to measure with current laser systems. In a nonequilibrium plasma, instabilities exist which enhance the fluctuation level. Measurements therefore provide a means of detecting these instabilities and of inferring their contribution to plasma confinement and equilibrium.

There are several methods of observing density fluctuations in a hot plasma, each with its own shortcomings. These include probes, plasma emission, and the scattering of radiation. Most widely used historically is the Langmuir probe which ideally is as simple as a fine wire inserted into the plasma to collect electrons and ions on its

surface. The potential of the probe, together with the current collected on its surface, yields information about the temperature, density, and electric potential of the plasma. By spectrum analyzing the probe output, the changes in these plasma parameters on short time scales--the fluctuations--can be recorded. Unfortunately the probe, as it is inserted into the plasma, develops an electric field around it and therefore perturbs the plasma's normal behavior. The enlargement of the surface area inserted into the plasma due to the necessary shielding and water cooling of the probe results in an increase in the perturbation of the local plasma. These perturbations include a cooling of the plasma due to the probe's cold surface, modification of the normal electric field structure of the plasma due to the probe shield's conductivity, and the effects of magnetic field lines intersecting the probe structure, thereby effectively terminating those lines. It is obvious from this argument that the deeper into a plasma a probe is inserted, the less reliable the information obtained. Typical probe usage is restricted to the outermost surface of the plasma depending upon the energy density of the plasma being studied.

It is desirable to diagnose the plasma without perturbing it from its natural state. The most straightforward way of doing this is to observe plasma emission of electro-magnetic radiation and particles. A simple photodiode can be used to measure electromagnetic radiation from infrared through the ultraviolet wavelengths. Since hydrogen is the gas used to create the plasma, emission is dominated by the H-alpha line of hydrogen at modest temperatures. When observing plasma emissions the

photodiode current output is largely the result of the H-alpha emission, which is itself dependent on the electron temperature and density, and the neutral hydrogen background density. Above 50 eV the temperature is no longer important. If it is assumed that electron density fluctuations dominate the neutral density fluctuation effects, then the photodiode current can be spectrum analyzed to obtain information about the density fluctuation distribution. To localize the portion of the plasma observed, the optics path to the photodiode is collimated to restrict the observation beam to a cylindrical beam through the plasma. This line integral measurement includes the outer surface of the plasma where plasma characteristics may not represent the characteristics of the central plasma due to the cooler temperatures (<50 eV) at the surface. The neutral density distribution also plays an important role in the emission rate at different locations in the plasma. Questions of reflected signals must be dealt with in order to ensure localized observations. To obtain spatial information about the signals, the method of Abel inversion may be applied which requires either a complex spatial scanning system or certain assumptions about the symmetry of the plasma. Deviations from circular symmetry may increase the risk of conclusions drawn from this method.

The final and most important method of observing density fluctuations involves passing a beam of electromagnetic radiation or particles, of sufficiently low power level so as not to perturb the plasma to an observable extent, through the plasma and observing changes in the beam as it exits the plasma. Particle beam diagnostics depend on

changes in the charge state of the particles exiting the plasma. Electromagnetic waves are phase shifted as they pass through regions of differing refractive index and are scattered off electrons as in classical scattering. Scattered signal levels depend strongly upon the electromagnetic wavelength (this is illustrated in more detail in Chapter 2). At shorter wavelengths, scattering from free electrons dominates and the scattered spectrum is a function of electron temperature and density. This is the basis for Thomson scattering diagnostics. Longer wavelengths, far infrared and microwave, scatter only from electrons that are weakly bound or what are called associated electrons. These electrons, which form the Debye shielding cloud, behave in a manner related to the ion distribution. A change in the ion distribution results in a change in the associated electron distribution and therefore in the scattered electromagnetic field. Ion fluctuations and waves will result in net scattered signal of magnitude and direction depending on the fluctuation wavelength and intensity. The shift in the electromagnetic frequency is the same as the fluctuation frequency. The scattered signal therefore contains information about the fluctuation level, frequency spectra, and fluctuation wavelength. The electromagnetic wave entering the plasma can be collimated and focused to a narrow beam through the interaction region and is referred to as the incident beam. In the same manner the observation angle and solid angle can be restricted, and the resulting viewing beam will be referred to as the antenna beam. The only scattered signal observed is from the volume where the two beams intersect. A suitable scanning mechanism therefore

could allow observation of fluctuations in a limited volume at any spatial location in the plasma. All this information can be obtained without perturbation of the plasma and at anytime during the plasma's existence.

1-3 Overview

The major portion of the work represented by this thesis was done with far-infrared (FIR) and microwave scattering on the EBT device. Considerable work was also done with photodiodes and Langmuir probes in support of these measurements. In addition FIR scattering was observed on ISX via the FIR interferometer system. Appendix C reviews photodiode and Langmuir probe results, which is considered work preliminary to the scattering measurements. The theory of Thomson scattering is reviewed in Chapter 2 as it applies to the experiment. In Chapter 3 a description of the FIR scattering system on EBT is given along with a discussion of physical constraints imposed on the design and operation. System reliability, the calibration procedures, and results are summarized in Chapter 4. A review of the important measurements attempted on EBT is given in Chapters 5 and 6 followed by a discussion of these results. In Chapter 7 a brief account of the measurements made on ISX is given followed by conclusions about those experiments. A complete summary and conclusions are given in Chapter 8 along with recommendations for future endeavors in this field.

Central to the discussion of the experiments performed are the plasma devices on which the measurements were made. Although the design

and characteristics of these machines are not part of the research work, the inclusion of their description is deemed appropriate and necessary. Appendix A gives a general presentation of these experimental machines and their operation. A brief review of two similar scattering measurements performed recently on other types of plasma devices is included in Appendix B.

CHAPTER 2

SCATTERING THEORY

2-1 Introduction to Scattering

The processes involved in the scattering of electromagnetic radiation are sufficiently well understood to allow the design of a specific scattering experiment to measure a restricted set of plasma phenomena or parameters. Because there are several scattering regimes which depend on the wavelength, polarization, scattering angles, and plasma parameters, care must be taken in the choice of coherent radiation sources as well as the scattering geometry and the type of detectors used.

Radiation scattered off a random distribution of electrons is diminished because of interference of the random phase fronts. If the electrons are weakly ordered, such as in a density wave, then a diffraction pattern results and the detectable scattered signal increases. The simplest case is electron density waves and fluctuations, which tend to be very short wavelength. On the other hand, ion fluctuations tend to be longer wavelength. The electron population is strongly influenced within the region of the Debye sphere by the ions' motion. A wave motion in the ion density causes a like motion in the electron density, and ion density waves can be detected by their effect on the electrons. Thermal fluctuations, plasma fluctuations, and plasma waves are divided into two broad categories. If the characteristic wavelength of the perturbation is much less than the Debye length, the wave will have

little effect on the ions and vice versa. Measurements of these effects will result in information about the electrons such as the electron temperature and density. On the other hand, if the characteristic length is close to or larger than the Debye length, then the wave and ion interact. An electron wave will lose energy to the ions, and an ion wave will carry with it an equivalent electron wave (same wavelength and frequency with a proportional amplitude). Measurements of the perturbation in electron distribution in this wavelength region will reflect the ion temperature and density fluctuations.

The scattering of radiation from electron density waves obeys the Bragg scattering relation obtained from the relation $\underline{k}_s = \underline{k}_i + \underline{k}_0$ which will be derived later. The subscript s refers to scattered waves, i to the incident wave, and zero to the density wave. The Bragg relation,

$$k_0 = 2 k_i \sin \theta/2 , \quad (2-1)$$

is obtained by taking the magnitude of $\underline{k}_s$ and assuming that the scattered and incident wavelengths are approximately equal. The fluctuation wavelength measured in an experiment is determined solely by the incident wavelength and the scattering angle θ . Additional limits on the incident wavelength are determined by refraction effects and the plasma cutoff limit, both of which are determined by the plasma frequency. This experiment was designed to measure characteristic lengths larger than the Debye length, and is therefore sensitive to ion fluctuations and long wavelength plasma waves. Ion thermal

fluctuations are ignored since the fluctuation amplitude is expected to be much smaller than the other two effects. Fluctuations will often be referred to as incoherent waves and plasma waves will be referred to as coherent waves, which must not be confused with incoherent and coherent scattering. The scattering of coherent radiation from incoherent waves will be treated in the next section by a standard derivation involving the summation of the classical scattering of radiation off of individual electrons. This derivation can be extended to include scattering from coherent waves but another approach to this problem is presented. The treatment of coherent density waves in a plasma is approached from the viewpoint of the resulting perturbations in the index of refraction. The result is then compared to those obtained from the standard derivation. The scattered power from an ion-acoustic wave in EBT is then estimated based on the measurements of the incident FIR power and an arbitrary wave amplitude.

2-2 Scattering from Incoherent Waves

The scattering of radiation from incoherent waves has been treated in great detail in various references. The best general reference for scattering theory is Sheffield,³³ who gives a detailed general treatment before specializing the arguments to shorter wavelength sources. Scattering by microwaves is treated by Marshall, and the general scattering of light is treated by DeSilva and Goldenbaum, in Reference 20. Treatment in the infrared region is given by Holzhauer and Massig,¹² and in the far infrared by Semet³² and Park.²⁵ Perhaps one of the most

detailed calculations is presented by Moresco and Zilli,²³ who describe application to 2.2-mm waves, taking into account the Gaussian beam shape and the wavefront curvature. Since the theory has been detailed so well and a complete derivation is very lengthy, only an abbreviated and rather simplified calculation is given here. Despite the several liberties that are taken, the end result differs from other treatments by only a numerical factor of 1/4 in the ratio of scattered power to incident power. A rigorous treatment such as that done by Moresco and Zilli includes several additional factors relating to the Gaussian beam parameters. It is generally assumed that these corrections are not necessary if the scattering volume is near the beam waist of both the incident and antenna beams where the wavefronts are almost planar. This is typically designed into the optic system and is therefore a valid assumption.

In order to derive the scattering from a single electron, we first assume a coherent, linearly polarized wave with the electric field parallel to the applied magnetic field in the plasma. Since the acceleration of an electron due to the incident radiation field is short-lived and of modest intensity, we will assume the electron to remain nonrelativistic during the interaction. Taking an arbitrary origin within the scattering volume, we can write:

$$\underline{r}' + \underline{R} = \underline{r} , \quad (2-2)$$

to define the spatial relationship of the electron at $\underline{r}'$, the observer at $\underline{r}$, and vector from the electron to the observer given by $\underline{R}$. We will

assume the interaction volume to be small compared with the observation distance such that $r \gg r'$, which allows the approximation:

$$R = |\underline{r} - \underline{r}'| \approx r - \frac{\underline{r}' \cdot \underline{r}}{r} . \quad (2-3)$$

In MKS units we can now write the electric scalar potential as:²⁸

$$\phi(\underline{r}, t) = \frac{1}{4\pi\epsilon_0} \int_V \frac{\rho(\underline{r}', t - r/c + \frac{\underline{r}' \cdot \underline{r}}{cr}) d^3r}{r - (\underline{r}' \cdot \underline{r})/r} . \quad (2-4)$$

Expanding this into a Taylor series, we obtain the potential from the static distribution and all the multipole terms. We keep only the dipole, p , term for a single electron and ignore higher order terms:

$$\phi(\underline{r}, t) = \frac{1}{4\pi\epsilon_0} \left[\frac{Q}{r} + \frac{\underline{r} \cdot \underline{p}(t - r/c)}{r^3} + \frac{\underline{r} \cdot \underline{p}(t - r/c)}{cr^2} \right] . \quad (2-5)$$

The retarded vector potential is given by:

$$\underline{A}(\underline{r}, t) = \frac{\mu_0}{4\pi} \int_V \frac{\underline{J}(\underline{r}', t - r/c + \frac{\underline{r} \cdot \underline{r}'}{cr}) d^3r}{r - (\underline{r}' \cdot \underline{r})/r} \quad (2-6)$$

In a manner similar to the scalar potential this can be written as,

$$\underline{A}(\underline{r}, t) = \frac{\mu_0}{4\pi r} \dot{\underline{p}}(t - r/c) , \quad (2-7)$$

where again higher multipole terms have been ignored.

To calculate the fields, the supplementary constitutive Maxwell equations are applied:

$$\underline{E} = - \frac{\partial \underline{A}}{\partial t} - \nabla \phi , \quad (2-8)$$

$$\underline{B} = \nabla \times \underline{A} . \quad (2-9)$$

After carrying out the derivatives, ignoring obvious small terms, and rearranging, we find:

$$\begin{aligned} \underline{E}(\underline{r}, t) &= \frac{1}{4\pi\epsilon_0 c^2} \frac{1}{r^3} \underline{r} \times (\underline{r} \times \ddot{\underline{p}}) \\ \underline{B}(\underline{r}, t) &= - \frac{\mu_0}{4\pi c r^2} \underline{r} \times \ddot{\underline{p}} . \end{aligned} \quad (2-10)$$

Insertion into the Poynting vector gives:

$$\begin{aligned} \underline{S} &= \frac{1}{\mu_0} (\underline{E} \times \underline{B}) \\ &= \frac{c}{\mu_0 r} \underline{r} B^2 \\ &= \frac{1}{16\pi^2 \epsilon_0 c^3 r^5} \underline{r} |\underline{r} \times \ddot{\underline{p}}|^2 . \end{aligned} \quad (2-11)$$

The z-axis is now taken in the direction of the electric field of the incident wave and therefore in the direction of $\ddot{\underline{p}}$. In spherical coordinates the radiated power is:

$$P_R = \oint_S \underline{S} \cdot \hat{n} da , \quad (2-12)$$

and the radiated power per unit solid angle is:

$$\begin{aligned}
 \frac{dP_R}{d\Omega} &= r^2 \underline{S} \cdot \hat{n} \\
 &= \frac{1}{16\pi^2 \epsilon_0 c^3 r^3} |\underline{r} \times \ddot{\underline{p}}|^2 (\underline{r} \cdot \hat{n}) \\
 &= \frac{1}{16\pi^2 \epsilon_0 c^3} \ddot{\underline{p}}^2 \sin^2 \theta .
 \end{aligned} \tag{2-13}$$

Using $\dot{\underline{v}} = \ddot{\underline{p}}/e$ and relating the acceleration to the incident electric field,

$$m\dot{\underline{v}} = e\underline{E} , \tag{2-14}$$

results in:

$$\frac{dP_R}{d\Omega} = \frac{e^4}{16\pi^2 \epsilon_0 c^3 m^2} E_o^2 \sin^2 \theta . \tag{2-15}$$

Dividing this by the incident power results in the scattering cross section:

$$\frac{d\sigma}{d\Omega} = \frac{\mu_o e^4 \sin^2 \theta}{16\pi^2 \epsilon_0 c^2 m^2} = \frac{e^4 \sin^2 \theta}{16\pi^2 \epsilon_0^2 c^4 m^2} . \tag{2-16}$$

The classical electron radius is defined as:

$$r_e = \frac{e^2}{4\pi\epsilon_0 mc^2} , \tag{2-17}$$

which simplifies the scattering cross section to:

$$\frac{d\sigma}{d\Omega} = r_e^2 \sin^2 \theta . \quad (2-18)$$

We obtain the total cross section by integrating over 4π steradians.

$$\begin{aligned} \sigma_T &= \oint_S \frac{d\sigma}{d\Omega} d\Omega \\ &= \oint r_e^2 \sin^2 \theta \sin \theta d\theta d\phi \\ &= \frac{8\pi}{3} r_e^2 . \end{aligned} \quad (2-19)$$

This is the well-known Thomson cross section for a single electron.

In order to evaluate the scattering from a collection of electrons we first return to the Poynting vector:

$$\underline{S} = \frac{1}{\mu_0} (\underline{E} \times \underline{B}) , \quad (2-20)$$

where $\underline{E} = \sum_{i=1}^N \underline{E}_i$ for N electrons:

$$\begin{aligned} \frac{dP_R}{d\Omega} &= r^2 \underline{S} \cdot \hat{n} \\ &= \frac{r^2}{\mu_0 c} (\hat{n} \cdot \underline{E})(\hat{n} \cdot \underline{E}) \\ &= \frac{r^2}{c\mu_0} \sum_{i=1}^N \sum_{j=1}^N \underline{E}_i \cdot \underline{E}_j . \end{aligned} \quad (2-21)$$

This relation is now separated into two parts; the first is for $i = j$ and the second is for $i \neq j$:

$$\frac{dP_R}{d\Omega} = \frac{r^2}{c\mu_0} NE^2 + \frac{r^2}{2c\mu_0} \sum_{\substack{i,j=1 \\ i \neq j}}^N E_i E_j . \quad (2-22)$$

The first term if evaluated as before will lead to the Thomson scattering cross section for N electrons. The second term, for a completely isotropic distribution, will sum to zero due to the random phase distribution of the scattered signals. However, the second term becomes important when the distribution is anisotropic. For coherent and incoherent plasma waves the second term dominates the first term. This is the basis for the FIR diagnostic.

We can write the electric field of the emitted radiation of an accelerated charge as:¹⁴

$$\underline{E}_s = \frac{e}{4\pi\epsilon_0 c^2} \left[\frac{\hat{n} \times (\hat{n} \times \dot{\underline{v}})}{R} \right] , \quad (2-23)$$

which is evaluated at the retarded time, t' . Here $\hat{n}$ is in the direction of R . The total scattered field would then be given by the integral over all electrons. Writing the distribution of electrons as $F(\underline{r}, \underline{v}, t')$ we get:

$$\underline{E}_s = \int_V \int \frac{e}{4\pi\epsilon_0 c^2} F(\underline{r}, \underline{v}, t') \left[\frac{\hat{n} \times (\hat{n} \times \dot{\underline{v}})}{R} \right] d^3r d^3v . \quad (2-24)$$

The electric field, $\underline{E}_0$, of the incident wave is parallel to the static magnetic field, and the incident magnetic field is small; so we ignore the magnetic effects on the electron motion. The acceleration can thus be written as:

$$\dot{\underline{v}} = \frac{e}{m} \underline{E}_0 , \quad (2-25)$$

which gives a scattered field of:

$$\underline{E}_s = \int_V \int \frac{e}{4\pi\epsilon_0 c^2} F(\underline{r}, \underline{v}, t') \left[\frac{\hat{n} \times (\hat{n} \times \frac{e}{m} \underline{E})}{R} \right] . \quad (2-26)$$

When $\underline{E}_0$ and $\underline{R}$ are at right angles to each other the cross products become $-\underline{E}_0$. We can now write:

$$\underline{E}_s = \frac{-e^2}{4\pi\epsilon_0 mc^2} \int \int F(\underline{r}, \underline{v}, t') \frac{\underline{E}_0}{R} d^3r d^3v . \quad (2-27)$$

The vector notation can be dropped since the incident electric field and the scattered field are parallel. The magnitude of the incident wave can be written as:

$$|\underline{E}_0| = E_0 \cos(\omega t' - \underline{k}_i \cdot \underline{r}) = \frac{1}{2} E_0 (e^{i(\underline{k}_i \cdot \underline{r} - \omega_i t')} + e^{-i(\underline{k}_i \cdot \underline{r} - \omega_i t')}) , \quad (2-28)$$

so that:

$$E_s = \frac{e^2}{4\pi\epsilon_0 mc^2} \frac{E_0}{2R} \int \int F(\underline{r}, \underline{v}, t') [e^{i(\underline{k}_i \cdot \underline{r} - \omega_i t')} + e^{-i(\underline{k}_i \cdot \underline{r} - \omega_i t')}] d^3 r d^3 v. \quad (2-29)$$

Since $n(\underline{r}, t') = \int F(\underline{r}, \underline{v}, t') d^3 v$ and $r_0 = e^2/4\pi\epsilon_0 mc^2$, then:

$$E_s = \frac{r_0 E_0}{2R} \int n(\underline{r}, t') (e^{i(\underline{k}_i \cdot \underline{r} - \omega_i t')} + e^{-i(\underline{k}_i \cdot \underline{r} - \omega_i t')}) d^3 r. \quad (2-30)$$

The Fourier transforms of n and E are given by:

$$n(\underline{r}, t') = \frac{1}{(2\pi)^4} \int \int n(\underline{k}, \omega) e^{-i(\underline{k}_0 \cdot \underline{r} - \omega_0 t')} d^3 k d\omega \quad (2-31)$$

$$E_s(\underline{r}, \omega) = \int_{-\infty}^{\infty} E_s(\underline{r}, t) e^{i\omega_s t} dt, \quad (2-32)$$

which upon substitution gives:

$$E_s(\underline{r}, \omega) = \frac{r_0 E_0}{2R} \frac{1}{(2\pi)^4} \iiint n(\underline{k}, \omega) e^{-i(\underline{k}_0 \cdot \underline{r} - \omega_0 t')} e^{-i\omega_s t} (e^{i(\underline{k}_i \cdot \underline{r} - \omega_i t')} + e^{-i(\underline{k}_i \cdot \underline{r} - \omega_i t')}) d^3 r d^3 k d\omega dt. \quad (2-33)$$

Combining the exponential terms the integral over time is given by

$$\int [\exp i(-\underline{k}_0 \cdot \underline{r} + \underline{k}_i \cdot \underline{r} + \omega_0 t' - \omega_s t - \omega_i t') + \exp i(-\underline{k}_0 \cdot \underline{r} - \underline{k}_i \cdot \underline{r} + \omega_0 t' - \omega_s t - \omega_i t')] dt'. \quad (2-34)$$

The retarded time is approximated by:

$$t' = t - R/c + \frac{\underline{r} \cdot \hat{n}}{c} = t - R/c + \frac{\underline{r} \cdot \underline{k}_s}{\omega_s}; \quad (2-35)$$

therefore

$$t = t' + R/c - \frac{\underline{r} \cdot \underline{k}_s}{\omega_s}, \quad (2-36)$$

and the integral becomes:

$$\begin{aligned} & \int [\exp i (-\underline{k}_0 \cdot \underline{r} + \underline{k}_s \cdot \underline{r} + \underline{k}_i \cdot \underline{r} + \omega_0 t' - \omega_s t' - \omega_i t' - \omega_s R/c) \\ & + \exp i (-\underline{k}_0 \cdot \underline{r} + \underline{k}_s \cdot \underline{r} - \underline{k}_i \cdot \underline{r} + \omega_0 t' - \omega_s t' + \omega_i t' - \omega_s R/c)] dt' \\ & = 2\pi \exp i (\underline{k}_0 \cdot \underline{r} + \underline{k}_s \cdot \underline{r} + \underline{k}_i \cdot \underline{r} - \omega_s R/c) \delta(\omega_0 - (\omega_s + \omega_i)) \\ & + 2\pi \exp i (\underline{k}_0 \cdot \underline{r} + \underline{k}_s \cdot \underline{r} - \underline{k}_i \cdot \underline{r} - \omega_s R/c) \delta(\omega_0 - (\omega_s - \omega_i)) . \end{aligned} \quad (2-37)$$

Similarly the volume integral yields:

$$\int \exp i (-\underline{k}_0 \cdot \underline{r} + \underline{k}_s \cdot \underline{r} + \underline{k}_i \cdot \underline{r}) d^3 r = (2\pi)^3 \delta(\underline{k}_0 - (\underline{k}_s + \underline{k}_i)) \quad (2-38)$$

and

$$\int \exp i (-\underline{k}_0 \cdot \underline{r} + \underline{k}_s \cdot \underline{r} - \underline{k}_i \cdot \underline{r}) d^3 r = (2\pi)^3 \delta(\underline{k}_0 - (\underline{k}_s - \underline{k}_i)) . \quad (2-39)$$

Ignoring the constant phase factor of $\exp i(\omega_s R/c)$, the electric field now becomes:

$$E_s(\underline{r}, \omega) = \frac{r_o E_o}{2R} \iint n(\underline{k}, \omega) [\delta(\omega_o - (\omega_s + \omega_i)) \delta(\underline{k}_o - (\underline{k}_s + \underline{k}_i)) + \delta(\omega_o - (\omega_s - \omega_i)) \delta(\underline{k}_o - (\underline{k}_s - \underline{k}_i))] d^3k d\omega, \quad (2-40)$$

which integrates easily to:

$$E_s(\underline{r}, \omega) = \frac{r_o E_o}{2R} n((\underline{k}_s + \underline{k}_i, \omega_s + \omega_i) + n(\underline{k}_s - \underline{k}_i, \omega_s + \omega_i)). \quad (2-41)$$

Since a homodyne detector cannot distinguish between the signs of $\omega_s \pm \omega_i$, we will combine them into one term $n(\underline{k}, \omega)$. The scattered power is now given by:

$$\begin{aligned} \frac{dP_s}{d\Omega} &= R^2 \underline{s} \cdot \hat{n} \\ &= R^2 c \epsilon_o |E|^2 \\ &= \frac{c \epsilon_o r_o^2 E_o^2}{4} |n(\underline{k}, \omega)|^2. \end{aligned} \quad (2-42)$$

This can be rewritten as:

$$\frac{dP_s}{d\Omega} = \frac{r_o^2 n_o V P_o}{4} S(\underline{k}, \omega), \quad (2-43)$$

which is an expression relating the scattered power per unit solid angle to the incident power P_o , the scattering volume V , and the spectral density function which is defined as:

$$S(\underline{k}, \omega) = \lim_{V, T \rightarrow \infty} \frac{1}{VT} \left\langle \frac{n(\underline{k}, \omega)n^*(\underline{k}, \omega)}{n_0} \right\rangle, \quad (2-44)$$

where T is the averaging time.

2-3 Scattering from Refraction Waves

For calibration of the FIR scattering system we chose the technique of Bragg diffraction in an optoacoustic cell. This measurement is described in detail in the Chapter 3, where a derivation of the equations used for submillimeter wave diffraction or scattering are given following the derivation given by Yariv.⁴¹ The derivation is then extended to acoustical waves in a plasma. The results can be applied to scattering of the FIR wave off a coherent density wave structure. Comparison is made of the end results with the results of calculations given by Park²⁵ using a method similar to that presented in Section 2-2.

For simplicity we chose the geometry used to optimize the Bragg cell measurements during the calibration trials. In this configuration the incident wave vector and the scattered wave vector lie in the same plane as the acoustical wave vector. The angle of incidence and the angle of scatter measured relative to the normal of the acoustical plane wavefront are equal, the geometry being identical to the reflection of light at a plane dielectric interface. Reflections from successive wavefronts interact to form a diffraction pattern.

We represent the acoustical wave as a modulation in the index of refraction:

$$\Delta n(\underline{r}, t) = \Delta n \cos (\omega_0 t - \underline{k}_0 \cdot \underline{r}) , \quad (2-45)$$

where n is the index of refraction and should not be confused with the density which is represented by n in other sections of this text. The electric displacement and polarization are described by:

$$\underline{d} = \epsilon_0 \underline{e} + \underline{p} = \epsilon \underline{e}$$

$$\underline{p} = \epsilon_0 \chi \underline{e}$$

$$n^2 = \epsilon / \epsilon_0$$

$$\chi = k - 1$$

$$\epsilon = k \epsilon_0 , \quad (2-46)$$

which are the microscopic constitutive equations. These are combined to obtain the differential:

$$\Delta \underline{p}(\underline{r}, t) = 2(\epsilon \epsilon_0)^{\frac{1}{2}} \Delta n(\underline{r}, t) \underline{e}(\underline{r}, t) , \quad (2-47)$$

where $\underline{e}(\underline{r}, t)$ is the sum of the incident and scattered fields. Maxwell's equations in microscopic form can be used to obtain the necessary wave equation:

$$\nabla \times \underline{h} = \underline{i} + \frac{\partial \underline{d}}{\partial t} = \sigma \underline{e} + \epsilon \frac{\partial \underline{e}}{\partial t} + \frac{\partial \underline{p}}{\partial t}$$

$$\nabla \times \underline{e} = - \mu_0 \frac{\partial \underline{h}}{\partial t}$$

$$\nabla^2 \underline{e} = \mu_0 \frac{\partial}{\partial t} (\sigma \underline{e} + \epsilon \frac{\partial \underline{e}}{\partial t} + \frac{\partial \underline{p}}{\partial t}) .$$

Assuming a lossless medium results in:

$$\nabla^2 \underline{e}_i(\underline{r}, t) = \mu_0 \epsilon \frac{\partial^2 \underline{e}_i}{\partial t^2} + \mu_0 \frac{\partial^2}{\partial t^2} (\Delta P(\underline{r}, t))_i , \quad (2-48)$$

where the index i refers to the incident wave and s will refer to the scattered wave. We represent the waves by the form:

$$\underline{e}_i(\underline{r}, t) = \frac{1}{2} \underline{E}_i(\underline{r}_i) e^{i(\omega_i t - \underline{k}_i \cdot \underline{r})} + \text{C.C.} , \quad (2-49)$$

$$\underline{e}_s(\underline{r}, t) = \frac{1}{2} \underline{E}_s(\underline{r}_s) e^{i(\omega_s t - \underline{k}_s \cdot \underline{r})} + \text{C.C.} . \quad (2-50)$$

The Laplacian for the incident wave is:

$$\begin{aligned} \nabla^2 \underline{e}_i(\underline{r}, t) = & \left(-\frac{1}{2} k_i^2 \underline{E}_i(\underline{r}_i) - i k_i \frac{d \underline{E}_i(\underline{r}_i)}{d r_i} + \frac{1}{2} \nabla^2 \underline{E}_i(\underline{r}_i) \right) \\ & \exp i(\omega_i t - \underline{k}_i \cdot \underline{r}) , \end{aligned} \quad (2-51)$$

with a like counterpart for the scattered wave. We set $\nabla^2 \underline{E}_i = 0$ by assuming it is small compared to the other terms so that:

$$\nabla^2 \underline{e}_i(\underline{r}, t) = \left(-\frac{1}{2} k_i^2 E_i(r_i) - ik_i \frac{dE_i(r_i)}{dr_i} \right) e^{i(\omega_i t - \underline{k}_i \cdot \underline{r})} \quad (2-52)$$

Substitution into equation 2-48 gives:

$$k_i \frac{dE_i}{dr_i} = i\mu_o \left[\frac{\partial^2}{\partial t^2} (\Delta p)_i \right] e^{-i(\omega t - \underline{k}_i \cdot \underline{r})} \quad (2-53)$$

Writing $\underline{e}(\underline{r}, t)$ as $\underline{e}_i(\underline{r}, t) + \underline{e}_s(\underline{r}, t)$, we can express $\Delta n(\underline{r}, t) \underline{e}(\underline{r}, t)$ as:

$$\begin{aligned} & \frac{1}{4} \Delta n [E_i(r_i) e^{i((\omega_i + \omega_o)t - (\underline{k}_o + \underline{k}_i) \cdot \underline{r})} \\ & + E_i(r_i) e^{i((\omega_i - \omega_o)t - (\underline{k}_i - \underline{k}_o) \cdot \underline{r})} + \text{C.C.} \\ & + E_s(r_s) e^{i((\omega_s + \omega_o)t - (\underline{k}_s + \underline{k}_o) \cdot \underline{r})} + \text{C.C.} \\ & + E_s(r_s) e^{i((\omega_s - \omega_o)t - (\underline{k}_s - \underline{k}_o) \cdot \underline{r})} + \text{C.C.}] \quad (2-54) \end{aligned}$$

Nonsynchronous terms are discarded and only the synchronous term is retained, such that $\omega_i = \omega_s + \omega_o$. Now,

$$(\Delta p)_i = \frac{1}{2} \sqrt{\epsilon \epsilon_o} \Delta n E_s(r_s) e^{i((\omega_s + \omega_o)t - (\underline{k}_s + \underline{k}_o) \cdot \underline{r})} + \text{C.C.} \quad (2-55)$$

Substitution into equation 2-53 gives:

$$\frac{dE_i}{dr_i} = -i \eta_i E_s(r_s) e^{-i(\underline{k}_s + \underline{k}_o - \underline{k}_i) \cdot \underline{r}} \quad (2-56)$$

$$\frac{dE_s}{dr_s} = -i \eta_s E_i(r_i) e^{-i(\underline{k}_i - \underline{k}_s - \underline{k}_0) \cdot \underline{r}}, \quad (2-57)$$

where $\eta_{i,s} = \frac{1}{2} \omega_{i,s} \sqrt{\mu_0 \epsilon_0} \Delta n$. For the fields to be continuous in the interaction region, then $\underline{k}_i = \underline{k}_0 + \underline{k}_s$, which is the precursor to the Bragg relation. We can now write the coupled equations:

$$\frac{dE_i}{dr_i} = -i \eta_i E_s \quad (2-58)$$

$$\frac{dE_s}{dr_s} = -i \eta_s E_i. \quad (2-59)$$

Since $\omega_i \approx \omega_d$, then we let $\eta_i = \eta_s$. The analysis is simplified by using a standard coordinate transformation of:

$$r_i = \zeta \cos \theta \quad r_d = \zeta \cos \theta \quad (2-60)$$

which gives,

$$\frac{dE_i}{d\zeta} = -i \eta E_s \cos \theta \quad (2-61)$$

$$\frac{dE_s}{d\zeta} = -i \eta E_i \cos \theta. \quad (2-62)$$

Combining by using an additional differentiation results in:

$$\frac{d^2 E_s}{d\zeta^2} = -\eta^2 \cos^2 \theta E_s \quad (2-63)$$

$$\frac{d^2 E_i}{d\zeta^2} = -\eta^2 \cos^2 \theta E_i . \quad (2-64)$$

Solutions are of the form:

$$E = ke^{\pm i\eta\zeta \cos \theta} + f(r) = ke^{\pm i\eta r} + f(r) , \quad (2-65)$$

which can be rewritten as:

$$E_i(r) = E_i(0) \cos(\eta r_i) - iE_s(0) \sin(\eta r_i) \quad (2-66)$$

$$E_s(r) = E_s(0) \cos(\eta r_s) - iE_i(0) \sin(\eta r_s) . \quad (2-67)$$

For $r_s = 0$, $E_s(r_s) = 0$ so that:

$$E_s(r_s) = -iE_i(0) \sin(\eta r_s) . \quad (2-68)$$

$$E_i(r_i) = E_i(0) \cos(\eta r_i) . \quad (2-69)$$

The ratio of scattered power to incident power can now be written:

$$\frac{P_s}{P_i} = \frac{E_s^2}{E_i^2} = \frac{E_i^2(0) \sin^2 \eta r_s}{E_i^2(0)} = \sin^2 \eta r_s . \quad (2-70)$$

If ℓ is the interaction length, then:

$$\frac{P_s}{P_i} = \sin^2 \left(\frac{\ell \omega \Delta n}{2c_o} \right) . \quad (2-71)$$

So far this derivation has closely followed Yariv. It is now applied to two different situations. The first is the normal application to a plastic Bragg cell. The change in the index of refraction can be expressed as:

$$\Delta n = - \frac{n_o^3 p}{2} s , \quad (2-72)$$

where p is the photoelastic constant of the plastic and s is the applied strain:

$$s = \sqrt{\frac{2I_o}{\rho v_s^3}} . \quad (2-73)$$

By defining the figure of merit as,

$$M = \frac{n_o^3 p}{\rho v_s^3} , \quad (2-74)$$

the final form is now written as,

$$\frac{P_s}{P_o} = \sin^2 \left(\frac{\omega l}{4C_o} \sqrt{2MP_A} \right) . \quad (2-75)$$

The calculations are now extended to calculate the scattered power from a coherent acoustical wave in a plasma. For ordinary mode:

$$\omega^2 = \omega_c^2 + k^2 c^2 , \quad (2-76)$$

and the index of refraction for a plasma can be expressed as:

$$n^2 = \frac{k^2 c^2}{\omega^2} = 1 - \frac{\omega_e^2}{\omega^2}, \quad (2-77)$$

where ω_e is the electron plasma frequency. The change in n is expressed as:

$$\omega \Delta n = \sqrt{\omega^2 - \omega_{e1}^2} - \sqrt{\omega^2 - \omega_{e2}^2}. \quad (2-78)$$

The small angle approximation is made for the sin term in equation 2-75 which can now be expressed as:

$$\begin{aligned} \frac{P_s}{P_i} &= \left(\frac{\ell}{2c_0}\right)^2 (\sqrt{\omega^2 - \omega_{e1}^2} - \sqrt{\omega^2 - \omega_{e2}^2})^2 \\ &\approx \left(\frac{\ell}{2c_0}\right)^2 \frac{1}{2\omega} (\omega_{e2}^2 - \omega_{e1}^2). \end{aligned} \quad (2-79)$$

Since

$$\omega_e = \left(\frac{e^2}{m\epsilon_0}\right)^{\frac{1}{2}} n^{\frac{1}{2}},$$

then

$$\omega_{e2}^2 - \omega_{e1}^2 = \frac{e^2}{m\epsilon_0} (n_{e2} - n_{e1}) = \frac{e^2}{m\epsilon_0} \Delta n. \quad (2-80)$$

Substituting for the classical radius of the electron gives the final expression:

$$\frac{P_s}{P_i} = \frac{1}{4} r_o^2 k^2 \lambda^2 \Delta n_e^2 . \quad (2-81)$$

This same quantity was calculated by Park²⁵ by means of the approach of Section 2-2 with identical results.

Applying the results (Eq. 2-81) to a coherent wave with the wave vector normal to the incident beam and in the scattering plane, and assuming an incident power of 1.5 mW the scattered power can be estimated. A wave amplitude of 1% at a density of $1.5 \times 10^{11} \text{ cm}^{-3}$ is arbitrarily chosen. The wavelength is .0447 cm and the scattering volume length is taken as 4.5 cm. For this case the scattered power is calculated to be of the order of $3 \times 10^{-12} \text{ W}$. This is very near to the threshold of the system sensitivity as will be demonstrated in Chapter 4. If we assume the same parameters for a 2 mm wavelength then the scattered power will increase by a factor of 20. The actual increase in scattered power will be much larger with a 2 mm system because of increased incident power and an increase in the scattering volume. The sensitivity of the 2 mm detection system was not measured.

The calculation of Raman-Nath scattering is not presented since it is similar, but quite lengthy, and does not relate strongly to FIR scattering. The equations used in Chapter 4 for Raman-Nath scattering can be found in References 31 and 10.

CHAPTER 3

THE EBT SCATTERING SYSTEM

3-1 Background

Work on the EBT scattering system was initiated several years ago by Dr. Lee Bigel with the assistance of Dr. Donald Hutchinson. A special cavity (see Appendix A for a detailed description of EBT) was modified for the mounting of a scanning mirror system, and an early design FIR laser system was installed outside the lead wall enclosure. The project was then abandoned temporarily. Meanwhile, a group at UCLA under the direction of Dr. N. C. Luhmann, Jr., completed a series of laboratory bench tests with a similar apparatus and began installing their system on the UCLA Microtor tokamak experiment. By the time the decision was made to continue the EBT scattering experiment as a doctoral dissertation project, the UCLA group was publishing the results of the first successful FIR scattering experiment performed on a major plasma device. The Microtor device is a short pulse machine so that not only did the scattering experiment have to take into consideration the spatial, frequency, and wave vector dependence of the scattered wave, but also the time evolution during a typical plasma shot of less than 50 ms. It was believed that the application of this technique to a steady state device such as EBT would eliminate the question of time evolution and therefore would provide more useful and reliable data on dispersion relations and spatial profiles. However, the EBT device is a microwave driven experiment and therefore imposes severe physical

constraints on the design of the scattering experiment. Because of these constraints, the scattering system was initially designed in a manner that severely limited the information obtained in terms of spatial and wavenumber measurements. Later when the system was rebuilt, the components which caused these limitations could not be replaced during the scheduled life of EBT. As a result, the measurements were not complete enough to give a clear picture of the fluctuation phenomenon. These restraints are discussed in Section 3-2.

3-2 Physical Requirements and Restraints

As described in Appendix A the EBT device consists of 24 near-identical sectors comprising a cavity mounted between two magnetic coils in a mirror-like arrangement. A vacuum manifold is connected to the lower 45-degree inside port of each cavity. This vacuum manifold is also used as an oversize waveguide for 28 GHz microwave power feed to each cavity. The amount of power injected into each cavity is balanced by mounting between the manifold and the cavity a microwave screen with a fixed center aperture. Microwave injection at 10.6 GHz and 18 GHz is accomplished through normal waveguide connections and can be actively controlled during machine operation. In order to contain the high power levels of the microwave field, the cavity walls should be solid reflectors at all points, especially opposite the microwave feed. All access ports to the machine must lead to totally enclosed metallic vacuum systems or be partitioned with suitable microwave screens. Appropriate microwave screens consist of honeycomb-type structures with extremely

thin walls and of a thickness sufficient to provide attenuation of the microwave field. The application to an FIR scattering system also requires that the attenuation of the infrared signals through the cavity be small enough to allow measurable signals to reach the detectors. Special square-cell microwave screens were constructed for the EBT experiment which allowed greater than 80% transmission of the scattered signal at normal incidence. Also, since the detectors as well as the laser system had to be mounted outside the vacuum vessel, fused quartz windows were installed at each vacuum-air transition point. The measured transmission of these windows at FIR wavelengths was also measured to be about 80%. These windows were extremely susceptible to coating from sputtered aluminum present in the surface plasma and rapidly degraded during normal machine operation. During special operations such as ICH experiments the rate of coating was substantially accelerated. It was therefore necessary that the windows be physically separated as much as possible from the plasma boundaries.

A reasonably simple system of scanning mirrors mounted within the vacuum system was chosen. Three rotatable mirrors (Figure 3-1) were mounted in a vacuum box which was attached directly onto the cavity. Windows were placed directly above each mirror and at the horizontal centerline level of the cavity. Viewing from above through a window, the mirror could be rotated to observe any point along the horizontal central diameter of the cavity. The input window was mounted on the opposite side of the cavity, which allowed for the beam to be injected along the horizontal diameter and out the centerline window on the

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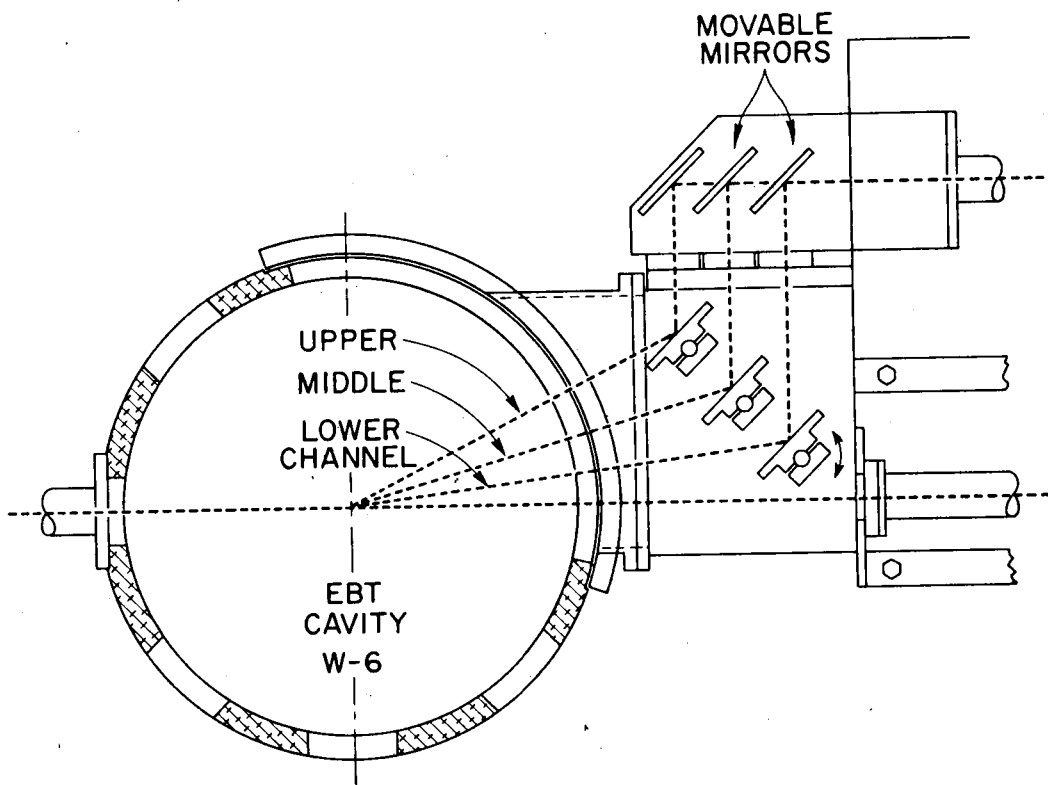


Figure 3-1. Scattering geometry and scanning mirror system installed on EBT.

mirror box. No beam dumps were installed since reflected signals were considered unimportant. Each mirror was mounted at a different height above the incident beam so that three different angles of scattering could be observed simultaneously. This was the original design which after construction limited the modifications possible due to operation restrictions.

The laser system, which consisted of a CO_2 pump laser and an FIR optically pumped laser, was mounted on a heavy optics bench located outside the lead enclosure shielding the EBT device. The time span for completion of the system and all the measurements was known to be limited to between two and three years. This did not allow time for the design and use of a test stand to optimize the system, or to gain experience in its operation.

The final restriction on the system design was the intense X-ray field present during operation of the EBT device. Since the laser was unstable and required constant manual adjustment, it had to be outside the lead wall. Because of the sensitivity of the FIR detectors to X-rays, they also had to be mounted outside the wall. This was convenient for adjustments that were often necessary to the detector bias controls and for shielding from rf radiation generated during ICH experiments. The remoteness of these systems was made possible by the use of long spans of oversize dielectric waveguide which passed through the lead wall in a Labyrinth fashion. The requirement for drilling holes through the lead wall and the precision mounting of waveguide made

reconfiguring the system after initial construction difficult and often impossible in the limited time available.

3-3 The Laser System

The initial laser system was of an early design. The CO₂ pump laser was made with a single anode and a single cathode which limited the length of the laser tube and the output power. Also, the stability of this laser was not adequate for practical use. The FIR laser cavity was totally enclosed in an aluminum vacuum chamber with O-ring type mechanical feed-throughs. The volume of the vacuum system was much larger than the cavity required, and there was at least a threefold excess of surface area exposed to the vacuum. The lasing gases, which had to be high in purity, were quickly contaminated by wall outgassing during operation. Operation and testing of this system pointed out these problems as well as a need for much more output power from the FIR cavity. A new laser system was then constructed.

It was decided for design and operational reasons to construct a laser which operated at a single wavelength. Because of the convenient wavelength and operational efficiency, methyl iodide was chosen as the lasing vapor gas, pumped by the 10P18 line of the CO₂ laser. Many modifications were made during operation of this system, so that only the final system will be described here. The design of both lasers was based on the proven design of the FIR interferometer system installed on ISX. Only minor modifications were made to the basic laser design during its construction.

The CO_2 laser (Figure 3-2) consists of a 2 m long, 1.1 cm internal diameter glass dielectric oversize waveguide with a single central anode and cathodes at each end, surrounded almost its entire length by an outer water cooling jacket. A gas mixture of 7% CO_2 , 80% He, and 13% N_2 was fed in at the center at a pressure of 36 torr and pumped out at each end. A vacuum-air interface at each end was accomplished with ZnSe Brewster windows. The output coupler, with a 20 meter radius concave curvature on the inside surface, and the focusing lens for the output beam were both also of ZnSe. The wavelength and polarization were selected with an aluminum grating mounted on the end opposite the output coupler and outside the vacuum. This configuration was capable of producing approximately 100 watts in the (0,0), (0,1), and (1,0) combined modes of operation. However, the ratio of power between these modes was not constant or stable. To increase mode control, small NiCr wire loops were installed within the laser tube to scrape off the outer portions of the laser beam which is predominantly from the (0,1), (1,0) modes. The resulting output beam had a typical power of 60 watts and showed improved stability in the higher frequency range but was still susceptible to slow changes in the mode output (30 sec to 10 min).

The FIR laser cavity consisted of a 2.1 m long pyrex dielectric waveguide with an inside diameter of 3.1 cm. The input coupler was a thick planar Cu-Be mirror with a 4 mm aperture through the center and was located just inside the cavity. The CO_2 beam was focused through a ZnSe Brewster window and the input coupler. The output coupler was of a base material of silicon crystal with a 98% reflective dielectric

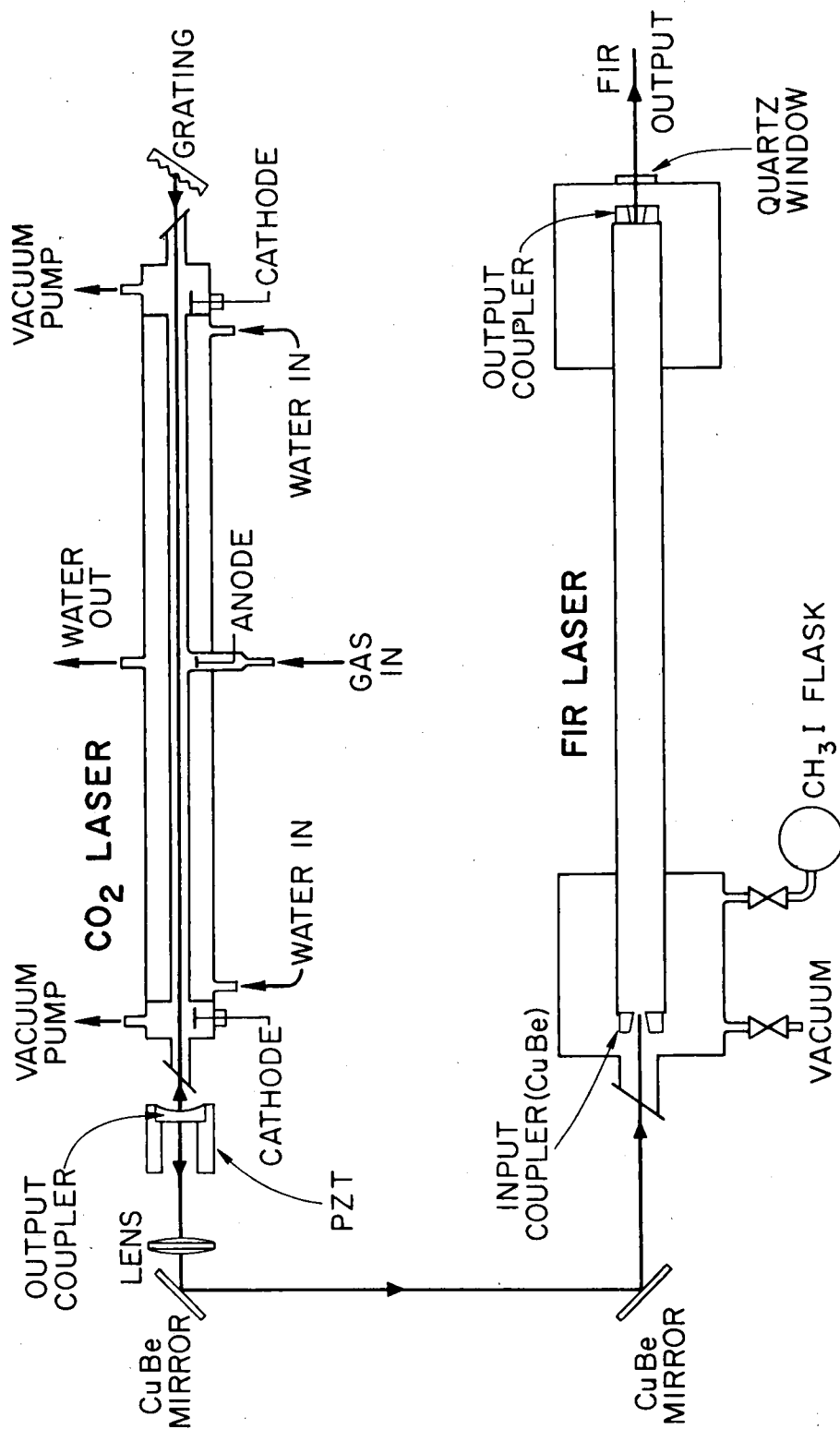


Figure 3-2. Laser configuration of CO₂ pump laser and optically pumped FIR cavity.

coating designed to reflect radiation from the CO_2 laser back into the cavity, thereby trapping the power between the couplers until it was absorbed by the methyl iodide vapor in the cavity. The output coupler was also coated with a thin layer of gold (about 1 micron thick) on its inside surface except for a 16 mm wide aperture at the center which allowed the FIR laser beam to exit. The output couplers, input coupler, and grating were all capable of being rotated to form the optimum resonant cavity, and both output couplers could be adjusted to change the cavity length to optimize the cavity and provide additional mode control. The FIR output beam exited the cavity through a Z-cut crystal quartz window at normal incidence. The laser beam was then immediately coupled into a 1.5 inch inside diameter dielectric waveguide which transmitted the beam through the lead wall to the cavity as described in Section 3-4. The output power from the FIR cavity was typically 10 to 20 mW although the system was capable of up to a 100 mW output.

3-4 The Waveguide System

The waveguides used to transmit the FIR beam from the laser to the plasma and back to the detector were made of 1.5 inch inside diameter sections of rigid plexiglas tubing. The variance in the inside diameter was often more than 1/8 inch (a result of the manufacturing process), and sections more than three feet long developed a sag over a long period of time. A schematic of the waveguide system is shown in Figure 3-3. The tubing was held in place by strong aluminum clamps

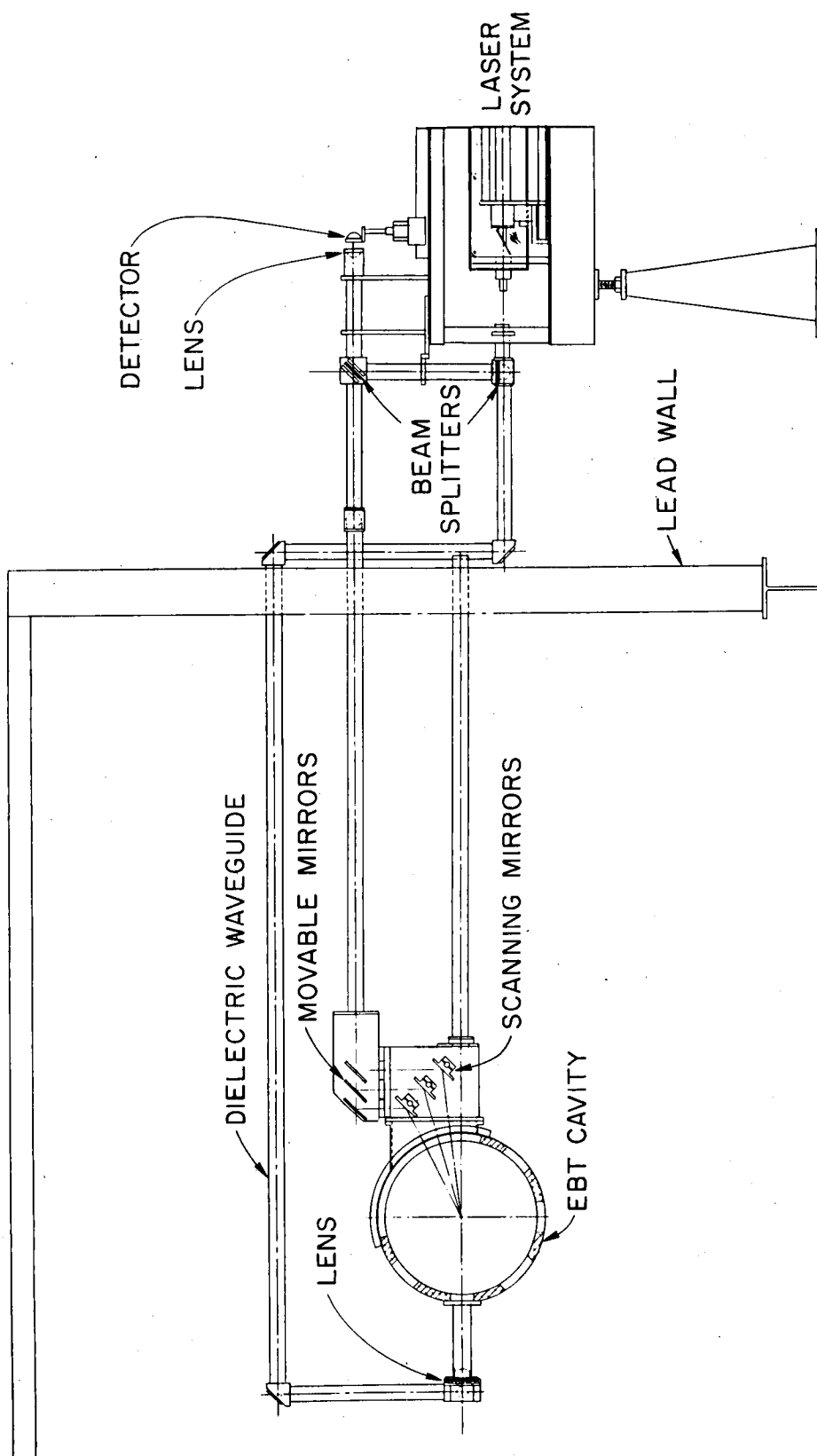


Figure 3-3. Dielectric waveguide distribution system on EBT.
Not shown is a chopper wheel which could be mounted on left side of lead wall on the upper beam line.

wherever possible. Corner pieces were machined from solid plexiglas blocks with gold-coated mirrors attached. Beam splitters were made from plexiglas blocks with thin mylar sheets, which reflected about 30% of the 447 micron incident beam and transmitted about 60% of the beam. Two of these beam splitters were installed; the first to divide off part of the laser power for a local oscillator beam, and the second to mix this L.O. beam with the antenna beam.

A waveguide switch was required to select the mirror used in the antenna beam scanning system. A large piece of plexiglas was machined to have one fixed mirror and three movable mirrors. The fixed mirror was located above the upper scanning mirror. The movable mirrors could slide in front of the fixed mirror over the middle and lower scanning mirrors and over an external coupler which could be used for testing. At the base of the waveguide switch and resting on the vacuum windows focusing lenses were mounted to collect the antenna beam with the focal point near the cavity center.

The waveguides were continuous at all points except for three narrow breaks. The optics table on which the lasers and detectors were mounted was supported by air-cushioned legs to reduce the effects of building vibrations. They allowed the table to move as much as two inches when the weight of the table was changed or was pushed from the side. To eliminate distortion of the waveguides, a 1/4 inch gap was made in the sections between the table and the lead wall. A change in the table position would thereby divide the waveguide into two rigid systems no longer in alignment. The legs would automatically compensate

and move the table back to its original position thereby realigning the waveguides. The third break in the waveguide was between the laser and the cavity just inside the lead wall (this is not shown in Figure 3-3). A high-speed chopper wheel (10-120 Hz) was mounted here to chop the incident beam going into the cavity. An LED source and photodiode mounted on opposite sides of the chopper were used to produce a reference signal in phase with the chopped FIR beam for use with phase sensitive detection. The entire waveguide system was kept carefully aligned with a HeNe laser alignment system.

3-5 The 2 mm Option

During the final two months of operation a 2 mm standard Varian commercial reflex klystron was mounted on the laser table such that its output beam could be coupled into the waveguide with an additional waveguide switch placed between the laser and the end of the optics table. This allowed switching the input beam from 447 microns to 2 mm simply by moving a mirror in and out of the waveguide switch. The klystron proved to be far superior to the laser system in reliability, ease of operation, stability, and output power. It did, however, lack resolution because of the longer wavelength. Also, the lenses mounted on the cavity were designed for FIR and were not suited for 2 mm wavelengths. The input beam and antenna beam, for all practical purposes, were not focused; and therefore these beams rapidly expanded, eliminating the possibility for spatial resolution. Despite these drawbacks some of the most important measurements were taken with the 2 mm option.

3-6 The Detector System

The detector used for the FIR wavelength was a Schottky-barrier diode mounted in a corner cube reflector and at the base of an antenna structure optimized for 447 microns. The 2 mm signal was also detected by a diode detector optimized for the longer wavelength. The diode was biased by a battery powered bias supply box that was rf shielded. The signal output from the detectors was amplified by a 50 dB gain low noise commercial rf amplifier also powered by a battery and rf shielded. The signal output from the amplifier could be routed to a spectrum analyzer, a crystal detector, or a lock-in amplifier. An additional 50 dB gain could be inserted when necessary.

Two spectrum analyzers were available, a Tektronics 7L5 and a Tektronics 7L14, which were capable of analyzing frequencies up to 5 MHz and over 1 GHz, respectively. The output of these analyzers could be recorded by data-acquisition computer, x-y plotter, or photographed on an oscilloscope display. Crystal detectors were used to convert the lower frequencies into dc voltages for direct recording or input into a lock-in amplifier. A low-frequency (1 Hz to 100 kHz) range lock-in was used in conjunction with the chopper wheel. This was used to record signals from plasma fluctuations. A higher frequency (100 kHz to 50 MHz) range lock-in could be used for phase sensitive detection of scattered signals during ICH heating, using the ICH frequency source as the reference signal. Outputs of both lock-ins could be recorded via computer or with an x-y plotter.

CHAPTER 4

SYSTEM PERFORMANCE AND CALIBRATION

4-1 Overview

During the design, construction, and operation of the EBT scattering system, many tests were performed to determine if the system was functioning correctly and to find ways of improving performance and reliability. The types of tests can be broken down into four categories. The first was the testing of separate individual components such as transmission in various lengths of waveguide, lens performance, power losses in beam splitters, windows, and mirrors, and electronic component performance. The second category was the measurement of important parameters such as beam diameters, scattering angle vs mirror position, and laser power measurements. The next category is the system calibration. Here much effort was expended in documenting the overall system performance by using complex calibration techniques. The final category is related to system reliability. Frequently small changes in the systems operating conditions could result in large changes in the output signals. The effects of laser drift and mode jumping were noted as well as the effects of atmospheric pollution and building vibrations. Included in this category are extraneous effects which show up in the data output such as the direct pickup of the ICH signals in the detector system. Each of these categories is discussed in Sections 4-2 through 4-6, with emphasis placed on those topics which have a strong direct effect on the data presented in Chapters 5 and 6. An effort has also been made to be

complete in describing difficulties encountered, since it is likely that the design of another scattering system will be initiated at ORNL soon.

4-2 Component Testing

Previous measurements had established the size and type of waveguide used as a suitable means of transmitting FIR radiation over reasonably long distances. Further testing showed that the primary difficulty was in coupling the beams into the waveguide in an efficient manner. This problem was minimized by eliminating gaps between sections of waveguide and restricting the distance between the waveguide and other components. Beam splitters and 90 degree elbows were machined out of solid plexiglas which were coupled directly onto the waveguide. Effort was also made to keep the waveguide from bending or sagging, although this may still have been a major source of waveguide loss. The waveguide used was of poor quality, even though it was the best commercially available of that material. The internal radius was nonuniform throughout the waveguide, which may account for some additional losses.

Large losses were also measured in the windows and microwave screens. These components alone could account for the loss of 60% of the signal. Exact estimates are not possible since the loss in transmission through two components may be more or less than the sum of the individual losses measured in each component. This is due to the interference and standing wave effects caused by the reflected signals. The lenses used in this system were of high-density polyethylene with one surface machined to the proper radius of curvature and the other

surface left flat. The flat surface was a cause for coherent reflection back into the system, resulting in additional changes to the system transmission.

Most electronic components were standard off-the-shelf items which were calibrated and tested according to standard procedures. The detectors, however, were not standard, and much interest was taken in their performance. Several attempts have been made in the past to measure performance of these detectors, but the techniques are either extremely complex or they are subject to large uncertainties. Figure 4-1 displays the noise from the spectrum analyzer with the input terminated. Shown above that is the amplifier noise. The upper trace is the amplified noise of the detector while operated with 400 microamps of bias current. The relative noise level for the detector-amplifier combination above the analyzer level ranges from 60 dB at 1 MHz to less than 40 dB at higher frequencies where the amplifier noise figure is about 1 dB. This places severe limitations on the system sensitivity at lower frequencies that could be overcome only by increasing the input signal level. Synchrotron radiation from the electron rings in EBT was used to measure the frequency dependence of the detector response. Figure 4-2 shows the frequency-analyzed detector output when only the local oscillator (L.O.) signal is present (lower trace) and when the L.O. is mixed with the radiation emitted from the plasma (upper trace). When only the L.O. is present, the $1/f$ noise at lower frequencies is obvious. The plasma emission to which the detector system is sensitive is synchrotron emission at $671 \text{ GHz} \pm f$, where f is the frequency displayed on the x-axis.

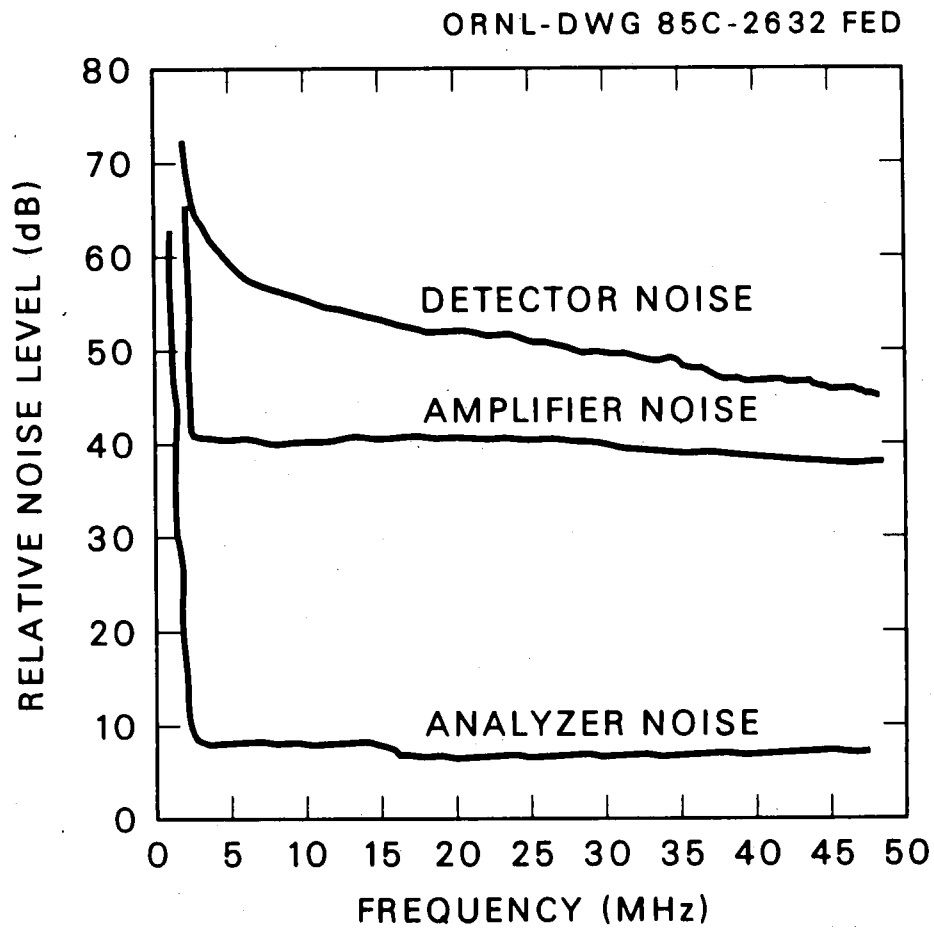


Figure 4-1. Contributions of the amplifier and detector noise relative to the amplifier noise in the EBT FIR detector system.

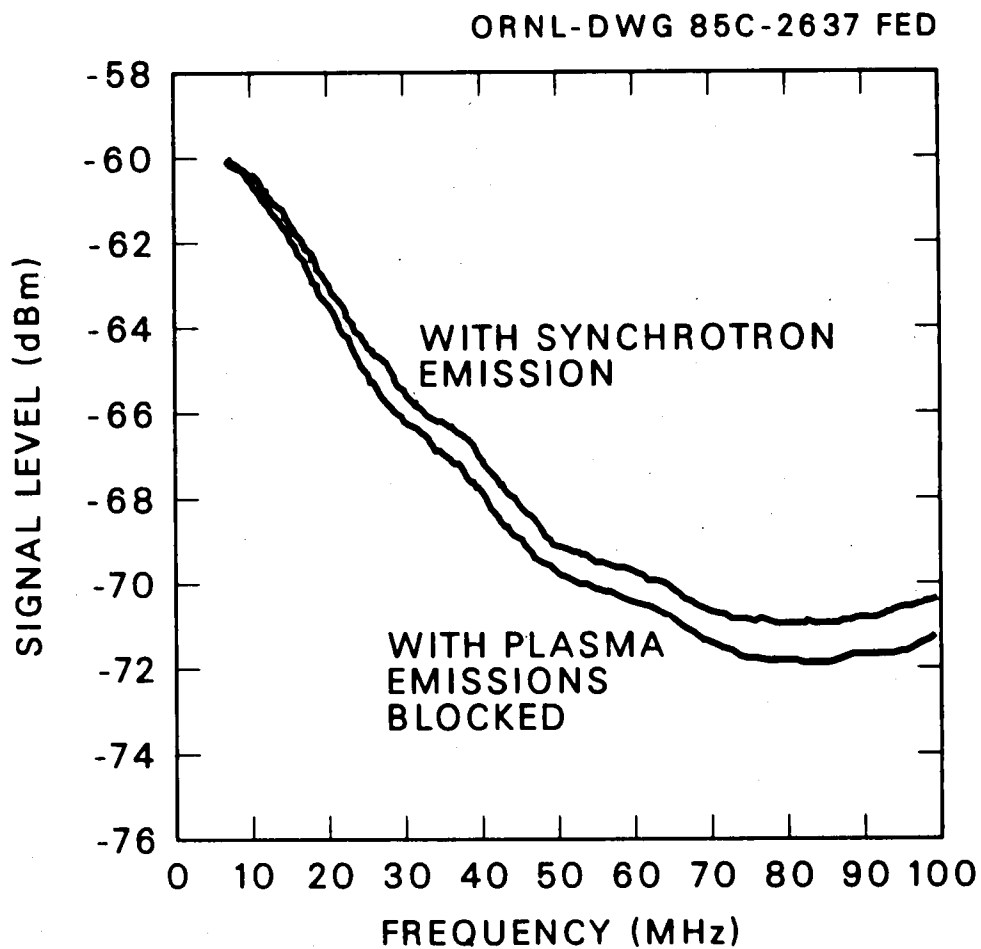


Figure 4-2. Relative increase in the amplified detector signal with detection of synchrotron radiation from the EBT plasma.

Since the full range of f is very small in comparison with the central emission frequency, it can be assumed that the variation in emission amplitude is small over the range of f and that the signal amplitude from the detector varies only as the sensitivity of the detector system. The change in the signal level is not dependable because the act of blocking the signal that is coming from the plasma changes the characteristics of the waveguide system and can therefore change the amplitude of the L.O. signal coupled into the detector. The ratio of the signals at any given frequency is therefore unimportant, while the change in that ratio with frequency indicates the dependence of the sensitivity on frequency. Although the variation in sensitivity with frequency shown in Figure 4-2 is obvious, it is also quite small for the range of frequencies displayed. Estimates of the expected scattered signal amplitudes in Chapter 2 suggest that the noise level is very close to the signal level and therefore may not be detectable without using phase-sensitive detection techniques. This is discussed more fully in Section 4-4.

4-3 System Parameters

Some of the important parameters had to be indirectly measured or calculated, but a few could be measured. The output power of the laser could be monitored for changes and optimized, but absolute measurements could not be made because of interference effects introduced with placement of the power meters in the laser beam path. A pyroelectric radio-meter was used to monitor the power whenever possible. It was

calibrated with a calorimeter of known efficiency. The radiometer measured the L.O. power that passed directly through the beam splitter that mixed the L.O. with the scattered signal. The radiometer has a built-in chopper wheel which reflects a chopped signal back into the system causing laser instabilities and oscillating detector outputs. A shutter was placed in front of the power meter which could be briefly closed during measurements. Estimates of laser power incident to the plasma show that for an output power of 20 mW the incident power should be 6 mW, but measurements indicate an incident power level of less than 2 mW. The beam waist going into the cavity is about 0.7 cm and expands across the cavity to 1.1 cm where it exits. The antenna beam has similar parameters.

Because this was a scanning mirror system based upon spatially fixed mirrors which rotate about an off-plane axis, the scattering angles for different mirror angles, and therefore different spatial locations of the scattering volume, had to be calculated for each mirror. Figure 4-3 shows the scattering angles for each mirror, and Figure 4-4 shows the wavenumbers taken from the Bragg condition for each mirror. A HeNe laser was used to measure the spatial location that the antenna beam intersected the incident beam path for each mirror position. The mirrors were mechanically linked and driven so as always to direct the three antenna beams to the same spatial location regardless of which mirror was selected. In this way activating the waveguide switch to change the antenna beam from one mirror to another changed only the scattering angle and k vector, but not the spatial location of the scattering volume.

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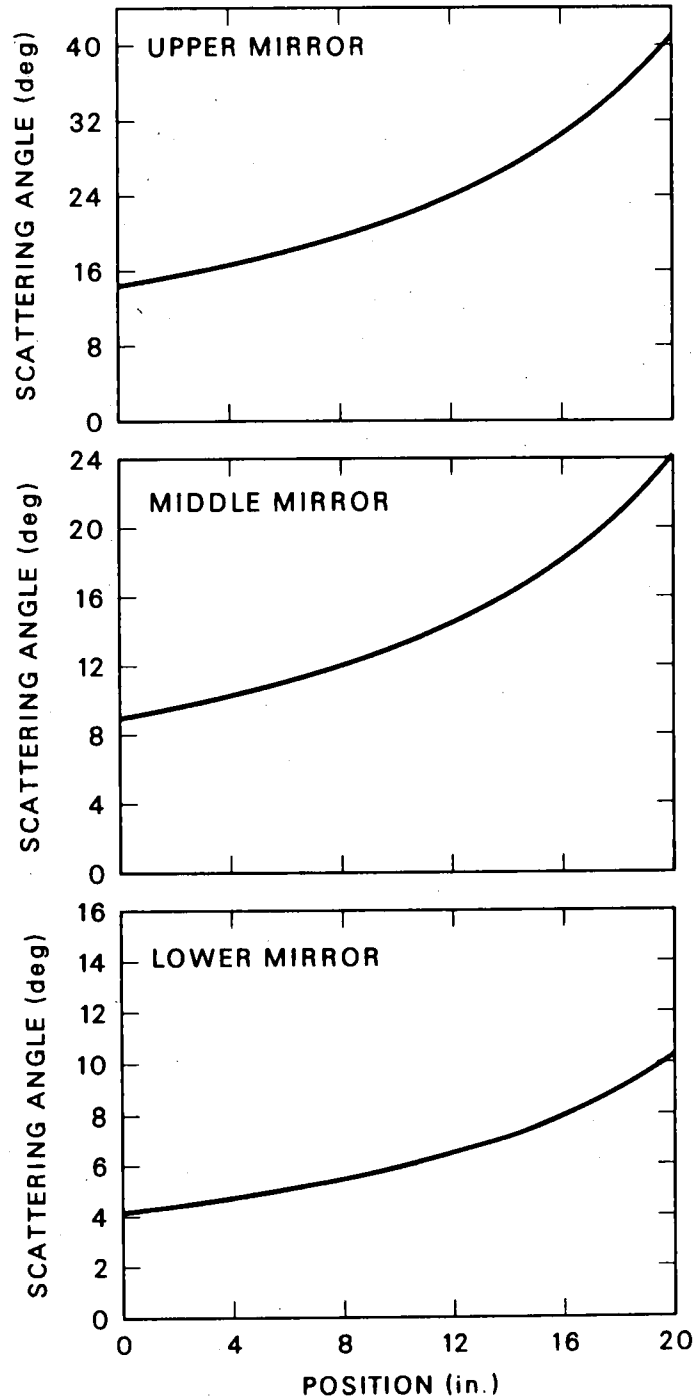


Figure 4-3. Calculated scattering angles for the three channels of the EBT scattering system vs the spatial location.

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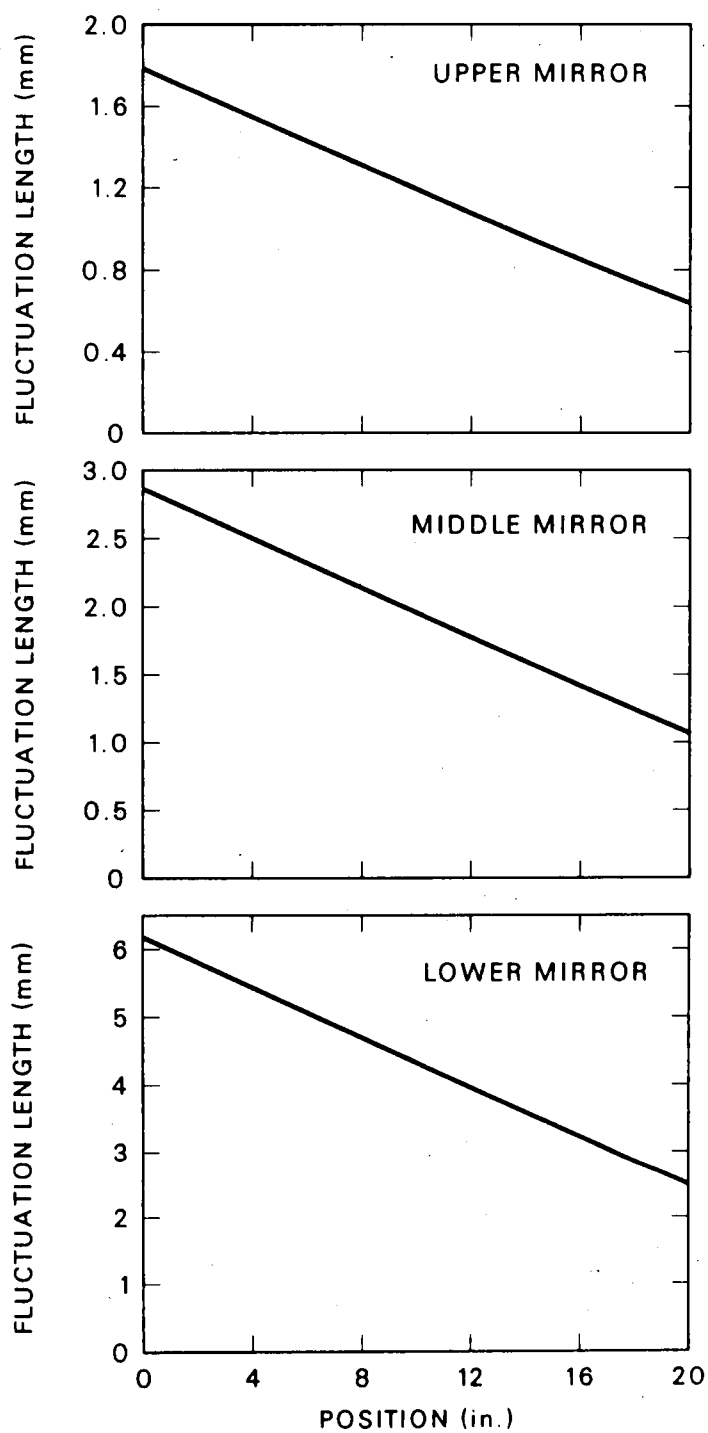


Figure 4-4. Wavevectors corresponding to the scattering angles shown in Figure 4-3 as calculated from the Bragg relation.

4-4 System Calibration

The most important check of the system performance was the measurement of a scattered signal from a well known source. This scattering source was an acoustical Bragg cell (see Figure 4-5). It is constructed of TPX plastic approximately 2 inches square in cross section and 8 inches in length. A 1/2 inch-thick piezoelectric transducer (PZT) was affixed to one end with vacuum grease and a strong clamping mechanism. The opposite end was machined with a sawtooth pattern two inches deep to act as an acoustical beam dump. By driving the PZT at one of its resonance frequencies (on the order of 1 MHz) an acoustical wave was made to propagate along the long axis of the cell. The velocity of sound in this material has been measured to be $2.0\text{-}2.2 \times 10^5$ cm/s.^{25,30} The interaction of FIR radiation with the acoustic wave is the same as the interaction of FIR with density waves in a plasma inasmuch as the interaction can be treated as moving periodic variations in the index of refraction.^{31,10} The results of Section 2-3 (Equation (2-75)) can therefore be applied to this case resulting in:

$$I_{\text{diff}} = I_{\text{inc}} \sin^2(wl \Delta n / 2c), \quad (4-1)$$

where $\Delta n = 1/2 (2MP_A)^{1/2}$. Here P_A is the acoustical power, and M is the figure of merit for the material which depends on the bulk modulus, photoelastic constant, and the index of refraction of the material. The ratio of intensities can be expressed as:

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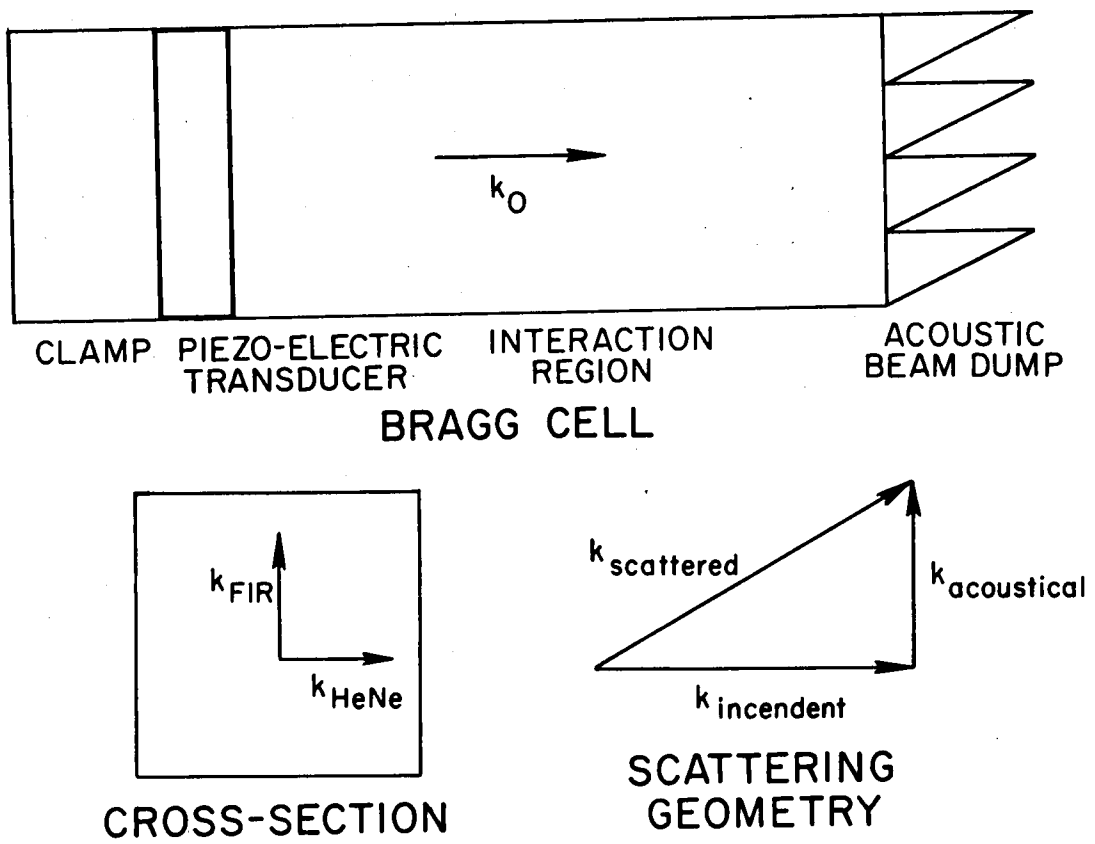


Figure 4-5. TPX acousto-optic Bragg cell configuration.

$$I_{\text{diff}}/I_{\text{inc}} = \sin^2(\pi l(2MP_A)^{1/2}/2\lambda) . \quad (4-2)$$

The interaction length, l , is taken to be the smaller of the cell width and the value $2a_0/\sin \theta$. The scattered power is of the order of 10^{-8} W or less. It is therefore not feasible to measure the scattered power directly. The scattered power must be calculated from the acoustic amplitude. This can be accomplished using Raman-Nath scattering of HeNe laser radiation in the same scattering volume and at the same time as the Bragg scattering of FIR radiation is measured.³⁰ In Raman-Nath scattering the laser beam enters the acoustic cell at normal incidence and is scattered into a diffraction pattern of multiple orders. The scattered intensity into each order is directly proportional to the square of the Bessel function of that order with the modulation index, v , as its only argument.^{31,10} For small values of v the only significant orders are the zero and the positive and negative first orders. Figure 4-6 shows a typical result of HeNe scattering with a large zero order peak and the two sidebands of the first order. The ratio of the scattered intensity into one sideband to the incident intensity is:

$$I_1/I_{\text{inc}} = J_1^2(v)/J_0^2(0) = v/4 . \quad (4-3)$$

The central peak is diminished in intensity to:

$$I_0/I_{\text{inc}} = J_0^2(v)/J_0^2(0) = 1 - v^2/2 . \quad (4-4)$$

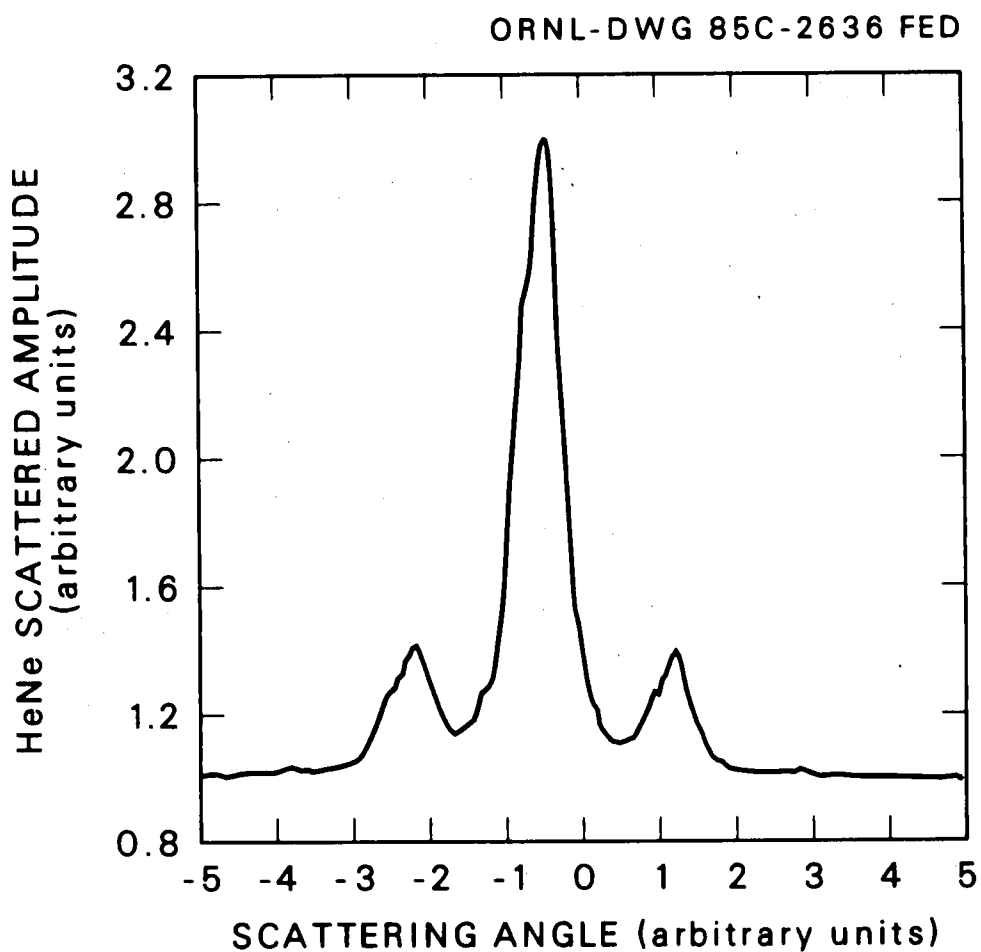


Figure 4-6. Typical HeNe laser radiation scattering from acoustical waves in the Bragg cell. Central peak is the non-scattered transmitted beam. Smaller peaks to each side are the first order Raman-Nath scattered signals.

In this approximation of the Bessel functions all the scattered intensity is accounted for in the zero and first order with all other orders being negligible. The modulation index for an acoustical wave is given by:^{31,10}

$$v = 1\pi/\lambda_{\text{HeNe}} (2MP_A)^{1/2} . \quad (4-5)$$

which results in a value of the acoustical power:

$$P_A = \lambda_{\text{HeNe}}^2 / 8\pi^2 I_1^2 M(I_1/(I_0 + 2I_1)) . \quad (4-6)$$

Substituting into Equation (4-2) for the scattered FIR power gives:

$$I_{\text{diff}}/I_{\text{inc}} = \sin^2((\lambda_{\text{HeNe}}/\lambda_{\text{FIR}})(I_1/(I_0 + 2I_1))^{1/2}) . \quad (4-7)$$

The ratio of the wavelengths is 1.42×10^{-3} , allowing an accurate approximation of the sine function by its argument. This results in the final form:

$$I_{\text{diff}}/I_{\text{inc}} = (1.42 \times 10^{-3})^2 (I_1/(I_0 + 2I_1)) . \quad (4-8)$$

For the case shown in Figure 4-6 the HeNe scattered ratio is 0.14 which gives a ratio of 2.8×10^{-7} for the FIR scattered signal. For an incident power of 1.5 mW, the scattered power is then estimated to be 4.1×10^{-10} W. Because of the shape of the interaction volume, the scattered power is reduced in proportion to the ratio of the signal incident on the collecting lens to the total integrated signal. This is accomplished by use of a numerical model of the gaussian beams.

Figure 4-7 shows the ratio of the scattered HeNe signal to the incident intensity signal vs the peak-to-peak driving voltage for the PZT. The relationship is linear except for the lowest and the two highest voltages. At the lower voltage the signal of the scattered beam is close to the same magnitude as the stray light. Therefore without compensating for stray light the ratio will always be high. At higher voltages a number of effects enter into consideration. The acoustical coupling between the PZT and the cell is very good for a limited range of frequencies and amplitudes. Increasing the frequency or amplitude above this range results in diminished coupling. Also, there are thermal effects to consider. The acoustical waves are partially damped by the plastic, converting the acoustical energy into heat. The PZT also produces heat. Since the plastic is a poor thermal conductor, the heat retention is nonuniform, resulting in local changes in the index of refraction. If the temperature of the plastic nearest to the PZT heats sufficiently, then the HeNe beam is refracted away from its initial position. In addition there is considerable distortion in the beam shape. Deliberate overdriving of the cell produced these results in the precise manner expected. During the test, data was taken in regular increments of the driving voltage up to the point where distortion started to be observed. The cell was then allowed to cool and become isotropic before the next series was started.

The scattered power estimated from the HeNe scattering and the scattering geometry can now be compared to the signal output of the

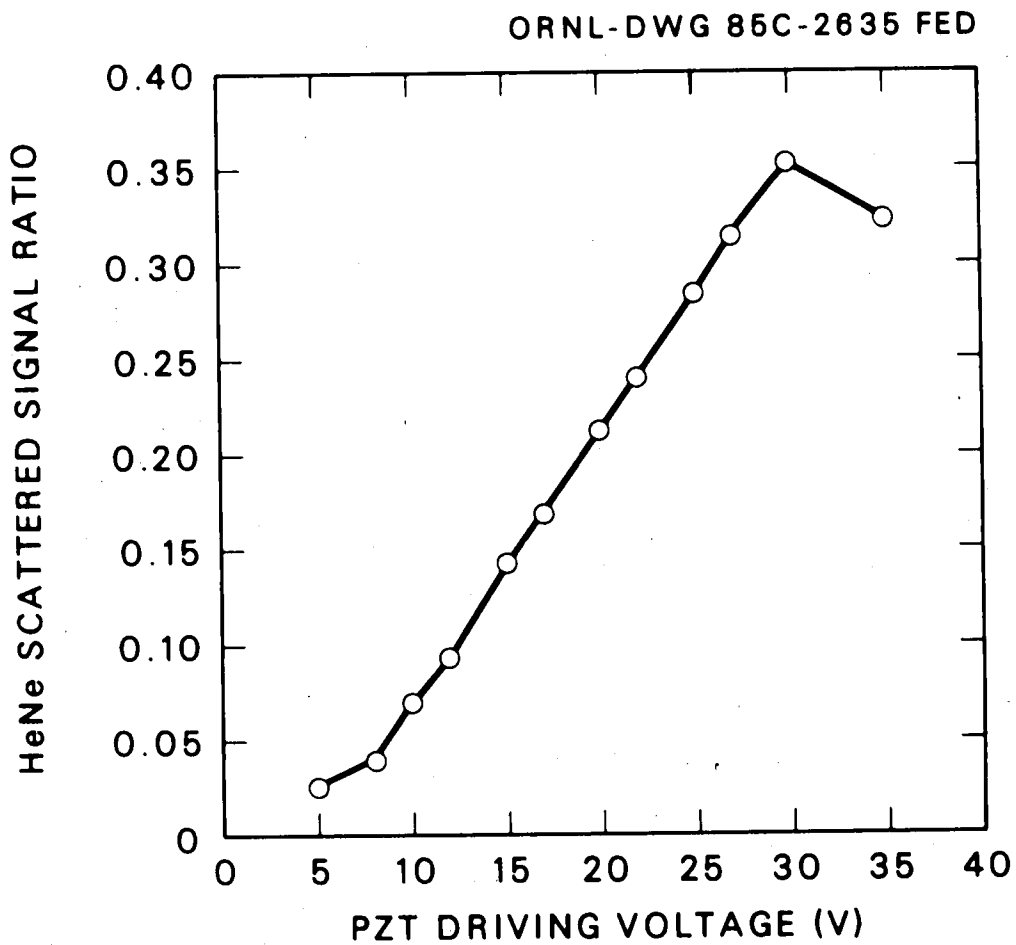


Figure 4-7. Ratio of detected scattered signal to the incident signal level vs the peak-peak sinusoidal driving voltage applied to the PZT of the Bragg cell.

detector system. The detector system is configured with 50 dB of gain, a crystal detector, and a lock-in amplifier referenced to the PZT driving signal. The scanning mirror was swept slowly across the Bragg cell while the signal level was recorded on an x-y plotter. The peak amplitude is used for comparison with the estimated scattered power. Figure 4-8 illustrates the results of one series of measurements using the upper mirror channel and a PZT driving frequency of 1.26 MHz. The result is a linear fit to within 10% of the measured values. The estimated error in this measurement is dominated by the measurement of the incident FIR power. This is mainly a systematic error which does not greatly effect the slope of the fit. Comparison with the other channels, Figure 4-9, shows the upper channel to be the least sensitive channel and the lower channel to be the most sensitive. This could result from system alignment and coupling differences. More probable, however, is that the upper mirror and window was closer to the plasma and therefore sustained more damage as a result of aluminum sputtering. Indeed, when the system was disassembled the upper window was heavily coated, the middle window was lightly coated, and the lower one was almost clear. Measurements of their transmission showed the upper channel to be attenuated by a factor of 6 over the other channels. This accounts for almost all the discrepancy shown. Since this is an effect which changes during machine operation and cannot be corrected or monitored, then a large uncertainty is introduced into all the measurements in terms of their absolute magnitude.

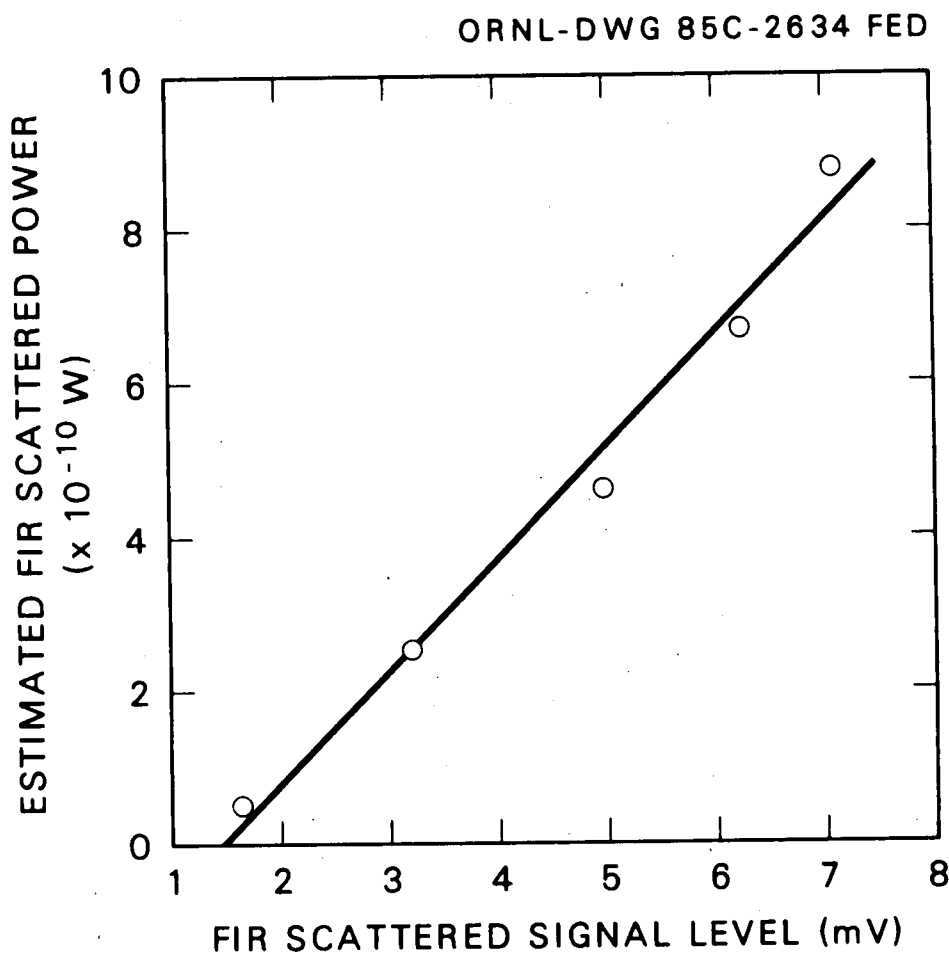


Figure 4-8. Estimated scattered FIR power vs the detected signal level of the FIR detection system on the upper channel. Scattered power was estimated from the measured HeNe laser radiation scattered signal ratio and the measured FIR incident power.

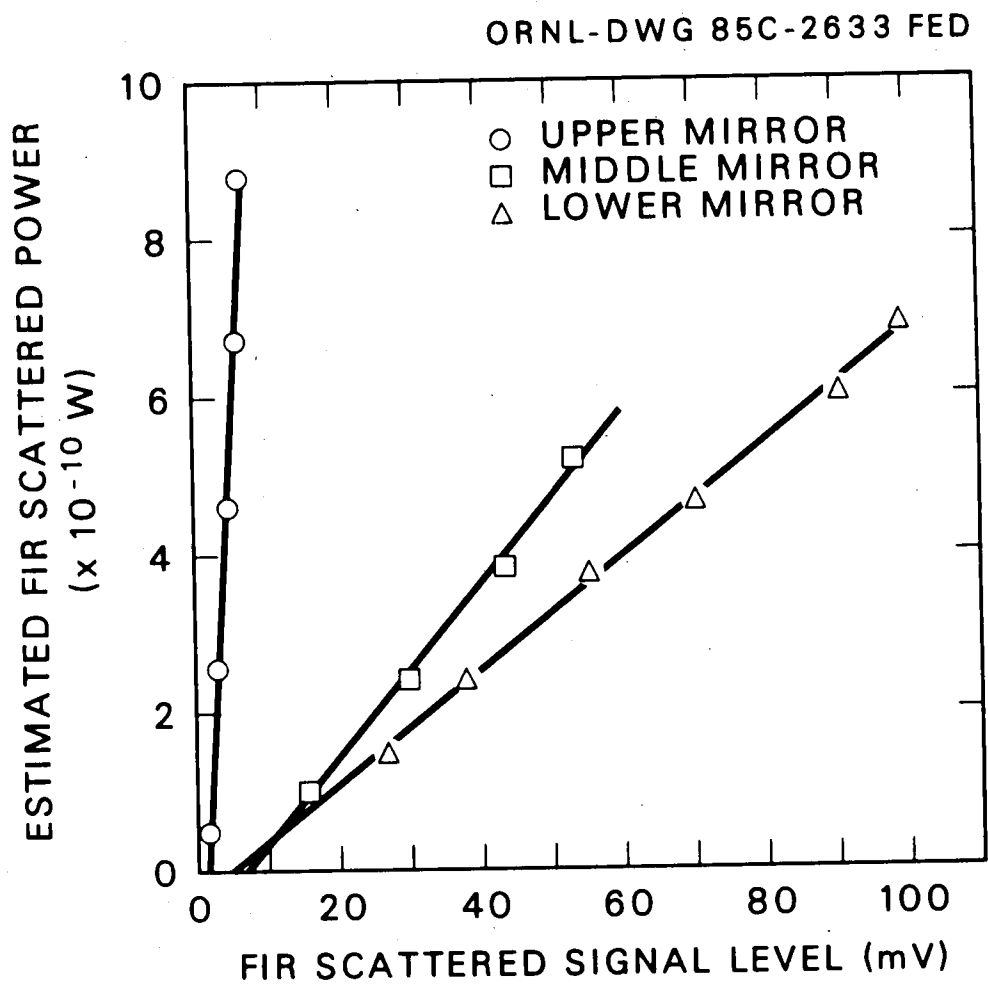


Figure 4-9. Estimated scattered signal level vs detected signal level for all three channels of the EBT scattering system.

From the recorded FIR scattered signals from the Bragg cell the minimum detectable signal was estimated to be on the order of 1×10^{-12} W, which is very close to that estimated by the UCLA group.²⁵ When a strong scattered wave was produced anywhere within the cavity the background noise level was increased at all angles and spatial locations. As such the minimum detectable signal in the presence of another larger signal may be as much as 20 times higher than when no other signal is present. In a similar effect the scattered signal from the Bragg cell can be coupled into the waveguide system at angles which do not correspond to k-vector matching. This problem, referred to as angle mismatching, can result in signals as large as 80% of the signal produced during proper matching. Figure 4-10 shows two recorded signals produced by the Bragg cell at different spatial locations. Positioning of the cell midway between these two points produced a much smaller signal. This is not the type of behavior that was expected nor that has been observed in other experiments.²⁵ It may, however, be a result of the microwave cutoff screens used, which could have acted as diffraction gratings, changing the antenna beam from a single gaussian into a multiple order diffraction pattern. Measurements made within the confinement of the EBT device were too crude to attempt a verification of this cause.

The most important result of the acoustical scattering in the Bragg cell was to verify the proper functioning of the detector equipment and the waveguide system. It also pointed out several problems which must be dealt with in the initial design stages of the next generation of scattering experiments.

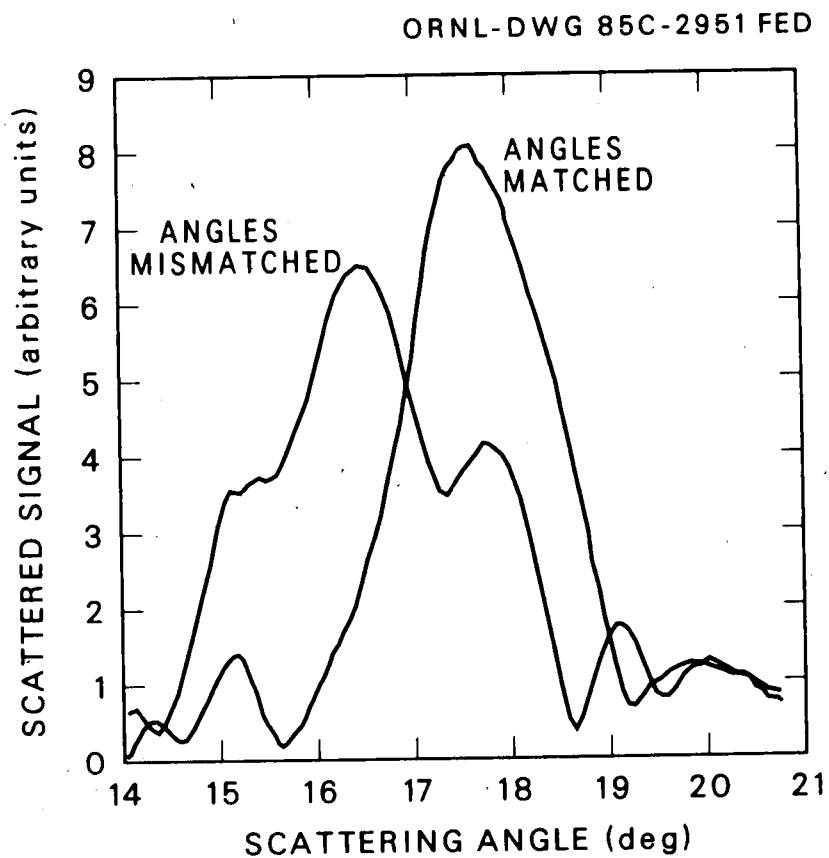


Figure 4-10. Demonstration of scattered signal detected without proper matching of the scattering angle and the detection angle. Signal peaked to the right is with proper angle matching.

4-5 Operational Reliability

The output characteristics of the FIR laser could be monitored by the radiometer power meter, the bias current level through the detector diode, and the noise levels on the signal output. The L.O. input to the diode was from 1-3 mW, while the scattered signals were of the order of 1-100 pW. Therefore, the smallest irregularity in the L.O. signal easily saturated the detector system. Frequently, experimental operations had to stop in order to retune the laser system, an operation that sometimes took hours of valuable time. The laser instabilities which resulted in this type of problem could often be traced to the CO₂ laser. It appeared that the CO₂ laser could be driven unstable by reflected signals from various optical elements. The problem was reduced by isolating the system from building vibrations, placing apertures throughout the CO₂ cavity, and by collimating the CO₂ laser output carefully. Although these steps helped reduce the problem it was never eliminated nor reduced enough so that it did not frequently interfere with operations.

An additional problem during experimental operations was the thermal drift in both the CO₂ laser and the FIR laser. During normal operations this drifting had to be constantly compensated for in the CO₂ cavity length. The CO₂ grating and output coupler had to be adjusted as often as every five minutes, and the FIR cavity length had to be readjusted around every half hour. The end result of these problems was a continuously changing laser beam that could not be adequately monitored. For example, adjusting the FIR cavity length to increase the

output power could result in a decrease in the coupling of the L.O. signal to the detector, thereby decreasing the detector bias current and the detector sensitivity. Another cause of instabilities was the presence of SF_6 which was occasionally released into the building. Due to the strong broadband absorption of SF_6 at 10 microns, this frequently caused a decrease of near 50% in laser power output as well as oscillations in excess of 50%. It took several hours before the pollution was dispersed enough to have no remaining visible effect.

Other problems in system reliability could be reduced or eliminated in a more direct manner. All cabling and electronics had to be shielded from rf pickup, especially the detector diode. Since the diode and amplifiers were extremely susceptible to pickup problems, they were isolated electrically by using battery powered bias supplies and amplifiers. This resulted in an additional problem of having the battery voltages drop. Although fresh batteries were installed at reasonable intervals, some data that was recorded with weak batteries could not be retaken and therefore had to be analyzed with a large uncertainty in the signal level and detector sensitivity.

The use of phase sensitive detection helped reduce the severity of random noise but increased pickup problems from harmonics of 60 Hz and the ICH frequencies when the ICH signal was used as the reference signal.

4-6 System Operations at 2 mm

The 2 mm klystron operated with good reliability and constant output. Apart from the initial tuning, additional adjustments were rarely

necessary. The diode detector was also reliable with very little noise. Transmission of 2 mm waves through the waveguide system, however, was extremely poor in comparison. When the klystron was operated at more than 100 mW the incident power into the plasma was measured to be about 4 mW. Similarly the L.O. signal was about 1 mW.

Calibration of the system was not possible since the Bragg cell could not conveniently be operated at frequencies which would produce scattering at an angle within the range of the system. Therefore, output signals could be analyzed only for changes in signal levels during changes in machine parameters.

CHAPTER 5

ICH EXPERIMENTAL RESULTS

5-1 Introduction

In this chapter the experimental data are reviewed, along with the conditions under which the data were obtained, for scattering from coherent waves. Chapter 6 deals with scattering from incoherent waves. The scattering system was developed over a period of two years. Many different methods were tried during that time in order to understand how the system was best configured and to understand better the results. Little was seen that was expected, and most of what was observed is difficult to interpret. The independent theories of ECH, ICH, plasma waves, fluctuations, and instabilities are all closely interrelated by their predicted effects on particle and energy transport in EBT. Heating a plasma by ECH results in higher temperatures in the resonance zones than in off-resonant regions. In a plasma with moderate temperatures and neutral particle densities this can also result in higher rates of plasma production in these regions. The plasma is not in total equilibrium and therefore is susceptible to instabilities and fluctuation phenomena. ICH is also a resonant zone heating technique, but the mechanism by which energy is transferred to the plasma may be dominated by other phenomena. In particular the conversion of electromagnetic waves into strongly damped electrostatic waves has long been advocated by theorists and recently demonstrated experimentally.^{25,26}

It was only in the last three months of operation that the scattering system was fully implemented and that the recorded signals could be reproduced on a reliable basis. This was due to improved techniques, better detectors, and in some cases unusual plasma conditions. All of the data presented here will be from the final three months of the experiment, so that the volume of material can be reduced and the question of data reliability can be better addressed.

Several types of ICH experiments were performed, and the signals observed may prove to be significant. Although a complete analysis of ICH wave theory is beyond the scope of this thesis, the significance of observing ICH related waves will be discussed in light of the experimental results. It is noteworthy that the last experiment to be conducted on EBT was a measurement with the FIR system during slow-wave and fast-wave heating. A failure of the slow-wave antenna caused contamination of the plasma during these experiments, and another antenna failure occurred at the end of the EBT experimental lifetime. These failures, as well as the demise of the device, resulted in an incomplete analysis of the observed wave phenomenon.

An attempt was made to operate the ICH system in pulsed mode. Although reliable signals were recorded, their relationship to ICH driven waves was not established in detail. A brief description of the results and analysis is given in Section 5-2. Finally, experiments substituting the 2 mm system for the FIR system are described in Section 5-3. The time devoted to this experiment was relatively short; but the results were considerably different from those obtained with the FIR

system, and they showed great promise for use on future EBT-like devices.

5-2 Pulsed ICH Measurements

The effect of ICH pulsing is not to create additional broadband turbulence or improve wave propagation. Instead, pulsing the ICH power gives another method of using phase sensitive detection for finding driven wave phenomenon. The ICH transmitters were set up similar to the ECH system as described in Chapter 6. The result was a 10 kHz square wave modulation output of the ICH system which served as supplemental heating to a steady state ECH plasma. In order to eliminate low frequency effects, a band-pass filter was used to attenuate frequencies below 22 MHz and above 26 MHz. The chopper wheel was removed from the input laser beam. A low frequency lock-in was used to observe the output of a crystal detector connected to the output amplifier via the band-pass filter. There is only a small amount of data available, and that which is given here was not verifiable.

The ICH was applied at 25 MHz via the fast-wave antenna structure. A spatial scan is shown in Figure 5-1 for the middle channel with 50 kW of peak ICH power at a field of 5000 A and a neutral pressure of 15 microtorr. Comparison of the signal level with the location of ICH harmonic zones shows only a limited correlation. The harmonic zones are roughly indicated by the upper scale at the lower edge of Figure 5-1. Only one spatial location should have the wavevector and magnetic field matched to the dispersion curve between any two harmonics. The lowest harmonic is the seventh for the cavity midplane, although the third to

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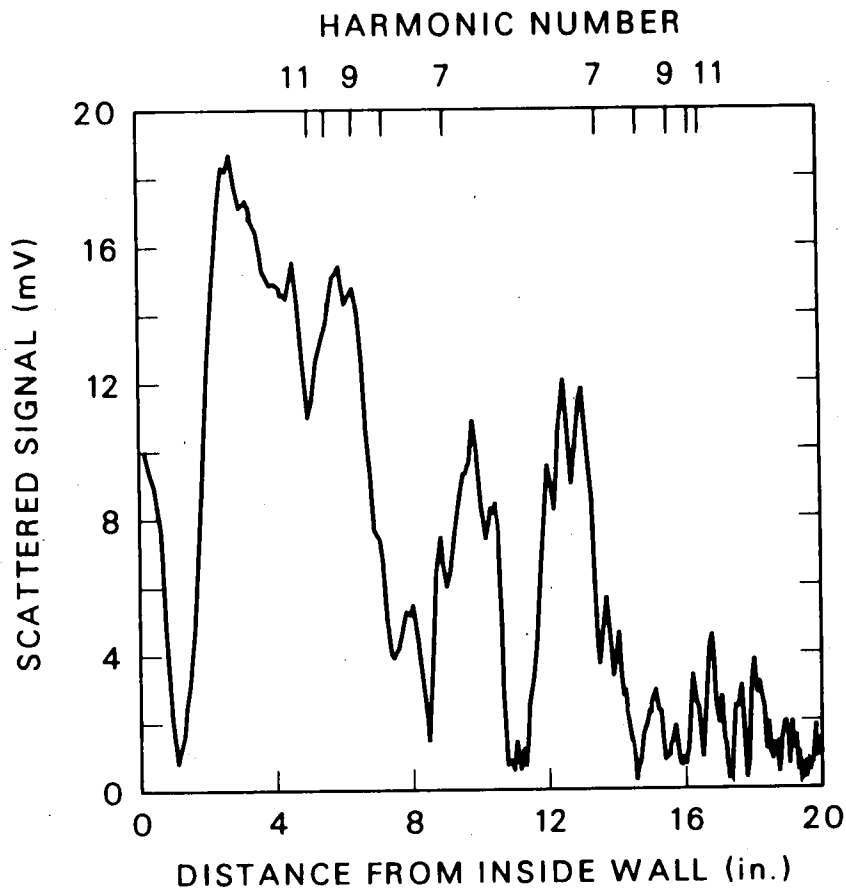


Figure 5-1. Spatial scan of FIR scattered signals resulting from ICH driven waves at 25 MHz using the fast wave antenna structure in pulsed mode. Plasma was formed at 5000 A with 43 kW of 18 GHz ECH with a neutral pressure of 15 microns. The upper scale shows the approximate location of the ion cyclotron harmonic zones.

the sixth are present in the throat regions. In the presence of a plasma the magnetic field is altered slightly, and the plasma has been shown to shift inward. The signals obtained were sensitive to machine conditions. The parameters which varied during these trials were limited to the spatial position/wavevector, the neutral pressure, and the magnetic field. Only two values of the field were used, 5000 A and 7250 A. At 5000 A the signals received were large and reasonably well confined to the central portion of the plasma within the location of the electron rings (Figure 5-1). Also immediately obvious are strong minima in the spatial distribution. The signals were observed to have a strong dependence on the wavevector. Locations showing a minima (such as at 8 inches in Figure 5-1) were the location of a maxima at another wavevector value. Figure 5-2 shows the values of k measureable with the FIR system vs the ratio of the driving frequency (25 MHz) to the local ion cyclotron resonance frequency. Ideally one should be able to pinpoint a data peak on a theoretical dispersion curve plotted between two harmonics. The resolution of the experiment is not sufficient to allow this type comparison. (Note: the values of k measured in the experiment are almost linear with position. See Figure 4-4, p. 52.) However, verification of the nature of the effect can be found in a pressure scan at the peak position near 3 inches. Two separate effects are involved in determining the wave amplitude that can be observed. The conversion of a fast wave to an ion Bernstein wave can be expected to be continuous between two harmonic points.²⁵ Conversion, however, is at a k vector determined by the dispersion relation (Figure 5-3). This dispersion

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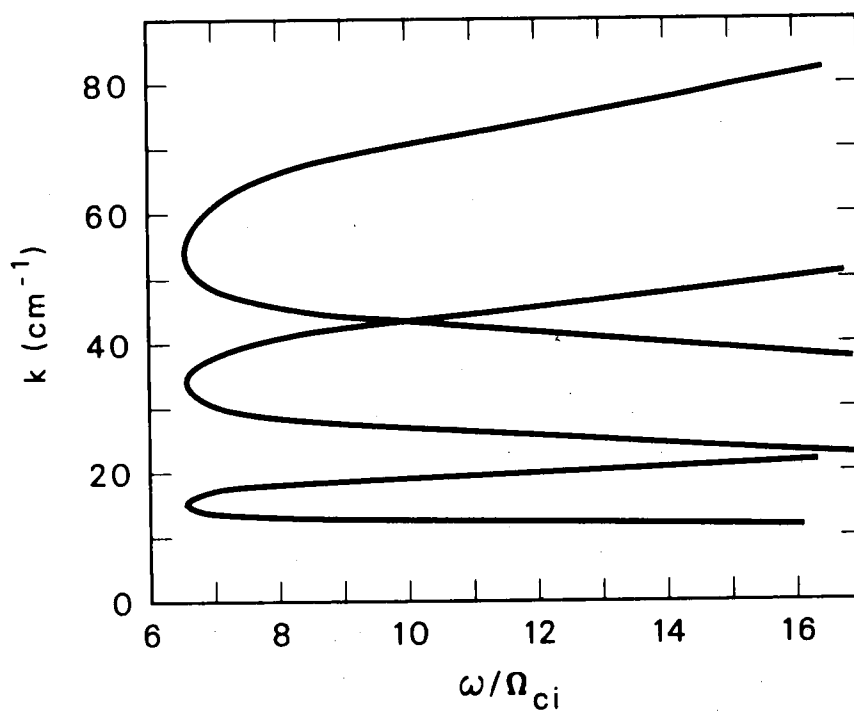


Figure 5-2. Range of sensitivity of the FIR scattering system, as determined by the scattering geometry, in terms of the wavevector and the magnetic field, displayed as the ratio of the driving frequency (25 MHz) to the local ion cyclotron resonance frequency (at 5000 A).

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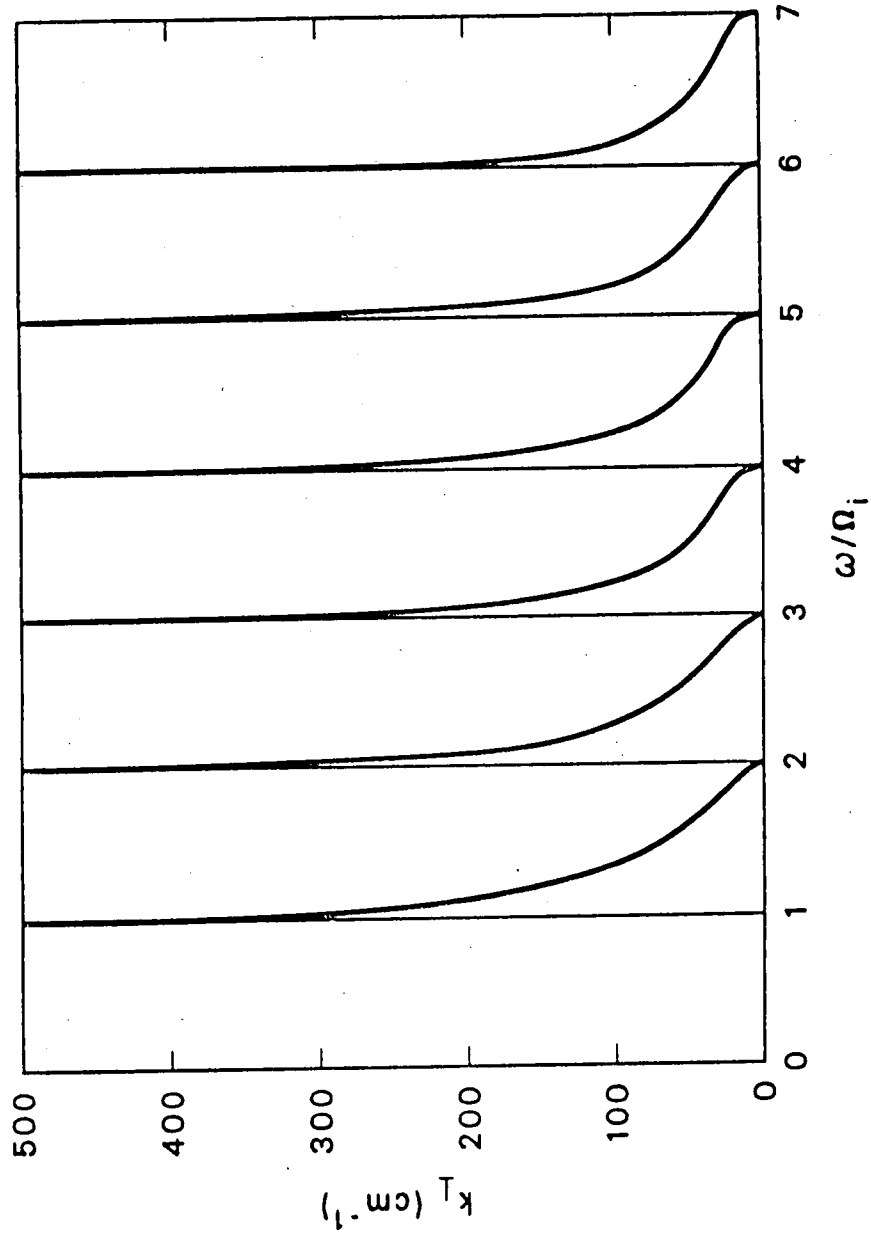


Figure 5-3. Calculated values of the wavevector perpendicular to the magnetic field for an electron density of $1 \times 10^{24} \text{ cm}^{-3}$, ion temperature of 50 eV, and an electron temperature of 300 eV.

curve is determined partially by the ion temperature. Assuming the FIR system looks at a large area of the distance between two harmonics, there is a good chance that a portion of the dispersion curve is observable. Generally the signal amplitude should increase with temperature at low ion temperatures due to the motion of k away from the harmonic points on the dispersion curve. The second effect is the fast-wave propagation in a plasma, which is a strong function of the electron density. It has been observed on EBT that the fast-wave propagation improves with increasing density.²⁴ In terms of these two effects, the significance of the pressure scan (Figure 5-4) becomes evident. At low pressures (deep M mode) the electron density is low, and the ion temperature is near zero. As the plasma enters the T mode region, the density and temperature both improve. As C mode is approached the ion temperature starts to level out. As the plasma enters C mode the density begins to increase rapidly. Deeper into C mode both ion temperature and electron density begin to decrease, thereby decreasing propagation. The signal amplitude is seen to follow the density, but the phase of the signal is changing while going through the T mode region. This is an effect that may be the result of the wave mode conversion process and reflects the changing ion temperature and density.

Although the measurements do not verify a specific theoretical wave dispersion relation, they do provide some evidence of the presence of ion Bernstein wave conversion and propagation. Also of significance is the fact that these measurements demonstrate that the ICH waves launched from three cavities away propagate both toroidally and radially through

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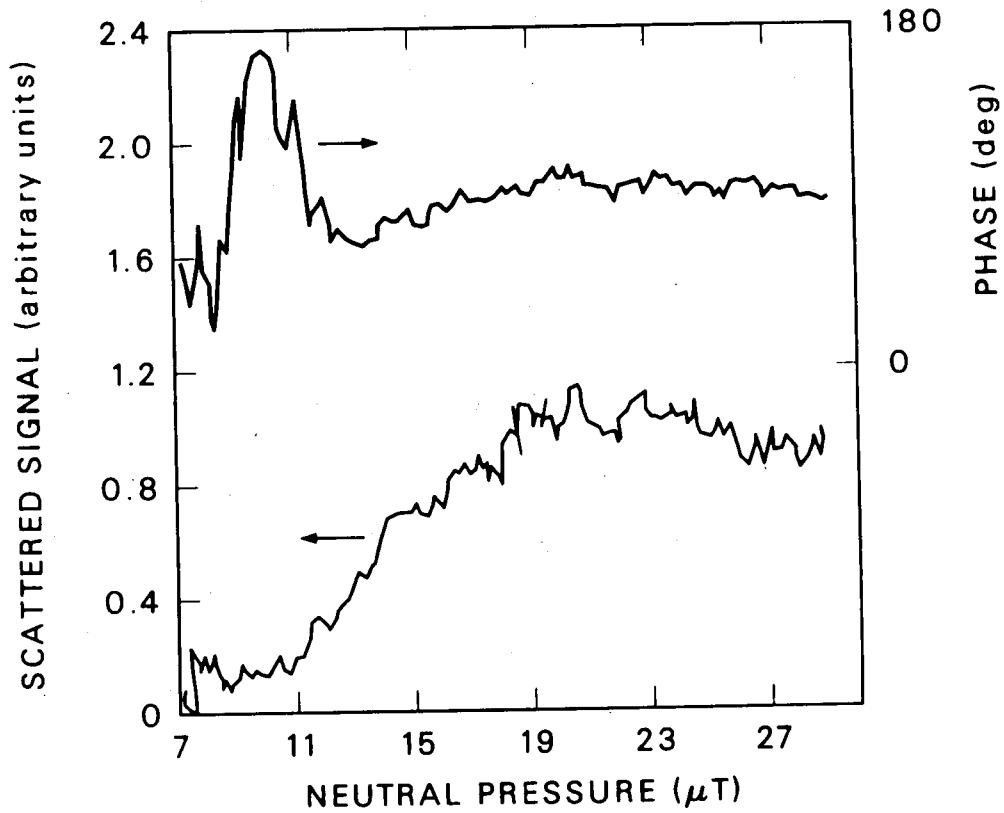


Figure 5-4. Scattered signal amplitude and phase as a function of the neutral pressure for a pulsed EBT-I plasma measured 6 inches from the inside cavity wall.

the plasma. Signals were observed at most spatial locations within the central plasma with a definite k /spatial (therefore ion cyclotron frequency) dependence, indicating that the driven waves are capable of completely penetrating the plasma if the plasma has reasonable densities and temperatures.

5-3 ICH Measurements with 2 mm Source

The scattering system was plagued by a lack of spatial resolution, especially when operated with the 2 mm source. To properly analyze the measured signals a better resolution than that achieved with the FIR is required. The 2 mm system is therefore marginal for this purpose. However, measurements were taken over a much larger range of parameters than with the FIR system, and the data taken was found to be generally reproducible. The conclusion reached from the sparse data taken with the FIR system is supported by the additional evidence provided by 2 mm scattering.

CHAPTER 6

RESULTS OF FLUCTUATION MEASUREMENTS

6-1 Introduction

Plasma waves can serve to enhance the transport of both energy and particles from regions of excess to regions of deprivation. In most fusion devices this means ultimate transport to the surface plasma and the enclosure walls. Normally discussions of plasma waves are restricted to single frequency, coherent waves or collections of waves in a narrow frequency bandwidth with a common source or driving mechanism. When several sources are present in such a manner that their interaction produces a very broadband mixture of random waves then no single source can be considered alone. These fluctuations often occupy large volumes and tend to equalize the temperature and density throughout that volume. As far as is known, all plasmas carry fluctuations at a level which depends on confinement and equilibrium. Low levels of fluctuations may be of no significance unless the lack of equilibrium causes an amplification of the wave amplitudes. This amplification process is referred to as an instability. There seem to be almost limitless sources for instabilities, and many have been observed and identified. The current understanding of the effect these phenomena have on confinement and stability in EBT is summarized in Reference 40.

The first significant scattered signals were observed during an unrelated X-ray diagnostic experiment using probes to destroy the high energy electron rings. Plasma conditions were being changed at short

intervals and were not recorded. It was evident, however, that the plasma entered a highly turbulent state which drove fluctuations large enough to be observed with the FIR system. The plasma returned to a more stable state after a few minutes. Although the information recorded during this brief period had no meaning for the experiment being conducted with the plasma, it did demonstrate that the FIR system would function if there were enough turbulence. The next steps were to increase sensitivity and to search for turbulent states in the plasma.

In comparison with other major plasma devices, EBT has relatively low density ($<10^{12} \text{ cm}^{-3}$) and low ion temperature. Central electron temperatures were modest, and overall the plasma was expected to be well confined. Compared to a tokamak, the general level of turbulence in EBT during steady-state operation is expected to be low. It was therefore decided to operate the plasma in a pulsed mode in order to raise the level of turbulence high enough to produce observable signals. The 18 GHz klystron amplifiers could be driven reliably in a pulsed configuration at almost any modulation frequency up to and exceeding 20 kHz. Further description of this experiment is given in Section 6-2. Improvements were eventually made to the system so that scattered signals could be recorded during steady-state operation. These signals were so faint, however, they could be seen only with phase sensitive detection and could not be spectrum analyzed. A sample observation is given even though not enough information was obtained to provide significant analytical results.

6-2 ECH Pulsing Experiments

In an attempt to increase turbulence to levels similar to what is found in tokamaks, the klystron amplifiers were amplitude modulated by an external square-wave signal. The frequency and the ratio of on-time to off-time, expressed as a percent duty cycle, could be varied to maximize the scattered signals which occurred when the system was operated at the typical frequency of 10 kHz and 50% duty cycle. In this case the ECH was turned off for 50 microseconds. Because this time scale is short relative to the particle and energy confinement times, it was anticipated that the electron density and the ion temperature would be only slightly modulated. On the other hand, the warm component of the hot electron rings (see Appendix A) may reach equilibrium with the surrounding plasma, and the surface plasma should be significantly dissipated. The initial effect of the start of the ECH pulse is to reheat the surface plasma and to increase the temperature of the warm component of the electron rings above that of the surrounding plasma. Heating rates in cold, low density plasmas have been observed to be very large.⁴ This can result in large energy gradients which may drive instabilities between the resonance zones and the surface plasma as well as between the rings and the core plasma. These instabilities can produce enough density turbulence to be observed with FIR scattering. The spatial location of the turbulence may be well confined to the region of the rings because the longer bounce times of the core plasma help thermalize it in the central regions. The observed effects of pulsing turned out to be much different from those expected.

For this experiment the input beam chopper wheel was removed, and the square wave that was driving the ECH modulation was used as a reference signal to the lock-in amplifier. Scattered signal was observed on all three mirror channels. The upper and middle channels were dominated by a large narrow signal coming from the cavity center. There was no trace of a similar signal on the lower channel. Further investigation showed that blocking the input beam into the plasma had no effect on the signal. A spatial scan on the upper channel with the input beam blocked is shown in Figure 6-1. Other tests indicated that the signal resulted from a reflection of the L.O. beam off the corner-cube reflector of the detector, through the antenna beam waveguide and into the cavity. The changing density of the plasma phase-modulated the beam as it passed through the cavity. When the antenna beam was directed toward the cavity center, the beam was reflected off the cavity wall and back along its previous path to the detector. The system then acted as a type of interferometer producing a large output signal phased with the pulsing plasma. This scenario is supported by the fact that the observed signal is narrower than the spatial resolution of the system at that point, due to interference effects in the reflected beam. This may also account for the subsidiary peaks normally observed on each side. The signal is not present on the lower channel because when the antenna beam passes through the cavity center it passes through an opening in the cavity wall and is not reflected back along the same path.

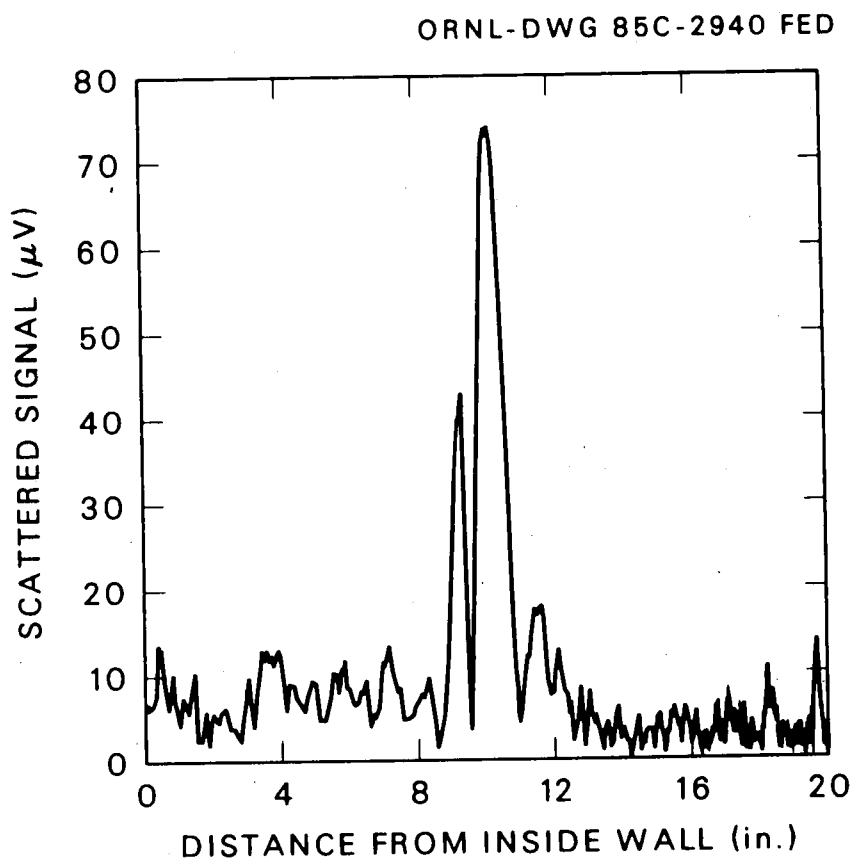


Figure 6-1. Spatial scan during pulsed ECH operation with only L.O. signal present. Central peaks were determined to be the result of reflections inside the EBT cavity.

In Figure 6-2 the input beam was present, resulting in additional signals from scattering. The large signal about 6 inches from the inside wall was present at all scattering angles and lies just inside the ring position. Also observed were smaller signals at 4 and 12 inches with all channels, and at 2 to 4 inches and 18 to 19 inches with the middle and lower channels (Figures 6-3 and 6-4). Occasionally signals were observed at other spatial locations, but they were strongly dependent on machine conditions and usually changed rapidly in time.

In order to determine the relationship between the microwave field and the stronger scattered signals, the 18 GHz feed into individual cavities could be blocked, reducing the power input into that cavity. When the microwaves were no longer fed into the scattering cavity, the signal amplitudes were noticeably reduced, but only by about 10%. Turning off the power feed into the two adjacent cavities also reduced the signal about 30%. General characteristics of the signals, such as location and profile, were unaltered.

The signal amplitudes were found to be strongly dependent on the percent modulation but weakly dependent on the percent duty cycle. Reducing the percent modulation by half roughly reduced the signal amplitudes by half. The dependence on the modulation frequency was more complex. Measurements were made using a programmable waveform generator to slowly change the frequency of the square-wave output from 1 kHz to 20 kHz. Figure 6-5 demonstrates the dependence of the scattered signal of the upper channel at 6 inches on the frequency of modulation. In addition, the phase of the signal changes continuously with frequency in

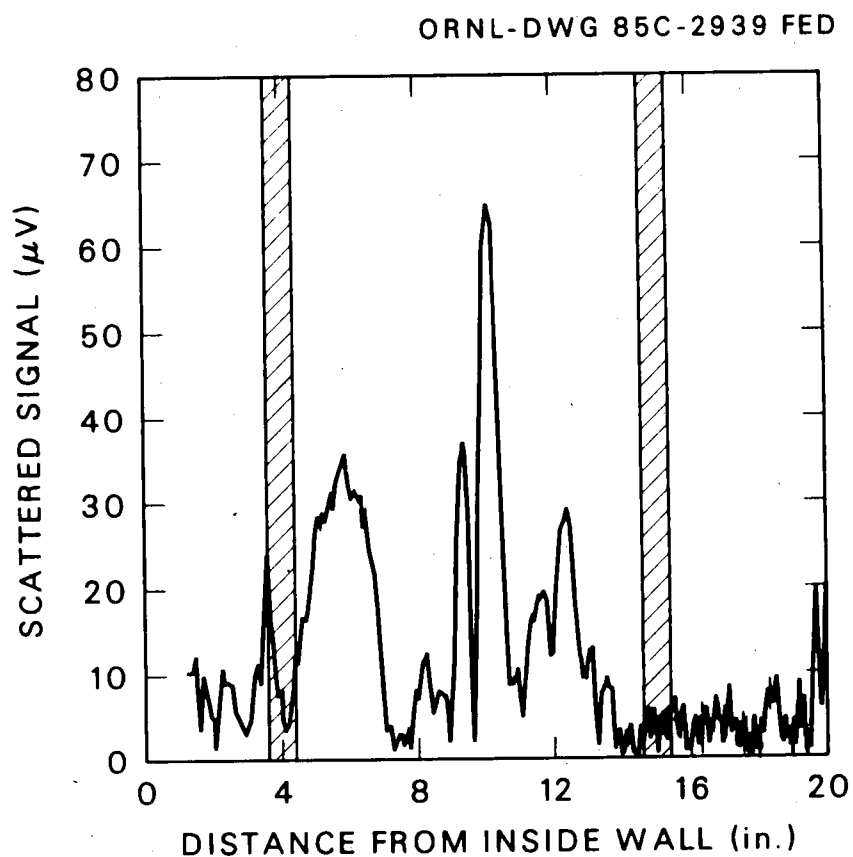


Figure 6-2. Spatial scan during pulsed ECH operation showing scattered signals detected on the upper channel at 5000 A, 43 kW of 18 GHz and 16 microns neutral pressure. Electron ring position is denoted by the shaded regions.

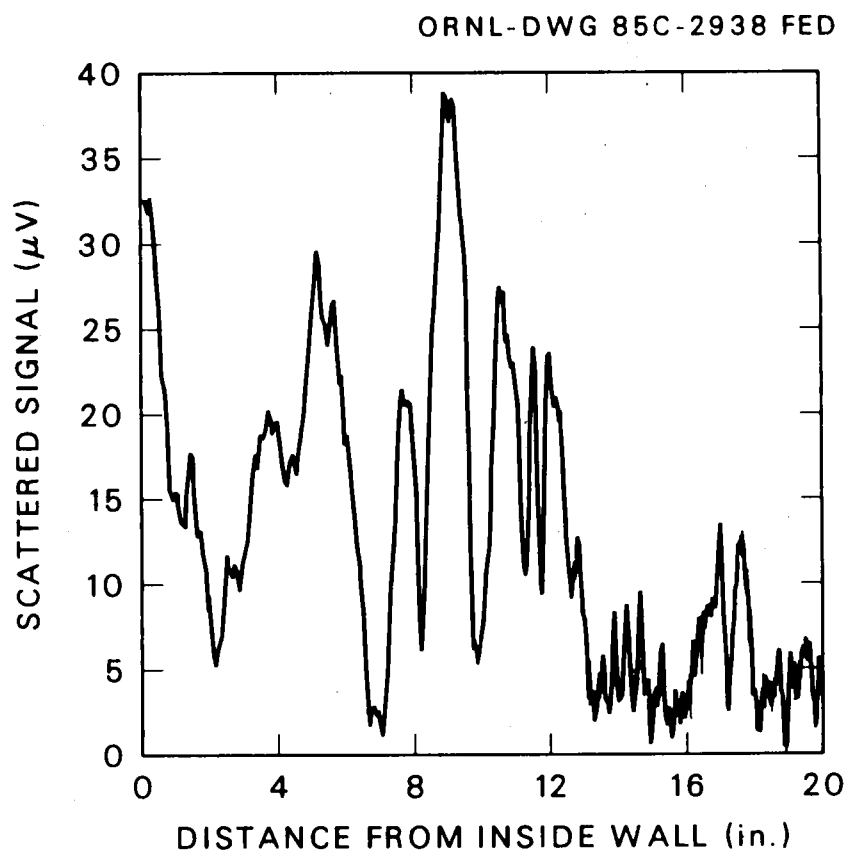


Figure 6-3. Spatial scan with middle channel under the same condition as the previous figure.

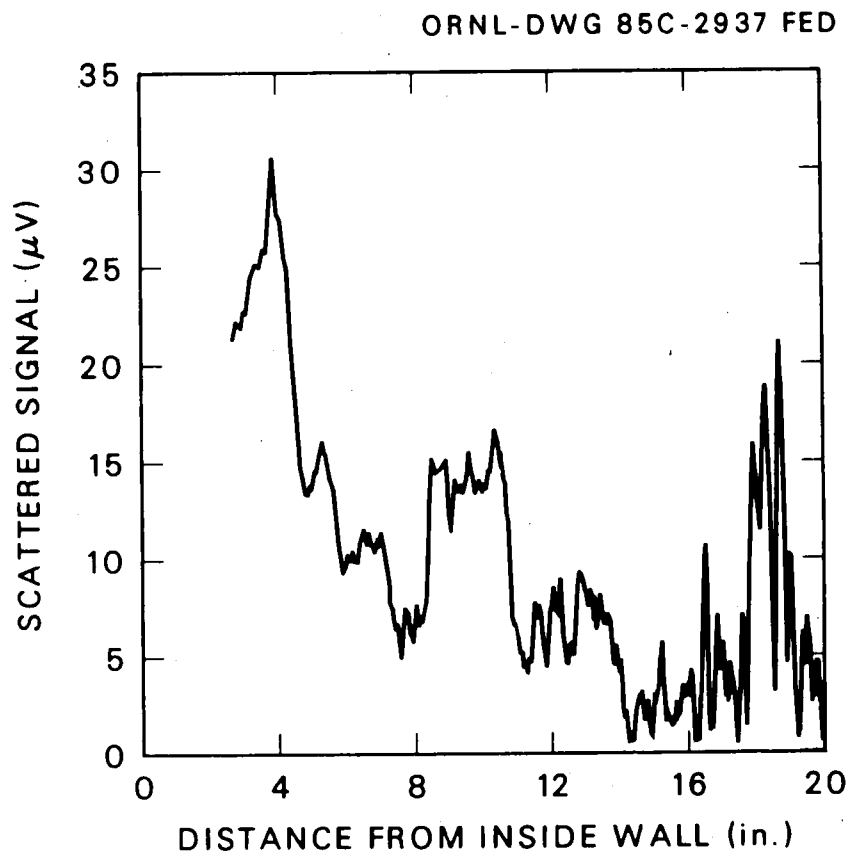


Figure 6-4. Spatial scan with lower channel under the same conditions as the two previous figures.

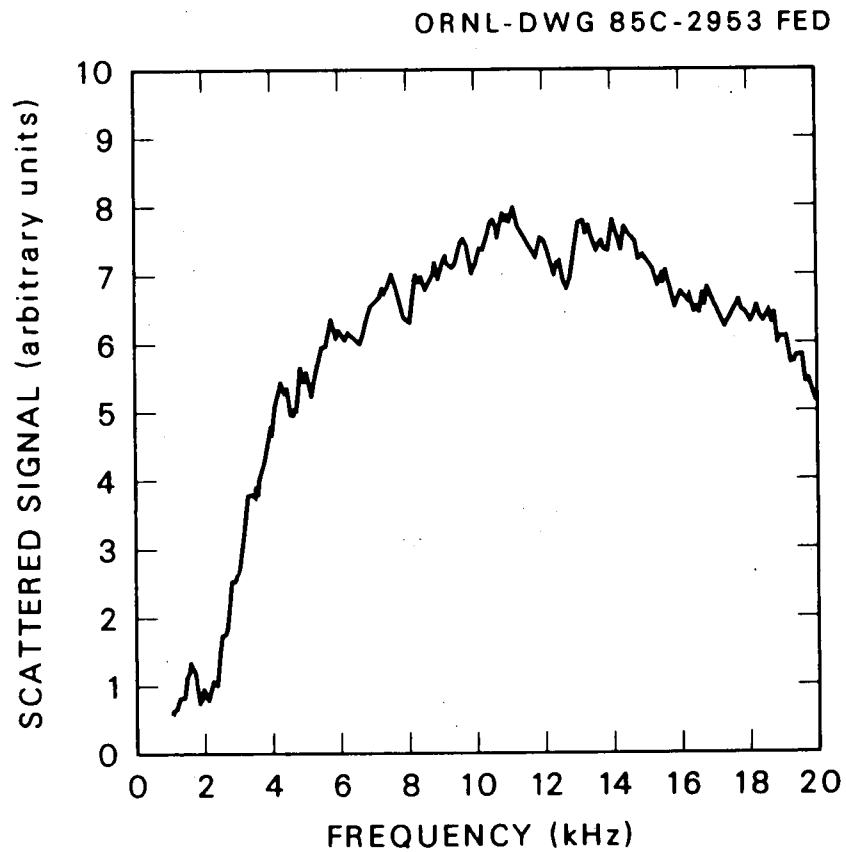


Figure 6-5. Dependence of the upper channel scattered signal (at 6 inches) on the frequency of ECH modulation at 5000 A and 16 microns neutral pressure.

a near-linear manner and at a rate of approximately 18° per kHz. Changes in the magnetic field also had a strong effect on the same signal. As shown in Figure 6-6, the signal reaches a minimum near 5.3 kA and a maximum near 6 kA. A similar measurement with the lower channel (Figure 6-7) shows the field dependence to be almost flat above 5 kA, but it still shows a significant maximum at 6.5 kA.

The behavior of the surface plasma is of less importance but still of interest. The lower channel showed strong turbulence along the inside wall which depended on the neutral pressure. This turbulence showed up strongest near the T-C transition and near the T-M transition. Levels were generally higher throughout the C mode. Turbulence at the outside wall was observed on all channels. The field dependence showed a marked minimum at 5.8 kA and a maximum near 6.5 kA. Although these correspond closely to the local extrema observed for scattering at 6 inches, the overall curve shape was notably different (Figure 6-8).

6-3 Discussion of Pulsed ECH Experiments

During operation of EBT in pulsed mode the fundamental harmonic zone should absorb most of the microwave power. The resulting change in temperature and density should then be transported to both the central plasma region and to the surface plasma. The surface plasma is a region with a small volume compared with a large surface area. It is relatively cold with lower densities but with large density and thermal gradients. Confinement is very poor, and large low frequency fluctuations can be expected and have been observed.¹⁷ These fluctuations are

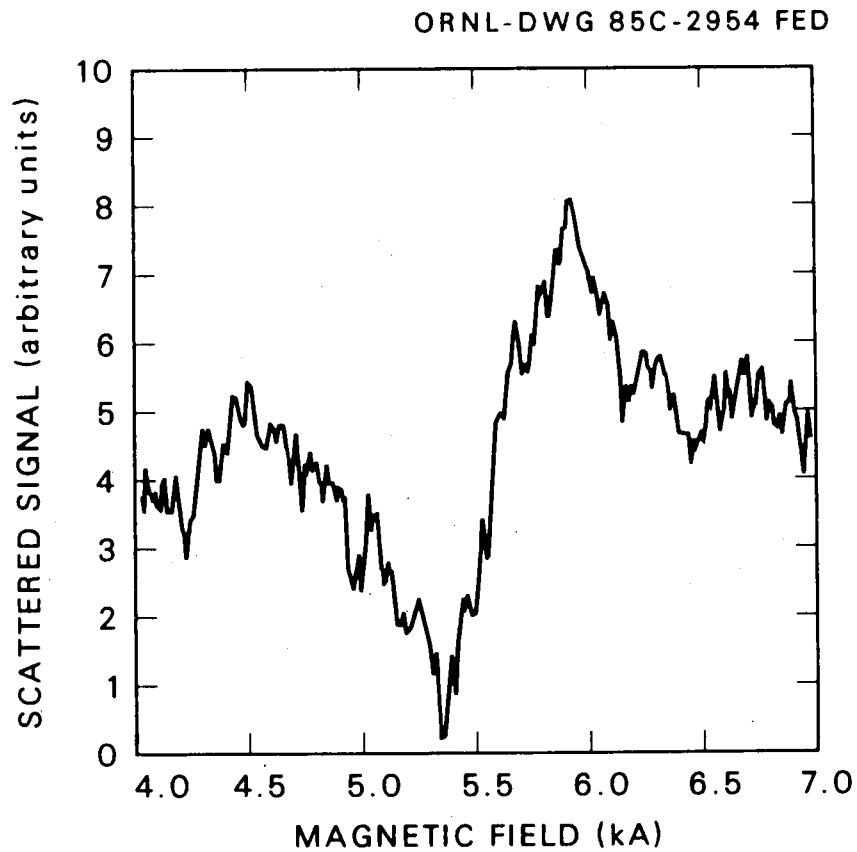


Figure 6-6. Dependence of the upper channel scattered signal (at 6 inches) on the magnetic field at 14 kHz ECH modulation and 16 microns neutral pressure.

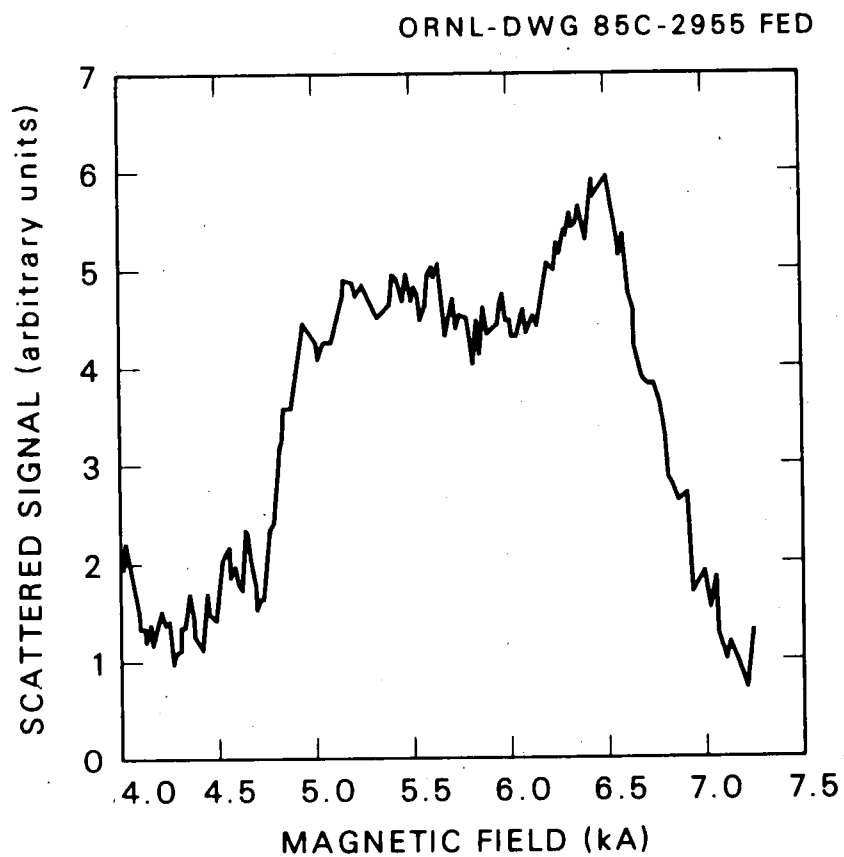


Figure 6-7. Dependence of the lower channel scattered signal (at 6 inches) on the magnetic field at 14 kHz ECH modulation and 16 microns neutral pressure.

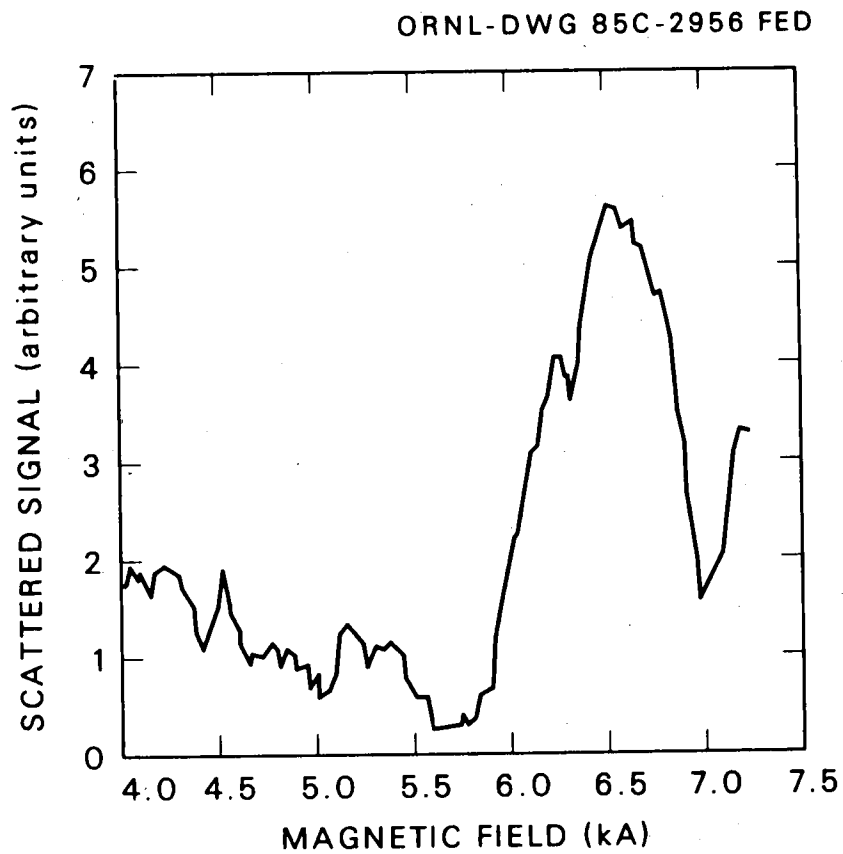


Figure 6-8. Dependence of the lower channel scattered signal at the outside wall on the magnetic field at 14 kHz ECH modulation and at 16 microns neutral pressure.

observed in both steady state and pulsed modes. The core plasma, on the other hand, may normally be stable with low fluctuation levels. When the ECH is pulsed on, the resulting gradients should result in fluctuations inside the ring region and towards the plasma center. The ring region itself may be stabilized by the ECH⁴ and thus may not exhibit any activity. Figures 6-2 and 6-3 (pp. 84 and 85) show what briefly seems to be exactly this type of behavior. The spatial resolution is reduced in Figure 6-3 so that the signals may not be as clearly separated as in Figure 6-2. Figure 6-4 (p. 86) shows the same behavior in the outside region. The inside region does show large fluctuations, although the even further reduced spatial resolution prohibits any conclusion about the structure.

These measurements were confined to the cavity midplane and therefore do not indicate the distribution of the fluctuations around the torus, especially through the mirror throat regions. To investigate the dependence of the enhanced fluctuation levels during pulsing on the high density microwave power levels in the cavity, the microwave feed into the measured cavity was terminated. The effect was measurable but not large. Reducing the input into two adjacent cavities on each side produced only a modest reduction in level. This indicates that the observed fluctuations are a global phenomena which demonstrates the strong coupling of the individual mirror cavities by the toroidal plasma core. In contrast to this, an increase in the magnetic field from 5 kA caused a decrease in signal, possibly because the second harmonic ring moved out to a region where the field lines all intersect the vacuum

wall. The signal sharply increases with a further increase in field and reaches a maximum at slightly less than 6 kA. This is the approximate field at which the fundamental resonance enters the cavity midplane. An effect which may be indistinguishable from the passage of the harmonic zones is the changing error fields. No attempt was made to minimize error fields during these experiments. Changes in other measured plasma parameters or properties have shown similar anomalies which have tentatively been attributed to the effects of the changing error fields.

The most important clue to the nature of these fluctuations comes from their dependence on the modulation frequency. At lower frequencies (<1 kHz) the signal exists only at a low level. At 3 kHz the signal level is increasing rapidly, and at 5 kHz it changes to a more gradual uniform increase. It peaks between 11 and 14 kHz, after which it slowly declines. This indicates that the phenomena is short-lived, since at lower frequencies it occupies a smaller portion of the signal averaging time in the lock-in amplifier. The signal should be a maximum at the region near the instability lifetime and should decrease at higher frequencies because of the losses outside the sampling time. This argument leads to an instability lifetime of about 40 ms. This period is far too short for decay of densities or temperatures as was expected.

In conclusion the ECH pulsing experiment has resulted in the observation of what may be a new type of instability which is produced or enhanced by the modulation of the microwave power input into the plasma. The instability has an extremely short reaction time and appears to be sensitive to the position of the ECH harmonic zones. It

is fixed in spatial location and seems to be globally driven. It can be either a result of the start of the ECH pulse or an early part of the plasma decay upon termination of ECH heating. The short reaction time and duration indicate that it is not related to normal drift type instabilities, since the plasma density does not significantly change on that time scale. The presence of the signal well into the toroidal plasma component separates it from fast surface effects such as large temperature changes. Other possible driving forces are hard to evaluate without more measurements, which seem unlikely on this type of device.

6-4 Steady State ECH Experiments

Operation of EBT-S (28 GHz ECH) in a steady state mode was one of the primary requirements for obtaining information on density fluctuations, a central goal of this project. It was discovered that the scattering system sensitivity could be improved by increasing the input beam chop rate from 10 Hz to 120 Hz. Before this, however, the 28 GHz gyrotron started to become unreliable and difficult to operate. During the last three months of operations the gyrotron was available only for a short period of time. The data taken could not be repeated, tested, or otherwise confirmed, and are therefore not considered dependable. The observations seemed to indicate that the plasma was nonturbulent throughout the central region in T mode and C mode. The outermost plasma region did show larger levels of turbulence, confined mostly to within an inch of the cavity walls. At a neutral pressure of 14 micro-torr, which corresponds to the T-C transition point, there was an

obvious change in the plasma state. The most central core region showed a marked increase in signal level, with little change elsewhere, as shown in Figure 6-9.

The 18 GHz klystron was much more reliable for driving the ECH plasma. Most of the ICH experiments were carried out with the 18 GHz system, as well as the pulsed experiments discussed in the previous section. The EBT-I plasma does not have as high a density as the EBT-S plasma and is therefore not as good a medium for studying plasma fluctuations with a FIR system. The measurements taken were unreliable and difficult to obtain. There were no significant characteristics observed under these conditions for a steady state plasma. The 2 mm system did prove to be more suited for these types of measurements and it is treated in detail in Section 5 of this chapter.

6-5 Two mm Steady State Measurements

Few opportunities were available for steady state measurements of a 28 GHz ECH plasma with the 2 mm system due to the limited availability of the gyrotron. When a measurement was made, however, the level of fluctuations observed was down by a factor of more than 6 (8 dBm) over a similar measurement of an 18 GHz heated plasma. This measurement pointed out the reason for the much lower signal-to-noise ratio encountered with the FIR system when attempting to measure fluctuations in EBT-S. The distribution of fluctuations was observed to be similar to the distribution in EBT-I.

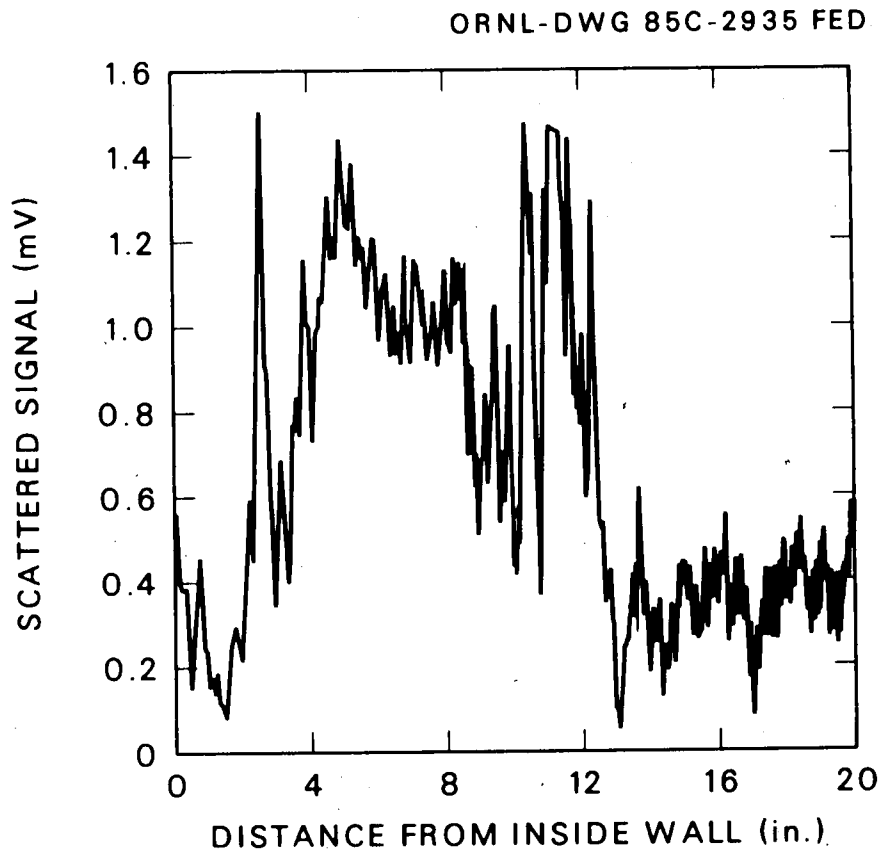


Figure 6-9. Upper channel spatial scan of a steady state plasma in EBT-S at the T-C transition point.

Measurements taken with 2 mm waves were difficult to interpret because of the lack of spatial and wavenumber resolution on the inside of the cavity, which is where most of the activity seemed to be located. Corrections were made for the scattering volume and the wall effects. However, there is not enough confidence in the corrections close to the wall to allow definite conclusions about the activity in this region. Figure 6-10 shows a plot of the corrected signal amplitude vs the spatial location and the neutral pressure in EBT-I. The tendency of the amplitude seems to follow the density with the changing pressure. Another plot, shown in Figure 6-11, is of the same data except that the amplitude has been divided by the approximate line density squared. Attempts were made to measure the effects of the applied error fields, but no significant change in the fluctuation level was observed. Figure 6-12 shows the signal level vs position at different frequencies for the same machine conditions. Due to a vacuum excursion that resulted from an antenna failure, the plasma was run with a large amount of impurities, mostly water, during a period of time at the end of the EBT experiment. Data taken with those conditions show a considerable change in the distribution of fluctuations at smaller k-vectors. A comparison of one of these measurements with a measurement of a clean plasma is shown in Figure 6-13. The frequency distribution was measured on the upper channel under the same conditions. Shown in Figure 6-14, the spectra fall off with frequency in the manner expected of drift wave turbulence and in agreement with measurements of Komori¹⁷ (see Appendix C).

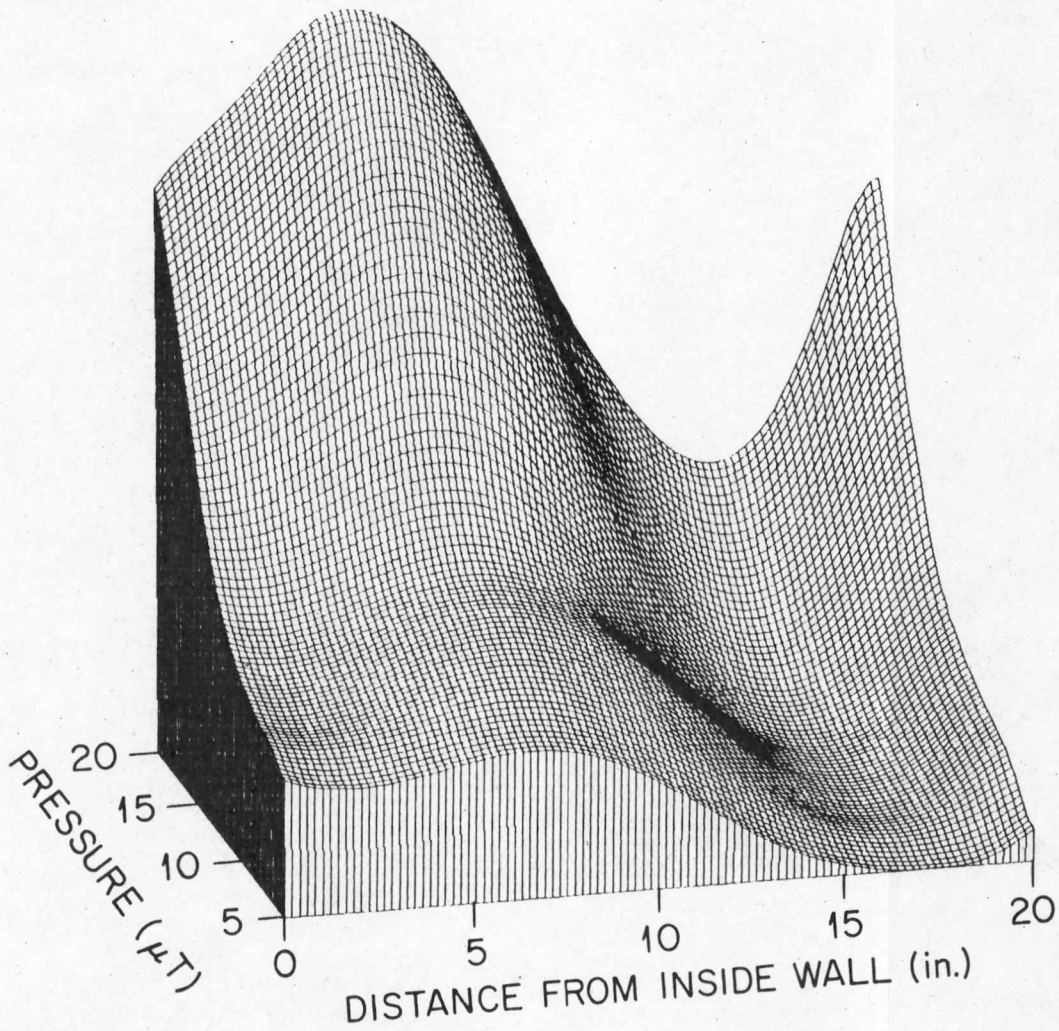


Figure 6-10. Scattered signal vs spatial location and neutral pressure for an EBT-I plasma as measured by 2 mm scattering at a frequency of 200 kHz.

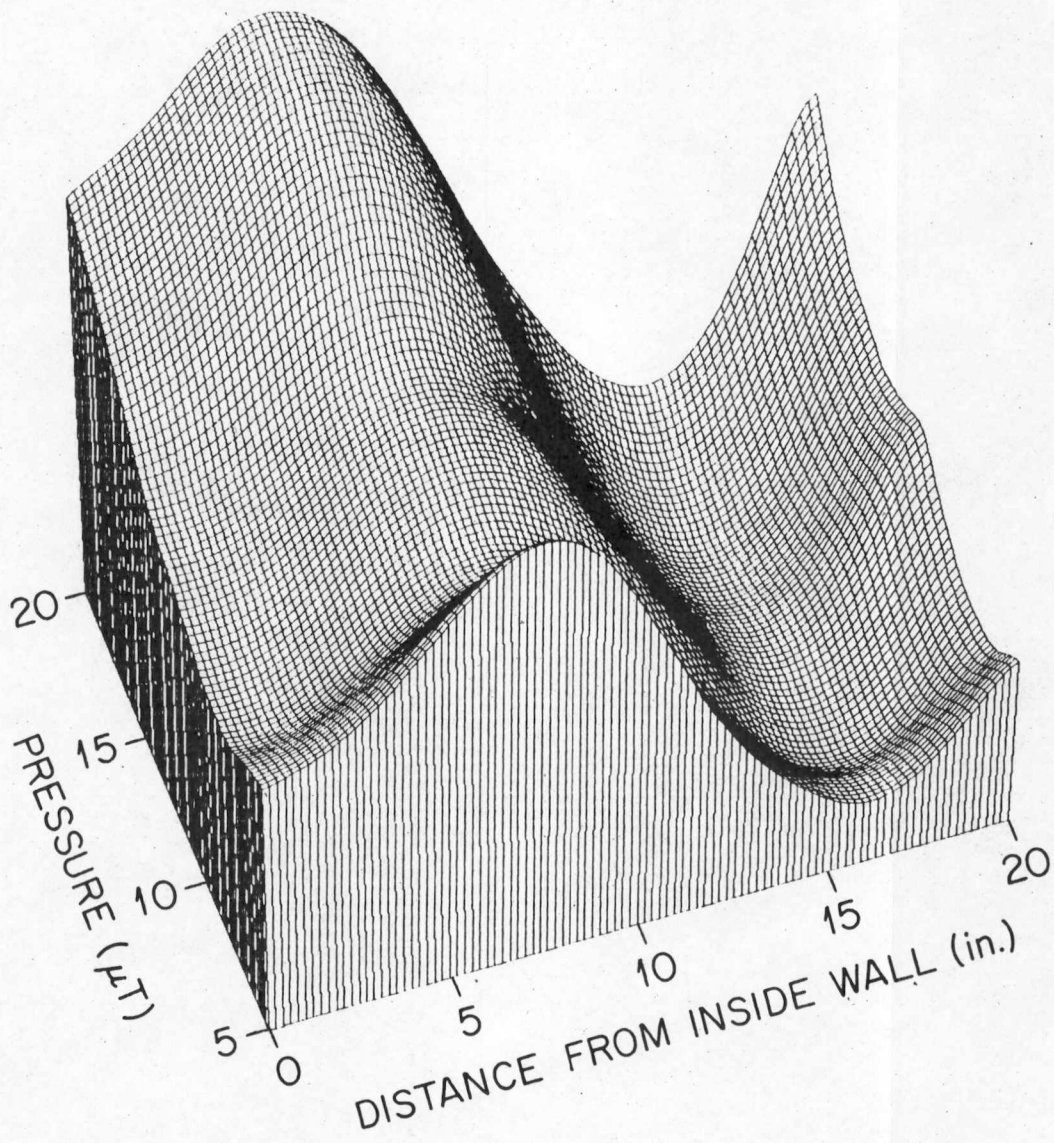


Figure 6-11. Data shown in the previous figure divided by the appropriate line density squared.

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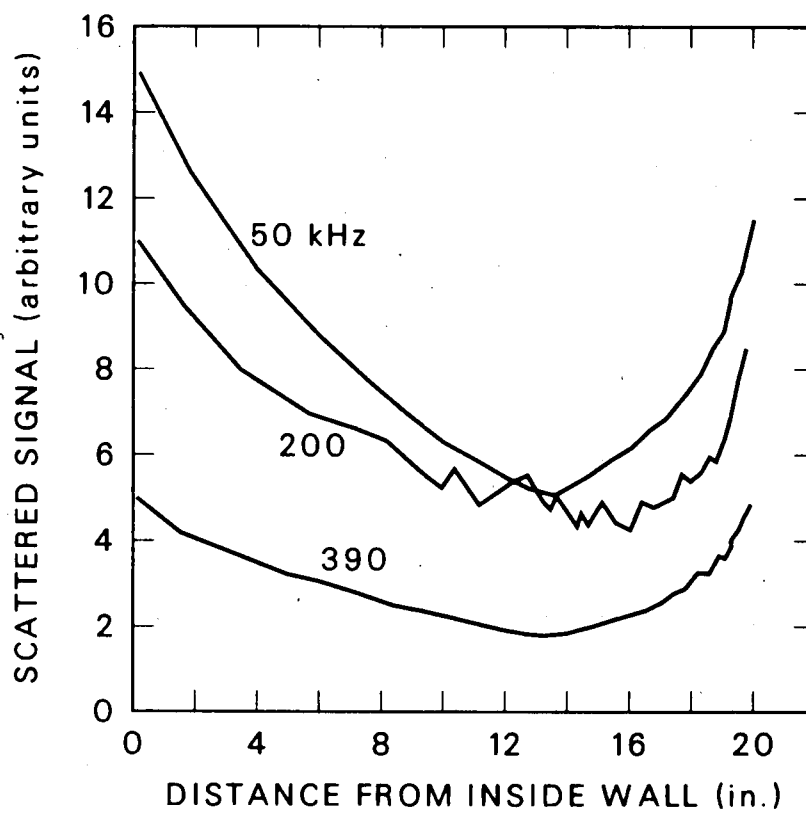


Figure 6-12. Scattered signal vs spatial location and observed frequency shift.

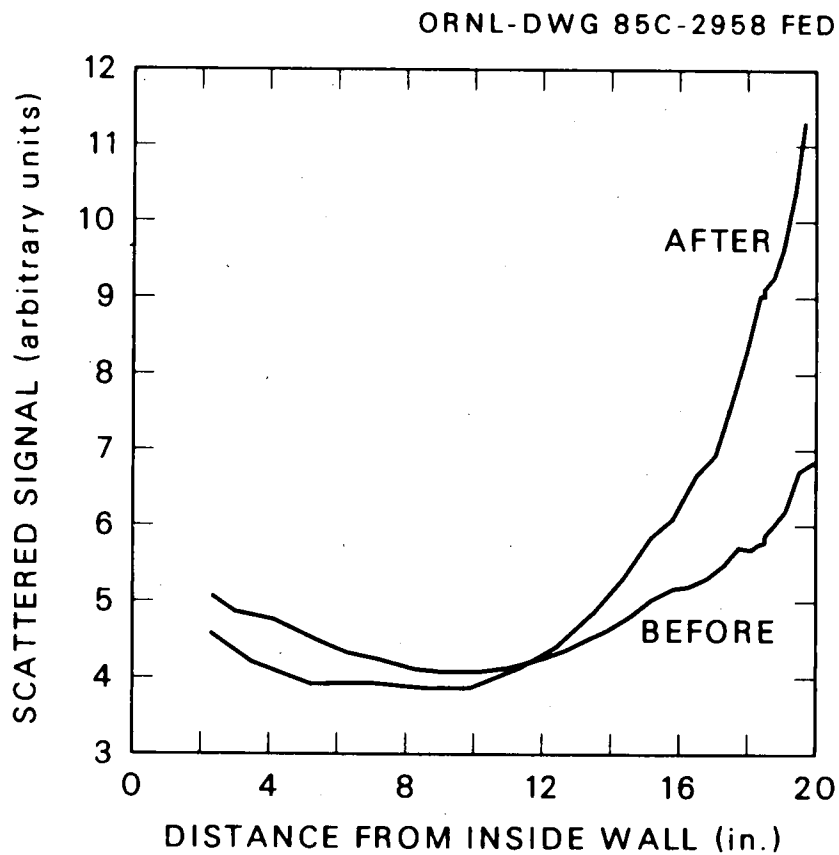


Figure 6-13. Comparison of scattered signals on lower channel before and after contamination of vacuum vessel with water. The spectra were taken at 200 kHz on the lower channel.

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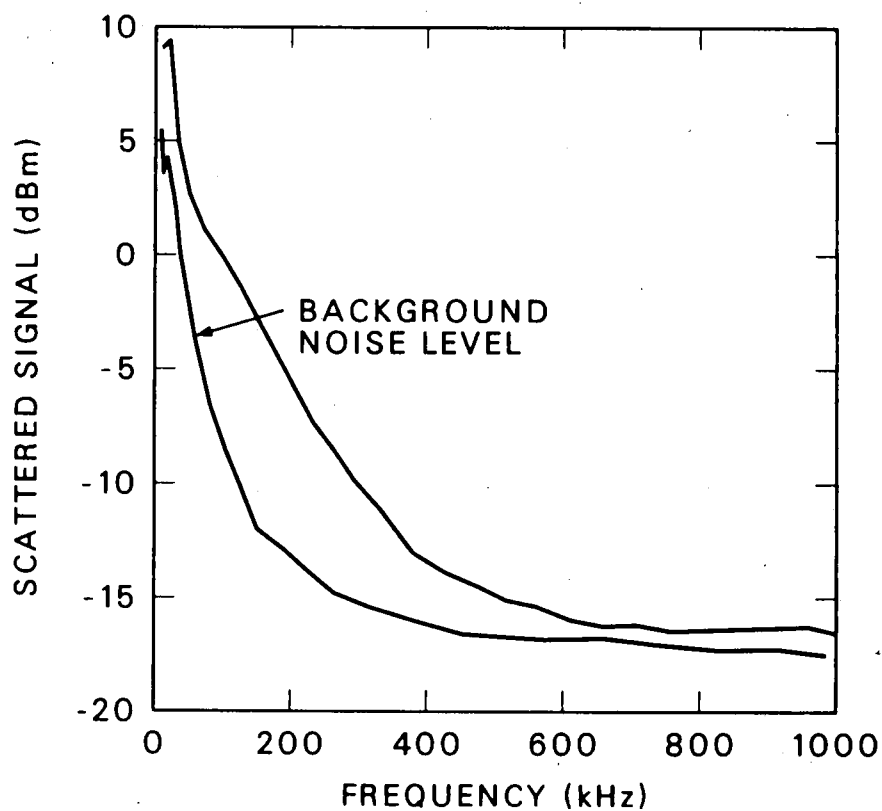


Figure 6-14. Frequency spectra of scattered signal observed after vacuum excursion compared to the noise level.

CHAPTER 7

SMALL ANGLE SCATTERING ON ISX

7-1 Introduction

The availability of a far-infrared laser system, used for interferometry, on ISX provided an excellent opportunity to measure fluctuation levels via FIR scattering. The limited time, availability of equipment, and machine access were factors which prevented the implementation of a complete scattering system. Also, the importance of the interferometer to everyday operations on ISX limited its availability for alterations. It was observed, however, that in the signals from the detectors there was a component that was a result of scattering in the plasma. This component could be separated out by spectrum analyzing because of the frequency shift that occurs during the scattering process. Little time was available for optimizing the signals, but a method was implemented whereby the signals were automatically recorded during each plasma shot. The following is a description of the interferometer used as a scattering diagnostic and a summary of the measurements taken during the limited time span the system was implemented.

7-2 Using an Interferometer as a Scattering Diagnostic

The ISX far-infrared interferometer is diagrammed in Figure 7-1. The laser system consists of two sets of lasers identical in makeup to the EBT FIR laser system. The output from the signal laser is divided by beam splitters into five channels which pass through the plasma. The

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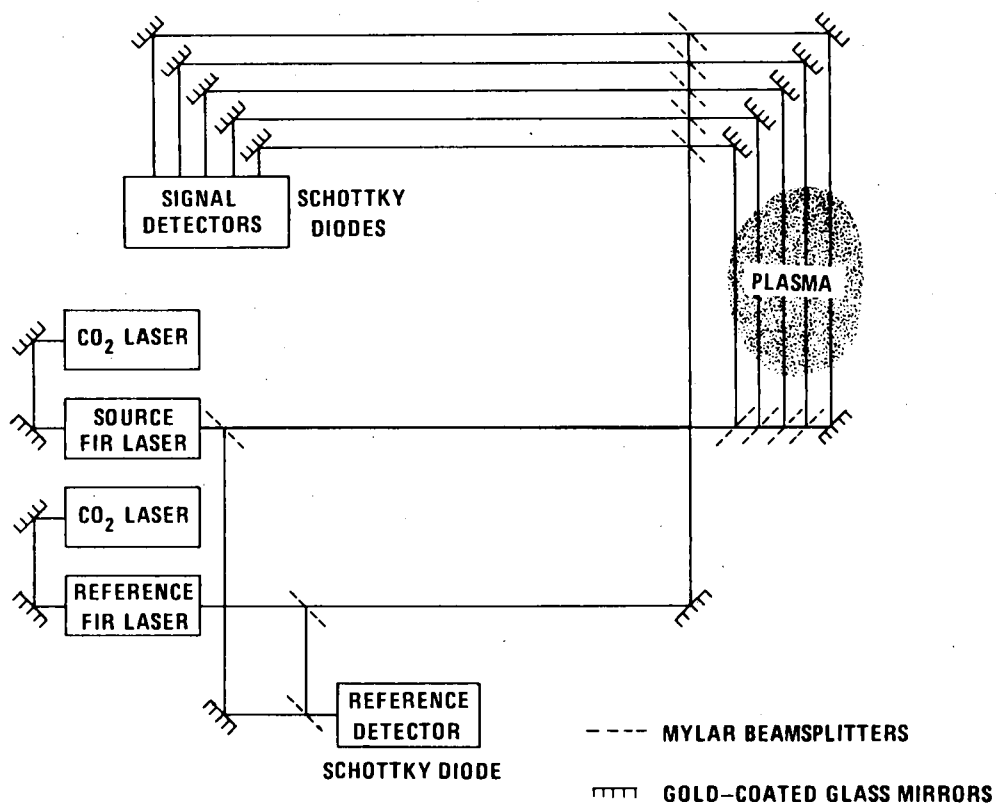


Figure 7-1. Schematic of FIR interferometer system installed on ISX and used for extreme forward angle scattering.

phase shifts of these beams are measured with respect to the reference laser. Each of these beams is subject to scattering as predicted in Chapter 2. There were no attempts made to collect these scattered signals into a separate waveguide system. However, signals scattered into small enough angles are incident upon the collecting lens and therefore are coupled into the interferometer output channel. The actual limitation on the range of angles which could be coupled efficiently into the waveguide does not depend upon the solid angle the lens subtends to the scattering volume, but instead depends upon the divergence angle of the antenna beam. Signals outside this range may strike the lens but are not refracted into a beam path that propagates within the waveguide. Analysis of the beam divergence, assuming Gaussian optics, gives a maximum scattering angle of 0.8° which corresponds to a fluctuation wavelength or characteristic length of 3 cm. The scattered signals recorded by this method are then the result of scattering from fluctuations or waves whose characteristic length is equal to or longer than 3 cm. It must be emphasized that the interferometer beam enters one side of the plasma and exits the other by a near-straight line trajectory. The recorded scattered signals are those signals which are not scattered enough to leave the general direction of the original beam path. No spatial resolution or wave vector measurement is possible. Since the plasma is not centered and tends to move, the refractive effects within the plasma can cause the original beam path to bend, thereby increasing the possible scattering angles. This effect can be quite significant, especially on channels toward the outside of the plasma. Most of the

data taken, however, were on the central channel where the refractive effects are known to be small. Also, measurements of the incident FIR power, L.O. power, and waveguide losses were not possible so that an absolute system calibration could not be made.

Each interferometer channel was separately mixed with the reference signal as a local oscillator. The beat signal represented the frequency difference between the two lasers which was typically 1 MHz. The output of the mixer/detectors was amplified and passed through a band-pass filter before being further processed. As shown in Figure 7-2 the signal could be tapped before filtering so that the entire spectral band could be analyzed. The spectrum analyzer used for this purpose had a built-in delay before resetting between frequency sweeps. It could be externally driven, however, by a uniform voltage ramp. To generate this ramp a sawtooth signal generator was employed with a gated output. The signal was gated with a delayed gate triggered by a start signal from the tokamak sequence controller. The sweep time could be thus controlled by the sawtooth shape, and the time at the start of the sweep, with respect to the start time of the tokamak shot, could be adjusted with the delay generator. All data taken were taken with a sweep time of 20 ms over a time period of 400 ms starting at about 20 ms before the formation of the plasma. This allows 20 spectra to be taken during each shot. The first spectrum is taken before the plasma is formed, allowing it to be used as a background measurement. The final spectrum is typically after the final disruption at the end of the shot and usually shows only weak scattering from the residual afterglow. During each

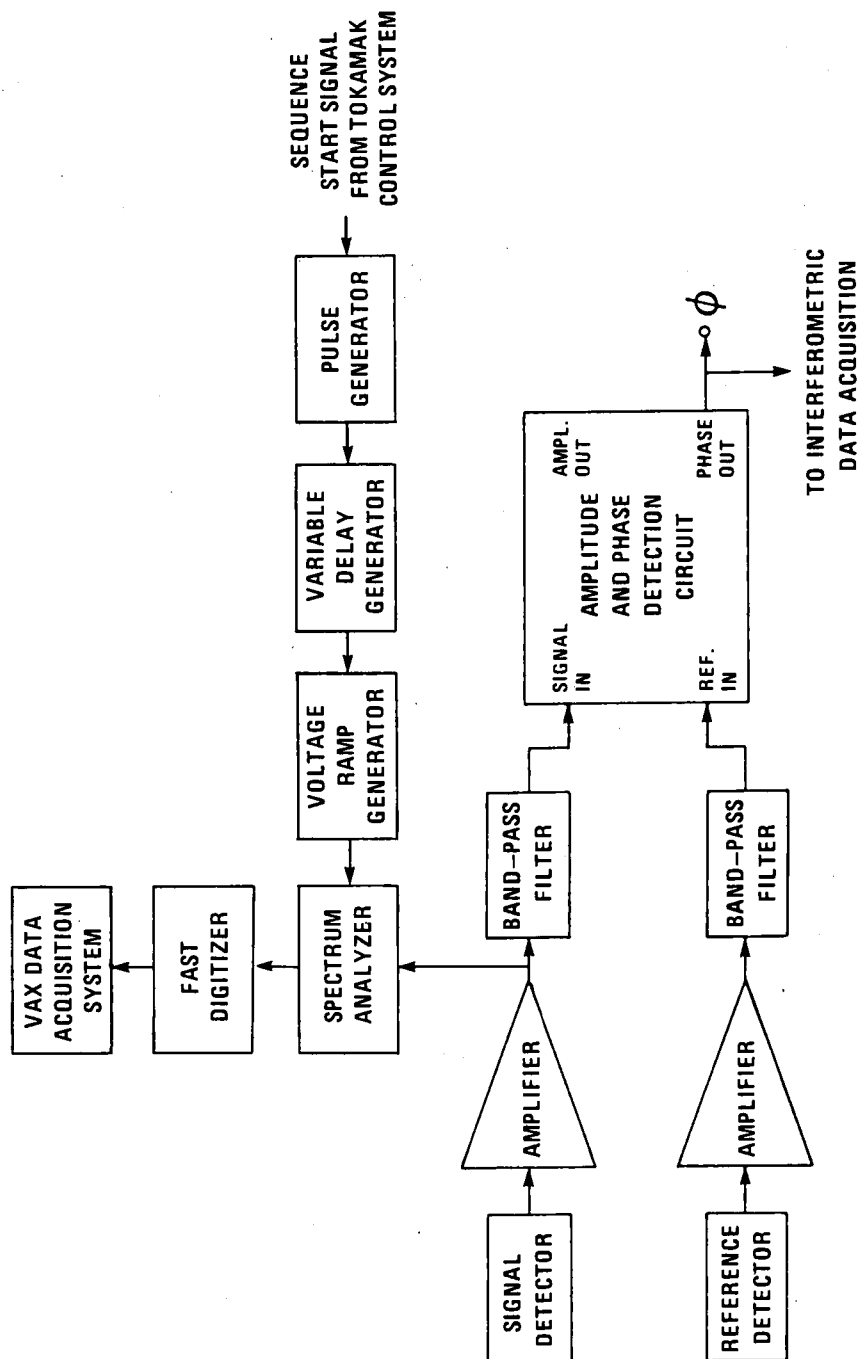


Figure 7-2. Electronics configuration of the ISX FIR detection system showing insertion of additional electronics to record the scattered signals.

shot there is always a nonnegligible frequency drift in the lasers which shows up as a drift in the lasers' beat frequency. Since this is a heterodyne system, both the plus and minus scattered signal beat frequencies are independently displayed separated by the lasers' beat signal, which is the zero scattered frequency of the scattered spectra. The data acquisition system stores the spectra as a continuous stream of data. The spectra are separated by searching for the strong beat signals and plotting the spectra for about 600 kHz on each side of the beat signal which is taken as zero. These spectra can then be arranged in temporal order to demonstrate the evolution of the plasma fluctuations during the cycle of the tokamak discharge. Time evolution of the spectra could also be recorded at a single frequency by using the spectrum analyzer as a band-pass filter and sweeping the analyzer over a 400 ms time span.

Frequency calibration of the system was accomplished by using a single frequency source and recording the spectra in a similar manner. The spectra display the given frequency and the normal harmonics, thereby allowing calibration of the x-axis.

7-3 Scattering Results

A typical series of spectra for a single shot is shown in Figure 7-3. The obvious characteristics are the beat signals and the reset signals. Dividing these spectra according to the position of the central peak allows a display of the plasma evolution (Figure 7-4). The scattered signals are now evident as sidebands or wings on each side of the central peak. The sharp narrow peak at plus 800 kHz is the reset

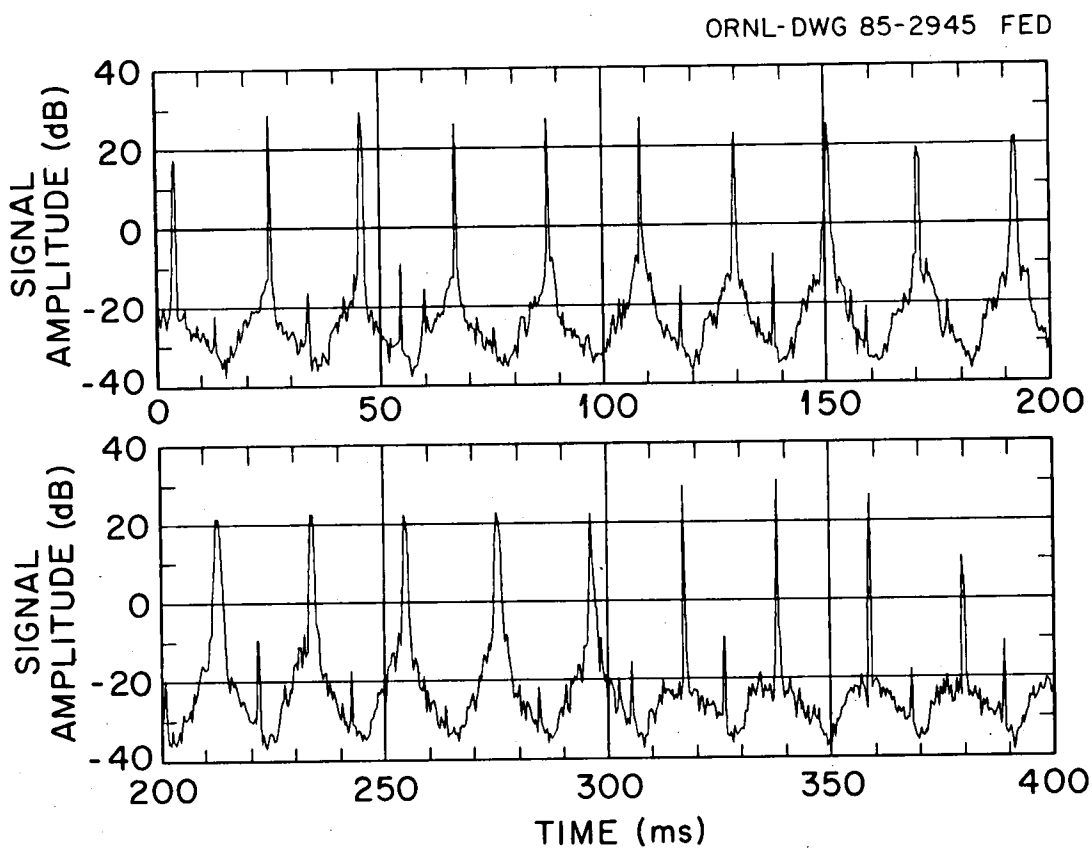


Figure 7-3. Sequence of spectra as recorded by the ISX data acquisition system. The large peaks every 20 ms are the result of the beat signal from the two lasers while the spectra on each side are from scattering within the plasma.

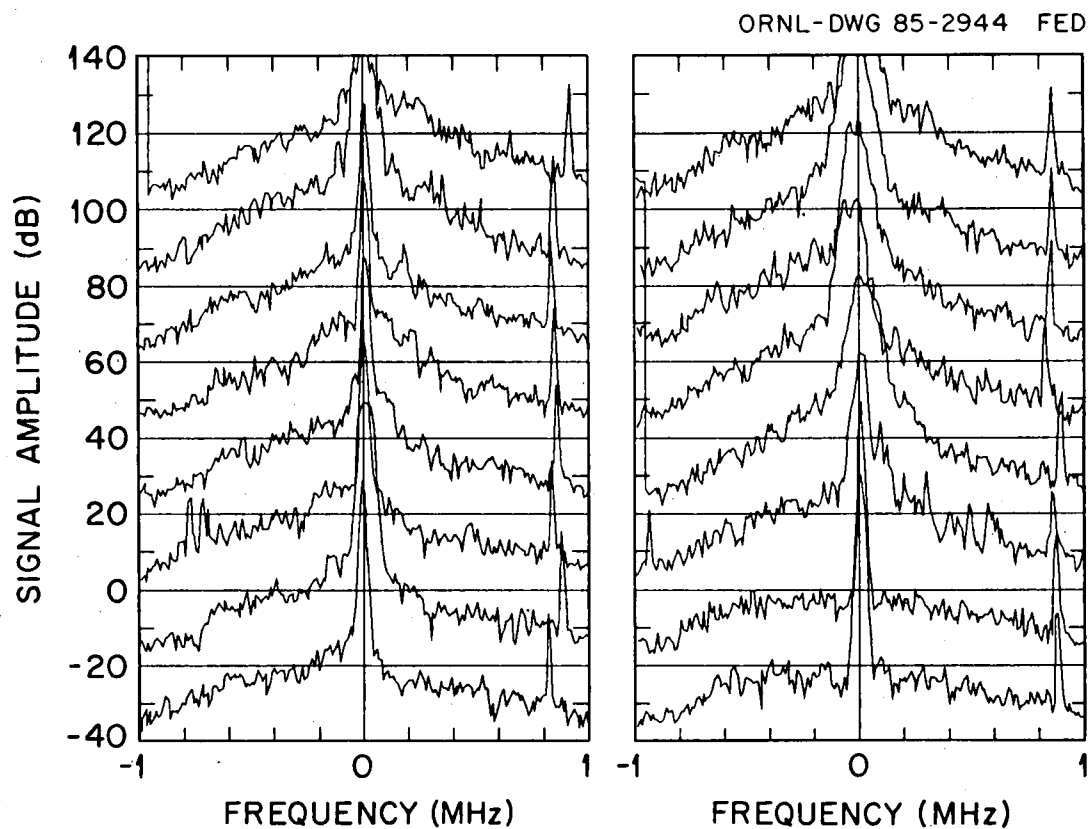


Figure 7-4. Separated spectra plotted as a function of frequency and temporally ordered from the lower left upward to the upper right downward.

signal. As the plasma evolves (lower left upward, then upper right downward), fluctuations first appear as broadband spectra with half widths on the order of 500 kHz. There appear to be some low frequency (<50 kHz) transient fluctuations that occasionally appear in one or two spectra. When the first neutral beam starts up, the fluctuation level generally increases in proportion to the increase in density. Lower frequencies (<100 kHz) tend to increase dramatically faster. Sharp spikes often occur that correspond either to coherent plasma waves or to laser instabilities which are indistinguishable from each other. Start-up of the second neutral beam causes another increase in signal but one much less dramatic than that in the first beam start-up. This is visible in the time evolution plot of Figure 7-5. Ohmic start-up is at 30 ms, the first beam line starts at about 100 ms, and the second at about 200 ms. This can be compared with Figure 7-6 which shows the time evolution of the density.

Fluctuation spectra were recorded for most of the ISX operating schedule for a period of about six months. During that time experiments were performed with beam heating, pellet injection, impurity injection and limiters.

7-4 Analysis

During each shot the main characteristic stages of the plasma evolution were observed in the fluctuation spectra. Besides those already mentioned, the plasma disruption at the end of a shot was frequently observed as a sharp increase in fluctuations followed by the near-total disappearance of all fluctuation frequencies. During neon

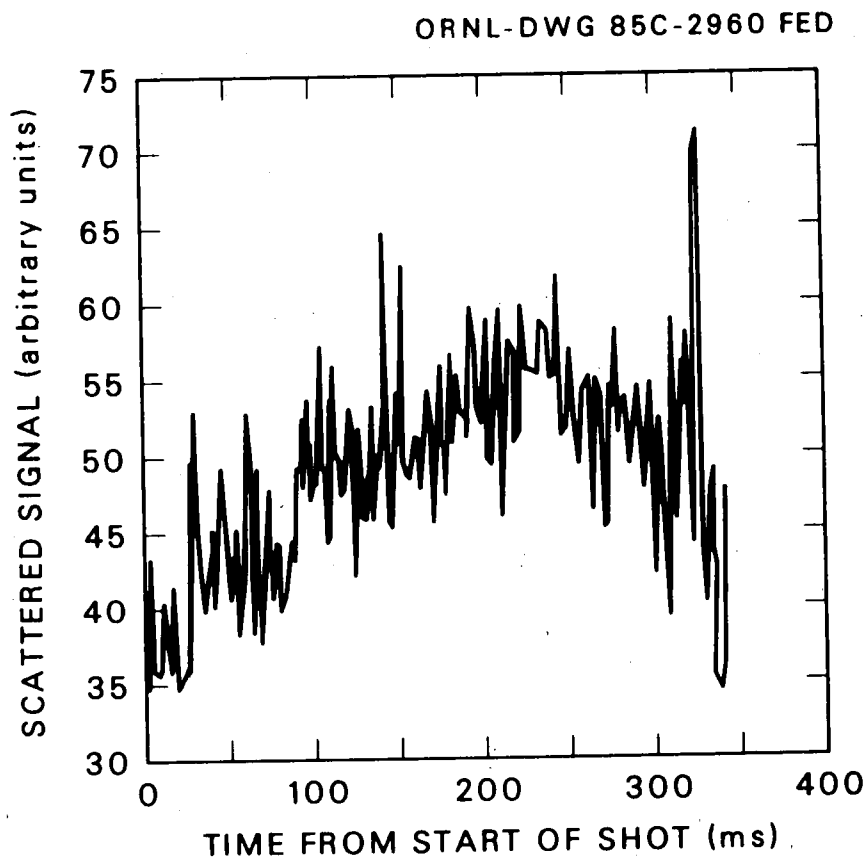


Figure 7-5. Time evolution of the scattered amplitude at a frequency of 100 kHz and with a bandwidth of 30 kHz.

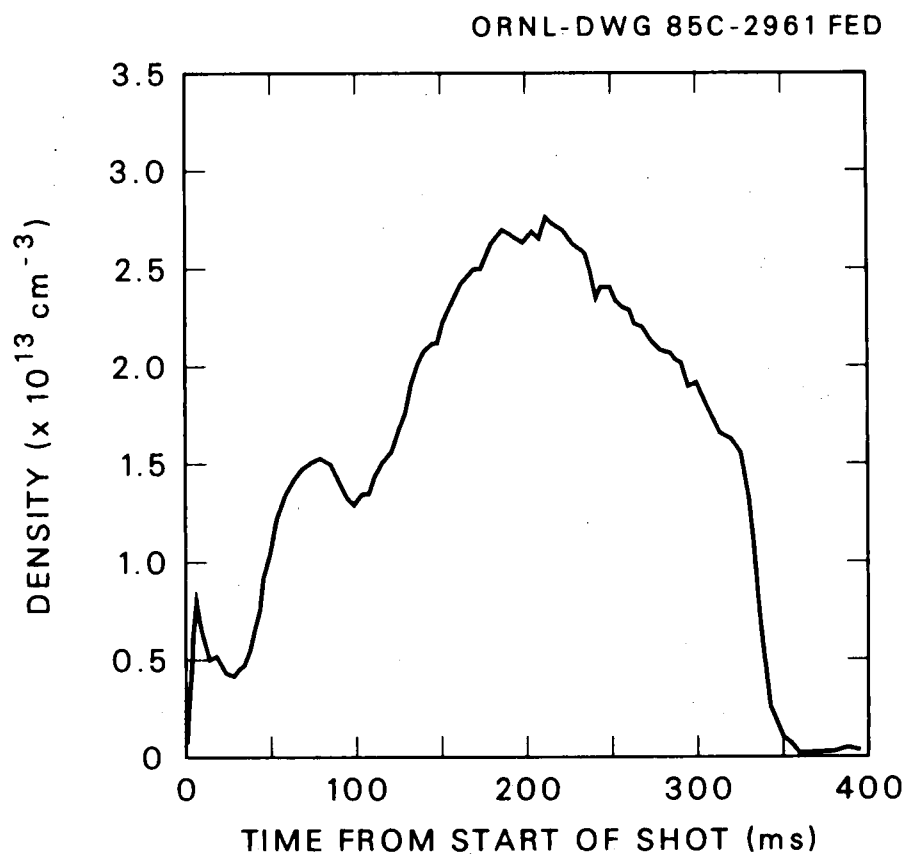


Figure 7-6. Density of ISX plasma vs time as measured by the central channel of the FIR interferometer.

injection this disruption was usually accompanied by a narrow width, high frequency spike of unknown origin. Another feature observed near the end of the sequence was a large increase in the fluctuation level below 100 kHz. This turbulence has been correlated with an X-ray diagnostic measurement and has been attributed to $m = 1/n = 1$ oscillations.⁵

A careful analysis was done on data taken during neon impurity injection experiments. Neon injection has been shown to improve particle and energy confinement in ISX.¹⁸ Initially this was attributed to a reduction in fluctuations due to the presence of the impurity. Changes in the fluctuation level were shown to be small by the FIR scattering measurement. The increase in the level observed was directly attributable to the accompanying increase in density. Concurrent measurements of the density fluctuation level by a heavy-ion beam probe diagnostic were in complete agreement. In later measurements it was observed that there was a decrease in the poloidal magnetic field fluctuations ($\tilde{B}_\theta/B_\theta$) with the injection of neon.

7-5 Conclusions

The observation of fluctuation induced scattering of FIR radiation in the unprocessed output signal of the FIR interferometer on ISX has led to a new method of monitoring fluctuation levels on a day-to-day basis. This method is almost ideal for any major fusion plasma experiment that involves the use of FIR interferometers. No modification of the existing equipment is required, nor is any special equipment other than standard off-the-shelf electronics common around such experiments. The only manpower required after initial setup is for analysis

of the acquired data. The method was found to be simple, reliable, and informative. This method is currently being applied to the largest operating research plasma device in this country at Princeton. It will no doubt become a standard technique for monitoring fluctuation phenomena.

CHAPTER 8

SUMMARY AND CONCLUSIONS

8-1 Summary

The primary purpose of this report is to detail the FIR scattering measurement carried out on the Elmo Bumpy Torus experiment. Similar experiments have recently been performed on other plasma devices. Two of the important experiments are reviewed in the appendixes. Also, measurements of density fluctuations have previously been done on EBT using conventional techniques that may be considered difficult to interpret. Two of the better documented series of measurements are reviewed in the appendixes. With that background, the foundation for the measurements is established by a series of theoretical calculations. It is demonstrated that the scattered power from a coherent density wave can be calculated using a simpler and more straightforward technique than the common method of summing the contributions from individual electrons. The calculation which is based upon the diffraction of light by modulations in the index of refraction produces a result which is in agreement with previous calculations. The experimental arrangement is described, including some historical notes about what eventually led to limitations on the system operation which resulted in a reduction in resolution, system flexibility, and reliability. Also details of the equipment used and the limitations that equipment imposed on the measurements are given along with an outline of the signal processing and data acquisition. Much of the time spent on this project was dedicated to system test and

calibration. An analysis of the overall performance of the scattering diagnostic is given. The calibration techniques are described along with the results.

Three basic types of experiments were performed. Steady state experiments with no ICH were done with both 18 GHz and 28 GHz ECH. The results were unreliable, and no conclusions could be drawn. Pulsed experiments turned out to be much more reproducible, but the lack of theoretical analysis of this operational mode (as well as the absence of measurements by other diagnostics) limits the usefulness of the results. A strong instability was detected during pulsing which was fixed in location. Although the nature of this feature cannot be established without more information, it is proposed that the instability is not of the drift type but may result from a density gradient located at a position where magnetic field lines go from being toroidally continuous to wall-terminated. Magnetic field scans indicate that the passage of the hot electron rings through this region reduce the fluctuations, thereby stabilizing the instability. Pressure scans show a monotonic increase in this signal until near the T-C transition as the pressure is increased. At a point between mid-T mode and the T-C transition, the signal leveled out and remained constant to pressures well above the T-C transition point. It is postulated that this favors theories which are based on electron ring stabilization effects but contradicted previous conclusions about fluctuation behavior and its effect on EBT transport.

Measurements were attempted with steady state ICH applied, but the results were largely negative. Pulsing the ICH led to more reliable

measurements. Evidence is presented that shows ICH driven waves were penetrating the plasma core and that mode conversion from fast waves to ion Bernstein waves was taking place. Measurements of spatial locations of the waves along with the dependence on neutral pressure are shown to support the ion Bernstein wave theory.

Because of the rather limited performance of the FIR scattering diagnostic, a 2 mm klystron was installed in place of the laser system. Means were provided to change easily from one to the other. Since the technology associated with this wavelength is better established, only a brief description of the apparatus is given. Both steady state ECH and ICH measurements are described. It is shown that fluctuations measured at the longer wavelength seem to be smoothly distributed. Also, the fluctuation amplitude is a strong function of density. ICH measurements were of poor resolution but were reliably reproducible. Distribution of the detected signals in relation to position, field, and pressure supports the conclusions drawn with the FIR system and pulsed ICH.

In a separate series of experiments on ISX, the FIR interferometer was used as a scattering diagnostic. The interferometer signal was spectrum analyzed to reveal a scattered spectrum that results from small angle scattering. Although the fluctuation length was long, the information obtained is believed to represent the overall fluctuation levels in ISX. The computer controlled data acquisition system allowed the scattering data to be taken during normal operations without additional manpower. Analysis of the data shows the expected features of a neutral beam heated tokamak shot. The system provides a constant monitoring of

the fluctuation level and is used to show that density fluctuations are not responsible for the improved confinement observed during neon impurity injection experiments.

8-2 Proposals for Future Measurements

Perhaps the most important result of the work reported here is its contribution to future scattering experiments. During the next two years the Advanced Toroidal Facility (ATF) will begin operation. Also, another small tokamak has been proposed and is entering the main design stage. Another proposal is being considered for an experiment similar to EBT called the Elmo Bumpy Square. Each of these machines should have installed a system capable of measuring fluctuations.

The ATF device will have an interferometer installed and operating before the first plasma. This also implies that a spectrum analyzer can be added and the fluctuations monitored in the same manner as on ISX. Also, a port will be available to measure scattering at a fixed location and a fixed angle. Problems may develop with this concept, however, because of polarization problems. A new laser is under development that operates at 337 micrometers and should be much stronger and more stable than previous systems. This laser can be used with the same port and may provide the possibility of a more versatile system. This system will most likely be capable of observing any k vectors within the range provided by the port access and any spatial location within the scattering plane along the incident beam.

The new tokamak will be a small compact torus with a limited diagnostic set. Again, the interferometer used may provide opportunity for observing fluctuation spectra.

Finally, there was a great deal of experience gained in operating a scattering diagnostic in the hostile environment of a microwave driven plasma. The future application to a device such as EBS may prove to be beneficial to the resolution of bumpy field equilibrium and stability questions. The first problem to address is the containment of the microwave field while allowing the desired signals to be transmitted. Damage to the internal components of the EBT scattering system suggests that a thin screen capable of attenuating the microwave field by 30 to 50% may keep the plasma from forming or penetrating into the vicinity of the mirror components. A screen similar to that used on EBT could then be used at the vacuum-air interface. A major problem with the EBT system is the limitation on wavevector measurements. With a computer control system a mirror could be driven by two units or ideally three units. The first could move the mirror linearly up and down, while the second could rotate it so that any position and k vector could be observed within the range of the geometry. A third drive could be used to move the input beam lens so that the focal point is always in the scattering volume. This allows better resolution and longer wavelengths. For an EBT-like plasma an ideal wavelength for scattering seems to be in the range of 0.5 to 2 mm. Access to the input lens also allows changing it for different wavelengths. If a drive system is too difficult, then a special curved reflector which focuses a parallel antenna beam to a

point can be used to provide continuous k vector measurements. Wavevector resolution would suffer slightly, but this can be minimized by proper optics design. The final problem to be addressed is the mounting of the waveguide and optics. It is suggested that a totally enclosed system be constructed with a heavy metal frame. The optics must then be mounted on an isolated structure within. Dielectric waveguides are not suitable in the form used with EBT. However, the waveguides may be more reliable if most of the right angle bends are eliminated. Ideally only two bends are necessary. One directs the beam down to the torus center (or, maybe better, up from below) and the other directs it into the vacuum vessel. A similar arrangement can be used for the antenna beam. A diagram of the improved system is shown in Figure 8-1. Laser development is proceeding at such a rapid pace that when this system is built, an increase in sensitivity of two orders of magnitude could easily be accomplished if most of these steps are taken to improve the system.

8-3 Conclusions

The technology involved in measuring fluctuations and density waves with the scattering of FIR laser radiation is rapidly approaching maturity. This dissertation represents the first thorough series of measurements attempted at a wavelength of 447 microns. The laser system which was ideally suited for interferometry lacks sufficient stability for steady state measurements of a low density plasma. The results of the measurements were not of high enough quality to impact significantly the research effort into EBT-like devices. However, some additional

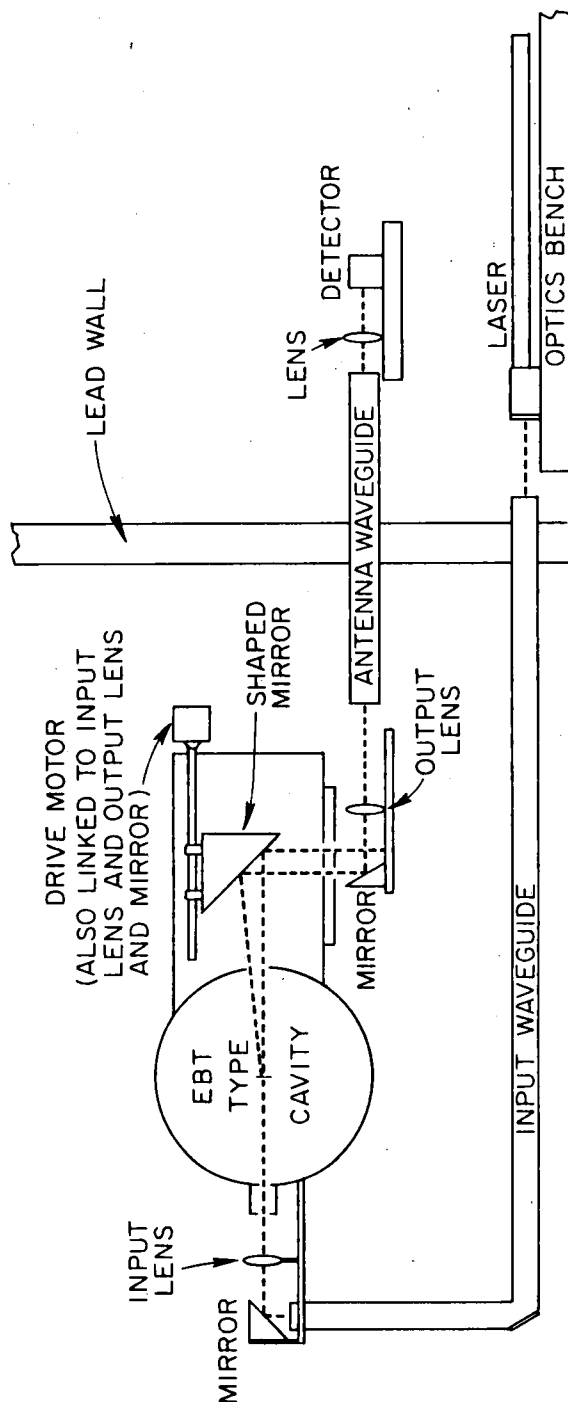


Figure 8-1. Improved scattering system design for an EBT-like device.

information was obtained about the plasma conditions. The full implications of these measurements may never be known due shutdown of the EBT program. Measurements made with a 2 mm system were found to be more sensitive and reliable as well as easier to install and operate. With the proper optics and geometrical design, this type of system may prove to be much more valuable for measurements in low density plasmas. The use of an in-place interferometer has been shown to be a simple and valuable method for monitoring plasma fluctuations in a turbulent plasma. Based on the experience gained on EBT, another scattering diagnostic has been designed and its principle features outlined. These features can easily be adapted to almost any other plasma device and should eliminate most of the problems encountered on the EBT device.

LIST OF REFERENCES

LIST OF REFERENCES

1. W. H. Casson, D. P. Hutchinson, C. H. Ma, P. A. Staats, J. B. Wilgen, Rev. Scien. Inst., 56, 917 (1985).
2. R. A. Dandl, F. W. Baity, M. C. Becker, K. H. Carpender, J. A. Cobble, et al., Oak Ridge National Laboratory Report No. ORNL-TM-6457 (1978).
3. R. A. Dandl, H. O. Eason, A. C. England, G. E. Guest, C. L. Hedrick, J. C. Sprott, Oak Ridge National Laboratory Report No. ORNL-TM-3694 (1971).
4. R. A. Dandl, H. O. Eason, H. Ikegami, Oak Ridge National Laboratory Report No. ORNL-TM-6703 (1979).
5. J. L. Dunlap, B. A. Carreras, V. K. Paré, J. A. Holmes, S. C. Bates, J. D. Bell, H. R. Hicks, V. E. Lynch, and A. P. Navarro, Phys. Rev. Lett., 48, 538 (1982).
6. O. C. Eldridge, J. B. Wilgen, A. C. England, Oak Ridge National Laboratory Report No. ORNL-TM-8738 (1983).
7. D. E. Evans, E. J. Doyle, D. Frigione, M. von Hellermann, A. Murdoch, Plasma Physics, 25, 617 (1983).
8. D. E. Evans, M. von Hellermann, E. Holzhauser, Plasma Physics, 24, 819 (1982).
9. A. M. Gondhalekar, Ph.D. Thesis, Victoria University of Manchester (1968).
10. M. Gottlieb, C. L. M. Ireland, J. M. Ley, Electro-Optics and Acousto-optic Scanning and Deflection, Dekker, New York (1983).
11. D. L. Hillis, Oak Ridge National Laboratory Report No. ORNL TM-8179 (1982).
12. E. Holzhauser, J. H. Massig, Plasma Physics, 20, 867 (1978).
13. W. Horton and P. W. Terry, Bull. Am. Phys. Soc., 27, 947 (1982).
14. G. Ichtchenko, W. P. O'Connor, M. Moresco, E. Zilli, J. Infrared Millimeter Waves, 5, 1543 (1984).
15. J. D. Jackson, Classical Electrodynamics, 2nd ed, Wiley, New York (1975).

16. E. F. Jaeger, L. A. Berry, C. L. Hedrick, and R. K. Richards, Nuclear Fusion, 25, 71 (1985).
17. A. Komori, Oak Ridge National Laboratory Report No. ORNL-TM-7906 (1984).
18. E. A. Lazarus, J. D. Bell, C. E. Bush, A. Carnevali, B. A. Carreras, W. H. Casson, J. L. Dunlap, P. H. Edmonds, A. C. England, W. L. Gardner, G. A. Hallock, J. T. Hogan, H. C. Howe, D. P. Hutchinson, R. R. Kindsfather, R. C. Isler, R. A. Langley, C. H. Ma, J. Mathew, P. K. Mioduszewski, M. Murakami, G. H. Neilson, V. K. Paré, D. J. Sigmar, C. E. Thomas, R. M. Weiland, J. B. Wilgen, W. R. Wing, A. J. Wootton, K. E. Yokayama, Nuclear Fusion, (to be published).
19. P. Lee, R. J. Taylor, W. A. Peebles, H. Park, C. X. Yu, Y. Xu, N. C. Luhmann, Jr., S. X. Jin, Phys Rev Lett, 49, 205 (1982).
20. T. C. Marshall, A. W. DeSilva, and G. C. Goldenbaum, Methods of Experimental Physics, Vol 9, Plasma Physics, Part A, Academic Press, New York (1970).
21. McDonnell Douglas Astronautics Company, Interim Contract Report, Subcontract #53Y-44000C, St. Louis, Mo., (1980).
22. K. Miyamoto, Plasma Physics for Nuclear Fusion, MIT, Cambridge (1976).
23. M. Moresco and E. Zilli, J. Phys. D: Appl. Phys., 17, 307 (1984).
24. T. L. Owens, F. W. Baity, and W. A. Davis, Nuclear Fusion, 24, 1561 (1984).
25. H. K. Park, Ph.D. Thesis, UCLA, (1984).
26. H. Park, N. C. Luhmann, Jr., W. A. Peebles, R. Kirkwood, Phys Rev Lett, 52, 1609 (1984).
27. W. A. Peebles, N. C. Luhmann, Jr., A. Mase, H. Park, Rev. Sci. Inst, 52, 360 (1981).
28. J. R. Reitz, F. J. Milford, and R. W. Christy, Foundations of Electromagnetic Theory, 3rd ed., Addison-Wesley, Reading (1979).
29. T. Saito, Y. Hamada, T. Yamashita, M. Ikeda, M. Nakamura, S. Tanaka, Nuclear Fusion, 21, 1005 (1981).
30. T. Saito, Y. Hamada, T. Yamashita, M. Ikeda, S. Tanaka, J. Appl. Phys., 52, 5305 (1981).

31. J. Sapriel, Acousto-Optics, Wiley, Chichester (1979).
32. A. Semet, A. Mase, W. A. Peebles, N. C. Luhmann, Jr., S. Zweben, Phys Rev Lett, 45, 445 (1980).
33. J. Sheffield, Plasma Scattering of Electro-magnetic Radiation, Academic Press, New York (1975).
34. A. E. Siegman, An Introduction to Lasers and Masers, McGraw-Hill, New York (1971).
35. A. G. Sitenko, Fluctuations & NonLinear Wave Interactions in Plasmas, Pergamon, New York (1982).
36. R. E. Slusher, C. M. Surko, Phys Fluids, 23, 472 (1980).
37. D. A. Spong, Oak Ridge National Laboratory Report No. ORNL-TM-9420 (1985).
38. D. W. Swain, J. A. Cobble, D. L. Hillis, R. K. Richards, and T. Uckan, (to be published).
39. S. Tamor, Final Contract Report, Science Applications, Inc., Appat-29, La Jolla, Ca. (1983).
40. N. A. Uckan, Oak Ridge National Laboratory Report No. ORNL-TM-8430 (1982).
41. A. Yariv, Introduction to Optical Electronics, Holt, Rinehart, and Winston (1971).

APPENDIXES

APPENDIX A

THE EBT AND ISX EXPERIMENTS

A-1 The EBT Experiment

A-1-1 Pre-EBT Experiments. The Elmo Bumpy Torus (EBT) experiment was a direct result of many years of experimental work with simple mirrors and electron cyclotron heating (ECH). Immediately preceding EBT were the ELMO experiment and the Canted-Mirror experiment. The ELMO device was a simple mirror with an adjustable mirror ratio and multiple frequency microwave heating capabilities. A neutral gas, usually hydrogen, was fed into the vacuum vessel at a pressure of 10^{-5} torr, and microwave power was applied to break down the gas into a plasma and to heat the electrons to high temperatures. The dominant mechanism for microwave absorption is electron resonant heating--the resonant acceleration of free electrons due to the matching of the electric field frequency with the electron gyro-frequency in the magnetic field. The location of the absorption for a single frequency microwave field is the magnetic surface corresponding to where the magnetic field strength matches the gyro-frequency to the microwave frequency. This is called fundamental resonance heating since it is possible also to heat at higher harmonics. For the simple mirror configuration the absorption took place in axis-symmetric bands or rings which have become known as hot electron annuli or hot electron rings. The electrons in these rings were well confined in the mirror geometry and continued absorbing power until the energy losses from collisions and scattering into loss cones

was at the same rate as it was being absorbed. Because of their confinement, electrons reached energies in the rings in excess of 5 MeV.

Energy transfer from the rings went mostly into two plasma components which coexisted with the rings. Inside of the rings and contained within the field lines which cleared the cavity walls was a moderately confined, stable plasma component which consisted of warm electrons and cold ions. Losses from this region were dominated by end losses through the loss cone in velocity space. On the outside edge of this plasma component was a region characterized by poor confinement and cold temperatures. The field lines in this region of the plasma terminated at the cavity wall and were responsible for carrying much of the input power to the walls. This component of the plasma is referred to as the surface plasma.

Two major effects were noted during operation of the ELMO device. The first one was an increase in the instability level due to the non-uniform distribution in the electron energy, especially in the region of the rings, when the ECH power was increased. The effects of those instabilities was to increase the scattering rate into the loss cone and to cause rapid changes in the pitch angles which effectively enlarged the loss cone. The second effect was due to having a large number of electrons processing in the gyro-orbits in identical directions and in a limited region. The magnetic fields generated by these small current loops were in the direction opposite to the applied field. This had the effect of causing a minimum B field region (min-B) and was actually capable of local field reversal. Referring to Figure A-1, it can be

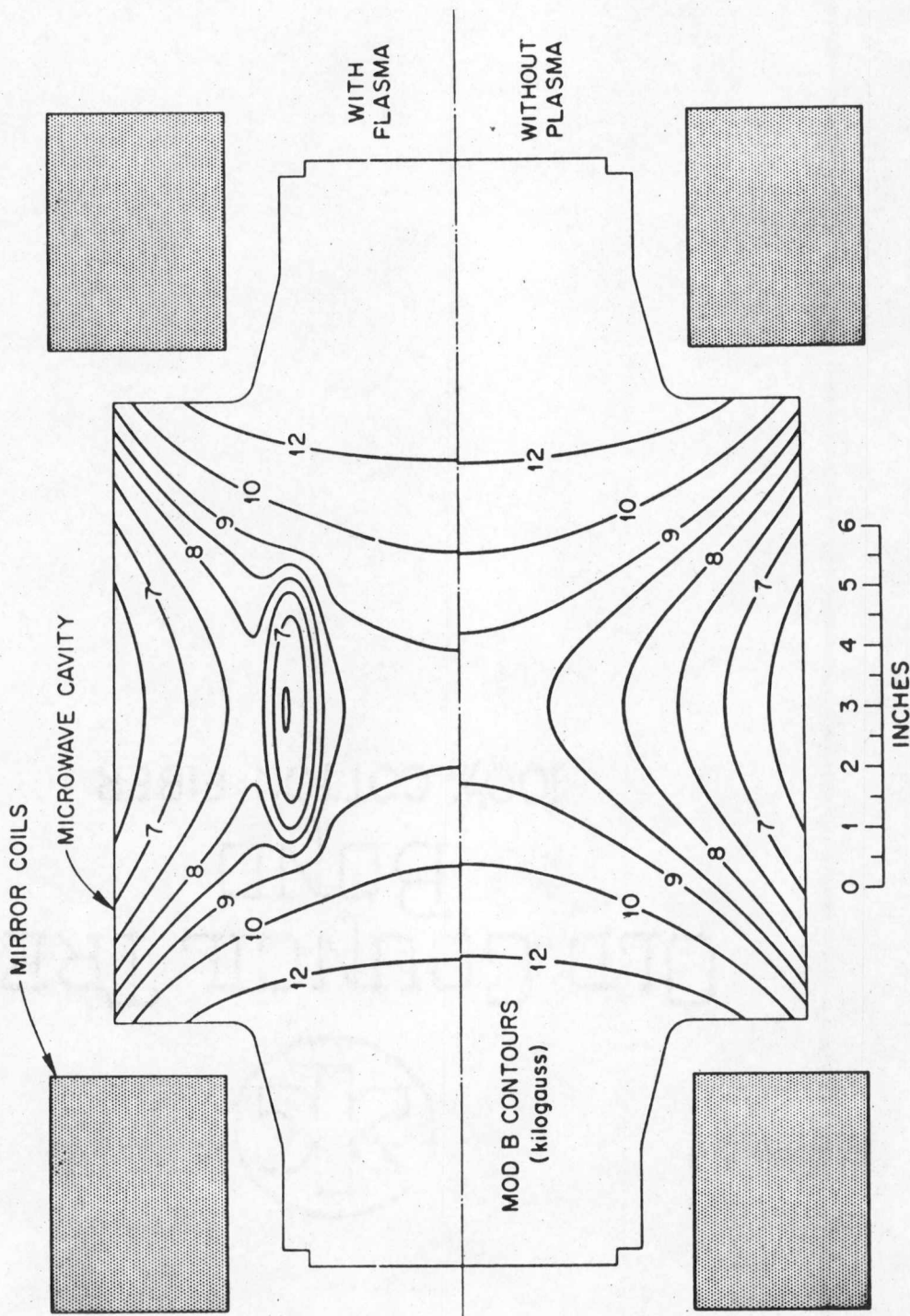


Figure A-1. Mod-B contours for ELMO device with plasma profile derived from diamagnetic data.

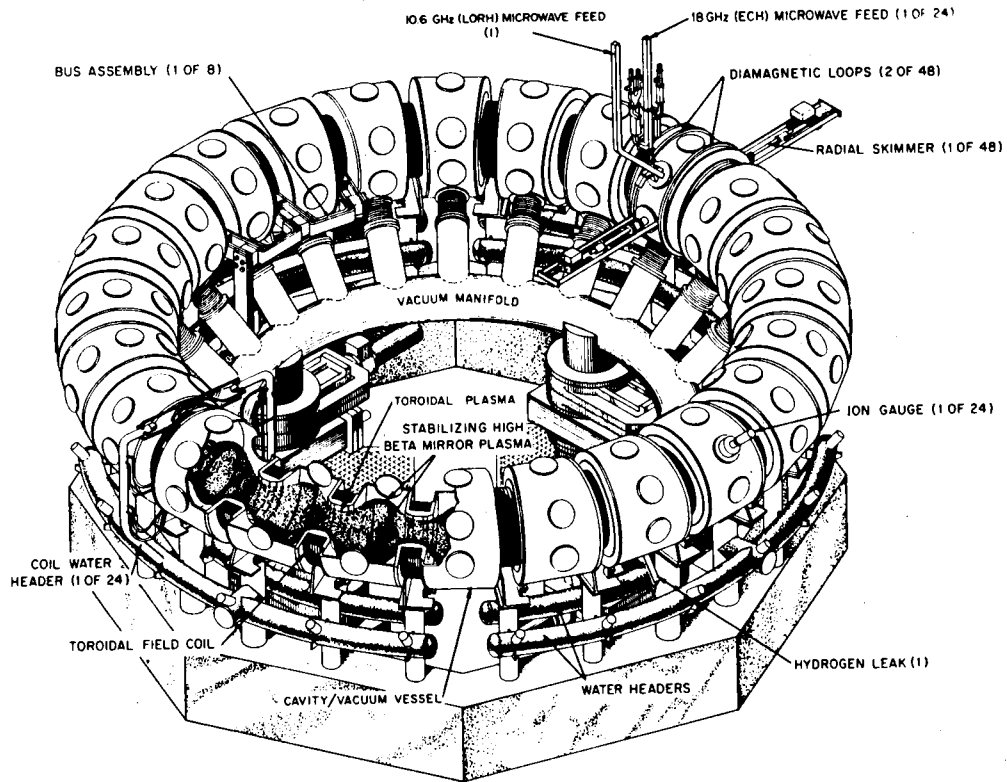
seen in the lower section that without a plasma the Mod-B contours are typical for a mirror configuration. The upper portion shows measurements with the plasma whose presence has caused a considerable change in the field contours. The field lines, passing perpendicular to the contour lines, are compressed in the region of the magnet throats, which results in the mirror confinement. The field lines are also compressed in the region of the rings, which lessens the number of particles passing through this region. Without the rings, this region has negative field line curvature (the lines are "cupped" toward the plasma confinement region) which can result in MHD instabilities (i.e., the interchange instability) and enhanced particle losses. The rings, however, not only reduce the number of particles in this region, but also reduce the size of the regions with negative curvature. The net result is increased MHD stability in the mirror configuration.

One of the most straightforward approaches to improving particle and energy confinement is to recycle the particles lost to the endplugs. If an identical cavity is constructed sharing one mirror coil, then energy and particles passing through that coil will enter the adjacent cavity. The ultimate goal is a closed-field configuration (one in which all the field lines remain within the vacuum vessel without intersecting the walls). If each cavity is angled slightly with respect to the previous cavity, then with sufficient cavities and mirror coils the field can be bent around into a circle or torus. To test the effects of the angles between mirror coils a smaller version of the ELMO experiment was built in which the angle of the coils could be adjusted with respect to

one another. This was the Canted-Mirror experiment which demonstrated that for small angles (about 15 degrees) the properties of the rings and internal plasma were only slightly modified. Increasing the cant-angle increased the size of the region of negative curvature and therefore decreased MHD stability. The presence of the min-B configuration improved MHD stability, therefore making a complete torus an attractive configuration.

A-1-2 EBT Experimental Design. As a result of the ELMO and Canted-Mirror experiments the EBT device was built with 24 mirror coils with a 2:1 mirror ratio and a 15 degree cant angle between neighboring mirrors (Figure A-2). The toroidal configuration had a major radius of 1.5 meters and a minor radius at the cavity midplane of 25 cm. The field strength at the coil center was 10 kG maximum, which was later upgraded to 14.5 kG. The total plasma volume was just over 500 liters. Each cavity enclosure was circular with eight access ports, one every 45 degrees on the vertical midplane. The direction towards the major axis is referred to as the inside direction. The inside lower port was attached to a vacuum manifold, and the inside upper port was usually used for microwave feed connections. The original configuration with 10 kG fields was driven by 60 kW of 18 GHz and 30 kW of 10.6 GHz microwaves. Later the maximum field was increased to 14.5 kG and a 200 kW gyrotron was added that operated at 28 GHz and the 10.6 GHz system was abandoned. The upgrade was a transition from EBT-I to EBT-S (S for scale up), but whenever the system was operated at 10 kG with 18 GHz feed the device was referred to as EBT-I. When operated with the

ORNL DWG 73-5045R3



Elmo Bumpy Torus.

Figure A-2. Principal components of the ELMO Bumpy Torus design.

gyrotron, then EBT was referenced as EBT-S. An important note in reference to the quoted magnetic field strength is that due to few measurements taken in the magnet throat regions, the field strength quoted is the field strength at the center of the cavity. Since the mirror ratio is 2:1, this value is half the strength in the throats. Therefore, normal EBT-I fields are reported as 5 kG, and EBT-S are 7.25 kG at the cavity center. This is a convenient value because the field vs current curve is a straight line for the values of interest and has a slope of one with a zero intercept. There is therefore a one gauss increase in field strength for every ampere of current added to the coils. Operating at 7250 amps results in a field of 7250 gauss at the cavity center. Throughout this work the field strength is referenced by the coil currents.

During normal operation of EBT-I/S (5000 A with 18 GHz/7250 A with 28 GHz) the fundamental resonance zone is a surface which forms a cup-like shape over each of the mirror throat openings (Figure A-3) while the second harmonic is just inside the cavity walls at the cavity mid-plane. It is the second harmonic in this case which creates the hot electron rings. Operating the device at a field strength which uses the fundamental resonance zone to form the hot electron rings is referred to as fundamental resonance mode or FR mode. The density created within the plasma is a strong function of the magnetic field strength, the microwave power, and the neutral background pressure.

If the power and fields are held constant and the pressure is varied, then the dependence of the density on pressure shows three

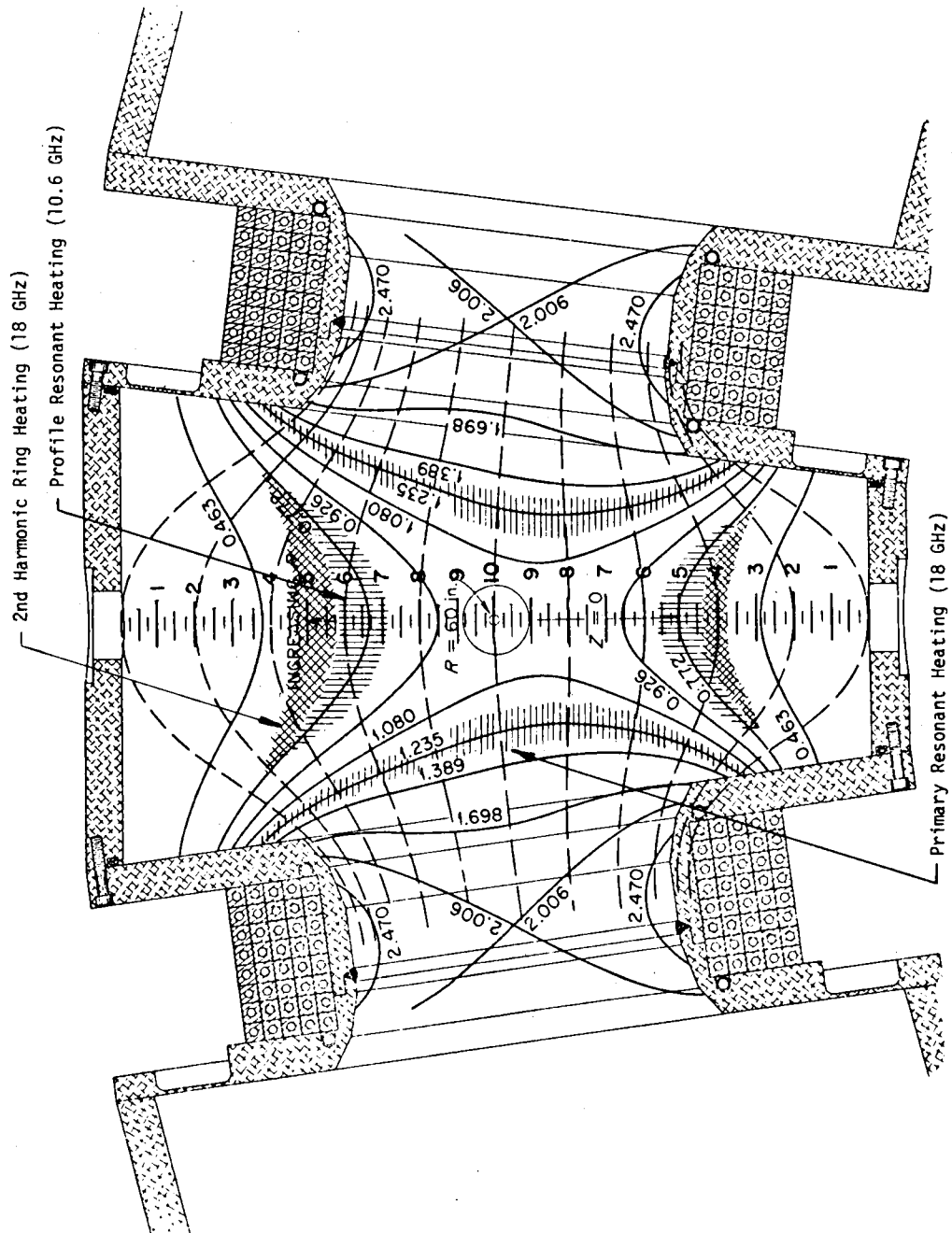


Figure A-3. EBT-I mod-B contours (—), flux lines (---), and heating geometry (\\\\)(XXXX). The 10.6 GHz system was discontinued.

distinct regions of operation. At higher pressures the plasma is cold and relatively poorly confined. As the background pressure is lowered, the density decreases monotonically to a minimum where there is a sudden increase along with an increase in stability and confinement. The higher pressure zone is called the C mode in reference to the cold plasma temperature. The zone where the density is improved is called the T mode indicating an improvement in the toroidal confinement. The boundary point is called the T-C transition point. If the background pressure is lowered further, the density reaches a maximum and then decreases slowly to a point where the density suddenly drops much more rapidly. This region is where the globular behavior of the plasma is lost, and the plasma behaves as 24 individual mirror confined plasmas with little toroidal interaction. This region of operation is called the M mode for its mirror-like confinement. The transition point is called the T-M transition. The locations of these transition points depend on other machine conditions, but they do exist for almost all normal values of field strength and microwave power as well as microwave frequencies.

Primary interest has always been in the T mode of operation because of the improved confinement times and higher temperatures at higher densities. A summary of EBT plasma parameters is given in Table A-1. These measurements are provided to indicate the range of the parameters and their typical values in the different modes of operation. Measurements with different diagnostics often result in different values and are seldom in close agreement. The given values can be used for inter-comparison but should not be accepted as the absolute correct value. In

Table A-1. Typical plasma parameters found during normal EBT operation.

		Operation Mode**	
		EBT-I	EBT-S
$n_e l^*$	M-mode	$1 \times 10^{13} \text{ cm}^{-2}$	$2 \times 10^{13} \text{ cm}^{-2}$
	T-mode	$1.2-1.8 \times 10^{13} \text{ cm}^{-2}$	$2.5-3.0 \times 10^{13} \text{ cm}^{-2}$
	C-mode	$1.5-2.8 \times 10^{13} \text{ cm}^{-2}$	$3.0-4.5 \times 10^{13} \text{ cm}^{-2}$
T_e	M-mode	450 eV	700 eV
	T-mode	250-500 eV	250-600 eV
	C-mode	150-200 eV	150-200 eV
T_i		10-40 eV	10-40 eV
Beta	ring	5-25%	10-30%
	core	.1-.3%	.1-.5%

* $n_e l$ is a chord integrated density measurement. Because the plasma size changes with the operating conditions the absolute density is not well known. It is found to be typically from 1×10^{11} to $1 \times 10^{12} \text{ cm}^{-3}$. Values given for M mode are those found near the T-M transition.

**EBT-I refers here to operation at 5000 Amps and 40 kW of 18 GHz ECH. EBT-S refers to 7250 Amps and 100 kW of 28 GHz ECH.

addition it has been proposed that the electron distribution function is divided into multiple populations which act with only limited interaction.³⁸ The colder component, which includes most of the electrons, consist of a uniform spatial distribution with temperatures less than 100 eV. There is also a warm tail component resulting from the ECH with a temperature of 200-800 eV. A third component is the hot ring component already discussed.

A-1-3 Auxillary Heating with ICH. In a manner similar to ECH, the ions in a plasma can be accelerated by the application of radio waves at a frequency which corresponds to the ion cyclotron resonance frequency. Experiments have shown that the absorption of radio waves is not solely dependent upon this resonance, but heating can be accomplished by off-resonance heating. This is still a result of the ion-gyro behavior in a magnetic field and is now commonly referred to as ion cyclotron heating (ICH). Methods for generating rf fields in a plasma are varied and depend on the nature of the plasma device. On EBT an antenna was mounted inside the vacuum vessel and was excited by an rf signal from a high power radio transmitter. Coupling of the rf power to the plasma is difficult, since changes in the plasma characteristics change the impedance loading on the antenna. A system of continuously adjustable capacitors was installed on the antenna to enable the operator to optimize the antenna loading for a particular plasma.

Several different types of antennas have been built with varying degrees of success. Two most important designs were intended for different types of wave propagation within the plasma. The fast wave

antenna, Figure A-4, was a quarter-turn antenna which was mounted in a cavity at its midplane parallel to the cavity wall. To protect the antenna structure a Faraday shield was mounted over it. Typical operation of the fast wave system was in the frequency range from 20 MHz to 48 MHz. During operation an increase of the ion-tail temperatures was measured, as well as an increased electron ring temperature and an increase in the ring stored energy. Another type of antenna was intended to create rf waves in the slow-wave regime. This type of antenna entered the vacuum vessel through a midplane port in one cavity and exited through a similar port in an adjacent cavity. Even though the antenna structure passed through the plasma in the mirror throats, no shielding was provided. Although similar effects in ion temperatures were measured during slow-wave operation, the overall performance of this type of ICH was disappointing in comparison with similar experiments on the Nagoya Bumpy Torus. Typical operation of the slow-wave system was at a frequency near 10 MHz.

A-2 The ISX Experiment

A-2-1 General Background. The Impurity Study Experiment (ISX) is a tokamak device designed for the investigation of the plasma physics involved in the development of plasma technology for fusion energy production. It was preceded by the Oak Ridge Tokamak (ORMAK) which achieved several milestones in fusion research. Both are designed on the tokamak principle developed in Russia and adopted in this country in the late 1960s. In this type of device a large toroidal field is

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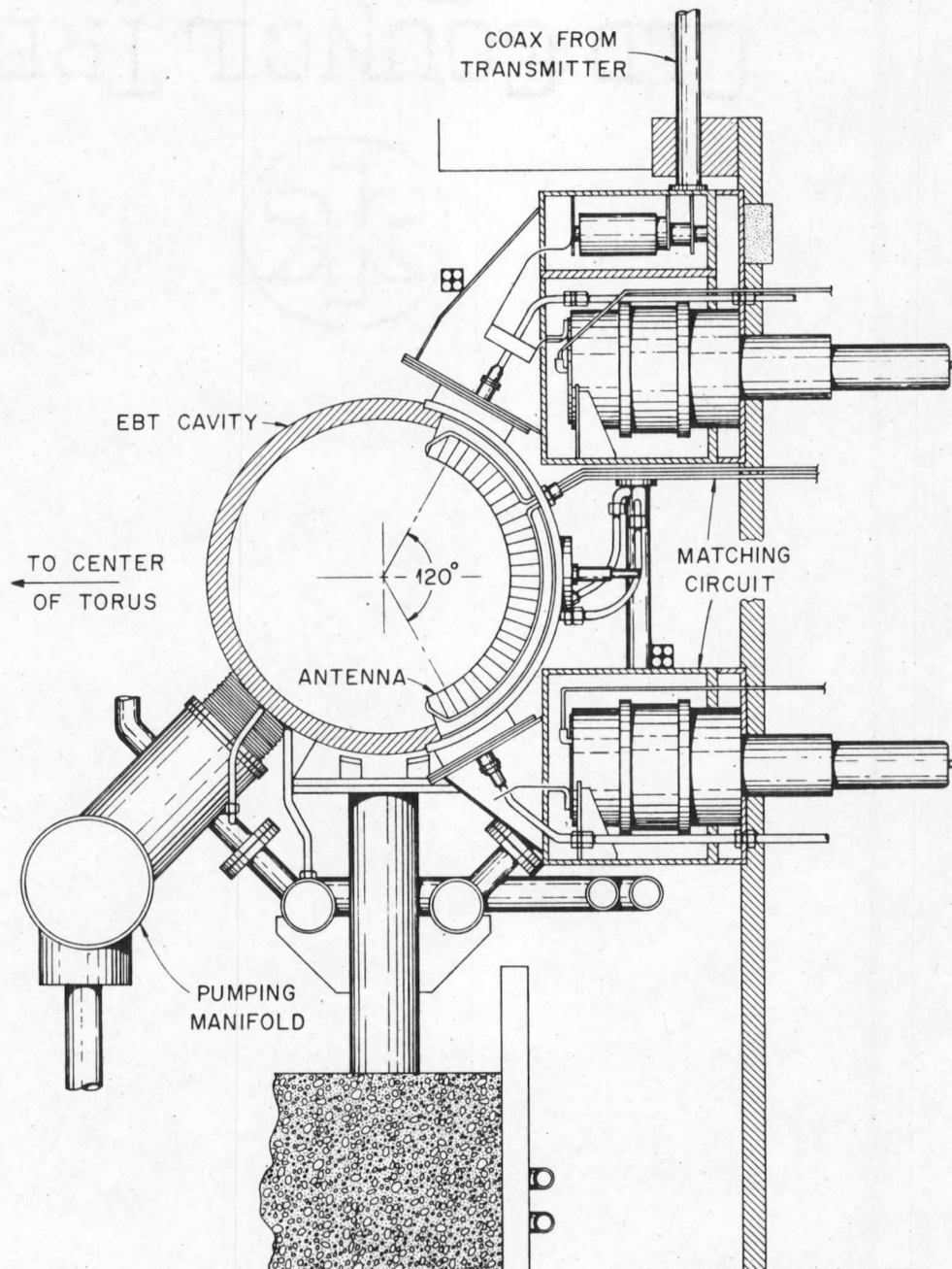


Figure A-4. Installation configuration of the fast-wave ICH antenna showing placement of the Faraday shield within the cavity. Extent of the antenna inside the shield is shown as 120 degree angle.

created by a series of coils in a basic solenoid configuration bent into a circular torus. Since a plasma confined in this simple field is unstable, as demonstrated by years of research work on stellarators, a rotational transform must be added by imposing a smaller poloidal field upon the toroidal field. The unique approach of the tokamak concept is in the manner that this transform is established. By generating a toroidal current through the plasma, the stabilizing fields are created by the plasma itself. The ohmic energy losses also contribute to the heating of the plasma. In fact, ohmic heating is so efficient that it is typically the primary heating method in a tokamak. The only method on a major device successfully employed thus far in producing the necessary currents is by magnetic induction. A large transformer core is placed around the plasma and driven with a strong shaped current pulse. This induces a large current in the conducting plasma for a period of time dependent upon how long the derivative of the primary current can be maintained. This naturally limits the amount of induced current as well as the period of time the plasma current can be sustained. Another important plasma property is the decrease in the resistivity with plasma temperature. As the plasma temperature increases due to the plasma current, the rate of energy transfer decreases, thereby limiting the temperature achievable with any specific tokamak device. The conclusion is that supplemental heating, the subject of a major portion of research today, is required to achieve fusion conditions.

A-2-2 ISX Design and Goals. Assuming an appropriate heating mechanism is found, there are still several obstacles to achieving

temperatures high enough for fusion. One of the primary means of energy loss from a hot plasma is radiation. The radiation emitted from a hot plasma spans the entire electromagnetic spectrum from radio waves to gamma rays. Included in this emission is bremsstrahlung and atomic line emission. The amount of energy transported from the plasma by these kinds of effects depends on the nuclear charge (Z) of the ions present within the plasma. Most plasma discharges of interest are comprised of the isotopic forms of hydrogen. Radiation losses from a low Z plasma such as pure hydrogen can be expected to be manageable. However, impurities are constantly being fed into the plasma from the walls and other sources. This increases the effective Z of the plasma and therefore greatly increases radiative losses.

The original objective of the ISX experiment was to study the effects of these impurities and their transport through the plasma. In 1978 the device was upgraded to ISX-B in order to study additional plasma properties, although the study of impurities was also still actively pursued. The final upgrade in 1982 added a total of 4 MW of neutral beam supplemental heating. The plasma current was increased to a maximum of 300 kA. The major radius was 0.93 m with a minor radius of 0.26 m. The maximum toroidal field was 1.5 T, and the maximum measured volume average beta, (the ratio of plasma pressure to magnetic pressure) was 2.5%. The energy confinement time was measured to be as high as about 40 ms. Electron and ion temperatures achieved were near 1.5 keV, and densities of over $1 \times 10^{14} \text{ cm}^{-3}$ were achieved.

APPENDIX B

OTHER SCATTERING EXPERIMENTS

B-1 Overview

The scattering of radiation by a plasma has been used as a plasma diagnostic for many years. Thomson scattering is used for electron temperature and density measurements in hot plasmas where probes would be destroyed. The use of ruby lasers enables focusing that gives high spatial resolution. Thomson scattering at longer wavelengths is capable of yielding ion temperatures and densities as well as changes in the distributions. The measurement of ion parameters, however, has not progressed nearly as far as electron measurements have, due to the necessity of developing new technologies and improving old ones to meet the demanding needs of those methods. The initial effort in using Thomson scattering as an ion diagnostic was directed at the measurement of ion density fluctuations. Microwaves were first utilized because the technology was considerably more well developed. Recently focus has been directed at wavelengths in the far infrared, using CO₂ lasers and newly developed FIR lasers operating in the 100-1200 micrometer wavelength region. Probably the most significant advancement that has enabled the use of radiation in this wavelength region is the development of new low-noise detectors which do not require special handling or cooling for operation. The availability of these detectors allowed both ORNL and UCLA to initiate development of FIR laser scattering diagnostics. A brief review of the work done at UCLA is given here because of

its important historical significance to FIR scattering system development and to provide additional information which may be helpful in understanding the results of the work completed at ORNL.

Another important scattering measurement was completed at ORNL on the ISX-B tokamak before measurements were made with the FIR system. These measurements were made with a 2 mm microwave scattering system, portions of which were later used on the EBT system. Results of this experiment are directly comparable with the FIR scattering results. A brief description of this experiment and the results are given in Section B-3.

B-2 FIR Laser Scattering at UCLA

There have been many published accounts of the experimental work done in FIR scattering at UCLA. The following description is drawn from Reference 25 which concentrates on the ICH and microturbulence measurements made on the UCLA Microtor Tokamak.

The FIR laser system used is similar to the system used at ORNL but is operated with a different lasing gas in the FIR cavity. The 9P32 line of the CO_2 laser is used to pump the carbon-13 isotopic compound of methyl fluoride (CH_3F) which lases at a wavelength of 1.22 mm. The UCLA scattering system itself (Figure B-1) is quite different from the ORNL version. The laser beam is first divided into a local oscillator (L.O.) beam and a probing beam. The probing beam enters the tokamak vacuum chamber through a large rectangular window. The transmitted portion of the probe beam, as well as the scattered signal, exits through another large rectangular window opposite the input window. A large array of

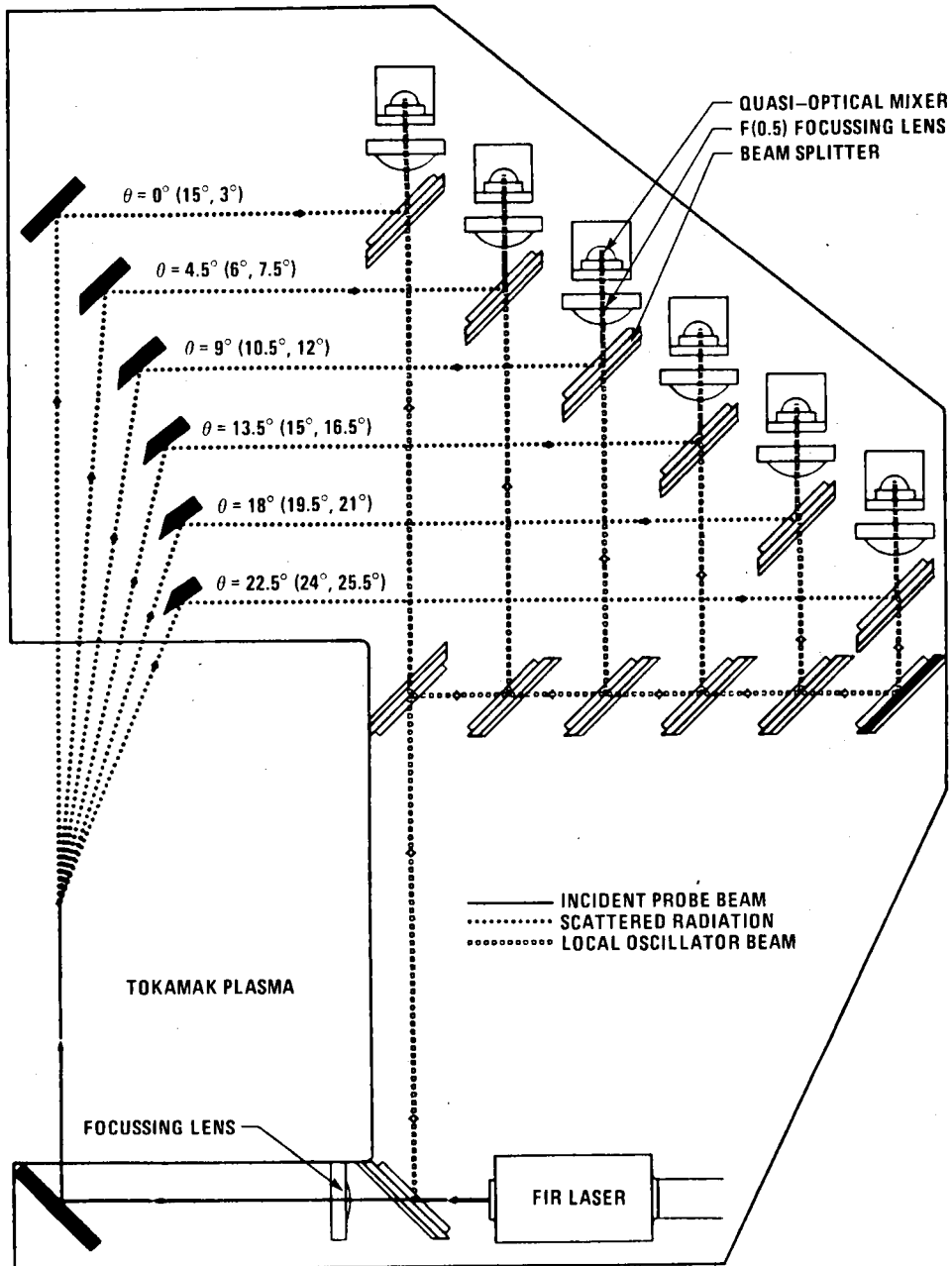


Figure B-1. Optical system for multichannel FIR scattering studies on the Microtor tokamak at UCLA. (Reproduced from Reference 25 with permission of the author.)

optical components and mixers are mounted on a vertical optics bench where the L.O. beam is divided and focused into the various mixers. The transmitted beam is reflected via an aluminum mirror to the mixer for that beam. Several mirrors are used to collect scattered signals from different scattering angles and form them into beams representing approximately equal solid angles of observation. The system is versatile inasmuch as the number of scattered beams, the scattering angles, and the position of the scattering volumes can be readily changed by rearranging the optics on the vertical optics bench. Also, the entire laser and optics systems are mounted on a mobile platform which can be moved away from the tokamak for calibration and adjustment. It can also be positioned at different locations along the major radius of the tokamak to allow shot-to-shot variation in the spatial location within the plasma. This versatile design was made possible because of the convenient access to the machine and most of all because there was no requirement for microwave cut-off screens at the vacuum-air interface or for lead shielding.

The calibration measurements on this scattering system were made with a TPX Bragg cell which was later borrowed for use in calibrating the EBT system. A detailed description of the cell is given in Chapter 4. The measurements made at UCLA, however, were much more rigorous and complete because of the capability of moving the entire scattering assembly away from the tokamak. Scattering from the cell could thus be made without the spatial limitations of the tokamak vacuum vessel or without the time limitations inevitable if the calibration work prevents

other experimental operations. The velocity of sound in the TPX was first found with a tone burst generator and the time-of-flight method. The velocity was estimated to be 2.2×10^5 cm/s, which is in reasonable agreement with other experimental measurements in similar TPX cells. The wavenumber resolution found with the TPX cell was $\pm 1.1 \text{ cm}^{-1}$, which agreed with a value calculated from the measured beam waist, a_0 , of 1.9 cm using the equation $k = 2/a_0$. Estimates were also made of the scattering length/spatial resolution which was in agreement with the calculated value found with the equation $L_v = 2a_0/\sin \theta_s$.

Calibration of the system sensitivity was accomplished by first comparing the relative sensitivity of the various scattering channels. Absolute calibration was made with an unmagnetized filament discharge plasma whose parameters could be measured with Langmuir probe techniques. The minimum detectable signal was determined solely by the system temperature and the receiver bandwidth. The system sensitivity was determined by the system temperature alone. The estimated system temperature was $20,000 \pm 5,000$ K DSB which resulted in a minimum detectable power of $5.5 \pm 1.4 \times 10^{-19}$ W/Hz. With a 3 MHz IF bandwidth the minimum detectable power was $1.66 \pm .4 \times 10^{-12}$ W. Predictions of the scattered power from ion acoustic waves in the filament discharge resulted from the measurements made with a Langmuir probe with corrections made for the probe sensitivity (peak fluctuation amplitude). The signal-to-noise ratio was found to be 1.6 ± 0.6 from these calculations, which compared well with the directly measured SNR of 1.3. The first measurements made with the FIR system on Microtor were of low frequency

microturbulence. The UCLA group recognized the turbulence phenomenon to be a randomly varying process which made direct correlations of the measurements taken on a shot-to-shot basis useless. Therefore, the multi-angle scattering system was designed to provide maximum information from a single shot. Scattering angles of 4.5° , 9° , 13.5° , and 18° were used during these measurements. The frequency spectra obtained for the different wavenumbers exhibit discrete peaks that are dependent on the scattering angle and spatial location. The phase velocities of these microturbulence waves were therefore calculated and compared. The phase velocities at the plasma edges were found to be three times smaller than at the plasma center. These values did not, however, vary significantly with changes of the density by a factor of two or of the magnetic field by a factor of two-thirds. Comparison of the measured frequencies and wavenumbers with calculations from electron diamagnetic drift wave theory at a plasma rotation velocity of 1.5×10^5 cm/s were favorable.

In another series of experiments ICH antennas were used to launch both electrostatic and electromagnetic waves into the plasma discharge. Calculations of the dispersion curves were made for fast magnetosonic waves and ion-Bernstein waves. Emphasis was placed on identifying the ion-Bernstein waves and using the dispersion curves to estimate the ion temperature. Attempts made with the electrostatic antennas were a failure, but measurements made with the electromagnetic antennas were successful. This indicated that the waves detected were solely dependent on mode conversion of the fast wave, an hypothesis further supported by

the independent detection of the presence of the fast wave and the agreement found between measured values of k at set ω/ω_{ci} and the calculated dispersion curves (Figure B-2). Since the calculations are a sensitive function of ion temperature, the temperature used to best fit the calculated curves to the measured points is taken as the measured ion temperature. The error in these measurements can be quite large, with increasing uncertainty toward higher temperatures. The claim was made that the use of a full electromagnetic wave calculation produced better fits to the data than the electrostatic dispersion relation; however, for the data presented the difference in the two calculations was quite small in comparison with the resultant error bars from the measurements. The comparison of the estimated ion temperature and the results from a charge exchange analyzer were acceptable. Direct scattering measurements of the fast wave were limited because the scattering occurs at very small angles, which makes determination of k difficult. However, the scattered amplitude was observed for its radial and temporal dependence.

B-3 Microwave Scattering on ISX

There have been several microwave scattering experiments performed on plasma devices. One of the most recent was conducted on ISX-B with a 2 mm microwave system.⁶ The klystrons used were the same as those used with the EBT 2 mm experiment described in Chapter 3. The system was set up as a heterodyne detection system with two separate sources locked at a 20 MHz frequency difference. The microwave signals were transmitted from the primary source to the plasma, from the plasma to the detector,

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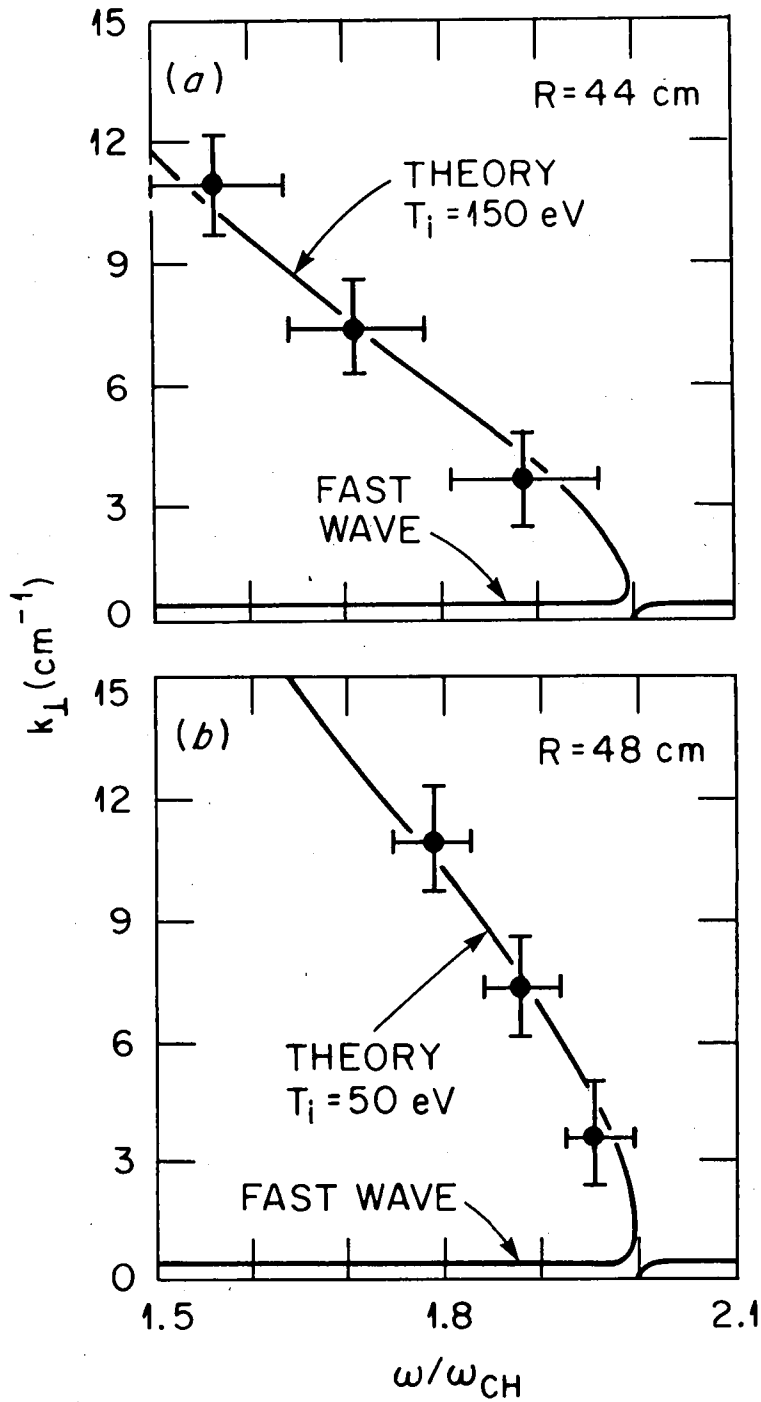


Figure B-2. Comparison of numerically computed dispersion curve to the measurements made by FIR scattering on Microtor at UCLA. (Reproduced from Reference 25 with permission of the author.)

and from the secondary source (L.O.) to the detector via rectangular cross-section metal waveguide. The incident wave to the plasma was launched along the central vertical cord of the plasma by a microwave horn mounted within the vacuum vessel. The receiver horn was mounted on an outside wall flange with the antenna beam directed above the plasma cross-section center approximately 16 cm as shown in Figure B-3. The resulting scattering angle of 70° could be changed to 110° for the same scattering location by mounting the transmitter horn on the wall opposite from where originally mounted, thereby reversing the direction of propagation. The system can look at fluctuation lengths of 1.3 mm or 1.9 mm.

The electronics setup is shown in Figure B-4. The sweep time of the spectrum analyzer was 20 ms, thus allowing several spectra to be recorded during each shot. The analyzer was free-running so that the starting time of the spectra varied from shot to shot. The digitizer was triggered 50 ms before the shot and recorded data for about 400 ms total. Two channels were digitized during each shot. One recorded the frequency analyzed signal amplitude, while the other recorded a sawtooth signal which was proportional to the frequency being analyzed.

The microwave input beam was reflected from the vacuum vessel walls, and part of it was picked up by the receiver--resulting in a large peak that corresponded to the frequency difference of the two klystrons. This corresponds to the zero frequency of the scattered spectra as shown in Figure B-5. In the presence of a plasma the scattered signal appeared as wings to each side of this central peak

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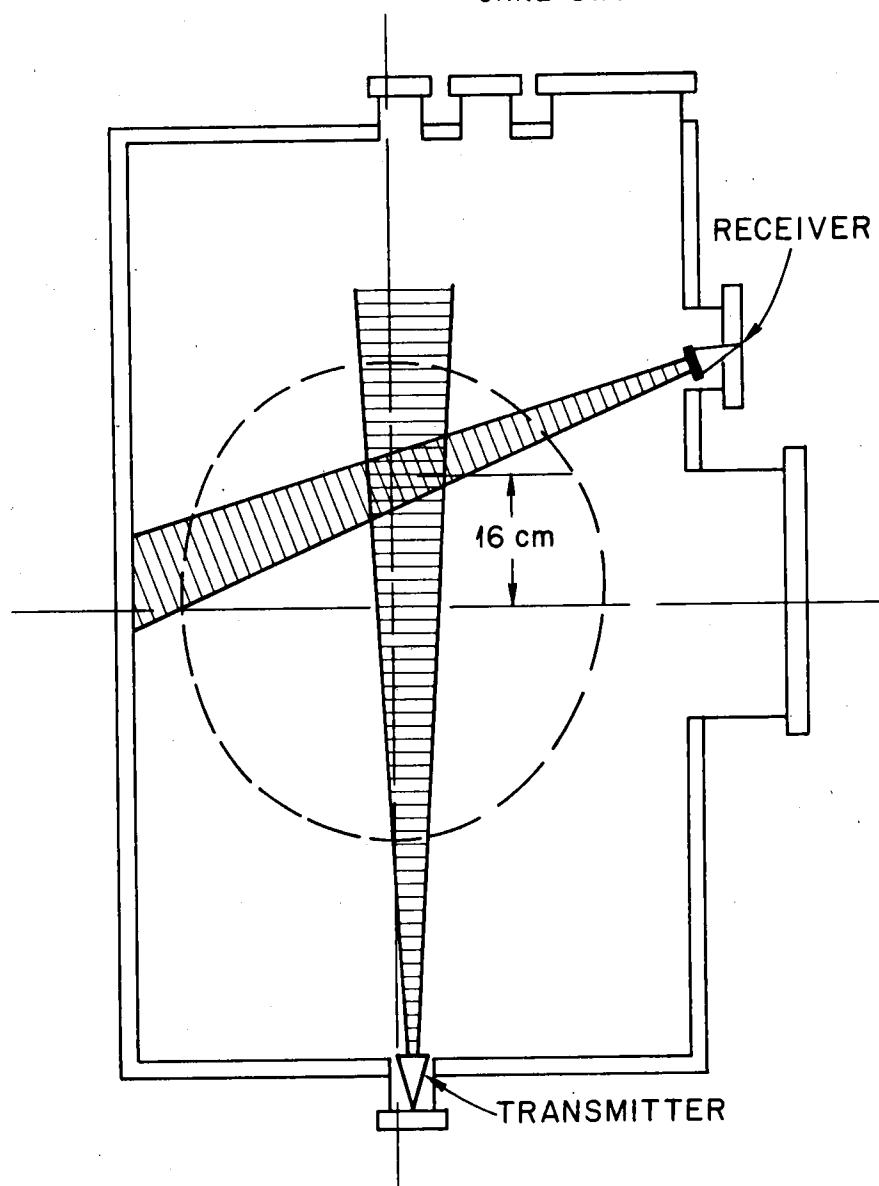


Figure B-3. Scattering configuration for 70° scattering of 2 mm radiation on ISX.

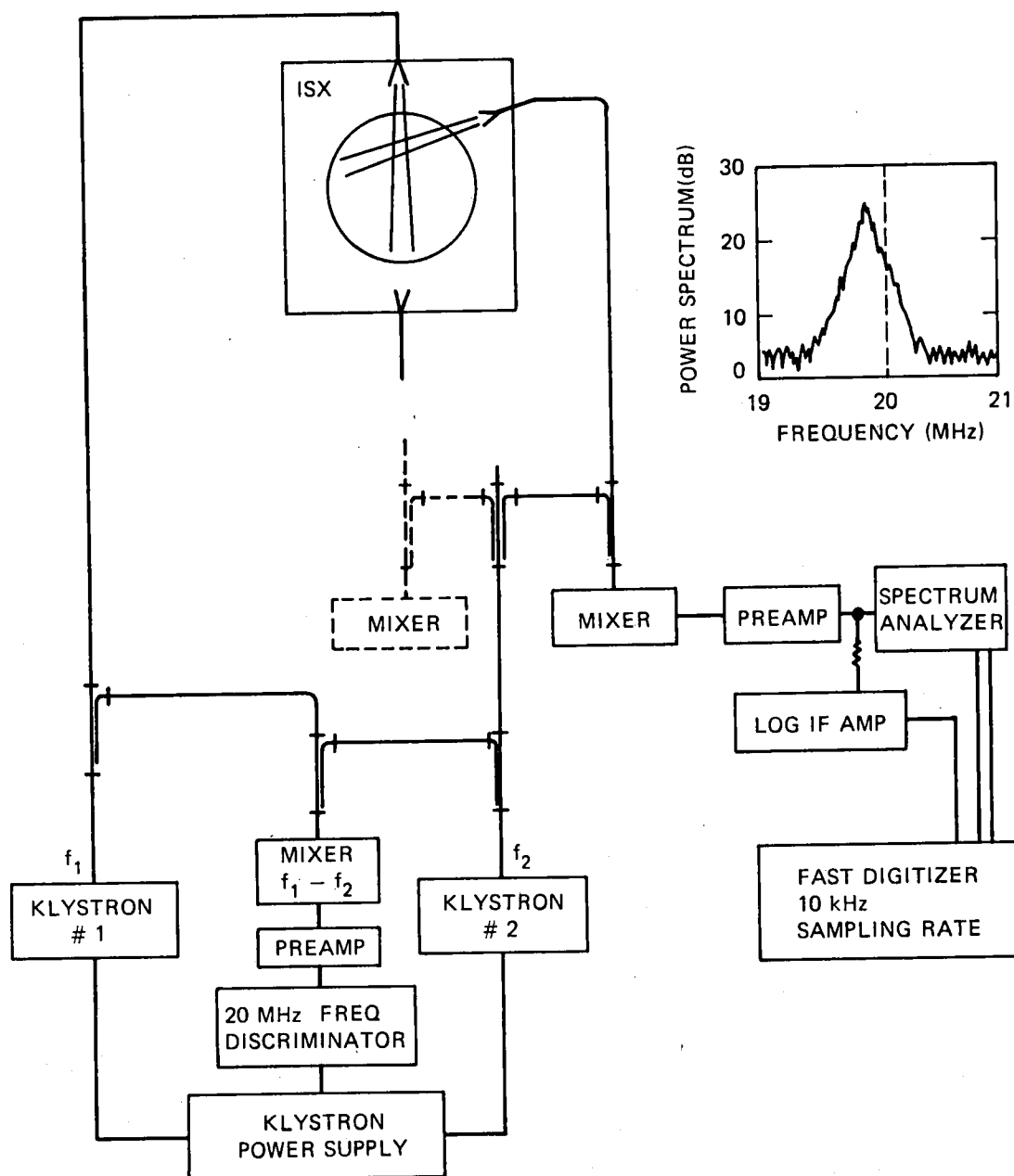


Figure B-4. Schematic diagram of the scattering system and supporting electronics on ISX.

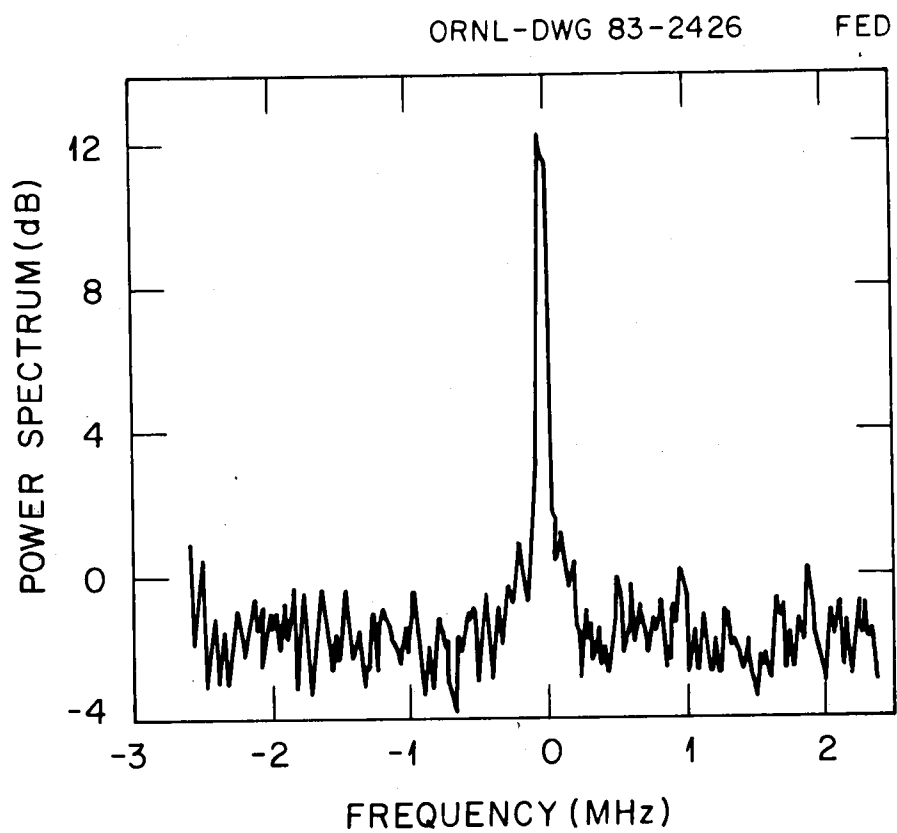


Figure B-5. Recorded spectrum as $t = -40$ ms before plasma shot showing principal beat frequency peak.

(Figure B-6). Integration of the scattered spectrum gives an accurate indication of the changes in fluctuation levels if the incident power is not significantly attenuated. There is considerable error in the absolute amplitude since the zero frequency peak is included. A plot of the numerically integrated data vs time from the start of the shot is given in Figure B-7. The strong signal at the end of the first 80 ms is the ohmic heating stage of the discharge. At the onset of neutral beam heating after 80 ms, the signal drops abruptly but increases gradually during the central portion of the shot. Again at 200 ms the signal levels drop, corresponding to the start of a second neutral beam injection. The shape of the frequency spectrum is near Lorentzian as predicted by recent work done by Horton and Terry¹³ for high levels of turbulence produced by drift wave fluctuations. The symmetry of the spectra indicates there is no Doppler shift observed, which therefore implies the poloidal rotation of the plasma is less than 200 m/s.

Because only two k vectors were observed, the amplitude of the fluctuations could not be inferred. There was no indication of coherent waves; in fact, the observed coherence times were remarkably short. One of the most difficult questions about this diagnostic concerns the effects of refraction and beam depletion. The effects of refraction are known to be severe at 2 mm, so there may be an uncertainty involved in the comparison measurement such as in Figure B-7. Beam depletion results from the scattering or refraction of the beam into a region which would enhance or reduce the signal received by the receiving horn.

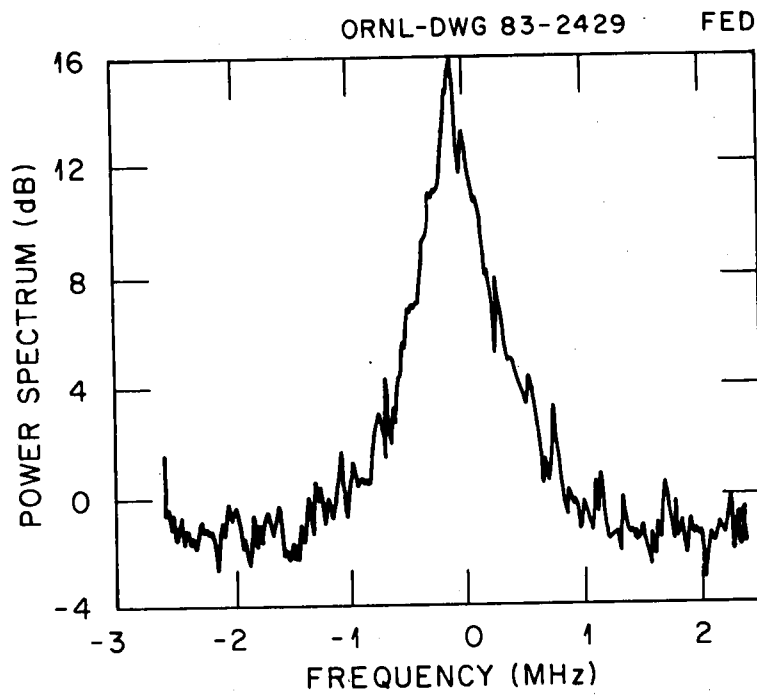


Figure B-6. Recorded spectrum at $t = 220$ ms after start of shot sequence. Plasma is being heated by 2 MW of neutral beam heating.

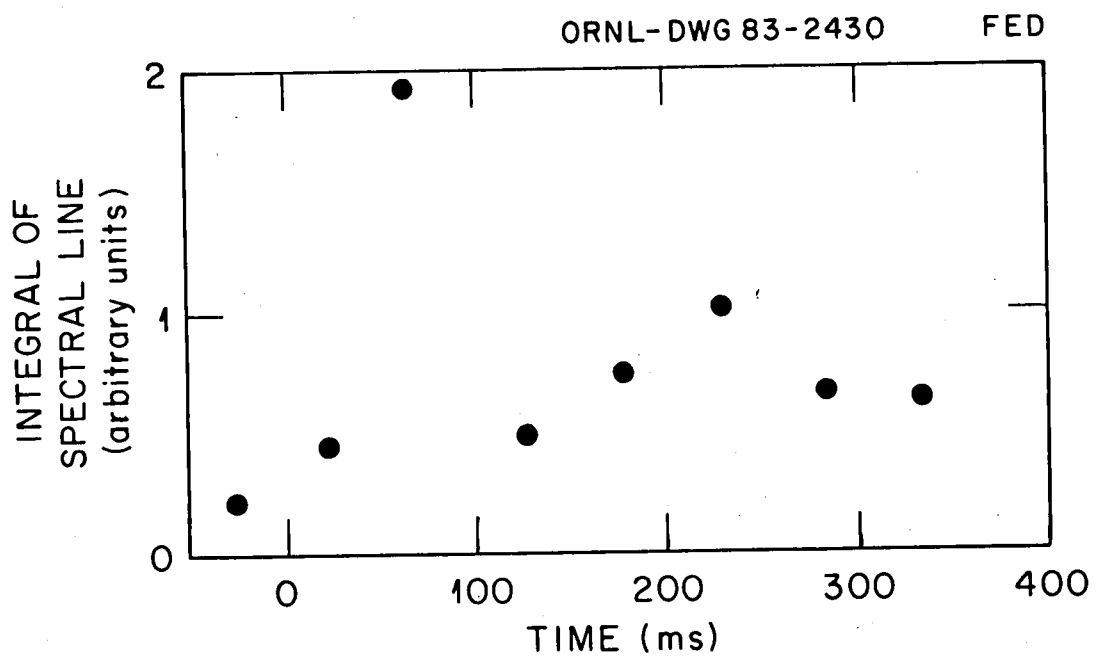


Figure B-7. Integral over the measured frequency range vs time during the plasma shot.

Comparison with FIR scattering may shed more light on this subject and is further investigated in Chapter 7.

APPENDIX C

PHOTODIODE AND LANGMUIR PROBE MEASUREMENTS

C-1 Photodiode Measurements

During the period of time when only the EBT-I option was available, many measurements were made using simple diagnostics such as probes and radiation detectors. A photodiode was used without filters for observing the strong emission from the hydrogen alpha line. Results of those measurements as well as measurements with probes are summarized by Komori in Reference 17. Also included is a detailed analysis of the effects fluctuations may play in confinement in EBT. Although more recently some measurements were made as preliminary work to the FIR scattering experiment, the results are not as detailed as those described by Komori. This appendix summarizes these measurements and conclusions for comparison with scattering results in Chapters 5 and 6.

The photodiode was installed with a collimation system to look across the central horizontal diameter of one cavity. A separate arrangement (Figure C-1) allowed a collimated beam to be scanned across the plasma by rotating a mirror mounted at the top of the cavity. The diode current is proportional to the volume integral of the neutral density, electron density, and the ionization coefficient:

$$I \propto \int n_o n_e \langle \sigma v \rangle \Omega dv, \quad (C-1)$$

which for a well collimated beam of small diameter can be approximated by a line integral:

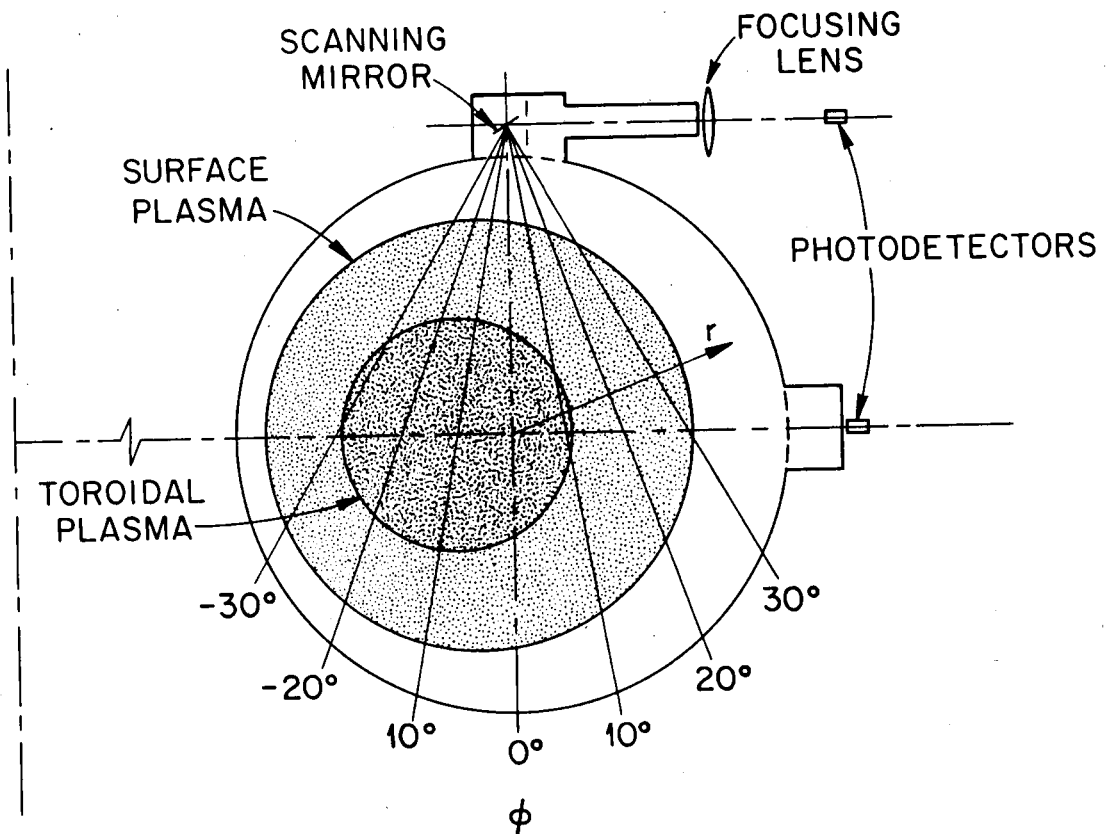


Figure C-1. Geometry for observing optical plasma emission with photodiodes.

$$I \propto \int n_o n_e \langle \sigma v \rangle dl . \quad (C-2)$$

The ionization coefficient or excitation rate coefficient is a function of the electron temperature. However, above a temperature of 50 eV the rate becomes almost constant. If we further assume the neutral pressure to be constant (a valid assumption at low electron densities), then the line integral is simplified:

$$I \propto \int n_o dl \propto P n_e l , \quad (C-3)$$

where P is the neutral pressure and where $n_e l$ is not a point product but is the electron line density, which is measured directly by interferometry. Since the function of temperature is weak for a hot plasma and fluctuations of the neutral pressure can be expected to be small then the diode current will fluctuate in direct proportion to the density fluctuations. Abel inversion is used to convert the chord averaged measurements into radial profiles.

A measurement of the Abel inverted profile of the H-alpha signal normalized to one is shown in Figure C-2 for three different pressures which correspond to C, T, and M modes. These plots are comparable only in slope since they were individually normalized. Outstanding features are the strong gradients near the ring locations (shaded areas) in T and C modes, weaker gradients through the central region, and the uniform gradient near the T-C transition (b) region. In C mode (a) the distribution is similar, but the density is known to be much higher and

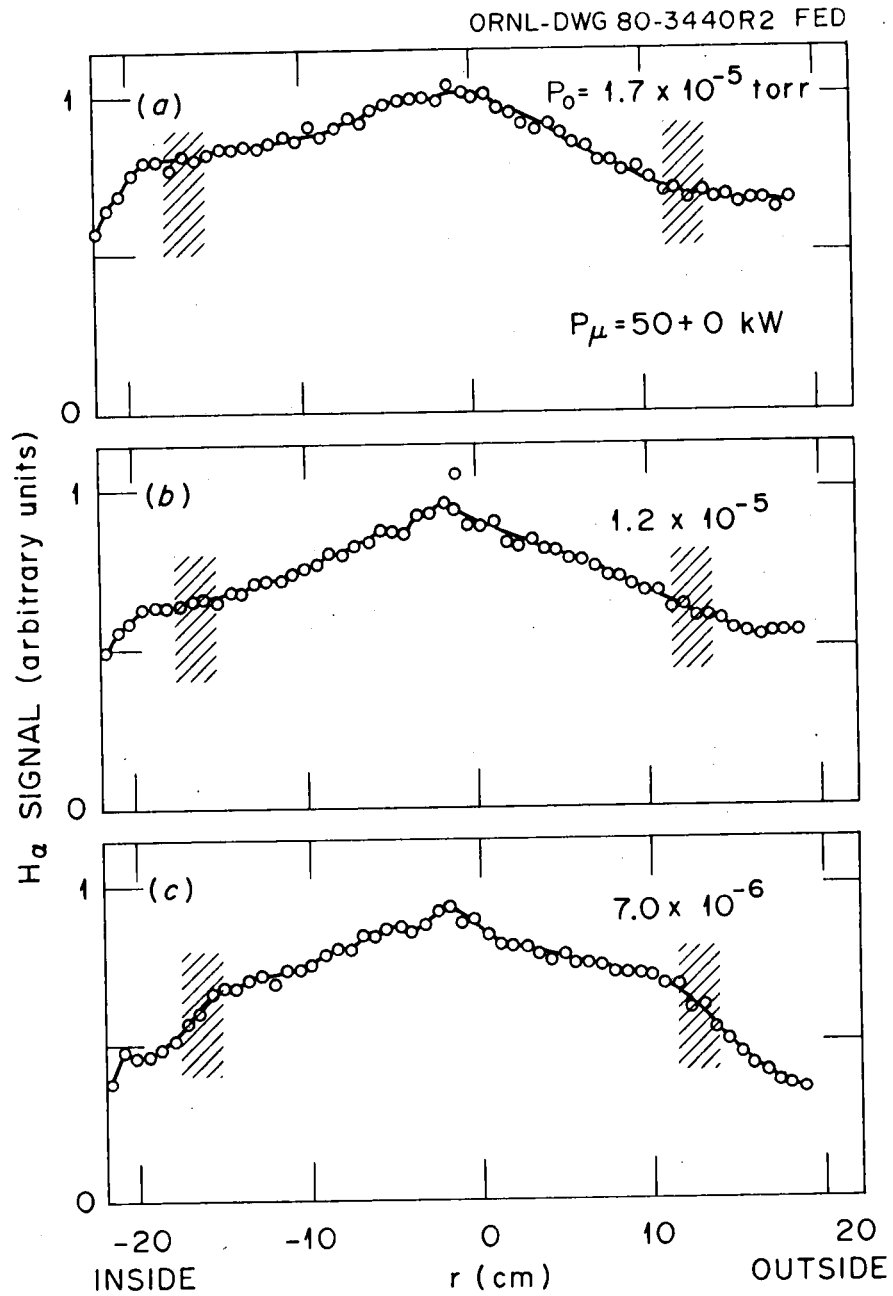


Figure C-2. Integral line density, n_l , as a function of position for different neutral pressures, P_0 . (a) is in C-mode, (b) is in T-mode near the T-C transition, and (c) is in M-mode.

therefore the gradients somewhat stronger. Measurements show that large fluctuations are present at and related to spatial locations having large density gradients as expected from drift instability theory. Figure C-3 shows the spectrum analyzed H-alpha signals for pressures in the C, T, and M modes. The M mode shows strong coherent fluctuations, but this region is of little interest. In C mode the fluctuations are all restricted to low frequencies (<100 kHz) and show only small signs of any extended coherence times.

The spatial scans of the plasma by the rotating mirror (not inverted) show some important features of these low frequency fluctuations. In Figure C-4 the H-alpha signal at 2 kHz is displayed vs the mirror angle. Position of the hot electron rings on the midplane are again shown as a shaded region. In C mode the fluctuations are strong and at higher pressures show regions of enhanced fluctuations. In T mode the overall level is decreased both because of a drop in density and because there are fewer fluctuations. In the central region the fluctuations are reduced even more. If corrected for the chord average density, then the percent fluctuation in the region of the ring and to the outside of the ring is far larger than in the central region. In the T mode the central region is quiet with a much smaller level of fluctuation percentage. The central region displays significant fluctuation levels only in the C mode near the C-T transition. Since the major portion of the observed fluctuations are in the region of the surface plasma, measurements with Langmuir probes may provide additional information.

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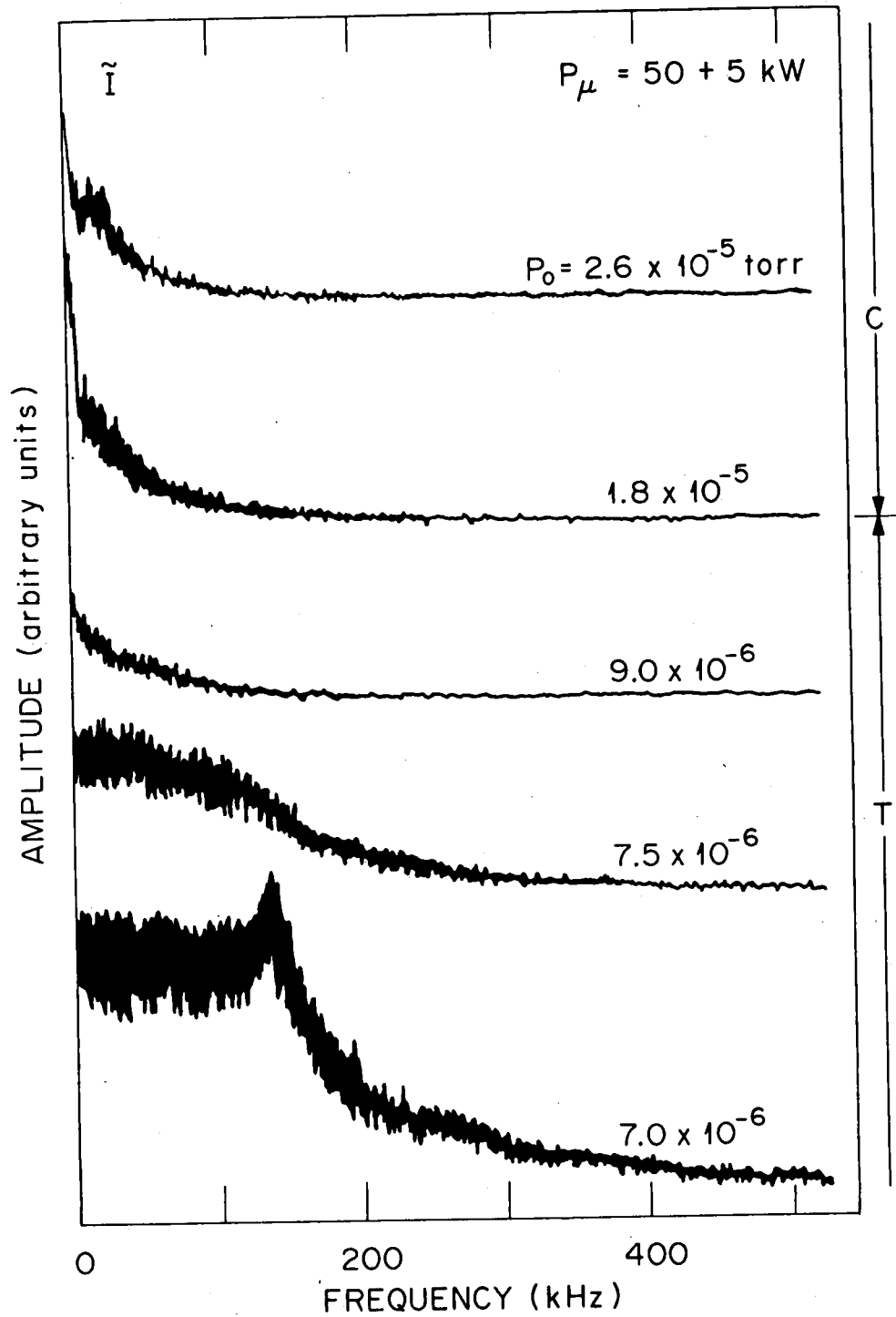


Figure C-3. Frequency spectra of photo-emission for various neutral pressures.

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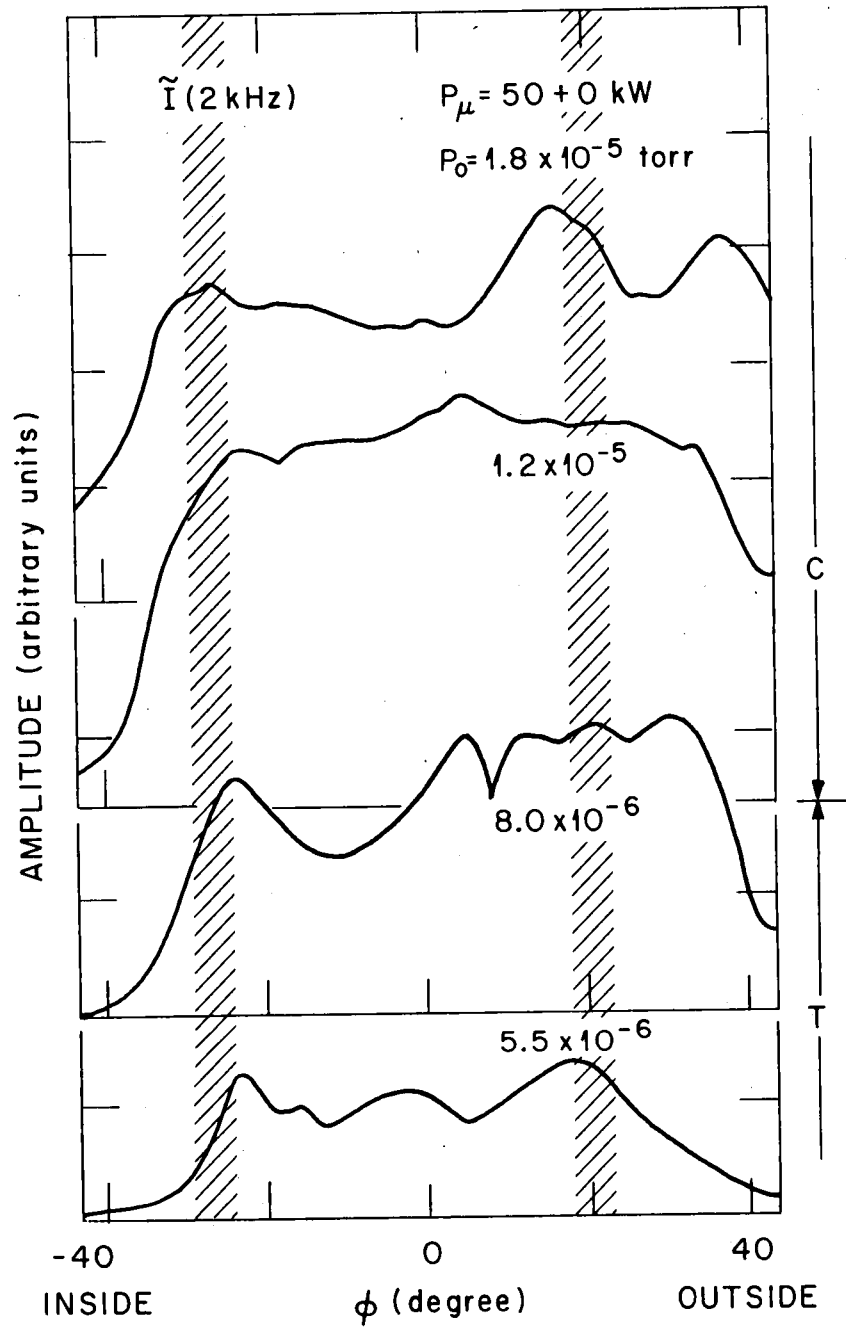


Figure C-4. Radial profiles of 2 kHz fluctuations in the detected photo-emission at different neutral pressures.

C-2 Langmuir Probe Measurements

There have been many measurements made on EBT with a variety of different probes. The measurements discussed here are only a small subset. The information presented is again based mostly on Reference 17. A typical Langmuir probe used on EBT is 3 mm long and 1 mm in diameter. Water cooling is provided to the probe to within one inch of the tip. The entire assembly is coaxially shielded except for the tip itself. Another probe type used in conjunction with the Langmuir probes are single-loop magnetic probes with axis parallel and perpendicular to the field and position fixed at the cavity wall on the vertical mid-plane. Measurements taken with these probes probably provide accurate frequency information, but the Langmuir probe does significantly perturb the plasma. Also, the high power levels in EBT are capable of destroying the probe if the tip actually comes in contact with the central plasma-electron ring region. These probes, therefore, must be regarded as limited in their usefulness.

Figures C-5 and C-6 demonstrate the measurement of electron density and temperature profiles of the surface plasma. The shaded region denotes the ring position. The density shows a large drop after passing through the T-C point and also shows a considerable change in profile. The temperature jumps at this transition, but the temperature profile retains the same overall shape with a general increase in the gradients. Frequency spectra, as shown in Figure C-7, indicate the low frequency nature of the surface plasma fluctuations. As the pressure is lowered an instability shows up as a coherent wave spectrum between 100 and

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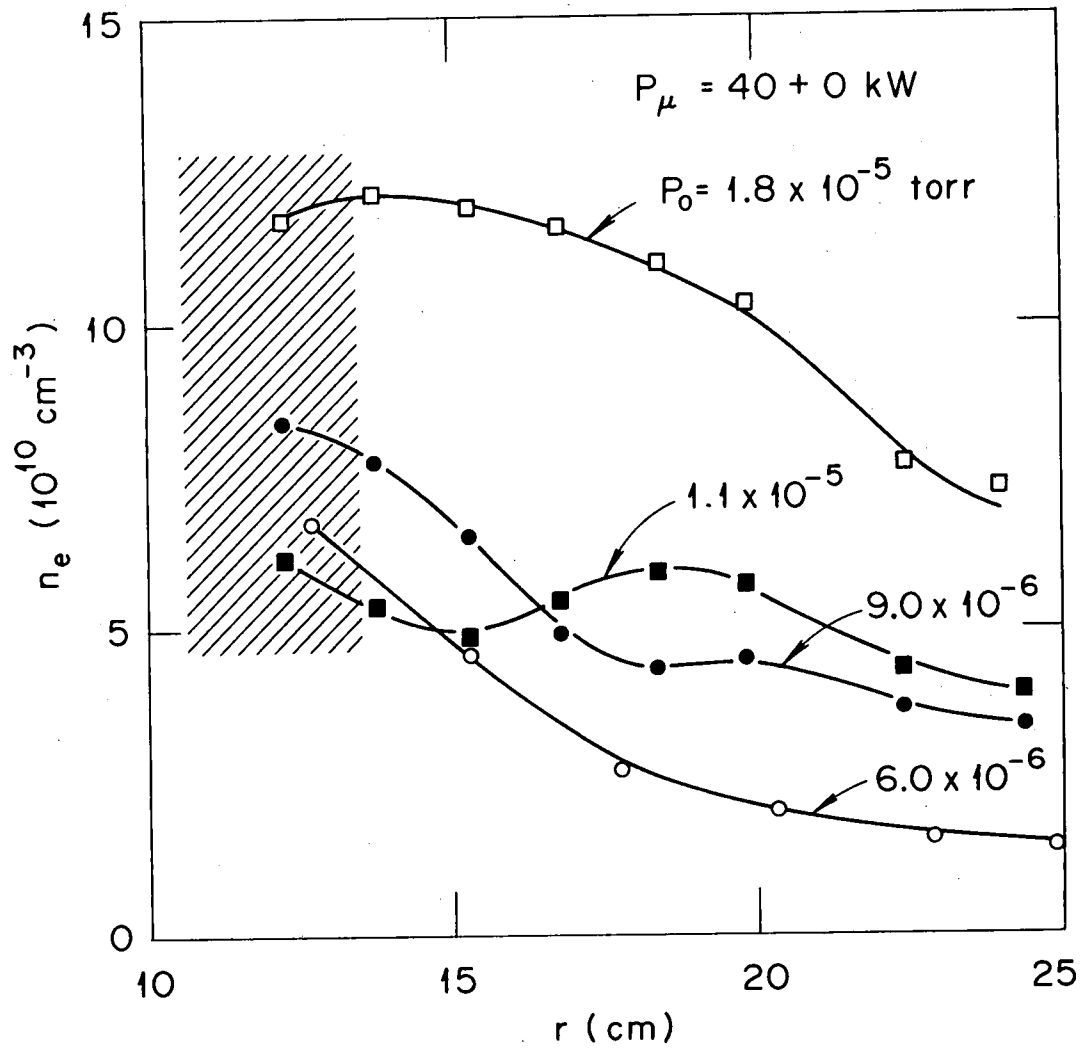


Figure C-5. Radial profile, at surface region of plasma, of the electron density at different neutral pressures.

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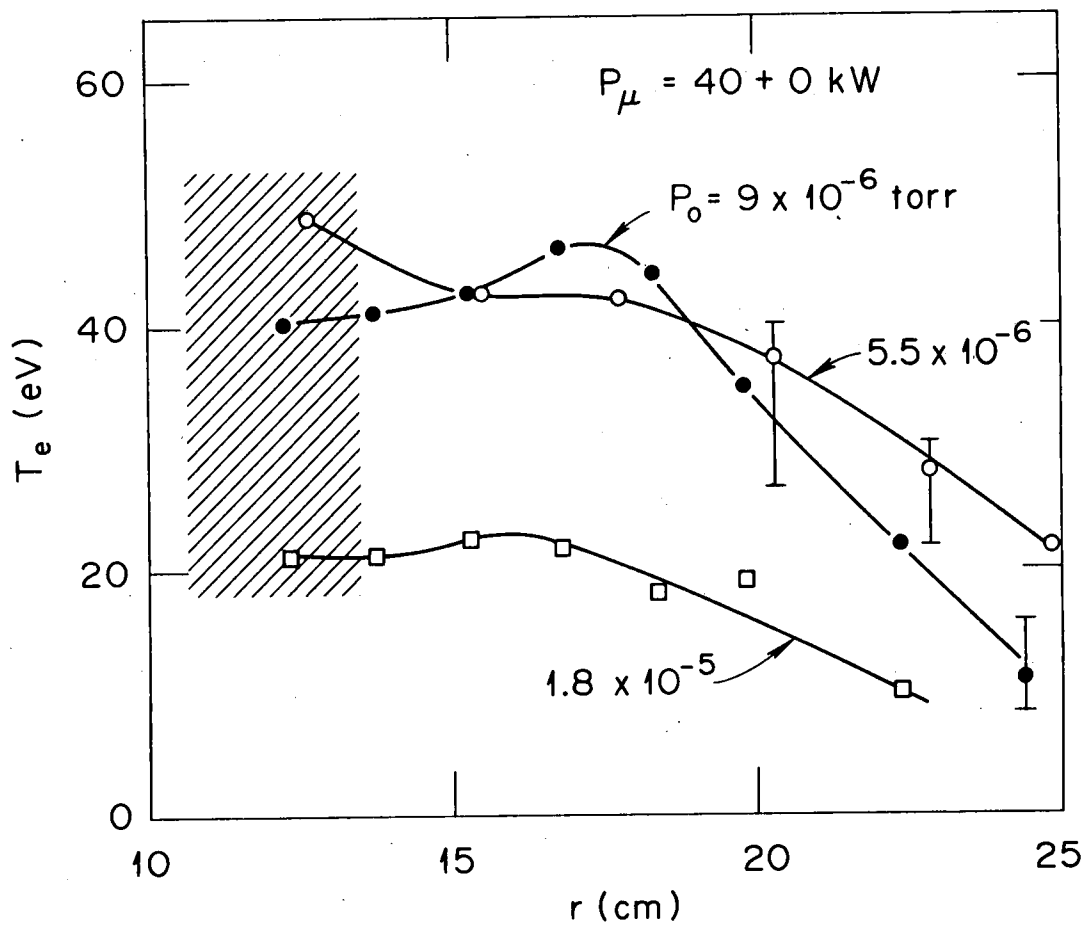


Figure C-6. Radial profile of equilibrium electron temperature at different neutral pressures.

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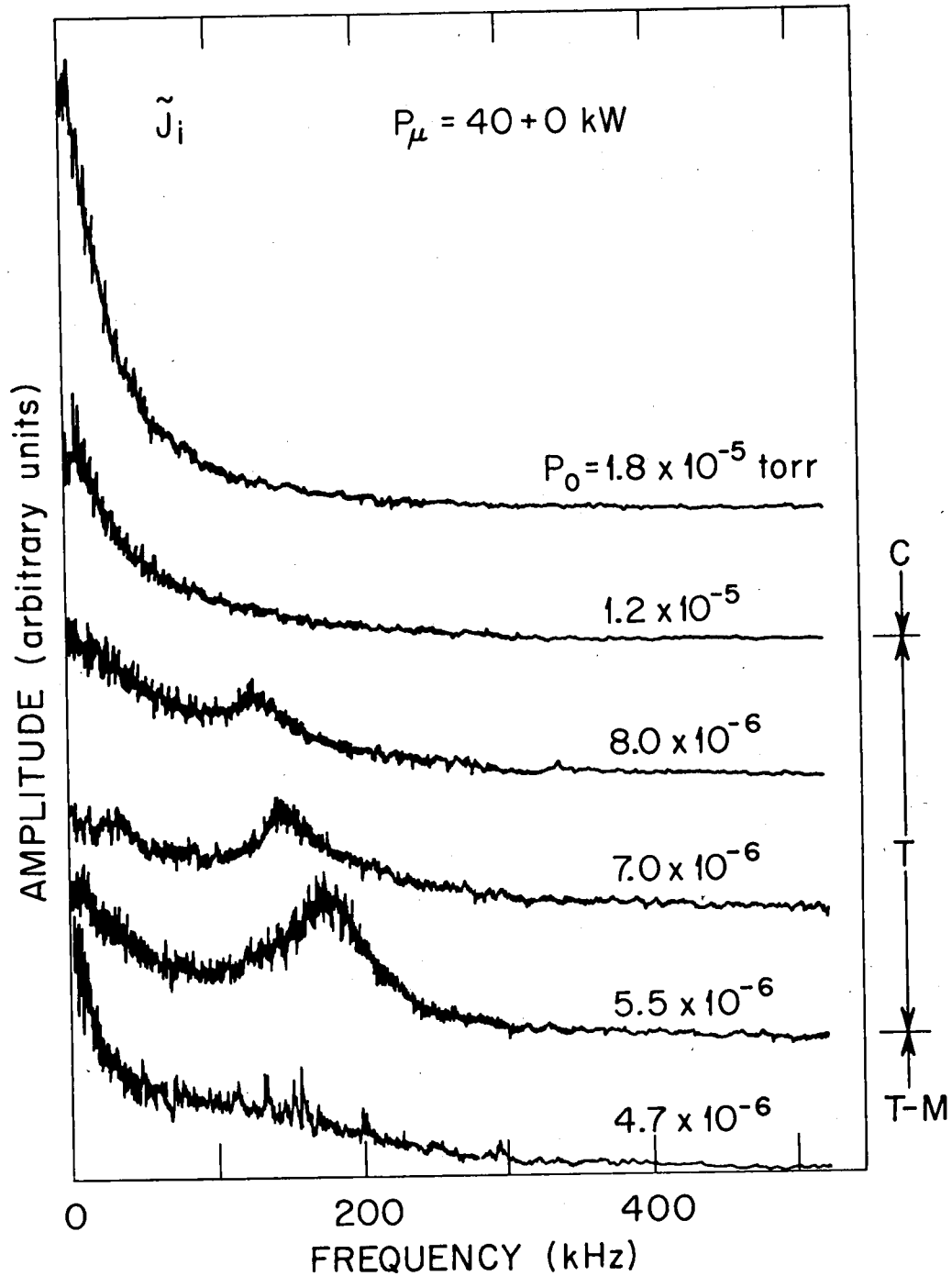


Figure C-7. Frequency spectra of the ion saturation current of a Langmuir probe positioned at a radius of 14 cm.

200 kHz, but this disappears in M mode again. These are fluctuations in the ion saturation current measured at $r = 14$ cm.

Measurements were made, using two Langmuir probes separated azimuthally by 45° , of the rotation velocity and the phase difference between the density wave and the potential wave. These types of measurements agree well with the fluctuations being a drift type instability. Similar measurements with magnetic probes demonstrate characteristics of an interchange type instability. Phase measurements using this technique depended upon comparing two small signals. As a result there was a lot of dispersion in the measurements, and they may be subject to interpretation.

C-3 Summary

Measurements made with photodiodes and Langmuir probes show two distinct types of instabilities identified by their location, phase velocity, and the phase angle between the potential and the density. The first is a drift type instability resulting from large density gradients in the outer portions of the plasma. Changing the neutral pressure through the three mode regimes of EBT results in the changing of these gradients and therefore of the fluctuation characteristics. The second was identified as an interchange instability which was located just outside the hot electron rings and is the result of the mixing of two electron populations of differing temperatures.

The role that these instabilities play in confinement is not clear. It had been suggested that the electron rings stabilize drift waves caused by strong density gradients within the ring region. Since it is

inevitable that a gradient will exist between the plasma and the wall, it would be beneficial to confinement if the strongest gradients occurred within this region. It was observed that in deep C mode the plasma extended outward further, resulting in the gradients being outside the ring region. Lowering the neutral pressure reduces the plasma size and therefore moves the strongest gradients inward. When these gradients enter the ring region, the stabilization effect would cause an increase in confinement, thus the T mode of higher densities and temperatures. Lowering the pressure further would soon lead to the return of the fluctuations, this time inside the ring region. The resulting loss of confinement corresponds to the M mode of operation. Although attractive, this theory was not found to be in agreement with other experimental evidence.² Komori still maintained that the electron rings prevented the drift instabilities from penetrating into the plasma and causing additional loss of confinement. The interchange instability is predicted by theory³⁷ and has been shown to be stabilized by a sufficient background neutral pressure.

Currently the view is that the presence of the hot electron rings has little effect on confinement.¹⁶ Although the rings may be a valuable source of energy absorption and electron heating, the diamagnetic current is unlikely to be large enough to cause a reversal of the slope in the integral of dl/B . This is an important stability criterion in the bumpy torus field configuration. Without a local maximum in this curve the hot electrons will not serve to stabilize the drift instability and

likely will contribute only additional instabilities such as hot electron interchange modes.

VITA

William Harry Casson was born in Batesville, Arkansas to Mr. and Mrs. Harry G. Casson, Jr., in September 1953. After graduating from Batesville High School and briefly attending Arkansas College he served his country for four years in the U.S. Navy.

Upon his return to Arkansas, he entered the University of Arkansas at Monticello where he completed the requirements for a BS degree in physics, math, and chemistry. He was awarded his degree summa cum laude in May 1979. During his enrollment he was given two summer appointments at the K-25 DOE facility in Oak Ridge as an undergraduate research assistant, and an appointment for four months at Argonne National Laboratory.

The Master of Science degree was earned at Kent State University in May 1981. He received an appointment in the summer of 1980 at Oak Ridge National Laboratory as a research participant in the Fusion Energy Division. He enrolled at The University of Tennessee, Knoxville, in the fall of 1981 and soon returned to Oak Ridge to complete his Ph.D. thesis project. He completed and received his degree in August 1985.

The author is married to Lynn G. Casson. He will be returning to Oak Ridge as a post-doc after graduation.