PROBE MEASUREMENTS OF THE MAGNETIC FIELD
STRUCTURE OF FAST WAVE TOROIDAL
EIGENMODES

by

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ABSTRACT

The magnetic field structure of fast Alfvén wave toroidal eigenmodes in the ion cyclotron range of frequencies has been investigated on a small research Tokamak. A study of various materials showed that boron nitride rods inserted deep into the plasma affect (and are affected by) the plasma considerably less than rods made of quartz, alumina, and Macor, for example. Differential magnetic loop probes, protected by boron nitride sheaths, were then constructed and used to make radial scans of $b_z(r)$, $b_\theta(r)$, their phases for the fast Alfvén wave. Analysis of the scans indicate the presence of two or more eigenmodes at the time of measurement.

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CHAPTER I

INTRODUCTION

It is well known that some form of supplementary heating will be required to bring ohmically-heated Tokamak plasmas up to thermonuclear fusion temperatures. The two major candidates for this supplementary heating are neutral beam injection and radio frequency (rf) heating. A major advantage of the rf approach is that the high power technology required has already been developed and is well understood. Problems still remain, however, in the implementation and protection of the rf antenna.

Radio frequency heating can be accomplished by launching fast Alfvén waves in the plasma and dissipating the waves' energy in the plasma through various damping mechanisms.^{1,2} In Tokamaks, this absorption can be greatly enhanced by toroidal resonances, or eigenmodes, which are a natural consequence of the toroidal geometry. Eigenmodes of particular interest are those with an azimuthal dependence of $m = \pm 1$. The maximum transverse electric fields for these modes occur at the center of the plasma column so that much of the energy is deposited near the core of the plasma where it is needed most for heating.

The objective of this experiment was to study the magnetic field structure of the fast wave toroidal eigenmodes. Magnetic probes with special protective sheaths were designed for probing deep into the plasma column.

Chapter II discusses the theory of fast wave propagation in plasmas. Equations are derived for the wave's magnetic field structure in the plasma and the surrounding vacuum layer. Discussion of boundary

conditions, examples of calculated magnetic field profiles, and the dispersion relation for this experiment are also given.

Chapter III contains a general description of the Tokamak. The operating parameters, the data acquisition system used in the experiment, and the rf arrangement used to launch and detect the waves are described. Finally, details of the protective probe sheaths are given.

Chapter IV is a survey of the materials that were tested for use as protective sheaths. Alumina, Macor, quartz, and boron nitride results are discussed.

Experimental measurements of the $\hat{z}$ and $\hat{\theta}$ components of the wave's magnetic field structure are presented and discussed in Ch. V. Appendices A and B show the design of the magnetic probe and phase comparator circuitry used in the experiment. Appendix C discusses the machining of a boron nitride sheath.

CHAPTER II

WAVE THEORY

A. Introduction

Many authors^{3,4,5,6} have examined the theory of fast Alfvén wave propagation because this wave seems to be very well suited for plasma heating in toroidal devices. Proper selection of the wave frequency, mode numbers, plasma composition and magnetic field strength, allows heating of ions and/or electrons, modification of the ion velocity distribution and control of the energy deposition pattern in the plasma.

B. Simplifying Assumptions

In modeling the deuterium plasma, several simplifying assumptions are made. The plasma is modeled as a straight uniform cylinder, immersed in a uniform magnetic field, surrounded by a vacuum layer, which is in turn surrounded by a conducting chamber. A diagram of this geometry is shown in Fig. II-1. Since the typical parallel wavelengths of interest here are only approximately 30% or less of the torus' major circumference, the curvature of the background magnetic field is neglected. The $1/R$ dependence of the toroidal magnetic field is neglected since it has little effect on any phenomena of interest here.^{6,7} Also the poloidal magnetic field, due to the plasma current, is neglected⁸ since it is considerably less, $\approx 5\%$, than the background toroidal field.

The plasma itself will be modeled as being uniform, cold (no thermal motion), and collisionless. The plasma density, n , is thus uniform throughout its region and zero in the vacuum layer. The cold plasma assumption allows pressure effects to be neglected, and dissipative processes are neglected by assuming the plasma to be collisionless.

Fig. II-1. Geometry of Plasma Model.

The displacement current in Maxwell's equations is neglected since the excitation frequency, ω , considered here is much less than ck .⁵ Also, since m_e is much less than m_i the electron mass is neglected. This assumption is usually valid as long as ω is well below the electron cyclotron frequency. Finally, only small amplitude variations of the form $\exp \{i(k_{||}z + m\theta - \omega t)\}$ will be considered, where $k_{||}$ is the parallel wave number and m is the azimuthal mode number.

C. Plasma Equations

The equations describing the plasma's behavior, under the above simplifying assumptions, are given below in MKS units. The equations of motion for the ions and electrons are

$$m_i \frac{\partial \vec{v}_i}{\partial t} = e (\vec{E} + \vec{v}_i \times \vec{B}_0) \quad (1)$$

$$m_e \frac{\partial \vec{v}_e}{\partial t} = -e (\vec{E} + \vec{v}_e \times \vec{B}_0) \quad (2)$$

The Maxwell's equations used are

$$\nabla \times \vec{B} = \mu \vec{J} \quad (3)$$

and

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}, \quad (4)$$

where

$$\vec{J} = n_e (\vec{v}_i - \vec{v}_e). \quad (5)$$

The above equations lead to the dispersion relations below.⁵

$$\left(\frac{\omega}{\omega_{ci}}\right)^2 = \left(1 - \frac{k_A^2}{k_{||}^2}\right) \left(1 - \frac{k_A^2}{k_{||}^2 + k_{\perp}^2}\right), \quad (6)$$

where:

$$\omega_{ci} = \frac{eB}{m_i} = \text{ion cyclotron frequency}$$

$$k_A = \frac{\omega}{V_A} = \text{Alfvén wave number}$$

$$V_A = \frac{B}{(\mu_0 n m_i)^{1/2}} = \text{Alfvén velocity}$$

$k_{||}$ = parallel wave number with respect to the z axis

$k_{\perp}$ = perpendicular wave number with respect to the z axis.

Figure II-2, a plot of the dispersion relation, shows various possible eigenmodes for this machine's parameters.⁹

Also from Eqs. (1-4) one obtains the wave magnetic field components, in the notation of Bernstein,⁵:

$$b_r^p(r) = \Lambda i k_{||} B_1 \left\{ \left(\frac{m}{r} \alpha J_m(k_{\perp} r) \right) - (\beta k_{\perp} J_{m-1}(k_{\perp} r)) \right\} \quad (7)$$

$$b_{\theta}^p(r) = \Lambda k_{||} B_1 \left\{ \left(\frac{m}{r} \alpha J_m(k_{\perp} r) \right) - (\Omega k_A^2 k_{\perp} J_{m-1}(k_{\perp} r)) \right\} \quad (8)$$

$$b_z^p(r) = B_1 J_m(k_{\perp} r), \quad (9)$$

Fig. II-2. Dispersion Relation for $p = .13 \text{ m}$, $n = 10^{19} \text{ m}^{-3}$.

where:

$$i = (-1)^{\frac{1}{2}}$$

$$\Lambda = \{(k_{||}^2 - k_A^2)^2 - k_{||}^4 \Omega^2\}^{-1}$$

$$\alpha = k_{||}^2 (1 - \Omega^2) - k_A^2 (1 - \Omega)$$

$$\beta = k_{||}^2 (1 - \Omega^2) - k_A^2$$

$$\Omega = \frac{\omega}{\omega_{ci}}$$

B_1 = arbitrary amplitude constant

J_m = Bessel function of the first kind, order m .

Note that only the first radial mode is considered.

D. Vacuum Equations

In the vacuum layer, $\vec{J} = 0$ so that the magnetic field can be expressed as the gradient of a scalar potential¹⁰, ψ ,

$$\vec{B} = \nabla \psi . \quad (10)$$

Use of the Maxwell's equation

$$\nabla \circ \vec{B} = 0 \quad (11)$$

leads to

$$\nabla^2 \psi = 0 . \quad (12)$$

The solution to this equation can be written as a linear combination of modified Bessel's functions of the first and second kind¹¹

$$\Psi = \{B_2 K_m(k_{||} r) + B_3 I_m(k_{||} r)\} \exp\{i(k_{||} z + m\theta - \omega t)\} , \quad (13)$$

where B_2 and B_3 are constants to be determined from the boundary conditions. Using Eqs. (10) and (13) the wave magnetic field components in the vacuum layer are found to be

$$b_r^v(r) = k_{||} \left\{ B_3 \left(I_{m-1}(k_{||} r) - \frac{m}{k_{||} r} I_m(k_{||} r) \right) - B_2 \left(K_{m-1}(k_{||} r) + \frac{m}{k_{||} r} K_m(k_{||} r) \right) \right\} \quad (14)$$

$$b_\theta^v(r) = \frac{im}{r} \{ B_2 K_m(k_{||} r) + B_3 I_m(k_{||} r) \} \quad (15)$$

$$b_z^v(r) = ik_{||} \{ B_2 K_m(k_{||} r) + B_3 I_m(k_{||} r) \} . \quad (16)$$

Again, only the first radial mode is considered.

E. Boundary Conditions

To obtain solutions for the natural modes that are compatible for all values of r , boundary conditions^{3,12,13,14,15} must be imposed on the plasma and vacuum field equations. In toroidal geometry, an eigenmode occurs when the periodic boundary condition

$$\frac{2\pi R}{\lambda_{||}} = k_{||} R = N , \quad N = 1, 2, 3, \dots \quad (17)$$

is satisfied, where $\lambda_{||}$ is the parallel wavelength, R is the major radius of the torus, and N is the toroidal mode number. Thus, only discrete

values of $k_{||}$ are allowed; consequently, only discrete values of $k_{\perp}$ and ω are allowed for each eigenmode, as well. Boundary conditions also determine B_2 and B_3 in Eqs. (14-16) in terms of the arbitrary amplitude constant B_1 .

At the conducting chamber wall ($r = w$), E_{θ} and E_z must be zero. This condition implies

$$b_r^V(k_{||}w) = 0. \quad (18)$$

Two more boundary conditions exist at the plasma vacuum interface. The plasma equations along with Maxwell's equations lead to³

$$b_z^P(k_{\perp}p) = b_z^V(k_{||}p) \quad (19)$$

and

$$b_r^P(k_{\perp}p) = b_r^V(k_{||}p). \quad (20)$$

Imposing Eqs. (18) and (19) on the plasma and vacuum field equations (7-9 and 14-16) leads to the solution of B_2 and B_3 in terms of B_1 , as follows,

$$B_2 = \gamma J_m(k_{\perp}p) B_1 \quad (21)$$

$$B_3 = \delta \gamma J_m(k_{\perp}p) B_1 \quad (22)$$

where

$$\delta = \frac{k_{||}w K_{m-1}(k_{||}w) + mK_m(k_{||}w)}{k_{||}w I_{m-1}(k_{||}w) - mI_m(k_{||}w)} \quad (23)$$

and

$$\gamma = \frac{-i}{k_{||} \{K_m(k_{||} p) + \delta I_m(k_{||} p)\}} \quad (24)$$

Imposing the boundary condition expressed in Eq. (20) yields:

$$\Lambda \left\{ \frac{m\alpha}{p} - \beta k_{\perp} \frac{J_{m-1}(k_{\perp} p)}{J_m(k_{\perp} p)} \right\} = i\gamma (\{K\} - \delta \{I\}) \quad (25)$$

where

$$\{K\} = K_{m-1}(k_{||} p) + \frac{m}{k_{||} p} K_m(k_{||} p)$$

$$\{I\} = I_{m-1}(k_{||} p) - \frac{m}{k_{||} p} I_m(k_{||} p) .$$

For a given toroidal eigenmode (fixed N and $k_{||}$), Eq. (25) along with the dispersion relation, Eq. (16), can be solved numerically to find the values of ω and $k_{\perp}$ that satisfy the boundary conditions. Once these are known they can be substituted into Eqs. (21) and (22) to find the values of B_2 and B_3 for the particular eigenmode considered.

Note that in the above solution to the natural mode equations, no boundary condition was placed on the component of the magnetic field at the plasma - vacuum interface. This circumstance allows b_{θ} to be discontinuous across the interface with the discontinuity being due to surface currents flowing in the $\hat{z}$ direction on the plasma surface.

F. Calculated Wave Field Profiles

Measurements made earlier on this machine indicate the most probable toroidal mode number to be $N = 3$.¹⁶ This information, along with the following parameter values, is used to calculate the magnetic wave field profiles:

$$k_{\parallel} = 6.67 \text{ m}^{-1}$$

$$B_0 = .67 \text{ T}$$

$$n_e = 1.0 \times 10^{19} \text{ m}^{-3}$$

$$p = .13 \text{ m}$$

$$w = .16 \text{ m}$$

$$\omega_{cd} = 3.2 \times 10^7 \text{ rad / sec} = \text{deuterium ion cyclotron frequency}$$

$$V_A = 3.27 \times 10^6 \text{ m / sec}$$

Radial profiles of the wave magnetic fields for the above parameters are given for the $m = -1$, $m = 0$, and $m = +1$ cases in Figs. II-3, II-4, and II-5, respectively.

Fig. II-3. b_r , b_θ , b_z vs r for $m = -1$.

Fig. II-4. b_r , b_θ , b_z vs r for $m=0$.

Fig. II-5. b_r , b_θ , b_z vs r for $m = +1$.

CHAPTER III

EXPERIMENTAL APPARATUS

A. Machine Description

The Texas Tech Tokamak is a small ($R = 46$ cm, $a = 16$ cm) research Tokamak with circular cross section. A block diagram of the machine is shown in Fig. III-1. The machine was built primarily for investigations of radio frequency wave propagation in plasma, particularly the fast Alfvén wave. The machine design, construction and cost is described elsewhere^{17,18}. A brief description of the device follows. A more extensive description of the machine performance can be found in an earlier report¹⁶.

Vacuum Chamber

A top view of the stainless steel vacuum chamber is shown in Fig. III-2. There are 22 ports with a total access area of 550 cm^2 . The angle θ refers to the toroidal position (the long way around) on the torus and ϕ refers to the poloidal position (the short way around) on the torus.

Toroidal Field

The toroidal field coil consists of # 1/0 cable wound directly on the insulated metal chamber. The coil is energized by a $2,560 \mu\text{F}$, 10 kV (126 kJ) capacitor bank, which is actively crowbarred at current maximum to give an L/R time of 59 ms.

Fig. III-1. Block Diagram of Texas Tech Toroidal Plasma Facility.

Fig. III-2. Top View of Vacuum Chamber.

Ohmic Heating

A 50 turn air core winding is the primary of the ohmic heating transformer. This winding is energized by a two stage capacitor bank. At the present time the fast bank is 980 μF at 3 kV (4.4 kJ), and the slow bank is 100,000 μF at 600 V (18 kJ). With this arrangement the ohmic heating primary current reaches a peak value of 3.5 kA. The slow bank's capacitance is being increased to 180,000 μF to enable future discharges in ^3He . This increased capacitance will be needed to supply the extra energy required to form and sustain the ^3He plasma.

Vertical Field

The vertical field coil is wound inside the ohmic heating transformer, and is also energized by a two stage capacitor bank: a fast bank of 500 μF at 3 kV (2.3 kJ), and a slow bank of 110,000 μF at 200 V (2.2 kJ).

Radial Field

The radial field coil forms a cusp field within the chamber. The coil is energized by sampling a controlled amount of the toroidal field winding's current.

Preionization

A preionized plasma, with a particle density of about 10^{11} cm^{-3} is formed 2 ms prior to the ohmic heating pulse by producing a ringing (15 kHz) capacitor discharge in the preionization coil.

Discharge Cleaning

A 40 kW, 25 kHz oscillator prepares the vacuum chamber for Tokamak discharges by producing low energy discharges that remove low Z impurities

from the vessel wall. The cleaning discharges consist of 10 ms duration rf pulses at 2 pps which result in a 1 kA_{pp} plasma current. A .03 T pulsed toroidal field is generated concurrently with the discharge cleaning pulses.

Machine Diagnostics

Several of the machine's diagnostics are discussed in detail in an earlier report.¹⁹ The toroidal field, ohmic heating, and vertical field energizing currents are monitored by self integrating current transformers. The single-turn voltage is measured using two one-turn loops in the equatorial plane, next to the vacuum chamber. The toroidal magnetic field and plasma current are measured using passively integrated Rogowski coils. The plasma column's position is monitored by a sine coil for axial (up - down) movement, and a cosing coil for radial (in - out) motion.

The line - averaged central electron density is measured with a 70 GHz ($\lambda = 4.3 \text{ mm}$) microwave interferometer. Presently, the interferometer is used with a zebra-stripe display; however, a direct reading interferometer is being developed.

The electron temperature is inferred from Spitzer resistivity calculations when $dI/dt (\text{plasma}) = 0$, by assuming a Z_{eff} of 2. Ion temperature measurements are made by observing the Doppler - broadening of a seeded He II line at $4685.7 \text{ \AA}$.

In order to investigate the effect of inserting various probe sheaths into the plasma, time integrated pictures of the test rods inserted in the plasma during the discharge were taken using the arrangement shown

in Fig. III-3. Three narrow band ($100 \text{ \AA}$ FWHM) interference filters with their passbands centered at D_α ($6561.0\text{\AA}$), D_β ($4859.6\text{\AA}$), and D_γ ($4339.3\text{\AA}$) are arranged in a configuration that allows the background plasma light (D_α , D_β , and D_γ) to pass through the filters while other wavelengths, being generated due to the sheath's presence, are reflected by the filters and sent to the camera. Care must be taken to insure that the angle at which the light strikes the filter is close to normal ($\approx 83^\circ$), since for interference filters, the center of the passband is a function of the angle of incidence. After filtering, the light passes through a focusing lens and then through crossed polarizers, which attenuate the light before it reaches the film.

Machine Performance

Oscillograms of the machine performance parameters, with no probe inserted into the plasma, are shown in Fig. III-4. The rapid loss of density after the first millisecond is typical for small Tokamaks.²⁰ Efforts are presently underway to sustain the density maximum for a longer period of time by puff-filling with a neutral gas during the discharge.

A summary of the machine parameters, with no probes inserted into the plasma, is given in Table I.

Fig. III-3. Time Integrated Photography Arrangement.

Fig. III-4. Oscilloscope of Machine Parameters. Time Scale is 2 ms/cm ($B_{\phi} = .67 \text{ T}$, $p_0 = 1.6 \times 10^{-4} \text{ Torr}$).

TABLE I

Summary of Typical Operating Parameters

B_{ϕ}	7 kG
I_p	15 kA (peak)
n_e	$1.2 \times 10^{13} \text{ cm}^{-3}$ (peak)
V_{loop}	1.5 volts
T_e	100 - 150 eV
T_i	20 - 40 eV
τ_p	10 - 14 ms

B. Data Acquisition System

A PDP 11/04 computer system controls a CAMAC based data acquisition system for the Tokamak. A block diagram of the system is shown in Fig. III-5. Extensive documentation of this system appears in a separate report²¹.

Three program languages are available for use. BASIC allows quick program development and good operator interaction with the program. FORTRAN programs execute quickly and have powerful subroutine features. Finally, PDP-11 MACRO assembly language allows fast and efficient machine code subroutines to be written.

Peripheral equipment to the computer includes a Tektronix 4025 intelligent video graphics terminal, a DEC RX01 dual floppy disc drive, and a low speed DEC printing terminal. The graphics terminal, which has a buffer memory, is used primarily to display data in a graphical form. The floppy discs store both programs and data. The low speed terminal presently serves as a line printer.

Planned improvements to the computer include: an 11/34 processor board to enhance the instruction set, extra memory to double the present capacity, and a hard copy unit for the graphics terminal.

The CAMAC system is an international standard that allows various data acquisition devices to be interfaced to the computer. The CAMAC crate contains two digitizers that record a total of 16 channels. Each digitizer has a maximum sampling rate of 500 kHz if all eight channels are being used or a rate of 4 MHz if only one channel is sampled. Also, each digitizer has 32 k byte of buffer memory for holding the digital information until the computer is ready to accept it.

Fig. III-5. Data Acquisition System.

A 32 channel A/D converter is used to monitor slowly varying inputs such as charging voltages, filling pressure, and so forth. Data from all these devices can be displayed on the graphics terminal in either a raw or processed state. Also, raw data from the two eight channel digitizers can be viewed on a monitor located next to the crate.

C. RF Experimental Arrangement

A diagram of the experimental arrangement for launching the Alfvén waves is shown in Fig. III-6. The broadband (1-200 MHz) linear amplifier allows the excitation frequency to be varied easily while other plasma parameters remain fairly constant from shot to shot. With a 1 mW input from the signal generator, the amplifier delivers 500 watts (57 dB gain), pulsed, into a $50\ \Omega$ load. A 30 kW amplifier is available for future experiments at higher power levels.

A bi-directional coupler is used to monitor the power flow between the amplifier and impedance matching circuitry. Matching conditions between the amplifier and antenna can thus be monitored during the discharge.

The circuitry shown in Fig. III-7 matches the load to the amplifier. Once the excitation frequency is set, capacitor C_2 is tuned to resonance with the antenna. Capacitor C_1 is then adjusted to match the amplifier to this predominantly resistive (at resonance) load.

The antenna current is monitored by a 35 MHz bandwidth Rogowski coil located at the antenna - vacuum feedthrough. The antenna, shown in Fig. III-8, consists of stranded copper wire insulated by 1.6 mm

Fig. III-6. Diagram of rf Experimental Arrangement.

C_1, C_2 are Jennings Vacuum Variable Capacitors

$C_1 = 15 - 350 \text{ pF}$, $C_2 = 160 - 2000 \text{ pF}$

Tuning range: 4.5 - 17 MHz

Fig. III-7. Detail of rf Impedance Matching Circuitry.

Fig. III-8. Detail of Antenna.

thick Pyrex tubing. The insulation prevents the plasma from shorting out the antenna and hence results in a much higher operating Q.

Magnetic probes monitor the plasma waves. Appendix A details the probes' construction. The phase comparator circuitry which determines the phase of the probe signal referenced to the antenna current, is the subject of Appendix B.

D. Probe Sheath Design

The sheath shown in Fig. III-9 protects the magnetic probes from damage by the plasma. Appendix C contains details about machining the sheath. Boron nitride was chosen as the protective covering for the probe because of its high melting point and excellent thermal shock resistance. Because of the boron nitride's porosity, however, the .56 O.D. cm Pyrex tubing acts as the vacuum lining. The larger, 1 cm O.D. Pyrex tubing supports and positions the sheath assembly, as shown in Fig. III-10. The sheath can be inserted to a depth of 1 cm past the chamber's center. The magnetic probe (see Fig. III-9), which is inserted into the .56 cm tubing, can be moved independently inside the sheath assembly.

The large number of ports (22) on the machine provides many possible locations for insertion of the probe assembly; however, most measurements were taken at the toroidal position $\phi = 60^\circ$ (see Fig. III-2), for convenience.

Fig. III-9. Magnetic Probe and Sheath Arrangement.

Fig. III-10. Probe Sheath's Position in Vacuum Chamber.

CHAPTER IV

PROBE SHEATH MATERIALS STUDY

A. Introduction

Detailed measurements of wave behavior deep into the plasma column requires a suitable protective probe covering to shield the probe from the plasma. Since the probes sense the magnetic field, the sheath material must be a dielectric for the field to reach the probe. The material must also withstand the high temperature and thermal shock from the plasma. In addition, the sheath must not inject large amounts of impurities into the plasma, or seriously disrupt any of the plasma parameters.

Inserting alumina, Macor, quartz and boron nitride rods into the plasma determined the relative suitability of these materials as protective sheaths for magnetic probes. Each rod tested was 3/8 inches in diameter and was gradually inserted into the plasma. Fig. IV-1 shows the rod's position in the plasma chamber. To monitor the effects of the rod's presence, the plasma current and density were recorded. Also, time integrated photographs of the quartz and boron nitride rods during the discharge were taken.

B. Alumina

Alumina (Al_2O_3), is an extremely hard polycrystalline ceramic, with a maximum operating temperature of 1900 °C and it makes a good vacuum seal. A high purity, 99.9%, rod was gradually inserted into the plasma. After two shots at 3 cm past the plasma limiter the alumina was unable to withstand the thermal shock and cracked. The plasma current and density, with the alumina at 3 cm past the limiter, are shown in Fig IV-2.

Fig. IV-1. Test Rod's Position in Plasma Chamber.

Fig. IV-2. Plasma Current and Density with Alumina Rod Inserted 3 cm Past the Limiter.

Since the alumina could not be inserted very deep into the plasma, these traces are essentially the same as with no rod present, as were shown in Fig. III-4.

C. Macor

Macor is a hard machinable glass ceramic consisting of: 47.2% SiO_2 , 16.7% Al_2O_3 , 14.5% MgO , 9.5% K_2O , 8.5% B_2O_3 , 3.6% F. It forms a good vacuum seal and has a maximum operating temperature of 1000 °C. Because of its microstructure, Macor is resistant to crack propagation and hence provides good thermal shock resistance.

The Macor rod was inserted to a depth of 3 cm beyond the plasma limiter. At this depth a minor density fluctuations occurred at approximately 6 ms into the discharge. This fluctuation caused an abrupt termination of the plasma current, as seen in Fig. IV-3. Inserting the rod further, to a depth of 6.5 cm past the limiter, led to even more pronounced density fluctuations. After approximately 100 shots at this depth the rod was removed for inspection. The rod's tip was somewhat discolored and slightly eroded on the side facing the oncoming electrons carrying the ohmic heating current. However, no cracks appeared as in the case of the alumina.

D. Quartz

Quartz (SiO_2), also studied as a possible sheath material, has excellent thermal shock resistance, a melting point of approximately 1700 °C and forms a good vacuum seal. The quartz was inserted to a depth of 7 cm past the limiter before density fluctuations began to occur, as seen in Fig. IV-4. The rod was then inserted further toward

Fig. IV-3. Plasma Current and Density with Macor Rod Inserted 3 cm Past the Limiter.

Fig. IV-4. Plasma Current and Density with Quartz Rod Inserted 7 cm Past the Limiter.

the center of the chamber. Although it was able to withstand the thermal shock, the density fluctuations became more pronounced, just as in the case of the Macor.

E. Boron Nitride

Boron nitride consists of 43.0 - 43.5% B, 55.6 - 56.3% N, 1.0% O, .2% C, and .01% other materials. It has a maximum operating temperature of 2000 °C and has good thermal shock resistance. Its principal disadvantages appear to be its low mechanical strength and its porosity, which prevents it from acting as a vacuum seal.

Figure IV-5 shows the effects of inserting the rod to the center of the chamber. The density is increased late in the discharge, but no abrupt increase occurs as it did for the Macor and quartz. After more than 100 shots, the rod was removed and inspected. There was a slight discoloration of the rod on the side that faced the oncoming electrons, but no evidence of cracking or melting.

F. Time Integrated Photographs

Time integrated photographs of the quartz and boron nitride rods inserted in the plasma during the discharge were taken with the arrangement shown in Fig. III-3. Photographs of both rods showed a higher luminosity on the side of the rod facing the oncoming electrons. Also, with the rods inserted to the center of the chamber, the luminosity was greatest on the 4 cm of the rod nearest its tip.

Fig. IV-5. Plasma Current and Density with Boron Nitride Rod Inserted
13 cm Past the Limiter.

G. Conclusions

Alumina was eliminated as a possible sheath material since it was unable to withstand the thermal shock. Macor, quartz, and boron nitride all disturbed the plasma when inserted deeper than 3 cm past the limiter. The peak density was reduced by a few percent. The plasma current was also reduced and terminated earlier.

Macor and quartz both show a much larger effect on the plasma late in time than the boron nitride. The lack of pronounced density disruptions in the case of boron nitride indicates that it contaminates the plasma to a lesser degree than the other materials.

Therefore, because of its ability to survive in the plasma environment without affecting the plasma parameters too seriously, boron nitride was chosen as the probe sheath material. The probe sheath arrangement shown in Fig. III-9 was then constructed.

CHAPTER V

WAVE MEASUREMENTS

Once a probe sheath had been designed and constructed, tests were made to determine the effects of the sheath's presence on the field structure of the fast Alfvén wave. The protected magnetic probe was then used to make radial scans of the b_z and b_θ fields of the wave. Profile data were stored using the data acquisition system described in Ch. III. The data were processed using an analysis program written for the PDP 11/04 computer and documented in a separate report²¹.

A. Effect of the Probe Sheath's Presence

It seemed that the presence of the protective probe sheath might affect the wave field structure. Therefore, scans were performed to measure the b_z component of the wave and its associated phase as a function of radius, both with the sheath fixed at the center of the chamber and with the sheath and probe moved simultaneously. The results for b_z amplitude and phase are shown in Figs. V-1 and V-2, respectively. The phase scan indicates that the sheath's presence does not seriously affect the basic phase structure of the mode. The b_z amplitude scan; however, indicates the amplitude of the component is strongly affected by the position of the sheath. To keep the sheath's effect constant for each radial position of interest, all profile data were taken with the sheath fixed at the center of the chamber while the protected probe was moved to perform the scan.

Fig. V-1. Sheath Effect on $|b_z|$ Amplitude.

Fig. V-2. Sheath Effect on b_z Phase,

B. b_z and b_θ Profiles

All scans reported here were made at a toroidal position of $\phi = 60^\circ$ (see Fig. III-2). An example of the temporal development of the eigenmodes and density for an excitation frequency of 8 MHz is shown in Fig. V-3. Profiles of $|b_z|$, $|b_\theta|$ and their phases were first recorded with the probe entering the chamber at the bottom, $\theta = 270^\circ$, and scanning to the center of the chamber. The profiles were then recorded for the probe entering the top of the chamber, $\theta = 90^\circ$, and scanning to the center. The composite profiles of b_z 's amplitude and its phase are shown in Figs. V-4 and 5, respectively.

The $|b_z|$ profiles appears to be symmetric about the origin except for the smaller overall amplitude of the scan performed at $\theta = 270^\circ$. One explanation for this unbalance is that more than one mode is present at the time of measurement. The dispersion relation, shown in Fig. II-2, suggests that the $(N = 3, m = +1)$ and $(N = 3, m = +2)$ eigenmodes may both be present. The theory of Ch. II predicts the b_z profile for $m = +1$ to be an odd function about the origin, meaning the field on one side is 180° out of phase with the field on the other side. For $m = +2$, however, b_z is even about the origin and there is no phase reversal. Therefore, if $m = +1$ and $m = +2$ modes are present, b_z fields on one side would add and fields on the other side would subtract leading to an unbalance about the origin, as was measured. A theoretical graph of this behavior is shown in Fig. V-6.

The observed $|b_z|$ profile has a minimum on axis, but does not have a zero as Fig. V-6 predicts. This may be due to small contributions of weakly excited $m = +1$ modes with radial mode numbers greater

Fig. V-3. Temporal Development of Eigenmodes and Density.

Fig. V-4. Radial Profile of $|b_z|$ Amplitude.

Fig. V-5. Radial Profile of b_z Phase.

Fig. V-6. Theoretical Plot of $|b_z|$ for Both $(N=3, m=+1)$ and $(N=3, m=+2)$ Eigenmodes Present.

than 1, that are neglected in the present theory. Addition of these modes leads to larger amplitudes near the axis so that, due to the finite spatial resolution of the probe, a minimum is observed instead of a zero.

Theoretically the resultant b_z phase of a $m = +1$ and $m = +2$ combined signal should have an abrupt jump of 180° at the center of the plasma. The observed phase shows a gradual transition of approximately 165° . Damping of the wave may be causing this smoothing out of the expected 180° phase jump.

Figures V-7 and 8 show the b_θ amplitude and phase profiles corresponding to the above b_z profiles. Inspection of the plots shows that neither b_θ 's amplitude or phase is symmetric about the origin as the theory of Ch. II predicts for the presence of a single eigenmode. This again suggests the possibility that more than one mode is present. The combined fields of the $(N = 3, m = +1)$ and $(N = 3, m = +2)$ modes alone do not adequately describe the observed b_θ profiles. Other, higher order, modes may be occurring since the machine may be operating higher in the eigenmode spectrum than expected due to an incorrect model of the plasma density profile and radius. For an eigenmode Q of approximately 7, the eigenmodes: $(N = 1, m = 0)$, $(N = 2, m = 0)$, $(N = 4, m = +2)$ and $(N = 5, m = +1)$ could all be contributing, in varying amounts, to the observed profiles.

To help resolve the question of what are the predominant eigenmodes present, toroidal and azimuthal arrays of probes could be used. A toroidal array of probes, spaced closely enough to resolve short parallel

Fig. V-7. Radial Profile of $|b_\theta|$ Amplitude.

Fig. V-8. Radial Profile of b_θ Phase.

wavelengths, could be used to determine k_z more accurately. An azimuthal array of probes, that are capable of resolving the phase unambiguously between 0° and 360° , could be used to distinguish between different azimuthal mode numbers by measuring the phase difference between probes. To help determine where in the eigenmode spectrum the machine is operating, a careful measurement of the occurrence of eigenmodes as a function of the excitation frequency could be made. This would lead to an experimental eigenmode spectrum which could be compared to the theoretical spectrum predicted by the dispersion relation.

C. Temporal Development of a Profile

Figure V-9 shows a $|b_z|$ profile at three different times in the eigenmode's development. Because of shot to shot variation, each time in the development of the mode was defined according to when the phase of a reference probe, located at the wall, passed through a certain value. The figure shows that the amplitude of the profile changes uniformly with time across the radius of the plasma column.

$f = 8\text{MHz}$
 $\phi = 60^\circ$
 $\theta = 180^\circ$

--- τ_1

— τ_2

--- τ_3

Fig. V-9. Temporal Development of $|b_z|$ Profile.

CHAPTER VI

CONCLUSIONS

A protective boron nitride probe sheath has been developed to allow probing of the magnetic field structure of the fast Alfvén wave deep into the plasma column. Detailed radial profiles of b_z , b_θ and their phases have been recorded and analyzed.

In designing the probe sheath, alumina, Macor, quartz and boron nitride were considered as possible sheath materials. Due to its high melting temperatures and good thermal shock resistance, boron nitride was chosen as the sheath material.

Analysis of the profiles obtained from the probe measurements indicates the possibility of two or more eigenmodes being present at the time of measurement. This could be the result of an overlapping of the $(N = 3, m = +1)$ and $(N = 3, m = +2)$ modes predicted by the dispersion relation. Another possibility is that the machine is actually operating higher in the eigenmode spectrum than expected. In this case, an eigenmode Q of approximately 7 results in a field profile which contains contributions from several broadened modes.

To simplify the investigation of the eigenmodes, installation of a system for puff-filling with a neutral gas during the discharge was begun. This system will lead to a more slowly varying density and hence allow a particular eigenmode to exist for a longer period of time. Another improvement to the machine would be the installation of a new antenna designed to enhance coupling to the modes and to excite certain modes selectively.

To identify more definitely which modes are present, a toroidal

array of probes spaced closely enough to determine the toroidal mode number ,N, for a particular eigenmode should be installed in the machine. An azimuthal array of probes with a phase resolving capability of $0^{\circ} - 360^{\circ}$ could be used to distinguish between the various azimuthal mode numbers.

Another helpful study for mode identification would be an investigation of when new eigenmodes appear, as the excitation frequency is increased. Comparison of these measurements with the theoretical predictions of when a particular eigenmode should appear would help determine which mode or modes are present at a given time.

The probes developed in this investigation could be used to investigate damping mechanisms of the fast Alfvén wave in this machine. Strong damping of the fast wave has been observed in deuterium-filled Tokamaks that contain a small amount of hydrogen impurity. There should be a minimal amount of proton impurities in this machine due to the exclusive use of deuterium for all operations so far. To study this damping, therefore, small, precisely known, amounts of hydrogen could be gradually added to the deuterium. Probes could then be used to investigate the fields near the resonance layers in the plasma. Knowing the behavior of these fields should then make it possible to distinguish between the different proposed damping mechanisms.^{1,2} Instead of deuterium, ^3He could be used in order to remove degeneracies present when using a deuterium-proton mixture and studying fundamental and harmonic ion cyclotron effects.

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APPENDIX A

RF MAGNETIC FIELD PROBES

A differential magnetic probe was constructed to measure the magnetic field structure of the fast Alfvén wave. The probe fits into the protective sheath shown in Fig. III-9 and moves independently of the sheath to allow radial profiles to be scanned.

The probe circuitry shown in Fig. A-1 is designed to sense the time varying magnetic fields associated with the waves while minimizing capacitive pick up. Two 2 X 5 mm cross section coils are wound concurrently, but connected in opposite directions. Therefore, the magnetically induced signals in the two coils will be opposite in phase, whereas any capacitive (electrostatic) pick up will be in phase. The transformer differentially adds the signals from the two coils so that the magnetically induced signals add together and the common mode voltages cancel, leaving a signal due almost entirely to the magnetic field. The entire probe assembly, except for the pick up coils, is surrounded by an electrostatic shield.

The frequency response of the probe, over the frequency range of interest, was measured using a one turn Helmholtz coil as a reference source. Figure A-2 shows a plot vs. frequency of the parameter A (proportional to the effective total cross sectional area of the probe),

$$A = KV_{\text{out}}/\omega I$$

where

K = normalization constant

Transformer: MCL TMO2-1T

Fig. A-1. Schematic Diagram of Differential Magnetic Probe. The 25Ω Resistor is for Increased Isolation Between the Coils, and the 51Ω Resistors Terminate the Transformer Secondary in its Characteristic Impedance.

Fig. A2. Frequency Response of rf Magnetic Probe.

V_{out} = output voltage of probe

ν = frequency of magnetic field signal

and

I = current in Helmholtz coil.

To determine how well the capacitive pick up was eliminated, the common mode rejection ration, CMRR, was calculated using the formula,

$$\text{CMRR} = \frac{\text{output voltage with coil signals subtracted}}{\text{output voltage with coil signals added}}$$

With a Helmholtz coil as a test source, the CMRR was found to be 20.1 : 1.

APPENDIX B

PHASE COMPARATOR CIRCUITRY

When studying the magnetic field structure of the fast wave, it is useful to measure the phase of the magnetic field as well as its amplitude. Modifications have been made to an existing phase comparator¹⁶ to allow analysis of signals from a scanning probe (used for making radial profile scans) and a reference probe fixed at $r = 14$ cm. A block diagram of the present phase comparator is shown in Fig. B-1.

Channel 1 is used to obtain 0° to 180° phase information from the reference probe. The reference signal is first filtered to remove any noise below 1 MHz. To obtain only phase information at the output, the signal's amplitude variations are removed by first amplifying the signal and then using a limiter to obtain a constant amplitude signal. The signal is then fed to a double balanced mixer which compares the phase of the probe's signal to that of the antenna current. The filtered output of the mixer then yields the 0° to 180° phase information associated with the reference probe signal.

Information from channels 2 and 3 is used to obtain the amplitude and the 0° to 360° phase information associated with the scanning probe's signal. The signal from the scanning probe is filtered to remove any signals under 1 MHz. The signal is then split in two, one part being passed through a 90° delay line. The two signals are then amplified and each sent to a double balanced mixer for phase comparison with the antenna current. Since no limiters were used, the filtered output of channels 1 and 2 contain both amplitude and phase information.

Fig. B-1. Block Diagram of Phase Comparator Arrangement.

The antenna current is monitored by a current transformer with a bandwidth of 35 MHz. After attenuation the transformer signal is split and sent to each mixer for phase comparison. The signal may also be detected to allow monitoring of the current during the discharge.

The double balanced mixer has three parts: the Radio Frequency port, the Local Oscillator port, and the Intermediate Frequency port. When a probe signal is applied to the RF port and the antenna current's signal is applied to the LO port, the output at the IF port is a DC voltage that is proportional to the amplitude of the probe signal and the cosine of the phase difference between the RF and LO port (see Fig. B-2). Therefore, since the amplitude at the RF port of channel one's mixer remains constant, due to the limiter, the channel one output is simply proportional to $\cos \phi_r$, where ϕ_r is the phase difference between the reference probe signal and the antenna current. The outputs of channels 2 and 3 are proportional to $A \cos \phi$ and $A \cos (\phi - 90^\circ)$ ($= A \sin \phi$), respectively, where A is the amplitude of the scanning probe signal and ϕ is the phase difference between the probe's signal and the antenna current.

Fig. B-2. Output of Double Balanced Mixer When Used as a Phase Detector (Adapted From Mini-Circuits Labs Data Sheets).

APPENDIX C

MACHINING OF THE BORON NITRIDE SHEATH

Boron nitride was chosen as the sheath material because of its high melting point and good thermal shock resistance. One disadvantage, however, is its low mechanical strength (Detailed technical data are available from Union Carbide.²²). The sheath design called for a closed end boron nitride tube in which the probe is inserted. Since no tubes of the proper dimensions were available from Union Carbide, a 17 cm long, .56 cm (7/32 in.) diameter hole was drilled down the center of a 1 cm (3/8 in.) O.D. rod.

To help support the fragile boron nitride during drilling, the fixture shown in Fig. C-1 was constructed. It consists of two aluminum halves, each having a 1 cm diameter trough milled in it. The rod is clamped between the two halves and hence receives support from all directions.

Once the rod has been clamped into the fixture, the assembly is mounted onto a lathe, one end clamped in the chuck and the other end being held by a free standing support. A 30 cm long, .56 cm (7/32 in.) bit is then used to slowly drill the hole. Care must be taken to prevent build up of the boron nitride shavings which can inhibit the cutting of the bit. The fixture supports the boron nitride rod well enough that tubes with closed ends can be fairly easily machined.

Fig. C-1. Drilling Fixture for Boron Nitride Rod.