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PLASMA PHYSICS DEPARTMENT

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1 INTRODUCTION

The Wills Plasma Physics Department undertakes research in three main areas – the study of hydromagnetic waves and RF heating using the TORTUS tokamak, the development of diagnostic techniques, particularly those based on submillimetre lasers and tunable gyrotrons developed in the department, and gas discharge studies.

In each of these three areas collaboration exists with groups in Australia and overseas. The groups and individuals involved in these collaborations include the Department of Applied Physics and the Theoretical Physics Department within the School of Physics, the Australian Nuclear Science and Technology Organisation (ANSTO), the Commonwealth Scientific and Industrial Research Organisation (CSIRO), Professor T. Fujimoto of the Department of Engineering Science at Kyoto University, Japan, Dr I.G. Brown of the Lawrence Berkeley Laboratory, USA and colleagues in the Faculty of Engineering, Fukui University, Japan.

During the year Dr B. James spent three months at the Plasma Engineering Laboratory of Kyushu University, Japan, working on laser induced fluorescence measurements in magnetron discharges, Mr G. Turner completed his Ph.D. and took up a position at the Advanced Materials Research Laboratory of the IBM Thomas J. Watson Center in U.S.A. and Mr M. Ballico also completed his Ph.D. and is now working on the Wendelstein VII-AS stellarator at the Max-Planck-Institut für Plasmaphysik in Germany.

At the end of 1990, Professor M. Brennan left the University after 10 years as head of the Plasma Physics Department to become Chair of the Australian Research Council. The members of the department express their appreciation for his leadership during this period and offer him best wishes in his new appointment. To mark the occasion, at the end of the report are appendices listing the publications, higher degrees awarded and visitors to the department during the decade (1981-1990) of Prof. Brennan's tenure. From the beginning of 1991, Assoc.Prof. R.C. Cross will be head of the Plasma Physics Department.

We were pleased to welcome a number of visitors to the department this year: Professors M. Mekata, T. Idehara and T. Tatsukawa from Fukui University.

We are, as always, appreciative of the support given by our technical staff, P. Denniss, P. Maul, N. Lowe, J. Pigott, G. Marlin and K. Weigert, and by our able secretary, N. Bergagnin, to the research staff and students.

We acknowledge financial and other assistance received during the year from:

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Australian Institute of Nuclear Science and Engineering
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2. TORTUS

2.1 THE TORTUS TOKAMAK

The small research tokamak TORTUS is the major plasma source in the Wills Plasma Physics Department. It has a major radius $R = 44$ cm, a rectangular cross section, 25 cm × 33 cm, and is used primarily for the study of low-frequency waves ($\omega \lesssim \omega_{ci}$ where ω_{ci} is the ion cyclotron frequency) in plasmas. TORTUS can be operated routinely and reliably at toroidal currents of 40 kA for up to 30 ms.

2.2 OBSERVATIONS OF SHEAR ALFVEN WAVES AT FREQUENCIES ABOVE THE ION CYCLOTRON FREQUENCY

M.J. Ballico and R.C. Cross

The dispersion relation of the shear Alfvén wave is given to a very good approximation by

$$\omega^2/k_{\parallel}^2 = v_A^2(1 - \omega^2/\omega_{ci}^2) \qquad (2.1)$$

where v_A is the Alfvén speed and ω_{ci} is the ion cyclotron frequency. A distinguishing property of the shear wave is that the dispersion relation is essentially independent of $k_\perp$, where $k_\perp$ is the component of the propagation vector in a direction perpendicular to the steady B field. The group velocity vector is therefore directed almost exactly parallel to B and the wave propagates as a narrow beam if it is generated from a small antenna. The behaviour of the shear wave, when $\omega < \omega_{ci}$, is well documented. In this report we describe observations of the shear wave in the frequency range $2 < \omega/\omega_{ci} < 4$, where, from Eq. (2.1), $k_{\parallel}^2 < 0$.

The observations were made in the edge of a deuterium plasma in TORTUS, where $T_e \sim 10$ eV and $n_e \sim 10^{18}$ m^{-3}. The primary motivation was to measure the edge wave fields generated by a number of different fast wave antennas under conditions of interest for ICRF heating (i.e. $\omega \sim 2\omega_{ci}$), using a rather extensive array of magnetic probes. In addition to the expected fast wave modes, we also observed a strong, narrow beam which emerged from the antennas and which was guided along the steady magnetic field lines passing through the antennas. We identify the beam as a shear wave since (a) the beam is evanescent in a direction parallel to B, with an attenuation length (0.43 m) consistent with Eq. (2.1), (b) the beam is essentially transverse magnetic, (c) the beam is left hand polarized and (d) the group velocity vector is closely parallel to B.

A schematic diagram of the apparatus is shown in Fig. 2.1, and typical results observed with the poloidal magnetic probe array are shown in Fig. 2.2. All probe coils were fed to hybrid combiners to eliminate electrostatic pickup. These results were obtained with $B = 0.64$ T at $f = 18.0$ MHz, giving $\omega/\omega_{ci} = 3.7$. The sharp peaks in the probe signals are $m = +1$ cavity eigenmodes. The large signal observed near $\theta = 80°$ corresponds to the guided beam. The beam has a full width of 4 cm in both the radial and azimuthal directions, regardless of the distance from the antenna. There is no phase difference between different points along the beam but the beam amplitude decreases with distance from the antenna, hence it is evanescent.

Results obtained at other values of ω/ω_{ci} are shown in Fig. 2.3. The beam persists over a wide frequency range but it is strongly attenuated at $\omega/\omega_{ci} = 2$. The beam reappears at $t > 10$ ms since B decreases with time by about 10 % during the discharge. We attribute the disappearance of the beam (as well as the disappearance of $m = +1$ eigenmodes) to second harmonic damping in deuterium or to fundamental ion cyclotron damping of hydrogen which is present as an impurity due to wall recycling.

The above results were obtained with a small (10 cm × 4 cm) rectangular antenna loop located at the plasma edge and aligned with the 10 cm conductors parallel to the steady B field. The beam amplitude is a maximum in this orientation. When the antenna is rotated by 90° so that all conducting elements are transverse to B the beam amplitude is reduced by a factor of about three. The beam amplitude is further reduced, and the azimuthal width of the beam is increased, if the loop dimensions are increased to 20 cm × 4 cm. The addition of an electrostatic screen does not significantly reduce the beam amplitude. The azimuthal width of the beam is approximately the same as the azimuthal extent of the antenna.

The main significance of these results is that fast wave antennas, as used in ICRF heating experiments, couple not only to the fast wave but also to an evanescent $k_{\parallel}^2 < 0$ shear wave beam when $\omega > \omega_{ci}$. The beam is strongly damped if the $\omega = 2\omega_{ci}$ layer passes through the beam, a result which will contribute to undesirable edge heating in the vicinity of the antenna.

2.3 SUBMILLIMETRE LASER SCATTERING

B.W. James and M.D. Bowden

An optically pumped formic acid submillimetre laser operating at 433 μm has been used to detect by far forward scattering density fluctuations associated with waves

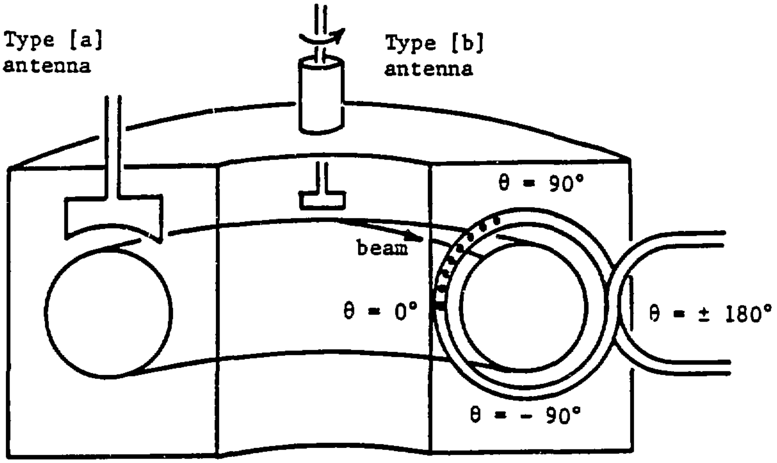

Fig.2.1: Experimental arrangement. The beam path from the small antenna to the 8 coil probe array is also shown.

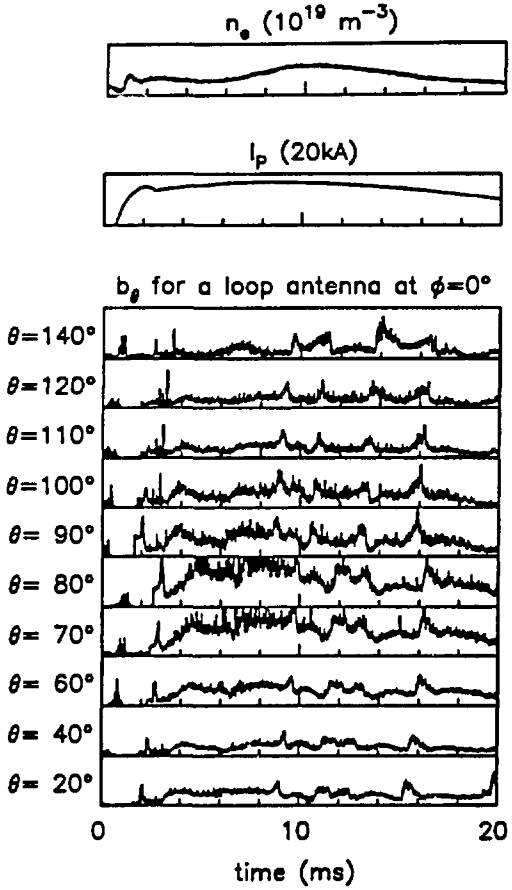

Fig.2.2: b_θ vs θ at $\omega/\omega_{ci} = 3.7$ showing fast wave eigenmodes and the strong shearwave beam centred around $\theta = 80°$. The antenna was located 67.5° toroidally from the probe array.

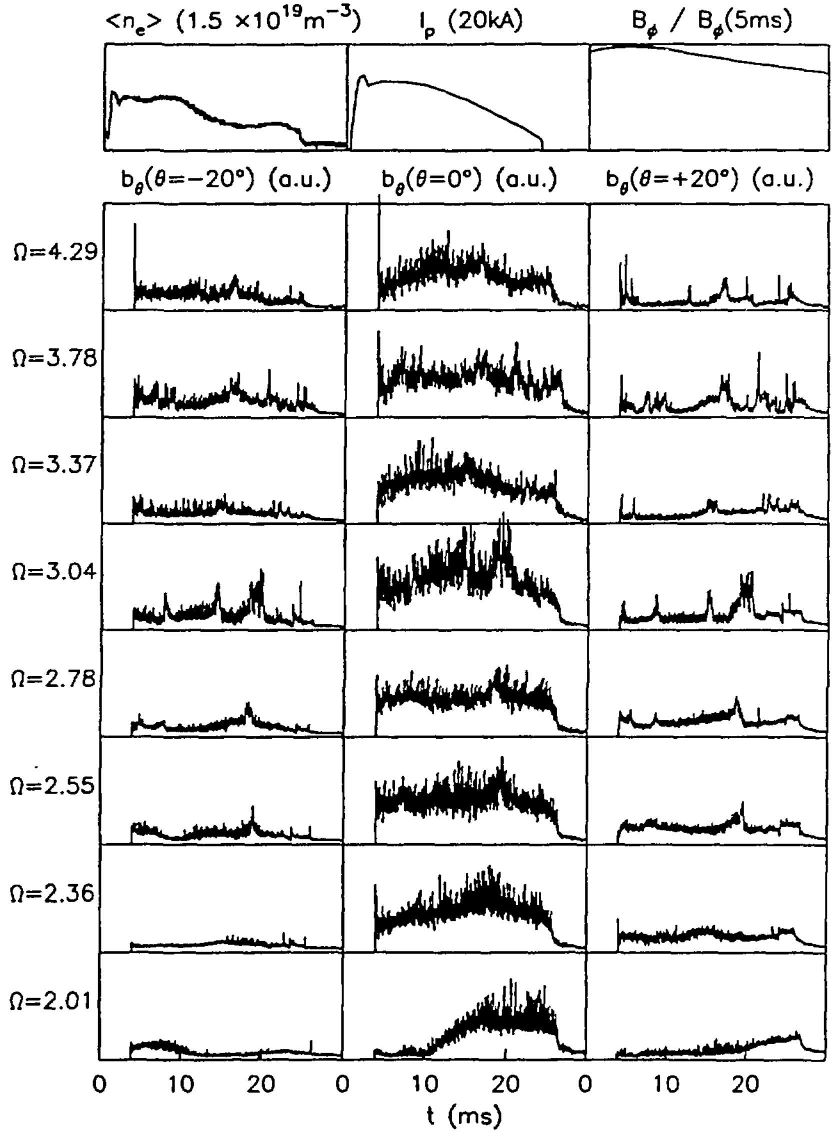

Fig.2.3: ***b_θ waveforms at three poloidal locations near the guided beam, for different values of $\omega = \omega/\omega_{ci}$. Note that θ is defined to be zero at the centre of the beam in this Figure.***

in TORTUS during Alfvén wave heating experiments. The scattering system is shown in Fig. 2.4. The laser beam waist, of diameter 8.4 mm, is located at the equatorial plane when the beam passes through the plasma centre and is displaced from this plane as the beam is translated across the plasma cross-section as shown in Fig. 2.4.

Figure 2.5 shows results from a typical TORTUS discharge in which scattering was detected. The top two traces show the plasma current and line averaged electron density along a vertical diameter. The latter is programmed to reach a maximum about 8 ms after breakdown then falls away. The third trace shows the amplitude of the poloidal wave magnetic field at the plasma edge and the bottom two traces are the amplitude and phase of the signal from the Schottky diode detector at the wave frequency. For this set of traces the laser beam was at chord r/a = 0.5 (on the outside of the torus).

The poloidal magnetic probe shows two strong peaks at the same value of electron density on both sides of the density maximum. As these peaks occur simultaneously on probes at different toroidal and poloidal locations, they are identified as being due to a discrete Alfvén wave (DAW) mode[1]. The signal from the scattering system is negligible at densities below that at which the DAW occurs and reaches its maximum value at densities above this when the DAW signal has disappeared and when a kinetic Alfvén wave resonance layer is expected to be present[1]. Figure 2.6 shows the amplitude of the scattering system signal as a function of the laser beam position at three times: (a) when the DAW was observed during the density rise; (b) when the density is a maximum and (c) when the DAW was observed during the density fall. Cases (a) and (b) show double peaked structure on each side of plasma centre while case (b), when scattering is strongest, shows a clearly different single peaked structure. This suggests that in case (b) the scattering is due to something other than a DAW mode, presumably a KAW resonance layer. In support of this identification calculations using a phase grating model for interaction of the laser beam[2] with expected density perturbations for DAWs and KAWs in TORTUS[3],[4] predict double and single peaked structures respectively.

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[1] Cross, R.C., An introduction to Alfven waves, *Adam Hilger Series on Plasma Physics*, IOP (1988).

[2] Evans, D.E., von Hellerman, M and Holzhauer, E., *Plasma Physics* 24, 819 (1982).

[3] Donnelly, I.J. and Clancy, B.E., *J. Plasma Phys.* (accepted)

[4] Donnelly, I.J., (private communication).

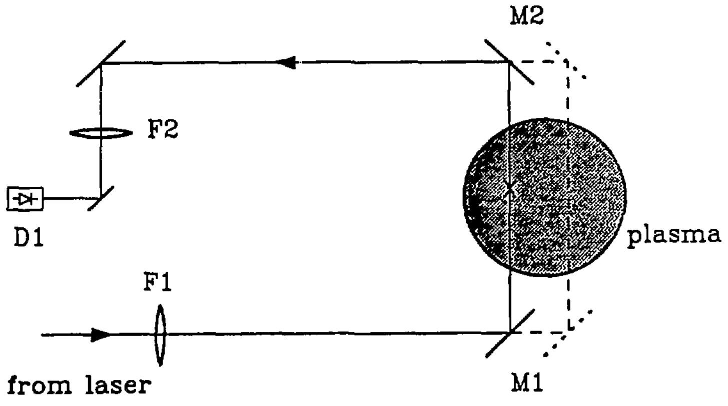

Fig.2.4 *The far-forward scattering system on TORTUS. The laser beam is focused to a waist in the plasma (X) by lens F1. Lens F2 focuses the beam on to D1, a Schottky diode detector which is placed at a beam waist. Mirrors M1 and M2 are movable, to allow the beam to scan across the plasma.*

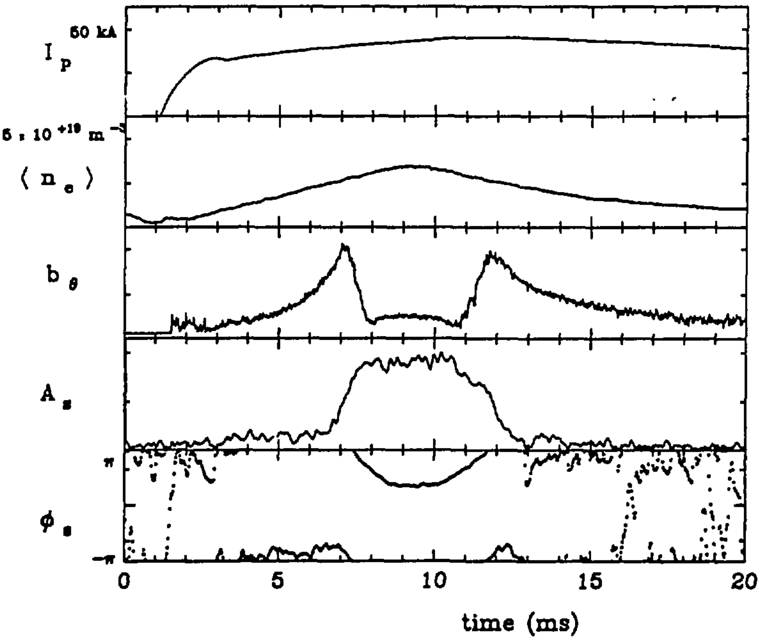

Fig.2.5 *Signals for a typical TORTUS Alfvén wave heating discharge: (a) plasma current; (b) average electron density; (c) poloidal wave magnetic field amplitude at the plasma edge; (d) and (e) amplitude and phase respectively of the scattering system signal for the laser beam at r/a = 0.5. The wave frequency is 3.2 MHz.*

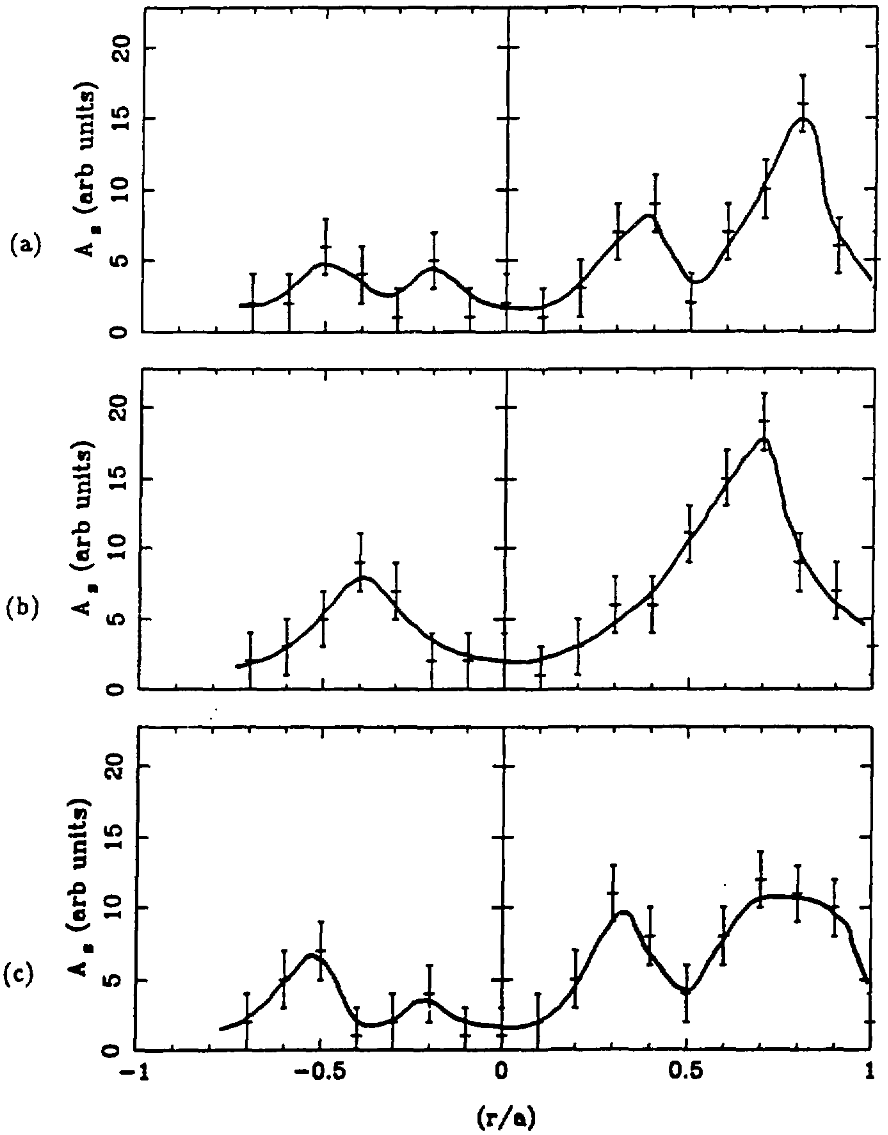

Fig.2.6 *The amplitude of the scattering system signal as a function of laser beam position for three different times during the discharge: (a) when the DAW was observed during the rise in density; (b) at density maximum and (c) when the DAW was observed during the fall in density.*

2.4 LASER INDUCED FLUORESCENCE

I.S. Falconer, N. Finn, J. Wilson, W. Wright

The aim of this project is to develop laser induced fluorescence (LIF) as a technique for investigating the properties of plasmas. During 1990 this work was directed towards the study of the basic physics of LIF in plasmas, and in particular the processes which determine the populations of excited states.

In this study a flashlamp pumped dye laser was used to pump the Balmer Hα transition ($n = 2$ to $n = 3$). This caused an enhancement in the population density of the n = 3 level which led to a collisionally induced enhancement of the $n = 4$ level population density giving rise to an increase in the Hβ emission. The LIF signals on Hα and Hβ transitions were measured as a function of electron density. Figure 2.7 shows the measured LIF Hα/Hβ plotted against electron density together with results predicted by a collisional radiative model. Clearly the experimental results do not agree with the calculated ratios.

Two collisional radiative models where used, one based on a paper by Johnson[5] and a more comprehensive model due to Fujimoto[6] . Both models were developed to study spontaneous emissions in a plasma; we have modified them to include laser excitation, hence allowing the prediction of LIF results. While there are significant differences in these models and some of their predictions for spontaneous emission intensity, they both give the same LIF Hα/Hβ ratio vs electron density curves.

Both models use semi-empirically derived values for transition cross-sections between excited states which have not been experimentally verified. The effect of changing these cross-sections in the Johnson program was examined. Even if the relevant cross-sections were changed by up to a factor of 10 the experimental data could not be made to agree with the calculated results.

It is possible that, due to the high intensity of the laser, the radiative transition rate between the $n = 2$ and $n = 3$ levels exceeds the collisional transition rate between the sublevels of these n levels[7]. This would lead to a non-statistical distribution of the populations of the sublevels. If this was the case the radiative transition rates in the

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[5] Johnson, L.C., *Astrophys. J.* **174** 227 (1972).

[6] Fujimoto, T. J., *Phys. Soc. Jpn* **54** 2905 (1985) and references therein.

[7] Sampson, D.H., *J. Phys. B.: Atom. Molec. Phys* **10** 749 (1977).

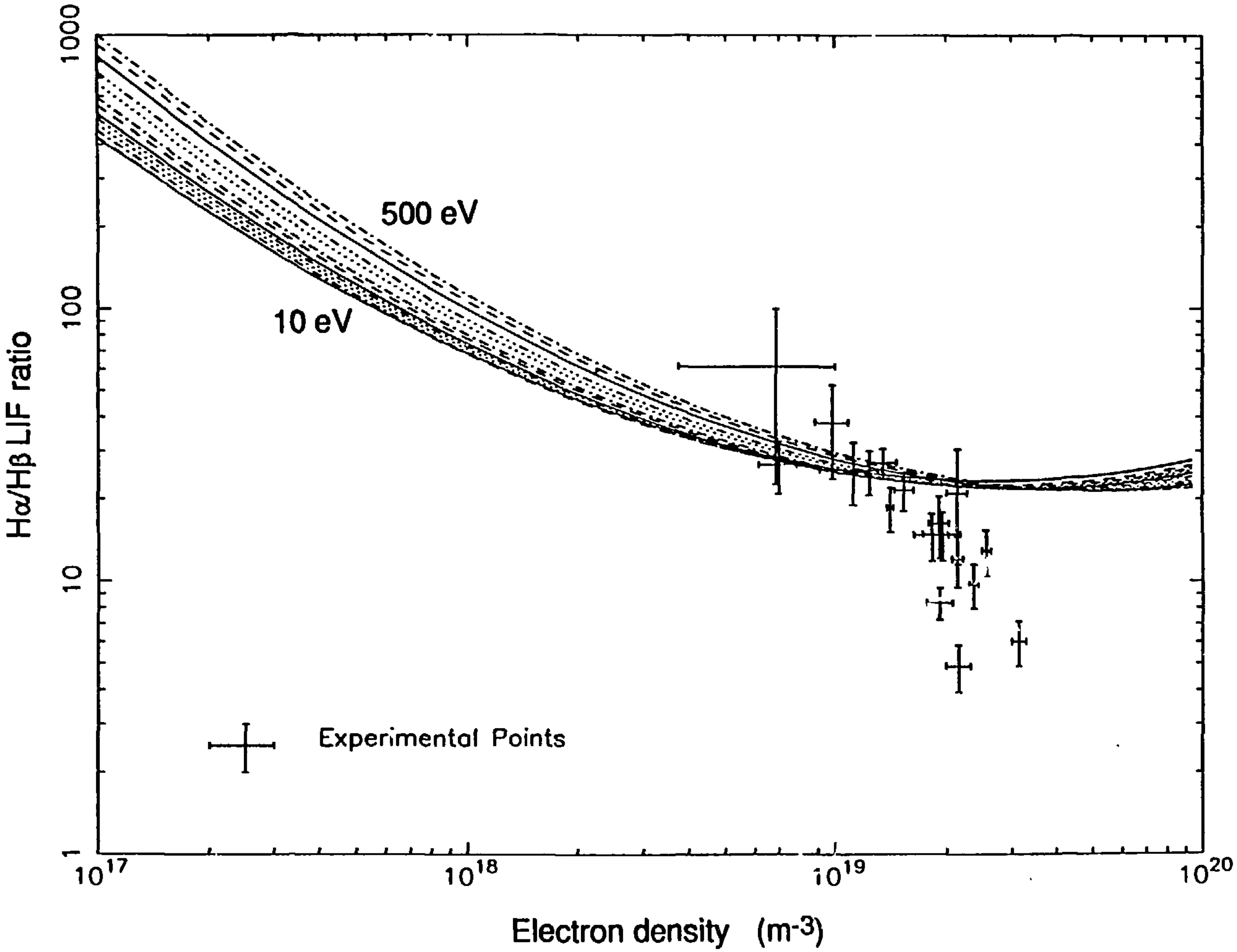

Fig. 2.7 Ratio of laser induced fluorescence on the Hα and Hβ transitions as a function of electron density. Points with error bars give the experimental values. The lines give the ratio calculated from a modified version of Fujimoto's collisional-radiative model for electron temperatures from 10 eV to 500 eV.

model as it stands would not be appropriate. The collisional-radiative model is being upgraded to include the l sublevels for the $n = 1$ to 5 levels of the H atom.

The effect of laser intensity on the ratio of LIF on the Hα/Hβ transitions was examined. It was found that the Hα/Hβ ratio did not vary with laser intensity. This suggests that the fields associated with the laser are not causing significant perturbation of atoms in the plasma[8].

We a [illegible]odifying the laser to lase at the Hβ wavelength so that the Hβ/Hγ ratio can be invest[illegible]. If the non-statistical distribution of electrons among the two sublevels is the [illegible] for the difference between theory and experiment the Hβ/Hγ ratio should be in better agreement with the theory as it stands. This is because for the higher ($n = 4$ and $n = 5$) energy levels the sublevels are closer in energy leading to a higher transition rate between these levels and hence to a population distribution which more closely approaches a statistical distribution of the population amongst these sublevels.

2.5 THOMSON SCATTERING ON TORTUS

N. Finn

The ruby laser Thomson scattering system for Tortus is now running routinely. The system layout is shown schematically in Figs 2.8 and 2.9. The details of the system are discussed in last year's annual report [9]. The optics have been slightly modified to make the path lengths to each photomultiplier equal and to increase the area of photocathode used in order to reduce the variation in sensitvity with alignment. Extra magnetic shielding has been added and the filter angles rearranged to avoid acceptance of H-alpha light by the fourth channel and to reduce background noise.

There are still problems with the reliable calibration of the relative sensitivity of the spectral channels. The method used for the results presented here was to measure the relative sensitivities using a LED with 30 nm half width centred on 660 nm and pulsed for 20 ns to illuminate a diffuser at the focus of the collection lens. This method is unsatisfactory because the spectrum of the LED is too narrow and results in too wide a range of signal amplitudes in the four channels and because the LED is not bright enough to uniformly illuminate the whole collection volume. The calibration factors so obtained do not always result in gaussian spectra for a range of temperatures as would be

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[8] Hirabayashi, A., Nambu, Y., and Fujimoto, T., *Jpn. J. Appl. Phys.* **25** 1563 (1986).
[9] Wills Plasma Physics, School of Physics, University of Sydney, *Annual Report* (1989)

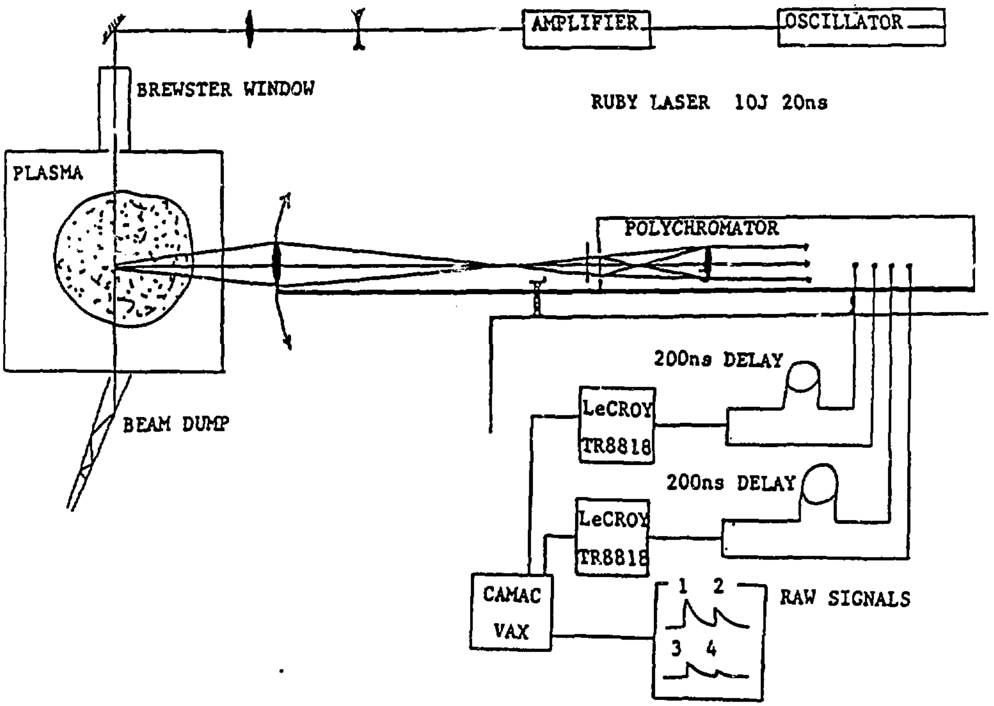

Fig. 2.8 Ruby laser Thomson scattering system on TORTUS

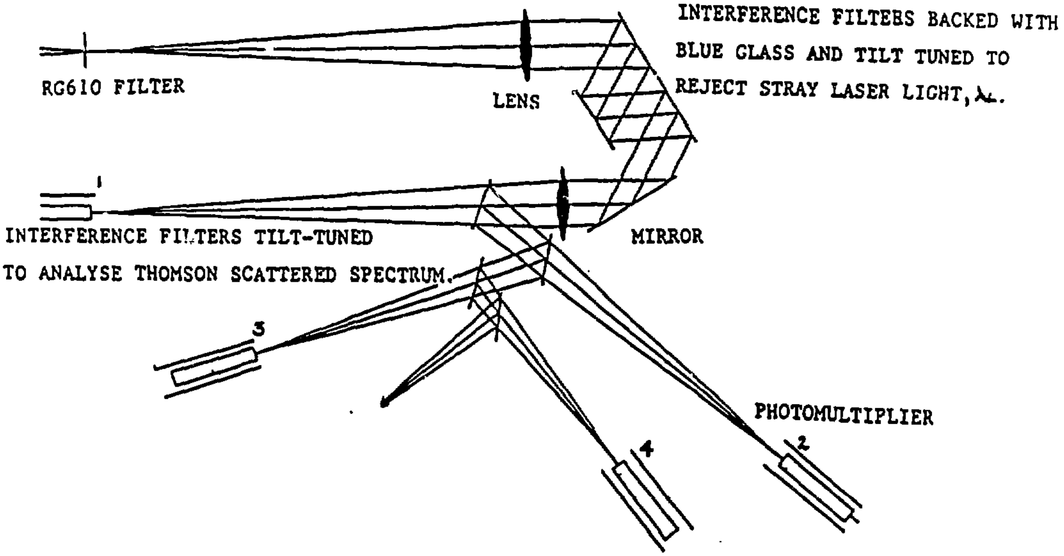

Fig. 2.9 Details of the polychromator for measuring the spectrum of the Thomson scattered radiation.

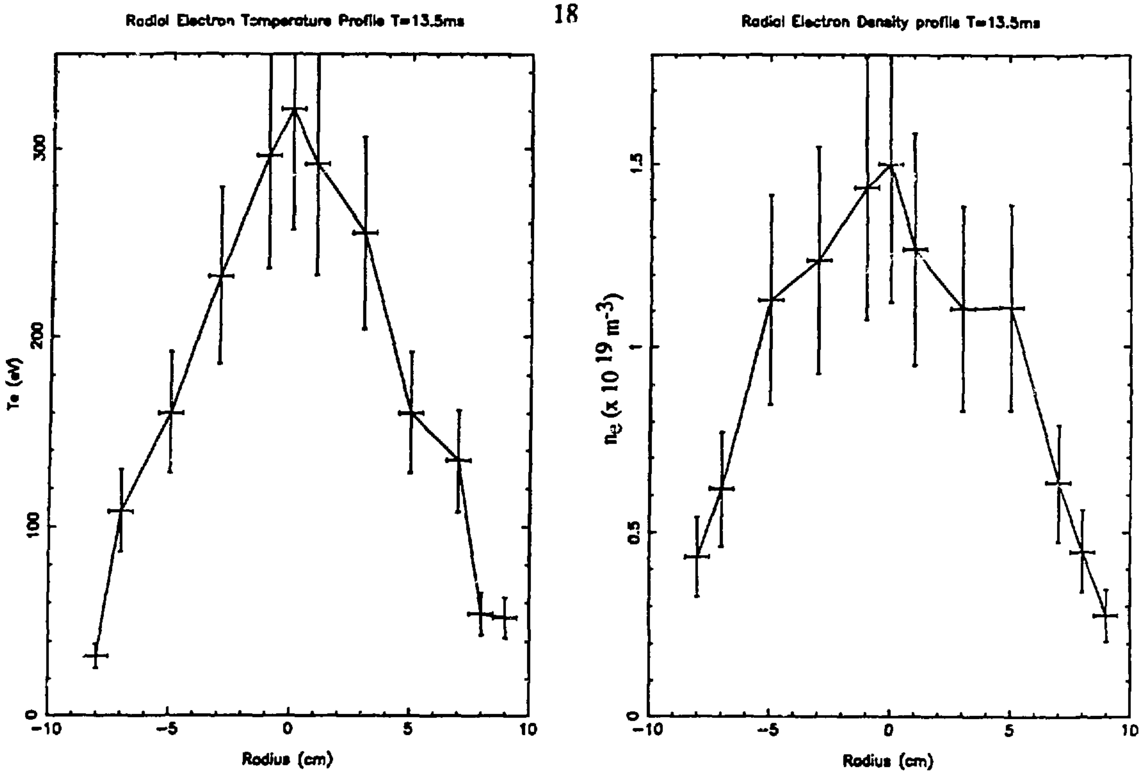

Fig. 2.10 Radial profiles of (a) electron temperature and (b) electron density for a 35 kA plasma in TORTUS.

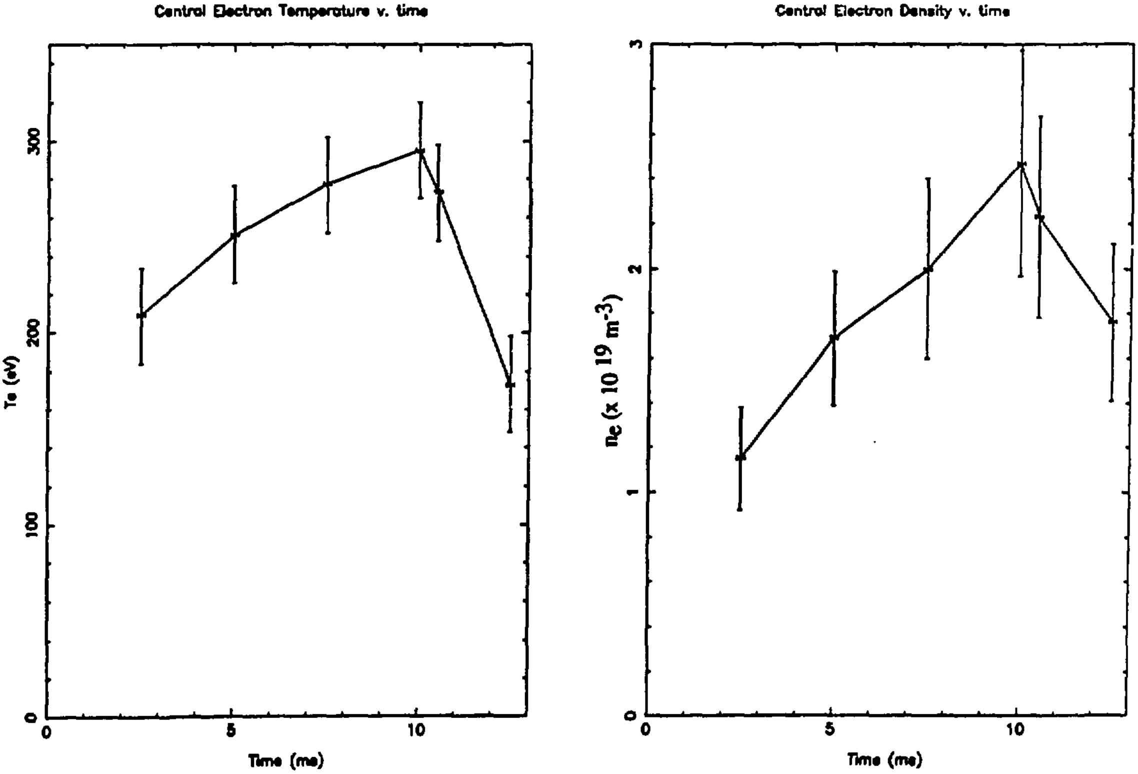

Fig. 2.11 (a) Electron temperature and (b) electron density on axis as a function of time for the first 10 ms of a 35 kA plasma in TORTUS.

expected, since the electron velocity distribution is always Maxwellian. However, the spectra obtained for a range of different times or radial positions i.e. different temperatures, can always be fitted to gaussian curves using one set of calibration factors. The combination of this fact and the calibration factors obtained using the LED give reasonably reliable temperature profiles but the errors are uncertain. The errors in the temperature and density measurements have been estimated to be 20% and 25% respectively, from the range of calibration factors measured and the statistical variation in scattered signals. Radial profiles of electron temperature and density have been obtained for 35 kA plasmas and temporal profiles obtained for the first 10 ms of a similar plasma at the centre and at $r = 5$ cm. Some of these are shown in Figs 2.10 and 2.11. The density is calibrated against the chord average measurement made by a microwave interferometer.

Various methods to overcome the calibration problem will be attempted soon and these include an array of LEDS to give a brighter and more spectrally and spatially uniform source, Rayleigh scattering with a dye laser from nitrogen in the plasma vessel and Raman scattering with the ruby laser from hydrogen[10]. The latter two will provide an absolute as well as relative calibration. Simpler methods of calibration are precluded by the design of the system.

The apparatus will then be used to measure the time history of the radial temperature and density profiles over the whole life of the plasma for a variety of plasma types including plasmas of low density and high temperature which might be favourable to Alfvén wave current drive experiments.

2.6 GYROTRON DIAGNOSTICS

G.F.Brand, P.W. Fekete, K. Hong, T. Idehara

Gyrotron IVA is used as a source of millimetre wave radiation for scattering experiments on the TORTUS tokamak.

Beam Formation

Power losses associated in coupling radiation from the gyrotron to an experiment (scattering, interferometer, etc) have been attributed to mode conversion of the high order modes in the waveguide at the corner reflectors.

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[10] Howard, J., James, B.W. and Smith, W.I.B., *J. Phys. D: Appl. Phys.* 12 1435 (1979).

For this reason we have now mounted the quasi-optical antenna directly on top of the gyrotron. The beam from the antenna couples into an oversized waveguide and travels along it from the gyrotron to the tokamak as the $TE_{1,1}$ mode, with very much reduced losses, even though there are three corner reflectors present. Over 1 W of power is delivered to the tokamak.

Profiles of the radiation pattern emerging from the end of the waveguide show a gaussian like beam with the waist parallel to the electric field larger than the waist perpendicular to the electric field, as expected. However, these beam waists are slightly larger than predicted, possibly due to the presence of some of the $TE_{1,2}$ mode, resulting in less divergence of the beam, fortunately to our advantage (see Fig. 2.12).

Scattering

Figure 2.13 shows the arrangement for scattering on the TORTUS tokamak. Radiation from the end of the oversized waveguide is focused, using a gaussian telescope, on to the centre of the plasma. Another lens at the opposite side of the tokamak collects the scattered beam and focuses it on to another oversized waveguide which takes it to a crystal detector and amplifiers. The DC level is recorded for normalisation. Quadrature mixing is used on the RF signal.

In our experiments the RF was set at 3.2 MHz. Two RF antenna pairs were used to launch radiation into the tokamak. The relative phases of the two antenna pairs were varied, however only the $n = -1$ mode was excited in the plasma[11]. Two magnetic probes were used to confirm the identity of a mode produced. The plasmas were produced with high currents at a high magnetic field (35 kA, 1.2 T). The tokamak was puff filled on top of a background level to achieve the required density ramp and fall.

Good scattered signals were observed radially across the plasma (see Fig. 2.14), corresponding to the $n = -1$ mode and sometimes the $n = -2$ mode if the peak density was great enough. Results for the $n = -1$ mode indicate a resonance layer at $r/a = 0.5$. For the $n = -2$ mode a resonance layer is seen at the plasma centre (see Fig. 2.15).

A variation in the amplitude and phase of the scattered signal occurs at about 1.5 kHz (see Fig. 2.16). This is only observed at the centre of the plasma. This indicates the possibility of sawtooth behaviour in the tokamak. Sawtooth activity stems from fluctuations in the current density of the plasma, which in turn affects the excitation of DAW

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[11] Ballico, M.J., *Alfven waves in the TORTUS tokamak*, Ph.D. Thesis, University of Sydney (1990).

modes, described by the dispersion equation. A soft X-ray detector has been installed on the tokamak to independently confirm sawtooth activity.

The above scattering has been done at several gyrotron frequencies taking advantage of the tunability of the gyrotron. In the future it is hoped to take greater advantage of this feature by scattering at a fixed angle while varying the frequency. Construction is under way for a multiple beam system to scatter at four radial positions at once. This will be tested in 1991.

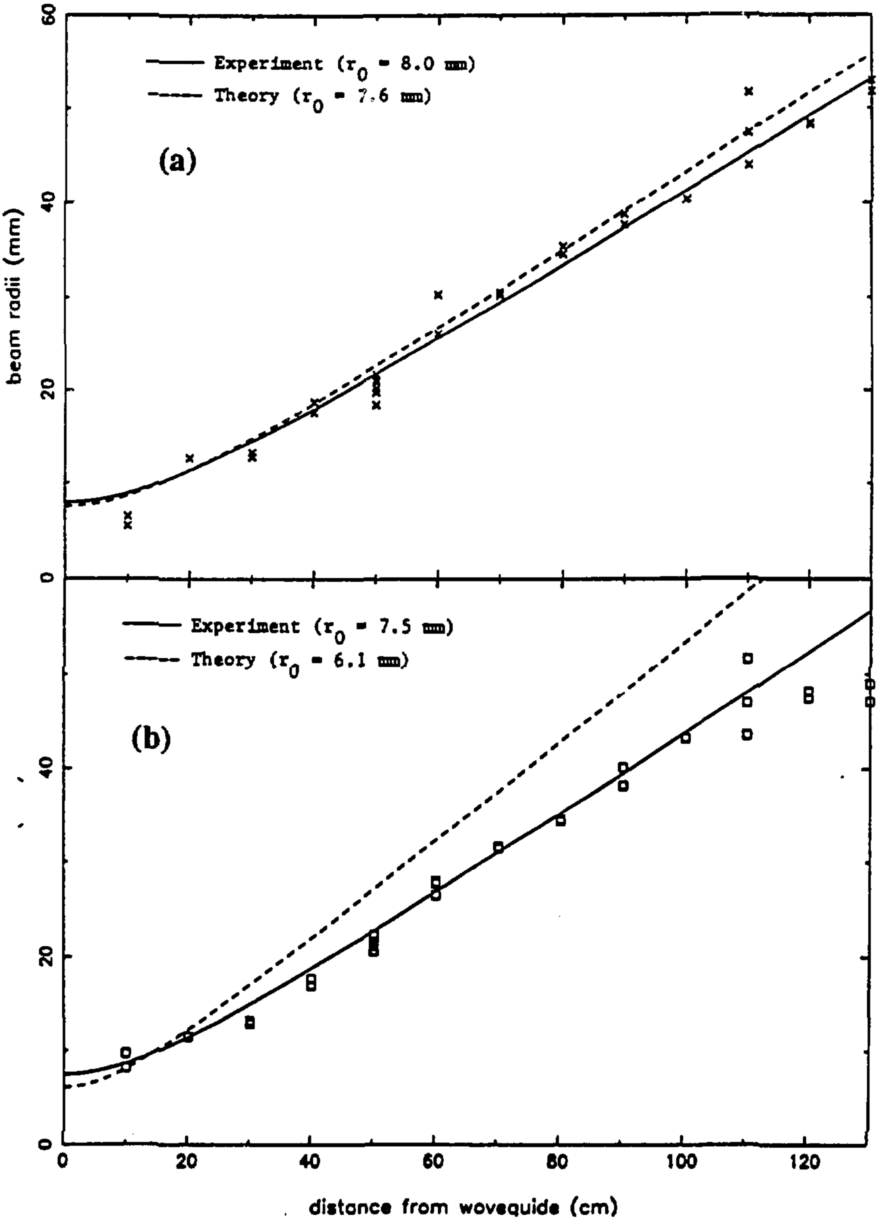

Fig. 2.12 Beam waist from an open waveguide. (a) parallel to electric field. (b) perpendicular to electric field.

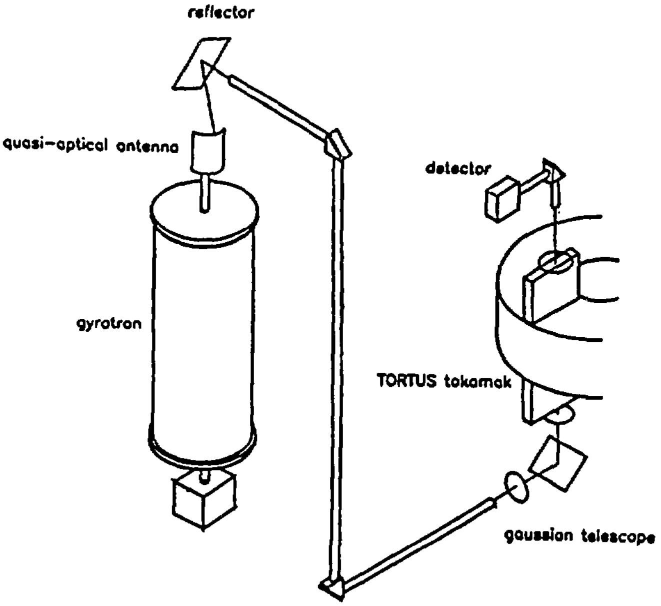

Fig. 2.13 *Experimental arrangement for scattering on the TORTUS tokamak. The quasi-optical antenna on top of the gyrotron couples radiation to the tokamak via an oversized waveguide with three corner reflectors and a gaussian telescope.*

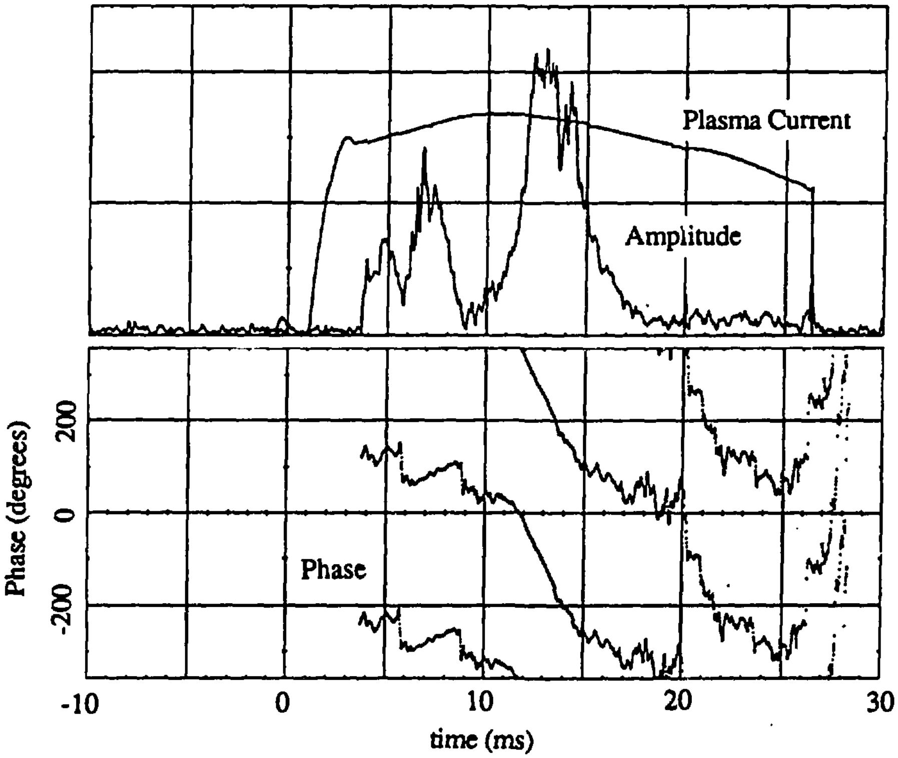

Fig. 2.14 *Scattered signal, amplitude and phase, for the n = -1 mode at r/a = 0.5. Gyrotron frequency is 218.8 GHz ($TE_{1,11,1}$ mode).*

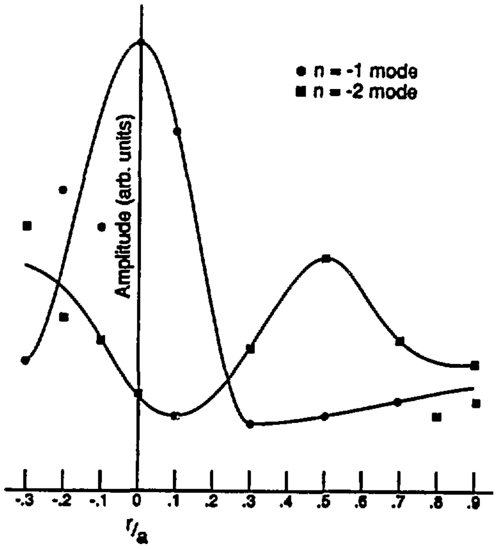

Fig. 2.15 Amplitude versus radial position for the n = -1 and n = -2 modes in the tokamak.

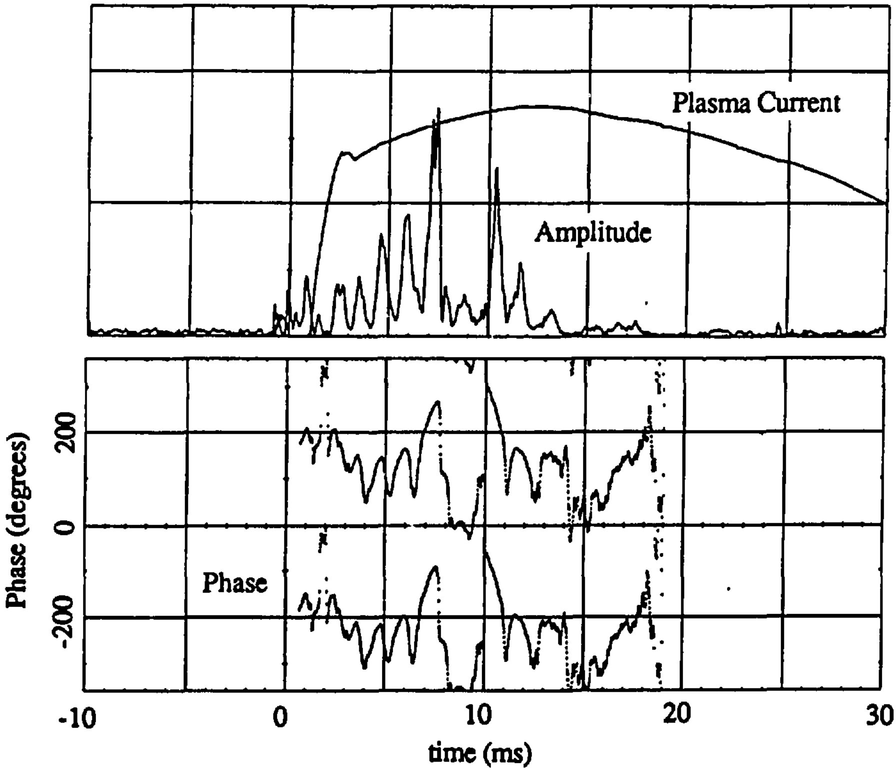

Fig. 2.16 Evidence of sawtooth activity, amplitude and phase at r/a = 0.0. Gyrotron frequency 180.0 GHz ($TE_{1,9,1}$ mode).

3. ALFVEN WAVE THEORY

3.1 KINETIC THEORY OF ALFVÉN WAVES IN PLASMAS WITH FORCE-FREE CURRENTS

I.J. Donnelly and B.E. Clancy[a]

We have derived wave equations that give a kinetic theory description of Alfvén wave heating of cylindrical plasmas with force-free currents. These equations are applicable to reverse field pinch configurations, as well as tokamaks. They have been incorporated in the code ANTENNAS and used to calculate the antenna impedance and the density fields associated with Alfvén resonance heating in a small tokamak. The main results are as follows.

(i) The plasma models considered indicate that, even in a small tokamak, measurements of the discrete and kinetic Alfvén wave density fields can give useful information on the plasma density and current profiles, although a precise determination of the Alfvén resonance position in the central region of the plasma will be difficult.

(ii) Further information on these profiles can be obtained from observation of the existence or absence of discrete Alfvén waves as a function of toroidal wavenumber.

(iii) For plasma and wave parameters such that two Alfvén resonance positions are present, the energy deposition and the wave fields are concentrated at the outer one.

(iv) For a poloidal loop antenna, the antenna resistance and wave field amplitudes for waves with toroidal and poloidal mode numbers n and m, increase strongly with $|n|$ for n small and $m \neq 0$.

(v) MHD and kinetic theory predictions of antenna resistance agree, provided negligible shear Alfvén wave energy returns to the Alfvén resonance position following reflection from the plasma centre or edge.

3.2 ALFVÉN WAVE CURRENT DRIVE

I.J. Donnelly

Efficient current drive using Alfvén waves requires that the following conditions are met.

(i) Existence of a discrete or a compressional Alfvén wave eigenmode, and efficient mode conversion to the kinetic Alfvén wave when the Alfvén resonance position lies in the central plasma region; in TORTUS this is best achieved for waves with

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[a] ANSTO

poloidal mode number $m = -1$ and toroidal mode number $n = -1$ or -2, and a plasma with safety factor $q(0) \approx 1$.

(ii) Good coupling of the antenna system to the discrete or compressional wave; for the (n,m) mode, this is optimised by aligning the antenna current elements in the $\theta - \phi$ plane at an angle $\psi = -\tan^{-1}[nr_a/mR]$ to the toroidal direction, where r_a is the radial position of the antenna and R is the major radius.

(iii) Strong electron Landau damping of the discrete or kinetic Alfvén waves; this requires $v_A/v_{te} \leq 2$.

(iv) High rf–driven current to power ratios; under the constraints in (iii) this requires medium to low densities and high temperatures.

Optimisation of all these conditions indicates that current to power ratios $I/P \approx 1$ A/W should be achievable in TORTUS if the following plasma conditions can be obtained: $n_e \approx 1 \times 10^{18}$ m^{-3}, $B_\phi = 0.4$T, Ohmic current $I_\Omega = 10$ kA and $T_e = 100$ eV. With the presently available rf power supply, in excess of 10 kA could be driven.

3.3 DENSITY FIELDS OF THE DISCRETE AND KINETIC ALFVÉN WAVES

I.J. Donnelly

Laser and microwave scattering techniques have and are being used to detect the density oscillations associated with Alfvén waves in TORTUS. The incident beam

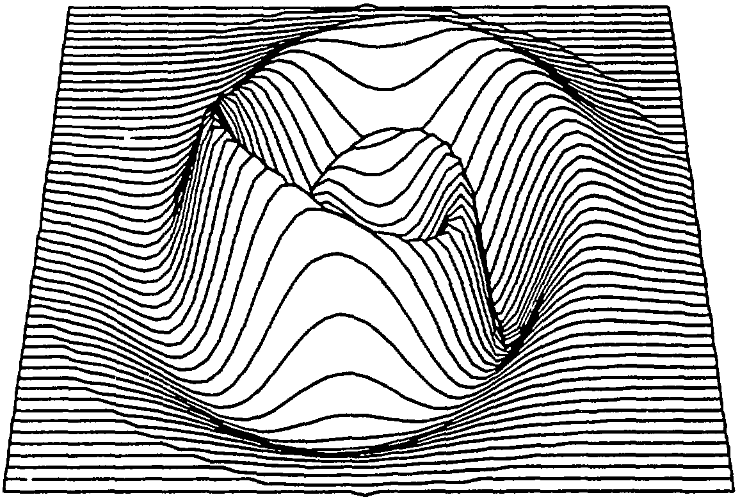

Fig. 3.1 Kinetic Alfvén wave density perturbation in the $r - \theta$ plane of a TORTUS plasma

traverses a chord in the $r - \theta$ plane (fixed toroidal position), and therefore samples the wave fields over a range of radial positions. To help visualise the density perturbations in the tokamak, analytic expressions for discrete and kinetic Alfvén wave density fields have been developed and used to plot the density perturbation in the $r - \theta$ plane at a fixed time. The analytic expressions can reproduce well the wavefields obtained from the ANTENNAS code. Fig. 3.1 shows typical results for a case in which the poloidal wavenumber is $m = -1$, and the Alfvén resonance position lies halfway between the plasma centre and the edge. This density perturbation will rotate in a clockwise direction around the central axis with time. The maximum amplitude of the electron density oscillation is predicted to be about 10^{17} m^{-3}.

4 SUBMILLIMETRE LASERS AND OPTICS

4.1 SUBMILLIMETRE LASER DEVELOPMENT

P.J. King, M.D. Bowden, B.W. James, I.S. Falconer, L.B. Whitbourn[a]

Efforts to improve the efficiency of cw optically pumped submillimetre laser have, to date, concentrated on optimising the diameter of the waveguide resonator[12] and on developing output couplers that are highly reflecting for the pump radiation and transmit the desired fraction of the submillimetre radiation[13]. Little attention has been given to improving the pumping geometry of the lasers.

Our Brewster window submillimetre laser[14], which uses a CO_2 pump beam of uniform cross-section has been used to investigate the effect of changing the pump beam diameter. Fig. 4.1 shows the output power of the 433 µm line of formic acid as a function of the pump beam diameter for a constant pump power of 25 W. The diameter of the pump beam was determined by measuring the diameter of the image of the beam on a thermal imaging plate. The output coupler, a strip grating with a reflectance of 87% was not necessarily optimum for the laser. Fig. 4.1 shows that there is clearly an optimum pump beam diameter of approximately 25 mm.

4.2 DEVELOPMENT OF RESONANT ARRAY LASER INPUT COUPLER

P.J. King, P.A. Krug[b]*, B.W. James, I.S. Falconer, W. Wright*[c]*,*
J.C. Macfarlane[c] *and L.B. Whitbourn*[a]

For a cw optically pumped submillimetre laser the ideal input coupler would be highly reflective at far infrared wavelengths and completely transparent at the pump wavelength. In an attempt to achieve performance approaching this ideal we are constructing input couplers consisting of an array of conducting rings on a ZnSe

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[a] CSIRO Division of Exploration Geoscience

[12] Whitbourn, L.B., Macfarlane, J.C., Stimson, P.A., James, B.W. and Falconer, I.S. *Infrared Phys.* **28** 7 (1988)

[13] Krug, P.A. Dawes, D.H., McPhedran, R.C., Wright, W., Macfarlane, J.C. and Whitbourn, L.B., *Optics Lett.* **14** 931 (1989)

[14] King, P.J., James, B.W., Falconer, I S. and Whitbourn, L.B., *Infrared Phys.* 30 359 (1990)

[b] Optical Fibre Technology Centre, University of Sydney

[c] CSIRO Div of Applied Physics

substrate. Such a structure behaves as a notch filter for wavelengths comparable to the circumference of the rings; at the resonant wavelength the reflectance has a maximum and the transmittance has a minimum. Fig. 4.2 shows the measured transmittance and reflectance in the millimetre/submillimetre region (100-1500 GHz; 0.2-3 mm) for an input coupler with a resonance at approximately 300 GHz (1 mm). At the CO_2 laser pump wavelength, well below the resonant wavelength, the transmittance is determined by the fraction of the substrate which is not coated and is in excess of 90%. The use of these input couplers would allow pumping of the submillimetre laser by a pump beam of uniform diameter.

Preliminary testing of the input coupler whose characteristics are shown in Fig. 4.2 on the 746 μm line of formic acid proved unsuccessful. It is suspected that the 746 μm line was too far away from the resonant wavelength of approximately 1 mm (300 GHz) and hence the far infrared losses would have been too high. Fabrication of input couplers suitable for use with the stronger formic acid lines in the vicinity of 400-500 μm is under way.

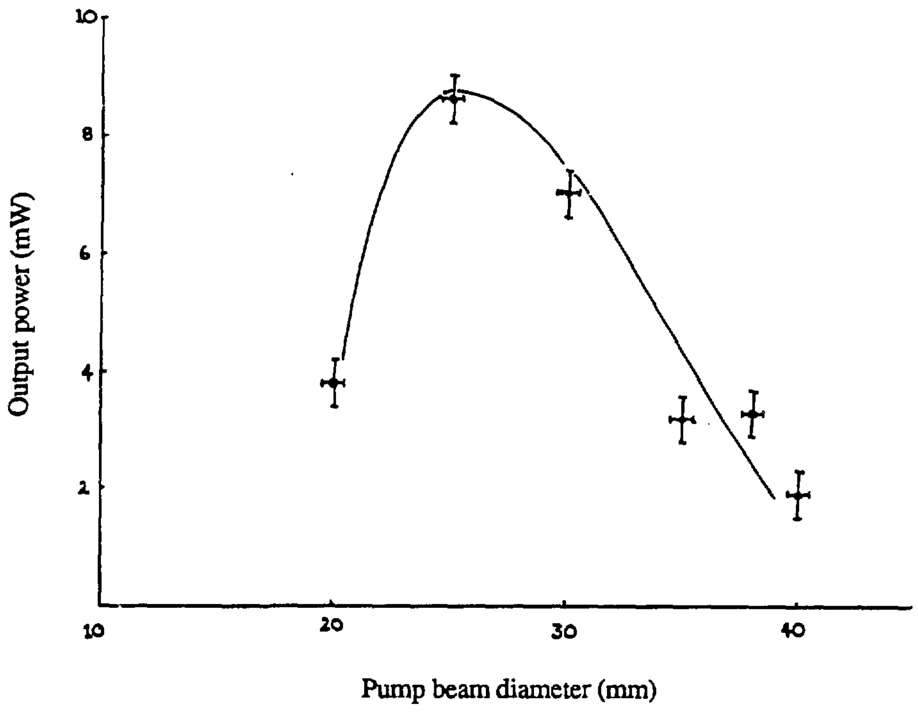

Fig. 4.1 Output power at 433 μm as a function of pump beam diameter for a pump power of 25 W.

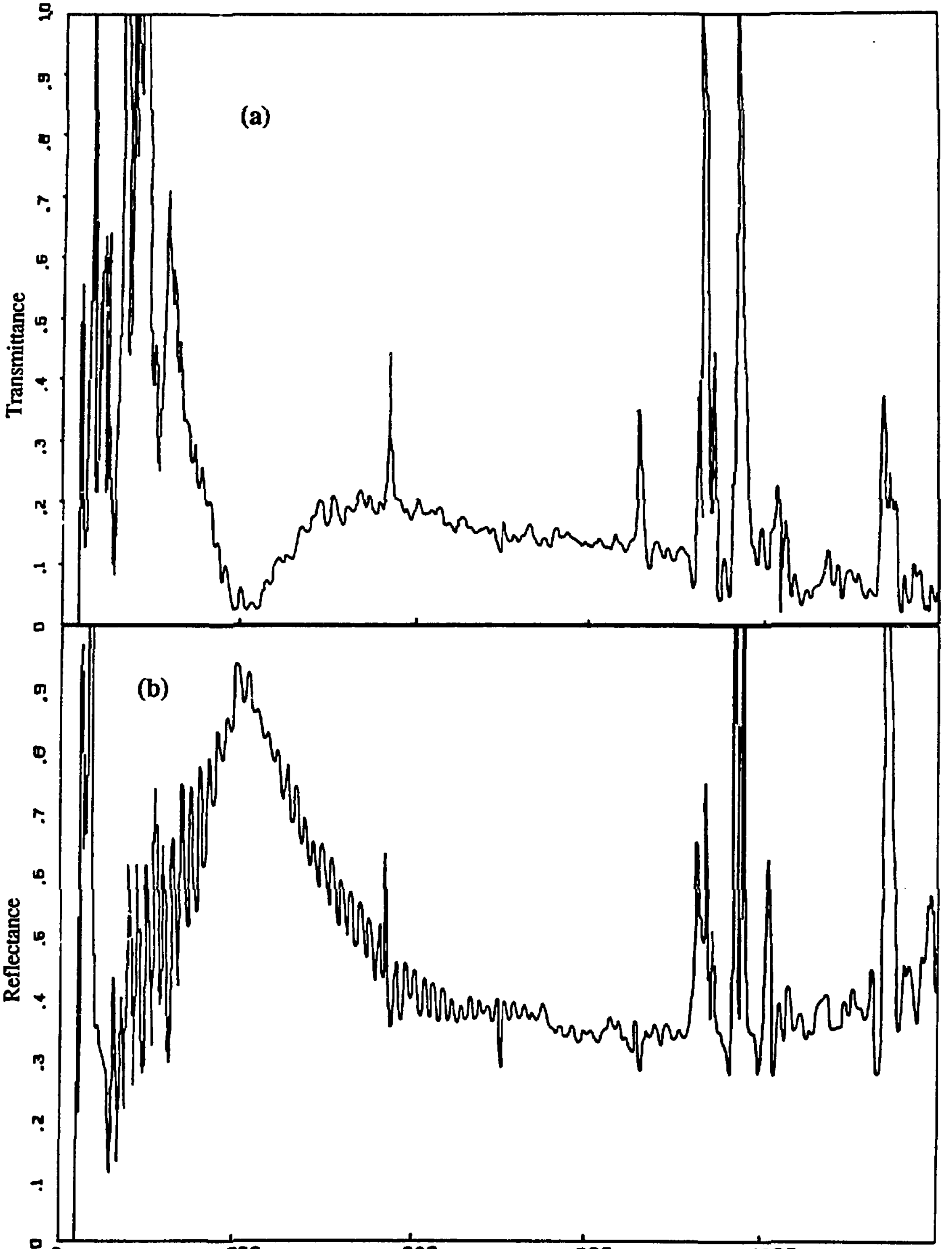

Fig. 4.2 (a) Transmittance and (b) reflectance of an input coupler with resonance near 300 GHz.

5. GYROTRON DEVELOPMENT

5.1 GYROTRON IVA

G.F.Brand, K.Hong, P.W.Fekete, T.Idehara[a] *and T.Tatsukawa*[a]

GYROTRON IV is a step-tunable source which produces an output exceeding 20 W CW over a broad range of frequencies from 100-300 GHz. The original cavity has been replaced by a new one (hence the IVA designation) with a much longer output taper (190 mm as opposed to 35 mm) in order to reduce mode conversion in the taper (Fig. 5.1). The resonant frequencies are slightly higher which indicates that the radius of the new cavity is about 0.2 mm smaller.

Our recent gyrotrons have used a simplified power supply arrangement to provide the voltages on the gun electrodes (Fig. 5.2). The cathode supply is conventional, but the anode voltage is provided by a single high-value resistor connected between the anode and ground. A small fraction of the electrons in the beam are reflected and the anode automatically finds an optimum operating potential. Fig. 5.3 shows calculated and observed anode potentials. The full line is calculated using a simple adiabatic approximation and the broken line is obtained by using the EGUN electron trajectory program[15]. The EGUN results are in good agreement with the potentials measured at low beam currents (open circles).

We have used this program to examine the axial velocities of the electrons in the cavity and their injection radii (the radial distance of the electron from the cavity axis). Figure 5.4 shows these quantities for 21 electrons which have started from uniformly-spaced points along the narrow cathode emitting ring. At B=6.2 T and V_{AR}=1.20 kV a small fraction of the electrons are reflected and many others move slowly along the cavity. At higher values of V_{AR} no electrons are reflected and all of the electrons are moving rapidly along the cavity.

One consequence of having slow moving electrons is to lower the starting currents (Fig.5.5). Two advantages follow. It becomes easier to operate low-power gyrotrons with modest power supplies and it becomes easier to achieve higher frequencies by exciting harmonics of the electron cyclotron frequency.

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[a] Faculty of Engineering, Fukui University, Japan

[15] Hermansfeldt, W.B., SLAC Report 331 (1988)

5.2 SECOND HARMONIC OPERATION AND GYROTRON V

G.F.Brand, K.Hong, P.W.Fekete and T.Idehara[a]

One of the current aims of gyrotron research is to generate shorter and shorter submillimetre wavelengths. Operation at the fundamental of the electron cyclotron frequency is limited by the maximum field of the superconducting magnet. Ours is a 12 T magnet. Second harmonic operation allows the maximum frequency to be doubled.

At certain magnetic fields, GYROTRON IV operates at the second harmonic of the electron cyclotron frequency. We have observed small amounts of power at frequencies as high as 522 GHz (a wavelength of 0.57 mm).

We have designed a new gyrotron, GYROTRON V, to try and obtain more power at the second harmonic. The electron gun will be similar to GYROTRON IV but the cavity will have a smaller radius to increase the likelihood of second harmonic operation by reducing competition from nearby fundamental resonances.

Extensive simulations have been carried out (i) to determine whether the output end of a cavity should or should not have a step before the tapered transition into the output waveguide (we have chosen to have a small step from a radius of 3.0 mm in the cavity to a radius of 2.7 mm) and (ii) to see how the starting current for the second harmonic operation is affected by the distance from the electron gun to the cavity. The starting current calculations have also revealed how sensitive the starting current is to the coincidence of the gyrotron and magnetic field axes. Fortunately, a small misalignment (even as small as 2 mm at the electron gun) usually allows the gyrotron to start at lower currents. Construction of GYROTRON V has commenced in our workshop.

5.3 DUAL BEAM INTERFEROMETER

G.F.Brand, and L.Elfassy[b]

This dual-beam interferometer will use the gyrotron, together with a quasi-optical antenna, as a radiation source and will allow the precise measurement of the complex dielectric constants of materials (Fig. 5.6). A prototype, using a 120 GHz impatt source, has been tested. The refractive indices of several plastics were measured.

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[a] Faculty of Engineering, Fukui University, Japan

[b] Physics III student

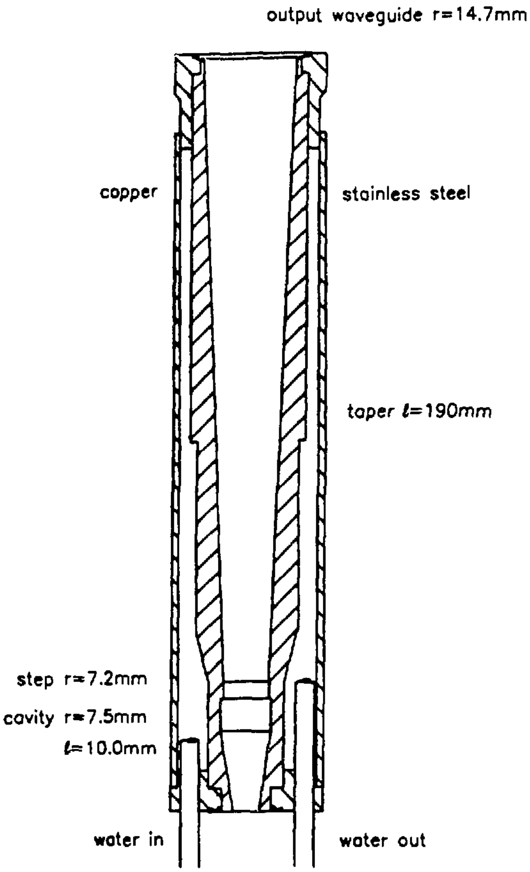

Fig. 5.1 GYROTRON IVA cavity with the longer output taper.

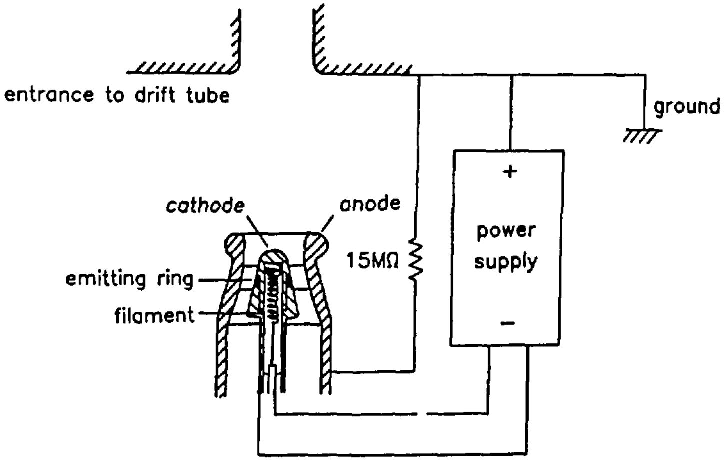

Fig.5.2 The simplified power supply used with GYROTRON IVA.

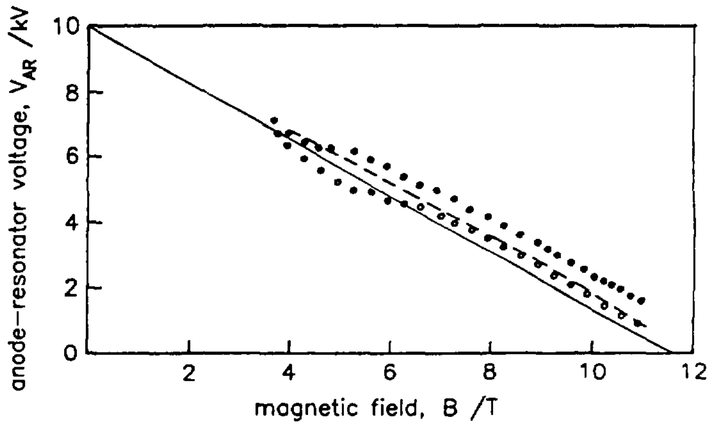

Fig. 5.3 *Anode potential V_{AR} vs. magnetic field B.*

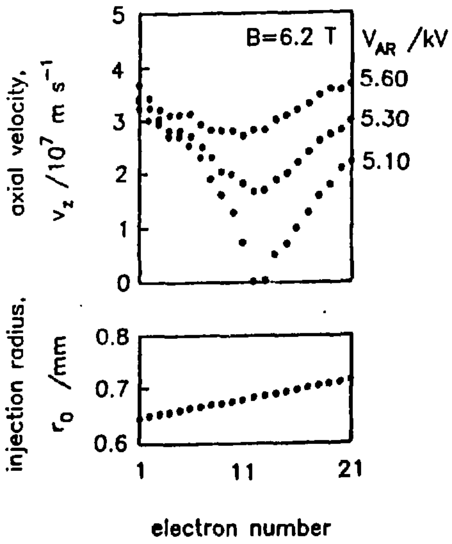

Fig. 5.4 *Axial electron velocity v_z and injection radius r_0 in the cavity for 21 electrons.*

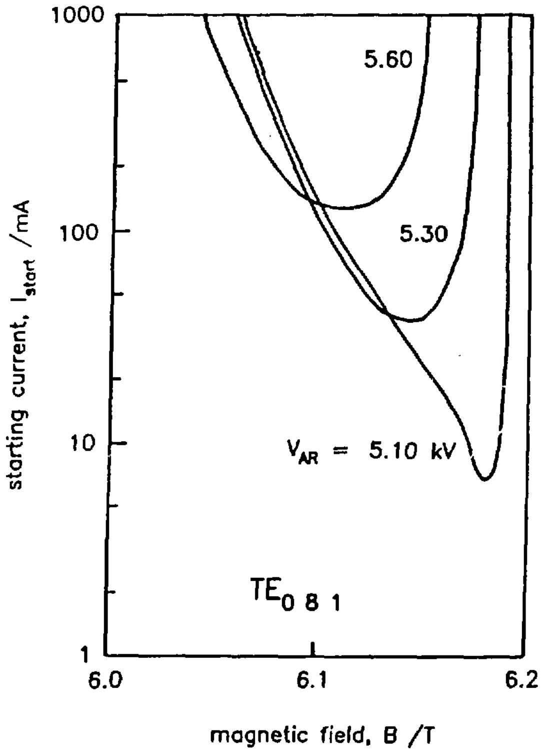

Fig. 5.5 Starting current I_{start} vs. magnetic field B.

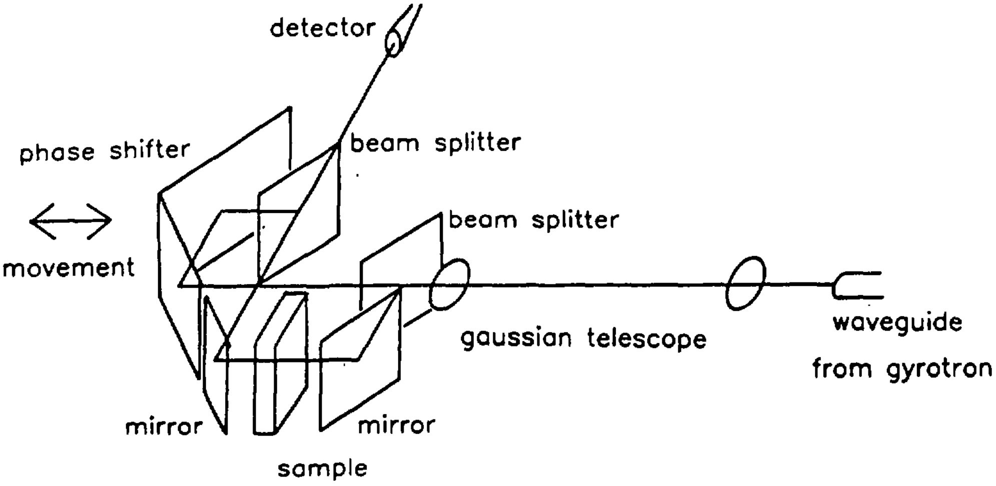

Fig 5.6 Dual-beam interferometer for measuring the dielectric constant.

6. GAS DISCHARGE STUDIES

This project was initially concerned with investigating the basic physics of the magnetron sputtering discharges employed by the Department of Applied Physics for the production of thin films for various commercial and scientific applications. The spectroscopic techniques we developed for studying the energy distribution of atoms sputtered from the cathode of a magnetron discharge from the shape of their emission lines have also been applied to the investigation of both the ion and neutral atom 'temperature' in the vicinity of the cathode spot of both pulsed and continuous vacuum arcs. Dr D R McKenzie, P D Swift, a postgraduate student, and technical staff of the Department of Applied Physics are collaborating with us in this project.

6.1 MAGNETRON SPUTTERING DISCHARGE STUDIES

I.J. Donnelly[a], *I.S. Falconer, B.W. James, D.R McKenzie,*[b]
G.M. Turner , T.A. van der Straaten[c] *and H-J. Kim*[c]

An extensive theoretical and experimental study of the interaction of sputtered atoms with atoms of the filling gas, and the influence of these collisions on the properties of the flux of sputtered atoms on to a substrate, has been completed, apart from measurements of the density distribution of the sputtered atoms between the cathode and the substrate.

The Monte Carlo computer code developed to study these interactions (see 1986, 1988 and 1989 Annual Reports) has achieved the following:

- Calculation of the average energy and velocity distribution of copper atoms sputtered by argon filling gas as a function of gas pressure, distance from the cathode and cathode-substrate separation
- The average impact energy and the angular distribution of the sputtered atoms as they reach the substrate, and the fraction which reach the substrate, for a range of cathode materials sputtered by argon.
- the energy dependence of the angular distribution of the sputtered atoms which reach the substrate, again for a range of cathode materials sputtered by argon.

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[a] On attachment from ANSTO
[b] Department of Applied Physics
[c] Physics IV student

- The spatial distribution of the sputtered atoms for a point source and the 'racetrack' of a magnetron for several cathode materials. This is pertinent to the estimation of spatial variation of composition for films produced by sputtering from multi-element cathodes. These calculations were made in relation to the production by sputtering of thin films of the high temperature superconducting material Y-Ba-Cu-O
- Calculation of the heating of the filling gas by energy transfer from sputtered atoms.

The velocity distribution and average energy of the sputtered atoms was determined experimentally as a function of filling gas pressure from the contribution of Doppler broadening to the spectral line shape of CuI lines, which was measured by means of a piezoelectrically-scanned Fabry-Pérot interferometer. The contributions of the hyperfine structure and the instrumental function were unfolded from the measured line shape by a deconvolution technique developed for this purpose to give the contribution of the Doppler broadening to the line shape. This technique, which is based on a piecewise iterative procedure, is not significantly affected by noisy signals, but requires some (physically reasonable) assumptions to be made about the velocity distribution. The experimental program was completed by measurements of the deposition rate as a function of pressure and the spatial variation of the composition of thin films of Y-Ba-Cu-O deposited by the magnetron.

Measurement of the density profile of the sputtered atoms between the cathode and the substrate as a function of discharge parameters is required to complete this study. To this end we have set up, and tested with a sodium vapour filled cell, a 'hook' interferometer for determining the density of the sputtered atoms from the anomalous dispersion near the emission lines. We have also assessed the value of absorption measurements as a technique for determining the density of the sputtered atoms.

The magnetron discharge studies are being extended to an investigation of the physics of the cathode fall region of the discharge. A series of measurements of the optical structure of this region is in progress. The variation with distance from the cathode of the emission from a long thin volume of the discharge parallel to the cathode is being measured to give an estimate of the thickness of this region of high electric field adjacent to the cathode. We are also calculating the trajectories of electrons in the region of crossed magnetic and non-uniform electric field adjacent to the cathode for which the effect of large impact parameter collisions is being introduced by including a 'damping' term in the equations of motion.

6.2 VACUUM ARC STUDIES

I S Falconer, B W James, D R McKenzie[a]*, A J Studer, and P D Swift*[a]

The energies of ions of the cathode material ejected from the cathode fall region of a vacuum arc, which are anomalously high, are of interest in relation to the application of vacuum arcs both as ion sources for accelerators, and as sputtering devices for producing thin film coatings. We have established a program of measurement of the spectral lineshape of both ions and neutral atoms in vacuum arcs in order to estimate the average energies of these species in conjunction with Dr Ian G. Brown and his co-workers at the Lawrence Berkeley Laboratory, University of California, and Drs Martin, Netterfield and their colleagues in the CSIRO Division of Applied Physics, Lindfield.

The Lawrence Berkeley Laboratory has supplied us with a pulsed vacuum arc, similar to that used in their MEVVA (MEtal Vapour Vacuum Arc) ion source for these lineshape measurements and for investigation of other aspects of the physics of vacuum arcs. This was also used for the investigation of the time evolution of pulsed metal vapour vacuum arcs , and is presently being used for the fabrication of thin films of the high temperature superconducting material, Y-Ba-Cu-O.

Measurements of the time evolution of the spectral line intensity and cathode spot number of a pulsed vacuum arc were concluded with a series of measurements of the cathode spot number as a function of time. These showed that the cathode spot number lags behind the arc current. This is inconsistent with observations on dc arcs which show that the current per spot is independent of the arc current. It has not been possible to demonstrate conclusively that this is not due to a residual glow associated with an extinct cathode spot.

A combination of a Fizeau interferometer and an Optical Multichannel Analyser (OMA) has been successfully used for the measurement of the spectral line shape of emission lines from both pulsed and dc vacuum arcs, from which neutral and ion temperatures were deduced (see 1988 and 1989 Annual Reports). Critical to the precise measurement of particle temperatures with this device is the achievement of a narrow instrumental line width and an understanding of the factors which determine this parameter. We are making an experimental and theoretical analysis of these factors in order to optimise the design of this instrument. Emphasis is being placed on the effect of

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[a] Department of Applied Physics

the angle subtended by the source on the line shape; as large an angle as possible is desirable to maximise the intensity of the image seen by the OMA.

A new cathode geometry has been developed for the application of the arc to the deposition of thin films of Y-Ba-Cu-O, to encourage initiation of the arc. The bulk sample of Y-Ba-Cu-O used as the cathode is not a good conductor, and in the past it was not possible to get the arc to fire reliably. Film thicknesses of 1μm and greater are now routinely be produced by this arc.

We are grateful to our colleague at the Lawrence Berkeley Laboratory for the provision of the arc, and in the Department of Electrical Engineering at the University of Sydney for the use of their image converter camera.

APPENDIX A PERSONNEL

Academic Staff

G.F. Brand
M.H. Brennan (Head of Department)
R.C. Cross
I.S. Falconer
B.W. James
J.A. Lehane

Honorary Associate

I.J. Donnelly (on attachment from ANSTO)

Research Fellows

N. Finn

Research Students

M.J. Ballico
M.D. Bowden
P.W. Fekete
K. Hong
P.J. King
A. Studer
G.M. Turner
J. Wilson

Technical Staff

P.J. Denniss
N.A. Lowe
P. Maul
J.R. Pigott

Secretary

N.J. Bergagnin

APPENDIX B PUBLICATIONS (1990)

(a) Journals

Ballico, M.J. and Cross, R.C., 'ICRF spectrum of fast Alfven eigenmodes in a cylindrical, current-carrying plasma', *Phys. Fluids B* **2**, 467 (1990).

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Donnelly, I.J. and Clancy, B.E., 'Kinetic Theory of Alfvén Waves in Plasmas with Force-Free Currents', *J. Plasma Phys.* (accepted)

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Falconer, I.S., Turner, G.M., James, B.W. and McKenzie, D.R., 'Interaction of sputtered atoms with the filling gas in magnetron sputtering discharges' *43rd Gaseous Electronics Conference*, Champaign-Urbana, Illinois, U S A (1990) *Conference Program and Abstracts*, p47 (Abstract only)

Falconer, I.S., Studer, A.J., Swift, P.D., James, B.W. and McKenzie, D.R., 'Time evolution of the cathode spots in metal vapour vacuum arcs' *43rd Gaseous Electronics Conference*, Champaign-Urbana, Illinois, U S A (Oct 1990) *Conference Program and Abstracts*, p68 (Abstract only)

Members of the Department also presented papers at:

Workshop on Radiowave Propagation and Applications, Sydney (February, 1990)

Fourth Symposium on Millimetre and Submillimetre Wave Research in Australia, Sydney (February, 1990)

APPENDIX C PUBLICATIONS 1981-90

Below is a list of books, chapters of books and journal articles by members of the Plasma Physics Department during the period 1981-90.

1981

Campbell, D.J., Krug, P.A., Falconer, I.S., Robinson, L.C., and Tait, G.D., Rapid scan phase modulator for interferometric applications, *Appl. Optics*, **20** 335-42 (1981).

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APPENDIX D HIGHER DEGREES AWARDED 1981-90

Year	Degree	Name	Thesis Title
1981	Ph.D.	D.J. Campbell	Investigation of electron cyclotron emission from a tokamak plasma
	Ph.D.	C.A. Schmidt-Harms	Some studies of magnetohydrodynamic waves in laboratory plasmas
1982	Ph.D.	P.G. Stokes	Experimental investigations of electron cyclotron emission from a tokamak plasma
1983	Ph.D.	G.A. Collins	Some studies of hydromagnetic waves in a collision dominated plasma
	Ph.D.	J. Howard	A study of transverse magnetohydrodynamic shock waves
	Ph.D.	P.A. Krug	Gas lasers and their application to interferometry of laboratory plasmas
	Ph.D.	A.R. Law	An experimental study of transverse magnetohydrodynamic shock waves
1984	–	–	–
1985	Ph.D.	N.G. Douglas	Development of tunable gyrotrons for millimeter/submillimeter applications
	Ph.D.	J.Y.L. Ma	Development of low power tunable gyrotrons
1986	Ph.D.	M. Gross	Experimental investigations of low-power tunable millimetre-wave gyrotrons
1987	Ph.D	G.G. Borg	Guided propagation of Alfvén waves in a tokamak plasma
	Ph.D.	L. Giannone	MHD activity and Alfvén waves
	Ph.D.	A.B. Murphy	Observations of Alfvén waves in a tokamak plasma
	Ph.D.	P.A. Stimson	Far infrared lasers and their application to plasma diagnostics
1988	Ph.D.	S.H. Law	Application of laser induced fluorescence as a plasma diagnostic technique
	M.Sc.	K.J. Moore	A neutral particle analyser for TORTUS
1989	–	–	–
1990	Ph.D.	W. Wright	Laser-induced fluorescence for the study of magnetically confined plasmas

APPENDIX E

VISITORS TO THE PLASMA PHYSICS DEPARTMENT 1981-1990

1981

Professor P.E. Vandenplas	Ecole Royale Militaire, Brussels, Belgium
Dr H.C. Kirbie	Old Dominion University, U.S.A.

1982

Dr B.D. Blackwell	M.I.T.
Dr Chen Zhiyi	Vacuum Electron Device Research Institute, Beijing, PRC
Dr Liu Jia-Rui	Institute of Physics, Beijing, PRC

1983

Professor Y. Amaghishi	Shizuoka University, Japan
Dr Chen Zhiyi	Vacuum Electron Device Research Institute, Beijing, PRC
Dr R.C. Grimm	Princeton Plasma Physics Laboratory, U.S.A.
Dr J. Killeen	Lawrence Livermore Laboratory, U.S.A.
Dr M.L. Sawley	CCRP-EPFL, Lausanne, Switzerland

1984

Dr Chen Zhiyi	Vacuum Electron Device Research Institute, Beijing, PRC
Dr E.L. Bydder	University of Waikato, New Zealand

1985

Dr I.H. Hutchinson	M.I.T., U.S.A.
Dr I.G. Brown	Lawrence Berkeley Laboratory, U.S.A.

1986

Professor J. Fujita	Institute for Plasma Physics, Nagoya, Japan
Dr A. Funahashi	JAERI, Japan

1987

Dr D.K. Mansfield	Princeton Plasma Physics Laboratory, U.S.A.
Dr E.L. Bydder	University of Waikato, New Zealand

1988

Dr E.L. Bydder	University of Waikato, New Zealand
Professor T. Idehara	Fukui University, Japan
Professor T. Fujimoto	Kyoto University, Japan

1989

Professor H. Iwasawa	Fukui University, Japan
Professor T. Tatsukawa	Fukui University, Japan
Professor I. Idehara	Fukui University, Japan
Professor Y. Amagishi	Shizuoka University, Japan
Professor A. Kritz	Hunter College CUNY/Princeton Plasma Physics Laboratory, U.S.A.