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ELECTRON-CYCLOTRON-HEATING RESULTS ON JFT-2, AND THEIR IMPLICATIONS FOR THE DOUBLET III ECH DESIGN

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ELECTRON CYCLOTRON HEATING RESULTS ON JFT-2, AND THEIR IMPLICATIONS FOR THE DOUBLET III ECH DESIGN*

Ronald Prater and Charles P. Moeller

General Atomic Company, P. O. Box 81608, San Diego, CA 92138 USA

Abstract

Electron cyclotron heating experiments are described in which 28 GHz microwave power is injected into the JFT-2 tokamak. Ordinary mode power injected from the low field side increased the central electron temperature from 600 eV to 1000 eV with 110 kW, for densities below the ordinary mode cutoff density of 1.0×10^{13} cm^{-3}. Extraordinary mode power launched obliquely from the high field side increased the temperature from 600 eV to 1200 eV with 85 kW, for densities well below the extraordinary mode cutoff density, and effective heating was maintained close to the cutoff density of 1.6×10^{13} cm^{-3}. The extraordinary mode launched obliquely was also found to heat more efficiently and to a higher density than the extraordinary wave launched perpendicularly. On this basis, the Doublet III ECH experiments which will use up to 2 MW of 60 GHz power are designed to make use of oblique inside launch of a pure extraordinary mode. The waveguide transmission system to accomplish this is discussed.

Introduction

Electron cyclotron heating (ECH) has a number of technological advantages which make it useful in plasma confinement devices. Under suitable conditions the waves are strongly damped, resulting in a highly

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local heat deposition. This effect can be expected to provide very efficient heating in tokamaks, for example, since the heat can be deposited at the plasma center; simulations have shown that central ECH requires only one third to one half the power and a fourth the energy of neutral beam heating to raise an INTOR-sized plasma to ignition, due to the much broader heat deposition profile of neutral beam heating[1]. Likewise, ECH can be used to broaden the temperature profile in tokamaks, which under an ohmic equilibrium leads to a current density profile much wider than that typical of tokamaks heated only by ohmic currents. These broadened profiles may in turn lead to higher beta operation of the tokamak, if they are frozen in by high power heating.

ECH appears to be useful in a variety of other applications in tokamaks, including preionization and startup[2,3], disruption elimination through suppression of internal kink modes[4], and current drive[5,6]. ECH also finds application in other geometries, for example plasma generation and heating in stellarators, ring formation and plasma heating in EBT's, and thermal barrier generation and heating in tandem mirrors.

Until quite recently, ECH was severely limited by the availability of high power sources. With the advent of the gyrotron, heating experiments were performed on a number of tokamaks, but interpretation of the results of most of these experiments has been difficult because a mixture of wave modes were launched. The experiments reported here, which were performed on the JFT-2 tokamak at the Japanese Atomic Energy Research Institute, were designed to test the propagation and damping of pure modes in order to facilitate comparison with theory. As the theory becomes more completely validated, new ECH experiments will be easier to design with some certainty.

ECH Experiments on the JFT-2 Tokamak[7,8]

Two separate sets of experiments were performed. In the first, a pure ordinary wave was launched nearly perpendicular to the toroidal field from the large major radius (low toroidal field) side of the plasma. In the second, a pure extraordinary wave was launched obliquely into the plasma from the high field side; alternatively, a mixture of the two modes could be launched perpendicularly. The power source was a 28 GHz gyrotron manufactured by Varian Associates, which was capable of 200 kW output for pulse lengths of up to 40 msec. Most of the data was taken with input power at the plasma of 80 to 110 kW due to inefficiencies in the transmission system.

The waveguide setups for these experiments are shown in Fig. 1. Since the gyrotron output is primarily in the circular electric TE_{02} mode, the power is converted immediately to the TE_{10} mode in the rectangular waveguide in order to facilitate generation of the linearly polarized or elliptically polarized waves required for the launching of pure modes. The TE_{10} mode is rather lossy in fundamental waveguide, but this approach was chosen in spite of the losses because of the ease with which the desired modes can be launched.

The JFT-2 tokamak has a major radius of 0.9 m and a minor radius of 0.25 m, and in these experiments the plasma current was 70-75 kA and the toroidal field was between 0.86 T and 1.12 T. The electron temperature without ECH is typically 600 eV. The basic diagnostics used in determining the heating effects are the Thomson scattering system and a soft

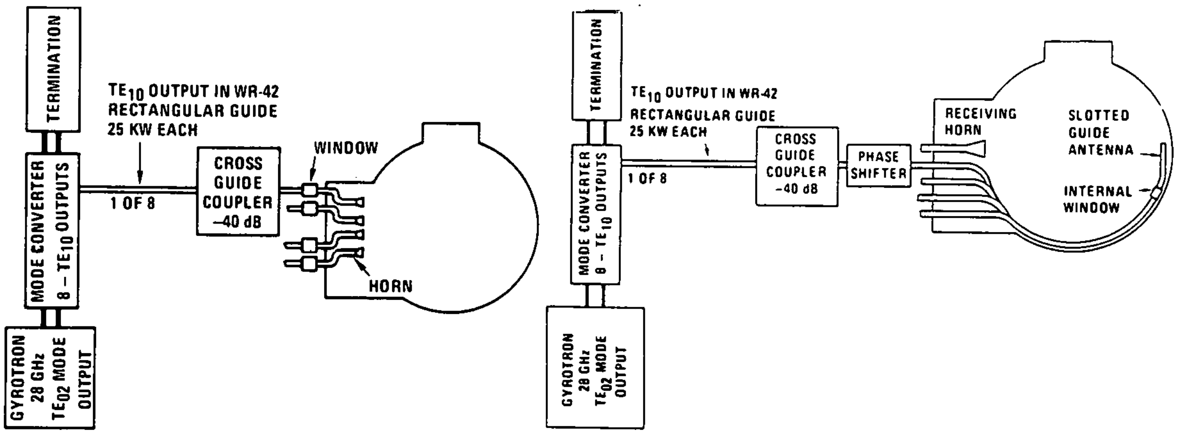

Fig. 1. Microwave transmission systems for the outside and inside launch.

X-ray pulse height analysis system. Other available diagnostics were a soft X-ray PIN diode array, a second electron cyclotron harmonic radiometer, bolometers, and visible and near UV spectroscopy. Line averaged plasma density was determined by the 2 mm microwave interferometer, and local density was determined by the Thomson scattering system.

Outside Launch Experiments[7]

The antenna for the outside launch experiments was an array of 8 horns stacked vertically in four pairs. Horn pairs were aimed alternately at ±10° to a major radius. The half power beam width of each horn was ±8°, and the horns radiated with the electric field parallel to the toroidal magnetic field.

Figure 2 shows the central electron temperature measured by Thomson scattering (circles) and soft X-ray pulse height analysis (squares) when 110 kW of rf power is launched into the plasma. The toroidal field is 10 kG, which places the resonance at the center of the plasma. The central density is 8.5×10^{12} cm^{-3}, which is 85% of the cutoff density of 1×10^{13} cm^{-3} ($\omega_p^2/\omega^2 \approx 1$). The ohmic power prior to the rf is 85 kW. The effect of the rf power is to raise the central temperature from 600 eV to 1000 eV. The one-turn voltage decreases by 32% due to the drop in plasma resistivity as the temperature rises.

The solid curves in Fig. 2 are the result of a transport code run which models the plasma behavior. The code uses an energy transport coefficient that varies inversely with density, and its magnitude is adjusted to fit the ohmic plasma measurements. Microwave power absorption is modeled as proportional to $n_eT_e^{1/2}$, in accordance with the theory of weak absorption of the ordinary mode. Under the JFT-2 parameters, only about 30% of the power is expected to be absorbed in a single pass, but the agreement between the code run and the experiment shows that close to 80% of the power is absorbed, assuming that the temperature and density profiles were unaffected by the heating. This implies that multiple pass absorption took place, and that wave reflection at the plasma boundary is important.

During the rf heating, the line averaged plasma density is observed to drop, typically by 15-20%. This effect has also been seen in ISX-B

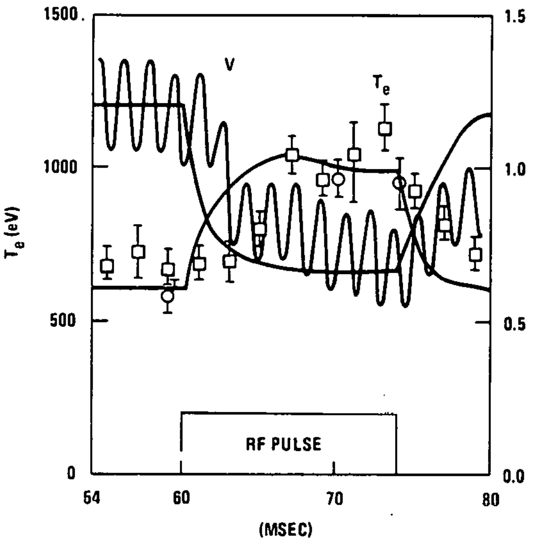

Fig. 2. One turn voltage V and central electron temperature T_e measured by Thomson scattering (circles) and soft X-ray pulse height analysis (squares). The microwave power is 110 kW, the plasma current is 70 kA, the toroidal field is 1.0 T, and the line-averaged density is 5 × 10^{12} cm^{-3}. Curves are predictions of empirical one-dimensional transport code.

ECH experiments[9]. The relative density decrease is larger at higher densities, and it takes place within a few msec of the start of the rf pulse, while the Thomson scattering temperature measurements are made 10 msec into the pulse. In plotting the final steady-state heating effect as a function of central density, it is therefore important to use the reduced density during the heating rather than the initial density. In practice, this is done by multiplying the line-averaged density during the microwave pulse by a factor of 1.7, which is the approximate ratio of peak to average density in the absence of heating.

The heating data so plotted are shown in Fig. 3. These data are consistent with simple theory: the heating falls off rapidly as the density approaches the cutoff density, 1.0 × 10^{13} cm^{-3}; and at low density the heating increases with increasing density. The latter observation implies that not all the power is absorbed effectively in the plasma even though the vacuum Q of the plasma chamber is fairly large. Power absorbed in a resonant magnetic field region near the plasma edge is not effective in raising the central electron temperature, but it reduces the effective Q of the cavity.

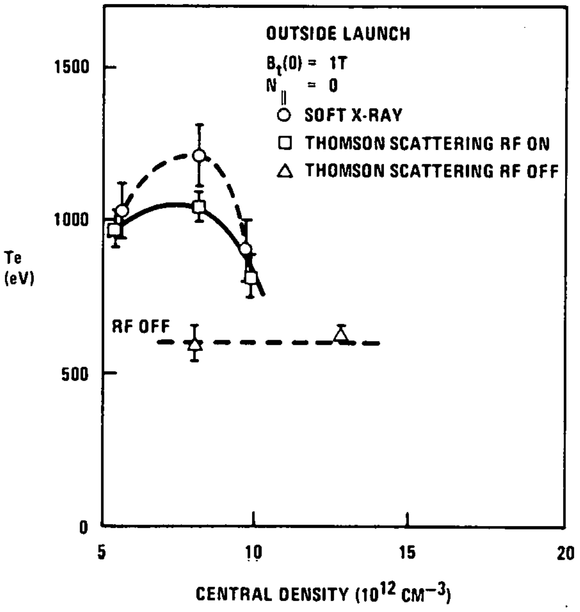

Fig. 3. Central temperature as a function of density measured 10 msec into the heating pulse for the perpendicular outside launch of the ordinary mode for a central toroidal field of 1 tesla.

The increase in electron temperature for fixed initial density of 7×10^{12} cm^{-3} and toroidal field of 1.0 T was observed to be proportional to the input microwave power, indicating that nonlinear heating effects are not important at the power used, 50 to 110 kW. The reduction in the one-turn voltage was also found to be proportional to the microwave power. Significantly, the relative line-averaged density drop when the microwave power was turned on was independent of power over that range, which implies that the density change is not dependent on the extent of the central electron heating.

When the toroidal field was varied to shift the resonance layer to different major radii, it was observed that the central heating effect was highly asymmetric. With the resonance moved 18 cm inside of the plasma center, the central temperature increase was nearly the same as when the resonance was at the center, while moving the resonance outside the plasma center caused a dramatic decrease in the central heating. This effect is shown in Fig. 4. A similar effect will be discussed for the inside launch case.

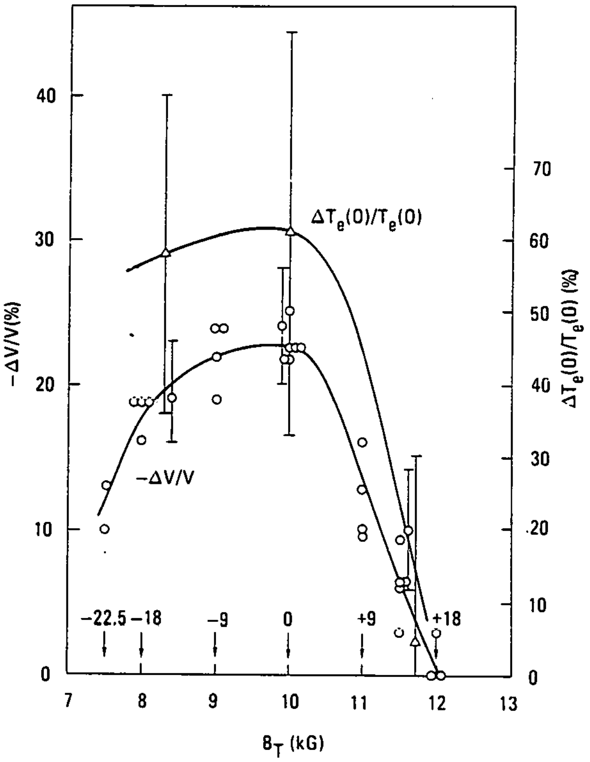

Fig. 4. Relative voltage drop and central electron temperature increase as a function of central magnetic field, for initial line-averaged density of 7×10^{12} cm^{-3} and 85 kW of microwave power. The locations of the cyclotron resonance on the midplane are shown in centimeters.

Inside Launch Experiments[8]

In these experiments the antenna was a slotted waveguide phased array mounted on the inside wall (high field side) of the tokamak, centered on the midplane[10]. The gyrotron output power was divided into the eight arms of a mode converter/power splitter, and each arm was routed to the antenna in fundamental mode rectangular waveguide. Seven slots were cut in the side of each waveguide at the antenna in a vertical pattern to form a vertical broadside resonant array. The antenna radiated a narrow beam ±8° wide at half power, and the angular incidence of the beam could be steered relative to a major radius by adjusting the phases of the input power external to the vacuum system. To launch a pure extraordinary mode at an oblique angle, an elliptically polarized field is required at the plasma edge. The antenna was made to launch an elliptic polarization which generated primarily the extraordinary mode for $0.66 < n_{\|} < 0.86$ (42-60° relative to the major radius at the location of the antenna), while for perpendicular propagation the division of power was 75% to the extraordinary mode and 25% to the ordinary mode.

The primary reason for having a steerable array was to facilitate testing the effect of launch angle on wave propagation and damping. For oblique launch angles, strong direct damping at the cyclotron resonance layer is predicted for the electron temperatures found in JFT-2, and the maximum density attainable is $2(1 - n_{\|}^2)n_c$, where $n_{\|}$ is the local parallel index of refraction. For perpendicular launch, the damping process is expected to be mode conversion at the upper hybrid layer to slow electrostatic waves which propagate back to the cyclotron layer and are damped. For this angle $n_{\|} = 0$, so the maximum attainable density is $2n_c = 2.0 \times 10^{13}$ cm^{-3}, a factor of 2 better than that for the ordinary wave, while for oblique launch at a 42° angle to the field ($n_{\|} = 0.66$ at the antenna and 0.44 at the plasma center) the maximum density is 1.6×10^{13} cm^{-3}. One purpose of these experiments was to observe whether the full predicted factor of two could be obtained by using perpendicular launch, or whether oblique launch at somewhat lower cutoff density is preferable.

Figure 5 shows the heating results for perpendicular launch for toroidal field of 1.0 T. The heating clearly becomes negligible for densities well below the predicted density maximum, while the mode conversion damping process would be expected to lead to heating only weakly dependent on density up to the central cutoff density of 2.0×10^{13} cm^{-3}.

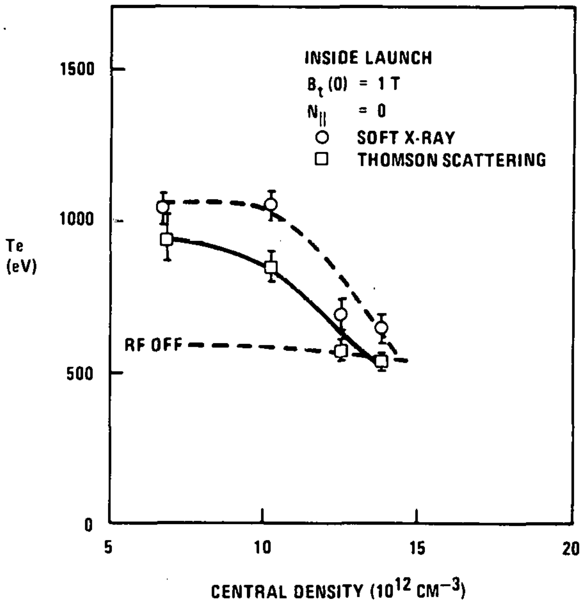

Fig. 5. Central temperature as a function of density measured during the heating pulse for the perpendicular launch of the extraordinary mode with a central toroidal field of 1 tesla.

Other data taken at other toroidal magnetic fields suggest that the failure of perpendicular launch to heat the plasma up to the cutoff density may be due to nonlinear effects at the upper hybrid layer. At a central toroidal field of 0.86 T, the resonance layer is located 12.6 cm inward of the plasma center, while the central heating is stronger and persists to higher density. In contrast, at toroidal fields which move the resonant surface outward by a like amount the central heating nearly disappears. This does not seem to be an optical refraction effect since it is true even at low density. An important parameter associated with the damping that also has such an asymmetry is the position of the upper hybrid layer. Since the inverse of the damping process, used by cyclotron radiometers, does not show such behavior[11], the asymmetry in the heating is may be due to a nonlinear effect. A possible candidate is direct stochastic damping near the upper hybrid layer. The asymmetry arises because as the toroidal field or the plasma density is raised, the upper hybrid layer moves into a lower temperature region nearer the edge. That results in both a higher local wave electric field and lower particle energy, both of which are conducive to nonlinear effects. It should be noted that the microwave power flux at the upper hybrid layer exceeds 600 W/cm^2 in this case. Any power damped through such effects close to the plasma boundary would be lost without contributing much to the central heating. If this is the correct explanation, then in larger tokamaks with higher edge temperatures the heating due to the mode conversion process may behave as expected from linear theory.

For the oblique launch case, the best results were obtained at the launch angle of 42° to the magnetic field at the antenna. At this angle, 80% single pass damping is expected from the direct cyclotron damping process when the electron temperature is 1 keV and the density is 1.0×10^{13} cm^{-3}. The theoretical curve in Fig. 6 is obtained from a transport code calculation in which the cyclotron damping at each flux surface is found using the local self-consistent plasma parameters. The values of τ_{Ee} and Z_{eff} are chosen to fit the initial ohmic discharge. The τ_{Ee} is assumed proportional to density, and the density drop, which is similar to that for the outside launch case, is added to the calculation phenomenologically. The calculation is a good fit to the Thomson scattering data and qualitatively consistent with the soft X-ray data.

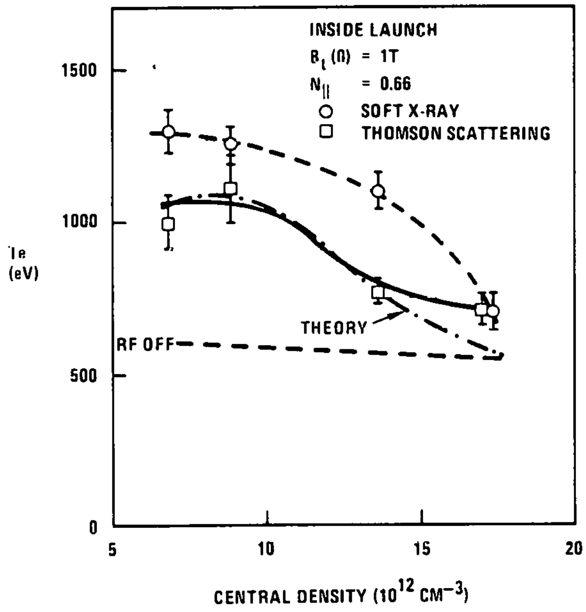

Fig. 6. Central temperature as a function of density measured during the heating pulse for the oblique launch of the extraordinary mode with a central toroidal field of 1 tesla.

The strongest heating under any condition was obtained for the oblique launch case with the toroidal field reduced to 0.93 T. In this case, shown in Fig. 7, the central electron temperature as measured by Thomson scattering rose from 600 eV to about 1200 eV. No information was obtained about temperature or density profile changes, due to the

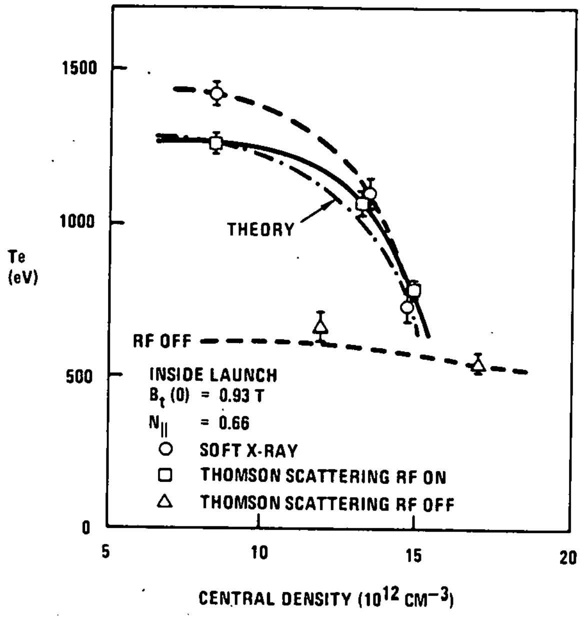

Fig. 7. Central temperature as a function of density measured during the heating pulse for the oblique launch of the extraordinary mode for a central toroidal field of 0.93 tesla.

difficulty found in determining the Thomson scattering temperature at the low densities used in these experiments.

In Fig. 7, the theory curve matches the experimental data when the input power in the code is adjusted to be 100 kW, of which 80 kW is absorbed. Since the experimental input power is only 85 kW, this implies that profile changes are taking place, other than what can be expected from the empirical electron heat diffusion coefficient, or that the efficiency of the mode conversion heating process for the power not damped in the first pass is high in the case of reduced toroidal field. For the strongest heating case, the central electron heating exceeds 7 eV/kW.

The density change when the microwave power is turned on behaves similarly to that for the outside launch. Figure 8 shows the relative local electron density change as indicated by the Thomson scattering system and the line-averaged density change as determined by the microwave interferometer, as a function of the initial line-averaged density. Also shown is the change in electron temperature, which is data

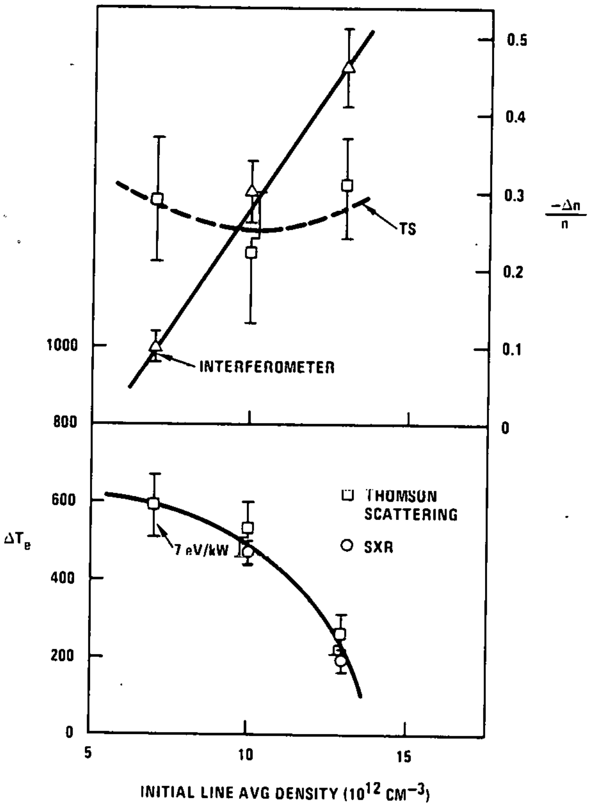

Fig. 8. Change in relative line-averaged density (interferometer) and central density (Thomson scattering) as a function of the initial line-averaged density, for B_t = 0.93 T and $n_{\|}$ = 0.66. Also shown is the temperature data replotted from Fig. 7.

reploted from Fig. 7. The change in line-averaged density is seen to be inversely correlated with the central electron heating, while the Thomson scattering data indicate little dependence on initial density or electron heating. It appears that at higher initial density, the density drop is larger and the post heating density profile is narrower, and the central heating declines. A possible explanation is that as the microwave absorption near the plasma center decreases, the excess power is absorbed by plasma above and below the plasma center along the resonance, resulting in strong changes in electron temperature on the wings of the profile. This in turn affects the neutral ionization rate at the plasma edge, which may change the density and the density profile. This explanation does not explain the fairly large change seen by the Thomson scattering system at the lowest density; however, the density determination by the Thomson scattering system this low density is not very reliable.

The toroidal field dependence of the central electron heating is asymmetric for the inside launch as it was for the outside launch, as shown in Fig. 9. Much higher heating efficiency is observed when the resonance is moved to the smaller major radius side of the plasma center than when the resonance is outside the plasma center. This is also the dependence found for perpendicular inside launch.

Asymmetry with resonance location is also observed in the intensity of plasma radiation at twice the local electron cyclotron frequency, measured 5 msec after the end of the microwave pulse. The data of Fig. 10 show very large increases in emission from the outer part of the plasma relative to the inner part, even on the same flux surface. This indicates the formation of an enhanced high energy tail on the perpendicular Maxwellian electron distribution which is trapped in the magnetic well on the outside region of a flux surface, even though the resonance region is on the inside.

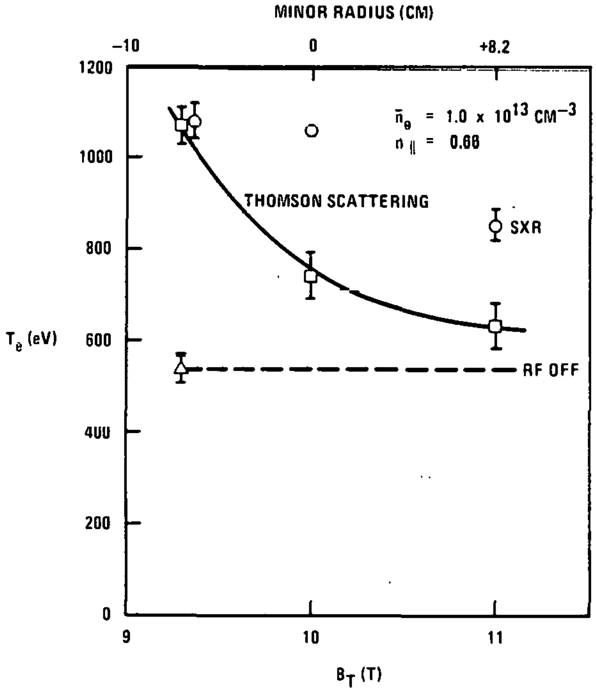

Fig. 9. Final central electron temperature as a function of central toroidal field, for a fixed initial line-averaged density of 1.0 × 10^{13} cm^{-3}.

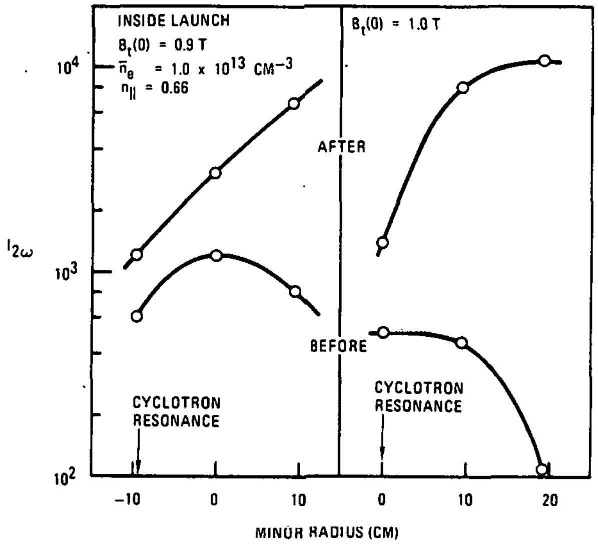

Fig. 10. Emission at the second harmonic of the electron cyclotron frequency, in arbitrary units, for toroidal field of 0.9 T and 1.0 T. The initial line-averaged density is 1.0 × 10^{13} cm^{-3}, and the measurements are taken 5 msec after the end of the microwave pulse.

Top Launch Experiments

In an effort to obtain maximum electron heating by simply applying the largest available microwave power, a flexible corrugated waveguide 2.5 in. in diameter was run directly from the gyrotron to a port on the top of JFT-2, at a smaller major radius than the plasma center. The circular electric TE_{02} mode was used in the entire run, and the waveguide simply terminated at a BeO window at the vacuum chamber wall. A directional coupler showed little reflected power. An absolute calibration of the forward power was not made, but gyrotron beam current and voltage measurements indicate a power output of over 150 kW, assuming that the gyrotron efficiency was the same as it was when the mode converter/power splitter was used.

The Thomson scattering and soft X-ray diagnostics both showed a central electron temperature increase of less than 300 eV for a toroidal field of 1.03 T. This indicates a maximum heating efficiency 28% of that for the optimal oblique inside launch of the pure extraordinary mode. This experiment shows that in spite of multiple pass effects and high plasma chamber Q, it is possible to apply ECH power in such a manner that it is ineffective in heating the plasma.

ECH for Doublet III

A number of conclusions can be drawn from the JFT-2 experiments that are directly applicable to the design of the 2 MW 60 GHz electron cyclotron heating system for Doublet III. First, inside launch of the extraordinary mode is clearly advantegeous in obtaining heating at the highest possible density. Second, for maximum confidence the wave should be launched obliquely rather than perpendicularly, although an important goal of the program is to determine whether the theoretically predicted density limits can in fact be attained in the higher temperature plasma of Doublet III. Wave refraction by the density gradients may well place a more restrictive limit on the maximum central density for reasonably well collimated wave patterns than the linear theory. Third, the heating efficiency can be expected to be quite high, probably in excess of 80%.

The scientific goals of the Doublet III ECH project are to clarify many of the issues left undecided in the JFT-2 experiments. Improvement can be expected in diagnostic capabilities, due in large part to the increase by a factor of 4.6 in the density limit at the higher frequency, which implies that the Thomson scattering and soft X-ray signal statistics will be greatly improved. Also, in Doublet III the electron temperature is higher, so that single pass damping will be more complete. An important issue is to verify the theory of damping of the ordinary mode, since most experiments including those on JFT-2 show much higher heating efficiency than can be expected from the theory of single pass damping; while this may be due to reflection at the plasma boundary and multiple pass absorption, it may also be due to wave damping in excess of that predicted. Another issue is to verify the effectiveness of ECH in strongly altering the temperature profile, which has been difficult to observe in smaller, lower density tokamaks.

The JFT-2 results have shown the importance of launching the proper mode. We expect this will be even more important in Doublet III due the large volume of low temperature, poorly confined plasma in the lower lobe which may damp microwave power not absorbed on the first pass through the upper lobe. The microwave transmission system is being designed to operate in a single mode so that efficient and effective microwave components can be designed and pure ordinary or pure extraordinary waves can be launched. Much greater emphasis is being placed on overall system efficiency, which is expected to be about 70% for power launched into the plasma in the desired mode.

The system schematic is shown in Fig. 11. Transmission takes place in the TE_{02} and TE_{01} modes, for which the dissipation is quite small in this overmoded waveguide (about 5%/100 ft). The circular waveguide tapers from 2.5 in. diameter at the gyrotron to 1.094 in., which is small enough to facilitate corrugated guide bends with relatively small radius while not having excessive ohmic losses. Mitre bends were not used because they are inherently discontinuous and would require waveguide about 5 in. in diameter to reduce mode conversion to acceptable levels. Waveguide of that size wuld be too large for an inside launch.

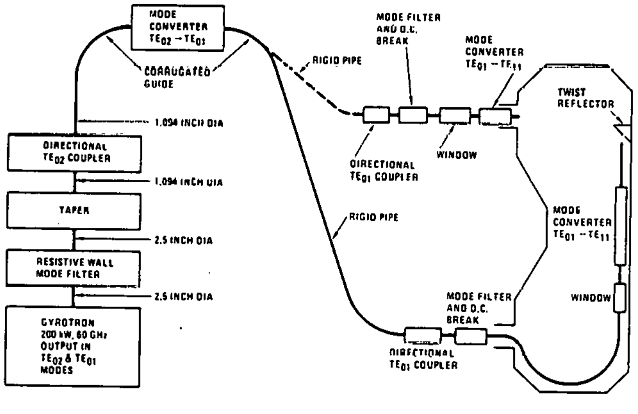

Fig. 11. Doublet III microwave transmission system.

The power is converted to the TE_{01} mode in a mode converter with periodic axisymmetric wall perturbations, in order to minimize waveguide wall dissipation, facilitate launching of linearly polarized waves, and reduce the waveguide electric fields to the minimum (about 5 kV/cm peak). For outside launch experiments, the power runs directly to an outside port adjacent to the plasma which is in the upper lobe of the Doublet vessel. After passing a vacuum window of nitrogen gas cooled quartz, it enters a second mode converter which transforms the power to the TE_{11} mode with horizontal linear polarization. This converter is aimed at 10° to a major radius, and it launches a pure ordinary mode.

For inside launch experiments, the waveguide enters through the unused lower lobe of Doublet III and runs up the inside wall. The vacuum window is located near the inner wall so that the waveguide is filled with dry nitrogen gas at atmospheric pressure at the place where it crosses the cyclotron resonance layer. The mode converter follows the window and leads to a mirror. For perpendicular injection, the mirror is planar and oriented radially, while for oblique launch the mirror is grooved in such a manner as to produce the elliptic polarization required to launch a pure extraordinary wave.

Power for the system will come from up to ten 200 kW 60 GHz gyrotrons, with one waveguide transmission system per gyrotron. The first two gyrotrons are expected by May, 1982, with experiments to start by mid-summer.

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