15-1 PPPL-1980

UC20-G

PPPL-1980

PPPL--1980

DE83 008980

DP-1270

RAY-TRACING STUDY OF
ELECTRON-CYCLOTRON HEATING IN TOROIDAL GEOMETRY

By

A.H. Kritz, H. Hsuan, R.C. Goldfinger, and D.B. Batchelor

MARCH 1983

PLASMA
PHYSICS
LABORATORY

PRINCETON UNIVERSITY
PRINCETON, NEW JERSEY

PREPARED FOR THE U.S. DEPARTMENT OF ENERGY
UNDER CONTRACT DE-AC02-76-CO-3073.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

RAY-TRACING STUDY OF ELECTRON-CYCLOTRON HEATING IN TOROIDAL GEOMETRY

A.H. Kritz,* H. Hsuan, R.C. Goldfinger,** D.B. Batchelor**

Plasma Physics Laboratory, Princeton University

Princeton, N.J. 08544

ABSTRACT

TORAY, a ray-tracing code has been developed to study electron-cyclotron heating and current drive in toroidal geometry. Ray patterns are initiated similar to those of an actual antenna and a full graphics package has been developed for displaying the behavior of the rays. We study the interplay of the plasma and wave parameters in order to establish which parameters are most important in determining the energy deposition.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

* Permanent address: Hunter College/CUNY, New York, NY

** Permanent address: Oak Ridge National Laboratory, TN

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

I. INTRODUCTION

The use of electron cyclotron heating in tokamaks has a number of objectives. These include providing some of the supplementary heating required to achieve ignition in a fusion reactor; generating a noninductive current in a tokamak; and producing the temperature, current, and pressure profiles required for stability and for possibly improved tokamak confinement. Electron cyclotron heating has some important advantages when compared with other supplementary heating schemes. The energy deposition is localized in the electron resonance zone (most important for profile control); the penetration of the microwave energy to the resonance zone is relatively independent of edge plasma conditions (density, temperature, etc.); and the propagation of the wave energy is nearly optical which allows for low-loss power transmission. Electron cyclotron wave heating has occurred in experiments on the ELMO bumpy torus and the ISX-B tokamak at Oak Ridge National Laboratory, on the TM-3 and T-10 tokamaks at Kurchatov, on the FT-1 at Ioffe, on the JFT-2 tokamak at JERI, and on the TOSCA tokamak at Culham. Currently, electron cyclotron heating experiments are underway or planned on a number of tokamaks, for example, ISX-B, T-10, Versator, THOR, CT-6B, Doublet-III, and PDX.

We have developed TORAY, a ray tracing code, to provide insight concerning the physics of electron cyclotron heating (ECH) in toroidal geometry, insight that will help guide experiments and help further define the role of ECH in the fusion program. Using TORAY we have gained some understanding of the dependence of energy deposition on wave and plasma parameters. However, the complex interplay of the wave and plasma parameter dependencies make it difficult to draw many general conclusions. Yet, it is this same interplay that makes the utilization of a ray tracing code all the more important.

Section II contains a brief description of the ray tracing code and associated graphics package. In Sec. III some of the studies carried out using TORAY are described and illustrated. In Sec. IV conclusions are presented.

II. TORAY - TRACING ELECTRON CYCLOTRON WAVES IN TOROIDAL GEOMETRY

TORAY is based on RAYS,¹ a code first developed for the study of electron cyclotron heating in EBT^{2,3} and then modified and used to study lower hybrid heating in EBT.⁴ In TORAY, we solve the Hamiltonian form of the geometrical optics equations in a toroidal equilibrium using either time or path-length as a variable. We can utilize the ray equations of geometric optics because the propagation of the electron cyclotron wave energy is nearly optical. To accomplish the required integration, we use ODE,⁵ a packaged routine for solving ordinary differential equations. Sets of rays are used to simulate ray patterns of an actual antenna. TORAY has a modular construction -- the dispersion relation, the equilibrium, and the damping computations are each contained in individual modules. The modular construction is possible since the functional dependence of the dielectric coefficient on position is through its dependence on the plasma and cyclotron frequencies. Thus, the details of the dispersion relation are separated from those of the equilibrium. The required values of the electron density, magnetic field, and their gradients are determined in an equilibrium module. It is the modular nature of TORAY that provides flexibility and makes this code particularly suitable for the study of a number of problems. Currently, we use the electromagnetic cold plasma dispersion relation to determine the electron cyclotron ray path. Previous work has shown that the cold plasma dispersion suffices for determining the ray path.³ If TORAY is used in a study that

requires the warm plasma dispersion relation, e.g., mode conversion at the upper hybrid resonance layer, the dispersion module in TORAY would be replaced, but the remainder of TORAY would remain intact. Below, we briefly describe the equilibrium and the wave energy absorption modules.

The equilibrium is given by an analytic description which includes a number of parameters for adjusting shapes of the q , the electron density, and the temperature profiles. We take the q profile to be of the form

$$q(r) = q_0 + (q_a - q_0) \frac{r^2}{a^2} \quad (1)$$

where a is the plasma radius and r the radial position in the plasma. The arbitrary parameters q_0 and q_a allow us to investigate the influence that the q profile has on wave propagation and absorption. The radial dependence of the electron density and temperature is

$$n_e = n_{eo} \left(1 - \left(\frac{r}{a} \right)^{p_1} \right)^{p_2} \quad T_e = T_{eo} \left(1 - \left(\frac{r}{a} \right)^{p_3} \right)^{p_4} \quad (2)$$

where the parameters, p_1 , p_2 , p_3 , and p_4 , enable us to examine the influence of the density and temperature profiles on wave propagation and energy deposition. The magnetic field B , has a toroidal component, B_ϕ , with the usual $1/R$ dependence, and a poloidal component, B_θ , calculated using $q(r)$ defined in Eq. (1).

$$\mathbf{B} = B_\phi(r, \theta) \hat{\phi} + B_\theta(r, \theta) \hat{\theta}. \quad (3)$$

The toroidal field is given by

$$B_{\phi} = \frac{B_0 R}{R + r \cos \theta} \quad (4)$$

where R is the major radius of the tokamak.

The poloidal field is expressed in terms of B_0 and the q profile:

$$B_{\theta} = \frac{1}{R} \frac{r}{q(r)} B_0(r, \theta). \quad (5)$$

The studies discussed in Sec. III are obtained using the analytic equilibrium described above. We have also developed an equilibrium module that uses a numerical description of the equilibrium. This numerical description may be provided by diagnostic data or by a transport code. TORAY has been coupled with the transport code BALDUR so that the self-consistent heating and evolution of the plasma can be studied.

The fractional damping of the electromagnetic wave energy along the ray path by the plasma electrons is given by

$$f = 1 - \exp \left[- \int_0^s \frac{2k_i \cdot v_g}{v_g} ds \right] \quad (6)$$

where k_i is the imaginary part of the wave vector and s is the path length. In order to perform the integration in Eq. (6), it is necessary to determine $k_i \cdot v_g$ as a function of s . Three approaches (each contained in a separate damping module) have been used to calculate this quantity. These are as follows:

1. In the vicinity of electron cyclotron frequency equal to incident frequency, the value is computed by expanding the warm plasma dispersion relation about the cold plasma limit.^{1,6}

2. The value of $k_i \cdot v_g$ is computed utilizing energy balance, that is by following the Poynting vector along the ray path.^{7,8}
3. The value of $k_i \cdot v_g$ is computed for a relativistic plasma with a non-thermal component.⁹

In each case, the required values of the plasma Z-function are obtained by using a separate module to compute Z. For the results presented in this paper only the first of these three damping modules was utilized. Future work will describe results obtained with the other damping modules, particularly results obtained using the third approach for non-thermal plasmas.

The utility of a ray tracing code depends on the thoroughness and clarity with which the results of the ray tracing are presented. This is particularly true for the study of electron cyclotron heating and current drive in the three-dimensional toroidal geometry. A complex interplay of parameters influences energy deposition, and the relative importance of the various parameters can be sorted out only with an effective display of the ray tracing results. Certainly, we need a clear presentation of the ray path and the location of energy deposition in physical space, but this alone is not sufficient. We also require graphs that provide insight as to how the parameters, which affect the ray path and energy deposition, vary along the ray path. We have produced a display package which helps fulfill this need and which help us understand the physical phenomena involved. In the discussion presented in Sec. III, examples of some of the graphs produced by the graphics package are used to illustrate results.

III. RESULTS OBTAINED USING TORAY

In order to understand how the interplay of parameters affects electron cyclotron energy deposition, we examine the ray paths and the associated energy deposition for a variety of conditions. While holding all but one or two of the wave or plasma parameters fixed, we vary the remaining parameter(s) in order to isolate the dependence of ray path and energy deposition on that parameter. Below, we indicate some of the studies carried out using TORAY, and we present results that illustrate some of the understanding that has evolved. In most of the results presented, the parameters used are those appropriate for PDX. Unless otherwise indicated, the values used to specify the q , the density and the temperature profiles are $q_0=1$, $q_a=3$, $p_1=p_3=p_4=2$, and $p_2=1$.

A. Single pass energy deposition

We find that with typical PDX operating conditions the single pass energy deposition, for both O-mode and X-mode waves, exceeds 60% and is often 80% or 90%. This is illustrated in Figs. 1 and 2 where each x along the ray path indicates an additional 10% energy deposition. Because of the location of the upper hybrid resonance in a tokamak, X-mode waves are launched from the inside (high field side) of the tokamak, while O-mode waves are launched from both sides. The rays, shown in Figs. 1 and 2, leave the antenna with poloidal and toroidal beam widths of 10° , typical beam widths for the planned PDX experiment. The poloidal launch angle θ is measured from the direction of the positive z -axis. The toroidal launch angle ϕ is in the x - y plane and is measured counterclockwise from the positive x -axis. Note, in Fig. 2, Ray 1 deposits 68% of its energy while Ray 3 deposits 95%. These two rays are launched with the same poloidal angle and with toroidal angles that differ by

only 10° . Thus, the energy deposition occurs at nearly the same physical location in the plasma. The basis for the different deposition levels is indicated in Fig. 3 where the index of refraction, along with its components parallel and perpendicular to the magnetic field are plotted as a function of the ray parameter, time. Because of the difference in the toroidal launch angle, the value of the parallel index of refraction, in the vicinity of energy deposition is greater for Ray 3 than for Ray 1. This accounts for the difference in the rate of energy deposition. In Fig. 3, the radial position of the ray (relative to the plasma radius) is also plotted as a function of the ray parameter.

B. Resonant layer location

The location of the resonant layer in the plasma may, in some instances, play an important role in determining the energy deposition. For example see the X-mode rays shown in Figs. 4 and 5. In Fig. 4 the resonance layer is at the poloidal midplane, while in Fig. 5 it is shifted closer to the antenna. Shifting the location of the resonance layer can be accomplished experimentally by controlling the level of the magnetic field in the tokamak. The difference in energy deposition for the rays shown in Figs. 4 and 5 results from the dependence on electron density. This dependence is discussed below. For O-mode rays that are significantly refracted, the location of the resonance layer may also play an important role. If the density gradient and magnitude cause the rays to refract to the edge of the plasma before they arrive at the resonance layer, little or no energy deposition will take place. However, in many of these cases it is possible to obtain strong single pass energy deposition by moving the resonance layer location closer to the antenna. In our study of resonant layer location, we

varied ω_{ce0}/ω from 0.9 to 1.1. Also shifting the location of the resonance layer has an indirect effect on the level of energy deposition since refraction is also affected by the magnetic field strength.

C. Density dependence

As indicated above, the energy deposition may depend strongly on the density level. This is illustrated in Fig. 6 where magnetic field and density along the ray paths is shown (OMA plot of the ray paths). On the left is the plot for the case with the resonance layer at the poloidal midplane (as shown in Fig. 4) and on the right is the similar plot for the case where the resonance layer is moved to a region of lower density (as shown in Fig. 5). For the case shown, X-mode rays crossing the resonance layer in a region of lower electron density deposit more energy despite the fact, as indicated below, that the deposition occurs at a low electron temperature.

D. Temperature dependence

The temperature profile, in the examples presented here, is specified with $p_3=p_4=2$. Consequently, when energy deposition occurs away from the radial center of the plasma, the temperature is significantly less than the peak value, T_{e0} , and the energy deposition may be reduced. In Fig. 7, the magnetic field and temperature are plotted along the ray paths. The rays shown are those rays whose paths are illustrated in Figs. 4 and 5 and which are described above in the discussion on density dependence. Shifting the resonance layer causes the rays to pass through the resonance where the electron temperature is 800 eV rather than 1000 eV. In many cases, the temperature dependence, associated with the temperature profile, is less important than the density dependence, and the energy deposition may be

decreased rather than increased. We have observed many instances for O-mode as well where shifting the resonance layer away from the location of peak temperature results in an increase rather than a decrease in energy deposition.

E. Q profile dependence

In general we find that the ray path (and thus energy deposition) is dependent on the q profile. Moreover, the direction of the rays relative to that of the toroidal current influences the ray path. This is illustrated in Fig. 8 where on the left $q_0=1$ and $q_a=3$ and on the right $q_0=-1$ and $q_a=-3$. As shown, when the sign of q is reversed, Rays 1 and 3 interchange roles. The significant difference in energy deposition occurs despite the fact that as shown, in Fig. 9, the density and magnetic field along the ray paths are nearly the same. In our study of the dependence of the rays on the q profile, we varied the values of the magnitude of q_0 and q_a from 1 to 10. Because of the ray path and energy dependence on the q profile, electron cyclotron waves provide the interesting possibility for use as a q profile diagnostic.

F. Density profile dependence

The parameters p_1 and p_2 , which appear in Eq. (2), determine the density profile. To analyze the profile dependence, we set $p_1=2.0$ and let $p_2=0.5$, 1.0, and 2.0. When significant energy deposition occurs, it generally occurs sufficiently close to the radial center of the plasma so that peaking or broadening the density profile has a limited effect. This is shown in Fig. 10 where the dashed line indicates the shape of the density profile. For the graph on the left $p_2=2.0$ and for the one on the right $p_2=0.5$. There are instances, however, when the density profile does influence energy

deposition. Modifying the density profile, in order to decrease the density (for X-mode) or to increase the density (for O-mode) at the location where the ray path crosses the cyclotron resonance layer, may result in greater energy deposition. This is illustrated for O-mode in Fig. 11. The wave and plasma parameters are the same as for the rays shown in Fig. 8 except that $p_2=1.0$ for the results shown in Fig. 8, and $p_2=0.5$ for the results shown in Fig. 11. With the broader profile there is a significant increase in the energy deposition for Rays 1 and 3.

G. Launch angle dependence

We find that there is a strong dependence on both the poloidal and toroidal launch angles. We consider 10° poloidal and toroidal angular beam widths which are the beam widths expected in the PDX ECH experiment. The energy deposition for the X-mode rays shown in Fig. 12 ranges from under 40% to over 80% even though the physical location where energy deposition occurs is nearly the same for all six rays. Since the physical location for the rays is close to one another, the plasma parameters in the vicinity of the energy deposition are approximately the same. The density, magnetic field, rate of energy deposition, and radial position along the ray are monitored using graphs of the type on the left side of Fig. 13. The graph on the right side of Fig. 13 shows the energy carried by each ray as a function position along the path length. The differences in energy deposition for the rays is mainly due to the differences in parallel wave number for the rays as they pass through the resonance layer. The plots of O-mode rays in Figs. 14 and 15 further illustrate the dependence of energy deposition on launch angle and, in particular, the sensitivity to the direction of launch. We show that changing the toroidal direction of the antenna by 5° results in a dramatic change in

the energy deposition. For the rays in Fig. 14, a significant fraction of the incident energy is not deposited; whereas, for the rays in Fig. 15, more than 60% of the incident ray energy is deposited. For the rays shown in Figs. 12-15, $q_0=2$ and $q_a=5$.

H. Tokamak size dependence

In Fig. 16, the poloidal view of O-mode rays is shown for comparable plasma conditions in Versator (on the left side) and in PDX (on the right side). As anticipated from theoretical considerations,^{10,11} size plays an important role in determining energy deposition. Thus, under comparable conditions, we find negligible deposition for Versator and significant deposition for PDX. Similar results are found for X-mode.

I. Current Drive

Current drive may play an important role in converting pulsed magnetically confined plasma devices into steady-state fusion reactors.¹² The possibility of using electron cyclotron waves to generate a toroidal current in a tokamak has been analyzed.¹²⁻¹⁴ The ratio of driven current, J , to deposited power, P_D , is a function of n , the parallel wave number when the ray is in the vicinity of the cyclotron resonance layer, i.e.,

$$\frac{J}{P_D} = \text{fn} \left(\frac{1 - \omega_{ce}/\omega}{n_{\parallel}} \right) \quad (7)$$

where fn denotes functional dependence. Using TORAY, we find that $n_{\parallel}$ near the resonance absorption layer sensitively depends on the wave and plasma parameters. With TORAY we can scan these parameters to determine optimum conditions for current drive, i.e., the conditions for maximizing J/P_D . If

the ray follows a path parallel to the toroidal magnetic field, it would be possible for the deposition to occur on one side of the resonant layer preferentially coupling energy to electrons traveling in one direction. In Fig. 17 we show that by proper choice of parameters it is possible to obtain ray paths that deposit their energy while traveling nearly parallel to the toroidal field.

IV. CONCLUSIONS

We have used TORAY, a ray tracing code, to study the dependence of electron cyclotron heating on wave and plasma parameters. By examining the results produced by TORAY, we have been able to develop some understanding of how the interplay of the parameters affects the wave propagation and energy deposition. In most examples, we used equilibrium and wave values appropriate for the upcoming ECH experiment on the PDX tokamak. When we compare the ray tracing and analytic^{10,11} predictions for energy deposition, we find that in many instances the ray tracing single pass deposition, for realistic profiles, disagrees with the analytic result by more than 20%. This disagreement is due, in part, to the fact that the energy deposition occurs over a region in space; and in this region, changes in parallel index of refraction and plasma parameters may be large enough to affect the deposition. For the cases where refraction is strong, our result for energy deposition may be completely different than the analytic result. We have also compared the ray tracing width of the energy deposition region with the analytic width due to Doppler shift.¹⁰ This analytical width is appropriate for the comparison since the parallel index of refraction is sufficiently large in the cases that we considered.¹⁵ We find that the energy deposition width predicted by ray tracing is typically 40% larger than the width predicted analytically.

ACKNOWLEDGMENT

This work was supported by U.S. DOE Contract DE-AC02-76-CHO-3073 and in part by the CUNY Faculty Research Award Program.

REFERENCES

- ¹D.B. Batchelor and R.C. Goldfinger, ORNL/TM-6844 (1980).
- ²D.B. Batchelor and R.C. Goldfinger, Nucl. Fusion 20, 404 (1980).
- ³D.B. Batchelor, R.C. Goldfinger, and H. Weitzner, IEEE Trans. Plasma Sci. PS-8, 78 (1980).
- ⁴R.C. Goldfinger, A.H. Kritz, and D.B. Batchelor, Bull. Am. Phys. Soc. 26, 1034 (1981).
- ⁵L.F. Shampine and M.K. Gordon, Computer Solution of Ordinary Differential Equation, The Initial Value Problem (W.H. Freeman and Co., San Francisco, 1975); Sandia Laboratories Report SLA-73-1060 (1973); Argonne Code Center Abstract 640 (1976).
- ⁶A.I. Akhiezer, I.A. Akhiezer, R.V. Polovin, A.G. Sitenko, and K.N. Stepanov, Plasma Dynamics (Pergamon Press, Oxford, 1975), Vol. I.
- ⁷G. Bekefi, Radiation Processes in Plasma (John Wiley, New York, 1979).
- ⁸M. Bornatici, presented at the Joint Workshop on Electron Cyclotron Emission and Electron Cyclotron Resonance Heating, Oxford, UK, (unpublished).
- ⁹I. Fidone, G. Granata, R.L. Meyer, E.H. Jornada, R.S. Schneider, and L.F. Ziebell, Phys. Fluids 23, 1336 (1980).
- ¹⁰O. Eldridge, W. Namkung, A.C. England, ORNL/TM-6052 (1977).
- ¹¹I. Fidone, G. Granata, R.L. Meyer, and G. Ramponi, Plasma Phys. 22, 203 (1980).
- ¹²N.J. Fisch, Phys. Rev. A: 24, 3245 (1981).
- ¹³N.J. Fisch and A.H. Boozer, Phys. Rev. Lett. 45, 720 (1980).
- ¹⁴C.F.F. Karney and N.J. Fisch, Nucl. Fusion 21, 1549 (1981).

¹⁵M. Bornatici, in Proceedings of the Second Joint Grenoble-Varenn
International Symposium on Heating in Toroidal Plasmas, edited by E. Canobbio
et al., (Commission of the European Communities, Brussels, 1981), Vol. 1,
pp. 143-158.

FIGURE CAPTIONS

FIG. 1 Poloidal and toroidal views of ray paths for O-mode wave propagation in PDX. ($n_{eo} = 4 \times 10^{13} \text{ cm}^{-3}$, $T_{eo} = 1 \text{ keV}$, and $\omega_{ceo}/\omega = 1$.) Single pass energy deposition equals 88% for Rays 1 and 6, 78% for Rays 2 and 5, and 87% for Rays 3 and 4. Each x along the ray path indicates an additional 10% energy deposition. The poloidal launch angle, measured from the direction of the positive Z-axis, ranges from 85° to 95°, and the toroidal launch angle in the x-y plane, measured counterclockwise from the positive x-axis, ranges from 175° to 185°.

FIG. 2 Poloidal and toroidal views of ray paths for X-mode wave propagation in PDX. ($n_{eo} = 4 \times 10^{13} \text{ cm}^{-3}$, $T_{eo} = 1 \text{ keV}$, and $\omega_{ceo}/\omega = 1$.) Single pass energy deposition equals 66% for Ray 1, 82% for Ray 2, 95% for Ray 3, and 98% for Ray 4. Each x along the ray path indicates an additional 10% energy deposition. The poloidal launch angle, measured from the direction of the positive z-axis, ranges from 130° to 140°, and the toroidal launch angle in the x-y plane, measured counterclockwise from the positive x-axis, ranges from 20° to 30°.

FIG. 3 Parallel, perpendicular, and total wave number as a function of time, the ray tracing parameter. (Either time or path length are used as the ray tracing parameter in TORAY.) The wave numbers are for Rays 1 and 3 shown in Fig. 2. The difference in energy deposition (66% for Ray 1 and 95% for Ray 3) results mainly from the difference in the value of n in the region where energy deposition takes place. The radial position along the ray path is also shown.

FIG. 4 Ray paths for X-mode wave propagation in PDX. Energy deposition is limited in high density plasmas ($n_{eo} = 8 \times 10^{13} \text{ cm}^{-3}$) if the ray path passes through the cyclotron resonance layer in the vicinity of peak electron density. For the case shown $\omega_{ce}/\omega=1$ and $T_{eo}=1 \text{ keV}$. The single pass energy is 13% for Ray 1, 0% for Ray 2, 21% for Ray 3, and 0% for Ray 4. The rays are launched with the same launch angles as in Fig. 2.

FIG. 5 Ray paths for X-mode propagation with the same conditions as for Fig. 4 except that the resonance layer is moved closer to the antenna, $\omega_{ce}/\omega=0.9$. Moving the resonance layer results in a dramatic increase in the energy deposition. The energy deposition for Rays 1 to 4 is 52%, 84%, 83%, and 95%, respectively.

FIG. 6 Magnetic field and electron density along ray paths, on the left, for the rays shown in Fig. 4 and on the right, for the rays in Fig. 5. The increased energy deposition by the X-mode rays, on the right, is mainly due to the lower electron density in the region where the ray crosses the resonance layer ($\omega_{ce}/\omega=1$).

FIG. 7 Magnetic field and electron temperature along ray paths, on the left, for the rays in Fig. 4 and on the right, for the rays in Fig. 5. In the plot on the right the resonance layer ($\omega_{ce}/\omega=1$) occurs at a lower temperature than in the plot on the left. Nonetheless, the rays on the right deposit more energy than do the rays on the left. This is because of the density effect described in Fig. 6.

FIG. 8 Poloidal view of ray paths to illustrate the q profile dependence. For the plot on the right $q_0=1$ and $q_a=3$; whereas, for the plot on the left $q_0=-1$ and $q_a=-3$. ($n_{e0}=4 \times 10^{13} \text{ cm}^{-3}$, $\omega_{ce0}/\omega=0.9$, and $T_{e0}=1 \text{ keV}$.) The poloidal launch angle, measured from the direction of the positive z -axis, ranges from 85° to 95° , and the toroidal launch angle in the x - y plane, measured counterclockwise from the positive x -axis, is 170° .

FIG. 9 Magnetic field and electron density along the ray path for the rays illustrated in Fig. 8. Note that Rays 1 and 3 are close to one another on the OMA (magnetic field versus electron density) plot and that small shifts on the OMA plot may be associated with significant changes in ray path and energy deposition.

FIG. 10 The density profile, $(\omega_{pe}/\omega)^2$, is indicated by the dashed line. For the sharper profile on the left, the density parameters are $p_1=2$ and $p_2=2$ and for the broader profile on the right, $p_1=2$ and $p_2=0.5$. In the case shown, the shape of the plasma density profile does not significantly affect the energy deposition. ($n_{e0} = 4 \times 10^{13} \text{ cm}^{-3}$, $T_{e0}=1 \text{ keV}$ and $\omega_{ce0}/\omega=1$.) The launch position is that shown for Ray 1 in Fig. 2. The poloidal angle is 130° and the toroidal angle is 20° .

FIG. 11 These plots are for the same plasma conditions as for the ray paths on the left side of Fig. 8 except that in Fig. 8, $p_2=1$, and for the plots in this Fig. $p_2=0.5$. With the broader density profile there is a significant increase in energy deposition. The energy deposition

for Ray 1 is 53%, for Ray 2, 71% and for Ray 3, 61%. On the right, the magnetic field, electron density, and energy deposition are plotted as a function of radial position.

FIG. 12 Poloidal and toroidal views of X-mode ray paths illustrating the strong dependence of energy deposition on the launch angle. With 10° poloidal and toroidal angular beam widths, energy deposition ranges from 37% for Ray 1 to 82% for Ray 6. The energy deposition for Ray 2 is 44%; for Ray 3, 60% for Ray 4, 66%; and Ray 5, 79%. ($n_{e0} = 4 \times 10^{13} \text{ cm}^{-3}$, $T_{e0} = 800 \text{ eV}$, and $\omega_{ce0}/\omega = 1$.)

FIG. 13 The plot on the left shows the density, magnetic field, rate of energy deposition, and radial position along the ray path for Ray 3 of Fig. 12. The plot on the right shows energy carried by each ray as a function of position along the ray path.

FIG. 14 Poloidal and toroidal views of O-mode ray paths illustrating the strong dependence of energy deposition on the launch angle. With 10° poloidal and toroidal angular beam widths, some fraction of the incident wave energy may be refracted and not cross the resonance layer. The poloidal launch angle ranges from 120° to 130° , measured from the z-axis, and the toroidal launch angle ranges from 35° to 45° , measured from the x-axis. The energy deposition for Rays 1 to 6 is 69%, 1%, 69%, 0%, 67%, and 0%, respectively. ($n_{e0} = 4 \times 10^{13} \text{ cm}^{-3}$, $T_{e0} = 800 \text{ eV}$, and $\omega_{ce0}/\omega = 1$.)

FIG. 15 Poloidal and toroidal views of O-mode ray paths. The sensitivity of energy deposition on the direction in which the rays are launched is seen by comparing Figs. 14 and 15. Except for a 5° change in the direction of the poloidal launch angle, the wave and plasma conditions are the same for the rays shown in Figs. 14 and 15. For the rays shown here, the poloidal launch angles are 115° and 125° . The energy deposition for Rays 1 to 6 is 64%, 76%, 64%, 84%, 62%, and 95%, respectively.

FIG. 16 Poloidal view of O-mode rays showing the dependence of energy deposition on tokamak size. Under comparable conditions ($\omega_{pe}/\omega=0.81$, $T_{eo}=500$ eV, and $\omega_{ce}/\omega=1$), there is negligible damping in a Versator size tokamak compared to a PDX size tokamak. For Versator, ≈ 35 GHz, $R=40.5$ cm; for PDX, ≈ 60 GHz, $R=112$ cm. The poloidal launch angles are 122° and 138° and the toroidal launch angles are 5° and 15° .

FIG. 17 Energy deposition on one side of the resonance layer by rays moving almost parallel to the toroidal field. For the X-mode case on the left, $n_{eo} = 8 \times 10^{13} \text{ cm}^{-3}$, $T_{eo} = 800$ eV, and $\omega_{ce}/\omega=1$, and for the O-mode case on the right, $n_{eo} = 4 \times 10^{13} \text{ cm}^{-3}$, $T_{eo} = 800$ eV and $\omega_{ce}/\omega = 1.05$. Deposition similar to that shown in Fig. 17 is required for current drive. For the X-mode rays on the left, the poloidal angle ranges from 115° to 125° and the toroidal angle ranges from 35° to 45° . For the O-mode ray on the right, the poloidal angle is 90° and the toroidal angle is 145° .

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11

Fig. 12

Fig. 13

#82X0439

Fig. 14

Fig. 15

Fig. 16

Fig. 17

EXTERNAL DISTRIBUTION IN ADDITION TO TIC UC-20

Plasma Res Lab, Austro Nat'l Univ, AUSTRIA
 Dr. Frank J. Paoloni, Univ of Wollongong, AUSTRALIA
 Prof. I.R. Jones, Flinders Univ., AUSTRALIA
 Prof. M.H. Brennan, Univ Sydney, AUSTRALIA
 Prof. F. Cep, Inst Theo Phys, AUSTRIA
 Prof. Frank Verheest, Inst theoretische, BELGIUM
 Dr. D. Palumbo, Og XII Fusion Prog, BELGIUM
 Ecole Royale Militaire, Lab de Phys Plasmas, BELGIUM
 Dr. P.H. Sakaneke, Univ Estadual, BRAZIL
 Dr. C.R. James, Univ of Alberta, CANADA
 Prof. J. Teichmann, Univ of Montreal, CANADA
 Dr. H.W. Skarsgard, Univ of Saskatchewan, CANADA
 Prof. S.R. Sreenivasan, University of Calgary, CANADA
 Prof. Tudor M. Johnston, INRS-Energie, CANADA
 Dr. Hannes Bernard, Univ British Columbia, CANADA
 Dr. M.P. Bachynski, MFB Technologies, Inc., CANADA
 Zhengou Li, SW Inst Physics, CHINA
 Library, Tsing Hua University, CHINA
 Librarian, Institute of Physics, CHINA
 Inst Plasma Phys, SW Inst Physics, CHINA
 Dr. Peter Lukac, Komenského Univ, CZECHOSLOVAKIA
 The Librarian, Culham Laboratory, ENGLAND
 Prof. Schatzman, Observatoire de Nice, FRANCE
 J. Radet, CEN-EP6, FRANCE
 AM Dupas Library, AM Dupas Library, FRANCE
 Dr. Tom Muai, Academy Bibliographic, HONG KONG
 Preprint Library, Cent Res Inst Phys, HUNGARY
 Dr. A... Sundaram, Physical Research Lab, INDIA
 Dr. S.K. Trehan, Panjab University, INDIA
 Dr. Indra, Mohan Lal Das, Banaras Hindu Univ, INDIA
 Dr. L.K. Chevda, South Gujarat Univ, INDIA
 Dr. R.K. Chhajlani, Var Ruchi Mora, INDIA
 B. Buti, Physical Research Lab, INDIA
 Dr. Phillip Rosenau, Israel Inst Tech, ISRAEL
 Prof. S. Superman, Tel Aviv University, ISRAEL
 Prof. G. Rostagni, Univ Di Padova, ITALY
 Librarian, Int'l Ctr Theo Phys, ITALY
 Miss Ciella De Palo, Assoc EURATOM-CNEN, ITALY
 Biblioteca, del CNR EURATOM, ITALY
 Dr. H. Yamato, Toshiba Res & Dev, JAPAN
 Prof. M. Yoshikawa, JAERI, Tokai Res Est, JAPAN
 Prof. T. Uchida, University of Tokyo, JAPAN
 Research Info Center, Nagoya University, JAPAN
 Prof. Kyoji Nishikawa, Univ of Hiroshima, JAPAN
 Sigeru Mori, JAERI, JAPAN
 Library, Kyoto University, JAPAN
 Prof. Ichiro Kawakami, Nihon Univ, JAPAN
 Prof. Seisshi Itoh, Kyushu University, JAPAN
 Tech Info Division, Korea Atomic Energy, KOREA
 Dr. R. England, Ciudad Universitaria, MEXICO
 Bibliotheek, Fem-inst Voor Plasma, NETHERLANDS
 Prof. B.S. Lilley, University of Waikato, NEW ZEALAND
 Dr. Suresh C. Sharma, Univ of Calabar, NIGERIA
 Prof. J.A.C. Cabral, Inst Superior Tech, PORTUGAL
 Dr. Octavian Petrus, ALL CUZA University, ROMANIA
 Dr. R. Jones, Nat'l Univ Singapore, SINGAPORE
 Prof. M.A. Hellberg, University of Natal, SO AFRICA
 Dr. Johan de Villiers, Atomic Energy Bd, SO AFRICA
 Dr. J.A. Taglie, JEN, SPAIN
 Prof. Hans Wilhelmson, Chalmers Univ Tech, SWEDEN
 Dr. Lennart Stenflo, University of UMEA, SWEDEN
 Library, Royal Inst Tech, SWEDEN
 Dr. Erik T. Karlson, Uppsala Universitet, SWEDEN
 Centre de Recherches, Ecole Polytech Fed, SWITZERLAND
 Dr. W.L. Weise, Nat'l Bur Stand, USA
 Dr. W.M. Stacey, Georg Inst Tech, USA
 Dr. S.T. Wu, Univ Alabama, USA
 Mr. Norman L. Oleson, Univ S Florida, USA
 Dr. Benjamin Ma, Iowa State Univ, USA
 Magne Kristiansen, Texas Tech Univ, USA
 Dr. Raymond Askew, Auburn Univ, USA
 Dr. V.T. Tolok, Kharkov Phys Tech Ins, USSR
 Dr. D.D. Ryutov, Siberian Acad Sci, USSR
 Dr. M.S. Rabinovich, Lebedev Physical Inst, USSR
 Dr. G.A. Eliseev, Kurchatov Institute, USSR
 Dr. V.A. Glukhikh, Inst Electro-Physical, USSR
 Prof. T.J. Boyd, Univ College N Wales, WALES
 Dr. K. Schindler, Ruhr Universität, W. GERMANY
 Nuclear Res Estab, Jülich Ltd, W. GERMANY
 Librarian, Max-Planck Institut, W. GERMANY
 Dr. H.J. Kaeppler, University Stuttgart, W. GERMANY
 Bibliothek, Inst Plasmaforschung, W. GERMANY