192
10/28/80 T.S

D. 1829

SEPTEMBER 1980

PPPL-1697

UC-20F

MODE CONVERTER FOR ELECTRON
CYCLOTRON RESONANCE HEATING
OF TOROIDAL PLASMAS

BY

R. W. MOTLEY, H. HSUAN,
AND J. GLANZ

MASTER

**PLASMA PHYSICS
LABORATORY**

**PRINCETON UNIVERSITY
PRINCETON, NEW JERSEY**

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

This work was supported by the U.S. Department of Energy
Contract No. DE-AC02-76-CHO 3073. Reproduction, transla-
tion, publication, use and disposal, in whole or in part,
by or for the United States government is permitted.

Mode Converter for Electron Cyclotron Resonance
Heating of Toroidal Plasmas

R. W. Motley, H. Hsuan, and J. Glanz

Plasma Physics Laboratory, Princeton University
Princeton, New Jersey 08544

ABSTRACT

A method is proposed for improving the efficiency of cyclotron resonance heating of a toroidal plasma by ordinary mode radiation from the outside of the torus. Radiation not absorbed in the first pass is reflected from the inside of the torus by a corrugated surface which rotates the polarization by 90° , so that a secondary source of extraordinary waves is created in the high field, accessible region of the plasma.

DISCLAIMER

This document contains information of a confidential nature. It is not to be distributed outside the United States Government nor any agency thereof, nor any of their employees, without the express written consent of the United States Government. It is the policy of the United States Government to protect its confidential information from unauthorized disclosure. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED *g*

The invention of the gyrotron,¹ an efficient source of power in the 10-100 GHz range, has greatly enhanced the attractiveness of the electron cyclotron resonance heating of toroidal plasmas. Moderate power gyrotrons (~100 kW) have already been used to heat plasmas in the TM-3² and ISX-B³ Tokamaks. Higher power experiments are being prepared by a number of groups.

It is possible to heat high temperature plasmas at both the fundamental cyclotron frequency ω_c and its harmonics. There is considerable incentive, however, to employ fundamental heating, because the higher frequency sources require further development and when available may be more expensive and unreliable than their lower frequency counterparts.

The magnetic field in a toroidal plasma varies as R^{-1} , where R is the major radius of the torus. This characteristic results in a well-known problem in heating a plasma at the fundamental frequency in the extraordinary mode ($E_{\perp}B_0$).⁴ As shown in Fig. 1 the two possible absorption layers, the cyclotron resonance layer, where $\omega_c = \omega$ and the upper hybrid layer, where $\omega_c = (\omega^2 - \omega_p^2)^{1/2}$, are shielded from the outside of the torus by a reflecting layer at $\omega_p^2 = \omega(\omega - \omega_c)$. The result is that direct heating in the extraordinary mode is not feasible if the antenna is placed in the most convenient location—near the outside of the torus.

Two solutions to this problem, neither completely satisfactory, have been implemented. One can direct the radiation from the outside in the ordinary mode (Method 1). Strong single-pass absorption will take place if both the plasma density and temperature are high ($n > 10^{13} \text{ cm}^{-3}$, $T_e > 1 \text{ keV}$), but otherwise the interaction is weak.⁵ This feature impairs the versatility

of a system in which it may be desirable to use ECR for cyclotron discharge initiation and temperature profile control, as well as supplementary heating.

In some installations, for example ISX-B,³ it is possible to place the radiating antenna on the inside of the torus, so that the absorbing layers are directly accessible. This solution is not a generally satisfactory one. Access to this region from the top or bottom of the torus is difficult; installation of the required waveguide may interfere with poloidal divertors.

In this note we propose a hybrid system in which both ordinary and extraordinary beams are sent through the plasma column. As shown in Fig. 2 microwave power is radiated into a torus from the outside in the ordinary mode. If the conditions are appropriate for strong absorption the system is identical to Method 1. In dilute or cold plasmas, however, radiation will pass through the column with only slight attenuation. On the inside wall of the torus we place a mode converter, which reflects the incident power and simultaneously rotates the plane of polarization 90° , so that the electric vector is perpendicular to the toroidal field. The rotator thus serves as a secondary source of extraordinary radiation. Since the extraordinary rays originate in a region of high field, they can propagate freely to the absorption layers, which are now in front of the reflecting layer. Within two passes, then, the beam should undergo almost complete absorption.

A similar process is believed to take place in toroidal EBT plasmas,⁶ where radiation is launched from the outside in the ordinary mode and converts gradually on multiple reflections from the vacuum walls to the extraordinary mode, which interacts

strongly with hot electron rings. In our design, the process is more controlled and should be completed after only one reflection, so that the overall efficiency may be greatly improved.

What is the optimum design of the polarization rotator? A number of designs involving wires and dielectric materials are possible, but must be rejected on the basis that they introduce serious problems of cooling and outgassing. A possible all-metal design is shown in Fig. 3, consisting of a series of triangular troughs running at right angles to the direction of incidence and 45° with respect to the incident electric field. The device possesses some of the advantageous properties of the corner reflector. On double reflection a ray returns in the same direction as it originated. Also, the path length of each reflected ray is identical, so that interference effects are not dominant.

To understand clearly how the triangular troughs rotate the plane of polarization we decompose the electric vector of the incident wave E_i into two components, one parallel to the grooves of the trough and other perpendicular ($E_{||}$ and $E_{\perp}$ in Fig. 3, 4). The important boundary condition is that the component of E parallel to the reflecting plane is shifted in phase by 180° , while the perpendicular component is not changed in phase. (Note that these components are not identical with $E_{||}$ and $E_{\perp}$.) Therefore on double reflection $E_{||}$ remains unchanged; $E_{\perp}$ rotates through 180° (Fig. 4). The vector addition of $E_{\perp}$ and $E_{||}$ then results in a total reflection vector E_r rotated by 90° from the incident E_i .

Incident rays that diverge in planes perpendicular to the grooves will be returned at the same angle, so that in this

direction a plane rotator will refocus the divergent rays from the antenna. In planes parallel to the grooves there will be no focussing. In a more practical design contoured to the inside of the torus there may be focussing in the minor cross section and defocussing in the long direction around the torus.

We have tested a converter with crests separated by $L = 5.08$ cm, using 8.5 mm microwaves, so that the ratio $L/\lambda = 6.0$. Plane polarized radiation was directed from a horn antenna (radiation half width 8°) to a converter placed 40 cm away. Fig. 5 shows how the amplitude of the signal reflected into a receiving horn (displaced vertically 5.5 cm from the transmitter) depends on the orientation of the converter grooves. As one expects, a 45° angle between E_1 and the direction of the grooves maximizes the power in the reflected signal with polarization rotated 90° and minimizes the power in the unrotated wave. At the 0° and 90° positions the wave polarization is not changed on reflection. There is a marked asymmetry between 0° and 90° . This feature arises because the two antennae are separated vertically and the mirror images a circular object into an elliptical image that preferentially intercepts the receiving antenna when the grooves are vertical ($\theta = 90^\circ$).

We have also checked the angular dispersion of the waves reflected from the mirror. As shown in Fig. 6 there is $\sim 8^\circ$ broadening of the reflected signal in a direction parallel to the grooves, consistent with the divergence of the rays from the transmitting antenna. In a direction perpendicular to the grooves one observes that the mirror focusses the radiation to a half angle of $\sim 1.8^\circ$. Also in this direction a small fraction of the

power ($<5\%$) is scattered into side lobes at 9° and 20° as a result of wave diffraction from the sharp corners of the mirror. Curve C (the reflected signal with unchanged polarization) appears to show that the converter efficiency is only 90%. We have determined, however, that this signal originates from multiple reflection between transmitting horn and the mirror. The actual converter efficiency, determined by angling the transmitting horn, is greater than 99%.

The height of the grooves must be chosen as a compromise in which one (1) minimizes the mass of material on the inside of the torus, and (2) simultaneously minimizes diffraction effects from the sharp angles of the troughs. We have found that the converter described here, in which $L/\lambda = 6.0$, represents a practical lower limit to the spacing between individual elements of the converter. Tests on a converter for which $L/\lambda = 3.0$ show that more than 50% of the power is reflected into side lobes. In other words, its characteristics are closer to an echelette grating than to a mirror.

The converter may find application in mode conversion in toroidal plasmas, either actively in cyclotron heating applications, or passively, in permitting observation of extraordinary waves radiated towards the inside of the plasma torus.

ACKNOWLEDGMENTS

The authors acknowledge useful discussions with V. Arunasalam, P. Efthimion, and J. Doane. This work was done under the U. S. Department of Energy Contract No. DE-AC02-76-CH03073.

REFERENCES

- ¹N. I. Zaytsev, T. B. Pankratova, M. I. Petelin, and V. A. Flaygin, Radio Engineering and Electronic Physics 19, 103 (1974).
- ²V. V. Alikaev, G. A. Bobrorskii, V. I. Pozniak, K. A. Razumova, V. V. Sannikov, Yu. A. Sokolov, and A. A. Shmarin, Fiz. Plazmy 2, 390 (1975); Sov. J. Plasma Phys. 2 212 (1976).
- ³R. M. Gilgenbach, et al., Phys. Rev. Lett. 44, 647 (1980).
- ⁴A. Y. Wong and A. F. Kuckes, Phys. Rev. Lett. 13, 306 (1964).
- ⁵P. C. Efthimion, V. Arunasalam, and J.C. Hosea, Phys. Rev. Lett. 44, 396 (1980).
- ⁶R. A. Dandl, et al., in Plasma Phys. and Controlled Thermonuclear Research, 1978, Vol. II (IAEA, Vienna, 1979) Nuclear Fusion Supplement 1979, 365 (1979).

(FPPL-806170)
 Fig. 1. Typical variation of the cyclotron resonance frequency $\omega_c = eB/m_e c$, the electron plasma frequency squared, $\omega_p^2 = 4\pi n e^2/m_e$, and the upper hybrid frequency $(\omega_c^2 + \omega_p^2)^{1/2}$ in a toroidal plasma. A reflecting layer at $\omega_p^2 = \omega(\omega - \omega_c)$ shields the extraordinary mode radiated from the outside of the torus. All frequencies are normalized to the wave frequency, $\omega = 1$.

(PPPL-806173)
 Fig. 2. Cross section of toroidal plasma showing transmitting antenna at the outside, the mode converter at the inside of the torus, and the 90° rotation between the incident E_i and reflected E_r electric fields.

Fig. 3. Mode converter, consisting of 45° triangular troughs at 45° with respect to the incident electric field. (PPPL-806171)

Incident Ray

Reflected Ray

Fig. 4. Reflection characteristics of rf wave fields parallel to ($E_{||}$) and perpendicular to ($E_{\perp}$) the axes of the converter grooves.

(PPPL-806174)

(PPPL-806333)
 Fig. 5. Reflection signals as a function of angle θ between E_i and the mirror grooves. The transmitting and receiving horns were separated from the mode converter by 40 cm and were displaced vertically from each other by 5.5 cm. The vertical separation is responsible for the marked asymmetry between 0° and 90° .

Fig. 6. Reflection as a function of the angle ϕ between the normal to the converter and the direction of the receiving antenna; $\theta = 45^\circ$. Curves A and B show the (polarization rotated) relected signals in directions perpendicular to (A) and parallel to (B) the grooves. Curve C shows the (unrotated) signal in the same direction as A.

(PPPL-806172)