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ELECTRON CYCLOTRON RESONANCE HEATING OF TANDEM MIRRORS AT RELAT--ETC(U)

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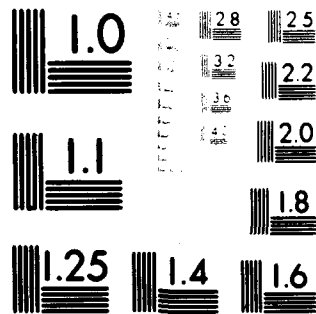
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## ELECTRON CYCLOTRON RESONANCE HEATING OF TANDEM MIRRORS AT RELATIVISTIC ENERGIES

Electron cyclotron resonance heating (ECRH) has been shown to be an efficient way of heating plasmas in tokamaks and Elmo-Bumpy-Torus.<sup>1</sup> Recently, Baldwin and Logan<sup>2</sup> proposed selective local heating of electrons of tandem mirrors, e.g., inside the Ying Yang and the A-cell to lower the power requirement of the neutral beam injectors. Small scale experiments are already being conducted.<sup>3</sup> Wave propagation and energy deposition in tandem mirrors are also under active theoretical investigation.<sup>4</sup> Most of the research or design so far uses a heating frequency  $\omega$  equals to the first or second harmonics of the cyclotron frequency  $\omega_{ce}(0)$  at the center of the plasma. For a 20 KG magnetic field, this would require a 56 GHz source, such as gyrotrons. High power gyrotrons at this frequency are still under development. In the following, we show that as the electron temperature ( $T_e$ ) increases, a lower frequency wave will actually deliver its energy closer to the center. For a 20 KG magnetic field and  $T_e = 90$  keV, wave frequency corresponds to 10 KG magnetic field (28 GHz) is sufficient. Gyrotrons at this frequency range are already available.<sup>5</sup>

To study the propagation and energy deposition of the wave in tandem mirrors, we use a ray tracing code which incorporates fully relativistic absorption coefficients. No expansion on  $\gamma$  is made, where  $\gamma$  is the relativistic factor. Shkarofsky's integrals are not used here.<sup>6</sup> A detail description of the code and the absorption coefficients will be reported elsewhere. Here, we shall concentrate on the results of ECR heating of plasma in the Ying Yang region of MFTF-B. We shall also comment on applying our results to the A-cell.

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The Ying Yang magnetic field is an absolute minimum  $B$  configuration and is approximated by the sum of a mirror field and a quadrupole field<sup>7</sup>

$$\mathbf{B} = \mathbf{B}_M + \mathbf{B}_Q$$

where the mirror field is given by  $\mathbf{B}_M = B_z \hat{e}_z - 1/2 B_z' r \hat{e}_r$ , and the quadrupole field by given by

$$\mathbf{B}_Q = -K_p B_z r (\hat{e}_r \cos 2\theta - \hat{e}_\theta \sin 2\theta)$$

where

$$B_z = \frac{B_0}{2} \left( 1 + \frac{\alpha}{2} \right) \left[ \frac{1}{1 + K_m^2 (z + L_m/2)^2} + \frac{1}{1 + K_m^2 (z - L_m/2)^2} \right]$$

and  $B_z'$  is the derivative of  $B_z$  with respect to  $z$ .  $B_0$  is the minimum magnetic field and is taken to be 20 KG;  $L_m = 360$  cm, is mirror to mirror distance.<sup>8</sup> The other constants are  $K_p = 0.1$ ,  $\alpha = 10.74$ ,  $K_m = 0.09$ . The density profile is modeled by

$$n(r,z) = n_0 \exp [-(r/l_r)^2 - (z/l_z)^2]$$

where  $n_0$  is the density at the center and  $l_r$  and  $l_z$  are density scale lengths in radial and  $z$  direction. The values of  $n_0$ ,  $l_r$ ,  $l_z$  are  $10^{13}$ , 48 and 60 respectively. The temperature profile is modeled by<sup>9</sup>  $T_e(r,z) = T_{e0} (n/n_0)^{2/5}$  and  $T_{e0} = 90$  keV. It should be noted that the exact functional forms of  $n$  and  $T_e$  are not crucial in our calculations.

First we use the first harmonic of the extraordinary mode with  $\omega = \omega_{ce}(0)$  where  $\omega_{ce}(0) = eB_0/mc$  is the cyclotron frequency (non-relativistic) at the center of the plasma. We fix  $\theta = 0^\circ$ ,  $r = 100$  cm and varies  $z = 0, 50, 100$  cm. We inject the rays  $5^\circ$  from the perpendicular to the magnetic field. The results are shown in Fig. 1. The rays are heavily damped at the edge of the plasma. Reducing  $T_e$  from 90 keV to 10 keV does not improve the picture too much. If we decrease  $\omega$  from  $\omega_{ce}(0)$  to some fraction of  $\omega_{ce}(0)$ , we find the energy deposition regions shift toward the center of the plasma (Fig. 2). Further reduction of  $\omega$  encounters a mode conversion and the ray is reflected back. Contrary to the accessibility condition  $\omega > \omega_{pe}$ , which requires a higher  $\omega$  to reach higher density, we find that lowering the frequency will actually help to deliver the energy to the center of the plasma. Similar results are obtained for the

ordinary mode (Fig. 3), except for this case, we can only reduce  $\omega$  to  $0.5 \omega_{ce}(0)$ . Further reduction in  $\omega$  results in violation of the accessibility condition  $\omega > \omega_{pe}$  and the ray is turned back.

The physics behind could be easily understood from examining the relativistic cyclotron resonance condition

$$\omega = \omega_{ce}/\gamma + k_{\parallel} v_{\parallel}$$

To simplify the arguments, we shall approximate  $k_{\parallel} \approx 0$  for almost perpendicular injection. The resonance condition becomes  $\omega \approx \omega_{ce}/\gamma$ . For a heating frequency  $\omega = \omega_{ce}(0)$  and relativistic temperature ( $\gamma > 1$ ),  $\omega_{ce}$  must be bigger than  $\omega_{ce}(0)$  to satisfy the resonance condition. The Ying Yang region is an absolute minimum  $B$  configuration. If the resonance condition is at  $\omega_{ce} > \omega_{ce}(0)$ , the resonance will be located away from the center of plasma, for  $T_e(0) = 90$  keV, it is near the edge as demonstrated in Fig. 1.

In order to move the resonance closer to the center of the plasma, we have to lower the magnitude of  $\omega_{ce}$  at resonance. This can be accomplished by lowering the heating frequency  $\omega$  to  $\epsilon \omega_{ce}(0)$  where  $\epsilon < 1.0$ . Fig. 2 shows  $\epsilon$  could be as small as 0.4. From the resonance condition, we find that  $\gamma$  must be about 2. For  $T_e(0) = 90$  keV, this means the energy is deposited at the tail of a maxwellian distribution function. We have not optimized the injection geometry, it may be for some particular parameters,  $\gamma$  could be smaller. A detail analysis of the Fokker Planck equation and the quasilinear diffusion equation will be needed to find how fast the energy is deposited at the tail and how fast it is transferred to the thermal electrons.

The preceding scheme could also be applied to the heating of the A-cell of MFTF-B, but it turns out that lowering the heating frequency may not be necessary. The A-cell is not a minimum  $B$  configuration in the radial direction, so the wave with  $\omega \approx \omega_{ce}(0)$  should be able to deliver its energy to the thermal electrons and close to the center of the plasma. The central magnetic field strength in the A-cell is about 10 KG, so again a 28 GHz source is sufficient.

In conclusion, we find that in the relativistic regime, the wave energy could be delivered closer to the center of the Ying Yang plasma of MFTF-B if  $\omega < \omega_{ce}(0)$ . A scenerio to heat the plasma in this region could be the following: a series of source at 28 GHz and 56 GHz are used, first, the 56 GHz source is turned on and then as the temperature of the electrons rises above a certain level, we switch off the 56 GHz source and turn on the 28 GHz source to continue the heating.

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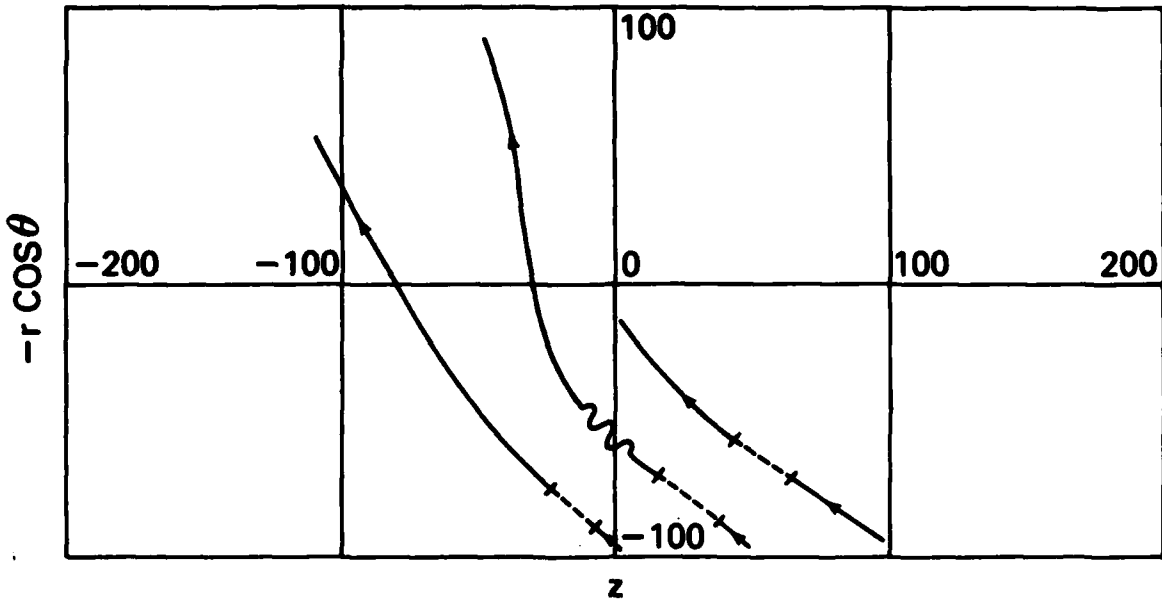


Fig. 1 - A  $r$ - $z$  plot of the Ying Yang region of MFTF-B. The extraordinary modes are injected at  $r = 100$  cm,  $\theta = 0^\circ$  and  $z = 0, 50, 100$  cm,  $T_e(0) = 90$  keV,  $n_0 = 10^{13}$  cm $^{-3}$ ,  $B_0 = 20$  KG,  $Y_0 = \omega/\omega_{ce}(0) = 1.0$ . The majority of the energy (>95%) are deposited at the broken curve regions (---). The wiggles (w) is energy desposition regions when  $T_e(0) = 10$  keV.

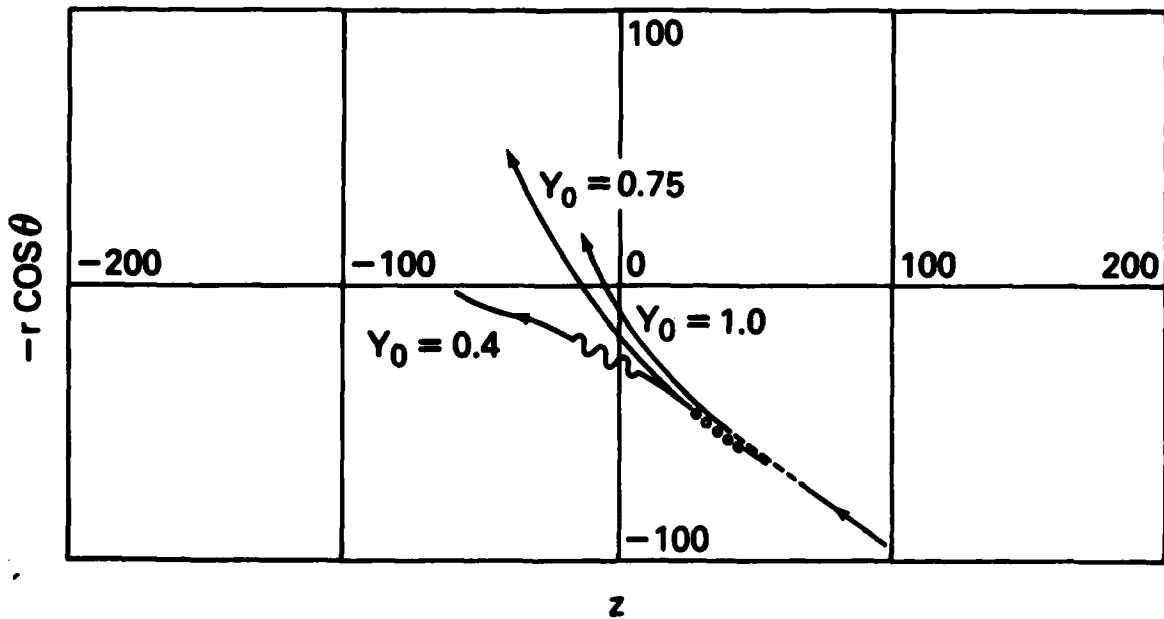


Fig. 2 - Same parameters as Fig. 1. The broken curve (---), open circles (OOOO) and wiggles (w) are energy desposition regions of  $Y_0 = 1.0, 0.75$  and  $0.4$  respectively,  $T_e(0) = 90$  keV.

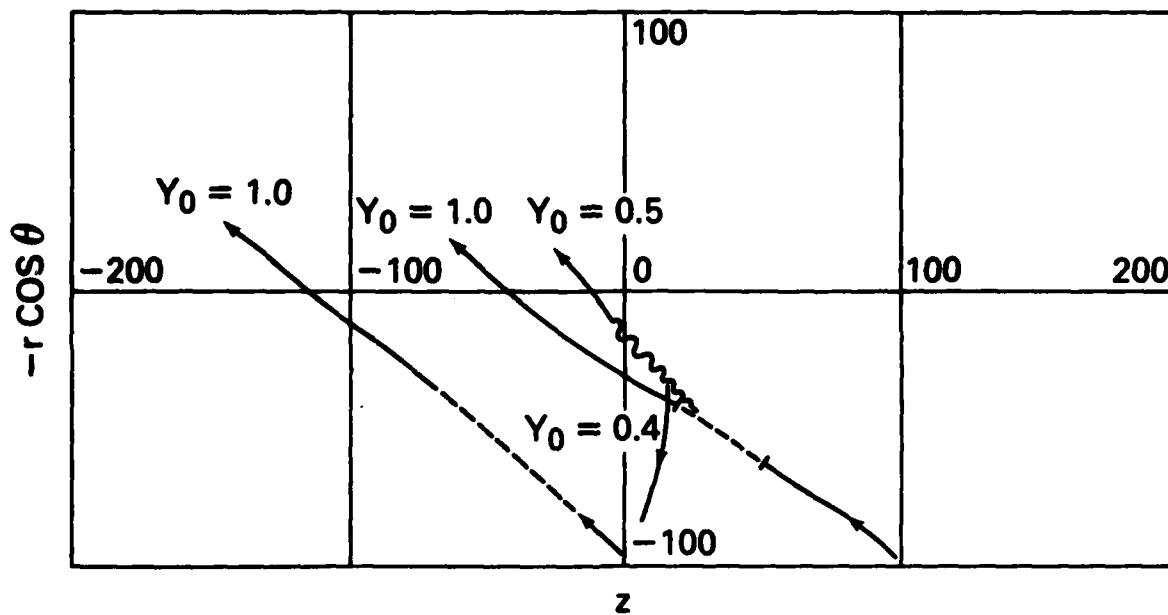


Fig. 3 - Same parameters as Fig. 1. The broken curve (---) and wiggles (~~~~) are energy deposition regions of ordinary modes with  $\gamma_0 = 1.0$  and  $0.5$  respectively;  $T_e(0) = 90$  keV. The mode with  $\gamma_0 = 0.4$  is reflected back.

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