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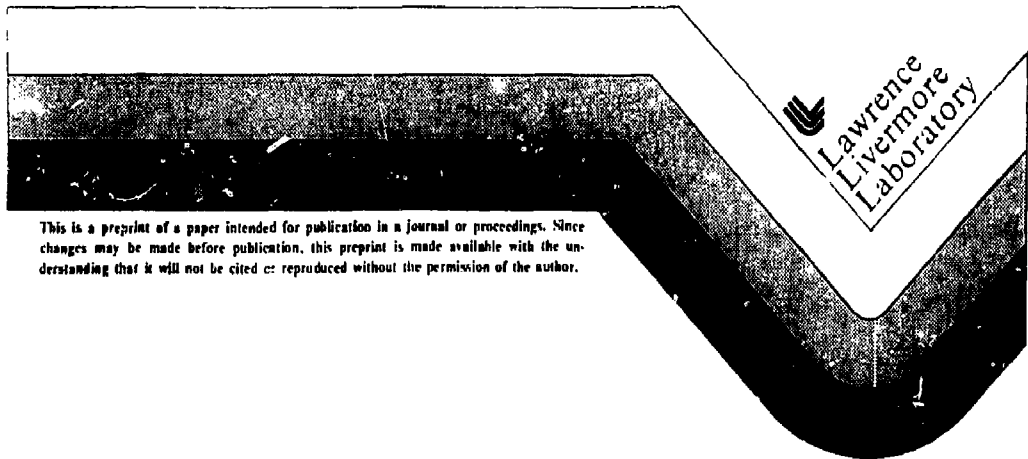
ELECTRON CYCLOTRON HEATING IN THX-UPGRADE

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**MASTER**

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Electron Cyclotron Heating in TMX-Upgrade.\*  
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Livermore National Laboratory.--TMX-Upgrade, an  
improved tandem mirror experiment under construction  
at LLNL, will use electron cyclotron resonance heating  
(ECRH) to create thermal barriers and to increase the  
center cell ion confining potential. Gyrotron oscil-  
lators (200 kW, 28 GHz) supply the heating power for  
the potential confined electron (fundamental heating)  
and the mirror-confined electrons (harmonic heating)  
in the thermal barriers. Important issues are  
temperature limitation and microstability for the hot  
electrons. Off-midplane heating can control aniso-  
tropy-driven microstability. Spatially restricting  
heating offers the possibility of temperature control  
by limiting the energy for resonant interaction.

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I. Introduction

TMX-Upgrade, an improved tandem mirror experiment under construction at LLNL, will incorporate end plugs with sloshing ions for improved ion microstability and electron thermal barriers to provide increased plasma confinement for center cell ions.<sup>1</sup> To create the thermal barrier the confining potential peak requires electron cyclotron resonance heating (ECRH) in both regions.

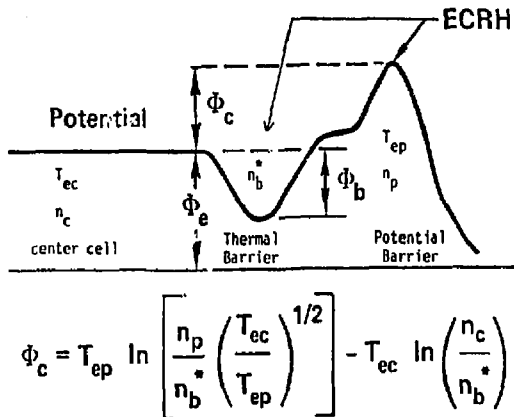


Fig. 1 Profile of plasma potential in each end plug. Electrons are heated by ECRH in the potential and thermal barriers.

A sketch of the potential profile in each end plug is shown in Fig. 1. The confining potential  $\phi_c$  for center cell ions is given by a Boltzmann-like relation between electron temperatures and densities as shown.

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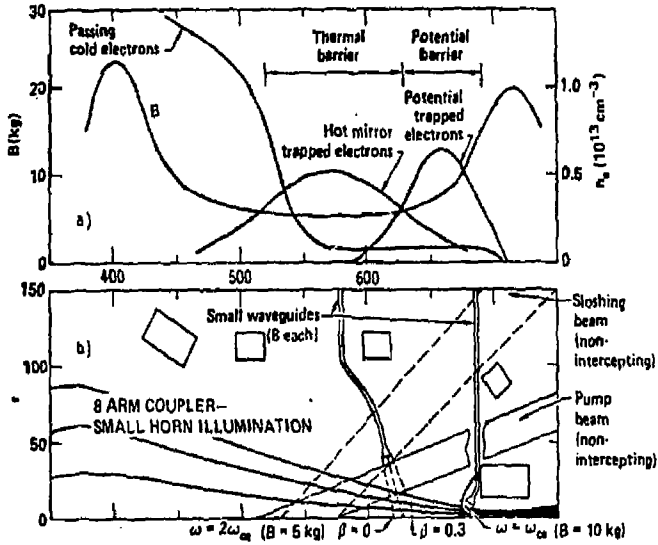


Fig. 2 a) Profiles of magnetic field and densities of microwave-heated mirror-trapped and potential-trapped electrons.  
 b) Small horn antennas (eight each location) for illuminating plasma.

## II. Electron Heating

Figure 2a shows the profiles of plug magnetic field and electron densities. From the equation defining  $\phi_c$ ,  $T_{ep} > T_{ec}$  is required to produce a confining potential for  $n_p < n_c$ . Electrons located at the outer peak of the hot sloshing ions are heated at fundamental resonance ( $B = 1T$ ,  $f_{Rf} = f_{ce} = 28 \text{ GHz}$ ) so that  $T_{ep} (\sim 1.4 \text{ keV}) > T_{ec} (\sim 0.6 \text{ keV})$ . These electrons are potentially confined by the requirement of charge neutrality. The thermal isolation from center cell electrons provided by the barrier reduces the required heating power to modest levels ( $\sim 40 \text{ kW}$ ). Both  $\phi_c$  and  $\phi_b$  are increased by reducing the density of cold passing electrons  $n_b^* = n_b - n_{eh}$  at the bottom of the barrier, where  $n_b(n_{eh})$  is the total (hot) density. For fixed total density set by charge neutrality with the sloshing ions,  $n_b^*$  is decreased by heating a hot, mirror-trapped population of electrons at the barrier minimum. These electrons have mean energy  $\langle E_{eh} \rangle \sim 50 \text{ keV}$  and are heated at  $B = 0.5 \text{ T}$  and  $f_{Rf} = 2f_{ce}$ .

A 200 kW, 28 GHz pulsed gyrotron oscillator (Varian model VHA-8050A), supplies power to each of four heating locations. The microwave system for each tube consists of a straight section of  $2\frac{1}{2}$  inch overmoded waveguide ending in an eight arm output, multi-hole coupler terminated by a water load.<sup>2</sup> The coupler converts the  $TE_{02}$  dominant mode of the gyrotron output into single mode  $TE_{10}$  in rectangular waveguide. Each coupler feeds an eight-horn array to illuminate the resonant surface.

For efficient absorption the microwave beams are launched with extraordinary mode polarization. For heating both populations absorption should be nearly total on a single pass.

### III. Hot Electron Energy Control and Microstability

Important issues under study for electron heating are temperature control and microstability for the hot electrons. The product of mean hot electron energy times density is beta limited. We would like  $n_{eh}$  as large as possible to maximize  $n_p/n_b^*$  and thereby maximize  $\phi_c$ . On the other hand,  $n_b^*/n_{eh}$  cannot be too small because of stability requirements set by the streaming ion mode for sloshing ions and loss cone modes for the hot electrons. These considerations determine the desired hot electron temperature. For our parameter range the hot electron power balance is dominated by scattering losses, i.e.,

$$P_{ECRH} \sim P_{SCATT} \gg P_{DRAG} > P_{SYNC} > P_{BREM}$$

Since  $P_{SCATT} \sim (E_{eh})^{-\frac{1}{2}}$ , it is desirable to limit heating for high energy electrons to avoid overheating the hot electrons. Since single-pass absorption is large, a limiting energy for resonant heating may be achieved through control of beam aiming which limits  $k_{\parallel}$  and the range in B for which heating can occur.

For the hot electrons interchange stability is assured by the min-B geometry for the magnetic field. Microstabilities can be driven by anisotropy and by the loss cone which exists for the mirror-confined population. Several modes which have been observed in hot electron experiments are the anisotropy driven Timofeev mode, the whistler mode, and the upper hybrid loss cone mode. The Timofeev and whistler modes are

stabilized for  $T_{\parallel}/T_{\perp} > 1/6$  and  $T_{\parallel}/T_{\perp} > (\beta_{\perp}/2)^{1/2}$ , respectively.<sup>3</sup> We plan to control anisotropy by electron heating away from the midplane. The upper hybrid mode is expected to limit the minimum cold plasma density. Satisfying stability requirements for these modes will determine the parameter ranges for machine operation. The sensitivity of plasma confinement to parameter variations is presently under investigation.

### References

1. Baldwin, D. E., Logan, B. G., Phys. Rev. Lett. 43, 1318 (1979).
2. Coupler designed by C. P. Moeller, General Atomic Company.
3. Guest, G. E., Sigmar, D. J., Nuclear Fusion 11, 151 (1971).

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