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UCRL- 92375
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CONF-8505130--5

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This paper was prepared for submittal to the Sixth Topical Conference on Radio Frequency Plasma Heating Meeting Proceedings, May 13-15, 1985, Pine Mountain, Georgia.

May 8, 1985

Lawrence Livermore National Laboratory

UCRL--92375

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The Role of ECRH in Potential Formation for Tandem Mirrors*

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The axial ion plugging potential in a tandem mirror is produced by electron cyclotron resonance heating (ECRH) applied at two locations in the end mirror cell.[1] A second harmonic ($\omega = 2\omega_c$) resonance is used near the midplane to generate hot electrons which yield an electron potential barrier between center cell electrons and electrons outboard of the end cell midplane. The latter group of electrons is then heated at the fundamental resonance ($\omega = \omega_c$) on the outboard side of the magnetic well which drives an ion confining potential. Fokker-Planck and Monte Carlo calculations show that such a configuration is achievable,[2] and the scaling obeys a rather simple set of equations.[3] Another aspect of this configuration is the experimental observation[4] that the fundamental heating drives the overall potential of the device relative to the wall to ~1 kV. An analytic model[5] predicts this behavior for very strong ECRH. In the first part of this paper, we give results of a numerical study of electron confinement in a mirror cell owing to fundamental heating as the level of the rf electric field, E_{rf}, is increased. For the second part of the paper, we show that moderate levels of uniformly distributed rf fields, called cavity fields, can result in very hot (> 250 keV) tails in the electron distribution as seen in the TMX-U experiment.[6]

To study the electron confinement in a mirror cell we choose parameters close to the TMX-U experiment[4]: mirror ratio = 4, density = 8 x 10" cm^{-3}, and confining potential of 1 kV. For simplicity, we consider a single mirror with

*Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.

fundamental heating at the 10 kG magnetic field point; the midplane field is 5 kG. The resulting confinement time for a range of E_{rf} is shown in Fig. 1. These points were obtained from a single region Fokker-Planck code.

There are three distinct regions in Fig. 1. The first corresponds to weak heating where the ECRH heats the bulk electron distribution to temperatures less than the confining-potential energy, $e\phi_c$. Here, collisional diffusion dominates rf, and the loss rate agrees with the Pastukhov rate. In the second region, labeled moderate rf, the electrons run away to energies *much greater than* $e\phi_c$. The E_{rf} where this begins, denoted E_{rfc}, is found by equating the rf and collisional energy diffusion at the energy $e\phi_c$, yielding

$$E_{rfc}^2 \approx 2 \times 10^{-10}\, nT_e^{-\frac{1}{2}} \left(\frac{T_e}{e\phi_c}\right)^{3/2} \frac{L_c}{L_B} B_r \quad . \qquad (1)$$

Here L_c is the length of the system and L_B is the magnetic scale length at the resonance point; the units are E_{rf}(V/cm), $n(cm^{-3})$, T_e(eV), and B_r(kG). The confinement time well into this region is determined by the 90^o angular scattering time of the hot electrons reduced by the logarithm of the mirror ratio. The maximum hot energy is determined by relativistic detuning,[1] and a conservatively small value of 20 keV was taken here.

Finally, for very strong rf, the rf diffusion causes rapid loss because any electron which angle scatters to a diffusion characteristic intersecting the loss boundary is lost. This is the region treated by Cohen[5] and the qualitative behavior is similar although some features differ. For example, the simulation finds a sizeable average kinetic energy per lost particle of ~2 keV compared to zero kinetic energy in the analytic model.

When the kick size is large (for large E_{rf}), the diffusion approximation begins to break down. Monte Carlo calculations of this same problem show the same general behavior except that the τ does not decrease significantly at large E_{rf}. However, TMX-U should be in the moderate rf regime because the estimated electric field is ~200 V/cm. This gives too long a confinement time compared to the experiment by a factor of ~4; this factor is even larger if the maximum energy for relativistic detuning is greater than 20 keV.

The second topic is the generation of hot electron tails by cavity fields. As mentioned previously, the energy of the hot electrons can be limited by relativistic detuning if the rf is confined to the primary beams by strong single pass absorption.[1] The allowable regions of rf diffusion in momentum space are shown in Fig. 2. The first two regions reaching down to $\gamma v = 0$ correspond to fundamental (with the ~45^0 boundary) and second harmonic heating. The regions starting at $\gamma v_{\parallel} = 0$ with $\gamma v_{\perp} = 3.3 \times 10^{10}$ and 5.2×10^{10} are the third and fourth harmonics, respectively. If the rf is localized, the diffusion becomes very weak at the larger γv values of the second harmonic region, before energies sufficient to reach the third harmonic are reached and no hot tail is formed. Cavity fields change this picture.

Figure 3 shows a case where a cavity field of 30 V/cm together with a second harmonic beam field of 200 V/cm is used. The ECRH has been on for 30 ms. Note that a significant tail has developed that includes interactions with the third and fourth harmonics. The energy of this tail is in the range observed experimentally.

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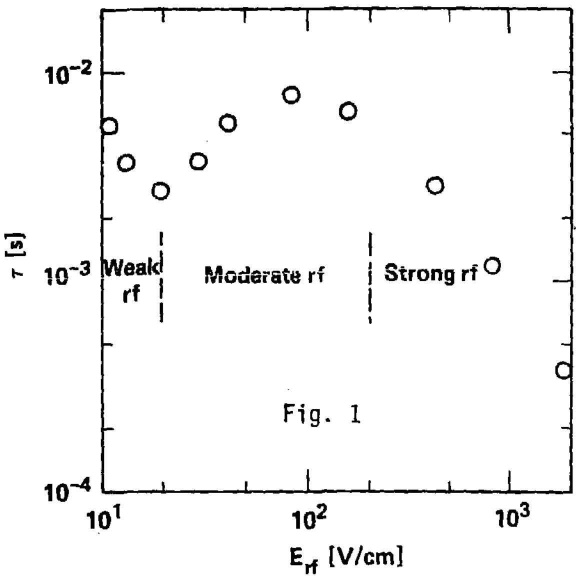

Fig. 1

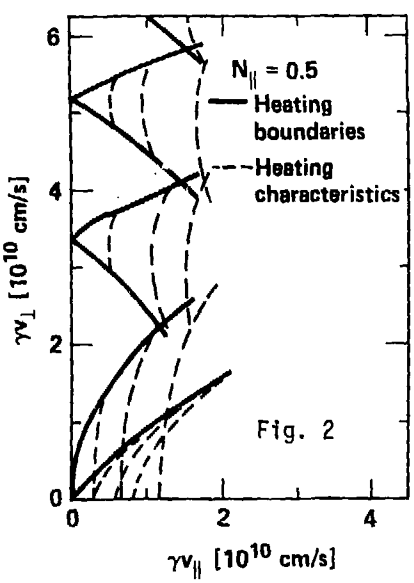

Fig. 2

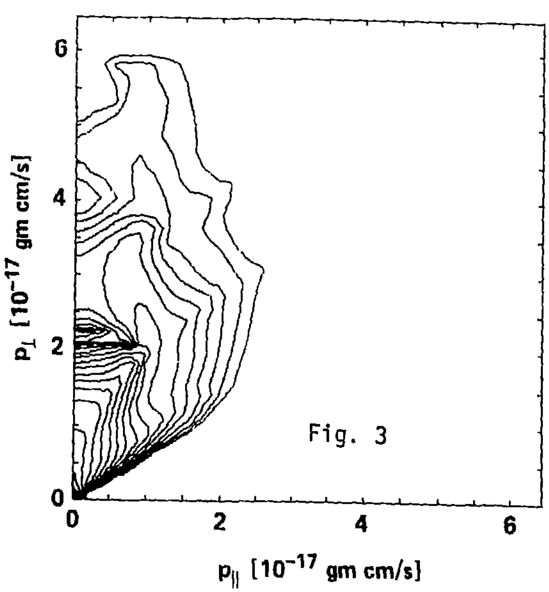

Fig. 3

Figure Captions

Fig. 1. Confinement time in single cell owing to fundamental ECRH.

Fig. 2. Regions in momentum space for ECRH diffusion including fundamental to 4th harmonic. $N_{\|} = k_{\|}c/\omega = 0.5$.

Fig. 3. Contours of electron distribution in TMX-U from Fokker-Planck calculation with beam plus cavity rf fields.