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Wave Generation and Heating Near the Ion Cyclotron Frequency in the ST Tokamak

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Abstract: A test coil is presently being used to determine the feasibility of employing waves to further heat the ions of the tokamak plasma. Initial results for wave loading of the coil and ion heating are very encouraging.

The efficiency of heating the tokamak plasma ohmically with its toroidal current I_ϕ falls off sharply as the plasma temperature is increased. Furthermore, I_ϕ is limited by stability requirements. These conditions dictate that ohmic heating alone will likely be insufficient to heat the tokamak plasma to the ignition temperature.[1] Consequently, we are studying an auxiliary heating scheme employing plasma waves generated in the vicinity of the ion cyclotron frequency and its harmonics to heat the ions (and possibly the electrons) directly.

The ion cyclotron heating system of the C stellarator, which proved to be very effective in heating both the ions and the electrons of that device,[2] was designed to generate waves in a straight plasma section with a very uniform magnetic field. The magnetic beach for the waves was located outside of the coil region. In a tokamak, the strong variation of the toroidal magnetic field B_ϕ with major radius R dictates that generation occur in a spatially varying magnetic field and that the beach exist at a specific R around the entire machine including the wave generation region. Consequently, a new generating structure must be used.

We have installed a single, half-turn, induction coil in the ST tokamak (Fig. 1) in the high-field region on the inner side of the torus. This coil can couple to ion-cyclotron waves which can resonate with the ions at a given R as they propagate around the torus and/or to the fast modes which propagate when the plasma density exceeds the critical value given approximately by

$$n_c = 1.64 \times 10^{12} \, (m_i/Z_i m_e)(\Omega p)^{-2}$$

where $\Omega = \omega/\omega_{ci_o}$, the ratio of excitation frequency (25 MHz) to the ion cyclotron frequency at the center of the plasma, and p is the limited plasma radius. This test coil has a Fourier spectrum which is essentially constant versus $k_{\parallel}$ (mode number along ϕ) and its azimuthal current distribution (Fig. 1) favors m = 0 and m = 1 mode numbers in θ. Thus, it allows the plasma to choose the modes it wishes to propagate and enables us to experimentally determine the normal modes which are most efficiently excited in toroidal geometry and which should be selectively coupled to with future coil structures. (This simple test coil thus reduces the need to use several types of coils for optimization of coupling.[3]) This empirical approach is necessitated by the lack of an applicable theory for hot toroidal plasmas. To estimate the waveloading to be expected for the coil of Fig. 1, we have analyzed the uniform cylindrical case for the m = 0 contribution to coil loading using the actual coil-plasma-vessel cross-section and the complete cold plasma theory which agreed well with experiment on the C stellarator.[4] The resulting coil loading resistance $R_S = 2\,P_{rf}/I_{rf}^2$ is plotted versus Ω in Fig. 2. This idealization is not directly applicable to the toroidal case except when the resonance zone falls outside the vessel. However, it does suggest that waveloading might give R_S values in the range of a few ohms.

Experimental loading curves found on ST are depicted in Fig. 3 for two plasma densities. The curves in the vicinity of the ion cyclotron frequency have the same qualitative shape as predicted in the uniform case of Fig. 2, except that they are broadened about $\Omega = 1$ by the magnetic field inhomogeneity. Maximum values of wave loading (superimposed on coil losses) of a few ohms are indeed observed. In addition, loading at higher Ω is observed for the higher density case corresponding to the generation of the

fast hydromagnetic waves (Eq. 1). This heavy loading is not apparent for the lower density case until Ω is increased to about 4.

Waveloading is not decreased as the plasma current is increased and the plasma is heated.

The test coil is designed to deliver the maximum rf power consistent with the small access ports of ST, so that some indications of plasma heating might be ascertained. The rf power delivered to the plasma waves ($\lesssim$ 15 kW at $\Omega \approx 1$) is a small fraction of the ohmic heating power ($\lesssim$ 15%) but its effect is observable. Figure 4 shows an increase of the Doppler-shift temperature of the impurity C IV of nearly a factor of two when the rf power is applied. This temperature increase arises presumably from collisions between deuterium ions heated at cyclotron resonance and the carbon ions a few centimeters inside the plasma surface. Non-Maxwellian heating is evident at $\Omega = 2$ as determined by charge exchange neutral measurements (Fig. 5). Under these conditions the fast modes are generated and according to theory their electric field is elliptically polarized with an appreciable component circularly polarized in the sense of the ion gyration. Thus the non-Maxwellian heating could be caused by acceleration of hot deuterons at $\omega = 2\omega_{ci}$.

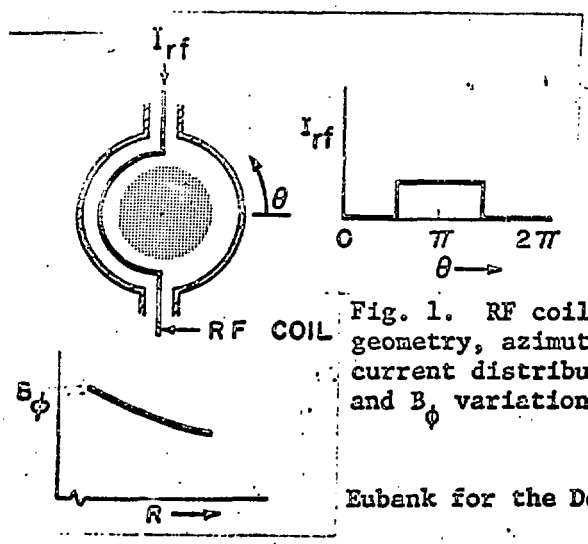

Fig. 1. RF coil geometry, azimuthal current distribution, and B_ϕ variation in R

The initial results reported herein make us optimistic that wave heating at the several megawatt level will be possible in ST.

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