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PLASMA PHYSICS

HIGH-POWER ION-CYCLOTRON HEATING ON THE LEVITATED OCTUPOLE

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J.C. Sprott, E.J. Strait, and J.C. Twichell

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HIGH POWER ION CYCLOTRON HEATING ON THE LEVITATED OCTUPOLE*

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Experiments are underway in the Wisconsin Levitated Toroidal Octupole to create hot, dense plasmas to facilitate the study of β limits and related phenomena such as Pfirsch-Schlüter and bootstrap currents. The question of ballooning mode instability limits on $\beta = 8\pi nk(T_i + T_e)/B^2$ is of general importance for all toroidal systems, and ICRF heating should permit study of high β plasmas with lower collisionality and smaller gyroradii than those of the high β gun-injected plasmas currently under study in the Octupole. To these ends we are developing sources capable of delivering 4 MW to the plasma (1.5 MW coupled to the plasma to date, the rest under development).

The present experiment is the third in a series of ICRF experiments at Wisconsin. A similar experiment was done at lower power and plasma density on the small supported octupole, in which ion temperatures of 600 eV were obtained. A fast-wave heating experiment at the second and higher harmonics has been performed on the Tokapole II, a tokamak with four poloidal divertors.²

The Levitated Octupole is a large toroidal device whose poloidal field is produced by four inductively-driven internal rings carrying a total current of up to 1.2 MA. A poloidal flux plot is shown in Fig. 1. A minimum average B magnetic well provides MHD stability over most of the machine's volume. The rings can be momentarily levitated with the supports remaining completely out of the plasma region for 20 msec. Target plasmas for ICRF heating with densities up to 10^{14} cm^{-3} are produced using various

combinations of Marshall guns, ECRH, and ohmic heating. Density can be controlled with programmed gas puffing.

A source capable of delivering 1.5 MW of rf power to the plasma at the ion cyclotron frequency (typically 1.3 MHz) for 10 msec has been operating on the Octupole for over a year. The oscillator uses a pair of triode tubes operated push-pull into an antenna which also serves as the inductor of the oscillator tank circuit. The antenna is Faraday-shielded and is located near the wall, as shown in Fig. 2a. It extends one-third of the way around the machine in the toroidal direction (see Fig. 2b) so as to produce an inductive electric field which is primarily perpendicular to the purely poloidal octupole magnetic field. Measurements of the rf field using magnetic probes show good penetration to the resonant surface at the fundamental of the proton cyclotron frequency. The resonant surface lies in the near field of the antenna where the electric field is linearly polarized.

A typical shot with a gun-injected target plasma is shown in Fig. 3. Under clean machine conditions the density decay (measured by a 70 GHz interferometer) is the same with or without rf. Ion temperature, measured by a neutral charge-exchange analyzer looking vertically along the toroid's midcylinder, rises to an early equilibrium value, with the ion distribution function showing two distinct Maxwellian components at about 50 eV and 300 eV. The two components have roughly equal line-integrated densities (see also Fig. 4). Without rf the ion temperature is too small for the charge-exchange analyzer to measure. Electron temperature rises steadily during the rf pulse to a maximum of 50 to 60 eV, as measured by Langmuir probes and C III line ratios, and confirmed by comparison of O III-VI radiation with a time-dependent coronal model.

For a fixed antenna voltage, the equivalent parallel resistance presented by the plasma varies inversely with density at low densities as expected from a single particle heating model. The maximum power coupled to the plasma therefore is linear with density up to about 600 kW at $2 \times 10^{12} \text{ cm}^{-3}$. At higher densities the process becomes power supply-limited, with the absorbed power rising more gently to the full 1.0 to 1.5 MW in the mid 10^{13} cm^{-3} range. No pronounced resonance effects are seen in the loading or ion heating as the magnetic field is varied at a fixed oscillator frequency.

The hot component of the ion energy distribution rises steadily in temperature with increasing magnetic field, though the absorbed rf power varies little. Evidently the energy confinement improves with increasing field, although the gyroradius is still much smaller than the machine dimensions. For a case such as that of Fig. 3, the ion energy confinement time is typically 1 msec. Ion temperatures as large as 1 keV have been observed at very low density ($n < 10^{11} \text{ cm}^{-3}$) and one such measured energy distribution is shown in Fig. 4. The hot ion temperature decreases with increasing density, but less than linearly, as shown in Fig. 5. Measured charge-exchange power varies linearly with absorbed rf power over a wide range of densities and powers, suggesting that this may be an important loss mechanism for the ions.

The electron energy confinement time (about 3 msec for the case of Fig. 3) appears to be limited by impurity radiation, as confirmed by impurity doping experiments. Electron temperature shows a strong correlation with machine cleanliness, and discharge cleaning has produced significant improvements in T_e . The impurity radiation evidently provides a strong negative feedback for T_e , as the electron temperature on a given day has only a weak dependence on density (see Fig. 5) and magnetic field strength.

Figure 6 shows a power balance for the plasma of Fig. 3 at the end of the rf pulse, using experimentally measured quantities where possible. Although not all the power is accounted for, the dominant loss mechanisms appear to be charge exchange for the ions and impurity radiation for the electrons. At higher density, of course, electron drag will begin to dominate the ion energy confinement unless T_e can also be raised. Preliminary bolometric measurements show that the radiation and charge exchange powers per unit volume are much larger in the "bridge" regions behind the rings than in the center of the machine, which could account for the missing power. "Obstacles" refer to the internal ring supports; these may be important for particle losses but so far levitation of the rings has not been found to improve T_i or T_e . Further reduction of hydrogen recycling and of impurity levels is required to bring the ions and electrons, respectively, to a regime where levitation will be of benefit.

In conclusion, it has been shown that the rf electric field penetrates and heats the plasma with no harmful effects on confinement. The full rf power available (1.5 MW) with a 70% oscillator efficiency has been coupled to the plasma at high density. Electron energy confinement is limited by impurity radiation. Ion energy confinement is probably limited by charge exchange at low density and electron drag at high density.

A duplicate of the present 1.5 MW rf system is now under construction. Improved discharge cleaning techniques and cleaner plasma sources such as ECRH should reduce impurities, and are now being developed. Also under development are titanium getters which can be extended to the center of the toroid for better coverage behind the rings, which should help reduce radiation and charge exchange losses. With the additional rf power it should then be possible to burn through the radiation-dominated regime so that the confinement properties of multipoles at high betas can be studied.

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¹J.D. Earter and J.C. Sprott, Plasma Physics 19, 945 (1977).

²A.P. Biddle and J.C. Sprott, Plasma Physics 23, 679 (1981).

Fig. 1.

Fig. 2. (a)

(b)

Fig. 1: Minor cross-section of toroid showing poloidal flux lines, typical ω_{ci} resonance zone, and antenna location.

Fig. 2: (a) Minor cross-section of antenna, with insulator and electrostatic (Faraday) shield. (b) (not to scale) Major cross-section of antenna. Current return is through vacuum tank lid.

Fig. 3.

Fig. 4.

Fig. 3: Time evolution of a typical shot with gun-injected target plasma.

Fig. 4: Ion energy distribution for a low-density shot. Fitted curves for two Maxwellian components and their sum are shown.

Fig. 5.

Fig. 6.

Fig. 5: Ion temperature (two components) and electron temperature vs. density at maximum rf power.

Fig. 6: Power balance for typical shot of Fig. 3. Experimental quantities are used where possible.

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