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Confinement of a Currentless Plasma in the Heliotron-E

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Confinement of a plasma initiated and heated by electron cyclotron-resonance–frequency waves has been studied in the Heliotron-E. The observed plasma parameters were T_e = 500–100 eV, $T_i \simeq 100$ eV, $\bar{n}_e = 4\times 10^{12}$ cm^{-3} at B = 10 kG. The electron energy decay time was 40 ± 8 msec and the particle confinement time was estimated to be more than 70 msec. These results offer a considerable improvement in energy confinement over Ohmically heated plasmas.

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In the toroidal plasma confinement devices using external helical conductors for forming the nested magnetic surfaces, such as heliotrons, torsatrons, and stellarators, the plasma equilibrium can be maintained without Ohmic-heating current. This property can, in principle, lead to the steady-state operation of a controlled thermonuclear reactor, and has led to recent efforts using injected energetic neutral beams[1,2] and radio-frequency waves[2,3] to sustain the plasma in stellarators and heliotrons. A nearly currentfree plasma was recently reported[1] in the Wendelstein VII-*A* stellarator in which substantial ion heating was observed by neutral-beam injection. The nature of energy confinement in the experiment, however, has not been fully resolved because of the dominance of radiative loss in the experiment.

This paper presents experimental results on confinement of a plasma initiated and heated by radio-frequency waves at the electron cyclotron-resonance frequency in a heliotron configuration. In the afterglow regime the radiative loss is measured to be small and the energy loss rate of electrons is dominated by equipartition with ions. This allows a comparison with neoclassical theory.

The Helotron-E device (major radius R = 2.2 m, average minor radius of plasma r_p = 0.2 m) is an asymmetric toroidal system with large rotational transform [$\iota(0)/2\pi = 0.5$, $\iota(r_p)/2\pi = 2.2$] and strong shear. The $l=2$ helical coils can produce a maximum magnetic field of 20 kG. The experiment was performed at 10 kG to match the electron cyclotron-resonance heating (ECRH) power available at 28 GHz. The microwave tube has a peak output power of 200 kW and pulse length of 10 msec. The cutoff density is 1.0×10^{13} cm^{-3} for the ordinary wave. The microwave output was in TE_{02} circular mode, transmitted to the Heliotron-E by a 2.5-in.-diam waveguide. The radiated power consists of an almost equal mixture of ordinary and extraordinary waves. As shown in Fig. 1, the wave was launched from the low-field side. The ordinary wave was expected to be transmitted directly into the plasma and the extraordinary wave would be reflected at the right-hand cutoff. It can be expected, however, that

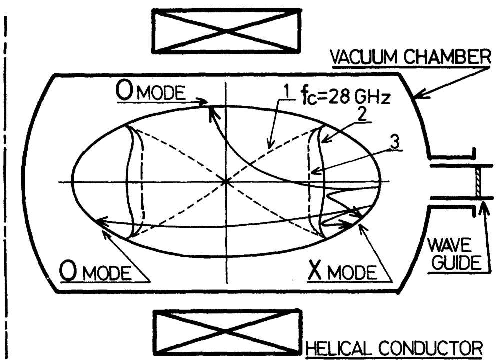

FIG. 1. Experimental configuration. 1: Resonance surfaces of f_c = 28 GHz (B = 1 T). 2: Right-hand cutoff. 3: Upper hybrid cutoff. Ray tracings of ordinary (O) mode and extraordinary (X) mode are indicated by solid lines.

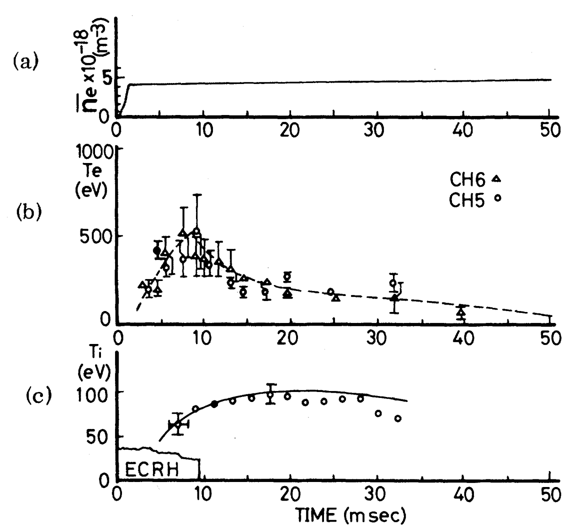

FIG. 2. (a) Line-averaged electron density, (b) central electron temperature, and (c) ion temperature vs time. The solid line is ion temperature calculated from neoclassical transport code.

a fraction of the reflected extraordinary wave could be retransmitted into the plasma from the high-field side by reflections at the wall. Quantitative estimates of the absorbed power of the two modes were difficult to make.

Here we present the experimental result of an ECRH plasma and its containment properties. No Ohmic heating current was applied. The 10-msec rf pulse was applied 40 msec after puffing of the working hydrogen gas. The filling gas pressure needed to get maximum line-averaged density of 5×10^{12} cm^{-3} is about 4×10^{-5} Torr. The plasma is considered to be fully ionized from measurements of neutral particles and spectral lines of hydrogen atoms. The evolution of the line-averaged electron density, the electron and ion temperatures are shown in Figs. 2(a), 2(b), and 2(c), respectively. The electron density remained nearly constant during the first 100 msec and lasted about 200 msec [Fig. 3(c)]. The electron temperature at the center, determined by laser Thomson scattering, increased to about 500 eV at the end of the rf pulse. No saturation was seen during the rf pulse, which suggests that the energy confinement time is longer than the rf pulse length. Immediately after the rf pulse, the central electron temperature decreased at a time constant of roughly 15 msec. The electron temperature was more peaked at the center during and immediately after the rf pulse and became flatter afterwards. The ion temperature kept rising till about 10 msec after the rf pulse and then decreased along with the electron temperature. The decrease of electron temperature in this period is determined mainly by the energy equipartition between ions and electrons. The apparent electron temperature decay time in the period is about 30 msec. No hard x rays were observed during the experiment. A small toroidal current of 300 A peak amplitude was observed after the rf pulse. The direction of the current is the same as that of the toroidal field. The mechanism producing the current has not been identified. The observed loop voltage was about 0.1 V, giving a small input power (<30 W) due to the current. Radiation loss estimated from a bolometer signal [Fig. 3(b)] was about 10 kW during the rf pulse but decreased rapidly to less than 1 kW after the rf pulse. This was a small fraction of the total electron energy loss. The estimated value of $Z_{\rm eff}$ is 1-2.5 and not so high as obtained in the Ohmic plasma. The time evolution of electron temperature and density profiles were also measured, and the time evolution of the total electron energy $W_e = \int n_e T_e \, dV_p$ is given by open circles in Fig. 4, where V_p is the plasma volume. The decay time of W_e was 40 ± 8 msec.

We compared this electron energy confinement time with those of Ohmically heated plasmas. The Ohmically heated plasmas were produced at B = 10 kG and the following parameter ranges of the plasmas were compared: 10 kA $< I_{\rm OH} <$ 90 kA, 2×10^{12} cm$^{-3} < \bar{n}_e < 1.5\times10^{13}$ cm^{-3}, 200 eV $< T_e$ < 600 eV. The plasmas are mostly in the plateau regime as was the ECRH plasma. The several

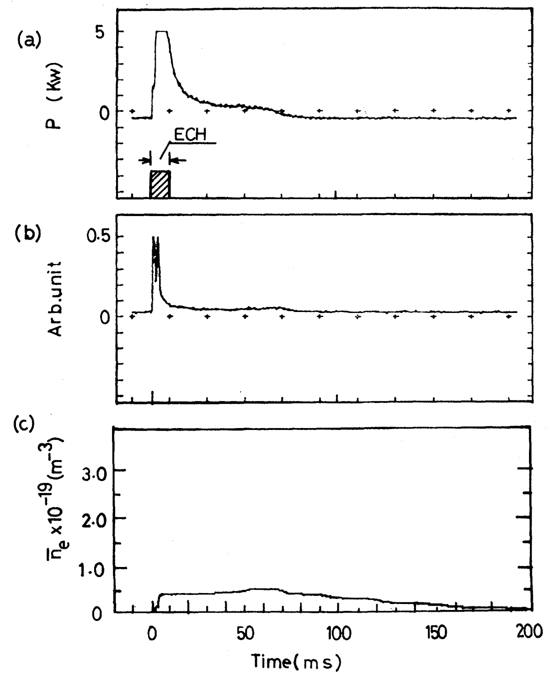

FIG. 3. (a) Bolometer signal, (b) spectral line signal of C III, and (c) line-averaged electron density vs time.

parametric dependences of the electron energy confinement time have been tested. One of the best fitting scaling laws was the drift parameter dependence $[\tau_E \propto (V_D/V_e)^{-1}$, where V_D is the drift velocity due to the current and V_e is the electron thermal velocity] as is shown in Fig. 5; the correlation coefficient was 0.85. For the so-called Alcator scaling $[\tau_E \propto \bar{n}_e (q_{\rm OH})^{1/2} a^2]$, the correlation coefficient was 0.65. In Fig. 5, the electron energy confinement time is given by $\tau_E = W_e / I_{\rm OH} V_L$, where V_L is the loop voltage. The effective Z values were in the range of 3 to 7 and larger than those of the ECRH plasma. The observed magnetic probe signals did not indicate definite correlations with the drift parameter. These facts suggest that the confinement of the Ohmically heated plasma could be related to the radiation loss and/or the current-driven drift instability.[4] The electron energy decay time for the ECRH plasma was also plotted in Fig. 5. The value of V_D/V_e was taken to be 0.001, which corresponds to the observed toroidal current. It is seen that the ECRH sustained plasma shows a considerable improvement in energy confinement over the Ohmically heated plasmas.

Since the electron energy containment of the ECRH plasma was dominated by equipartition, we solved a transport code to estimate the ener-

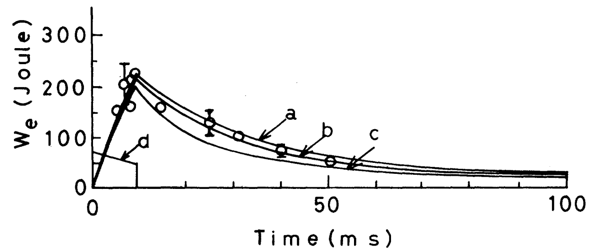

FIG. 4. Total electron energy W_e vs time. The solid lines are total electron energies calculated from transport code with different values of anomaly factor C: Curve a, $C = 1$; curve b, $C = 3$; and curve c, $C = 10$. Curve d is the rf power used in the calculation. The power is 70 kW at $t = 0$ and 50 kW at $t = 10$ msec.

gy loss due to the electron and ion thermal conduction relating to the neoclassical theory. Here we calculate simply the volume-averaged energy balance equations for electrons and ions. The plasmas are in the plateau regime. The ion energy losses were due to the charge exchange and the neoclassical thermal conduction. The ion thermal conductivity in the plateau regime is $\chi_i = 3.8 \times 10^{-4} T_i^{3/2}/(\iota/2\pi) Z^2 R B^2$ (in MKS units), where Z is the ionic charge number of the working gas. The average value of $\iota/2\pi$, $\langle \iota/2\pi \rangle = 1$, and $Z = 1$ were used in the calculation. The electron energy losses included the energy transfer to the ions and the thermal conduction loss (the radiation loss is neglected). We assumed the electron thermal conductivity as $\chi_e' = C\chi_e$ where χ_e is the neoclassical thermal conductivity

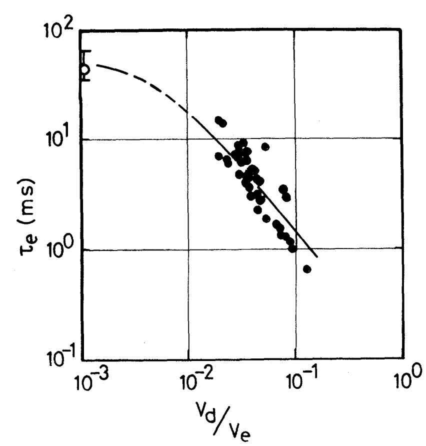

FIG. 5. Electron energy containment times vs the drift parameter V_D/V_e. Results from Ohmically heated plasmas are given by filled circles and that from the ECRH plasma is given by an open circle.

in the plateau regime given by $\chi_e = (m_e/m_i)^{1/2} \times (\chi_i)_{T_i=T_e}$ and C is an anomaly factor. The absorbed power estimated from the observed initial gradient of T_e and $\bar{n}_e = 4\times10^{12}$ cm^{-3} of Fig. 2 was roughly 70 kW. The rf input power used in the calculation was assumed to be a monotonically decreasing function of time during the rf pulse, as is seen in Fig. 2(c), from 70 to 50 kW. The computed variation of ion temperature with time is shown in Fig. 2(c) by the solid line; the ion-temperature profiles in these calculations are assumed to be flat, as in the measured ion-temperature profiles. In Fig. 4, the computed electron energy as a function of time is shown for $C=1$, 3, and 10 (curves a, b, and c, respectively). The experimental data were mostly between the curves with $C=1$ and $C=3$. However, the time sequence of the electron energy is not so sensitive to the anomaly factor. Thus further investigation of parametric dependence should be performed to confirm the neoclassical transport, but these results indicate that electron anomalous loss is considerably smaller than that observed in discharges sustained by Ohmic-heating current.

From absolute measurement of fast neutral particles by the fast neutral-particle analyzer, the neutral-particle density n_0 was estimated to be 5×10^8 cm^{-3} at the end of the rf pulse and 2×10^8 cm^{-3} at 7 msec after the rf pulse. The calculated charge-exchange loss time was longer than 50 msec. Since the electron density was nearly constant during the first 100 msec, we can also estimate the particle confinement time by $\tau_p = (n_0\langle\sigma v\rangle_i)^{-1}$, where $\langle\sigma v\rangle_i$ is the ionization rate. These gave $\tau_p \sim 70$ msec at the end of the rf pulse and $\tau_p \sim 160$ msec at 7 msec after the rf pulse, which agreed well with the neoclassical particle confinement time in the plateau regime within the experimental errors. We note that the particle confinement times close to the neoclassical values both in the plateau and the Pfirsch-Schlüter regimes have been reported in Proto-Cleo,[5] Heliotron-D,[6] and octupole machines[7] for lower plasma parameters ($T_e < 10$ eV, $n_e < 10^{11}$ cm^{-3}).

In conclusion, radio-frequency waves at the electron cyclotron frequency are very effective in producing and heating a currentless discharge in the heliotron configuration. Significant improvements of confinement properties were observed in such plasmas over those in Ohmically heated plasmas. The measured particle and energy confinement times for electrons and ions in the plateau regime can be explained by the neoclassical values within the experimental errors, but further investigations are necessary to confirm the neoclassical transport process.

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