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Experiments in a Tandem Mirror Sustained and Heated Solely by rf

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A tandem-mirror plasma has been sustained and heated by rf alone without the need for neutral beams. End plug density and energy are maintained by ion cyclotron-resonance heating which traps and heats a fraction of the central-cell loss stream. The central-cell plasma is maintained by gas fueling and rf heating. Magnetohydrodynamic stability limits the ratio of the central-cell to plug plasma pressure, and the central-cell electron temperature must be kept high enough for ionization. A quasi steady state is achieved that lasts much longer than the decay times of the plugs and central cell.

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The tandem-mirror approach to the development of a fusion reactor promises to have many advantages over simple mirrors as well as other magnetic confinement devices.[1] In a tandem mirror, a central-cell plasma in a solenoid is bounded by "plug" plasmas in mirror cells. The TMX experiment[2] demonstrated that electrostatic confinement of central-cell ions by the plug plasmas significantly reduced end losses. Calculations indicate that the overall Q (power gain) of a tandem-mirror fusion reactor can be quite high (~5–10) if the volume of the central cell greatly exceeds that of the plugs.[3] In previous experiments, plug plasmas were fueled and heated by energetic neutral beams. However, technological constraints on neutral-beam heating when scaled to a reactor could be eased or eliminated by supplementing or replacing neutral-beam power with rf power. We show in the Phaedrus experiment that a tandem-mirror plasma can be sustained by rf alone, without the application of neutral beams.

The operation of a tandem mirror can be thought of as taking place in two stages, a transient stage followed by a quasi-state stage. In the transient stage, plasma is injected into the machine by stream guns. In fact, earlier experiments with Phaedrus[4] and Gamma 6[5] were restricted to the transient stage. Such plasmas side-stepped many of the issues of tandem-mirror physics because plasma characteristics were dominated by the external plasma between the plugs and the stream guns. The high-density external plasma line-tied the plasma to the stream guns, significantly reducing both magnetohydrodynamic (MHD) instabilities and microinstabilities and fixing the electron temperature. When the stream guns were turned off in Phaedrus, the plasma decayed away in approximately 150 μs in the plugs and 400 μs in the central cell. Quasi-steady-state operation after stream guns are turned off requires sources of particles and energy for both the plug and central-cell plasmas and also adds constraints that must be satisfied in order to maintain microstability and MHD stability. In TMX, fueling and heating were provided by neutral beams in the plugs and gas puffing in the central cell. In the Phaedrus experiment, fueling is provided only by gas puffing in the central cell while rf provides heating. In both experiments, stability was provided by high plug energy density and the presence of the central-cell loss flow.

The idea of fueling a tandem-mirror plug by rf trapping of the central-cell ion loss stream with fundamental resonance ion cyclotron heating has been proposed by Kesner and Post *et al.*[6] Assuming rf diffusion as the trapping mechanism, Kesner showed that a steady-state density could be achieved.

A cold central-cell ion can be trapped in the plug if it receives a sufficient increase in perpendicular energy, $\Delta W_\perp$, in a single pass through the ion cyclotron-resonance zone to become mirror trapped. This condition may be written as

$$\Delta W_\perp \gtrsim (R-1)^{-1}(W_\parallel - q\Delta\Phi) - W_\perp, \tag{1}$$

where R is the mirror ratio between the throat and the resonance, $W_\perp$ and $W_\parallel$ are the perpendicular and parallel ion energies at the resonance, q is the ion charge, and $\Delta\Phi$ is the ambipolar potential between the throat and the resonance. The change in perpendicular energy produced by the rf in a single pass through resonance can be estimated by[7]

$$\Delta W_\perp = q|E_+|\,V_\perp|G|\cos\theta + (q^2|E_+|^2/2m)|G|^2, \tag{2}$$

where $|G| = (2\pi/\omega_c{}' V_\parallel)^{1/2}$. Here E_+ is the leftcircularly polarized rf electric field, $V_\perp$ and $V_\parallel$ are the ion perpendicular and parallel velocities, m is the ion mass, θ is the phase between the ion gyromotion and E_+, and ω_c' is the axial gradient in the cyclotron frequency. All quantities are evaluated at the resonance position. The first term in Eq. (2) represents rf diffusion, while the second term represents rf heating. For a low-energy stream, the second term can be made dominant and efficient trapping in the first pass can be expected. For $E_+=3$ V/cm and a 2-eV stream ion, $\Delta W_\perp = 70$ eV, trapping the ion and giving it much more than its initial energy. In subsequent passes through resonance while the ion is being heated, rf diffusion can play an important role. A Monte Carlo simulation[8] of stream trapping in a magnetic mirror predicts a steady-state plasma under conditions very close to those available in Phaedrus. Choice of a 7-A, 10-eV central-cell ion stream, with the resonance in the plug located 15 cm from the midplane and $E_+ = 3$ V/cm, results in a 300-eV, 4×10^{12}-cm^{-3} plug plasma.

The axial magnetic field profile and rf antenna locations in the Phaedrus tandem mirror are shown in Fig. 1. The minimum-$|B|$ quadrupole end plugs are located at each end of a solenoidal central cell. The rf system is composed of a single-sided antenna in the fan region of each plug and a $\frac{1}{2}$-turn antenna in the central cell. The plug antennas are each shielded from direct plasma contact by a completely enclosing ceramic tube; the central-cell antenna is shielded by a Faraday shield of copper straps. The plug antennas are located 20 cm from the plug midplane and 5 cm from the fundamental ion cyclotron resonance, on the central-cell side in the west plug and the gun injection side in the east. The plug midplane field is 2.6 kG and the rf frequency is 4.35 MHz. The central-cell antenna is located 75 cm from the midplane in the rising central-cell field. The central-cell field is 590 G, sufficiently high that no fundamental ion cyclotron resonance exists in the device for the central-cell rf frequency of 704 kHz. This minimizes ion heating but electron heating is still observed.

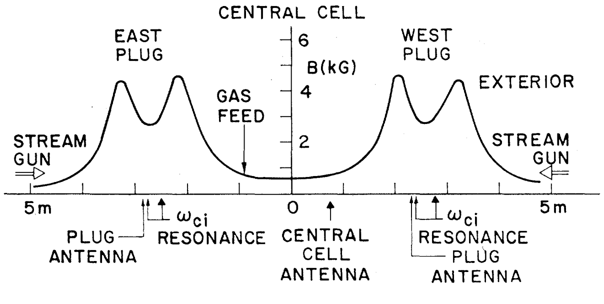

FIG. 1. The experimental configuration.

The plasma in each region is initially produced by a 0.6-ms pulse from two on-axis, hydrogen-loaded, titanium-washer plasma guns. The plug rf is turned on during the gun pulse, doubling the plug density, n_p, and increasing the average ion energy E_{ip} from 75 to 500 eV.[9] The central-cell density, n_c, is maintained by gas fed into a central-cell gas box. Gas is puffed just before the gun pulse and again 5 ms later to help maintain the plasma density. Baffles between the central cell and the plugs reduce neutral-gas cooling of the hot-ion plugs. The central-cell rf is turned on at gun turnoff to assist in maintaining the electron temperature for ionization in the central cell. The tandem configuration is thus sustained in a quasisteady state for 8 ms, until rf turnoff. At that time, the plugs and central cell decay with characteristic times of 300 and 500 μs, respectively. These times agree with classical hot-ion confinement in a mirror and the axial flow time of a collisional central cell.[10]

A time sequence of important physical parameters is shown in Fig. 2. Density profiles in the central cell measured with Langmuir probes give a radial scale length R_c of 12 cm which remains fairly constant (± 2 cm) during the entire sustained operation. This maps to a 5.7-cm radial scale length in the plugs. Then, from Fig. 2, n_p/n_c is approximately 1.5 with $n_p = 4\times10^{12}$ cm^{-3}. Thomson-scattering measurements of the electron temperature in the center of the east plug give $T_e = 30 \pm 4$ eV, decreasing to 22 ± 4 eV during the 7.5 ms after gun turnoff. Without central-cell rf the electron temperature falls to 12 eV at 0.9 ms after gun turnoff and the density in all regions decays away by 1.3 ms. Diamagnetic-loop and interferometer data are used to estimate a plug ion energy of 400–500 eV. A single-channel charge-exchange analyzer looking near the midplane of the west plug gives the ion energy as 550 ± 150 eV. Two diamagnetic loops in each plug (at 5 and 30 cm from the midplane) give a two-point axial pressure profile with a scale length of 30 cm. This indicates that the plug ion pressure is contained between the resonance locations.

Data from a voltage-swept, gridded end-loss analyzer near the east end wall ($B\sim 500$ G) give a peak plug plasma potential of 80 ± 15 V (approximately $3.5T_e$). A swept Langmuir probe in the

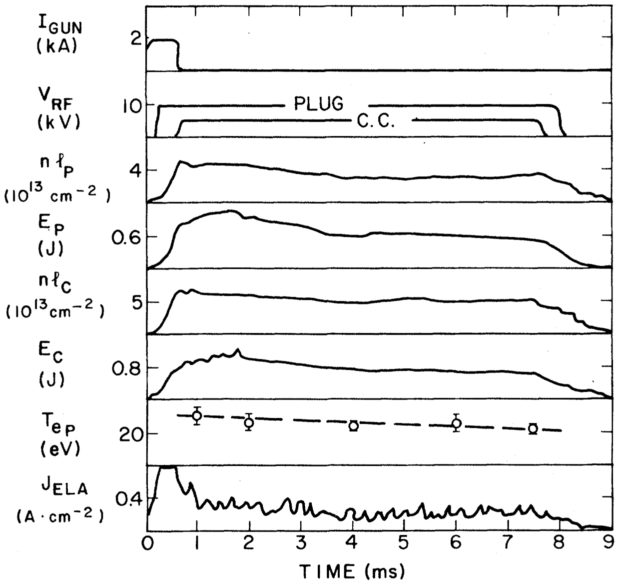

FIG. 2. The time evolution of experimental parameters during rf sustained operation. Reading from the top: the plasma gun pulse, the rf heating pulses in the plugs and central cell, the plug line density, the plug energy content, the central-cell line density, the central-cell energy content, the plug electron temperature, and the end-loss current density out of one end near the axis, scaled to the center of the plug.

same location gives a local plasma potential of 30± 5 V, making the maximum $\Delta\Phi$ in Eq. (1) 50 ±20 V. This is the ambipolar potential that the rf-heated stream ions must overcome to remain trapped in the plugs and is lower than the estimate of $\Delta W_\perp$. The end-loss analyzer data show that the temperature of the escaping ions is 100 ± 20 eV. From diamagnetic-loop data in the central cell, the central-cell ion temperature is estimated to be $T_{ic} = 15 \pm 10$ eV. This indicates that many of the stream ions are trapped and somewhat heated in the plug by the plug rf and are then expelled by rf diffusion and ion-ion scattering. These ions appear to have the right energy to provide microstability.[8]

The observed density ratio between plug and central cell of 1.5 indicates the presence of electrostatic confinement. With $n_p/n_c = 1.5$, $T_e = 24$ eV, and the Boltzmann relationship $\varphi_c = T_e(\ln n_p/n_c)$ the plug to central-cell potential difference, φ_c, is 10 V. This is consistent with data from a swept probe in the central cell and a swept end-loss analyzer. If we define a confinement factor, f_c, as the ratio of the free-flow flux of central-cell plasma through the center of the plug to the actual flux in the presence of electrostatic confinement, f_c is predicted to be equal to $\exp(\varphi_c/T_{ic})$ for a collisional central-cell plasma.[11] Taking T_{ic} to be 15 eV gives $f_c = 2$.

Alternatively, f_c can be evaluated as the ratio j_F/j_{ELA}, where j_F is the free-flow ion current density given by

$$q/4(nl_{cc}/R_c\sqrt{\pi})(8T_{ic}/\pi m)^{1/2}$$

$$= 0.7 \pm 0.2 \text{ A/cm}^2$$

and j_{ELA} is the measured end-loss current scaled to the center of the plug. From Fig. 2 $j_{ELA} = 0.3 \pm 1$ A/cm^2 so $f_c = 2 \pm 0.7$. Measurements of the power balance in the sustained operation indicate that the rf power absorbed by the plasma varied from 20 to 10 kW and that the power was lost axially. The total rf power coupled to the plasma was approximately 40 kW. Details of the power balance will be given elsewhere.

In the case shown in Fig. 2, the gas fueling was tailored to maintain constant central-cell density. By increasing the gas fueling throughout the plasma pulse we found that the plug and central-cell densities could be built up well above (2–4 times) those provided by the guns. However, under such conditions the central-cell density increased to equal the plug density. This technique provides a superior target plasma for the start-up of a neutral-beam-powered tandem mirror since the negative effects of the stream guns have been eliminated and higher densities can be achieved.

Although increasing plug rf heating always enhances rf tandem operation, increasing central-cell rf heating can disrupt it. As the central-cell pressure increases it eventually violates the MHD stability condition. Just before the plasma is lost in this way, probes on the periphery of the central cell measure a threefold increase in the amplitude of low-frequency (5–10 kHz) oscillations. These oscillations have an $m = 1$ azimuthal mode number and a parallel wave number $\simeq 0$, indicative of a flutelike fluctuation. In this experiment, the ratio of central-cell β to plug β must be less than 3 ± 1.5 (with $\beta_p = 1.0\% - 1.3\%$) for stable operation. The zero-gyroradius MHD theory prediction[12] for this magnetic field configuration is 1.5. This is lower than observed but within error limits. More detailed results on MHD stability experiments in Phaedrus are described elsewhere.[13]

We have shown that a tandem-mirror plasma with isolated end plugs can be sustained by rf and gas fueling for 8 ms beyond gun turnoff. This time appears to be limited only by the rf pulse length and is much longer than the characteristic decay times of the plugs and central cell. Weak electrostatic confinement has been demonstrated. By increase in rf power, it appears that higher densities and temperatures can be achieved. This suggests that pure rf operation should be taken seriously as an option for future tandem-mirror reactors. At present, the technique provides a configuration for tandem-mirror confinement studies and a superior start-up plasma for neutral beams.

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