Ion Heating and Confinement in a Toroidal Plasma Device with a Cusped Magnetic Field

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A novel toroidal plasma device has been tested in which the plasma is confined in a surfacelike multipole cusp field generated by permanent magnets. A toroidal current, driven by an induced electric field, is preferentially carried by the ions which are directly Ohmically heated ($T_i > T_e$). Plasma β's of 20%–30% have been observed. Computer simulations verify a simple model of device operation.

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A new magnetic confinement device called the Toroidal Cusp Experiment (TCX) has been constructed and operated. The TCX employs surface magnetic confinement. The cusp field restrains electron motion so that a toroidal electric field drives mainly ion current thereby directly heating the ions to high temperatures. In addition, the cusp field acts as a series of magnetic lenses which focus the ions towards the center of the device giving good ion confinement. High β's have been achieved in the experiment with typical ion currents of 2.3 kA. With increased Ohmic heating voltage, up to 6 kA has been driven. If the expected scaling of this configuration continues to be favorable, a device capable of producing plasma with parameters relevant to fusion would be simple and economical to construct.

The magnetic geometry and operation principle of TCX are similar to those in a previous experiment[1] in which operation was limited to high-density argon plasmas of short duration and short energy confinement (<10 μs).

The typical discharge parameters in TCX are $T_i = 40$ eV, $T_e = 20$ eV, $n_e = 1.2\times10^{13}$ cm^{-3}, and $\tau_E = 140$ μs. In addition to the experimental data, the results of a particle simulation code modeling TCX will also be presented.

A schematic of the experimental arrangement is shown in Fig. 1. The thin-walled ($t = 0.32$ cm) vacuum chamber ($R = 45$ cm, $r = 15$ cm) was constructed with stainless steel and has a square cross section. The surface cusp field is produced by 48 poloidal rings of permanent magnets mounted on mild steel. Alternate rings have opposite magnetic polarity. The maximum field in the cusp is 1.3 kG and the bridge field halfway be-between cusps is 0.5 kG at the outer wall. The field strength at the inner wall is slightly higher since the rings of magnets are closer together there.

The toroidal electric field is produced by an iron-core transformer providing a maximum of 3×10^{-2} V s. An iron core was chosen over an air core to minimize the required primary current. A set of vertical field coils is provided to cancel the leakage flux from the Ohmic-heating transformer. In TCX, the vertical field does not provide a radially inward $\vec{J}\times\vec{B}$ force to balance the hoop force from the toroidal current as in tokamaks. As mentioned previously, the axisymmetric cusp field functions as a periodic lens array which focuses accelerated charged particles toward the axis.

After the working gas (hydrogen, helium, argon, etc.) is pulsed into the chamber, the gas is preionized with a tungsten filament discharge. Filaments are positioned near the outer wall, at two locations around the torus, to minimize interference with the main discharge which is initiated by energizing the Ohmic-heating transformer and vertical field coils.

Diagnostics to measure the plasma parameters include double and single Langmuir probes to measure density and floating potential; a Rogowski coil to determine total plasma current; a four-grid particle-energy analyzer to obtain T_i, T_e, and the ion drift velocity; visible-light spectroscopy to determine T_i from Doppler-broadened Hα emission and to monitor impurities; a far-infrared laser interferometer and scattering system to monitor plasma density and electrostatic fluctuations; and an array of probes along

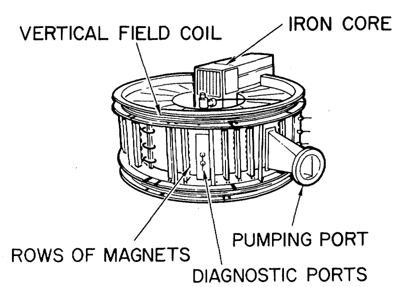

FIG. 1. Schematic of the experimental arrangement.

the wall to measure particle losses in the cusp field. The loop voltage was measured across the insulating gap.

Raw data from a typical plasma discharge are presented in Figs. 2(a)–(e) which show toroidal current, loop voltage, ion saturation current on axis, and light emission from Hα and O IV. The hypothesis that the ions carry a large portion of the toroidal current was verified by measurement of the ion distribution function both parallel and antiparallel to the toroidal electric field. The difference in the distributions accounts for all the toroidal current with an ion drift velocity of about 50 V. It is likely that some of the current is carried by electron but the electron drift velocity was not resolvable. We find that $T_i/T_e \simeq 2$ and that 40-eV ion temperatures are produced repeatedly. Occasional shots up to 110 eV have been observed with optimal tuning of the Ohmic-heating and vertical-field compensation supplies together with thorough outgassing of the preionization filaments.

Figure 2(f) shows the spectrally resolved Hα emission which is bi-Gaussian. The brighter 5-eV component is consistent with the expected distribution of excited neutrals from the dissociation of molecular hydrogen, by electrons with energy greater than 15 eV, via the Franck-Condon process.[2] The less bright 40-eV component is due to charge-exchange neutrals which reflect

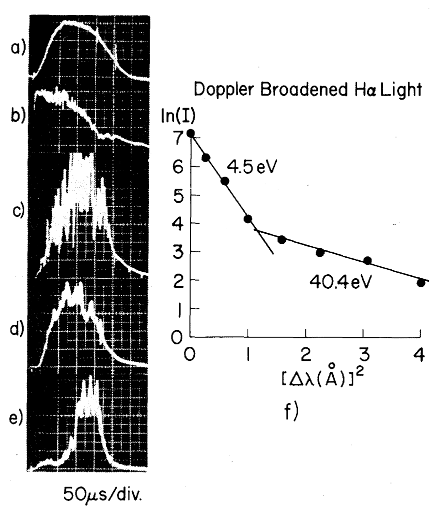

FIG. 2. Data from a typical plasma discharge: (a) Toroidal plasma current (0.76 kA/div.). (b) Loop voltage (55 V/div.). (c) Plasma density (2×10^{12} cm^{-3}/div.). (d) Hα radiation intensity (arb. units). (e) O IV radiation intensity (arb. units). (f) Spectrally resolved Hα radiation plotted as log(intensity) vs $(\Delta\lambda)^2$.

the ion temperature and is in good agreement with the energy analyzer result. The ion temperature profile, as measured with the particle energy analyzer, was found to be flat across the plasma while the density profile was more parabolic. The time history of the O IV light is more slowly rising and clearly more sharply peaked than the Hα light which indicates that the plasma heats until the peak in the current and then cools.

Charge exchange appears to account for power balance in TCX for hydrogen discharges. We can estimate the equilibrium temperature by balancing the Ohmic heating input power against charge-exchange losses using the energy balance equation:

$$d(N_iW)/dt = VI - N_i\sigma_x v_i n_n W,$$

where N_i is the number of plasma particles, W is the average energy per ion, VI is the Ohmic heating power, σ_x is the charge-exchange cross section, v_i is the ion velocity, and n_n is the neutral density. Setting the time derivative equal to zero yields $T_i = 40-100$ eV which is about the observed range.

Results from the wall probe array indicate that the loss aperture is comparable to the ion Larmor radius which is the same result obtained in early spindle cusp research.[3,4] By measuring the average ion flux to the wall, we infer a plasma particle lifetime of 6 μs while the energy confinement time inferred from $\tau_e = \mathcal{E}/VI$ ($\mathcal{E}$ is the total plasma energy) is typically 140 μs. Apparently, the hot accelerated ions (which are of the most consequence) are confined while the cold ions are lost to the wall.

In a device with nonuniform B it is difficult to give a precise definition of β. However, in these experiments the ratio of the central plasma pressure to the B-field pressure halfway between the cusps is in the range 20%–30%.

The plasma duration [see Fig. 2(a)] is limited by the volt-second rating of the Ohmic-heating transformer. The time-integrated value of the induced loop value is 2×10^{-2} V s which is in reasonable agreement with the estimated core value of 3×10^{-2} V s. Also, the imperfect coupling between the Ohmic-heating primary and the plasma leads to a limit on the maximum rate of rise for the toroidal current.

To further confirm our physical picture of the TCX device, a plasma simulation was performed with a two-and-one-half dimensional, electromagnetic, finite-size particle code.[5] The system size is $L_x \times L_y = 64\Delta \times 64\Delta$, with the unit grid spacing Δ equal to the initial electrons' Debye length λ_e. There are four electrons and four ions per unit cell. The ion-to-electron mass and temperature ratios are $M_i/M_e = 20$ and $T_i/T_e = 1$, respectively. The speed of light is such that $c = 5\omega_{pe}\Delta = 5v_{te}$, with ω_{pe} and v_{te} being the plasma frequency and the initial thermal velocity of the electrons. The external magnetic field geometry is illustrated in Fig. 3(a); it is created by appropriate sheet currents at the top and bottom y boundaries. The field strength is such that the electrons' gyrofrequency $\omega_{ce} = 3.5\omega_{pe}$ at the sheets and falls off to $\omega_{ce}/\omega_{pe} = 5\times10^{-3}$ at the midplane (of course, it is zero at the x points). The ions have essentially straight orbits over the whole volume. The smaller Larmor radius of the electrons means that they are tied to the field over a good portion of the plasma. The inductive electric field $E_{\rm dc}$ is such that $eE_{\rm dc}/m\omega_{pe}^2\Delta = 0.05$. Only the electrons with perpendicular energies greater than $(e^2/mc^2)\{\int B_y(y)dx\}^2$ where the integral is between x_1 and x_2 [Fig. 3(a)] can jump between cusps and will have a tendency to run away. The ions, on the other hand, should just fall free in the dc electric field. We observe in Fig. 3(c) that the ions do indeed fall free (70% run away) while a good fraction of the electrons are trapped by the magnetic field (15% run away).

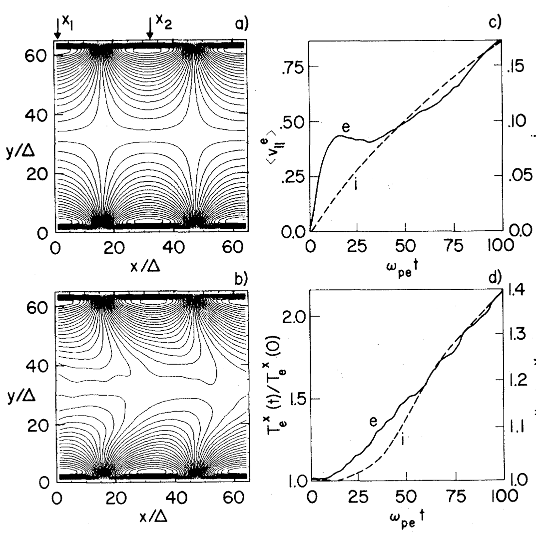

FIG. 3. (a) External magnetic field geometry. (b) Total field (external plus plasma) at $\omega_{pe}t = 100$. (c) Average electron and ion velocities parallel to the dc field as a function of time. (d) Time evolution of the electron temperature T_x parallel to the dc field and of the ion temperature T_y transverse to it.

The ratio of electron to ion x-directed current (after three ion-cyclotron periods) is only $J_e/J_i = 4.3$, as compared to the free-fall value of 20. Some rough theoretical arguments predict $J_e/J_i \propto (m_i/m_e)^{1/2}$ and 1 for the slab and cylindrical cases, respectively, which is in rough agreement with the experiments and simulations. The drag of the electrons on the field is also demonstrated by Fig. 3(b) where the total field (external plus plasma) is displayed. The electrons pull on the B field which stretches as shown; it appears that the B field snaps both because of the increase of electron current after $\omega_{pe}t = 40$ and because the lines appear less stretched at later times; the point of maximum stretch is where the electrons are clamped [$\omega_{pe}t = 40$ in Fig. 3(b)]. Figure 3(d) illustrates that the temperature of the electrons doubles along the dc field direction (this is also true in the y direction). The temperature of the ions increases by 10% along the dc field and 40% along the y direction. The simulations serve as a "proof of principle" of preferential ion acceleration and heating by an inductive electric field in picket-fence-type magnetic fields. Recent calculations have shown that with a field that increases more rapidly near the axis and that has larger values of $\int B_y\,dx$ between nulls, the electrons are tied to the field lines more tightly and the ratio of ion current to electron current increases.

It is of interest to compare other high-β experiments to TCX. Internal conductor devices such as multipoles[6] and Surmac[7] rely on average minimum-B stability. These devices show some promise but suffer from problems with initial plasma production and losses to the conductor supports. Levitated, superconducting designs pose severe engineering difficulties.

As mentioned previously, the Polytron[1] is the most similar to TCX since it is toroidal with multipole cusps. However, operation has been limited to high-density ($n_e = 10^{15}$) argon plasmas of short duration. Tormac[8] combines a low-order toroidal cusp stuffed with a toroidal field. The toroidal field allows electrons to carry current easily so that the ions are not directly heated as in TCX. Also, poloidal cusps were chosen for TCX since the poloidal field generated from the toroidal current cancels the bridge field on alternate cusps when the cusps are oriented toroidally.

Extrap[9] employs external conductors combined with a toroidal current to produce a purely poloidal field. This scheme has only been tested in linear geometry where end losses dominate device performance.

In summary, a new magnetic confinement device has been built and tested. The principal advantages of this device are direct heating of the ions and high plasma β values (30%) since the confining field is surfacelike and the hot plasma is confined in the interior low-field region. The physical picture of enhanced ion current with the electron flow impeded by the cusp field and direct ion heating was confirmed with a particle simulation. The experimental results are a significant improvement over previous experiments. We feel that a suitably constructed TCX is possibly scalable to a reactor suitable for burning DT and advanced fuels.

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Radio-Frequency Current Drive in a Fusion-Producing Plasma

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A method for driving current in a fusion-producing plasma is proposed. Radio-frequency power is used to prohibit fusion-produced energetic particles from slowing down isotropically or to push them in a preferential direction. As a result, a net plasma current is generated whose efficiency is comparable to other current drive schemes.

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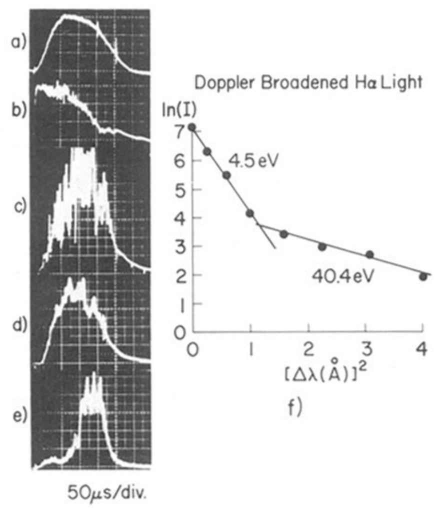
Advantages of steady-state operation of fusion reactors have long been recognized. In some reactor concepts, such as tokamaks and pinches, the magnetic field produced by the current flowing in the plasma is an essential part of the confinement. The most commonly used method for driving plasma current in these experiments is to induce a toroidal electric field in the plasma by means of a time-varying magnetic flux. This method cannot operate in a steady-state fashion; therefore, alternative methods capable of driving plasma current continuously are desirable. Neutral beams,[1] heavy charged-particle beams,[2] and various rf waves[3-8] have been proposed for maintaining a steady-state plasma current by imparting to the electrons the momentum needed to compensate the resistive losses or by making the resistivity asymmetric.

In this paper, we propose to use the high-energy α particles produced by fusion reactions to sustain a steady-state current in plasma. The idea is to use rf power to prohibit the α particles from slowing down isotropically and to push the α particles in a preferential direction and thus form an α-particle beam. This α-particle beam will then transfer the momentum to electrons and



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