Stable Confinement of High-Beta Collisionless Toroidal Plasmas

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High-β, collisionless, toroidal multipole equilibria with parameters $n = 5\times10^{13}$ cm^{-3}, $T_i = 200$ eV, $T_e = 25$ eV, and bridge $\beta = 8\%$ have been obtained in the University of California at Los Angeles dodecapole. The equilibrium is characterized by perturbed vacuum magnetic fields, flat internal pressure profile with sharp edge, and a steep hoop bridge profile 2 ion-gyroradii wide centered on the separatrix. The transition from diffuse profiles at low $\beta < 1\%$ to sharp profiles at high $\beta \geqslant 5\%$ is observed. A stable equilibrium is observed in excess of 400 Alfvén times.

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High-β equilibrium and stability properties of high-temperature, collisionless plasma in average minimum-B confinement systems such as tokamaks, tandem mirrors, and multipoles are of great current interest. In the high-β regime, vacuum field topology is altered significantly, and the character of the plasma equilibrium differs greatly from that in the zero-pressure limit. Also, although closed toroidal and tandem mirror systems can be designed to stabilize flute-($k_{\parallel} = 0$) type instabilities, there are unavoidable regions of locally unfavorable magnetic curvature where sufficiently large plasma pressure gradients may drive modes with $k_{\parallel} \neq 0$ unstable. Such modes, called ballooning instabilities, may place a pressure or β limit on stable confinement. There has been much theoretical activity[1-6] in this area but experimental work[7,8] addressing these problems is just beginning. In this Letter, we describe the achievement of both high-β and collisionless conditions simultaneously and present the first experimental observation of stable, high-β, collisionless equilibria in a toroidal multipole.

The experiment was performed in the University of California at Los Angeles (UCLA) dodecapole Surmac[9,10] (Fig. 1). The dodecapole is a six-hoop toroidal multipole with 45 cm major radius, 20 cm mean minor radius, 490 kA hoop sum current, and field strength 2.3 kG on the separatrix in the outer end hoop bridge (region between hoop and wall) where β is determined. Each hoop is supported vertically by a single pair of dipole guarded supports.[11] The plasma source is cross-field plasma (Marshall) gun injection through a drift tank and 20-cm-diam aperture. Base pressure $\sim 3\times10^{-9}$ Torr is obtained with two turbomolecular pumps, two 15 °K helium cryopumps, liquid-nitrogen cryopump, and titanium gettering.

Following ignition of the 10-kJ plasma gun capacitor bank, a 50-μs period is required for the plasma stream to fill the torus and reach equilibrium. Equilibrium is defined as the plasma state when turbulence associated with the injection process decays, the plasma is quiescent and axisymmetric, and the electron and ion distributions are Maxwellian. Peak separatrix density at equilibrium was determined to be 5×10^{13} cm^{-3} with a 2-mm microwave interferometer and swept double Langmuir probe. The density decay time is 2 ms ($\sim 50\%$ agreement with best estimates of classical particle-confinement time) and the ion temperature decays on a 90 μs time scale which is consistent with charge-exchange ion-energy loss on the neutral hydrogen gas background of density $\sim 2\times10^{11}$ cm^{-3}. Energy confinement time increases to 0.5 ms as the plasma and neutral densities are lowered an order of magnitude.

The plasma is hydrogen doped with 5% helium to provide a light, low-Z impurity ion for diagnostic purposes. The ion temperature at equilibrium was determined to be 200 eV from the energy distribution of charge-exchange neutrals, the Doppler width of the He II 4686-Å line, and with a gridded energy analyzer probe. Results from the three diagnostics agreed to within 20%. Electron temperature at equilibrium was measured to be 25 eV with a swept double probe. Maxwellian electron and ion distributions are concluded from the hyperbolic tangent waveform of the double probe curve, Gaussian shape of the Doppler-broadened He II line, and the exponential energy distributions of the gridded energy analyzer and charge-exchange neutral flux. The plasma is fully ionized, $n_0/n_i = 4\times10^{-3}$, and collisionless with $\nu_{ci}/\nu_{ii} > 400$ and $\lambda_{ie}/L_c = 2$ where $\nu_{ci} \equiv$ ion cyclotron frequency, ν_{ii} = ion-ion collision frequency, $\lambda_{ie} \equiv$ electron-ion mean free path, and L_c $\equiv$ connection length between regions of good and bad curvature as indicated in Fig. 1(b). An upper bound of 1% is placed on the impurity concentration by assuming the total observed electron power loss to be due to impurity line radiation and with use of published cooling rates for impurities observed spectroscopically such as oxygen and carbon. With use of the measured carbon Doppler temperature of 15 eV the correlation on our β determination due to impurity concentration is only 0.07%.

By varying the magnetic field strength, T_i was found to scale as B^2 up to 250 eV. This scaling is a result of the requirement to have a minimum number of $\rho_{ci} \propto (T_i/B^2)^{1/2}$ in the weakest flux interval of the machine in order to achieve equilibrium. Because of the toroidicity of the device, this weakest region is in the outer hoop bridge where the minimum number of gyroradii was found to be 2.4 between ψ_s, the separatrix, and ψ_c, the vacuum critical flux surface where $(\partial/\partial\psi)\oint d\vec{l}\cdot\vec{B}=0$. Under these conditions there are ten ion gyroradii between the hoop and the wall.

From these density and temperature measurements made in the low-field region on the major radius near ψ_s, β may be determined on ψ_s in any hoop bridge since the pressure is constant along flux surfaces, or $p=p(\psi)$ only except near the guarded supports where ∇B drifts, nonuniform electrostatic fields, and $\vec{E}\times\vec{B}$ drifts destroy the axisymmetry locally (over a region equivalent to only 0.7% of the poloidal flux). Axisymmetry and $p=p(\psi)$ only are confirmed by an array of high bandwidth (~ 100 MHz) Langmuir probes placed on the same flux surface at different azimuthal positions around the torus in both the bridge and good curvature regions. Probe current amplitudes agree to within 10% indicating constant pressure on flux surfaces. The 10% variation is due to uncertainty in probe positioning and to differences in probe collection surface conditions. Thus, in the outer end hoop bridge where $B=2.3$ kG, β is 8%. It is most appropriate to define β at this point in the device since it is here where ballooning instabilities would occur. The volume-averaged β is ~4% and in the interior low-field region, $\beta=1$.

This high-β equilibrium is characterized by perturbed vacuum magnetic fields, flat internal pressure profile with sharp edge, and a steep hoop-bridge pressure profile 2 ion-gyroradii wide centered on the separatrix. Perturbation of the vacuum magnetic field is detected with two magnetic probes, one located in the bridge outside ψ_c near the outer wall by point 2 in Fig. 1(b)

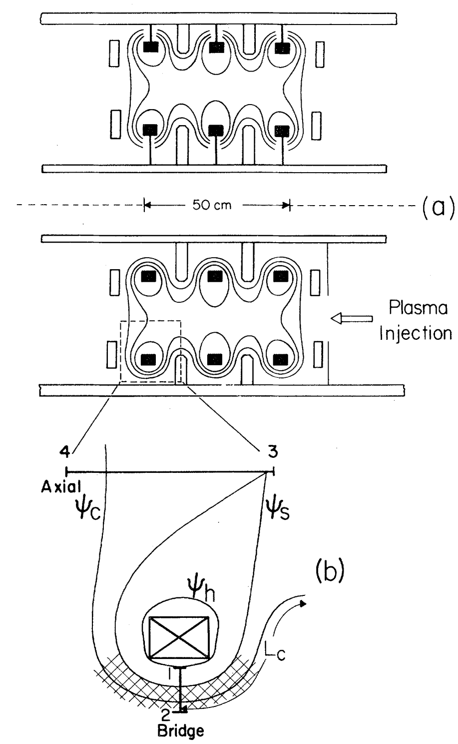

FIG. 1. (a) Schematic of the dodecapole magnetic field configuration showing vertically supported internal rings and plasma injection location. (b) Schematic of region near outer end hoop showing location of vacuum flux surfaces and Langmuir-probe scans plotted in Fig. 2. The shaded region indicates the location of observed fluctuations.

and one located inside the plasma midway between points 3 and 4 in the same figure. The magnetic probe outside the bridge records a paramagnetic perturbation with $\delta B/B=1.6\%$ at equilibrium which agrees in sign but falls 40% short in magnitude with the theoretically predicted perturbation from an equilibrium numerical code[6] which used a flux-conserving single-fluid ideal magnetohydrodynamics (MHD) model. Discrepancy between experiment and code results is due to lack of perfect flux conservation in the experiment. The magnetic probe located inside the plasma in the good curvature region records a much larger perturbation which is initially paramagnetic with $\delta B/B=80\%$, then becomes diamagnetic with $\delta B/B \sim 60\%$ as β decays.

By varying the injected plasma density, the transition from diffuse profiles at low $\beta<1\%$ to profiles with flat interior and sharp edge at high $\beta>5\%$ is observed. Figure 2 displays Langmuir-probe ion saturation current ($\propto n\sqrt{T}$) profiles measured in real space with a 0.5-mm-diam

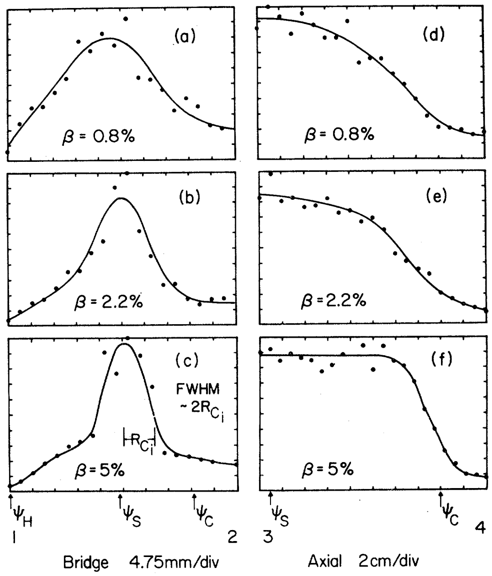

FIG. 2. Langmuir-probe ion saturation current scans of bridge and axial plasma profiles between points located in Fig. 1(b). Arrows indicate locations of vacuum flux surfaces.

probe in the bridge between points 1 and 2 in Fig. 1(b) and along the axis at the major radius through the good curvature region between points 3 and 4 in Fig. 1(b). The profiles were generated by sampling the probe current 60 μs after gun ignition at different positions on a shot-by-shot basis for bridge separatrix β values of 0.8%, 2.2%, and 5.0%. Scatter in the data points reflects shot-to-shot variation of the self-similar discharges.

At low $\beta \simeq 0.8\%$ the bridge profile [Fig. 2(a)] is diffuse, peaked on the separatrix, and changes slope near ψ_c. As β is raised to 2.2% [Fig. 2(b)], the profile sharpens, changes slope inside the vacuum ψ_c position and becomes concave on the hoop side of ψ_s as well. Finally, at $\beta \simeq 5\%$ [Fig. 2(c)] the profile steepens into a sharp central peak with a full width at half maximum equal to 2 ion gyroradii and changes slope at points well inside the vacuum ψ_c and ψ_h, the flux line just outside the edge of the hoop. Variation of the axial profile [Figs. 2(d)–2(f)] with β is similar. At low $\beta \simeq 0.8\%$, the axial profile is diffuse and begins to flatten inside the plasma and sharpen on the edge as β is raised to 2.2%. At high $\beta \simeq 5\%$, the profile becomes flat inside the plasma and falls rather sharply at the edge. As time evolves and β decays, the steep pressure profiles in the bridge and along the axis [Figs. 2(c) and 2(f)] evolve into diffuse profiles similar to Figs. 2(a) and 2(d).

Although the experimental value of bridge $\beta = 8\%$ corresponds to the theoretical critical β for destabilization of ballooning instabilities predicted by a single-fluid ideal MHD stability code,[6] no ballooning modes were detected and a stable equilibrium was observed in excess of 400 Alfvén times limited by ion charge-exchange cooling. One Alfvén time is defined as $\tau_A \equiv L_c/v_A$, where $L_c \equiv$ connection length, previously defined, and $v_A \equiv$ Alfvén speed. The observed stability is probably due to kinetic or other nonideal effects such as finite ion gyroradii ($\rho_{ci} \approx n/|\nabla n|$ for $\beta \geqslant 3\%$ in the bridge) and finite mode number. No change in plasma confinement was observed as the high-β regime is entered other than the faster density decay time encountered at higher density which is characteristic of classical particle transport.

However, a coherent 100-kHz driftlike instability was observed with amplitude $\delta n/n \sim 30\%$ localized in the bridge on the steep pressure gradient between ψ_s and ψ_c in Fig. 2(c) and in Fig. 1(b) (shaded region). The instability was absent from the absolute minimum-B private flux side of ψ_s in the bridge (between ψ_s and ψ_h) even though the pressure gradient there is just as steep as on the common flux. Also, it did not appear on the axial pressure gradient where the curvature is good in Figs. 1(b) and 2(f). The mode does not appear until bridge β reaches $\sim 3\%$, where the density gradient steepens to a scale length $\approx \rho_{ci}$. Furthermore, when the discharge begins at $\beta \geqslant 5\%$, the instability appears at equilibrium, then decays in both amplitude and frequency (to $\delta n/n \simeq 5\%$ and $\nu \simeq 50$ kHz in 150 μs) until $\delta n/n < 1\%$ as time evolves over 250 μs and the steep profile evolves into a diffuse profile similar to Fig. 2(a). The density decay rate is unaffected by the appearance of the mode.

The instability characteristics observed here (frequency, localization to bad-curvature regions, lack of enhanced transport, amplitude inversely proportional to density gradient scale length) are quite similar to those found in a previous low-β experiment[12] where the wave was identified as a "ballooning-like" collisionless drift mode driven unstable by sharp pressure gradients across flux surfaces of bad curvature and long connection length.

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Observations of High-Beta Toroidal Plasmas

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A wide range of magnetohydrodynamically stable high-β plasmas is produced in the University of Wisconsin Levitated Toroidal Octupole. Near the single-fluid regime we obtain, in the bad-curvature region, $\beta = nk(T_e + T_i)8\pi/B^2 \approx 8\%$, twice the theoretical single-fluid ballooning instability limit of 4%. We also obtain stable plasmas at $\beta = 35\%$, nine times the theoretical limit, in a regime in which finite–ion-gyroradius (e.g., gyroviscosity) effects are important. Experimental spatial profiles of the equilibrium diamagnetism are compared with theory.

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The high-β [= (plasma pressure)/(magnetic pressure)] magnetohydrodynamic (MHD) ballooning instability is predicted to set a β limit for any average minimum-B system such as tokamaks,[1] tandem mirrors,[2] and multipoles.[3] Ballooning-mode study in a toroidal multipole contains simplifications in that multipoles may be operated without magnetic shear (unlike tokamaks) and possess an ignorable coordinate (unlike tandem mirrors). Thus high-β multipole experiments[4,5] can test ballooning-mode theory; if multipole β limits are incorrectly predicted, the present theory will likely be unreliable for other configurations. These β limits also influence the feasibility of a multipole advanced-fuel reactor.[6]

A broad range of extremely high-β MHD stable plasmas are obtained in the University of Wisconsin Levitated Toroidal Octupole. Plasma parameters vary from nearly the ideal single fluid to the kinetic regime. We have previously reported observation of $\beta \approx 12\%$ plasmas in a collisionless, kinetic regime with only 2 ion gyroradii within a pressure-gradient scale length.[4] In all cases, β is evaluated locally in the bad-curvature, high-field region (Fig. 1). β is higher at nearly all other locations.

Near the single-fluid regime, we have attained $\beta = nk(T_e + T_i)8\pi/B^2$ of 8%, twice the theoretical single-fluid ballooning limit of 4%. $L_p \sim 5\rho_i$, where $L_p = p/|\nabla p|$ is the pressure scale length and ρ_i is the ion thermal gyroradius. 25 ion gyroradii are contained between the ring and wall. The electron-ion Coulomb mean free path (~ 20 cm) is smaller than the magnetic connection length (~ 100 cm), eliminating kinetic–free-streaming and particle-trapping effects. The magnetic Reynolds number, S = (resistive skin time)/(Alfvén time), is about 1000, so that resistivity is ignora-