Plasma Equilibrium and Confinement in a Tokamak with Nearly Zero Central Current Density in JT-60U

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A high confinement equilibrium with nearly zero toroidal current in the central region (a "current hole") has been observed for the first time to persist stably for several seconds in the JT-60U tokamak. This observation indicates the possibility of stable tokamak operation without central toroidal current; the central current has previously been believed to be necessary in tokamaks. The radius of the current hole extended up to 40% of the plasma minor radius. It was observed that the current hole was formed by the increase of the off-axis noninductive current.

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In a toroidal system for confining a high temperature plasma, the poloidal magnetic field is necessary to suppress the drift of charged particles (ions and electrons) and to obtain good confinement. In a tokamak, which is one of the axisymmetric toroidal systems, the poloidal magnetic field is produced by a toroidal current in the plasma. The current density has its maximum at the center in ordinary tokamaks. A hollow current profile ("reversed shear configuration") has also been produced recently, in the context of advanced tokamak concepts [1], but a finite current at the center has been believed to be necessary for stable sustainment of the plasma. Though an equilibrium with zero central current has been previously proposed theoretically [2], the stability has not been considered there, and hence the reality of such an equilibrium has been unknown. The current at the center was also considered necessary as a "seed" current for initiation of the self-generating "bootstrap" current [3]. In this Letter, we report on the first observation of stable and sustained equilibrium of tokamak plasmas with nearly zero toroidal current in the central region.

The safety factor (q) is used to represent the magnitude of the pitch of a magnetic field line, and is defined on each flux surface as the number of times a field line goes around the torus toroidally as it completes one poloidal circuit around the magnetic axis. A high value of q corresponds to a low poloidal field and a low plasma current inside the flux surface. In JT-60U reversed shear plasmas, in which high fusion performance was obtained, q appeared to be very high near the axis [4,5]. The q profile was reconstructed with a magnetohydrodynamics (MHD) equilibrium code using data from a motional Stark effect (MSE) diagnostic [6,7]. However, the exact value of q on the axis $q(0)$ was unknown because of (i) insufficient accuracy of the MSE measurement, especially near the axis where the pitch angle of the field line was small, (ii) possible effects of a radial electric field E_r on the MSE measurement [8,9], and (iii) the inability of our MHD equilibrium code to deal with a high $q(0)$ equilibrium. Recently, these problems have been resolved by improvements in our MSE measurement system and equilibrium code. One of the major improvements in the MSE system is the installation of new optics viewing a beam line codirectional (in the same direction) to the plasma current, in addition to existing optics viewing a beam counterdirectional, which enables us to compensate for the effect of E_r by using data from both optics [8]. In the equilibrium code a spline function on the normalized minor radius was implemented for current profiles, in addition to polynomial functions on the poloidal flux.

By using the upgraded MSE system, we found that a region with nearly zero poloidal magnetic field existed in the central part of reversed shear plasmas in JT-60U. A poloidal cross section of plasma, in which such a region was observed, is shown in Fig. 1(a) with MSE measurement points. Here the toroidal magnetic field at the plasma

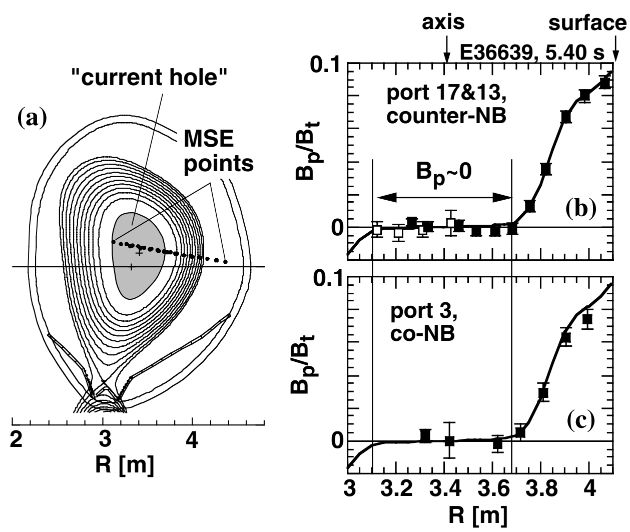

FIG. 1. (a) Poloidal cross section of plasma and MSE points. The region of the "current hole" is shown by the shaded area. (b), (c) B_p/B_t as a function of major radius. Rectangles denote measured data, and solid lines denote calculated values from equilibrium reconstruction. (b) Channels viewing a counter-NB. (c) Channels viewing a co-NB.

center (B_{t0}) is 3.7 T, the plasma current (I_p) is 1.35 MA, and the horizontal plasma minor radius (a) is 0.76 m. The MSE points are located along tangential neutral beam (NB) lines, which are used for plasma heating. The radial profiles of B_p/B_t measured by MSE (neglecting the effects of E_r) are shown in Figs. 1(b) and 1(c) where B_p and B_t are the poloidal and toroidal magnetic fields, respectively. We have two optics for a counter-directional beam and one for a co-directional beam. It is found that B_p is nearly zero at $R \sim 3.1-3.7$ m, which accounts for 40% of the plasma diameter ($2a = 1.52$ m), in the MSE optics viewing both co- and counterbeams. This observation indicates that the effects of E_r are small and can be neglected, and that the current density is certainly nearly zero in the central part, which we call a "current hole." Radial profiles of current density (j) and q reconstructed by the equilibrium code are shown in Fig. 2 together with profiles of electron density n_e, ion temperature T_i, and electron temperature T_e. The horizontal axis is the normalized minor radius ρ. The region of the current hole is indicated by a shaded area in Fig. 1(a). The solid lines in Figs. 1(b) and 1(c) are values of B_p/B_t calculated from the equilibrium shown in Fig. 2. Though the MSE data seem to show zero current density in the central region, our equilibrium code is unable to model such an equilibrium. Hence the equilibrium with the smallest $j(0)$ [highest $q(0)$] obtained so far is shown in Fig. 2. In this equilibrium the current density inside $\rho = 0.4$ is about only 5% of the averaged current density in the poloidal cross section ($\langle j \rangle$), and the current integrated inside $\rho = 0.4$ is only 12 kA, or less than 1% of the total plasma current. The central value of q is $\sim$100, which is about twenty times as high as $q_{95} \sim 5.2$, where q_{95} is the safety factor at the flux surface with 0.95 of normalized poloidal flux. Considering the errors in the MSE data, the uncertainties in $j(0)$ and $q(0)$ are estimated as $|j(0)/\langle j \rangle| \lesssim 7\%$ and $|q(0)| \gtrsim 70$. The uncertainty in q in the central region is denoted by a shaded area in Fig. 2(b). It is noted that only the poloidal magnetic field vanishes in our experiments, while the total magnetic field vanishes (due to a strong diamagnetic effect) in the equilibrium with zero central current proposed theoretically before [2].

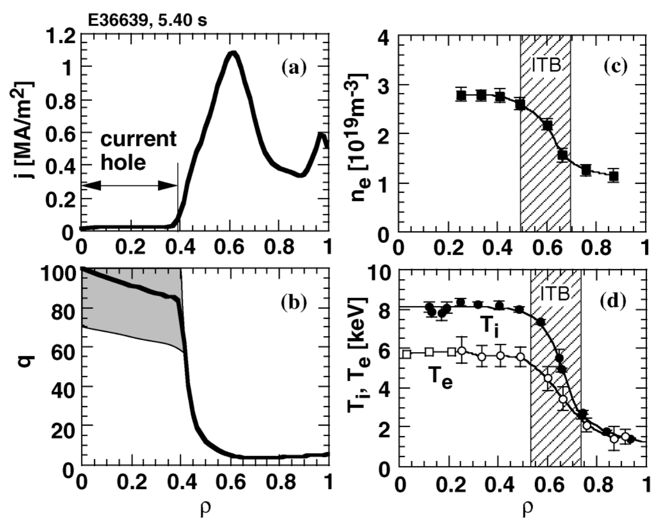

FIG. 2. Radial profiles of (a) current density j, (b) safety factor q, (c) electron density n_e, and (d) ion and electron temperatures (T_i and T_e). Here, n_e was measured by YAG (yttrium-aluminum-garnet) laser Thomson scattering, T_i by charge exchange recombination spectroscopy (CXRS) on carbon ions, and T_e by YAG laser Thomson scattering (open circles) and electron cyclotron emission (ECE) (open rectangles).

Steep gradient zones or internal transport barriers (ITBs) are recognized in the n_e, T_i, and T_e profiles in Figs. 2(c) and 2(d). These steep gradients indicate the reduction of radial transport of heat and particles in this region. On the other hand, the density and temperature gradients in the central region ($\rho \lesssim 0.5$) are very flat, which indicates extremely large radial transport in this region. This flat region is often observed in JT-60U reversed shear plasmas [4,10]. One of the reasons for this poor confinement in the central region is attributed to the existence of a current hole or very low poloidal magnetic field in the central region. The flat region seems to extend further outside the region of the current hole in Fig. 2. This extension may be caused by the radial shift of the orbits of ions from a flux surface. For the profiles shown in Fig. 2, the orbits of thermal ions whose energy is equal to the central ion temperature of 8 keV cover the region from the magnetic axis to the radius of $\rho = 0.47-0.65$, depending on the pitch angle of their velocity. This implies that poor confinement is expected in the region inside $\rho = 0.47$, where the flat profiles are actually observed. However, in another discharge, a large flat portion whose radius of $\rho \sim 0.45$ was also observed when the current hole was small and the orbits of thermal ions extended only to $\rho \sim 0.27$. Therefore the low poloidal field is not the only cause, but there are other causes for the flat portion inside the ITB.

Figure 3 shows the time evolution of parameters for the same discharge shown in Fig. 2. In this discharge, electron cyclotron waves (ECW) of 0.75 MW (110 GHz, ordinary mode) were injected into the central region during the current ramp. The current hole was also observed in other discharges without ECW injection. The neutral beam heating, together with EC heating, was started at $t = 3.4$ s (0.3 s after the plasma breakdown) and continued during the current ramp. The ITBs were formed soon after the start of heating, or at $t \sim 3.5$ s, and grew up until $t = 6.8$ s, as shown by the increase in β_N (normalized beta) in Fig. 3(b). Here, β_N is defined as $\beta_N = \beta_t[\%] \times a[m]B_{t0}[T]/I_p[\mathrm{MA}]$. β_t is the toroidal beta or the ratio of the plasma pressure to the pressure of the toroidal magnetic field. In (b), β_p (poloidal beta) is also shown, which is the ratio of the plasma pressure to the pressure of the poloidal magnetic field, and is roughly proportional to the fraction of bootstrap current in the total plasma current. In (c), B_p/B_t at five MSE points near the axis are shown. The values of the inner three points, $\rho < 0.27$, stay nearly zero from

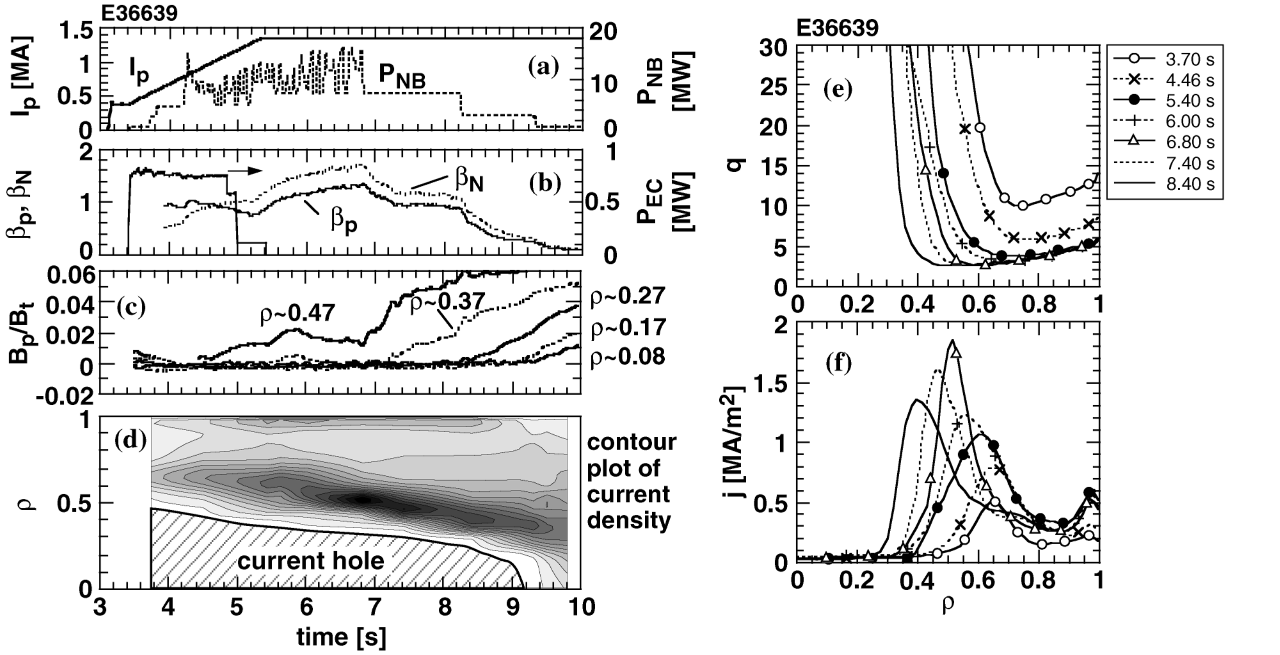

FIG. 3. (a)–(c): Waveforms of a discharge in which the current hole was sustained for several seconds. (a) Plasma current (I_p) and NB power ($P_{\rm NB}$; dotted line). (b) β_p (solid line), β_N (dotted line) and EC power ($P_{\rm EC}$; solid line). (c) B_p/B_t at the MSE measurement points. (d) Contour plot of current density, where darker regions have a larger current density. The region of the current hole is indicated by a hatched area. (e)–(f): Radial profiles of safety factor (q) and current density (j) at several times. The symbols on the q and j profiles are not measured points, but only for distinction of curves.

$t = 4$ to 8 s, which indicates that no substantial current existed within $\rho = 0.27$ during this period. A contour plot of current density is shown in (d). The hatched region indicating the current hole remains for 5 sec, though its radius shrinks slowly according to the shrinkage of the peak in the current density and of the ITB radius. At $t = 9.2$ s when the heating power dropped to 1 MW, the ITB and the current hole disappeared. The radial profiles of q and j at several times are shown in (e) and (f), respectively. In this discharge, the current hole with a radius of $\rho > 0.25$ was sustained for 4 to 5 sec without any global MHD instabilities. This fact implies that the equilibrium with the current hole has good stability. The high temperature [$T_i(0) \sim 8$ keV as shown in Fig. 2(d)] and high confinement with $\tau_E \sim 0.40$–0.54 s and $HH_{98y2} \sim 1.16$–1.45 were also sustained with an H-mode edge for $t = 5.4$–6.8 s. Here τ_E denotes the energy confinement time, and HH_{98y2} denotes the confinement enhancement factor relative to standard H-mode scaling [11]. The zero current density in the central region has been also reported from JET recently [12]. However, the observed zero current density region was transient in time and small in space, and sawtoothlike MHD modes were present. In contrast, our observation is quite convincing in that the current hole existed over large intervals of time and space. Furthermore, high confinement without any global instabilities indicates the possibility of stable operation of tokamaks with no toroidal current at the axis and may lead to new concepts for tokamak reactors with respect to current profile and/or plasma current drivers.

In the discharge shown in Fig. 3, the current density inside $\rho = 0.35$ was already nearly zero at $t = 3.5$ s when the MSE data became available after the start of NB injection, and hence the process of formation of the current hole could not be studied. One possible explanation is that the penetration of inductive current from the surface toward the axis was delayed because of the large plasma radius and high electrical conductivity (high electron temperature) due to the heating just after the plasma breakdown; but this was not the case as shown below. In the discharge shown in Fig. 4, NB units for MSE (co and counter, total 1.7 MW) were injected at the same time as the plasma breakdown, and the MSE data were available as early as $t = 3.2$ s, or 0.1 s after the plasma breakdown. At $t = 3.2$ s, the central current density was finite and no current hole was observed. The current ramp was started at $t = 3.4$ s, and the heating power remained at 1.7 MW until $t = 3.8$ s, when an additional 2 MW of heating was applied. The central current density increased slowly before $t = 3.6$ s, but it started to decrease after that time. This decrease in the central current density was not due to counter-current drive, since the codirectional beam power was higher than the counterdirectional beam power (by 15%) and the loss of beam ions was larger for the counterdirectional beam. The remaining possibility is the increase of off-axis noninductive current. When a noninductive current increases at some radius, the toroidal electric field is decreased there by Faraday's law of electromagnetic induction. This decrease in the toroidal electric field diffuses toward the center and reduces the current density there. This process has been

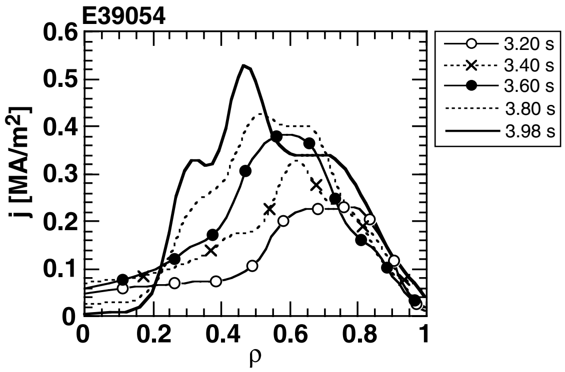

FIG. 4. Evolution of current density profile during formation of current hole. The central current density started to decrease after $t = 3.6$ s.

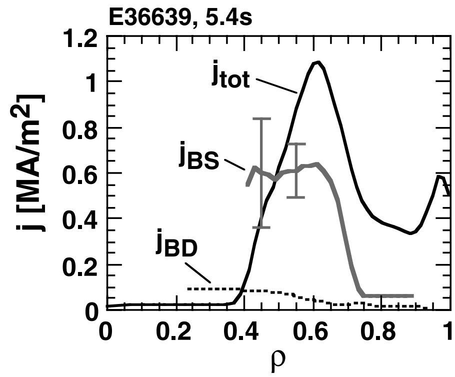

FIG. 5. Radial profiles of total current density reconstructed using MSE data (j_{tot}), calculated beam driven current density (j_{BD}), and calculated bootstrap current density (j_{BS}) in the discharge shown in Fig. 2.

observed in an experiment in which ECW was injected near the magnetic axis [13]. If the noninductive current density is larger than the total current density locally, the toroidal electric field becomes negative there, and its diffusion can cause zero toroidal current density in the neighboring region. This process was also invoked to explain the formation of a zero current density core in the JET tokamak [12], in which lower hybrid current drive supplied the noninductive current. In the discharge shown in Fig. 4, the off-axis noninductive current is thought to be the bootstrap current, since the estimated beam driven current is only $\sim$20 kA and other sources for noninductive current were absent. However, the estimation of the bootstrap current density (j_{BS}) around the current hole ($\rho \sim 0.25$) was difficult because of insufficient density profile data there and difficulty in the calculation of beam pressure at $\rho \lesssim 0.3$ in a high $q(0)$ equilibrium.

A steep gradient in the j profile around the current hole as shown in Fig. 4 is commonly observed and sustained for a long time. In the discharge shown in Fig. 3, the steep gradient in j with a scale length of 0.1 m (0.1 in ρ) was sustained for several seconds, which is longer than the estimated current diffusion time for that scale length (1.5 s). This fact implies the existence of substantial noninductive current in this region. Since j_{BS} is proportional to the pressure gradient divided by B_p, it can be large near the current hole where B_p is small, even with a small pressure gradient. Figure 5 shows the profile of calculated j_{BS} for the profiles shown in Fig. 2 together with the profile of calculated beam driven current (j_{BD}). Though the errors of j_{BS} are large in a high q region, j_{BS} is comparable to the total current density around $\rho \sim 0.5$, while j_{BD} is much smaller than j_{BS}. The fact that the bootstrap current is dominant just outside the current hole supports strongly the conjecture that the current hole is formed by the growth of the bootstrap current.

One interesting point is that no substantial negative central current has been observed so far. This fact suggests that the decrease of central current caused by the growth of off-axis noninductive current stops when the central current becomes zero. On the other hand, in the discharge shown in Fig. 3, ECW was injected tangentially, and a current driven by ECW was expected. The driven current was, however, smaller than the resolution of the MSE measurement, which indicated that the driven current was much smaller than the theoretical value. Hence it seems that the ECW did not change the current profile in the current hole. These observations of the stiffness of the current hole suggest that the current hole is not a result of transient zero toroidal electric field in the plasma core, but of some kind of self-organized structure. This issue will be investigated in more detail in future experiments.

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