Stable Existence of Central Current Hole in the JT-60U Tokamak

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Abstract. In an extreme state of a reversed magnetic shear configuration, it was found in JT-60U that there is almost no plasma current in the central region (called Current Hole). The Current Hole region extends to 40% of the plasma minor radius and it exists stably for several seconds. The Current Hole is formed by the growth of the bootstrap current and it is impossible to drive current in either positive or negative direction by ECH or N-NB inside the Current Hole. In that region, there is almost no gradient of density, temperature and toroidal rotation velocity. It means that there is almost no confinement in the Current Hole and the large energy in that region is sustained only by an internal transport barrier (ITB). The effects of the Current Hole on particle orbits and the effects on an error field on the Current Hole are also discussed.

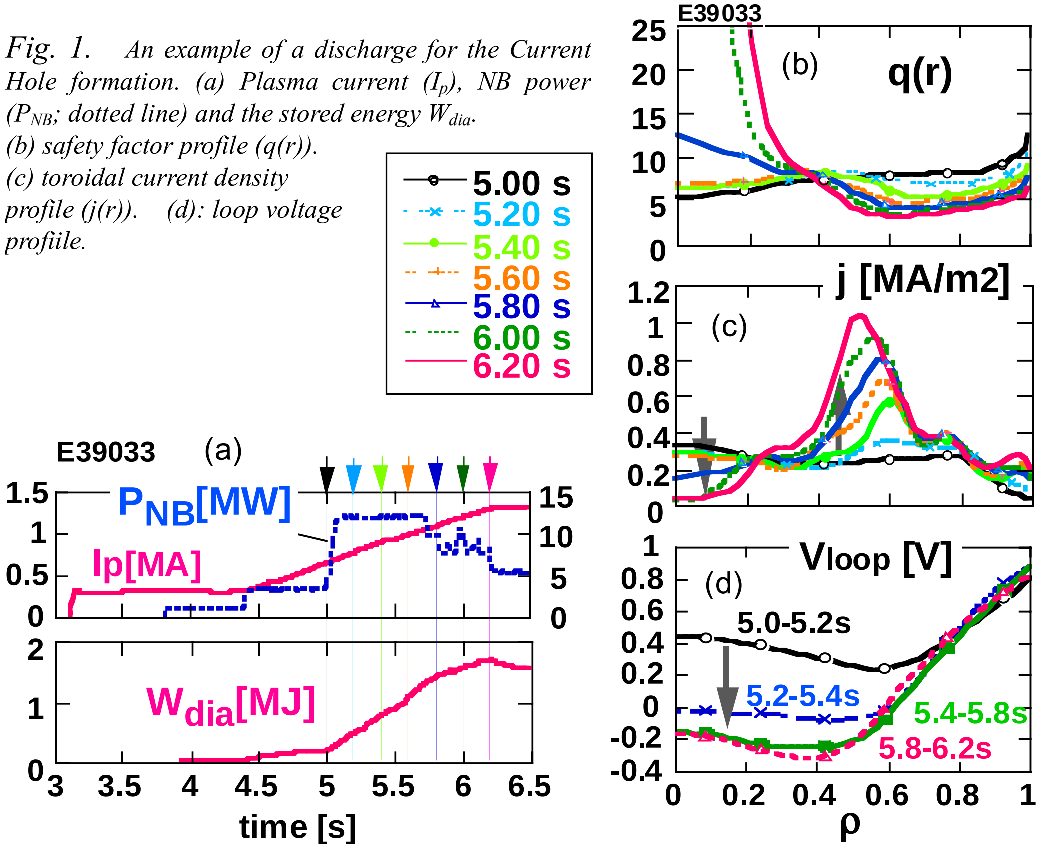
1. Introduction

An advanced tokamak scenario by a reversed magnetic shear configuration has a hollow current profile and shows very high confinement with an internal transport barrier (ITB) inside the position of the minimum safety factor, q_{min}. In an extreme situation of the hollow current profile, it was found for the first time in JT-60U [1] that there is almost no plasma current in the central region. Though the current was believed to be necessary for tokamak plasma equilibrium. Moreover, it was observed for the first time that the Current Hole region extends to 40% of the plasma minor radius and it exists stably for several seconds [2]. The Current Hole is formed by the growth of the bootstrap current and it is impossible to drive current in either positive or negative direction by ECH or N-NB inside the Current Hole. In that region, there is almost no gradient of density, temperature and toroidal rotation velocity, and ECH heat wave travels very rapidly. It means that there is almost no confinement in the Current Hole and the large energy in that region is sustained only by an ITB. The property of the Current Hole plasma is studied.

2. Formation of the Current Hole and Stable Existence of the Current Hole

Figure 1 shows an example of the formation of the Current Hole. High power neutral beams are injected during plasma current ramp-up as shown in Fig.1 (a). The q-profiles and current density profiles are shown in Fig.1 (b) and (c), respectively. The profiles of loop voltage are shown in Fig.1 (d). After increasing the neutral beam power at 5.0 sec, off-axis current increases. Since no counter current expected due to balanced NB injection in this case, the off-axis current comes mainly from the bootstrap current. The growth of the bootstrap current makes the central loop voltage decrease, then the central current density decreases and finally goes to nearly zero (q (0) goes up very high value). After 5.4 sec, even the central loop voltage goes below negative, a negative central current is not observed. The central current is likely to be clamped zero. This special feature will be discussed in section 4. The Current Hole is also observed in JET with off-axis lower hybrid current drive [3]. The big difference in the observation between JET and JT-60U is the existence of MHD modes. The sawtooth like MHD modes present in the JET observation, but not present in JT-60U. Figure

Fig. 1. An example of a discharge for the Current Hole formation. (a) Plasma current (I_p), NB power (P_{NB}; dotted line) and the stored energy W_{dia}. (b) safety factor profile (q(r)). (c) toroidal current density profile (j(r)). (d): loop voltage profiile.



2 shows the sustainment of the Current Hole. In this discharge, ECH of 0.75 MW was injected into a central region during the current ramp. Though the Current Hole was also observed in other discharges without ECH, the high central electron temperature by ECH may be related to the formation of Current Hole with a large radius. In Fig. 2 (c), B_p/B_t at five Motional Stark Effect polarimetry (MSE) points near the axis are shown. The values of inner three points, $\rho < 0.27$, stay nearly zero from t = 4 sec to 8 sec, which indicates that no substantial current exists within $\rho = 0.27$ during this period. In Fig. 2 (d) the contour plot of current density is shown. The hatched region indicating the Current Hole remains for 5 sec though its radius shrinks slowly according to the shrinkage of the peak in current density and of ITB radius. Since the power is reduced to about 8 MW at 6.8 sec to avoid a collapse and when the heating power dropped to 1 MW leaving only one NB unit for MSE diagnostics at 9.2 sec, the ITB disappeared and the Current Hole disappeared. In this discharge, the

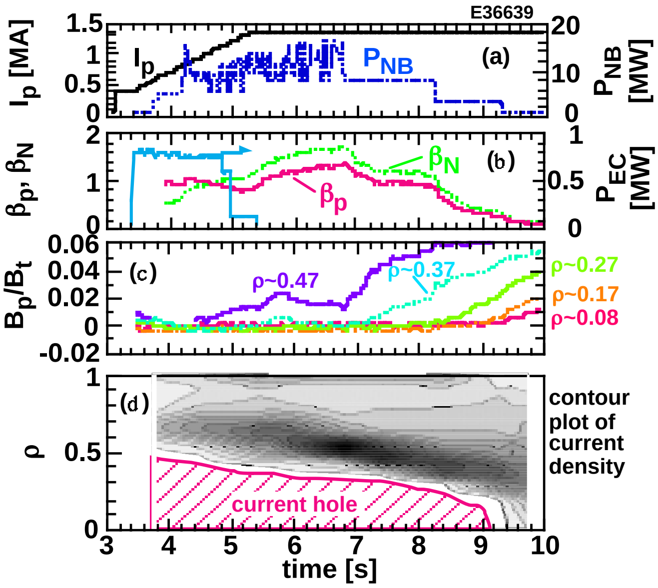


Fig. 2. Waveforms of a discharge in which the Current Hole was sustained for several seconds. (a) Plasma current (I_p) and NB power (P_{NB}; dotted line). (b) β_p (solid line), β_N (dotted line) and EC power (P_{EC}; solid line). (c) B_p/B_T at the MSE measurement points. (d): contour plot of current density, where darker regions have a larger current density. The region of the Current Hole is indicated by a hatched area.

Current Hole is sustained for 4 to 5 seconds without any global MHD instabilities. This implies that the equilibrium with the Current Hole has a good stability.

3. Confinement and Particle orbit in the Current Hole and Effect of Error Field

Figure 3 shows the temperature profiles at 5.4 sec of the discharge shown in Fig.2. These profiles inside the Current Hole show nearly flat, but steep gradients are formed outside the Current Hole where j(r) is peaked. In the case of injecting ECH, the heat wave travels very rapidly inside the Current Hole. These results mean that there is almost no confinement in the Current Hole and the high temperature plasma can be sustained only by the ITB. In this situation, it is very important to know how large the radial excursion of particle orbit is. The orbits of thermal ions with 8 keV, which is equal to the central ion temperature shown in Fig. 3 are calculated and shown in Fig. 4 (a). Here, the ion orbits are traced from the magnetic axis varying the pitch angle of the velocity. In the Current Hole region, ions move almost vertically due to grad-B and curvature drifts and start to move in the poloidal direction when they go out of the Current Hole and enter the region with a significant poloidal field. The largest radius reached by each orbit is plotted as a function of pitch angle at the axis in Fig. 4 (b). The largest banana width is as large as 65 % of the plasma minor radius and any particle starting from the axis reaches ρ = 0.47. This implies that the poor ion confinement is expected in the region inside ρ = 0.47. This position is almost equal to the ITB shoulder in this plasma as shown in Fig. 3. On the other hand, the radial drift of orbit of thermal electrons is much smaller than that of thermal ions or a few cm for the case with q(0) = 100. Hence the flat portion in T_e profiles cannot be understood by the orbit size if q(0) = 100. These imply that large anomalous transport exists or q(0) is much larger than 100.

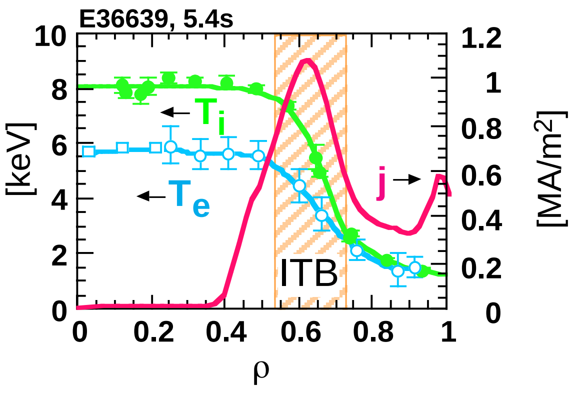


Fig.3. Temperature profiles and current density profile at 5.4 s of the discharge shown in Fig.2.

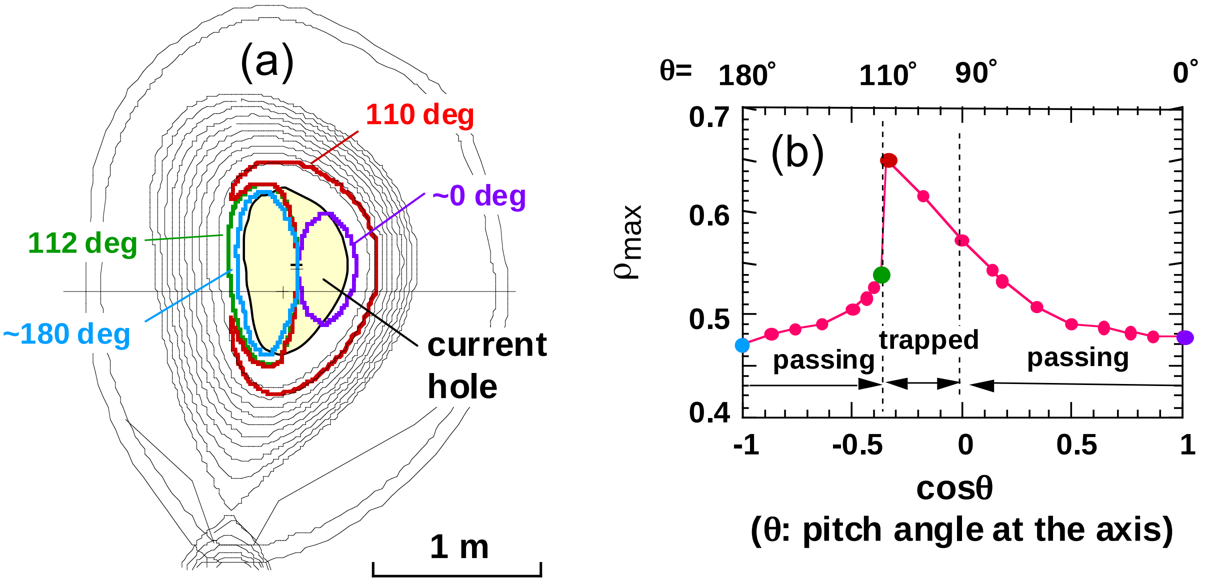


Fig.4. (a) Deuterium ion orbits with temperature 8keV and different pitch angle at the magnetic axis. (b) Maximum radial excursion of ions with different pitch angle started from the magnetic axis.

We also have the case that the shoulder in T_i is located at $\rho \sim 0.45$ while the width of largest banana of thermal ions is $\rho \sim 0.25$. This suggests that the location of shoulder is not directly related to the weak poloidal field or existence of the Current Hole.

To investigate the relation between weakness of poloidal field and radial transport, a non-axisymmetric error field was applied to plasma with the Current Hole. The radial component of the error field had a maximum value of ~40 Gauss in the plasma region, which is comparable to the poloidal field just outside the Current Hole. We expect that the radial transport, if it is determined by the weak poloidal field, is affected by the applied error field. Figure 5 shows the time evolution of ion temperatures at several locations. The error field was applied during quasi-steady phase with constant heating power. We find that the ion temperatures were hardly affected by the error field. No large responses were either observed in T_e, n_e, V_ϕ (toroidal rotation of carbon ions) and MSE polarization angle (poloidal field). It shows that the radius of the Current Hole is not determined by the error field.

The density fluctuation in the flat density region (different shot), which is evaluated by the reflectometry measurement, is about one order of magnitude smaller than that at the ITB region [4]. Small density fluctuation in the flat density region suggests that nearly flat electron temperature profile may not be the result of anomalous transport, but may be the result of larger q(0) value (q(0)>100). Since it is not found a clear effect of the error field on confinement, the confinement region with small B_p (outside of the Current Hole) may be determined by the anomalous transport. Further studies are necessary to conclude these explanations.

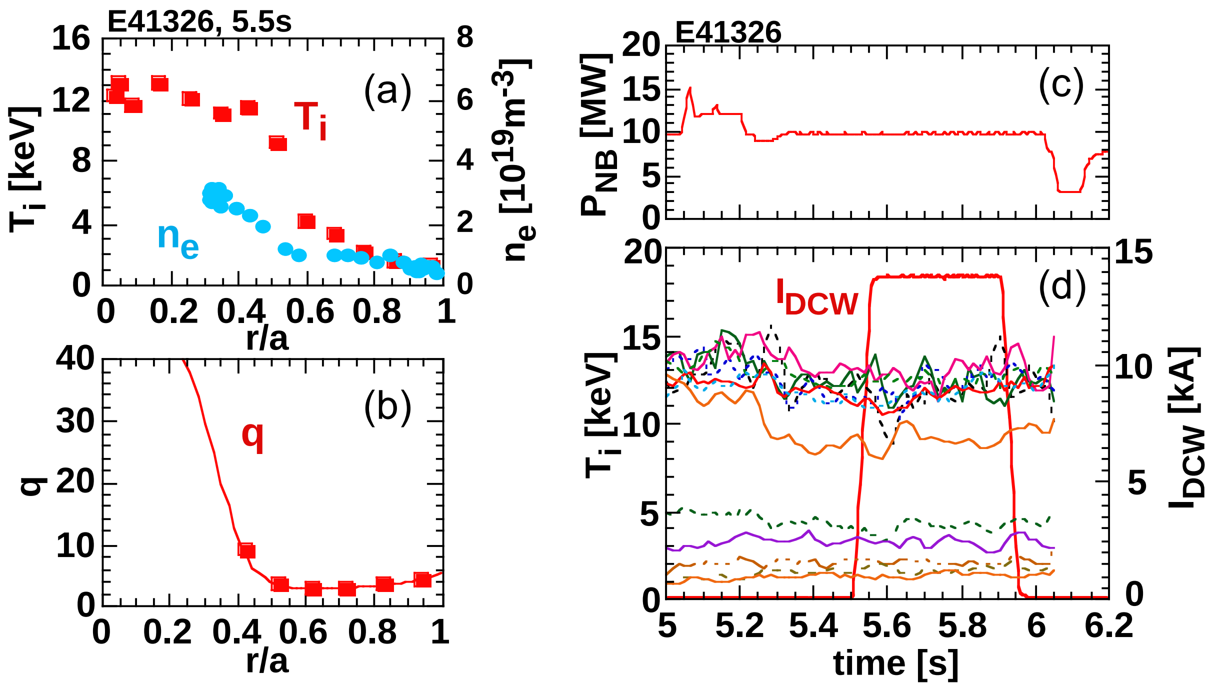


Fig.5. Application of an error field (DCW) to the Current Hole I_P =1.4 MA, B_t =3.7T q_{95} = 4.4 β_N~0.8. (a) Ion temperature and electron density profile. (b) Safety factor profile. (c) Time evolution of NB power. (d) Time evolution of ion temperature at several points and DCW coil current.

4. Response of the Current Drive inside the Current Hole

One of the interesting points is that no substantial negative current in the central region was observed so far. This suggests the decrease of central current caused by the growth of off-axis bootstrap current stops and does not go below negative when the central current becomes zero. On the other hand, in the discharge shown in Fig. 2, ECH was injected tangentially and a non-inductive current by ECH was expected. The driven current by the injection of 0.75 MW ECH is estimated 44 kA and localized inside ρ = 0.2 according to the analysis using a ray-tracing Fokker-Plank code. This current would have generated poloidal fields of $B_p/B_t \sim 0.010\text{-}0.014$ at three MSE channels at ρ = 0.17, 0.27 and 0.37. However, as shown in Fig. 2 (c), these poloidal fields are not detected during ECH. In Fig. 6, compared with the change of MSE measured pitch angle for the case with finite current, no change of the pitch angle by ECH is observed in the Current Hole. Even the central electron temperatures are high in both cases and around 6 keV, the constant pitch angle in the Current Hole is not explained by the delay of current penetration. These observations show the existence of the mechanism to keep nearly zero current in the central region. Recently, Huysmans et al. proposed the influence of a resistive kink MHD instability as the mechanism of the zero central current density and the absence of negative central current [5]. However, since no global MHD activity is observed in JT-60U, it may not explain the observation in JT-60U result, or the expected MHD instability is too small to detect.

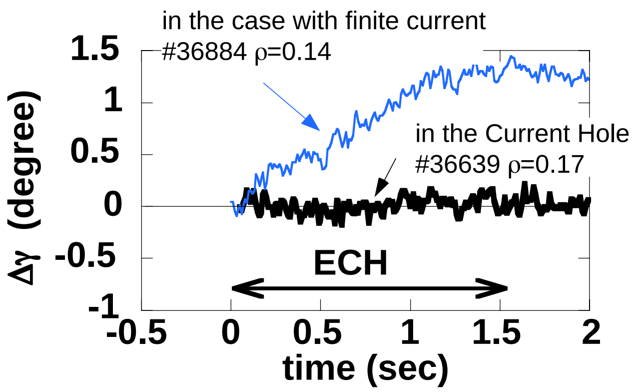


Fig.6. Waveforms of MSE measured pitch angle. Thick line shows the case with Current Hole and thin line shows the case with finite current of about 0.3MA/m² at the center. The time of zero is the start time of ECH.

5. Summary

In JT-60U experiment, the Current Hole state, which is characterized with nearly zero central toroidal current density, is found. The Current Hole region extends to 40% of the plasma minor radius and it exists stably for several seconds. The Current Hole is formed by the growth of the bootstrap current. In that region, there is almost no gradient of density, temperature and toroidal rotation velocity. The radial excursion of ion orbit is very large and the ion orbit is not kept inside the Current Hole. It is different from electron orbit with q(0)=100 which is well confined within the Current Hole. Those results suggest that large anomalous transport exists or q(0) is much larger than 100. The EC current drive experiment shows that it is impossible to drive current in either positive or negative direction inside the Current Hole. And it is not found the clear effect of the error field (Br~40G). It means that there is mechanisms to clamp the central current density nearly zero and the radius of the Current Hole is not determined by the error field.

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