

## Formation and Sustainment of Current Hole in JT-60U

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### 1. Introduction

Existence of a nearly zero current density region (a “current hole”) has been proved in JT-60U and JET tokamaks recently [1,2]. In JT-60U, a current hole with a normalized radius of  $\rho > 0.25$  was maintained for 4-5 s ( $\sim 10\tau_E$ ) without any global MHD instabilities [1]. In a typical discharge with  $q_{95} \sim 5$ , the radius of the current hole extended up to  $\sim 40\%$  of plasma minor radius and the absolute value of safety factor at the axis,  $q(0)$  was estimated to be greater than 70. The decrease in the inductive toroidal electric field  $E_\phi^{\text{ind}}(\rho)$ , which is caused by the increase of the off-axis non-inductive current, is a cause of the formation of the current hole. Though the temperature and density profiles were extremely flat in the current hole, internal transport barriers (ITBs) were formed outside the current hole, and high temperature plasmas with  $T_i(0) > 10$  keV were confined in the current hole by ITBs. These observations imply the possibility of stable operation of tokamaks with no toroidal current at the axis. There remain many things unresolved on the current hole, which are important from the viewpoints of both plasma physics and application to a reactor. In this paper, relation between the current hole and flat profiles inside the ITB layer, compatibility of current hole with a high performance plasma, and anomalous response of current hole to ECCD are discussed.

### 2. Particle orbit and relation to the location of ITB shoulder

In reversed shear plasmas with strong ITBs, a box-type shape of temperature profiles is often observed, where a flat portion exists around the axis or inside the ITB layer [3]. The point connecting the flat portion and the steep gradient region (ITB layer) is called an ITB ‘shoulder.’ One may suppose that the appearance of the flat portion, which implies very poor confinement there, is related to the existence of current hole. Since the poloidal field is very weak in and just outside the current hole, it is expected that the radial shift of particles from the magnetic surface is large. The orbits of thermal ions with 8 keV, which is equal to the central ion temperature in a plasma shown in Fig. 2 in ref. [1] are calculated and shown in Fig. 1 (a). Here, the ion orbits are traced from the magnetic axis varying the pitch angle of velocity. In the current hole region, ions move almost vertically due to the 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. 1 (b). The largest banana width is as large as 65% of the plasma minor radius and any particle starting from the axis reaches  $\rho = 0.47$ . This implies that the poor ion confinement is expected in the region inside  $\rho = 0.47$ . This position is almost equal to the ITB shoulder in this plasma as shown in Fig. 2 (d) in ref. [1]. 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  $q(0) = 100$ . This implies that anomalous transport

exists or  $q(0)$  is much larger than 100. 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 current hole.

To investigate the relation between weakness of poloidal field and radial transport, a non-axisymmetric error field was applied to a plasma with a current hole. The error field had a maximum value of  $\sim 40$  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 2 shows time evolution of ion temperatures at several locations. The error field was applied during a 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  $T_e$ ,  $n_e$ ,  $V_t$  (toroidal rotation of carbon ions) and MSE polarization angle (poloidal field). This supports that the position of ITB shoulder is not determined by large orbits of ions or electrons in a weak poloidal field but by other mechanisms (turbulence). It is also noted that the radius of current hole was not determined by error fields.

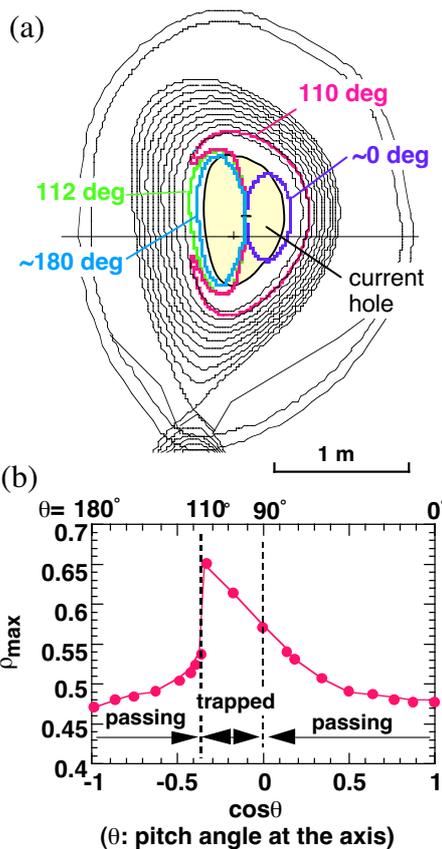


Fig. 1 (a) Orbit of thermal ions projected onto the poloidal cross section passing through the center of the current hole. (b) Radial extent reached by each orbit as a function of pitch angle at the axis.

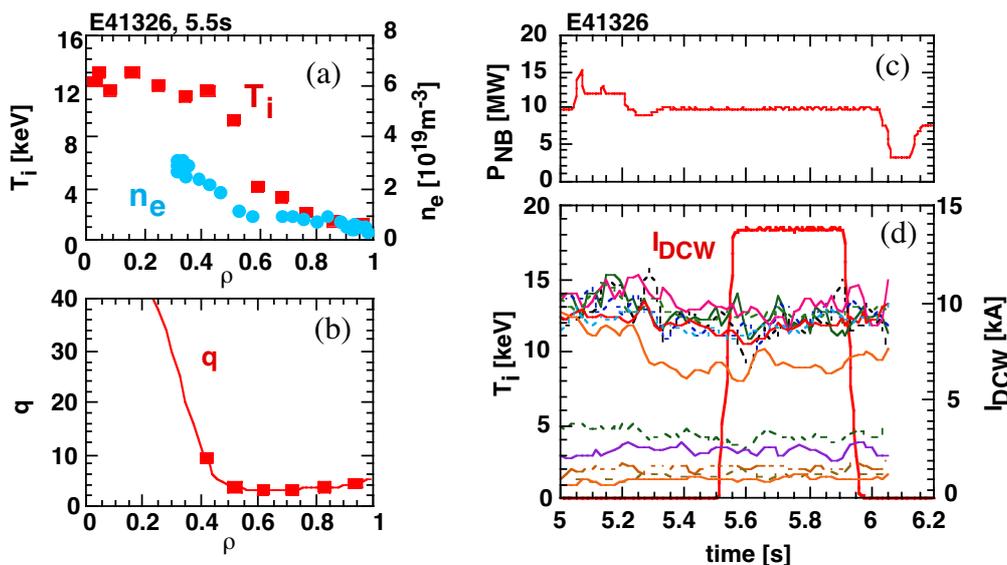


Fig. 2. Application of error field to a current hole. (a) Radial profiles of ion temperature and electron density. (b) Radial profile of  $q$ . (c) Time evolution of NB power. (d) Time evolution of ion temperature at several points and coil (DCW coil) current for error field generation.  $I_p = 1.4$  MA,  $B_t = 3.7$  T,  $q_{95} = 4.4$ ,  $\beta_N \sim 0.8$ .

### 3. Current hole in a high performance plasma

It was observed that the current hole was maintained for 5 s in a plasma with  $I_p = 1.35$  MA and  $q_{95} = 5.2$  [1]. In JT-60U, high fusion performance ( $Q_{DT}^{eq} > 1$ ) was obtained in a higher  $I_p$  ( $> 2.5$  MA) reversed shear plasmas [4]. The  $q$  profile of those plasmas was measured and reconstructed with the upgraded MSE system and equilibrium code. The profiles of MSE polarization angle,  $T_i$ ,  $T_e$ ,  $q$  and  $j$  are shown in Fig. 3. The polarization angle, which is proportional to  $B_z/B_t$ , is very close to zero near the axis and the existence of current hole with a normalized radius of 0.3-0.35 was confirmed as shown in  $q$  and  $j$  profiles in Fig. 3 (b). In this discharge, the  $T_e$  ITB and the current hole were established by EC injection in a low  $I_p$  phase with a limiter configuration and they were maintained during  $I_p$  ramp. The discharge terminated in a disruptive beta collapse when  $q_{min}$  became less than 2. Just before the collapse we achieved the plasma stored energy = 8.3 MJ, DD neutron production rate =  $4.6 \times 10^{16}$  /s,  $\beta_N = 1.6$ ,  $\tau_E = 0.89$  s,  $H_{89} = 3.0$  and  $Q_{DT}^{eq} = 1.2$  with  $I_p = 2.60$  MA and  $q_{95} = 3.3$ . Hence it was confirmed that the current hole was compatible with a high  $I_p$ , low  $q$ , high performance plasma.

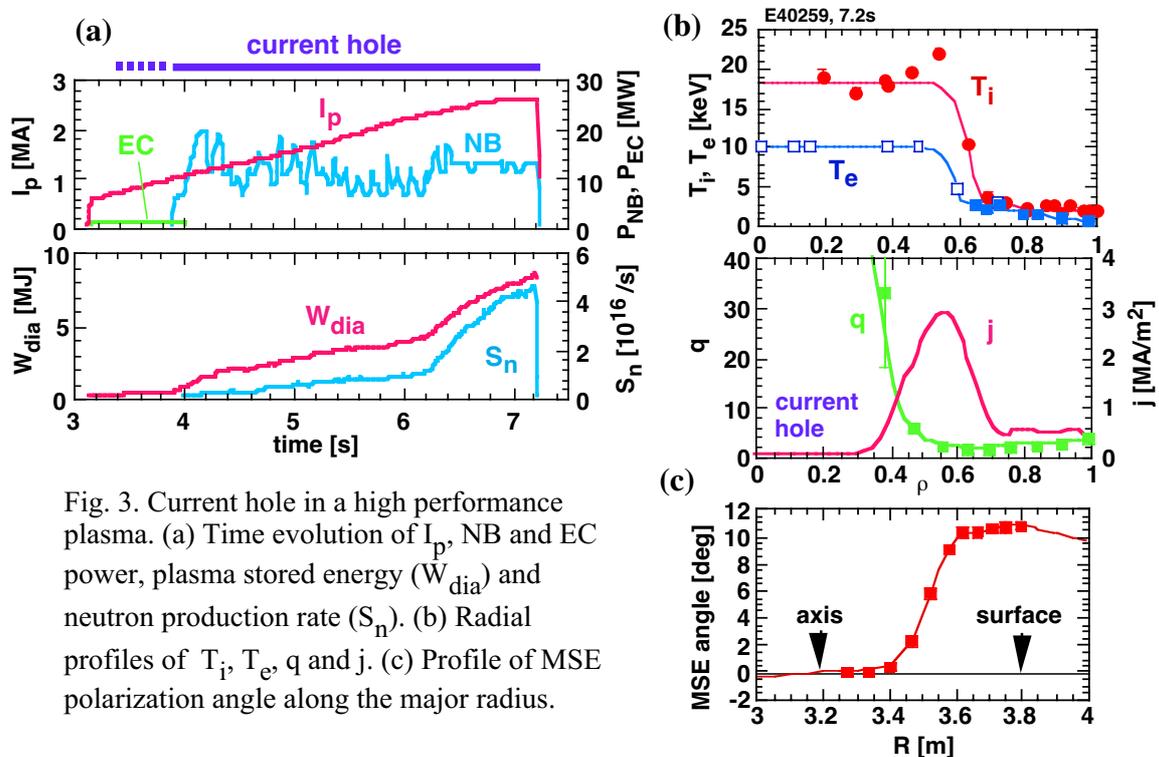


Fig. 3. Current hole in a high performance plasma. (a) Time evolution of  $I_p$ , NB and EC power, plasma stored energy ( $W_{dia}$ ) and neutron production rate ( $S_n$ ). (b) Radial profiles of  $T_i$ ,  $T_e$ ,  $q$  and  $j$ . (c) Profile of MSE polarization angle along the major radius.

### 4. Anomalous response to ECCD and current clamp

The response to ECCD into the current hole was investigated. The  $j$  profiles before and during ECCD were shown in Fig. 4 for (a) a plasma without a current hole and (b) a plasma with a current hole. The plasma configuration and injection angle of EC wave were the same for both cases. The electron density and temperature were also similar;  $n_e(0) = (1.3-1.4) \times 10^{19}$  m<sup>-3</sup> and  $T_e(0) = 5.6-5.8$  keV. In Fig. 4 (a), an off-axis peak due to the EC-driven current was observed in the  $j$  profile as predicted by the ray-tracing and Fokker-Planck calculation [5] within 0.5 s after the start of EC injection. On the other hand, when EC wave was injected into a current hole, no peaked current density was observed at the location predicted by the code (chain-dotted curve) as shown in Fig. 4 (b). This indicates clearly that

radial confinement of electrons is absent in the current hole, as suggested by a flat  $T_e$  profile. However, even if a uniform  $j_{EC}$  is generated in the current hole, the current density will become  $0.22 \text{ MA/m}^2$  as shown in Fig. 4 (b) and it should be detected by the MSE measurement. Absence of this current suggests that  $j$  is clamped at zero in the current hole, though further analysis including  $E_\phi^{\text{ind}}(\rho)$  is required to estimate the generated driven current.

It is also noted that no significant negative  $j(0)$  has been observed so far. This fact implies that  $j(0)$  cannot be negative for some reasons though  $E_\phi^{\text{ind}}(0)$  may be negative. At least the result of Fig. 4 implies that the picture that both of  $E_\phi^{\text{ind}}(0)$  and  $j(0)$  are zero in the current hole is improbable; if so changes in the  $j$  profile should be caused by ECCD. These observations of clamping  $j(0)$  at zero level suggest that the current hole is not a result of a transient zero  $E_\phi^{\text{ind}}(\rho)$  near the axis, but rather of some kind of self-organized structure. A resistive kink instability was proposed to explain the absence of negative  $j(0)$  [6], but this is unlikely to be the case in JT-60U where no MHD instabilities are observed.

## 5. Summary

The radial displacement of ion orbit can be quite large ( $\sim 0.5a$ ) due to the small poloidal field in the current hole. However, it is found that the location of ITB shoulder is not directly related to the weak poloidal field from the facts that the ITB shoulder can be located far away from the width of central banana of ions and that temperature profiles were not affected by error fields. The current hole was found in a high  $I_p$  (2.6 MA), low  $q$  ( $q_{95} = 3.3$ ), high performance ( $Q_{DT}^{\text{eq}} = 1.2$ ) plasma and the compatibility of current hole with such plasmas has been confirmed. When ECCD was applied in the current hole, peaked current density was not established. This indicates clearly absence of radial confinement of electrons in the current hole. Not only a peaked current but also a uniform current was not generated in the current hole. This suggests that the current density is clamped at zero in the current hole.

## References

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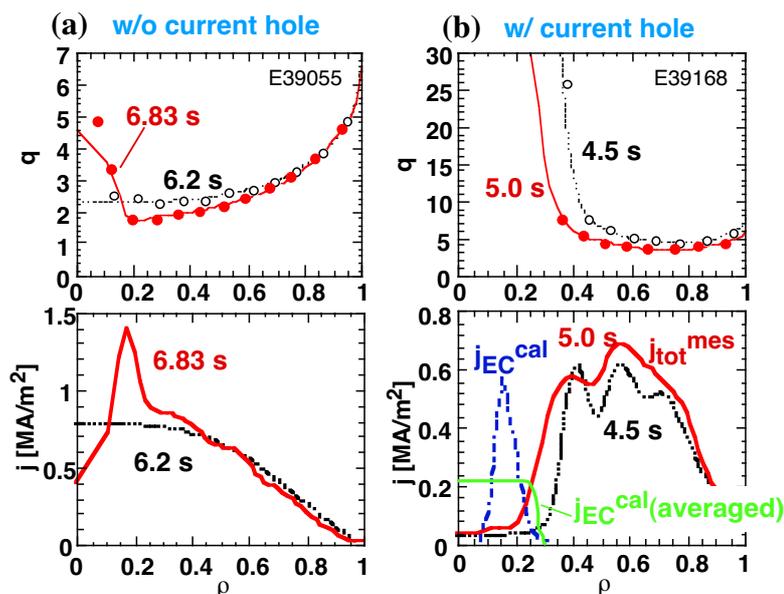


Fig. 4. Response to ECCD in plasmas (a) without and (b) with a current hole.