Formation and sustainment of tokamak equilibrium with a current hole in JT-60U

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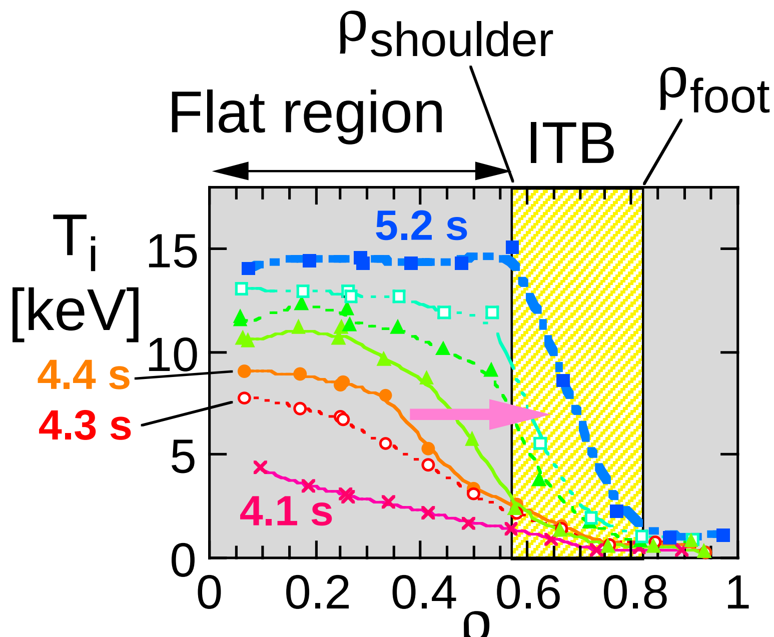
Introduction

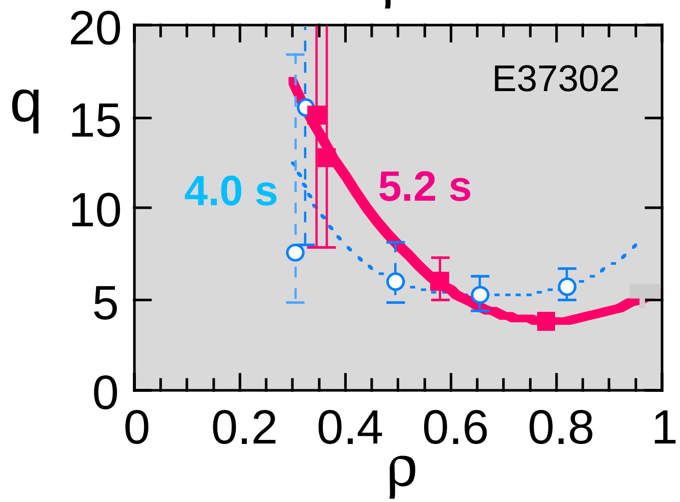
In JT-60U reversed shear plasmas,

The MSE data indicate q(0) is very high (B_p is very low in the central region).

Since the confinement of particles in toroidal systems depends on the poloidal field, it was an important issue to evaluate how high q(0) was.



However, the resolution of MSE was insufficient to address this issue, because the error in q becomes large by nature near the axis where B_p/B_t is small.



The MHD equilibrium code was unable to deal with a high q(0) equilibrium.

→ **Improvement in MSE and equilibrium code**

Improvement in MSE

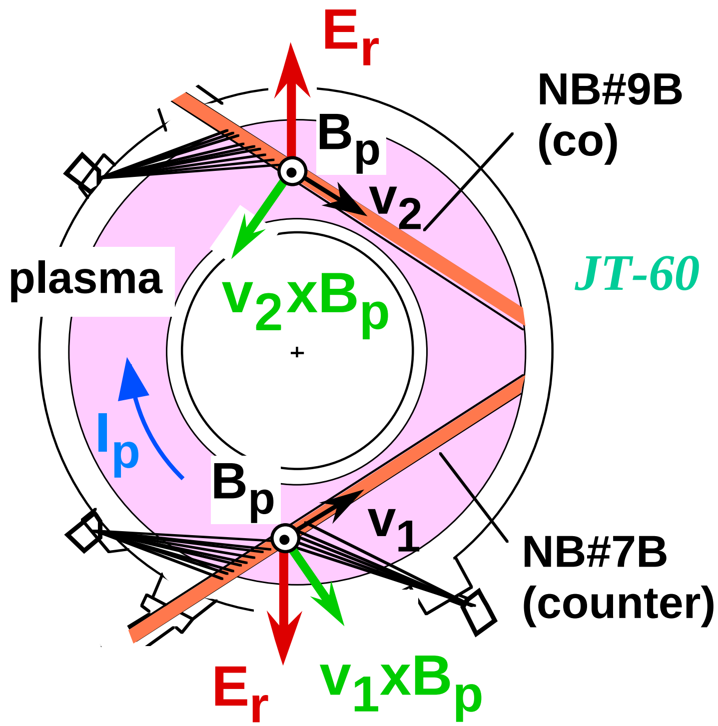
(1) Correction of E_r effects (E_r measurement)

MSE measures the direction of
$E_{tot} = E_r + vxB$

Conventional MSE views one of counter-tangential beams.

New MSE system viewing one of co-tangential beams was installed in 2000.

From E_r+v_1xB and E_r+v_2xB,
E_r and B (B_p) can be separated.



(2) Improvement in calibration (correction of changes in mirror properties)

Dielectric multilayer mirrors are used in MSE.

Their polarization properties depends the temperature, which is raised to ~70 degC during the experiment (300 degC VV).

Calibration was done heating up the mirrors to same temperature.

Improvement in MHD equilibrium code

Generation of various current profiles has become possible to fit MSE data by following improvements.

(1) Function for j(r) (dp/dψ, FdF/dψ) is changed from a polynomial of ψ (poloidal flux) to a spline of ρ (normalized radius).

(2) Introducing a deceleration factor in the iteration of Grad-Shafranov equation solver.

Grad-Shafranov equation;

$$-\Delta^*\Psi = \mu_0 R j(R, \Psi)$$

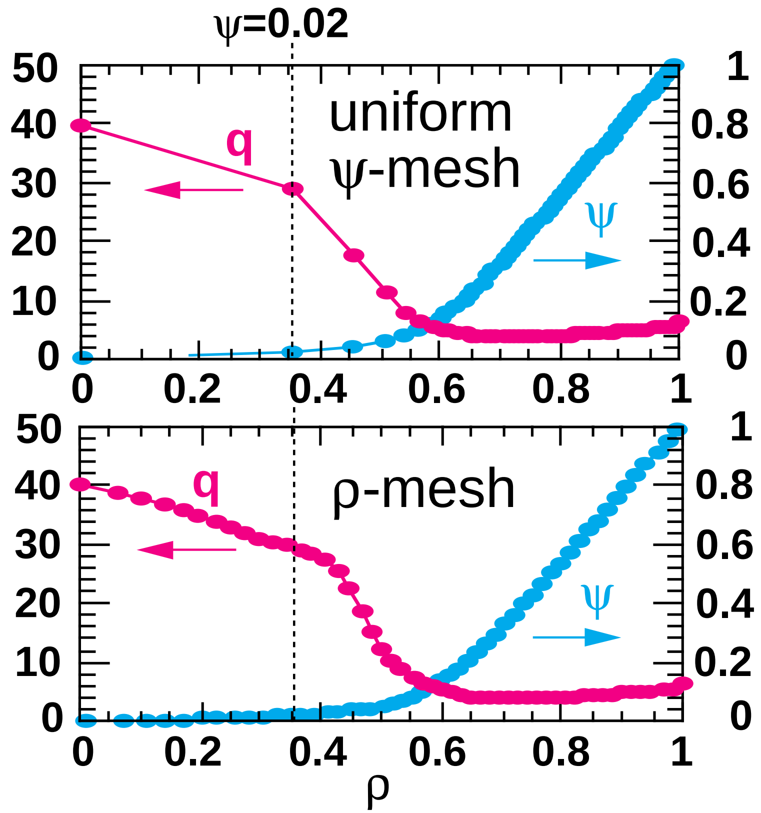
$$j(R, \Psi) = Rp'(\Psi)+(1/\mu_0 R)*F(\Psi)F'(\Psi).$$

In an equilibrium with high q(0), Ψ is not a proper parameter to specify a position.

$Y(\Psi)$ [$=p'(\Psi)$ or $F(\Psi)F'(\Psi)$] is represented by a third-order spline function of ρ, $g(\rho)$;

$$Y(\Psi) = g(\rho(\Psi)).$$

$Y(\Psi)$ or $\rho(\Psi)$ is evaluated on a mesh in a real space (~ρ) NOT in a Ψ space.



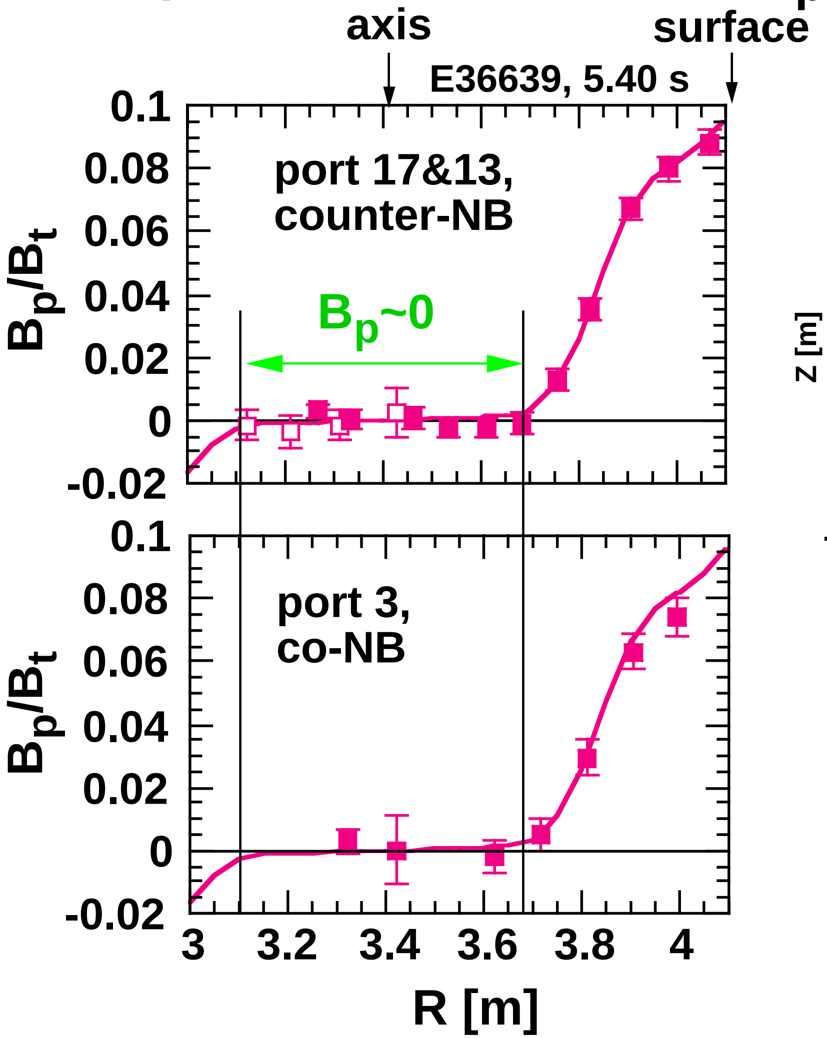
B_p~0 was observed in a central region

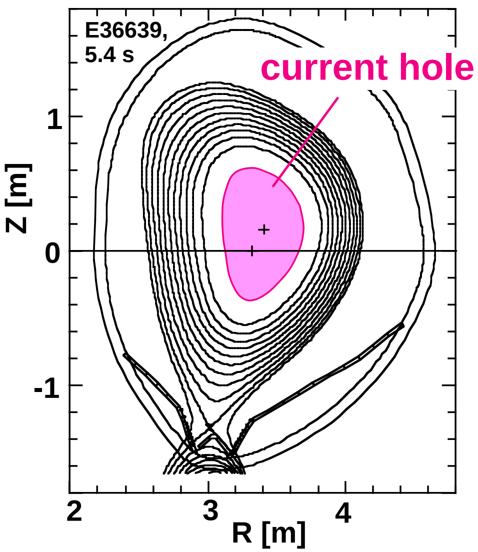
- **Projected angle was ~0 in a central region for both MSE viewing co and counter beams.**

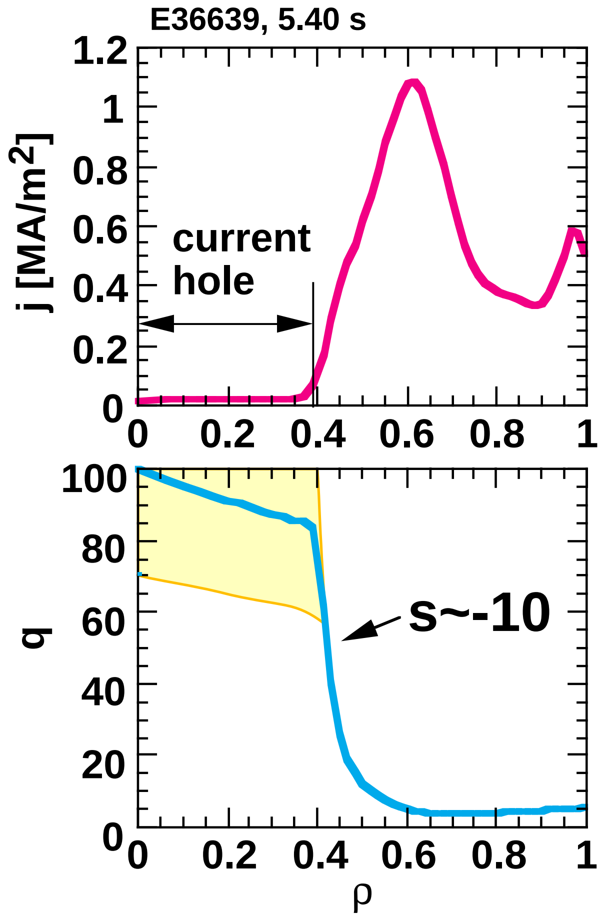
➡ E_r effect was small and B_p~0.

- **Equilibrium withq(0)~100 almost agrees with MSE data.**
- **Very small current in a central region; |j(0)| <~ 0.07<j>**

➡ "Current hole"







B_t = 3.7 T
I_p = 1.35 MA
q_{95} = 5.2

High temperature plasma in the current hole

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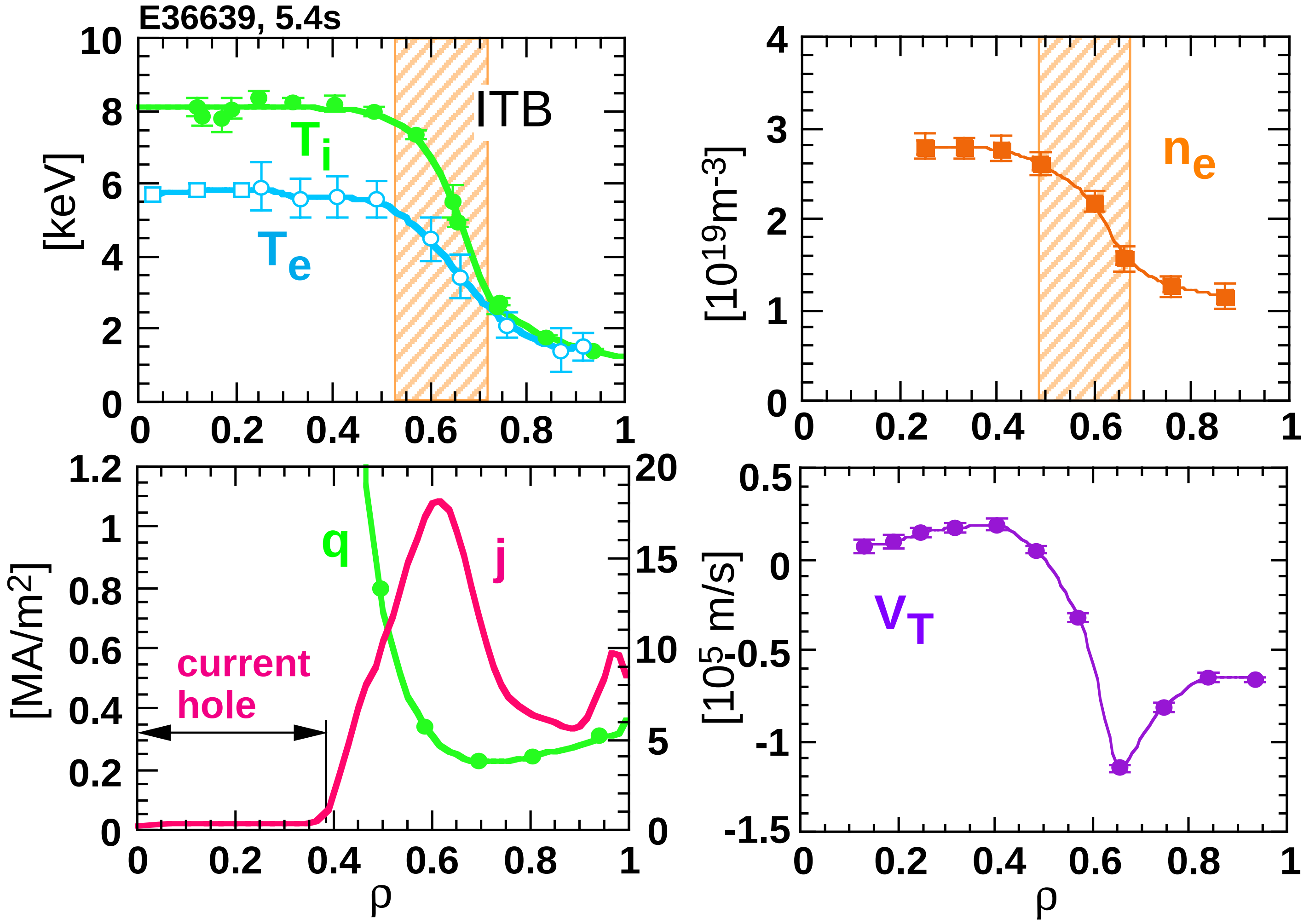
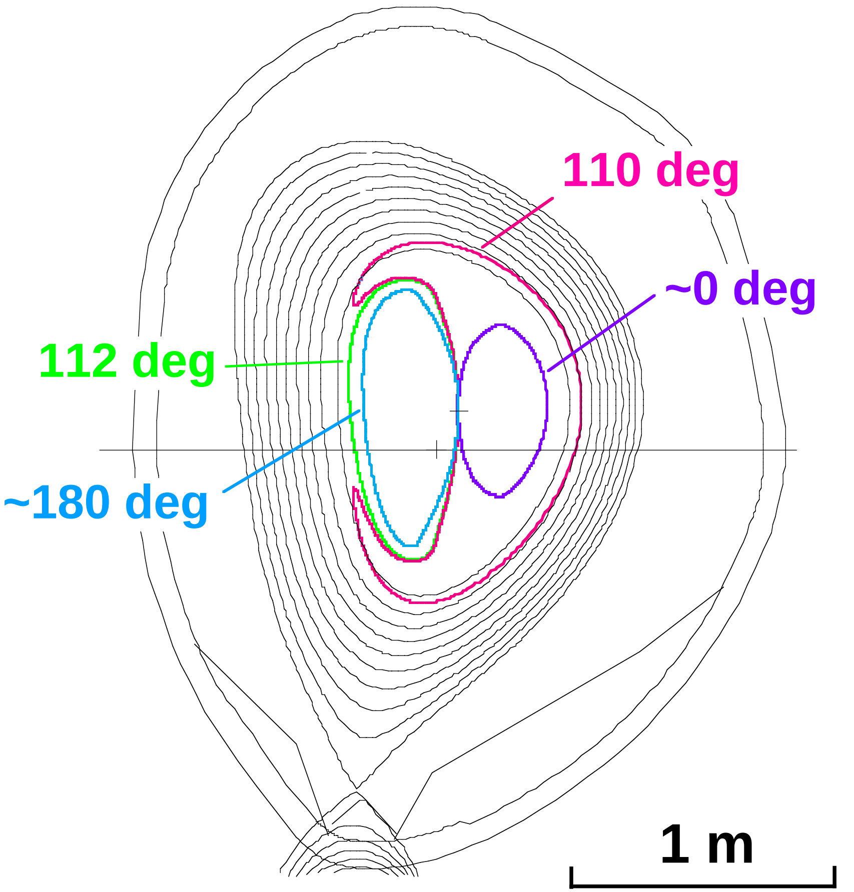
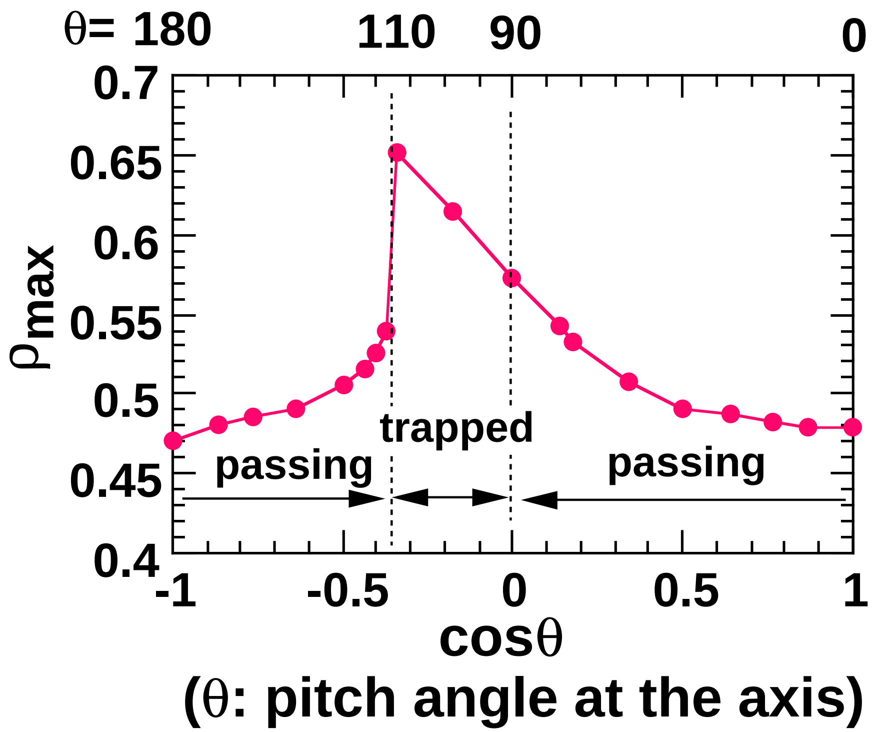
- **T(r) and n(r) are flat in the current hole, but steep gradients (ITBs) are formed outside the current hole where j(r) is peaked.**
- **High temperature plasmas can be confined in the central region only by B_p at a half radius.**



Orbit of thermal ions

- **Orbit of thermal ions with 8 keV (=$T_i(0)$), passing through the axis, was calculated using the equilibrium with q(0)=100.**
- **The largest banana extends to ρ~0.65.**
- **Even passing ions drift to ρ>~0.47 (~$\rho_{shoulder}$)**



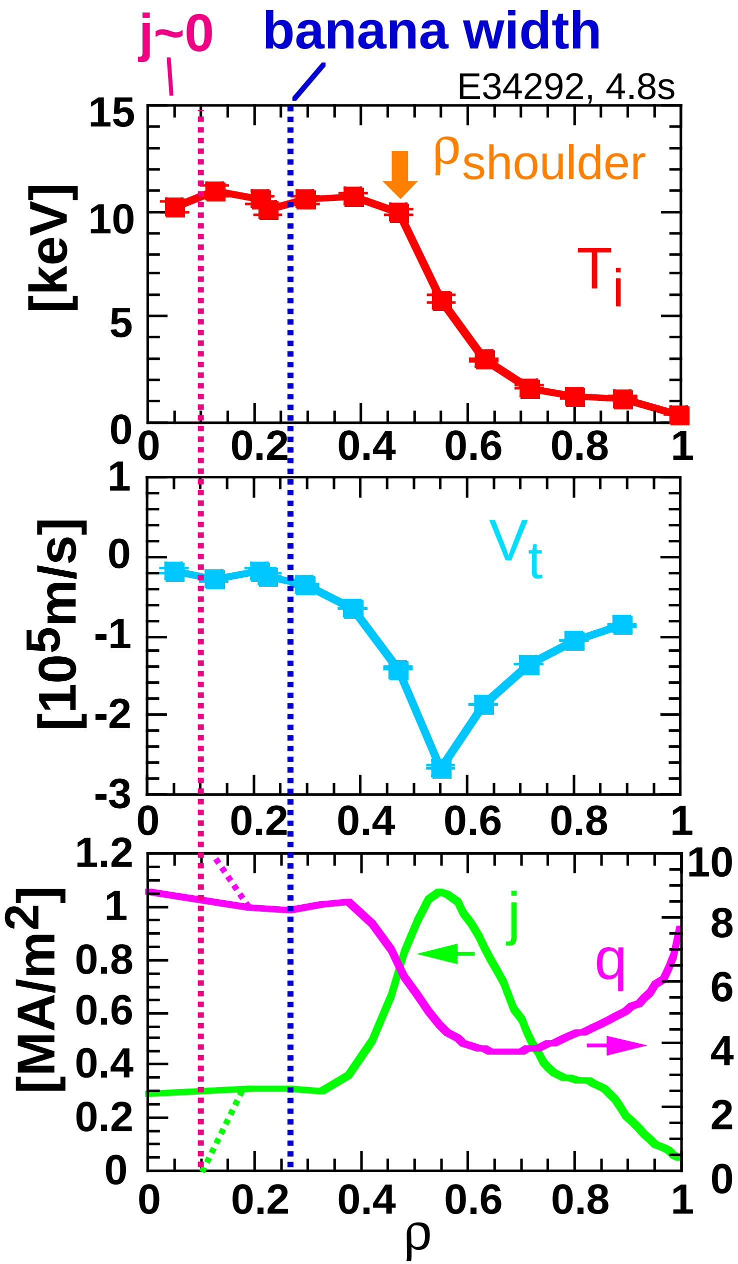


Shoulder radius can be larger than banana width

- **No current hole or small current hole with ρ<0.1 if any.**

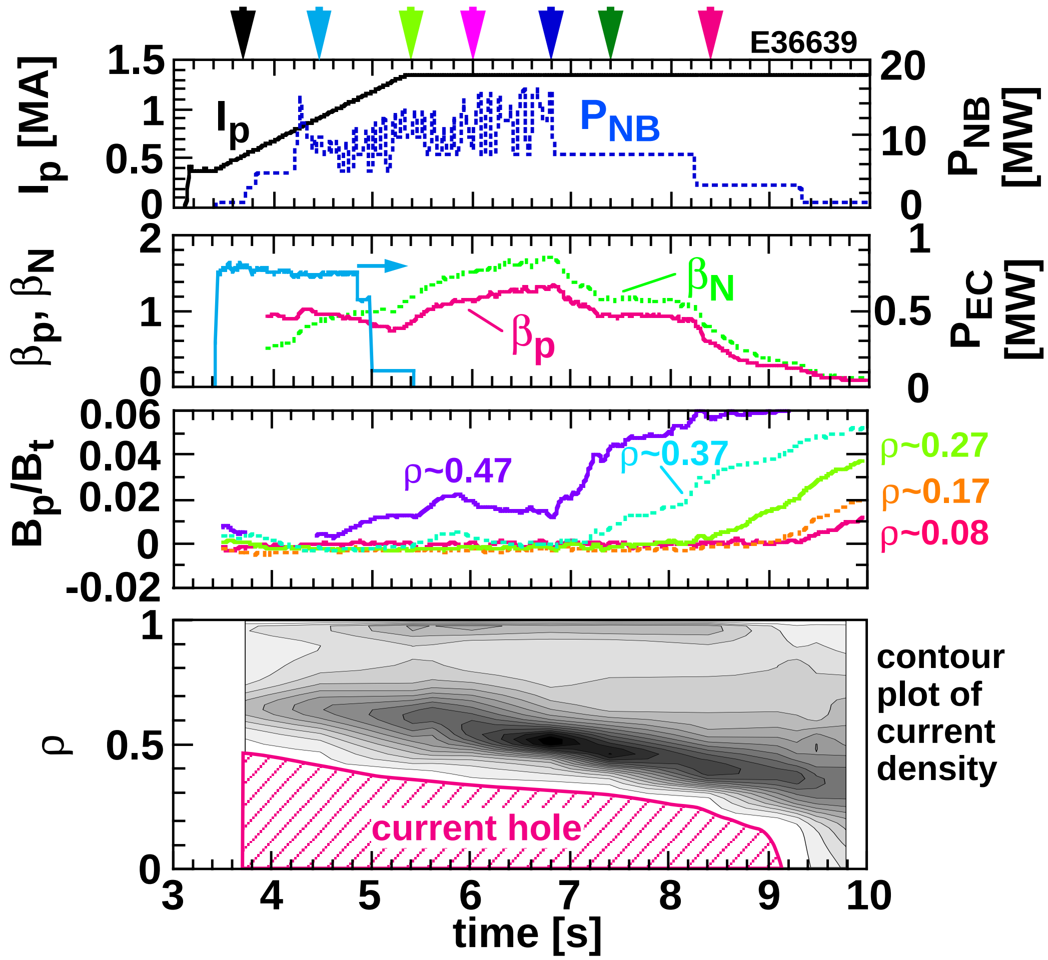
- **The width of largest banana of thermal ions is ρ~0.25 while $\rho_{shoulder}$~0.45.**

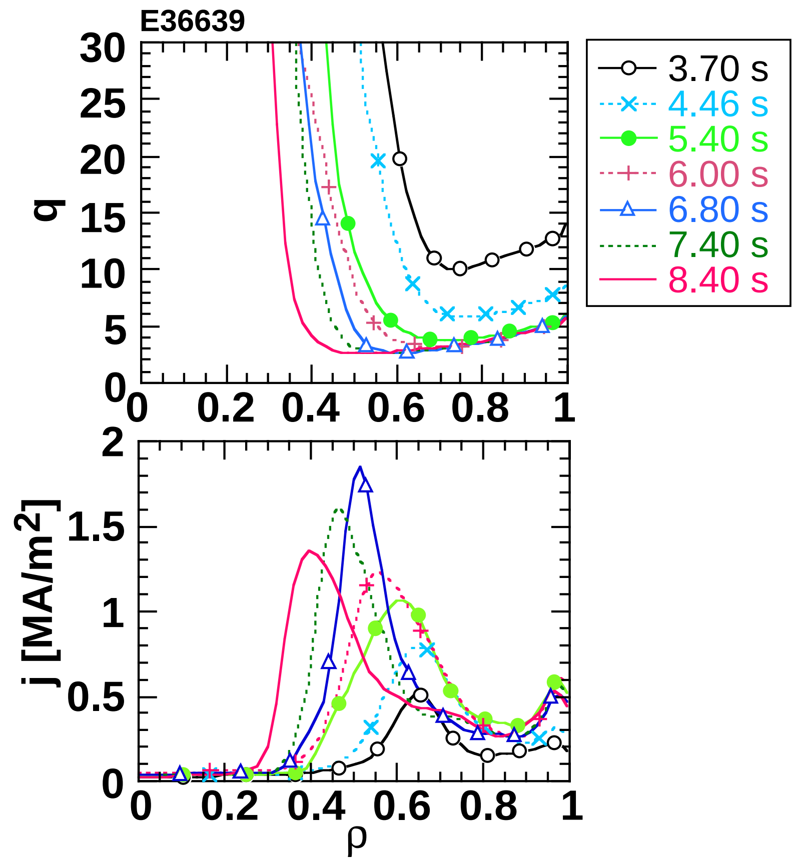
- **The radius of flat region of V_t is ρ~0.25 and equal to the banana width.**



Current hole was sustained stably

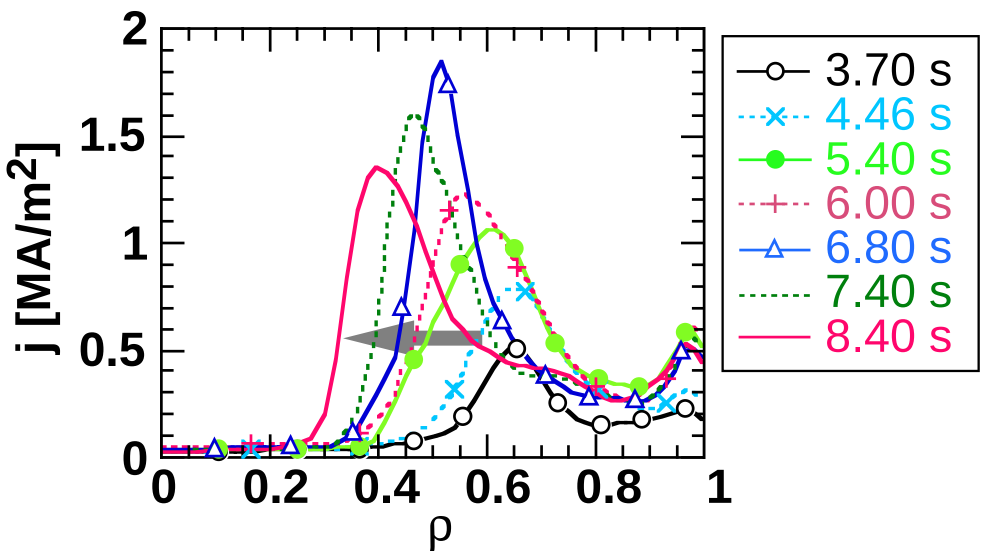
- **The current hole was sustained for ~5 seconds without any global instabilities though its radius continued to shrink due to the penetration of inductive current.**
- **High confinement (HH_{98y2}<~1.5) and moderate beta (β_N<~1.7) were obtained, suggesting possibility of stable operation of tokamak reactors without on-axis current.**

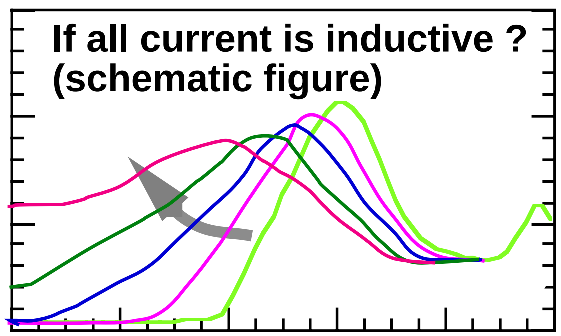




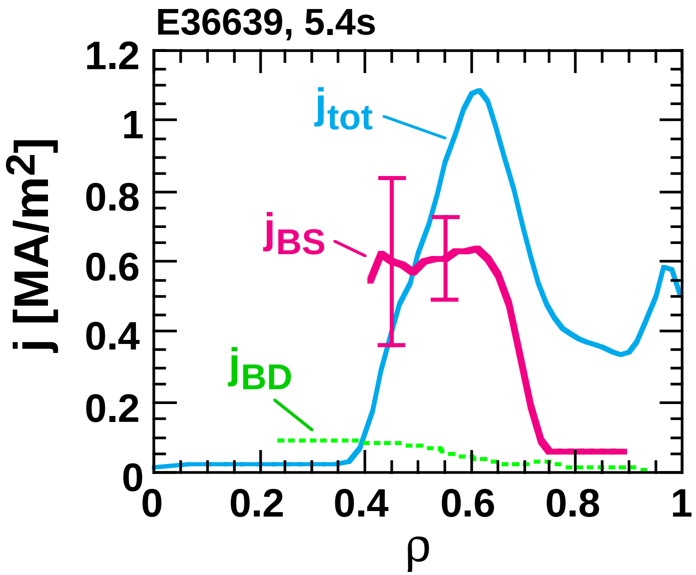
Bootstrap current is dominant around the current hole

- **While the peak of j moves inward, a steep gradient in j (scale length ~10 cm or 10% of minor radius) was sustained around the current hole.**
- **Since the current diffusion time for 10 cm is ~ 1.5 s, the gradient should decrease if all current is inductive one. ➡ non-inductive current**





- **Since B_p is small around the current hole, j_{BS} is large and comparable to the total current, while j_{BD} is small due to balanced NB injection.**



Formation of current hole (1)

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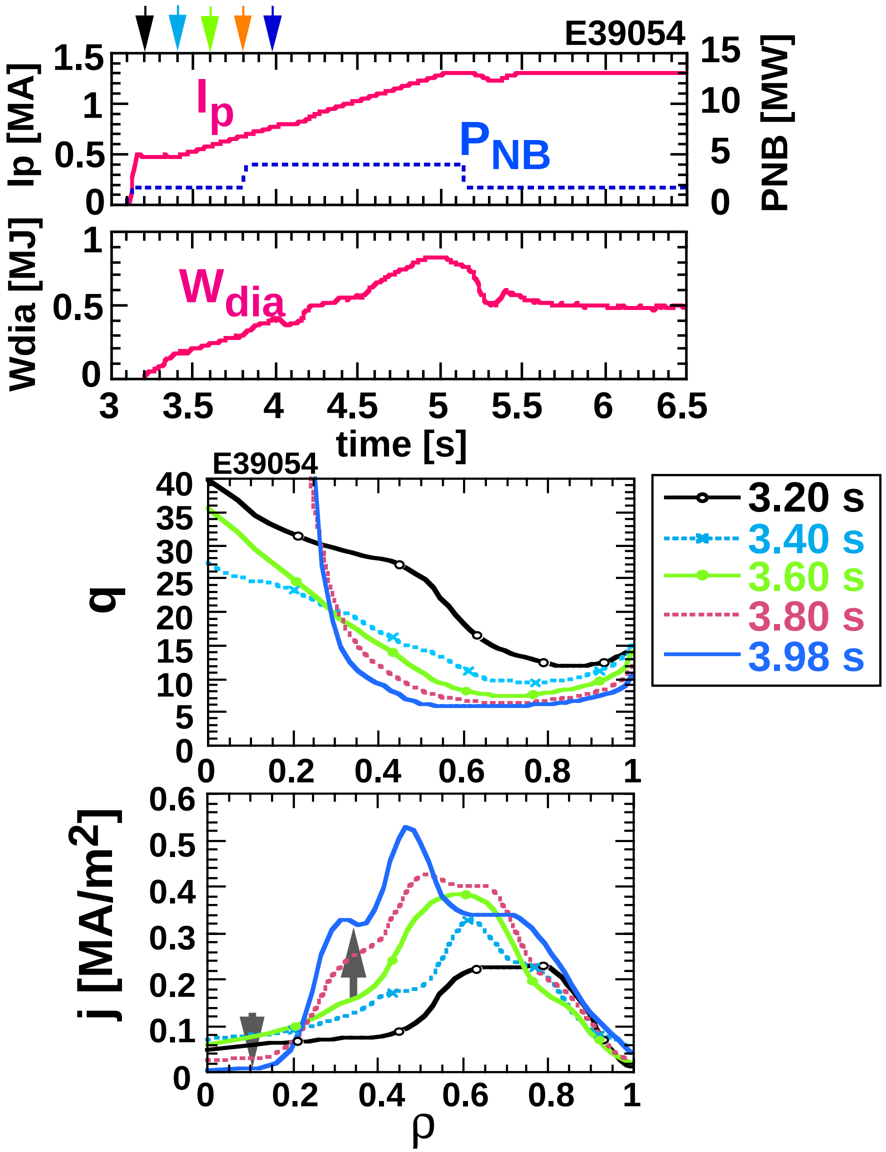
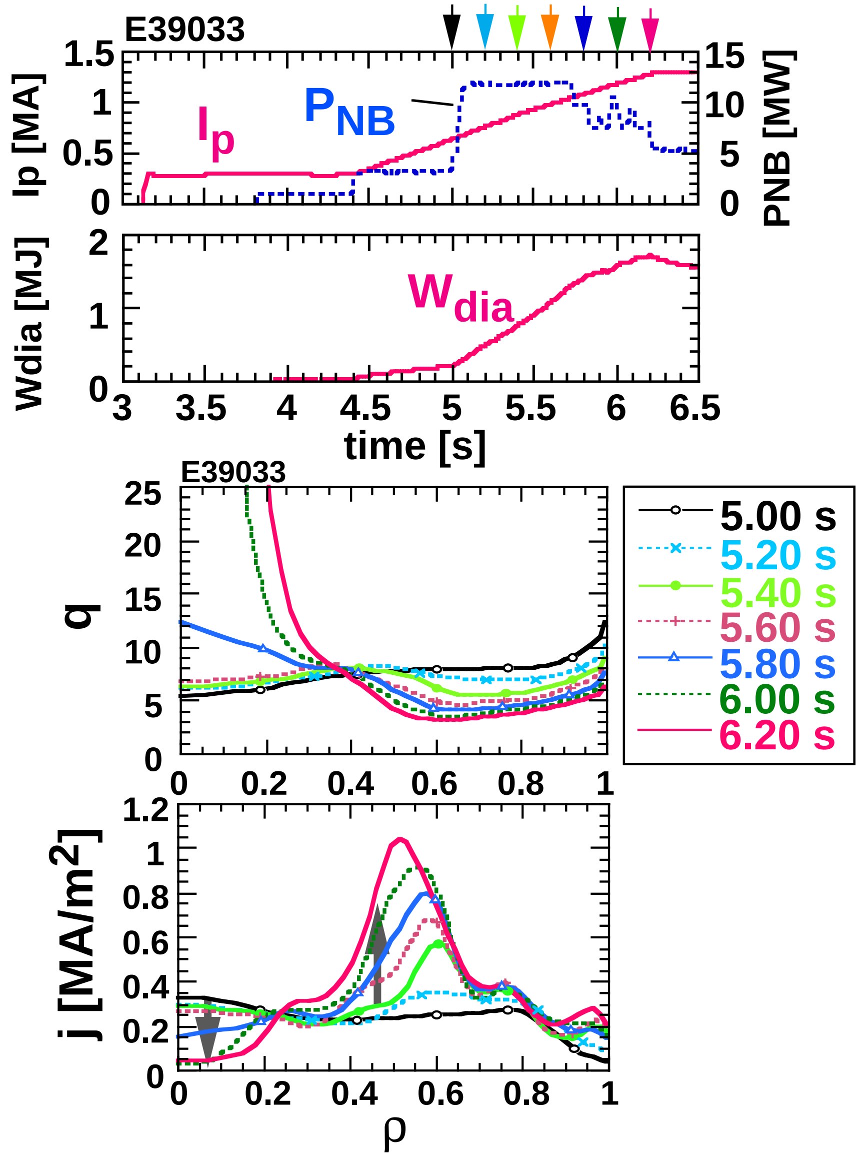
- **Central current started to decrease after the growth of off-axis current.**
- **No counter current drive is expected due to balanced NB injection.**





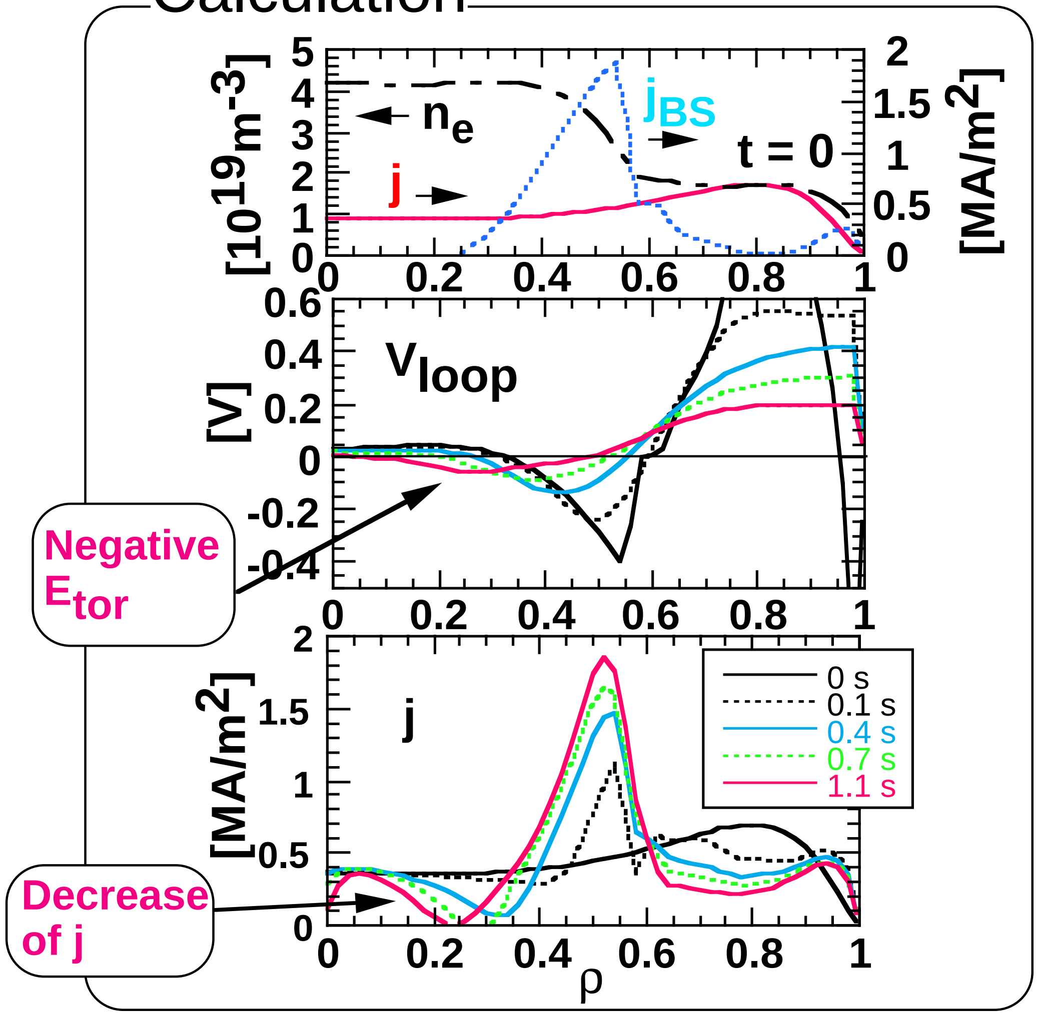
Formation of current hole (2)

- **Increase of off-axis non-inductive current generates (transient) negative $E_{toroidal}$, which penetrates into the central region and reduces j_{OH}.**

- **Since j_{NBCD} was small,**
  j_{BS} seems to be a cause.
  (In JET, j_{LH} produces current hole .)

[N. C. Hawkes et al., Phys. Rev. Lett. 87, 115001 (2001)]

Calculation



The central current is clamped at zero ?

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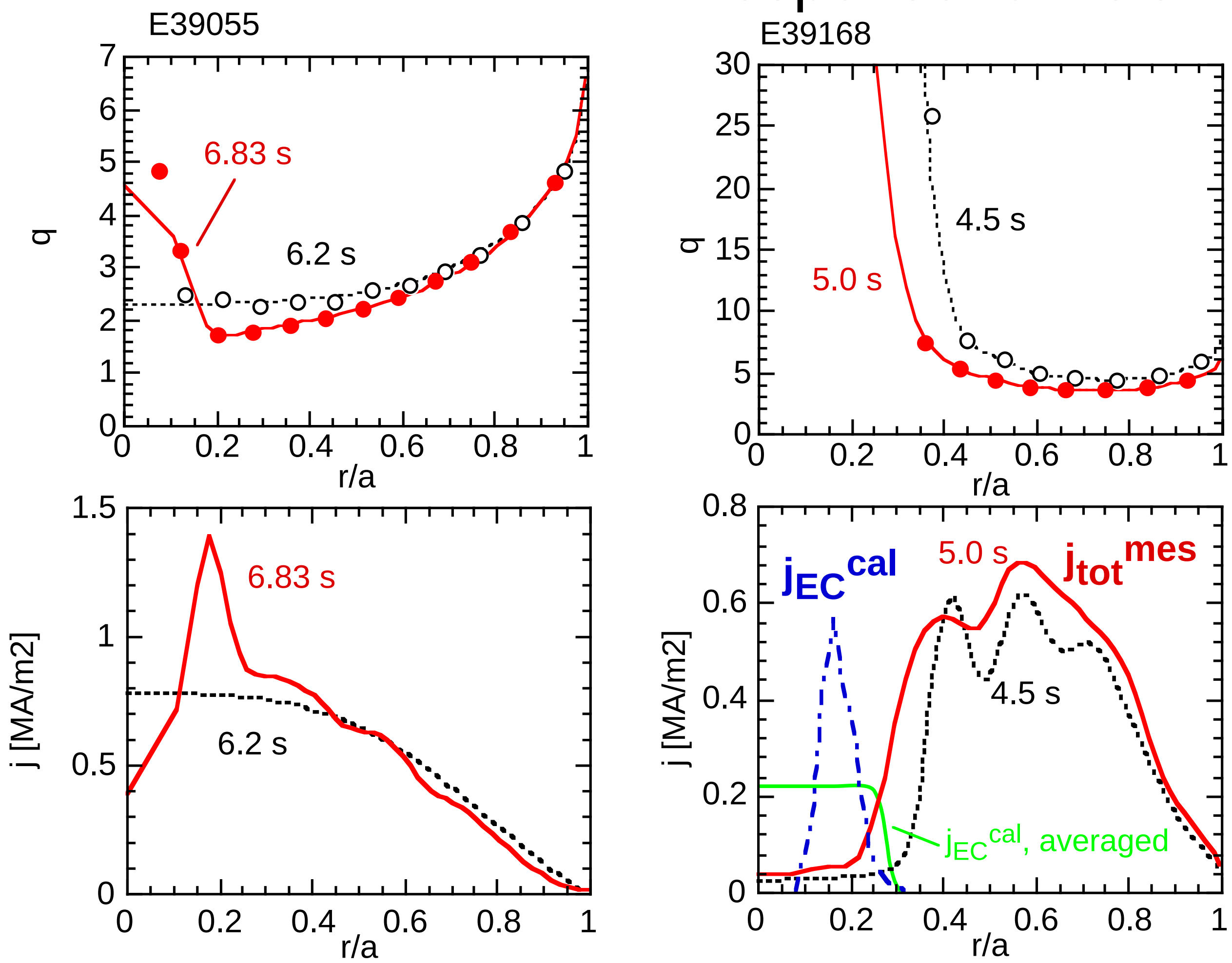
The negative j(0) may be produced through the transient negative $E_{tor}(0)$, but was not observed.

j(0) seems to be clamped at zero.

No driven-currrent was observed when EC was injected into the current hole.

Response to ECCD



The peaked j_{EC} profile may not be generated in a flat T_e region (no confinement of electrons). However, if a uniform j_{EC} is generated in the current hole, it should be detected (green curve).

What happens in the current hole ?

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Observation of clamping the central current density at zero for a several seconds seems to exclude

A) $j_{OH}=\sigma E_{tor}$ ~0 and j_{NI}~0 (j_{NI}: non-inductive current)

but suggest existence of some mechanism to keep j(0)~0 under following conditions

B) $\sigma E_{tor}+ j_{NI}$~0
(j_{BS} is automatically adjusted to cancel j_{OH}.)

C) $\sigma E_{tor}+ j_{NI}<0$ but j_{tot}~0 due to instabilities
(eg. Huysmans et al, PRL 87, 245002 (2001).)

D) $\sigma E_{tor}+ j_{NI} \neq 0$ but j_{tot}~0 once j_{tot} becomes zero.
(current cannot be driven in a torus without B_p or B_v)

To clarify which is the case (B or C or D), analysis of internal voltage or E_{tor}(r) is important and essential. However, even if E_{tor}(r) is known, it is not so easy to distinguish B/C/D because we have a large ambiguity in j_{BS} in a very low B_p region.

Summary

- **Equilibrium with nearly zero toroidal current in a central region or "current hole" has been observed to persist stably for several seconds.**

- **The radius of current hole extended up to 40% of plasma minor radius.**

- **A high temperature plasma was confined in the current hole and good confinement was obtained.**

- **The current hole was generated by a negatively induced toroidal electric field through the increase of off-axis bootstrap current.**

- **The current hole seems to be one of causes for formation of ITB shoulder, but other cause also exist.**

- **Clamping at zero current for several seconds and no response to ECCD suggest existence of some mechanism; anomalous resistivity or formation of self-organizing structure (reaching equilibrium limit).**