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Steady-State Operation Scenarios with a Central Current Hole for JT-60SC

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1. Introduction

Central "current hole" has been recently discovered in JT-60U reversed shear plasmas [1][2]. A central current hole region was a minor radius of r/a <0.4 at the maximum. Although the hole width gradually shrunk, the current hole has been stably kept for about 5 seconds without any global instabilities. Stable discharges with the current hole are potentially of interest as it may offer a significant impact on the development of non-inductive current drive scheme in tokamaks since the requirement for external sources of non-inductive current drive in the plasma centre such as a high energy neutral beam injector can be very much reduced. While such a discharge can be sustained with much lower energy of neutral beams than generally considered necessary or only off-axis non-inductive current drive mechanisms, the feasibility study of the non-inductive steady-state operation with a large bootstrap current fraction consistent to the current hole is important for experimental demonstration. The purpose of this paper is to study the feasibility of such an operation scenario to determine whether the scenario can be demonstrated in JT-60SC where the reactor-relevant plasma can be produced for a sufficiently long duration.

This paper presents the simulation analysis of the steady state current hole formation based on the 1.5D time dependent transport code and the stability analysis code performed for JT-60SC, which is designed to operate for more than 100s discharge.

2. JT-60SC Programme and Design

The superconducting tokamak, JT-60SC, to be modified from JT-60U is designed towards the establishment of steady-state high performance plasmas in deuterium with high normalised beta (β_N=3.5-5.5) in a regime of sufficiently low collisionality (ν*~0.01) and Larmor radius (ρ*~0.01), which are relevant to reactor plasmas [3][4]. Typical parameters of JT-60SC are summarised in Table 1. The current flat-top duration of 100 s exceeds a current diffusion time of ~30 s. The cross-sectional view of JT-60SC is compared with that of present JT-60U in Fig.1.

Table 1. Typical machine parameters of present JT-60U and JT-60SC

Parameter	JT-60U	JT-60SC
Pulse length	15 s	100 s (flat top)
Max. input power	40 MW (10 s)	44 MW (10s) 15 MW (100s)
Plasma current I_p	3 MA	4 MA
Toroidal field B_t	4 T	3.8 T (R_p=2.8m)
Major radius R_p	3.4 m	2.8-3 m (2.8m*)
Minor radius a_p	0.9 m	0.7-0.9 m (0.85m*)
Elongation κ_{95}	1.8 (δ_{95}=0.06)	≤ 2 (1.8*)
Triangularity δ_{95}	0.4 (κ_{95}=1.33)	≤ 0.5 (0.35*)

*Nominal

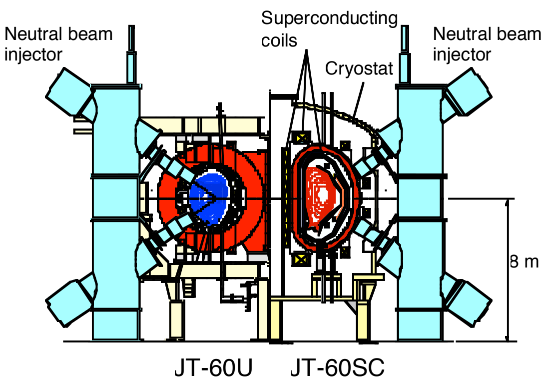

Fig. 1 Cross-sectional views of present JT-60U and designed JT-60SC.

3. Operation Scenario of Current Hole for JT-60SC

3.1 Plasma simulation with transport analysis code

In order to investigate whether a steady state operation with the current hole is feasible only by off-axis current drive schemes consistent with a high bootstrap current, the temporal evolution of the plasma current and the plasma profile is analysed by a 1.5D time-dependent plasma simulation code (TOPICS) from the current start-up phase to the flattop phase. Transport model of reversed shear configuration, which is described as a function of magnetic shear inside the plasma, is expressed as,

$$\chi_{e/i} = C_{e/i\,1}\,\chi_i^{NC} + C_{e/i\,2}\,(1+C_{e/i\,3}\,\rho^2)\,a^2\,E_{e/i}(s)\,/\,\tau_E^{y2},$$
$$E_{e/i}(s)= [\,1+\exp\{\,\alpha_{e/i}\,(\,s+\Delta_{e/i})\}]^{-1} + [\,1+\exp\{\,\alpha_{e/i}\,(\,s-\Delta_{e/i})\}]^{-1}, \qquad \text{(Eq.1)}$$

where $\chi_{e/i}$ and χ_i^{NC} are the electron/ion thermal diffusivity and the ion neo-classical diffusivity, s (=r(dq/dr)/q) is the magnetic shear, a is the minor radius, $C_{e/i1}$, $C_{e/i2}$, $C_{e/i3}$, are constant, and $\alpha_{e/i}$, $\Delta_{e/i}$ are the coefficient for the shear depth and width [5]. The quantity τ_E^{y2} is the confinement time deduced from IPB98(y,2) scaling. Power deposition of neutral beams is calculated by the Fokker-Planck code. The beam trajectry is illustrated in Fig.2. On the view point to simulate no current drive at the plasma centre, the scenario is investigated without the injection of the negative-ion based neutral beam, which is trapped mostly in the plasma centre and contributes to the central current drive.

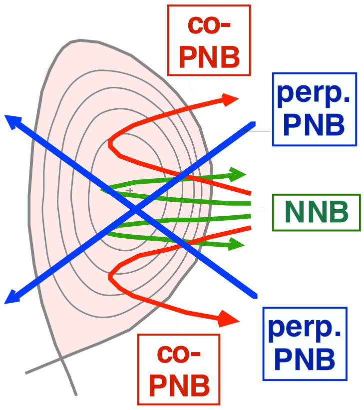

Fig. 2 Trajectory of the neutrall beams in the poloidal cross section.

Thermal and particle transport coefficients deduced from observations in JT-60U are used as a function of the magnetic shear, representing the formation of internal transport barriers near q-minimum. In order to form a reversed shear configuration observed in JT-60U, the shear parameters are set at α=4, Δ=0.7. The plasma current ramp-up rate is set at 0.4MA/s for the formation of reversed shear configuration on the basis of the discharge scenario of JT-60U. The target plasma parameters are I_p=1.5 MA, B_t=2 T and q_{95}=5 to achieve the β_N~4.

3.2 Formation of current hole

In Fig.3 the temporal evolution of the current fraction and electron, ion temperature is shown. Tangential off-axis positive neutral beams of 6.7MW is injected at the current ramp-up phase. With the additional injection of perpendicular positive neutral beams of 4.5MW, bootstrap current fraction increases up to ~75% of the plasma current and the current hole region is enlarged up to ~30% of the minor radius in t=35 s from the discharge initiation. At the same time, ohmic current becomes zero. Therefore, the full non-inductive current drive with the central current hole is kept constant for the rest discharge duration of 60 s. The toroidal electric field at the plasma centre is negligibly small. Normalised beta and H-mode enhancement factor deduced from IPB98(y,2) scaling are kept at 3.7 and 1.4, respectively. The current drive efficiency of 0.5×10^{19} A/m^2/W is obtained at the central electron temperature of 4.7 keV, and at the average electron density of 0.32×10^{20} m^{-3}.

Figure 4 shows the radial profile of the safety factor, q, total current density, j_p, bootstrap current density, j_{BS}, beam driven current density, j_{CD}, ohmic current density, j_{OH}, ion/electron temperature, and density at t=80s. Ohmic current density is almost zero in the whole region. Bootstrap current density and beam-driven current density decreased within r/a~0.3, which produces the central current hole. The q-minimum of about 3.75 is located at r/a=0.9 where the transosport barrier is formed. Relatively wide reversed shear region with a flat q profile is formed between the transport barrier and the current hole. Steep gradients in the density and temperature of electron and ion are formed at the transport barrier. Those are almost constant in the current hole region.

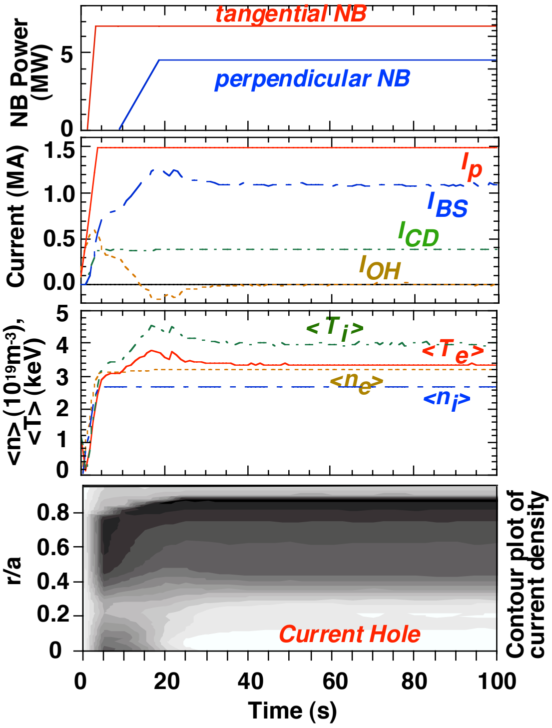

Fig. 3 Time trace of the injected NB power, current fraction, ion/electron temperature and average density, and the contour plot of the current density during the formation of current hole

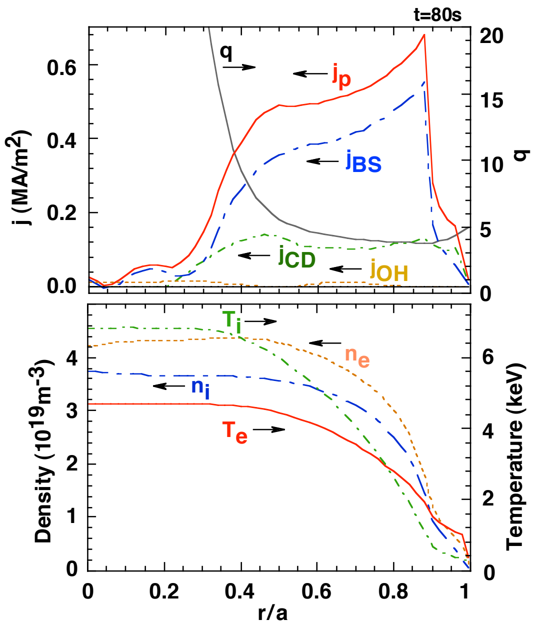

Fig. 4 Radial profile of the safety factor, current density, temperature and density of electron and ion, during the steady state phase of current hole (t=80s).

3.5 Dependence of current hole formation

The dependence of the current hole radius in a steady state phase is investigated by the change in the shear parameters. Figure 5 shows the current density profile for the three sets of shear parameters. The clear formation of a current hole is observed for the shear parameters of a =4, and D =0.7, for which the shear coefficient $E_{e/i}(s)$ has steepest profile among three cases. In Fig.6 the hole radius at the constant phase is plotted as a function of the barrier location. Strong correlation between the hole width and the barrier location appears, and the formation of wide hole radius seems to require the location of barrier in outer region.

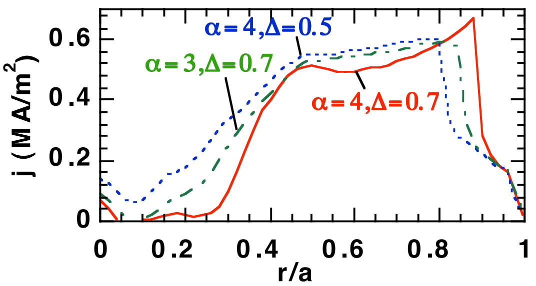

Fig.5 Current density profile for the 3 cases of shear parameters, a and D.

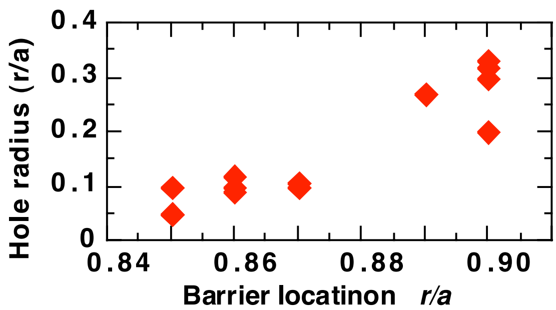

Fig. 6 Hole radius as a function of the barrier location at the steasy state phase.

The line averaged electron density, and the injected power of perpendicular neutral beams are also changed in the scenario. Higher density and/or lower injected power decrease the bootstrap current fraction and disturb the growth of the current hole. To the contrary, lower density and/or higher injected power increase the bootstrap fraction and cause the overdrive of the plasma current. There seems to exist some window in the density and the power for the proper operation of the stable current hole. The increasing rate of the tangential neutral beams is also tuned not to be overdrive in order to avoid the instability expected at the plasma current ramp-up phases.

3.6. Stability analysis of a current hole plasma

MHD stability for equilibria with current holes is investigated by the stability code for an ideal MHD mode (ERATO-J). Up-down symmetry and the remaining 15% of peak current density in the hole region at r/a <0.2 (see Fig.7) are assumed in the equilibrium of 1.5MA scenario for ERATO-J. Figure 8 shows the analysed result of the normalised β limit for the ideal MHD mode of n=1-4 as a function of the ratio of the conducting wall radius to the plasma minor radius, b/a. At the conducting wall location of b/a =1.3 in the present design of JT-60SC, the stability limit is around 4.5 for the obtained profiles. Therefore, the full non-inductive current drive with a current hole at β_N=3.7, and the bootstrap current fraction of 75% in the scenario described here is considered to be stably operated for any ideal MHD mode.

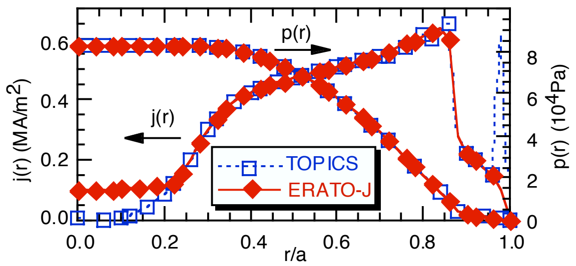

Fig. 7 Radial profiles of the current density, j(r), and the plasma pressure, p(r), for ERATO-J (solid diamonds), and for TOPICS (open squares).

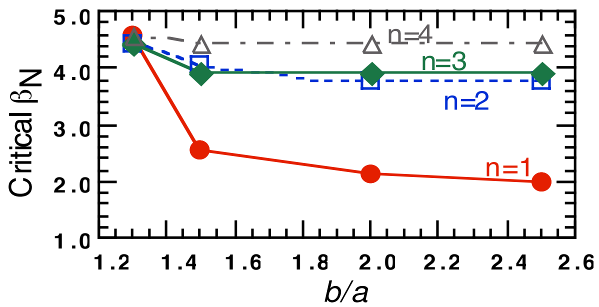

Fig. 8 Normalised-β limit for the ideal MHD mode (n=1-4) as a function of the ratio of conducting wall radius to plasma minor radius analysed by ERATO-J.

4. Summary

Full non-inductive current drive scenarios with a central current hole plasma are developped for the super-conductive tokamak JT-60SC. The simulation is performed by a time-dependent transport code on the basis of the observed current hole in reversed shear plasmas of JT-60U. A current hole of ~30% of the minor radius is found to be formed and sustained with the bootstrap current fraction of ~75% in a combination with the off-axis tangential and central perpendicular neutral beams. The growth of the hole strongly affects the plasma shear and the barrier location. The stability analysis shows that the normalised beta limit of the current hole plasma is about 4.5 for the conducting wall in the present design of in-vessel structure.

It should be noted that the presented current hole scenario is performed without any central current drive such as negative ion-based neutral beam injection, which suggests the alternative features of current drive scheme for the steady state operation.

References

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