Plasma Domains and Development of Operation Scenarios in JT-60SA*)

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JT-60SA will be operated in several operational domains to pursue its objectives, to support researches on ITER and develop physics and engineering basis towards DEMO reactor. Evolution and tailoring of the current profile, or the safety factor (q) profile in other words, is important in preparation for plasmas expected in the operational domains. Especially in the high normalized pressure (β_N) domain, tailoring of the q profile is indispensable to achieve high performance. In this paper, evolution of the q profile during the current ramp-up in a candidate plasma for a steady-state high β_N and modification of the q profile by means of ECRF are examined by modeling simulation. Impact of the target q profile modification on the energy confinement is also discussed.

Keywords: JT-60SA, steady-state, high β_N, current profile optimization, ECRF, TOPICS, CDBM

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1. Introduction

The JT-60SA project has been pursued under the Broader Approach Satellite Tokamak Programme jointly implemented by Europe and Japan, and under the Japanese national program [1]. The objective of the project is to support researches on ITER and develop physics and engineering basis towards DEMO reactor [2]. Towards achievement of the objectives, JT-60SA is designed to operate in key operational domains. One is the high plasma current (I_p) domain to explore at burning plasma relevant dimensionless parameters such as normalized Larmor radius (ρ^*) and normalized collisionality (ν^*). The other is the high normalized pressure (β_N) domain. In this domain, achieving high bootstrap current fraction (f_{BS}) simultaneously is also indispensable.

To establish plasmas appropriate to exploring these domains, tailoring of the safety factor (q) profile is a key issue. For a standard H-mode plasma, sawteeth during or even in prior to the main heating would be acceptable. This means q at the plasma center (q_0) can be below unity. For an advanced inductive plasma [3], which is known to have a better confinement and β_N limit than those in a standard H-mode plasmas, q_0 being around unity or even higher is thought to be required in the target plasma. And for plasmas in the high β_N and high f_{BS} domain, an advanced tokamak plasma, in other words a reversed q profile is thought to be beneficial. In this paper, simulation results of a JT-60SA plasma ramp-up with emphasis on the q profile evolution and tailoring are presented.

2. JT-60SA and its Plasma Domain

The JT-60SA tokamak is a full super-conducting coil machine, both the toroidal and the poloidal coils. The strength of the toroidal field (B_t) is up to 2.3 T. And it is designed to operate up to $I_p = 5.5$ MA. In the high I_p domain, JT-60SA will explore plasmas with burning plasma relevant parameters. In this domain, expected plasmas will be standard H-mode plasmas and advanced inductive plasmas. On the other hand, in the lower I_p (~2-3 MA) range advanced tokamak plasmas will be pursued. A typical plasma expected in this domain is a plasma of $I_p = 2.3$ MA at $B_t = 1.7$ T with $\beta_N = 4.3$. In order to produce and heat these plasmas, the neutral beam (NB) system of negative-ion based with 10 MW and of positive-ion based with 24 MW will be installed. Also the electron cyclotron range of frequency (ECRF) power of 7 MW will be installed. Some of these heating systems also drives a fraction of the plasma current non-inductively.

3. Simulation of the I_p Ramp-Up Phase

A simulation was carried out using a 1.5-D transport code TOPICS [4]. TOPICS can solve 1-D transport equation with solving 2-D free boundary equilibrium. The equilibrium can vary in time, even transform from a limiter configuration to a divertor configuration. TOPICS can adopt various transport models, such as CDBM, GLF23, Bohm gyro-Bohm, MMM95 and so on. For the simulation shown in this paper, the CDBM (Current Diffusive Ballooning Mode) [5] model was used. Though CDBM is a semi-empirical model, it is found to predict H-mode core plasmas and be good at reproducing JT-60U ITB plasmas.

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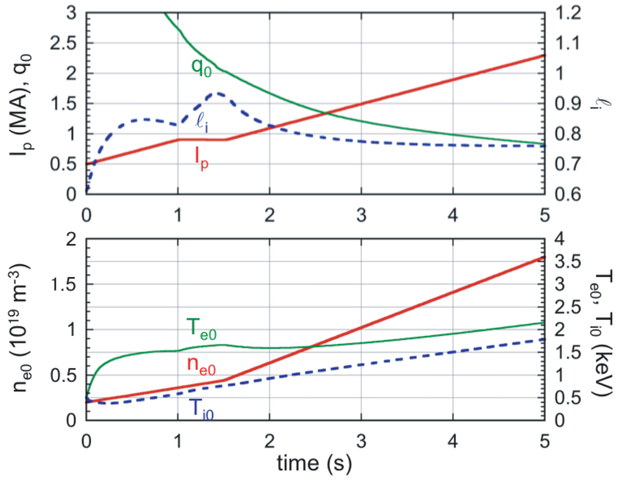

Fig. 1 The temporal evolution of I_p, ℓ_i, q_0 n_{e0}, T_{e0} and T_{i0} in a 2.3 MA/1.7 T Ohmic plasma.

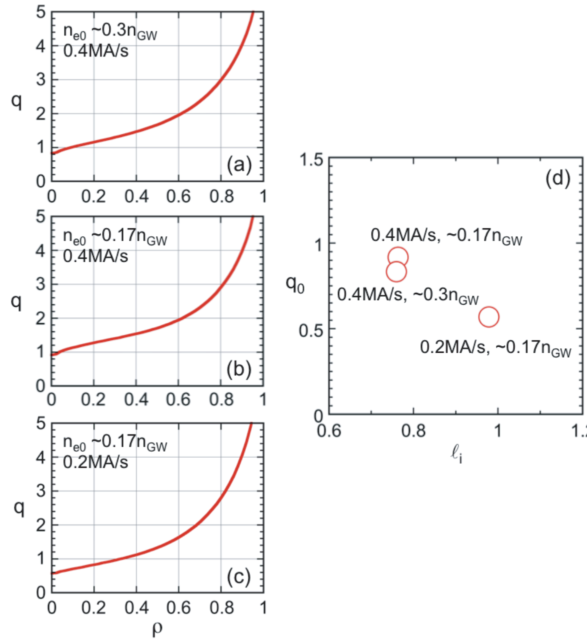

Fig. 2 (a)~(c), the q profile at 5 s for various combination of n_{e0} and dI_p/dt. Plot of q_0 against ℓ_i corresponding to (a)~(c).

In the simulation, designed geometries of the heating systems, such as the NB beam lines, the ECRF injection antenna positions and so on are used, to be as realistic as possible.

The target plasma used here was that expected for the 2.3 MA steady-state high β_N plasma shown before. The temporal electron density profile is prescribed as

$$n_e(\rho, t) = n_{e0}(t) \cdot (1 - \rho^2)^{0.5}. \tag{1}$$

Energy transport of both electrons and ions is solved, assuming the ion anomalous thermal conductivity is identical to that of electrons. The plasma edge is assumed to stay in the L-mode. The boundary condition of the electron temperature is assumed to increase linearly from 10 eV to 50 eV between 0 s and 5 s. Further detailed investigation on the effect of the boundary condition will be a future work. Temporal evolution of the q profile is solved consistently with the neoclassical conductivity.

An example of the temporal evolution of I_p, the internal inductance (ℓ_i), the values at the plasma center of; the safety factor (q_0), the electron density (n_{e0}), the electron temperature (T_{e0}) and the ion temperature (T_{i0}) in an Ohmic plasma is shown in Fig. 1. Among them, I_p and n_{e0} are prescribed, while others are results of simulation as mentioned above. The evolution of the equilibrium starts from a limiter configuration and changes into a divertor configuration just before 1.5 s. As the toroidal current keeps penetrating to the plasma center, q_0 continues to decrease and becomes below unity at reaching the I_p flattop (5 s). However, ℓ_i does not change very much after 2 s. The most effective control knobs to change the q profile evolution, that is the current penetration, are n_{e0} and the current ramp-up rate, dI_p/dt. In the result shown in Fig. 1, $n_{e0} = 0.44 \times 10^{19}$ m^{-3} at 1.5 s and $= 1.8 \times 10^{19}$ m^{-3} at 5 s, and $dI_p/dt = 0.4$ MA/s, which is almost the fastest ramp-up rate in JT-60SA. The densities correspond to 17% and 30% of the Greenwald density (n_{GW}), respectively. Two other cases, one is keeping lower density of 17% of n_{GW} until 5 s ($n_{e0} = 1.0 \times 10^{19}$ m^{-3} at 5 s) and the other is a slower ramp-up case with $dI_p/dt = 0.2$ MA/s, were carried out for comparison. In Fig. 2, shown are the q profiles at 5 s for the reference cases and a plot of q_0 against ℓ_i. It seems that even in the higher density case (Fig. 2 (a)), in which q_0 becomes below unity, sawteeth can be avoided, since the region of $q < 1$ is very small. Halving the ramp-up rate affects largely while nearly halving the density does not affect much. It seems that even at the modest density, sawteeth could be avoided with the faster ramp-up.

4. Effect of ECRF during the I_p Ramp-Up Phase

As mentioned earlier, preparation of q profile is more important for plasmas in the steady-state high β_N domain. Therefore, how the q profile can be modified during the I_p ramp-up was also examined. The higher target density was chosen, that is $n_{e0} = 0.3n_{GW}$ at 5 s. The ECRF of 3 MW at 110 GHz is injected perpendicular to the toroidal field for the second harmonic X-mode heating. As the ECRF is injected perpendicularly, the ECRF is for pure heating and with no ECRF driven current in principle. As the toroidal field was chosen to be 1.7 T, the ECRF resonance is off-axis for the 110 GHz wave in any case.

The temporal evolution of I_p, ℓ_i, q_0, n_{e0}, T_{e0} and T_{i0} is shown in Fig. 3. The ECRF power of 3 MW is applied from 1.5 s as schematically shown in the figure. Evolution of q_0 is quite different from that in Fig. 1, an Ohmic case. As ECRF is injected q_0 becomes almost constant in about 0.5 s. The internal inductance saturates at lower

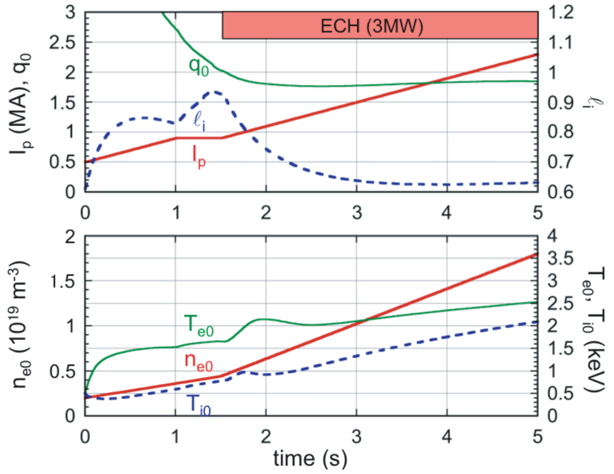

Fig. 3 The temporal evolution of I_p, ℓ_i, q_0, n_{e0}, T_{e0} and T_{i0} in a 2.3 MA/1.7 T plasma with 3 MW of ECRF.

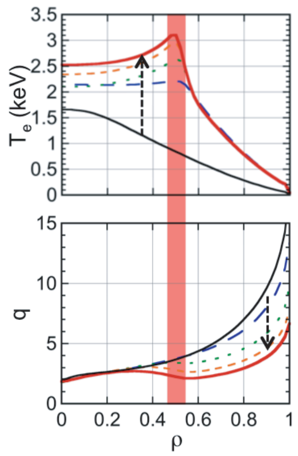

Fig. 4 Temporal evolution of the T_e and the q profiles at 1.5 s (thin solid line), 2 s (broken line), 3 s (dotted line), 4 s (dashed line) and 5 s (bold solid line). The arrow in each boxes indicates direction of the evolution from 1.5 s to 5 s. Hatched region at ρ~0.5 indicates the ECRF power deposition.

value. Evolution of the T_e and q profiles is shown in Fig. 4. As mentioned earlier, the ECRF deposition is off-axis and at around ρ= 0.5 in this case. As shown in the figure, a broad T_e profile develops owing to the off-axis ECRF heating. And the broad T_e profile prevents current penetration to the central region and the q profile becomes reversed.

In order to see in what extent such a reversed q profile can be obtained, the ECRF deposition was scanned by changing the ECRF injection angle in the poloidal direction. Here the injection power is again 3 MW. The result is shown in Fig. 5 (a). Here, the ECRF deposition was changed as illustrated in the figure, at ρ~0.4, ρ~0.5 and ρ~0.6. The q profiles with a dashed line, solid line and dotted line correspond to these depositions respectively. As clearly seen in the figure, the local location

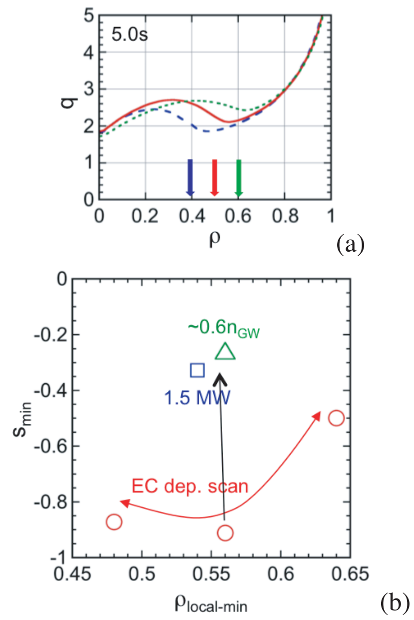

Fig. 5 (a) Change in the q profile when the ECRF deposition (3 MW) was scanned as illustrated with arrows. (b) A plot of s_{min} and $\rho_{local\text{-}min}$. Circles: for the cases shown in (a). Square: when the ECRF power was halved to 1.5 MW. Triangle: when n_{e0} is doubled.

($\rho_{local\text{-}min}$) of the local minimum q ($q_{local\text{-}min}$) follows the ECRF deposition. And it should be noted that the value of $q_{local\text{-}min}$ increases as the ECRF deposition moves outward. Though it is natural that $q_{local\text{-}min}$ increases as $\rho_{local\text{-}min}$ expands, it is worth considering what value of $q_{local\text{-}min}$ will be obtained, because $q_{local\text{-}min}$ is an important parameter in view of the MHD stability. Another important parameter is the magnetic shear (s), because s is believed to play an important role in the energy transport characteristics of a plasma, especially when it is negative. Roughly speaking, deeper shear (more negative s) would reduce energy transport more. The minimum value of s (s_{min}) is plotted against $\rho_{local\text{-}min}$ for the ECRF deposition scan case in Fig. 5 (b). The plot suggests that the case that has $q_{local\text{-}min}$ at ρ~0.56, corresponds to the solid line case in Fig. 5 (a), would be the best. This is because it has the largest $\rho_{local\text{-}min}$ maintaining the deepest shear. The local minimum q location can go further outside, but depth of the shear can be reduced. One that has $\rho_{local\text{-}min}$ ~0.64 corresponds to such a case. For comparison, lower injection power (1.5 MW) and higher target density ($0.6 \times n_{GW}$ at 5 s) cases were considered. They were changed from one shown with a solid line in Fig. 5 (a). The location of $q_{local\text{-}min}$ is found be almost unchanged, while the shear becomes weaker in both cases. And the effect of either halving the power or doubling the density is quite similar.

This reversed q profile is what is believed to be beneficial in preparation for the steady-state high β_N plasma. In order to highlight a difference in the transport, central NB heating was applied from 5 s when I_p reaches the flat-top.

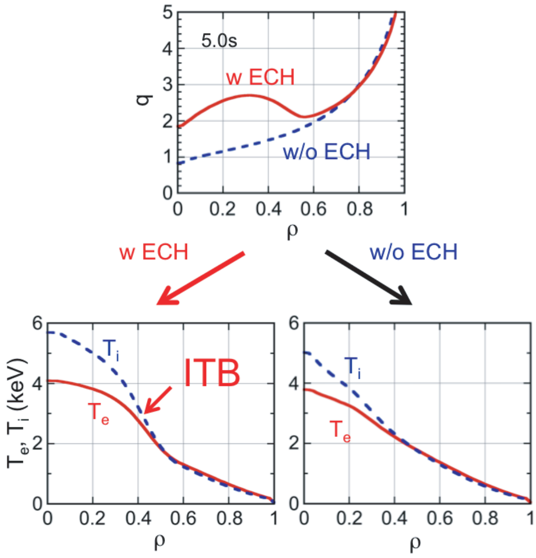

Fig. 6 Comparison of the q profile at 5 s with and without ECRF during the I_p ramp-up (top figure). Difference in the T_e and T_i profiles with 8 MW of NB injection into these target q profiles.

Here, real NB geometry was used. That is, four perpendicular P-NB units were used. The target q profile at 5 s for with and without ECRF during the I_p ramp-up is shown in the upper box in Fig. 6. The difference in the q profile is clearly seen in the figure. And the T_e and T_i profiles after 0.5 s from the injection of NB of 8 MW are shown in the lower boxes in Fig. 6. Due to the shine through, the absorption power is lower and evolves especially at this 0.5 s, but the same for both cases as the density is the same. Clear difference is observed between the cases with and without ECRF. In the case of ECRF injection during the I_p ramp-up, formation of the internal transport barrier (ITB) is observed. This observation, formation of an ITB for a reversed q profile, also agrees with our experience of the ITB formation in JT-60U and also results in other tokamaks.

5. Discussion and Summary

One of the main purposes of this study is to clarify, how the q profile evolves and in what extent it can change in response to knobs that can be controlled or modified externally with actuators expected in JT-60SA. Of course we should be careful in looking at and understanding the results obtained in this work. Since we have used just one transport model. And as often said, yet no transport model is perfect for everything. Nevertheless, the results highlight some key points that would give clues in establishing operational scenarios in JT-60SA in preparation for actual experiments.

In the investigation of the q profile evolution in an Ohmic ramp-up, it was indicated that the I_p ramp-up rate could have large effect. This suggests what is the first knob to change for the effective control. At the same time, this would attract attention to the technical constraints, such as limitation in the poloidal coil power supplies, cryogenics and so on, which prevent us from changing the ramp-up rate freely. Final goal of simulation of operation scenarios is not only to design operation from a view point of physics but also to find a real operation to cooperate with technical constraints. TOPICS does not include such technical constraints to date.

The results of ECRF injection during the I_p ramp-up are also suggestive within the assumptions. They showed a clear preparation of a reversed q profile, which plays an important role in steady-state high β_N plasma development. They also indicated how the ECRF deposition changes the location of $q_{\text{local-min}}$ and the depth of the magnetic shear. Moreover, it should be noted that change in the ECRF power or the target density would not change the $q_{\text{local-min}}$ location largely but does the depth of the shear reversal.

Benefit of producing the reversed q profile was demonstrated by adding more power.

Using another transport model will give different values, but not lead to different trend or interpretation of physics. It might just change extent of resultant parameters such as s. Solving the particle transport will be another future issue. It would be reasonable to assume that a scalar value such as n_{e0} can be feed-back controlled, while the shape of the density profile would vary depending on the particle transport. Evolution of the density profile shape would affect detailed evolution of q profile, but might be in limited extent. Benchmark with other transport models and solving particle transport will be important issues in the next step towards more detailed and realistic development of JT-60SA operational scenario.

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