Investigation of Non-inductive Plasma Current Start-up by RF on QUEST

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Abstract. Formations of a closed flux surface (CFS) on QUEST are achieved by fully non-inductive current start-up driven by RF, which is 8.2GHz in frequency and more than 40kW in power. It found that appropriate magnetic configuration with positive n-index and reduction of particle recycling was crucial to achieve the non-inductive plasma current start-up (PCS) successfully. Especially the controllability of particle recycling should be improved by wall conditioning based on successive plasma production and wall cleaning with electron cyclotron resonance heating (ECR) plasmas induced by RF in frequency of 2.45GHz.

1. Introduction

Spherical tokamak (ST) is a tokamak whose aspect ratio \( A = R/a : R \) is major radius and \( a \) is minor radius) is significantly low. Lower aspect ratio provides the possibility to obtain higher \( \beta \) plasma and therefore ST is a promising candidate for future cost-effective fusion reactors [1].

In tokamaks, toroidal plasma current is required to confine plasmas. For plasma current start-up (PCS) in conventional tokamaks, ohmic heating (OH) due to significant loop voltage induced by the time variation of central solenoid coil current is a popular way. But, for forming ST configuration, the aspect ratio should be reduced and tighter central space should be satisfied. This indicates that the magnetic flux supplied from the coil located inside the plasma is significantly restricted. ST with no central solenoid coil is ideally the best. Thus, the way to make a closed flux surface (CFS) and subsequent PCS under lower or fully non induction of loop voltage is quite essential for obtaining confined plasmas in ST. Moreover PCS with the lower loop voltage is likely to be also required in super-conductive tokamaks like ITER because of the difficulty of making fast flux swing [2]. Therefore, the study for non-inductive PCS is one of the most important issues in future tokamaks and the experiments were done in many devices such as, WT-2, 3, JIPPT-IU, PLT, TRIAM-1M, JT-60U,
FIG. 1. Cross-sectional side view of QUEST including positions of the PF coils and the flux loops is shown. The ellipse inside the vacuum chamber is the most outer shape of current distribution model as introduced in ref. 10.

In this study, only 8.2GHz one is used to drive plasma current and 2.45 GHz one is used to make ECR plasmas for wall cleaning.

The schematic view of QUEST is shown in figure 1. QUEST is constructed to study plasma wall interaction (PWI) under an all-metal hot wall in long duration plasma [9]. 11 PF coils and a 16 turns toroidal field coil for confinement of the plasma are set at outside of the vacuum vessel. The PF4-1, 2 and 3 coils, which located at center of the torus, are used as an OH coil. Besides, a pair of cancel coils (CCs), which will be normally used to connect with PF4-1, 2 and 3 in series, are set to make a null point in the vacuum chamber at the start-up phase. It should be noted that the PF4-1, 2, 3 coils and CCs were not used in the experiments presented in this paper.

The diameter and the height of a cylindrical inner limiter are 0.44m, 2.5m, respectively and those of outer wall are 2.74m and 2.79m. A pair of diverter plates is set at \( Z = \pm 1 \)m, where the mid-plane is \( Z = 0 \)m. The design value of plasma size in QUEST is major radius \( R_0 = 0.64 \)m, minor radius \( a = 0.36 \)m and aspect ratio \( A = 1.78 \) [9].

In QUEST, 61 flux loops and one Rogowski coil are utilized to reconstruct magnetic surfaces. All flux loops are located along the inside surface of the vacuum chamber wall. Numerical integration is done to obtain the flux values. In this paper, distribution of plasma current is estimated from the measured flux values with the modified method introduced in ref. [10] and then the reconstruction of the magnetic flux surface is done. In the method, the parabolic model of plasma current distribution shown in Fig.1 is assumed. This model has 8 parameter \( j_0, R_c, Z_c, a_1, a_2, a_3, a_4 \) and \( \alpha \). The current density in section \( A \) shown in Fig. 1 is written as follows,

\[
j = j_0 \left[ 1 - \frac{(R - R_c)^2}{a_1^2} - \frac{(Z - Z_c)^2}{a_2^2} \right]^{\alpha} \tag{1}\]
FIG. 2. The comparison of plasma current (top picture) and $H_\alpha$ signal (bottom picture) in the term1 (black line, sn6616) and term2 (gray line, sn6878) are shown. In these two shots, vertical field is 1mT and n-index is 0.35. ($H_\alpha$ should be changed to $H_\alpha$ in the figure.)

3. Experimental Results

Formation of CFS can be observed in non-inductive PCS experiment by RF in QUEST. Figure 2 shows the development of plasma current in this experimental campaign. In the experimental term before first observation of formation of CFS (term1), typical plasma current is around 1kA (sn6616: black line in Fig.2) under time-constant external vertical field of 1mT, n-index=0.35 on the mid-plane at $R = 0.64m$, where n-index is expressed by

$$ n = \frac{R}{B_z} \frac{\partial B_z}{\partial R} $$

(2)

The projections of magnetic line to poloidal cross section with positive and negative n-indexes are shown in Figure. 3.

In this term, particle recycling indicated by $H_\alpha$ signal is significantly large because of lack of the wall cleaning. After the wall cleaning using 2.45GHz was done, CFS is obtained (term2) in the almost same operational condition with sn6616, and then the plasma current goes up to about 4kA (sn6878: gray line in Fig.2). The distributions of the plasma current and the flux surface obtained by the magnetic measurement in sn6878 are shown in Fig.4. The clear formation of CFS can be observed. The plasma parameters estimated from last closed flux surface are: $R_d=0.64m$, $a=0.41m$, $A=1.56$, elongation $\kappa=1.47$ and triangulality $\delta=0.35$. This analysis indicates that a part of current exist out of last closed flux surface. This condition is same as the condition discussed in ref. [4], [8] and [10] and...
FIG. 4. The plasma current distribution estimated by the magnetic measurement (right picture) and the closed flux surface reconstructed with the current distribution (left picture). Solid line in left picture shows the last closed flux surface.

FIG. 5. The relation between plasma current and $H_\alpha$ in several tens of shots is shown. Circles show the shots with positive n-index in term2, square shows the shots with negative n-index in term2 and triangles show the shots with positive n-index in term1. Each shot has different vertical field strength from 0mT to about 3mT. Squares means the shot operated vertical field and n-index is 1mT and -0.067 at R=0.64m. This is peculiar feature of RF discharge in the STs. Figure 5 shows the plasma current inversely depends on the $H_\alpha$ signal in several tens of shots. This suggests that the recycling of particle should be reduced to achieve CFS by RF. While two shots (square markers) shown in region B of Fig. 5 was not obtained CFS even in term2. In these two shots, external vertical field is 1mT, which is same value with that in sn6878, and n-index is -0.067 at R=0.64m. This indicates that PCS is done successfully only in term 2 with positive n-index configuration (region A in Fig. 5).

4. Discussion

It is shown that positive n-index of magnetic flux induced by external PF coils and low recycling is a key parameter to start-up plasma current successfully as described in the section 3. Lower recycling leads to lower neutral density. These results agree with the idea which plasma current in OMFC is driven by energetic electrons [11]. When the n-index is negative, electrons generated at ECR layer by RF go to low field side and cannot be confined in OMFC. On the other hand, with positive n-index, a part of energetic electrons are well-confined in OMFC according to particle orbit calculation. The confined electrons have asymmetric movement in toroidal direction and this asymmetric movement can generate plasma
FIG. 6. The relation between particle confinement and initial velocity of electron is shown. The orbit calculation is started from mid-plane on fundamental ECR layer and horizontal and vertical axis shows the velocity of electrons at the start point of the calculation. Open circles show the confined electrons and closed circles show the electrons lost by the direct contact of the orbit to the wall. The dot line in the figure shows the electron energy. Inner, middle and outer dotted circles show the contours of energy at 1keV, 10keV and 30keV, respectively.

FIG. 7. The results of hard X-ray (HX) measurement are shown at the beginning of plasma discharges. Black line shows the result in sn10154 (positive n-index case, around 4kA plasma current) and gray line shows the result in sn10159 (negative n-index case around 1kA plasma current). These may suggest electrons confined in OMFC carry significant plasma current in the plasma current start-up. The existence of confined energetic electrons only in positive n-index case is confirmed by X-ray measurement.

5. Summary and Conclusion
Formation of a closed flux surface can be observed in non-inductive current start-up experiments by RF of 8.2GHz, 40kW in QUEST. Remarkable reduction of Hα signal is observed after discharge wall cleaning with 2.45GHz RF system and formation of the closed flux surface is obtained. This result indicates that the reduction of recycling is a key for the formation of the closed flux surface. Even in good wall condition, plasma current start-up cannot be done successfully in the magnetic field with negative n-index. These may suggest electrons confined in OMFC carry significant plasma current in the plasma current start-up. The existence of confined energetic electrons only in positive n-index case is confirmed by X-ray measurement.

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