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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 β 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-IIU, PLT, TRIAM-1M, JT-60U,

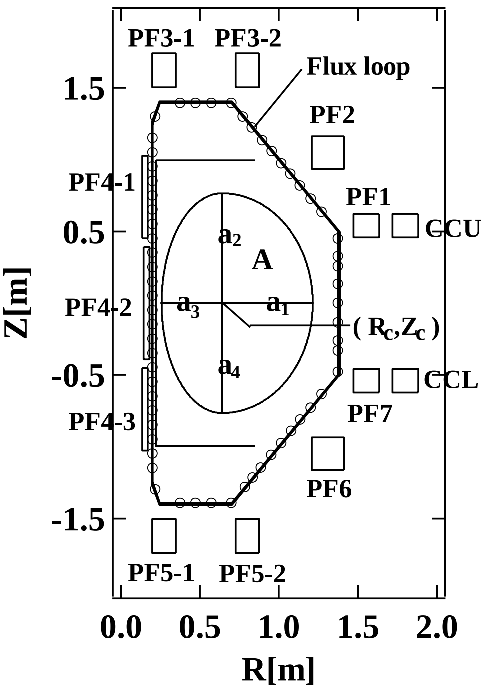

FIG. 1. Cross-sectional side view of QUEST including positions of the PF coils and the flux loops is shown. The ellipse inside the vacuum chamber is the most outer shape of current distribution model as introduced in ref.10.

CDX-U[3], LATE[4], TST-2[5], MAST[6], NSTX[7] and so on. Especially, some devices have made remarkable experimental results in PCS with RF injection [4, 5, 6].

Initial current should be induced by RF injection in an open magnetic field configuration (OMFC) formed by external poloidal field (PF) coils. It was reported that CFS was formed when initial current reached to a certain large value [8]. The formation of CFS is a drastic phenomenon, which contains the topological change of magnetic field, and an essential step for forming tokamak configuration. The formation of CFS on the ST named Q-shu University Experiment with Steady-State Spherical Tokamak (QUEST) is obtained with non-inductive way induced by RF. In this paper, this result will be reported. In section 2, the experimental apparatus of QUEST is shown. The experimental results are shown in section 3 and some discussions are done in section 4. Conclusion and summary is presented in section 5.

2. Experimental Apparatus

QUEST (R=0.68m, a=0.4m, B_T=0.25T at R=0.64m) [9] has two RF systems. One is the 2.45GHz system up to 50kW and the other is 8.2GHz oneup to 400kW. 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 = 0m. The design value of plasma size in QUEST is major radius R_0 = 0.64m, minor radius a = 0.36m 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 α. The current density in section A shown in Fig. 1 is written as follows,

$$j = j_0 \left\{ 1 - \frac{(R - R_c)^2}{a_1^2} - \frac{(Z - Z_c)^2}{a_2^2} \right\}^{\alpha} \quad (1).$$

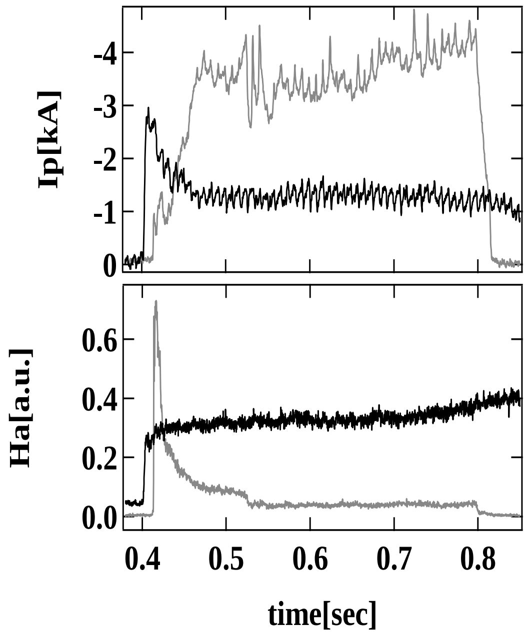

FIG. 2. The comparison of plasma current (top picture) and H_α signal (bottom picture) in the term1 (black line, sn6616) and term2 (gray line, sn6878) are shown. In these two shots, vertical field is 1mT and n-index is 0.35.(Ha should be changed to Hα in the figure.)

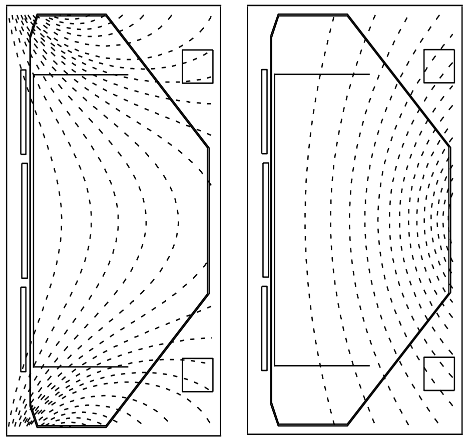

FIG. 3. The open magnetic field configuration with positive n-index (left side) and negative one (right side). Dashed line shows the projection of magnetic line to poloidal cross section. In QUEST layout of coils, positive n-index configuration is made by charging only PF26 coils and negative one is made by charging only PF17 coils.

Where, j_0 is the peak value of current density. In QUEST, j_0 is decided as the total amount of plasma current measured by the Rogowski coil. This is the main modification of the method from that in ref. [10]. The other parameters are scanned to find the best condition by use of the least square methods to the measured flux value.

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

$$. \ n = -\frac{R}{B_z}\frac{\partial B_z}{\partial R} \quad (2).$$

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_α 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_0=0.64m, a=0.41m, A=1.56, elongation κ=1.47 and triangulality δ=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

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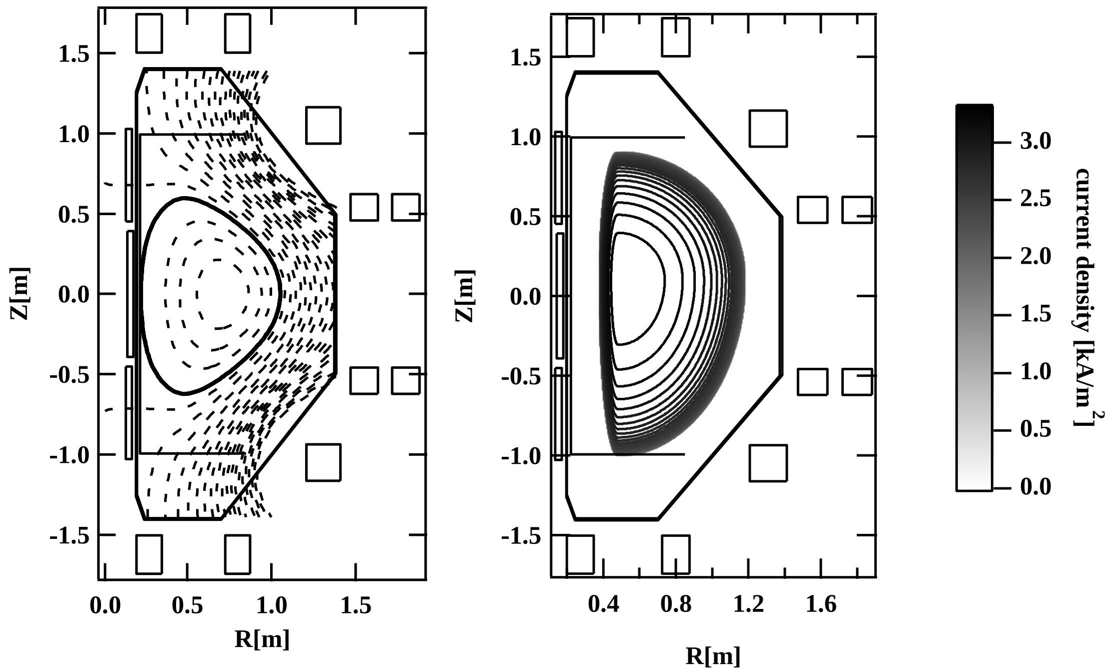

FIG. 4. The plasma current distribution estimated by the magnetic measurement (right picture) and the closed flux surface reconstructed with the current distribution (left picture). Solid line in left picture shows the last closed flux surface.

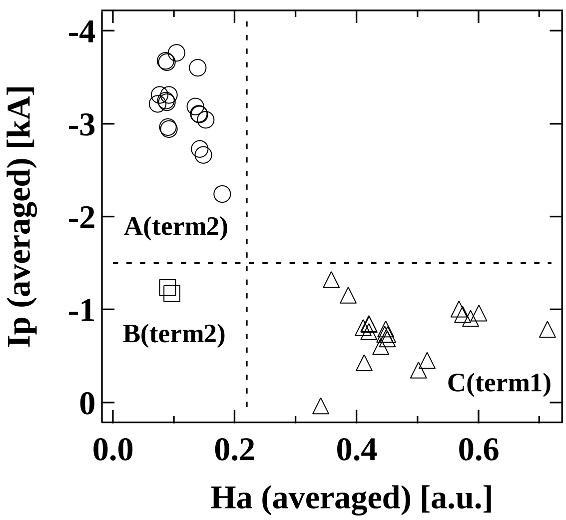

FIG. 5. The relation between plasma current and H_α in several tens of shots is shown. Circles show the shots with positive n-index in term2, square shows the shots with negative n-index in term2 and triangles show the shots with positive n-index in term1. Each shot has different vertical field strength 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_α 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

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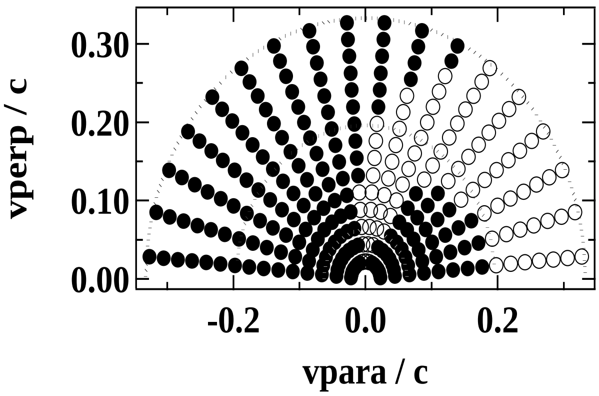

FIG. 6. The relation between particle confinement and initial velocity of electron is shown. The orbit calculation is started from mid-plane on fundamental ECR layer and horizontal and vertical axis shows the velocity of electrons at the start point of the calculation. Open circles show the confined 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.

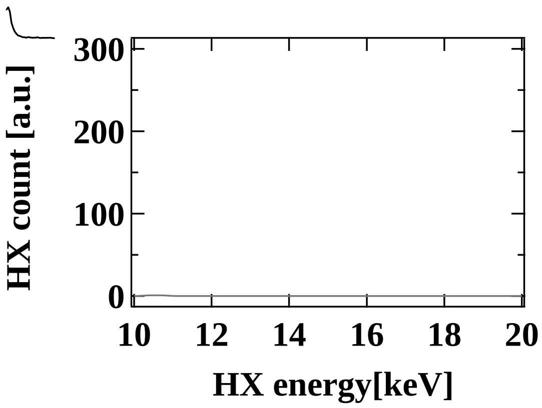

FIG. 7. The results of hard X-ray (HX) measurement are shown at the beginning of plasma dicharges. Black line shows the result in sn10154 (positive n-index case, around 4kA plasma current) and gray line shows the result in sn10159 (negative n-index case around 1 kA plasma current).

current. The contribution of such current to total plasma current in PCS is considered. Larger energy of electrons gives the enhanced asymmetric movement. But, electrons with too high energy cannot be confined in the weak vertical magnetic field. The appropriate range of electron energy in typical experimental condition of QUEST is estimated with the orbit calculation as shown in Fig. 6. At the condition, electrons of energy from a few hundred eV to several tens of keV are confined in OMFC and these electrons have asymmetric movement in toroidal direction. Thus, these electrons can be regarded as candidates of the electrons carrying the plasma current.

Then, the experimental results concerned about confined electrons which may have some contribution to total plasma current are introduced. In figure 7, the results of hard X-ray measurement in sn10159 (negative n-index and around 1kA current) and sn10154 (positive n-index and around 4kA current) are shown. In sn10159 little or no X-ray is detected. On the other hand, X-ray of more than 10keV is detected in sn10154. It should be noted that 10keV is the lower limitation of sensitivity of the X-ray detector. This result indicates that confined energetic electrons exist only in positive n-index configuration. Now, it is difficult to estimate the absolute value of plasma current driven by these electrons, therefore the contribution of these electrons to forming CFS is not clear. It is a future work.

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 H_α 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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