Solenoid-free start-up utilizing outer PF coils with the help of EBW pre-ionization and change of external inductance in VEST

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Abstract

Solenoid free start-up scenario is the way to utilize loop voltage from the evolution of equilibrium field using outer PF coils. Also, it can be expected to be as an attractive start-up scheme in the fusion machines with low aspect ratio since flux from external inductance change can be utilized. With decreasing vertical field, the experiments for formation of CFS shows that improved pre-ionization with EBW enhances the initiated plasma current by lowering plasma resistivity. The CFS is formed successfully when the poloidal field from plasma current exceeds the vacuum vertical field and the quantitative condition for CFS formation has been derived in the consideration of pre-ionization plasma resistivity. The pre-ionization plasma with low resistivity is necessary for CFS formation. The enhanced particle confinement along mirror ratio in TPC is helpful for lowering resistivity of pre-ionization plasma near outboard and EBW collisionless heating makes possible to have lower resistivity of pre-ionization plasma due to the existence of harmonic resonance near outboard. After the successful CFS formation, the plasma current has been demonstrated to be ramped-up with loop voltage from outer PF coils with help of reduced external inductance. The plasma current evolution has been presented with 0-dimensional power balance modelling with consideration about force balance along plasma current. The initial plasma current evolution has difficulty due to the size of CFS that causes resistive dissipation. Also, the induction voltage from outer PF coils has limitation that it is not easy to change rapidly due to eddy current from vessel wall and causes increase of vertical field that affects to CFS formation and equilibrium. The solenoid free start-up using outer PF coils must consider the distribution between flux from external inductance and resistive dissipation. The solenoid free start-up scheme utilizing outer PF coils has been suggested considering the condition of CFS formation including the location and minor radius of CFS and resistivity of pre-ionization plasma.

1. INTRODUCTION

The fusion devices such as tokamak have relied on the inductive loop voltage of central solenoid during operation including breakdown and start-up. Spherical Torus (ST) with low aspect ratio is important to utilize the loop voltage efficiently that has the relatively high beta but narrow central region. To overcome the limitations of the limited loop voltage, the solenoid free start-up scenario is the way to utilize loop voltage from the evolution of equilibrium field using outer poloidal field (PF) coils. Also, it can be expected to be as an attractive start-up scheme in the fusion machines with low aspect ratio since flux from external inductance change can be utilized when the plasma is started from outboard and moved inward [1].

The formation of closed flux surface (CFS) near outboard region is essential for successful solenoid free start-up. However, the mechanism of CFS formation during start-up has not been studied well. The CFS formation has been explained with the relation of the poloidal field from plasma current without inductive voltage and external vertical field and the plasma current jumps via CFS formation [2]. The plasma burn through simulation using DYON that simulates the start-up process in JET and ITER has an assumption that CFS has been formed when the plasma current has reached 100 kA based on the experimental results [3]. Also, the failure of CFS formation has been studied in KSTAR using TECHP0D with control of impurity fraction [4]. However, the pre-ionization plasma has strongly affected to the successful CFS formation and an analysis about the effect of pre-ionization and CFS formation with inductive voltage has not been studied well.

The solenoid free start-up experiments using outer PF coils have been conducted in various devices. In NSTX, the solenoid free start-up scenario has difficulties on formation and maintenance of CFS with shortage of sufficient auxiliary power [5]. The solenoid free start-up experiments have been conducted with sufficient ECH power and have relatively low plasma current compared to ECH power in TST-2 and JT-60 [6-7]. In PEGASUS, the CFS has been successfully formed near outboard region with help of local helicity injection (LHI) and the plasma current has been ramped-up to 110 kA with help of external inductance change [8]. It tells that the effective pre-ionization plasma near the location of plasma current start-up has important role on CFS formation.

The electron Bernstein wave (EBW) has been utilized for effective pre-ionization plasma in this paper. The electron cyclotron resonance heating (ECRH) is widely used in various fusion devices for local heating and current drive. But there are limitations on ECRH with low toroidal field machines. The EBW is an electrostatic wave converted from electromagnetic wave regardless of cut-off density, which can be generated through XB or OXB mode conversion (MC) processes [9]. The direct XB MC has the merits on simple design of waveguide system and single MC but it must surpass the evanescent layer. The injected X wave must pass through the cut-off density layer and can be converted to EBW near Upper Hybrid Resonance (UHR). The relatively longer wavelength of injected wave than the length of evanescent region has an advantage for tunneling the evanescent region [10]. After tunneling, the wave can encounter the UHR and Electron Cyclotron Resonance (ECR) and the steep density gradient near UHR can enhance the efficiency of direct XB MC. The converted EBW has heated the plasma via collisional damping and collisionless heating near resonance layer. The enhancement of pre-ionization plasma near outboard by EBW makes the formation of CFS and successful solenoid free start-up possible.

VEST is the first ST in Korea for studying innovative start-up and non-inductive current drive methods [11]. The first plasma has been generated successfully and the plasma current has been achieved 100 kA with 0.1 T toroidal field [12]. In addition, the efficient plasma start-up study has been conducted with trapped particle configuration (TPC) that enhances the ECH assisted pre-ionization plasma and make the low loop voltage and low volt second consumption start-up possible in VEST [13]. The TPC concept for start-up has been adopted to the KSTAR and improved and efficient start-up using TPC than conventional null configuration is achieved by enhanced pre-ionization plasma quality [4]. Therefore, the enhancement of pre-ionization plasma with TPC has increased the feasibility of successful CFS formation and solenoid free start-up.

In this paper, the condition for formation of CFS along the pre-ionization is investigated for successful start-up. EBW collisionless heating near outboard and enhancement of particle confinement with change of mirror ratio in TPC have been utilized to reduce the resistivity of pre-ionization plasma. Also, flux from change of external inductance has been distributed effectively for successful plasma current ramp-up using outer PF coils.

2. FORMATION OF CLOSED FLUX SURFACE

The start-up experiment has been conducted with double swing circuit on the central solenoid in the case of ECR layer at R = 0.22 m. In Figure 1, the plasma current has been increased successfully at the different timing along the MW injection power. The central solenoid supplies the loop voltage steadily inside the vessel and the stray field from the central solenoid decreases slowly along the current inside the central solenoid. The plasma current has been determined by the loop voltage and the resistivity of the pre-ionization plasma and when the poloidal field generated by plasma current overcomes the vertical field from central solenoid, the closed flux surface has been formed and the plasma current has been ramped up rapidly inside the surface. In the top graphs of Figure 1, the poloidal field has been calculated with the loop voltage and resistivity of the pre-ionization plasma and the timing of the plasma current ramp-up in start-up experiment concurs in the moment of for the calculated poloidal field overcoming the vertical field that 404.1~404.2 ms in case of 6 kW MW injection, 404.4 ms in case of 4 kW MW injection and 404.8~404.9 ms in case of 2 kW MW injection. The smaller resistivity of the pre-ionization plasma makes the bigger plasma current and the bigger poloidal field overcomes the decreasing vertical field in the different timing that is the moment of formation of closed flux surface and plasma current kick-off.

In Figure 2, the 2D model has been depicted for more detailed information about CFS formation. At first, the 2D resistivity of pre-ionization plasma has been estimated by the resistivity of pre-ionization plasma measured in the central region. And then normalized 2D current density profile has been calculated by 2D resistivity, loop voltage from PF coils and measured plasma current. The normalized 2D current density profile has been depicted in the background of Figure 2 graphs and the red means higher current density and the blue means lower current density. The poloidal field has been calculated from 2D current density profile and the vertical field from PF coils has been calculated with consideration on eddy currents. The sum of the poloidal field and vertical field has been depicted in red line of Figure 2 graph. The magnetic field lines tells the process of CFS formation during start-up that 404.3~404.4 ms in case of 6 kW MW injection, 404.4~404.5 ms in case of 4 kW MW injection and 404.7~404.8 ms in case of 2 kW MW injection and it is similar timing of Figure 1. The CFS formation has been occurred when the poloidal field from plasma current overcomes the vertical field from external PF coils and after CFS formation, the plasma current inside CFS increases rapidly.

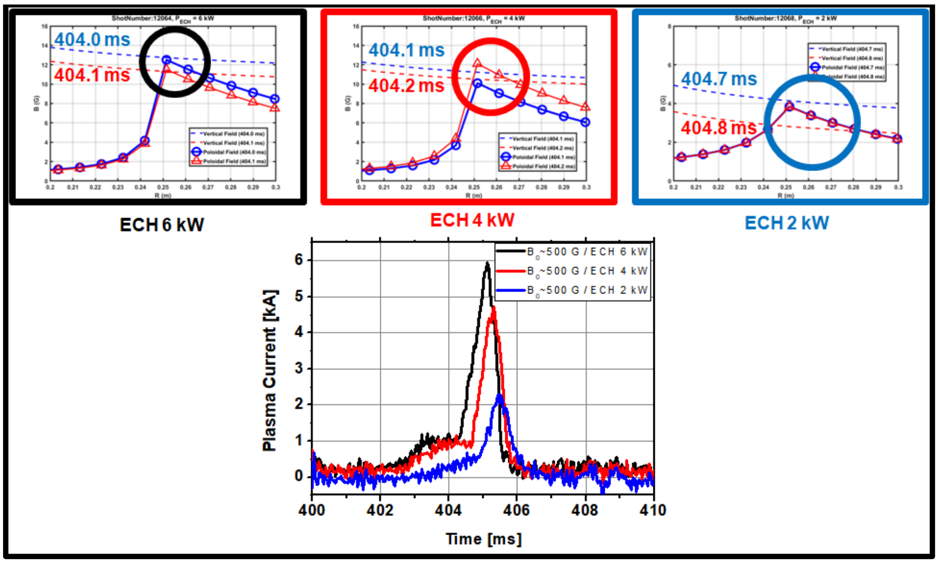

Fig. 1 Timing of the CFS formation along ECH power

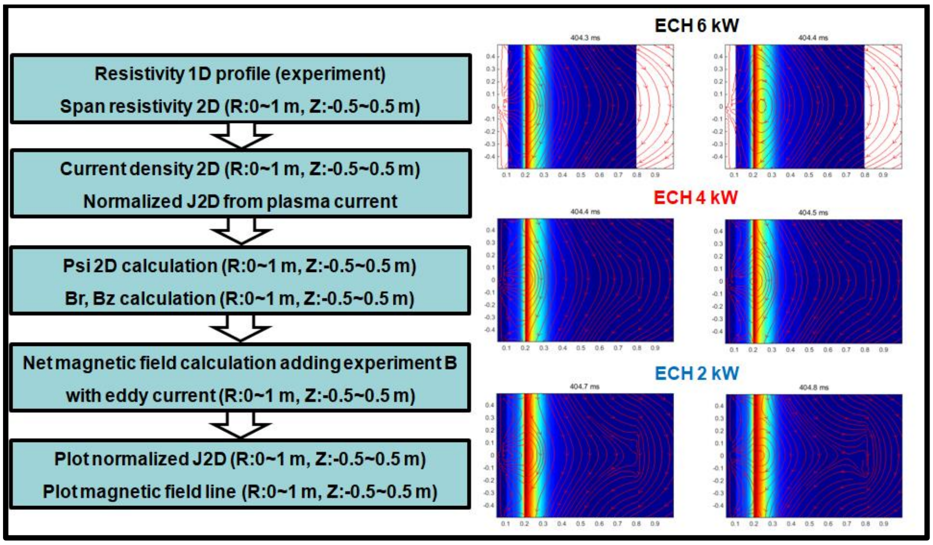

Fig. 2 2D plot of CFS formation along ECH power

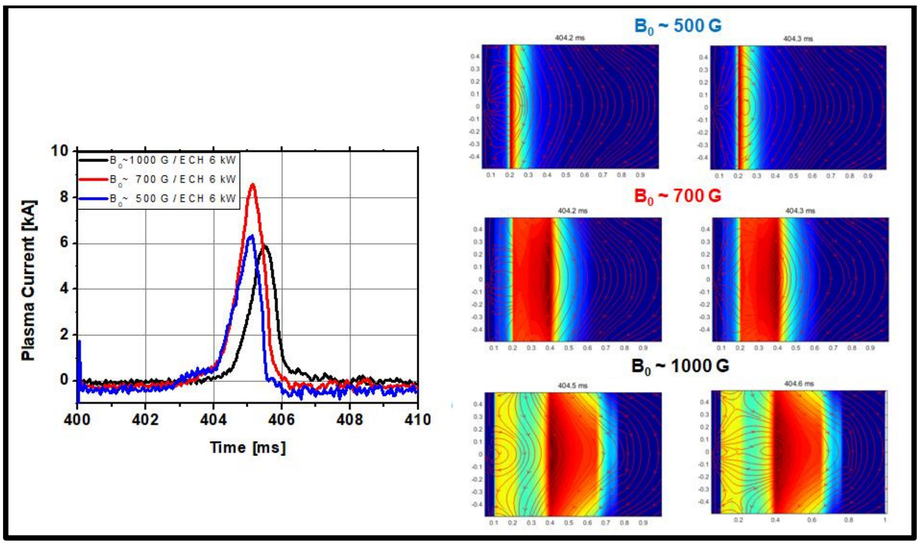

Fig. 3 2D plot of CFS formation along toroidal magnetic field

The start-up experiments along toroidal field have been conducted with 2D model for CFS formation. The experimental condition is same with Figure 1 but the only toroidal field has been changed to 500 G, 700 G and 1000 G. The background of Figure 3 graphs shows the 2D current density profile from measured resistivity of pre-ionization plasma. As the toroidal field increases, the ECR resonance layer moves outward that ECR exists 0.22 m in case of 500 G, 0.3 m in case of 700 G and R_0 = 0.45 m in case of 1000 G. The timing change of the CFS formation has been occurred along the different current density profile and it is similar to the experimental results of the timing of plasma current initiation. In addition, the location and size of CFS formation has been differed with 2D current density profile. It tells that the location of CFS formation and plasma current kick-up has been determined by pre-ionization plasma and loop voltage by external PF coils.

Based on the experimental results, the quantitative condition for CFS formation has been derived in the consideration of pre-ionization plasma resistivity as following (1).

$$\frac{B_p}{B_v} > 1 \rightarrow \frac{E_t\, a}{B_v \eta} > 1.6 \times 10^2 \left[\frac{V}{G\Omega m}\right] \qquad (1)$$

Although the derivative does not calculate the poloidal field using Green's function, the poloidal field has been calculated simply in one torus. The derivative tells that the CFS formation has the advantages for larger electric field, lower resistivity of pre-ionization and lower vertical field. 'a' is a minor radius of CFS when the CFS is formed. The minor radius of CFS has the difficulties for measurement and the minor radius is estimated by the measurement of plasma current when the plasma current has been increased rapidly. In this experiment in VEST, CFS has been formed when the plasma current reaches 1 kA and the minor radius is estimated to 10 cm.

With this 2D model of CFS formation, it makes the quantitative analysis about CFS formation and plasma current start-up possible. The standard condition for successful start-up is Lloyd condition as an empirical formula so far [14]. This condition tells that the condition is relaxed with the existence of pre-ionization plasma but the quantitative analysis on pre-ionization plasma has not been considered. There is a comparison between Lloyd condition and 2D model for CFS formation in Figure 4. With all successful start-up conditions, some cases do not satisfy the relaxed Lloyd condition but 2D model for CFS formation satisfies with all cases. Although the analysis has not been adapted to all cases, the successful start-up must be considered the effect of pre-ionization plasma.

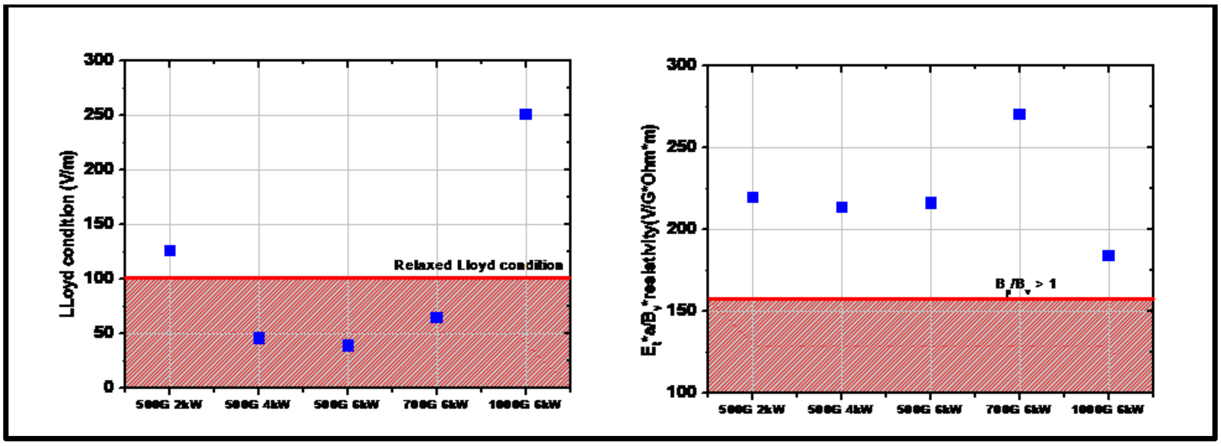

Fig. 4 Comparison between Lloyd condition and 2D model for CFS formation

3. EBW ASSISTED PRE-IONIZATION PLASMA EXPERIMENTS

The CFS formation is essential for successful start-up in tokamak. Based on the 2D model of CFS formation, the efficient pre-ionization plasma with help of auxiliary heating system is important for effective CFS formation. The EBW has been utilized for efficient pre-ionization plasma generation and the EBW experiments have been conducted with TPC.

In case of toroidal field 500 G as depicted in Figure 5 (a), the ECR resonance locates in 22 cm. The experiments have been conducted with only TF and TPC and the density in case of TPC is higher than that in case of only TF [13]. In addition, the over-dense plasma overcoming the L cut-off density has been generated with increasing ECH power. The over-dense plasma has been made by EBW collisional damping that mode converted EBW near UHR moves to ECR resonance and damped away in the collisional plasma [15]. In case of toroidal field 1000 G as depicted in Figure 5 (b), the enhancement of pre-ionization with TPC has been confirmed. The over-dense plasma from EBW collisional damping has been generated near outboard region. However, it is important to decrease the resistivity of pre-ionization plasma to make CFS near outboard easily and EBW collisionless heating as well as collisional damping is required to increase electron temperature.

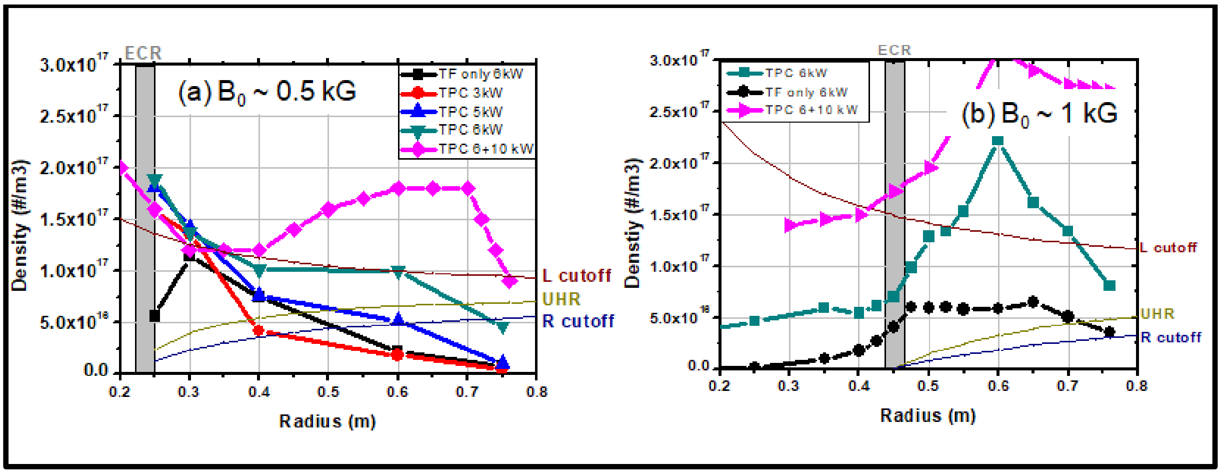

Fig. 5 The enhancement of pre-ionization plasma by EBW collisional damping in case of B_0 (a) 500 G (b) 1000 G

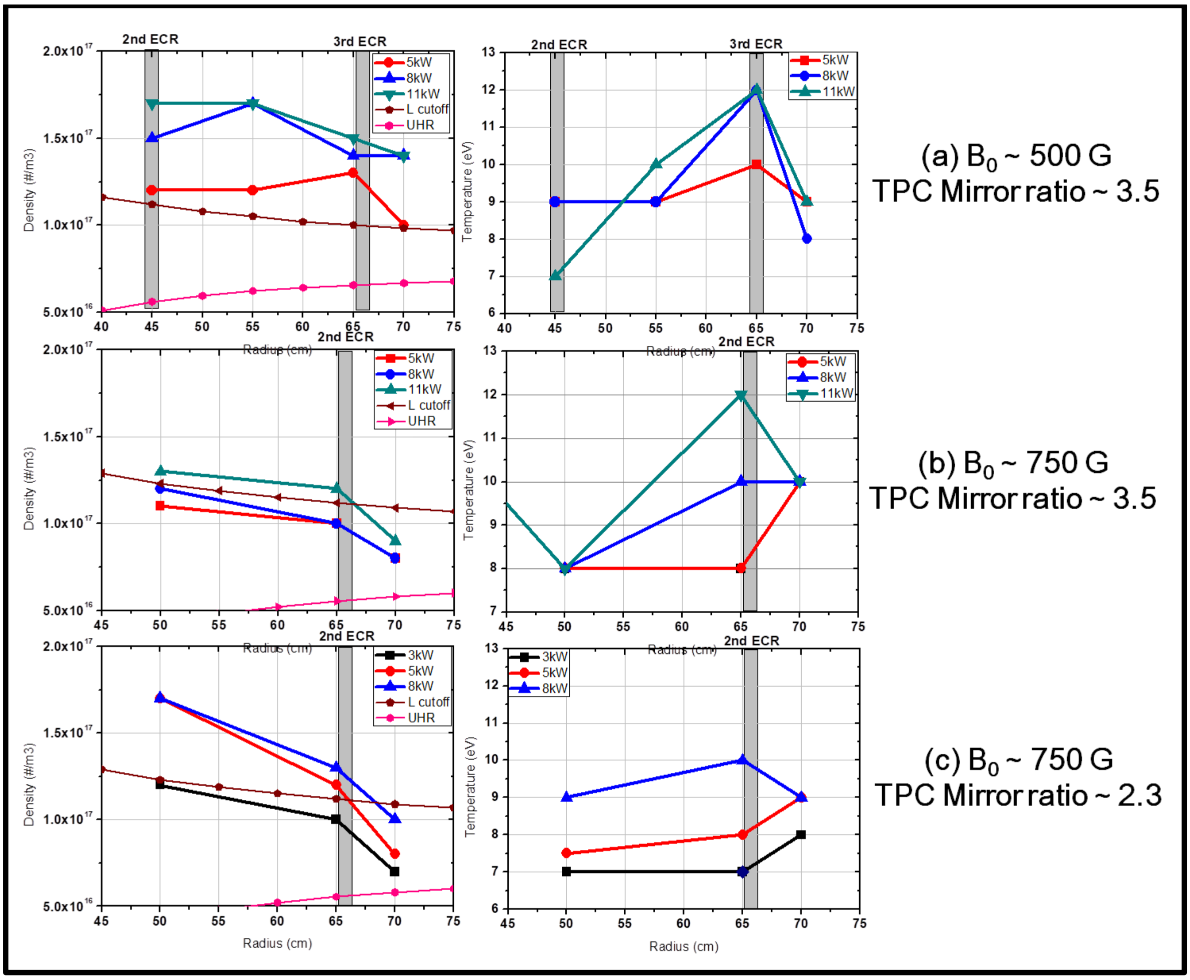

Fig. 6 The electron temperature rise near harmonics along ECH power in case of
(a) B_0 ~ 500 G and TPC ratio ~ 3.5 (b) B_0 ~ 750 G and TPC ratio ~ 3.5 (c) B_0 ~ 750 G and TPC ratio ~ 2.3

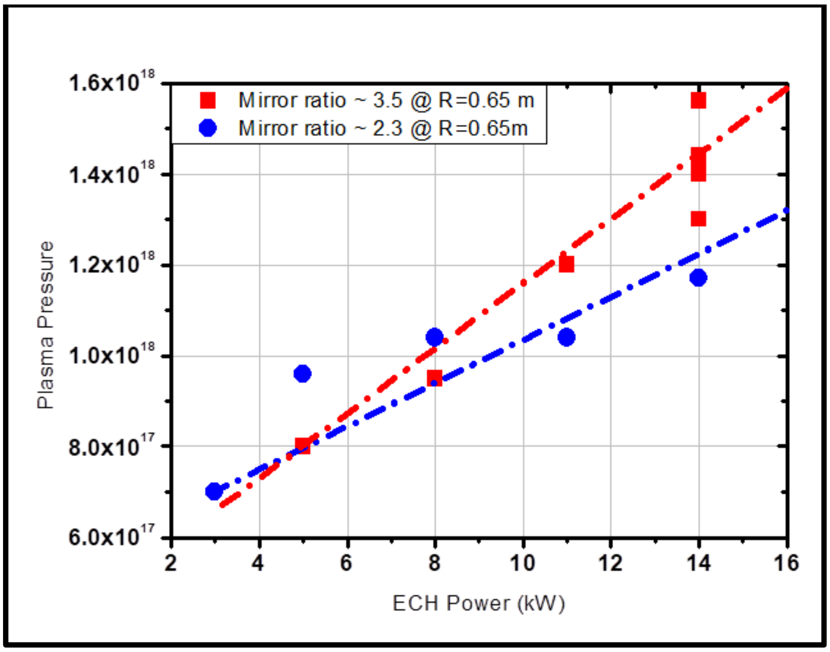

Fig. 7 The dependency on plasma pressure along ECH power with TPC mirror ratio

To decrease the resistivity of pre-ionization plasma, the ECR harmonic resonance is located near outboard to increase the electron temperature as shown in Figure 6. In case of Figure 6 (a) that the 3rd resonance is located near outboard, the over dense plasma has been generated via EBW collisional damping and the electron temperature rise near 3rd resonance along ECH power increases. In case of Figure 6 (b) which 2nd resonance is located near outboard to control the toroidal field, the electron temperature rises near 2nd resonance. In case of Figure 6 (c) that is the same condition of Figure 6 (b) but the change of TPC mirror ratio, the over-dense plasma via EBW collisional damping and the electron temperature rise have been occurred simultaneously near 2nd resonance. The change of TPC mirror ratio affects to the change of particle confinement time and the higher mirror ratio make the higher plasma pressure possible with larger ECH power. It is expected that the much lower resistivity of pre-ionization plasma has been generated near outboard region.

4. DEVELOPMENT OF SOLENOID FREE STARTUP SCENARIO

Based on the 2D model of CFS formation, the poloidal field from plasma current must overcome the vertical field from outer PF coils. With the loop voltage from outer PF coils single swing, the vertical field increases simultaneously. Lower resistivity of pre-ionization plasma make higher poloidal field and under the resistivity of 2.5×10^{-5}, it satisfies with the condition of successful CFS formation as shown in Figure 8 (a). In previous chapter, the EBW experiments have been conducted to lower the resistivity of pre-ionization plasma. The pre-ionization plasma near outboard via EBW collisional damping and collisionless heating near harmonic resonance, have been generated with auxiliary heating system of higher power to decrease the resistivity under 2.5×10^{-5} as depicted in Figure 8 (b).

After the successful CFS formation, the plasma current has been demonstrated to be ramped-up with loop voltage from outer PF coils with help of reduced external inductance when the plasma column grows and moves inward. The plasma current evolution has been presented with 0-dimensional power balance modelling with consideration about force balance along plasma current [16]. The initial plasma current evolution has difficulty due to the size of CFS that causes resistive dissipation. Also, the induction voltage from outer PF coils has limitation that it is not easy to change rapidly due to eddy current from vessel wall and causes increase of vertical field that affects to CFS formation and equilibrium. The solenoid free start-up using outer PF coils must consider the distribution between flux from external inductance and resistive dissipation. In the CFS size of R~0.70 m and a~0.05 m, the huge flux from external inductance has been acquired from great change to the plasma shape and the resistive dissipation is also significant due to small size of CFS. In case of resistivity of 2.0×10^{-6}, the plasma current of R~0.70 m and a~0.05 m has the most increase from biggest flux from external inductance since the resistive dissipation has little influence as depicted in Figure 9 (a) and 9 (b). In case of resistivity of 1.0×10^{-5}, the plasma current doesn't grows up easily due to enormous resistive dissipation although the help of external inductance exists as shown in Figure 9 (c) and 9 (d). Therefore, it is important to make appropriate size and location of CFS formation for successful solenoid free start-up in VEST and for decreasing the resistivity of pre-ionization plasma, it is possible to utilize the limited flux from external inductance change efficiently.

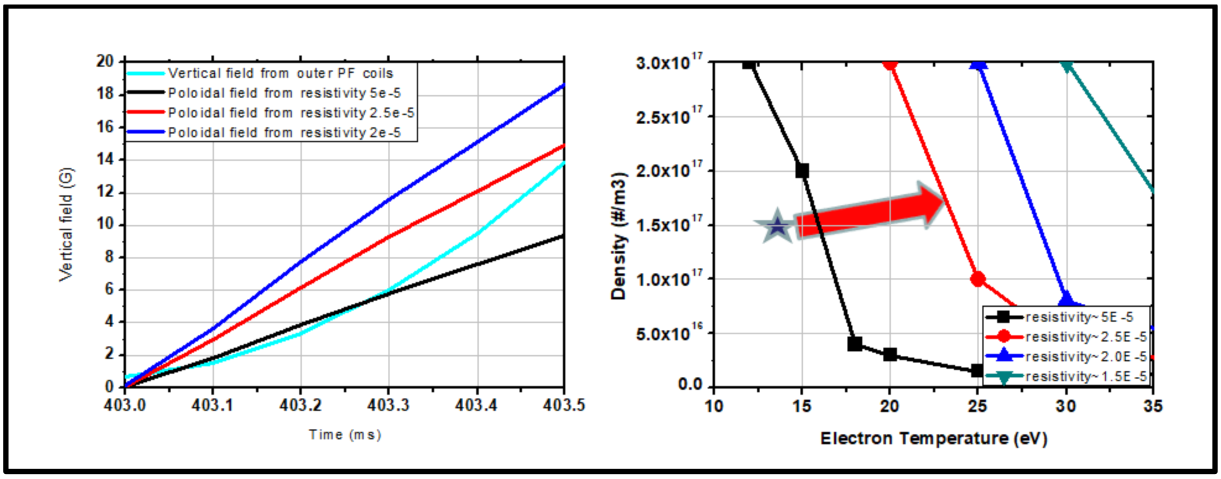

Fig. 8 (a) The condition for CFS formation near outboard (b) Lowering the resistivity of pre-ionization plasma

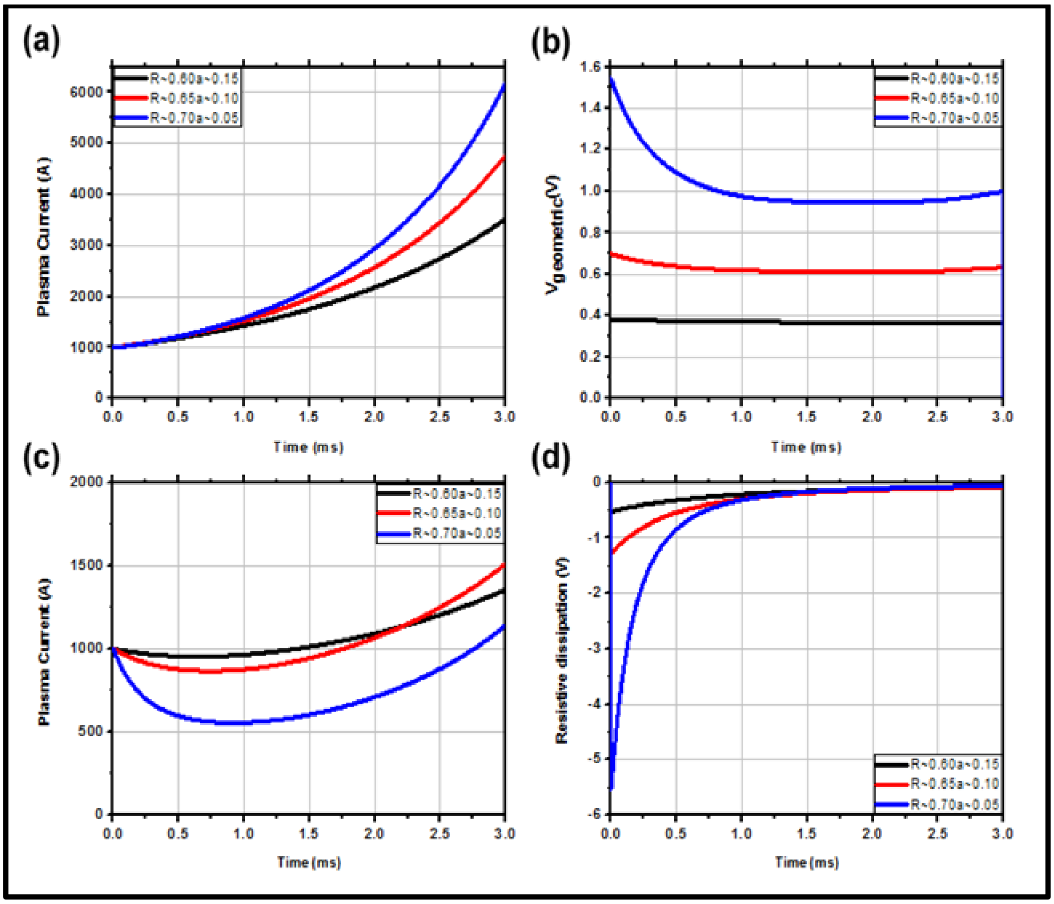

Fig. 9 in case of resistivity 2.0×10^{-6} (a) plasma current (b) voltage from external inductance change and in case of resistivity 1.0×10^{-5} (c) plasma current (b) resistive dissipation along the location and size of CFS

5. CONCLUSION

CFS formation, main factor of successful start-up, is convinced with 2D model and experiments with decreasing vertical field. The new criterion for CFS formation is suggested by considering quantitative resistivity of pre-ionization and the size of CFS.

The power of mode converted EBW has been deposed moving toward ECR by collisional damping and electron temperature increases in ECR harmonics by EBW collisionless heating near 2nd or 3rd harmonic resonance. For lower resistivity of pre-ionization plasma, the higher mirror ratio makes the higher plasma pressure possible with larger ECH power.

After successful CFS formation with the plasma of resistivity under 2.5×10^{-5}, the solenoid free start-up scenario using outer PF coils has been developed with 0D power balance model with consideration of the location and the size of CFS. For decreasing the resistivity of pre-ionization plasma, it is possible to utilize the limited flux from external inductance change efficiently.

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