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Plasma current ramp-up experiments in QUEST

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The Ohmic heating (OH) plasma currents up to 48 kA with a discharge duration of 65 ms are obtained in the Kyushu University Spherical Tokamak (QUEST) with the help of the electron cyclotron wave (ECW) and cancellation coils. In the first experimental campaign, some results were observed in the plasma current ramp-up phase which initially appeared contradictory. A smaller plasma current is obtained using an larger OH coil bias current of 8 kA while slightly larger and smoother plasma current is obtained using an lower OH coil bias current of 5 kA. We have found that the relatively short plasma current ramp-up time of 15~20 ms employed in these experiments provides the opposite vertical field to the equilibrium field due to the current induced in the vacuum chamber. The vertical field penetration time is ~5 ms, which is comparable to the current ramp-up time. Using the slower OH coil current variation in the initial OH coil current rise-up phase but with the reversed connection, a plasma current of 48 kA is obtained in 65 ms.

Keywords: spherical tokamak, current start-up, Ohmic discharge, Cancel coil, EBCD, vertical field

1. Introduction

Plasma current ramp-up has been recognized as a major difficulty in low aspect ratio spherical tokamaks (ST) [1] due to insufficient room for the central solenoid (CS) on the inboard side of the torus. A new concept has been proposed for ramping up the plasma current using the vertical field and heating power [2,3], and was successfully demonstrated on the JT-60U tokamak [4-6], TST-2 [7] and MAST [8] spherical tokamaks. In the first experimental campaign at QUEST, the maximum plasma current of 17 kA was obtained with the duration of 320 ms, where the plasma current was induced to 10 kA by an OH coil, and the additional 7 kA was driven by the vertical field after the OH coil current decayed to zero ("Ohmic clamp" phase[9]) [10]. Although the Ohmic pulse duration is very short, a much longer discharge duration can been obtained as a result of vertical field induction and runaway electron effects. During this first experimental campaign we have also found that larger OH coil current induces less plasma current in the plasma current ramp-up phase contrary to our expectation. In this paper, we describe the cause of these unexpected results and how, by considering these effects, it is possible to increase the plasma current. We demonstrate that the slower OH coil current variation method can induce the larger plasma current by reducing the vacuum chamber effect.

2. Experimental layout

QUEST has been constructed to achieve steady state operation with a plasma current of ~20 kA using the electron Bernstein current drive (EBCD) and to study the plasma wall interaction in high temperature (~500 degree C) environments [11]. Operation scenarios of the experiment could be categorized as follows: (1) pure Ohmic discharge, (2) Ohmic and RF current drive and (3) pure RF start-up to the steady state, and (4) vertical field assisted plasma current start-up and RF current drive to the steady state.

In QUEST, we have employed the canceling coil method to reduce the stray field from the OH coil and to simplify the vertical field control during the plasma current flat top phase as employed in TST-2 [12], KTM [13] and Globus-M [14]. As the Ohmic transformer and the cancellation coils are connected in series, the cost of the power supply circuit can be reduced, and its ripple effect disappears. In QUEST, the major radius is R ~ 0.68 m, the minor radius is a ≤ 0.40 m, the elongation is κ≤ 1.8, and the toroidal field is $B_t \le 0.5$ T. The launcher for the electron cyclotron wave (ECW) and for the Electron Bernstein Wave (EBW) heating at a frequency of 8.2 GHz is installed on the outboard side of the torus in QUEST [15]. The cut-off density for the O-mode is 0.83×10^{18} m^{-3}. A weak toroidal field of $B_t = 0.14$ T at R = 0.68 m was used in the first experimental campaign, resulting in the resonant position of 8.2 GHz RF being at 33 cm. Since the power supply circuit for the high field tokamak TRIAM-1M is used without modification, the OH coil current waveform is not controllable.

3. Comparison of the plasma current evolutions for the OH coil bias currents of I_{CS}=8 and 5 kA.

Waveforms of the plasma current, OH coil, and PF26 and PF17 coil currents are shown in Fig. 1, which were

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obtained during the first experimental campaign. The left column shows the case for the central solenoid current I_{CS} = 8 kA while the right column shows the case for I_{CS} = 5 kA. As can be seen in Fig. 1,the observed plasma current during the current ramp-up phase is always larger and smoother in the case of I_{CS}=5 kA. It is known that the larger Ohmic coil current induces a larger plasma current. However, these results show no such dependencies. Attempts to optimize the plasma position by adjusting the vertical field coil current proved unsuccessful. As the OH coil ramp-down rate cannot be controlled due to circuit limitation, it is difficult to make an optimization during the plasma current ramp-up phase. In the following section we discuss this problem in greater detail.

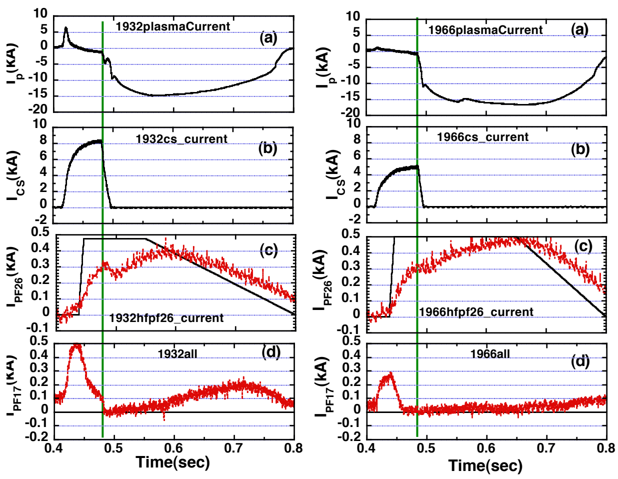

Fig. 1. Plasma current evolution in QUEST at B_t=0.14 T with the one turn cancellation coil. Left column shows I_{CS}=8 kA (#1932) and right one I_{CS}=5 kA (#1966). (a) Plasma current, (b) CS (or OH) current, (c) PF26 vertical shaping coil current (N_{PF26}=72 turns) and set value, (d) PF17 vertical field coil current.

4. Experimental and numerical results of the effect of the vertical field induced by the vacuum chamber current

In order to study the effect of the vacuum chamber on plasma breakdown, we performed the flux measurements inside the vacuum chamber during a period of machine maintenance. The various sized arch-shaped flux coils were first arrayed horizontally in the mid-plane of the vacuum chamber in order to measure the flux Φ and then the OH coil circuit alone was turned on. By numerically differentiating the flux with respect to the flux coil area S, the magnetic field was determined by B=dΦ/dS. In Fig. 2, the OH coil current, the measured vertical field inside the vacuum chamber at the major radii of R=0.4 m, 0.6 m, 0.8 m, 1.0 m and 1.2 m, and the loop voltage are shown for the OH coil current of I_{CS}=8 kA. It is seen that the measured vertical field (Fig.2-(b)) is not proportional to the OH coil current. This means that the vertical field produced by the vacuum chamber current due to OH coil induction is superimposed on the magnetic field produced by the OH coil. It is also seen in Fig.2-(b) that the null point exists on R=0.8 m at just the beginning of the OH coil current ramp-down.

In Fig. 3, the same measurement is shown for I_{CS}=5 kA. It is clearly seen that the vertical field induced by the vacuum chamber is lower than that in the I_{CS}=8 kA case.

Numerical calculations of the vacuum chamber current using the computer code ("EDDYCAL"(JAEA)) have been conducted separately. Results are shown in Fig. 4 and 5 for I_{CS}=8 kA and 5 kA, respectively.

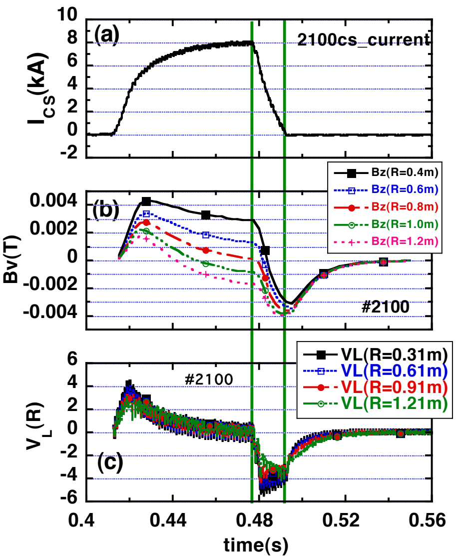

Fig.2. Measured vertical field inside the vacuum chamber for I_{CS}=8 kA. (a) the CS coil current, (b) measured magnetic fields Bv at various positions and (c) the loop voltages. (#2100)

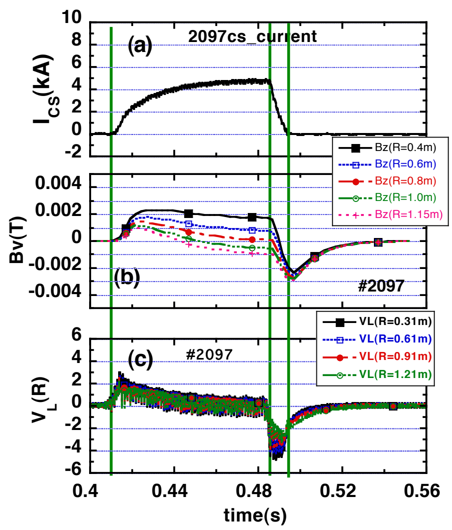

Fig. 3. Measured vertical field Bv inside the vacuum chamber for I_{CS}=5 kA. (#2097)

The total vertical field from the OH coil current and the vacuum chamber current (corresponding to experimental results), the magnetic field produced by the OH coil

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without the vacuum chamber effect, and the magnetic field created from the vacuum chamber current are shown for the positions corresponding to experimental results. The calculated waveform of the total vertical field in Fig. 4-(a) is quite similar to the experimental waveform, however the measured values are almost 50~80% of the calculated values. This discrepancy is the result of not taking into account in the numerical calculations the effect of the diagnostic ports. The effect is especially large on the outward side of the vacuum chamber which has several large diagnostic ports, for example, six circular ports with a diameter D = 498 mm, five ports with D = 345 mm, three ports with D = 249 mm, and four ports with D = 200 mm. This may result in a reduction of the actual vacuum chamber current and hence a smaller magnetic field would be produced inside the vacuum chamber. The null point exists on R = 0.8 m at the beginning of the OH coil current ramp-down as well as in the experimental results shown in Fig. 4-(a). We should note that it is quite advantageous to conduct numerical calculations because the magnetic fields from the OH coil and vacuum chamber current can be separated. It is seen in Fig. 4-(c) that the magnetic field created by the vacuum chamber current has a uniform magnitude inside the vacuum chamber. At t=0.012s in the initial rise-up phase of OH coil current, the peak vertical field produced by the vacuum chamber current is ~45 Gauss, and 60 gauss at t=0.08 s in the OH coil ramp-down phase. It should be noted that these measured and calculated vertical fields have an opposite direction to the equilibrium vertical field. The outer vacuum chamber current contributes to make this opposite vertical field.

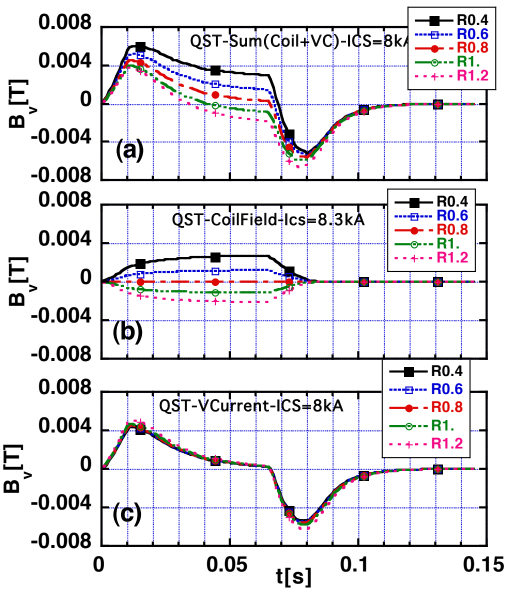

Fig.4. Calculated vertical field inside the vacuum chamber for I_{CS}=8 kA. (a) Total magnetic field, (b) magnetic field from the CS coil without the effect of the vacuum chamber, and (c) magnetic field produced by the vacuum chamber current.

For the lower OH coil current of I_{CS}=5 kA, the magnetic fields from the vacuum chamber current are smaller as shown in Fig. 5. The waveform of the total vertical field in Fig. 5-(a) is also quite similar to the experimental waveform, but the measured value is almost 50~80 % that of the calculated value, similar to the case of I_{CS}=8 kA. A vertical field of 40 Gauss is produced by the vacuum chamber current at t~0.085 s in the OH coil current ramp-down phase as shown in Fig. 5-(c).

The opposite vertical field produced inside the vacuum chamber together with the slower penetration of the vertical field may make it problematic to achieve equilibrium during the short plasma current ramp-up phase. In Fig. 1-(a) with the use of an OH coil current of 8 kA, the actual vertical field produced inside the vacuum chamber in the initial OH coil current ramp-down phase is smaller than that produced in the case of 5 kA operation for the same PF26 coil current, preventing a smooth current ramp-up.

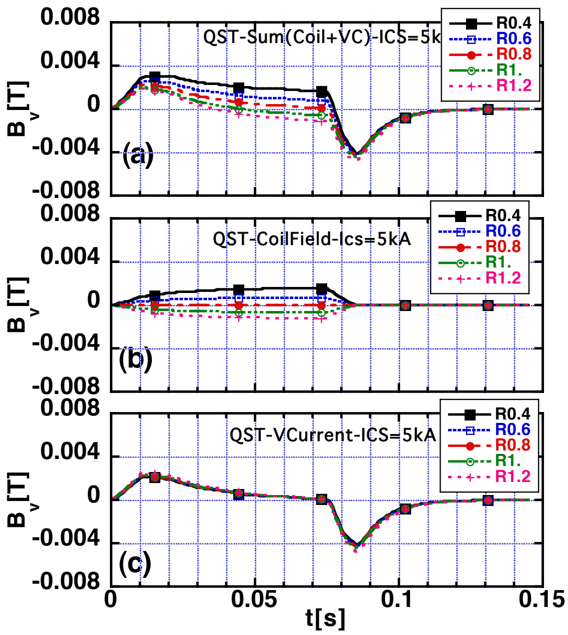

Fig.5. Calculated vertical field inside the vacuum chamber for I_{CS}=5 kA. (a) Total magnetic field, (b) magnetic field from the CS coil without vacuum chamber effect, and (c) magnetic field produced by the vacuum chamber current.

These experimental and numerical results imply that employment of the slower ramp-down of the OH coil current could produce the better plasma equilibrium and larger plasma current during the current ramp-up phase working together with better vertical field penetration.

5. Slower OH coil current ramp-down experiments for larger plasma current.

After careful analysis of the vertical field created by the vacuum chamber current as described above, it was

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concluded that OH coil currents should be ramped down slowly in order to create a larger plasma current. As it was impossible to increase the OH coil current decay time due to circuit limitations in this stage, we have used the initial slower rise-up phase of the OH coil current, but with the reverse connection to the OH coil circuit for the same plasma current polarity. Since both vertical fields produced by the vacuum chamber current in the initial rise-up phase of I_{CS} = 8 kA and in the ramp-down phase of I_{CS} = 5 kA are comparable, a good plasma current evolution is expected.

Such discharges were tested. The overall discharge waveforms for various parameters (#3310) are shown in Fig. 6. The OH coil current is ramped down from 0 kA without a bias current in the initial breakdown phase. After optimization of the PF26 coil current, the plasma current was eventually ramped up to 48 kA in 65 ms. As the maximum current of PF26 coil was limited at 2 kA for safety reason, the pulse length of the plasma current was limited at 65 ms.

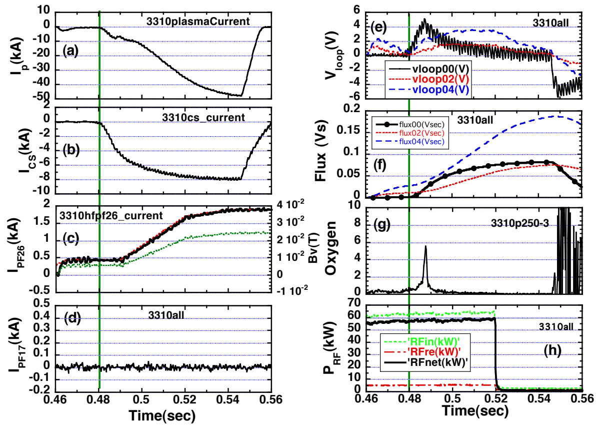

Fig.6. The plasma current evolution for the slower OH coil ramp-down. (a) Plasma current, (b) CS current, (c) PF26 vertical shaping coil current (N_{PF26}=36 turns) and vertical field, (d) PF17 vertical field coil current, (e) loop voltage measure at three locations, (f) measured fluxes at three locations, (g) oxygen impurity line, and (h) 8.2 GHz RF power. (#3310)

We note that without any bias Ohmic coil current in the initial phase, a magnetic field does not exist in the entire regime inside the vacuum chamber when the vertical field is not applied. However, in the actual discharge, a constant vertical field was initially applied for reliable breakdown. The magnetic field strength distribution in the breakdown phase is shown in Fig. 7. At the resonant position the vertical field is 80 Gauss. For a bias current of I_{CS} = 8 kA as shown in Fig. 1 (left column), the resulting magnetic field strength distribution is shown in Fig. 8 and the initial vertical field at the resonant position is ~110 Gauss. As the plasma current could be started up as demonstrated in Fig.1 (left column), it would be possible to employ the slow OH coil current ramp-down method from +8 kA to 0 kA, although the initial vertical field is different by 30 Gauss.

A fast TV camera was used to monitor the cross-section and position of the plasma for 3 ms after the plasma current start-up as shown in Fig. 9. The plasma current appears to start on the central Ohmic transformer at R ~ 0.23 m at t = 0.4852 s and begins to expand outwards at t = 0.4866 s, and the closed flux surface could be seen on the limiter at 0.48745 s. After this time the plasma boundary is no longer clear due to low-density operation as shown in Fig. 9-(d). The TV camera can only be used to monitor the initial phase as a result of the very low density. In this experiment no attempt was made to increase the density by gas puffing. In future experiments utilizing larger plasma currents and longer duration discharges it may be possible to observe the plasma edge by employing the gas puffing technique.

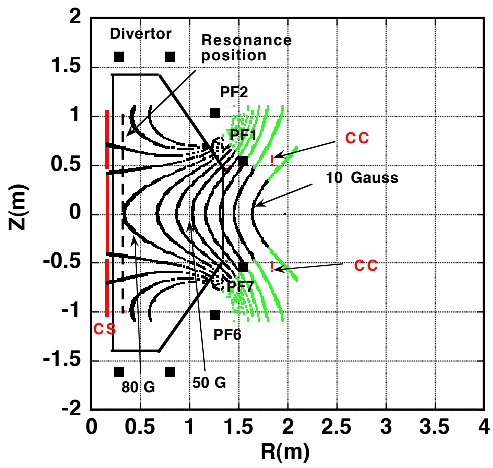

Fig. 7. Magnetic field strength for I_{CS}=0 kA and I_{PF26}=0.5 kA. Black contour lines show the direction of the equilibrium vertical field and green contour lines show the opposite direction to the equilibrium vertical field.

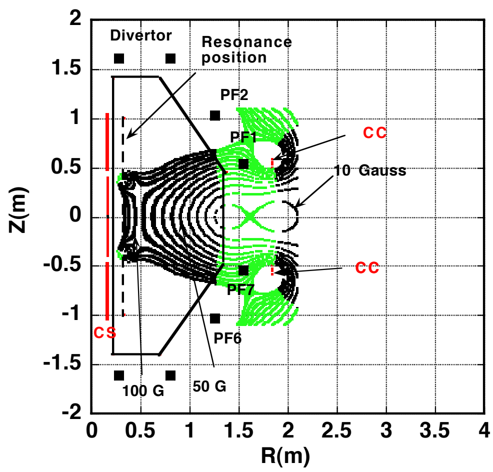

Fig. 8. Magnetic field strength for I_{CS}=8 kA and I_{PF26}=0.5 kA. Black contour lines show the direction of the equilibrium vertical field, and green contour lines show the opposite direction to the equilibrium vertical field.

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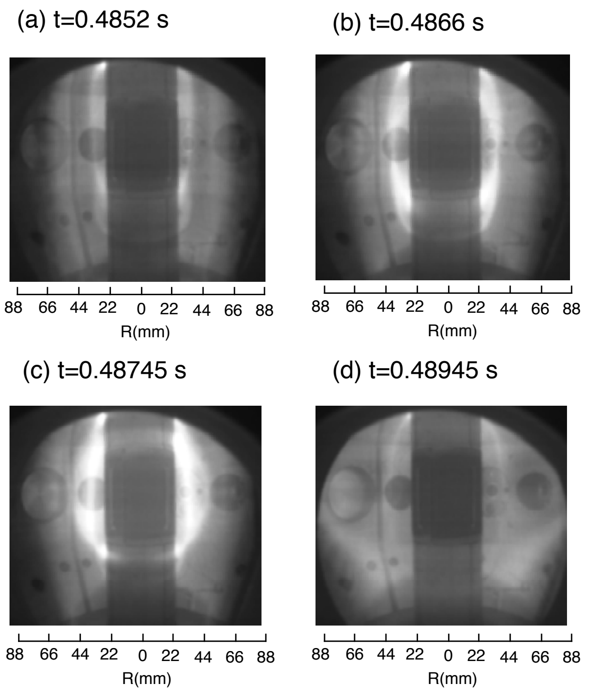

Fig. 9. Fast TV camera in the initial plasma current start-up phase. (#3310)

6. Record value of the previous operation scenario for I_{CS}=5 kA

Using the fast OH coil current ramp-down method shown in Fig.1 (right column), a record value for the operation of QUEST was achieved. Further adjustment of the vertical field allowed a plasma current up to 22 kA to be achieved, as shown in Fig. 10, exceeding the previously obtained value of 17 kA (#1966). It is clearly seen that the plasma current of 10 kA is due to OH coil induction between 0.49 and 0.50 s. The remaining 12 kA is driven by the vertical field induction which occurs between 0.50 and 0.60 s, when the Ohmic coil current is zero.

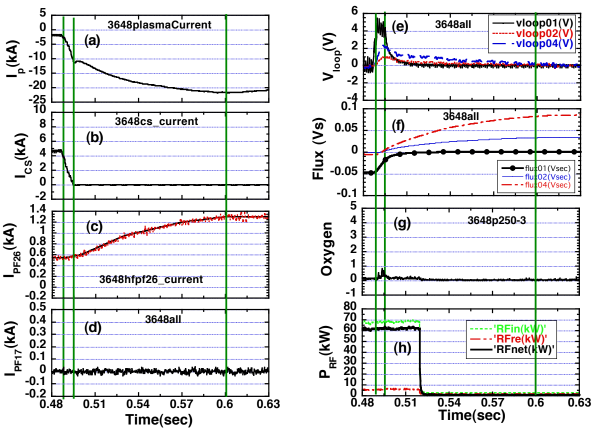

Fig. 10. The plasma current evolution for the slower OH coil current ramp-down. (a) Plasma current, (b) CS current, (c) PF26 vertical shaping coil current and set value, (d) PF17 vertical field coil current, (e) loop voltage measured at three locations, (f) measured fluxes at three locations, (g) oxygen impurity line, and (h) 8.2 GHz RF power. (#3648)

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7. Other plasma current ramp-up experiments

For the experiments described in the preceding sections the toroidal field was B_t = 0.14 T, which is less than 0.25 T for the EBCD. Therefore, a higher field of 0.175 T was tried with the OH coil bias current of I_{CS} = 5 kA. The resonant layer was around 0.38 m. However, the plasma current ramp-up was not as good as in the 0.14 T case, as can be seen in Fig. 11. Although this operation has not yet been fully optimized this result suggests that the outward resonant layer away from the stronger electric field side induced by the OH coil may not be suitable for better plasma current ramp-up. If the sound plasma evolution cannot be made in the higher toroidal field, the toroidal field could be increased to 0.25 T after the plasma current ramp-up.

However, we have not yet tried the slower current ramp-up experiment with the higher toroidal field. There remains the possibility to ramp up the plasma current smoothly in the higher toroidal field.

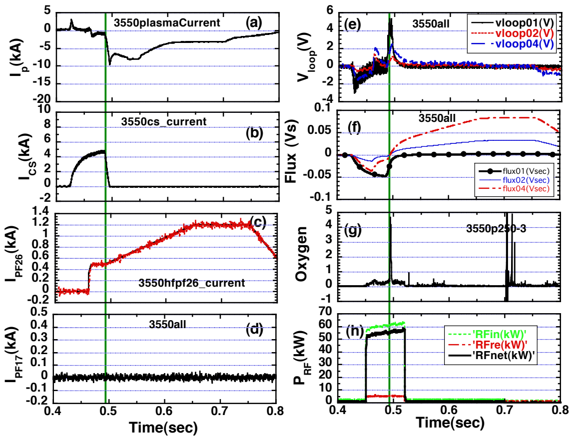

Fig. 11. The plasma current evolution for the higher toroidal field of 0.175 T. (a) Plasma current, (b) CS current, (c) PF26 vertical shaping coil current and set value, (d) PF17 vertical field coil current, (e) loop voltage measured at three locations, (f) measured fluxes at three locations, (g) oxygen impurity line, and (h) 8.2 GHz RF power. (#3550)

CS-less operation would be the ultimate goal of the plasma current ramp-up experiments in QUEST. Some experiments on CS-less operation have been tried as shown in Fig. 12. Here, the OH coil is completely disconnected. The PF26 coil current for the vertical field is swung from the opposite to the equilibrium direction. In the start-up phase a plasma current of 3 kA is induced and then decreased quickly, however a small plasma current remains for ~0.1 s. In this operation, the vertical field initially applied is too large for equilibrium, causing the plasma to be pushed inward. A smaller vertical field should be applied although the induced plasma current would become smaller. In this operation scenario, the divertor coil may push the plasma outward, helping to control the plasma position. This will be attempted in the near future.

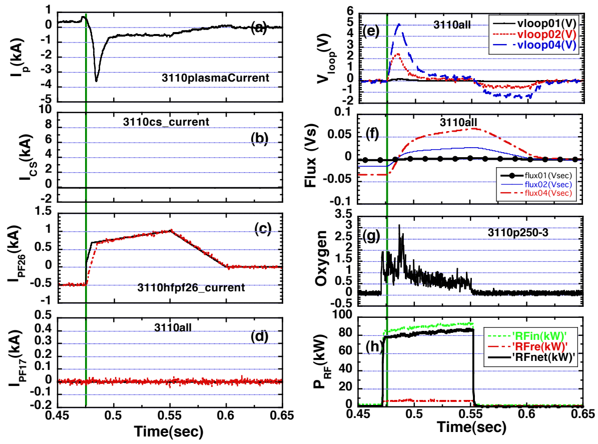

Fig. 12. The plasma current evolution in the CS-less operation. (a) Plasma current, (b) CS current is zero, (c) PF26 vertical shaping coil current and set value, (d) PF17 vertical field coil current, (e) loop voltage measured at three locations, (f) measured fluxes at three locations, (g) oxygen impurity line, and (h) 8.2 GHz RF power. (#3110)

8. Discussions, summary and future plan

Inconsistencies in some results observed in the first experimental campaign at QUEST, where a larger OH coil bias current provided a smaller plasma current ramp-up, have been resolved. We have found that the relatively short OH coil current ramp-down time of 15~20 ms employed in these experiments provides the opposite vertical field to the equilibrium field as a result of the current induced in the vacuum chamber. It is therefore difficult to control the plasma position in equilibrium during the short plasma current ramp-up phase. Taking these results into consideration it is demonstrated that by using a slower OH coil current ramp-down and reversing its connection it was possible to generate a larger plasma current of 48 kA in 65 ms in QUEST.

Another aspect of these experimental results is worth noting. The plasma current formed on the inner limiter was observed using a TV camera where the resonant position is 0.33 m and the electric field is strongest. The stray vertical field (parallel to the equilibrium vertical field) from the OH coil is stronger at the resonant position in the case of I_{CS} = 8 kA, resulting in the plasma current initially being pushed inward. However, the opposite vertical field produced by the vacuum chamber current can cause the plasma to move in the outward direction. Thus the OH coil bias current of I_{CS} = 5 kA may provide the most suitable vertical field.

It has been demonstrated that the slower OH coil current variation is favorable for ramping up to larger plasma currents. The OH power supply circuit is currently being modified to enable a slower OH coil current decay waveform as shown in Fig. 13. Using this new circuit it should be possible to achieve larger and longer plasma currents, resulting in a much better plasma current evolution.

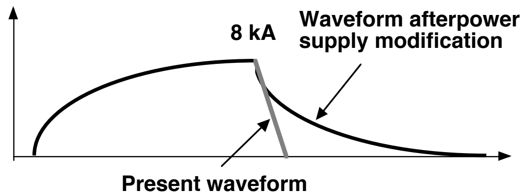

Fig. 13. Schematic waveform for future CS operation.

This will be of considerable advantage for the EBCD experiment because there will be sufficient time to increase the toroidal field from 0.14 to 0.25 T, and for increasing the density to $2x10^{18}$ m^{-3}. There will also be sufficient time to adjust the injection angle of the EB wave, which takes ~30 ms [15]. If the density could be further increased then the plasma current would be decreased. In this case the slower OH coil current operation would be necessary for future ~20 kA EBCD experiments. The operational waveform already achieved is also suitable for the steady state operation of QUEST in the future, because the Ohmic transformer is already switched off.

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References

[1] Y-K M. Peng et. al., Fusion Technology, **30** (1996) 1372.

[2] O. Mitarai, Plasma Physics & Controlled Fusion, **41** (1999) 1469.

[3] O. Mitarai and Y. Takase, Fusion Science and Technology, **43**, No. 1 (2003) 67.

[4] O. Mitarai, R. Yoshino and K. Ushigusa, Nucl Fusion, **10** (2002) 1257.

[5] Y. Takase et. al., Journal of Plasma and Fusion Research **78** No.8 (2002) 717

[6] S. Shiraiwa, et al., Physical Rev. Lett., **92** No. 8, (2004) 035001-1

[7] O. Mitarai, Y.Takase, A.Ejiri, S. Shiraiwa, et al., Journal of Plasma and Fusion Research, Vol. **80**, p549-550 (2004)

[8] A. Sykes, et al., in 19th IEEE/NPSS Symposium on Fusion Engineering (SOFE), (Atlantic City, USA, January 22-25), (2002) 125

[9] O. Mitarai, C.Kessel and A. Hirose, JEEE (2009) Sec. A, Vol. **129,** No. 9. p605

[10] O. Mitarai et al., (2009,10) submitted

[11] K. Hanada et al., "Physical design of MW-class steady state spherical tokamak QUEST", in 22nd IAEA Fusion Energy Conference, (13-8, Oct. 2008, Geneve, Switzerland) FT/P3-25.

[12] S. Shiraiwa,"A study of electron Bernstein wave heating for diagnostics and heating of spherical tokamak plasmas", PhD theses (Univ. of Tokyo, April 27, 2007) .

[13] V. A. Korotkov et al., Fusion Engineering and Design **56 – 57** (2001) 831.

[14] V. K. Gusev et al., Nuclear Fusion Vol 41 ,7 (2001) 919

[15] H. Idei, et al., "Ray tracing and Fokker-plank analyses for electron Bernstein wave heating and current drive in QUEST", ICCP 2009 (Fukuoka).

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