Stable plasma start-up in the KSTAR under various discharge conditions

J. Kim[1]+,++, S.W. Yoon[1], Y.M. Jeon[1], J.A. Leuer[2], N.W. Eidietis[2], D. Mueller[3], S. Park[4], Y.U. Nam[1], J. Chung[1], K.D. Lee[1], S.H. Hahn[1], Y.S. Bae[1], W.C. Kim[1], Y.K. Oh[1], H.L. Yang[1], K.R. Park[1], H.K. Na[1] and the KSTAR team

[1]National Fusion Research Institute, Republic of Korea
[2]General Atomics, USA
[3]Princeton Plasma Physics Laboratory, USA
[4]Pohang University of Science and Technology, Republic of Korea
+Lead Author, ++Speaker - *jayhyunkim@nfri.re.kr*

1. Background

The goal of tokamak start-up treated in this research is to raise plasma current up to 100 kA in the Korea Superconducting Tokamak Advanced Research (KSTAR) device. At that level, the Plasma Control System (PCS) can switch from preprogrammed coil control to plasma feedback control.

Start-up of the KSTAR device differs from typical tokamak start-up in two aspects. First of all, the KSTAR device requires a Blip Resistor Insertion System (BRIS) to produce sufficient change of poloidal field (PF) coil current during the initial stage of discharge due to limited voltage capability of PF power supplies[1]. In order to use the BRIS, outer PF coils also need to be charged even though magnetic field generated by the outer PF coils degrades initial field null quality[1]. This complicates the start-up of the KSTAR device due to short connection length of charged particles to the wall.

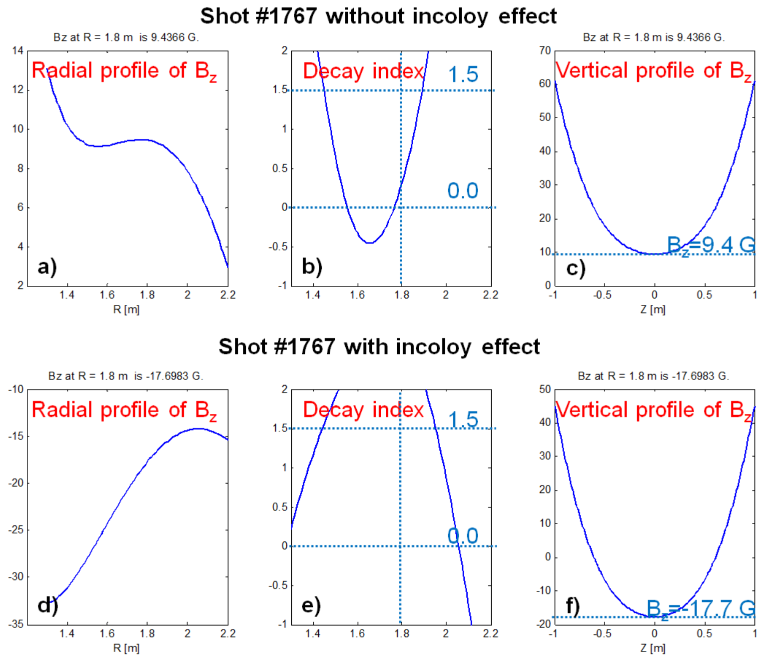

Fig. 1 Deformation of the inital magnetic field structure due to the ferromagnetic effect of incoloy 908.

The other unconventional aspect of KSTAR start-up originates from ferromagnetic material incoloy 908 used in the PF and toroidal field (TF) coils. Figure 1 shows numerical simulation result of initial magnetization with and without inclusion of the ferromagnetic effects[2]. The initial magnetization depicted in Fig. 1 was used in electron cyclotron heating (ECH) assisted start-up during the 2009 KSTAR campaign. It was found that the ferromagnetic effect dramatically changes the radial profile of the vertical magnetic field along with the field strength itself. The numerical result of nonlinear ferromagnetic simulation exhibits good agreement with direct Hall sensor measurement[2].

Due to the magnetic field of non-solenoidal outer PF coils, the KSTAR start-up scenario utilizes delicate counter-balance among the PF coils. The tolerable level of field null quality is only several tens of gauss for successful start-up in the KSTAR device. Therefore the ferromagnetic effect becomes more significant under the circumstance of subtle field balance during the plasma start-up.

In detail, the result presented in the first row of Fig. 1 is calculated without considering the ferromagnetic effect. When compared with the nonlinear ferromagnetic simulation depicted in the second row of Fig. 1, the radial gradient of the vertical magnetic field alters its sign due to relatively strong ferromagnetic effect near the inboard side. The decay index profiles illustrated in figures 1b) and 1e), which determine positional stability of tokamak plasma, show totally opposite shapes from each other. It is noteworthy that most of the failed shots in the KSTAR 2009 campaign exhibited an inboard crash during the initial stage while a vertical crash was hardly ever observed. It seems that the start-up scenarios used in 2009 could not guarantee the stability of the radial position. The nonlinear ferromagnetic simulation illustrated in Fig. 1e) reveals that the decay index indicates radially unstable values, i.e. above 1.5, over most of the discharge area. This could explain well the experimental observation contrary to the result without the ferromagnetic effect shown in Fig. 1b).

2. Approach

As a matter of fact, the establishment of tokamak start-up scenarios necessitates time-dependent calculation with consideration of eddy currents in conducting structures such as the vacuum vessel and passive stabilizers. The nonlinear ferromagnetic effect makes the problem difficult because numerical method based on the Green's function cannot be directly applied in calculating the magnetic field structure. In order to overcome this difficulty, we adopted slightly simplified method. In this work, time-dependent simulation is mimicked by a series of nonlinear ferromagnetic calculations with given PF coil currents and eddy currents at specific times. Prior to these nonlinear calculations, time-dependent PF coil currents and eddy currents need to be obtained by solving coupled circuit equations based on the Green's function method. It could be justified because the ferromagnetic material only exists in the PF and TF

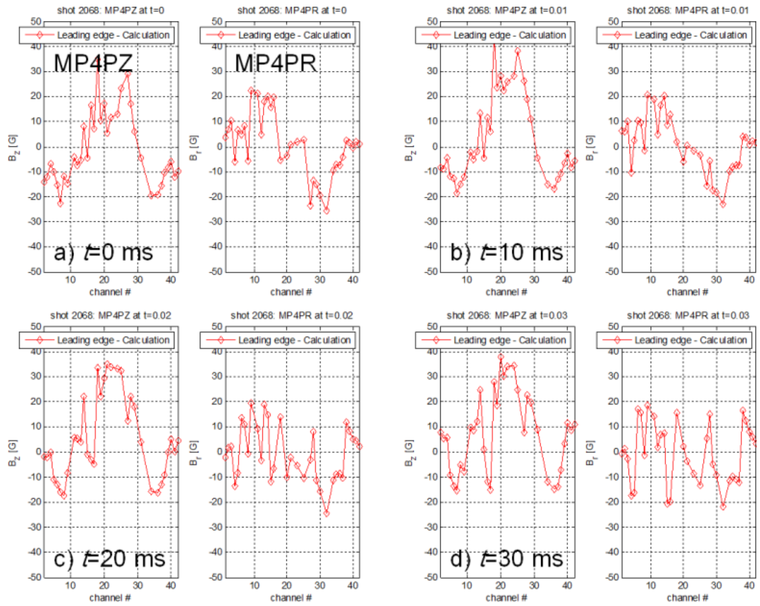

Fig. 2 Discrepancies between the measured MP signals and the calculated values at specific times. The channel numbers are designated in counter-clockwise order from the outboard mid-plane. The MP channels #21 and #22 are positioned near the inboard mid-plane.

coils and mutual coupling between the conducting structures might not be seriously affected by the ferromagnetic effect.

In addition to the assumption, the feasibility of the proposed method was checked by comparing measured magnetic probe (MP) signals with calculated values at specific times. Figure 2 represents discrepancies between the measured MP signals and the calculated values in the KSTAR vacuum shot 2068. Most of the MPs show reasonable agreements within 20 gauss level, while the discrepancies of the inboard MPs become more than 50 gauss level without inclusion of the incoloy effect even at the initial magnetization state.

There exists a tendency that the discrepancies near the inboard mid-plane grow as time passes. The increment of discrepancies could be explained by two reasons. One reason is an imperfectness of the circuit model in describing real conducting structures. For instance, inboard limiter is not included in the model because toroidally-separated limiter segments do not form a concrete circuit in toroidal direction, whilst eddy current could flow through loose contact with the vacuum vessel. The time behavior of eddy current near the inboard mid-plane agrees well with that of the MP discrepancies. It is noteworthy that the increase of MP discrepancies is saturated within 30 gauss level after wall penetration time (~40 ms). The other possible explanation comes from nonlinear behavior of the incoloy magnetization especially in the self/mutual inductances of central solenoid coils (*i.e.* PF1~4 coils). In fact, the measured PF current waveform slightly differs from the calculated one with using the Green's function-based self/mutual inductances. The quantitative analysis is beyond the research scope.

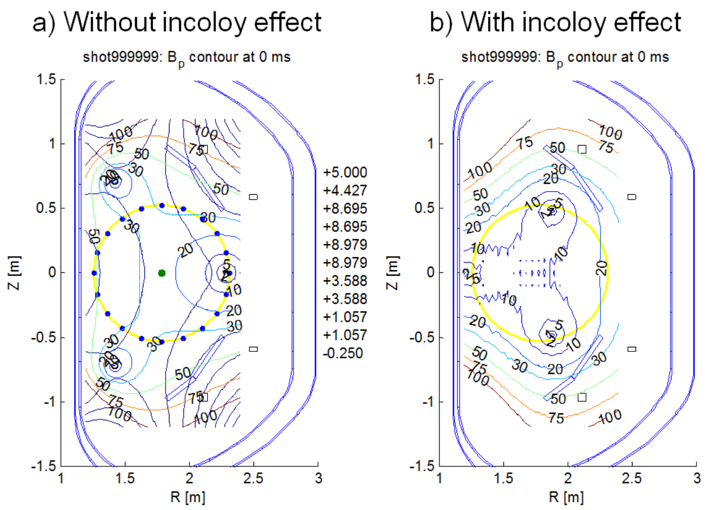

Fig. 3 Initial magnetization state of ECH-assisted start-up for the 2010 KSTAR campaign. Field null structure is formed when incoloy effect is included.

3. Established start-up scenarios

Systematic efforts are being conducted to establish robust start-up scenarios with compensation of the above mentioned ferromagnetic effects. The efforts are aimed at both ECH-assisted start-up and pure Ohmic start-up. It is expected that positional stability will guarantee stable start-up against variations of the operation conditions. The developed scenarios were applied in the 2010 KSTAR campaign and the start-up experiments based on the scenarios showed good positional stability.

3.1 ECH-assisted start-up with 110 GHz 2nd harmonic EC resonance

Although conventional tokamak start-up relies on toroidal electric field induced by a transformer action of PF coils to ionize neutral gas, ECH-assisted start-up utilizes EC resonance of electro-magnetic wave at resonant position to produce a pre-ionization state before PF coil blip. In the KSTAR device, 110 GHz EC wave makes 2nd harmonic resonance at *R*=1.8 m with 2 T toroidal magnetic field.

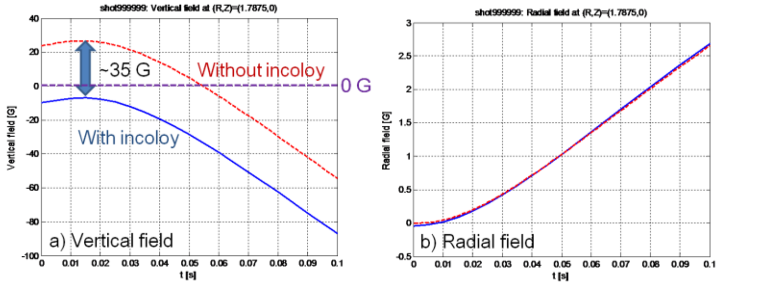

Fig. 4 a) Time-dependent evolution of B_z at field null center, R=1.8 m, b) time-dependent evolution of B_r at field null. Red-dashed line is a result without the incoloy effect and blue-solid line is a result with incoloy effect.

In order to prevent a direct loss of charged particles along open magnetic field line, it is crucial to maintain field null area, which has low magnetic field level perpendicular to toroidal magnetic field, as large as possible until closed flux surface is formed. When incoloy effect is added, field structure in Fig. 3a) is transformed to field null structure as shown in Fig. 3b). Indeed, charged particles feel the field structure depicted in Fig. 3b) rather than in Fig. 3a).

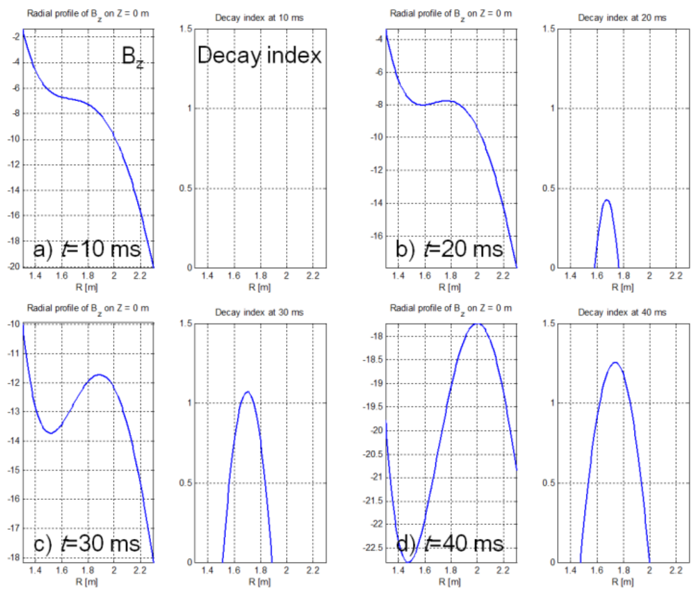

Fig. 5 Time-dependent evolution of radial B_z profile and corresponding decay index in ECH-assisted start-up scenario for the 2010 KSTAR campaign.

After the formation of plasma current channel, vertical magnetic field needs to increase along with plasma current ramp-rate to satisfy a toroidal equilibrium. According to the result of previous KSTAR campaigns, plasma current channel starts to form around *t*=15 ms after PF coil blip. The early control of vertical magnetic field has to depend on feedforward control by pre-programmed PF coil current rather than feedback control since plasma current level is too low to guarantee stable feedback signal. Figure 4a) shows time-dependent evolution of vertical magnetic field at field null center. According to incoloy effect, the actual value is almost 35 gauss lower than the value without the incoloy effect. On the other hand, incoloy distribution is up-down symmetric thus the incoloy effect does not affect radial magnetic field. In Fig. 4b), radial magnetic field at field null center evolves as time increases because the KSTAR cryostat has an up-down asymmetric geometry.

If a positional stability is assured in pre-programmed scenario, plasma current naturally moves to equilibrium position and grows there even though the plasma current ramp-rate is slightly mismatched with pre-programmed vertical field evolution. In contrast, with unfavorable positional stability, plasma is easily ended with a crash on vacuum vessel because equilibrium point exists only at limited area. A decay index, which measures a positional stability of plasma current channel, is examined around the channel formation time under the established ECH-assisted start-up scenario in Fig. 5. As shown in Fig. 5, a decay index has a stable value between 0 and 1.5, which guarantees both radial and vertical stabilities on fairly large area.

It is noteworthy that gradual transition from initial field null state to favorable field curvature is essential. Magnetic field control within the accuracy of several gauss level is uneasy thus in-situ tuning might be required to compromise the insufficiency of model accuracy.

3.2 Pure Ohmic start-up

Although ECH-assisted start-up assures stable start-up in large operation range, it has an intrinsic limitation that toroidal magnetic field should be set to certain value for EC resonance condition. The limitation prevents attempts to reveal toroidal field dependence on tokamak performances such as H-mode threshold power. In order to overcome the limitation, pure Ohmic start-up will be undertaken in the 2010 KSTAR campaign in parallel with ECH-assisted start-up.

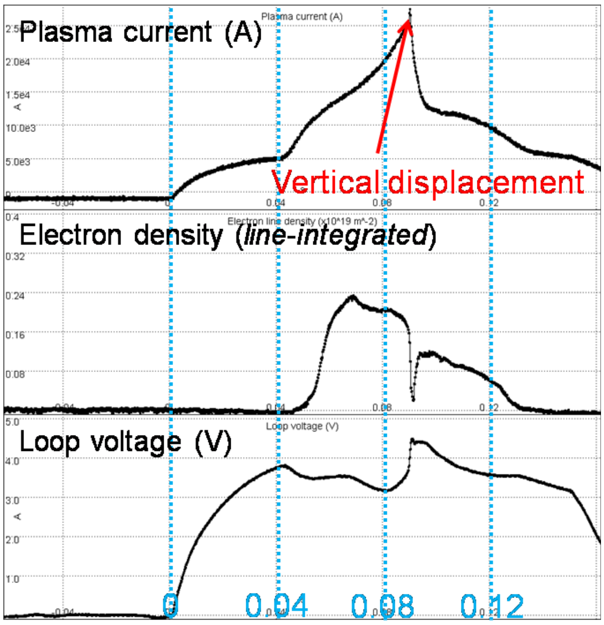

Fig. 6 Vertical displacement during the current ramp-up of Ohmic discharge due to vertically unfavorable field curvature.

During the 2009 KSTAR campaign, we proved that there is a possibility of pure Ohmic start-up in the KSTAR device. Nevertheless, it was difficult to match the current ramp-rate with preprogrammed field evolution because the current ramp-up of Ohmic discharge is very sensitive to operation conditions such as changes of wall conditions and prefill neutral pressure. Since most of Ohmic discharge attempts had been ended with an inboard crash, the radial stability was deliberately enhanced by adjusting radial gradient of vertical field in the KSTAR shot 1994. Although the plasma current started to rise after current channel formation, the enhanced radial stability caused vertical displacements at a plasma current of 25 kA as shown in Fig. 6. It was concluded that radial gradient of vertical field changed its sign thus the vertical stability condition was violated at that time. It means that the delicate field control to fulfill both radial and vertical stabilities is important after the current channel formation.

As mentioned the above, pure Ohmic start-up makes breakdown of neutral gas by toroidal electric field which is induced by the transformer action of PF coils. Thus the field null should be formed for confining charged particles when toroidal electric field reaches at sufficient level to make breakdown. In the KSTAR device, loop voltage has its maximum value around t=40 ms after PF blip.

In the established Ohmic start-up scenario, field null formation timing is controlled to coincide with maximum loop voltage timing. For the purpose, time evolution of eddy currents on conducting structures is self-consistently considered with PF coil current evolution, whilst ECH-assisted start-up needs to consider PF coil current alone for the initial field null formation. We performed time-dependent optimization to obtain PF coil operation scenario which generates field null after t=40 ms of PF blip. When the constraint of optimization is imposed, the compensation against incoloy effect is included. As a result, field structure shown in Fig. 7a) can be converted to field null structure shown in Fig. 7b) when incoloy effect is added.

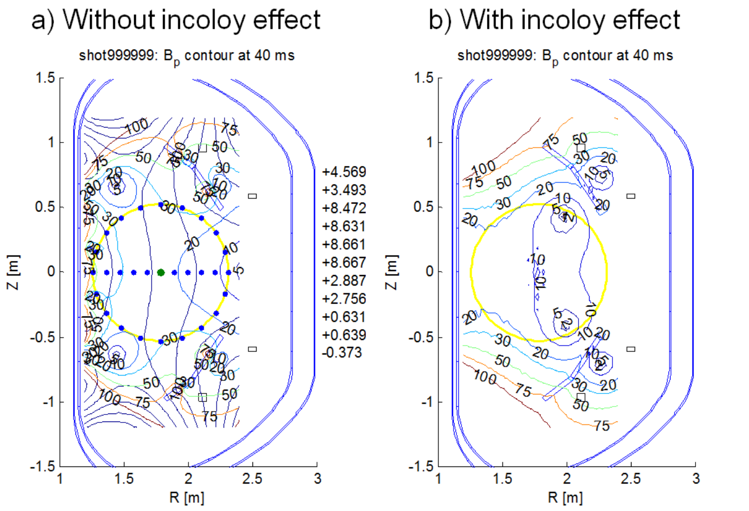

Fig. 7 Magnetization state of pure Ohmic start-up for the 2010 KSTAR campaign. Field null structure is formed when incoloy effect is included.

The confinement of charged particles should be taken into account along with the generation of them since direct loss along open field line is significant during the initial start-up phase. According to the JET empirical formula, stable breakdown is guaranteed within the area which satisfies the condition, $E\dfrac{B_t}{B_\perp} > 1\ \mathrm{kV/m}$ where E, B_t, and $B_\perp$ represent toroidal electric field, toroidal magnetic field, and magnetic field perpendicular to toroidal magnetic field, respectively. In the formula, toroidal electric field, E stands for the generation of charged particles by avalanche process. On the other hand, the ratio between B_t and $B_\perp$ is related to direct loss time along open field line.

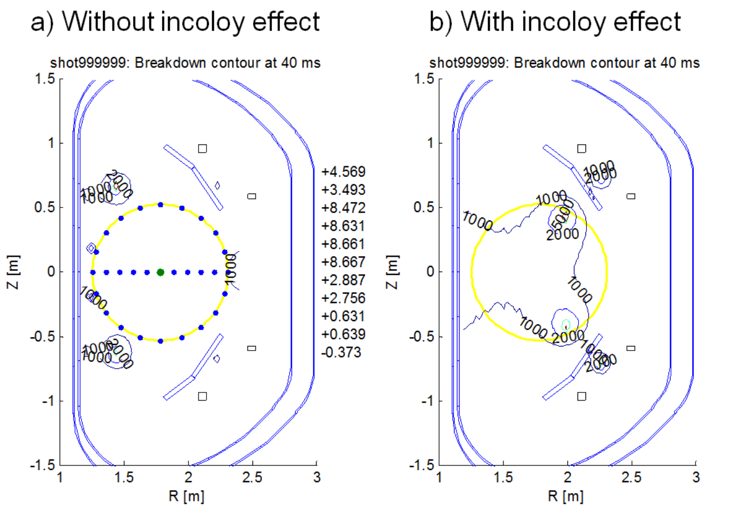

Fig. 8 Stable breakdown contour of pure Ohmic start-up for the 2010 KSTAR campaign. Field null structure is formed when incoloy effect is included.

In Fig. 8, toroidal electric field induced by poloidal flux change is attained by solving coupled circuit equations. It is noteworthy that only $B_\perp$ is influenced by incoloy effect. As shown in Fig. 8b) the stable breakdown contour covers large area of vacuum vessel when we use $B_\perp$ value with inclusion of incoloy effect.

3.3 ECH-assisted start-up with 110 GHz fundamental harmonic EC resonance

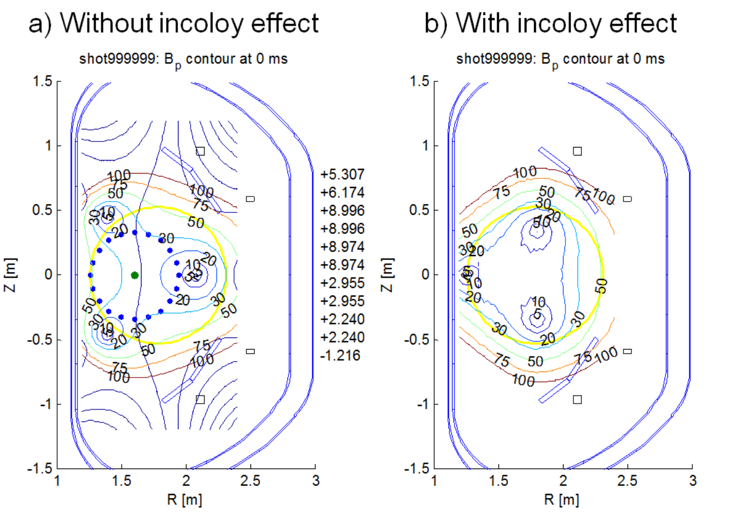

Fig. 9 Initial magnetization state of ECH-assisted inboard start-up for the 2010 KSTAR campaign. Field null center is set to R=1.6 m.

Despite the fact that fundamental EC resonance with 84 GHz gyrotron under 3 T toroidal field at R=1.8 m had been adopted as the KSTAR original start-up scenario, 2nd harmonic EC resonance with 110 GHz gyrotron under 2 T toroidal field was actually used in the 2009 KSTAR campaign due to the problem of 84 GHz gyrotron. Since the absorption efficiency of 2nd harmonic resonance is only one forth of fundamental harmonic case, insufficient EC power frequently hampers robust start-up. For instance, the breakdown of neutral gas shows shot-by-shot variance.

To solve the problem without upgrading the gyrotron source power, fundamental resonance with 110 GHz gyrotron at R=1.6 m is suggested. In the case, toroidal magnetic field needs to increase 3.5 T and field null center should be matched with the resonance point. Figure 9b) represents the initial magnetization state of suggested scenario which has field null center at R=1.6 m.

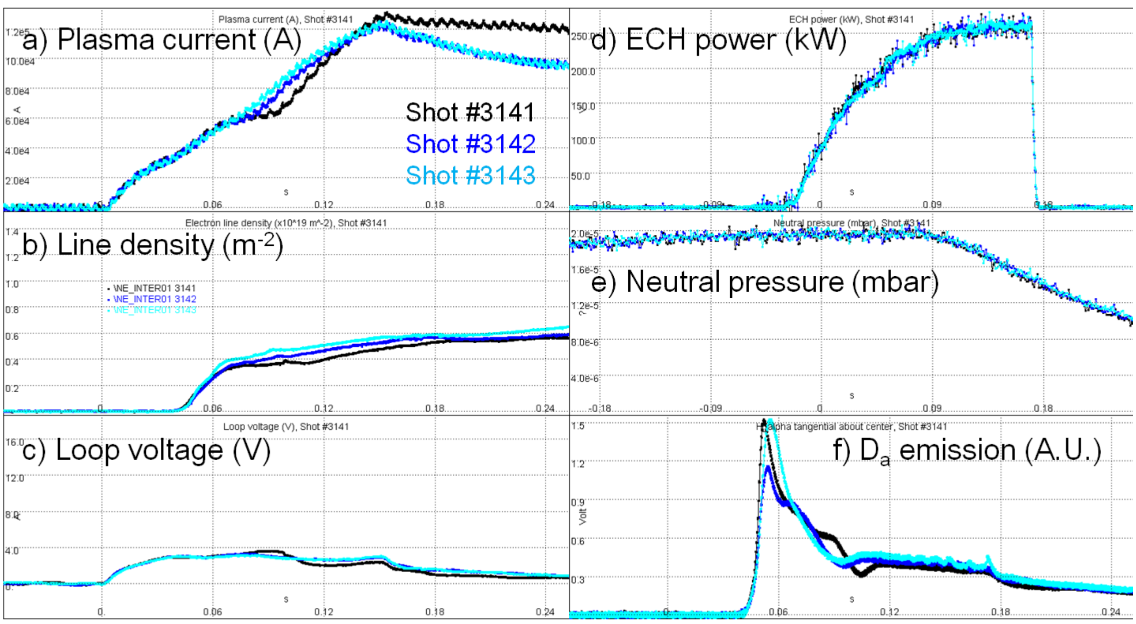

Fig. 10 Three recovery shots (KSTAR shot #3141~3143) in row from the failed shot (KSTAR shot #3140).

It should be mentioned that inboard start-up also takes an advantage in low loop voltage start-up because plasma feels higher electric field compared with outboard start-up case. It means that we can reduce the load on PF coils and it is beneficial to the engineering stability of superconducting coils.

4 Conclusion

The newly developed scenarios were applied in the 2010 KSTAR start-up. As expected from the nonlinear ferromagnetic effect calculation, the start-up scenario with the compensation of ferromagnetic effect exhibits good reproducibility and robustness against various discharge conditions.

Figure 10 depicts three successive shots after intended discharge failure (KSTAR shot #3140). In the failed shot, 300 kW ECH beam power was launched during 190 ms on plasma facing component (PFC) without plasma power absorption. As shown in Fig. 10a), it seems that initial current ramp-rates of following shots (KSTAR shots #3141, 3142, and 3143) were affected by the change of wall condition.

However, it is seen that the start-up of plasma is very stable although no feedback control against the variation of current ramp-up rate is employed in the start-up scenario. Thus we concluded that the positional stability is one of key point to acquire the robust discharge under various discharge conditions such as shot-by-shot variation of wall condition.

Further experiment is still on-going in the 2010 KSTAR campaign and following analysis will be added.

5 References

[1]Kim, W.C. *et al*., “Key Features in Start-up of KSTAR Tokamak” in IAEA 2008 FEC, EX-C, PD/P1-2.
[2]Yoon, S.W. *et al*., “Magnetics and its control” in KSTAR 2010 program advisory meeting.