Key Features in Start-up of KSTAR Tokamak


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Abstract. As a final step in the integrated commissioning of fully superconducting KSTAR tokamak, plasma start-up has been successfully implemented. Available initial magnetization was 1.0 Weber. The toroidal magnetic field was 1.5 Tesla. Blip resistor system has been adopted to overcome the low output voltage of the PF magnet power supplies so as to increase the loop voltage during breakdown and current ramp-up. An 84 GHz gyrotron with 500 kW power was used as the second harmonic ECH assisted pre-ionization system. A reference start-up scenario has been developed with these availabilities. Pre-ionization by the ECH system was highly reliable. With ECH heating during the current ramp-up, the discharges were less sensitive to wall conditioning since there have been no hard-baking of vacuum vessel or boronization for first plasma. ICRH-assisted Helium discharge cleaning is routinely applied during the shot-to-shot interval. For first plasma, circular plasma limited by inboard belt limiter and outboard poloidal limiter has been produced. Some MHD phenomenon has been observed but with the limited diagnostics, only qualitative analysis has been performed.

1. Introduction

KSTAR is a fully superconducting device to be operated as a steady-state-capable advanced tokamak [1]. The reference design parameters of KSTAR are major radius of 1.8 m, minor radius of 0.5 m, toroidal field of 3.5 Tesla and plasma current of 2 MA with the elongation and the tri-angularity of 2.0 and 0.8, respectively. After the machine construction, integrated commissioning of the tokamak has been progressed since March 2008. Plasma start-up was the final step in the integrated commissioning and has been successfully implemented by mid of July 2008[2]. But in the plasma commissioning, all the tokamak sub-systems had not been comprehensively commissioned. It means that minimum hardware for producing first plasma has been prepared. Only circular plasma could be produced with the limited magnetic hardware such as PF magnet power supplies and in-vessel vertical control coils. Very limited conditioning of vacuum vessel wall has been carried out because no hard baking of vacuum vessel and no boronization of inner wall has been considered. As the first plasma, Circular plasma limited by inboard belt limiter and outboard poloidal limiter has been produced. All the limiters are made of graphite. Initial target of the first plasma was plasma current of more than 100 kA and pulse length of more than 100 msec.

Since KSTAR is fully superconducting tokamak, producing toroidal electric field is not as simple as the conventional normal conductor tokamak, because superconducting coils have higher L/R time and rather sensitive thermal stability conditions at cryogenic temperature are imposed on the coils. Therefore, it is required to find more optimized magnetic configurations rather than the conventional magnetic configurations which are developed for normal conductor tokamaks. A KSTAR-specific operation scenario has been developed to get optimized breakdown conditions.
One of the critical issues in the start-up of KSTAR was the second harmonic ECH-assisted pre-ionization due to the relatively low toroidal magnetic field for the initial risk handling and the limited toroidal electric field produced by PF coils. The ECH-assisted start-up using the second harmonic pre-ionization has never been carried out in the fully superconducting tokamak device with a limited toroidal electric field. In KSTAR, the reliable Ohmic start-up with toroidal electric field of 0.24 Vm⁻¹, which is less than ITER reference value (~0.3 Vm⁻¹) has been achieved by applying 350kW of ECH power.

Other constraint being a superconducting machine is the problem of discharge cleaning between-shot period. Since toroidal field was applied during the daily operation time, conventional DC glow discharge cleaning is inapplicable. To deal with the wall conditioning during operation, the ICRH discharge cleaning has been applied to control the particle and impurity influxes from the first wall.

During the start-up, a maximum peak plasma current of 133 kA has been obtained with pulse length of 210 msec and the average loop voltage was around 2 V. With the help of the fully-digital plasma control system, the pulse length could be extended up to 862 msec. Some MHD phenomenon has been observed such as sawtooth oscillations. But with the given diagnostics, analysis of sawtooth activities is limited to a qualitative one.

In this paper we report the results of the first plasma and key operating features of KSTAR tokamak.

2. Operation Scenario

Generation of the first plasma in KSTAR was expected to be challenging because the available PF coil currents were limited due to the restricted capabilities of power supplies and the initial wall conditioning was not sufficient. The available initial magnetization was limited to about 1 Weber.

Considering these constraints, a specific magnetic scenario, called "dipole-like mode" has been developed and its effect on the plasma breakdown and current ramp-up was compared with the conventional one [3]. The term "dipole-like" is originated from the opposite biasing of the outer PF6 and PF7 coil currents as shown in Fig. 1.

In comparison with the conventional mode, the advantage of dipole like configuration over the conventional one is basically higher induced toroidal loop voltage and poloidal magnetic flux obtainable. This is achieved by charging-up of the outer PF coils, i.e., PF6 and PF7 as shown in Fig. 1, and it will increase the available magnetic flux significantly. The biasing of PF6 and PF7 should be opposite for better field-null configuration. In addition, adding a blip resistor on PF6 circuit will also increase toroidal electric field. In contrast, in conventional mode, the charging-
up of the outer coils is negligible and these outer coils are for the vertical field generation during the current ramp-up phase. Therefore, initial charging of the outer coils produces surpluses for magnetic flux and loop voltage. The weak point of dipole-like mode comes from the significant charging of the outer coils which might causes electrical and mechanical problems in the coil hardware and the relatively reduced field-null size.

In FIG. 2, the measured plasma current ($I_p$) and the loop voltage ($V_{loop}$) are shown. The loop voltage was measured by the inner-post flux loop. It is clear that the overall $I_p$ ramp-up is faster and $V_{loop}$ is higher for "dipole-like" mode. At the initial phase, the conventional mode results in a higher $I_p$ ramp-up rate, this might be that in the dipole-like mode, the field-null size is reduced by additional charging-up of outer coils and hence, particle loss along the field-line becomes larger during the initial $I_p$ ramp-up phase.

After the plasma current channel is formed (~50ms after blip), the $I_p$ ramp rate is higher for dipole-like and it reaches up to ~1MA/s. In the 1st experimental campaign, the detailed study of the characteristics of dipole-like scenario had not been done yet, however, it is clear that it is better magnetic configuration for the initial phase and more compatible with superconducting tokamaks in general.

3. ECH assisted pre-ionization

The toroidal magnetic field coil current was initially 14 kA to have 1.5 T, the second harmonic electron cyclotron resonance, at R ~ 1.7 m. The available microwave power at the output of the gyrotron was 500 kW, and the power of microwave beam up to 400 kW was launched into the vacuum vessel. In the experiments, the microwave beam is launched with the linearly polarized pure X-mode.

Figure 3 shows the parameters for the first plasma using the second harmonic ECH pre-ionization with 84 GHz, 350 kW. The microwave beam was launched perpendicular to the toroidal magnetic field. The $H_2$ pre-fill gas pressure at the vacuum pumping duct was 4.5 x $10^{-5}$ mbar. It was observed that the pre-ionization was delayed about 21ms after the ECH injection, but occurred 9ms before the onset of the toroidal electric field as shown in $H_\alpha$ signal in FIG. 3 (e). The line-averaged plasma density and ECE intensity also starts at the same time as the $H_\alpha$ signal. ECH pre-ionization and additional EC heating during the plasma current ramp-up have made the successful Ohmic start-up with a lower loop voltage of 2.0V, which corresponds to the toroidal electric field of 0.24 Vm$^{-1}$. Moreover, vacuum vessel was baked only at 100°C and no getter films such as boron or beryllium has been coated, the wall condition was relatively poor. But with the help of ECH during the burn-through, plasma current could be easily sustained and discharges were less sensitive to the impurity level.
FIG. 4. Shows the generation of plasmas in the ECH pre-ionization phase by the wide-angle fast CCD camera. FIG. 4 (a) shows well-localized pre-ionized plasma at the second harmonic electron cyclotron resonance at $R \sim 1.8$ m for shot 794, the first plasma with conventional magnetic configurations as shown in FIG. 1 (a). FIG 4 (b) and (c) shows the pre-ionized plasmas in the dipole-like field null configuration. The pre-ionization occurred more promptly in the dipole-like configurations. Detailed results of the pre-ionization have been reported by Bae et al [4].

4. ICRH Discharge Cleaning

As for the initial wall conditioning, GDC (Glow Discharge Cleaning) was performed several hours overnight and also in early morning before start of operation. Pure 1 ~ 2 hours of hydrogen discharge was followed by 1 hour He discharge for removing hydrogen on the vessel wall during H discharge. The partial pressures of hydrogen, water, nitrogen and carbon compound were increased during He-GDC.

During the steady state operation of TF magnet, GDC is not feasible. In this case, ICRH discharge cleaning could be a promising means for various wall conditioning purposes such as impurity cleaning, boronization or siliconization or recycling control. KSTAR has a 2 MW, 300 sec capable ICRH system with a frequency range from 25 to 60 MHz [5], during the first plasma operations this ICRH system has been used as an ICRH discharge cleaning systems. Since the antenna cooling has not been provided, ICRH DC has been implemented in pulsed mode. Since the characteristic pumping time of vacuum vessel is about 10 sec, 2 seconds pulse in every 12 seconds for 10 minutes has been carried out just after plasma shot.

The injected RF power was limited to 30 kW by induction of high voltage on the transmission line and the antenna due to the low antenna loading resistance. The operational pressure
5. Plasma Control

The plasma control system (PCS) for KSTAR has been developed in collaboration with DIII-D Plasma Control team. Two feedback algorithms have been prepared in the PCS [7]: control of 7 sets of poloidal field (PF) coils for initial flux swing and for magnetic force-balance, and a positive feedback of electron density by piezoelectric gas valve. In the initial phase of the start-up, break down was controlled in a feed-forward manner. The breakdown of the first plasma has been performed by providing feed-forward set of current waveforms to 7 coil power supplies with coil current feedback and feed-forward gas puff.

For initial breakdown, blip system was operated for 150 msec, during this period plasma current was increased up to 100 kA level. After the blip, feedback control of the plasma radial position $R_p$ and the plasma current $I_p$ was initiated. The serially connected up-down symmetric pair of PF coils made the vertical control of plasma inappropriate and the vertical position was inherently close to $Z=0$.

Two shots with same start-up scenario until $t=150$ ms are compared in FIG. 6. In shot 1058, the “limiter plasma” algorithm for $R_p$ and $I_p$ is turned on at 150 ms with 330kW ECH power lasting until 300 ms. The PF1-PF5 coils are used to

region is from $10^{-3}$ to $10^{-4}$ mbar for He and H discharge. The $B_{TF}$ was from 0.5 to 1.5 T. The antenna loading resistance was increased and plasma density was decreased as $B_{TF}$ was increased. As shown in FIG. 5, the effect of ICRH DC is confirmed by the variation of plasma densities in consecutive shots. The plasma density is decreased shot by shot when we applied between-shot ICRH DC as in FIG 5 (a), but plasma density is at constant level in case of without ICRH DC.

Only hydrogen partial pressure has been reduced from ICRH DC, the estimated hydrogen removal rate was about $3.6 \times 10^{-3}$ Pa, m$^3$/hr. This result was less effective considering the results from other machines [6]. With high power and long pulse capabilities, systematic study on the discharge cleaning with a more refined RGA system is expected in the next campaign.

FIG. 5. Line integrated density behaviour for consecutive shots. (a) With between-shot ICRH DC. (b) Without between-shot ICRH DC

FIG. 6. Utilizing plasma control: A shot without any feedback (shot 977) and the other with $I_p$ & $R_p$ controls set on at 150 ms (shot 1058). In the latter, the plasma is sustained over 720 ms and maintains over 100 kA for 384 ms. The camera capture represents (a) ECH is still operative (b) after the ECH turned off and (c) onset of vertical displacement event (VDE).
control Ip and the outer pairs of PF6 and PF7 for stabilizing Rp. The total flux that PF coils could supply including blip is about 0.9 Weber. As a result, the PCS successfully sustained Ip above 100 kA for over 200 ms after the ECH turned off and the plasma lasted over 720 ms with vertical displacement event (VDE) after 0.50 seconds. VDE occurred when pulse length is longer than ~ 500 ms. This might be due to the lack of available poloidal flux, since when t ~ 500 ms the flux from PF1 ~ PF5 has been nearly consumed up while the flux from outer coils remaining nearly constant. This could cause unfavorable field index near the end of the shot. The excursion of Rp from the target value was within ± 3 cm and the largest one occurred when the ECH power was turned off and the plasma shrank as seen in Fig. 9(b), accompanied with a little Ip drop. It has been found that the marginally stable radial position is ~ Rp=1.75 m. The longest pulse length was about 862 ms.

6. MHD Observations

Although the attained plasma current was relatively low considering the intensity of toroidal magnetic field, some MHD activities have been observed during the first plasma operation. In this section, observations of several MHD modes are discussed which might limit the operational boundary of KSTAR’s first plasma.

6.1 Current and Density limits

During the campaign, attained plasma current (Ip) was ~130 kA and the toroidal field was 1.4~1.5T. Therefore, the plasma is well below the limit of external kink. In FIG.7 the Hugill diagram is shown for current flattop phase. This Hugill diagram is plotted not for identifying the operation boundary of the first plasma, but for identifying the characteristic scatter of the plasmas obtained. It shows that the plasma current and density lie far below in the boundaries of the diagram.

Since the plasma current is fairly low due to the lack of volt-second, the safety factor qa is ~ 10 and well above the limiting value of 2. Also, for first plasma, as the low pre-fill gas is preferred to reduce the resistive consumption, the line averaged density is well below the Greenwald density limit for Ip flattop phase. However, during the Ip ramp-up and ramp-down phases, Ip is decreased and the plasma is vulnerable for disruption by density limit.

6.2 Sawtooth Oscillations after Ip ramp-up

As Ip ramp-up phase is followed by flattop phase, Ip is relaxed to a more radially-peaked profile by resistive current penetration and therefore, when the profile is relaxed, the central safety factor can be lower than the classical onset condition of sawtooth oscillation which is an m=1, n=1 internal kink mode. As the eigen-mode of sawtooth is confined in the core region only, it is benign in typical Ohmic plasmas and the collapse of plasma is moderate during a sawtooth event. However, in KSTAR, the collapse of electron temperature (Te) during a sawtooth is
relatively large. This is primarily due to the additional ECH heating after Ip ramp-up and Te is higher than similar Ohmic plasma. As reported by the previous work, the sawtooth period is proportional to $T_e^{2/3}$ [8] and the measured period is up to 20~30ms, which is significantly larger than the values in a conventional Ohmic plasma. Sometimes, sawtooth oscillations are followed by a harmonic coherent oscillation which has similar mode frequency as sawtooth precursors however it does not show any non-linear crash and remains as an coherent mode. The estimated inversion radius of safety factor from the measurements is around 10 cm typically by electron cyclotron emission spectroscopy which covers the radial 8 channels at the outer mid-plane (FIG.8).

To assess the effect of ECH heating on the sawtooth oscillations, the position of Ip center is scanned using feedback control in shot-by-shot manner with ECH heating layer. As the Ip center is shifted outside, i.e, as ECH power deposition is shifted to the outside of inversion radius, the sawtooth oscillations change its characteristics. As Ip center is moved outer than R=1.8 m, sawtooth oscillations are suppressed. This observation is in good agreement with the previous observations and theoretical predictions [9]. However whether it is due to the modification of Ip profile or kinetic effect of fast electrons are still unclear.

### 6.3 Mode activities at the early phase of current ramp-up

At the early phase of Ip ramp-up ~10kA, when Ip ramp is faster, an oscillation of line density and H-alpha is observed with frequency of ~1 kHz as shown in FIG.9. It seems this mode is responsible for early plasma disruptions which are observed at the faster Ip ramp-up which results mainly from the earlier ECH breakdown or lower pre-fill gas. By applying additional gas puff just before onset of this event or controlling pre-ionization time, the mode is stabilized. This mode is more frequently found at "dipole-like" magnetic configuration and its frequency is slowed-down at the later phase which suggests mode-locking signature.

### 7. Conclusions

The start-up of KSTAR tokamak has been implemented as the final step of the integrated machine commissioning. First plasma was successfully obtained with rather limited machine capabilities. During the start-up, some features relevant to ITER or fully superconducting device have been tested. More in-depth investigation on these start-up issues in KSTAR would contribute more to the ITER’s initial start-up studies.
The key features in the start-up of KSTAR tokamak are;
1) KSTAR specific operation scenario suitable for fully superconducting tokamak with limited initial magnetization has been developed and the successfully tested.

2) Second harmonic ECH assisted start-up has been achieved. System was reliable and it made the discharge less sensitive to wall conditioning and magnetic configurations. The operation parameters for the pre-ionization have been fully scanned. The results could give positive impact on the ECH assisted start-up scenario for ITER.

3) ICRH system for plasma heating has been used as a discharge cleaning system. ICRH discharge has been routinely used as a between-shot discharge cleaning means under toroidal magnetic field. Its use as a wall conditioning method was highly feasible in the shot-to-shot basis plasma operation.

With the plasma control system (PCS), plasma current and radial position could be controlled within the limit of available volt-seconds. Plasma current was raised up to 130 kA by feed forward manner and then PCS sustained plasma current by controlling the radial position. MHD sawtooth of magneto-hydro-dynamic instabilities has been observed during the first campaign of KSTAR operation. But more tailored experiments are required for exact identification and analysis of operation boundary.

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References