ECH-assisted Startup using Pre-ionization by the second harmonic 84 GHz and 110 GHz EC Waves in KSTAR

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Abstract. The second harmonic electron cyclotron heating (ECH)-assisted startup has been established to provide the reliable plasma startup with low toroidal loop voltage in the Korean Superconducting Tokamak Advanced Research (KSTAR) which is a fully superconducting tokamak device in Korea. The experimental results during KSTAR 2008 and 2009 campaigns showed the feasibility of the second harmonic 84 and 110 GHz ECH-assisted startup with the low loop voltage ranged from 3 V to 4 V. The pre-ionization failed with a pure toroidal field and no poloidal magnetic field null (FN) structure. Also, the small amount (~ 1 kA) of the toroidal plasma current was observed in the pre-ionization phase. It is considered that the vertical field component of the FN structure plays something role of confining the electrons during the pre-ionization phase. During the 2009 plasma campaign, the optimized condition of ECH pre-ionization was investigated with parameter scans of deuterium pre-fill gas pressure, resonance position, polarization, and vertical magnetic field without Ohmic discharge. In the KSTAR 2010 campaign, the interrelationship between the reliable and reproducible plasma discharge in Ohmic phase and the ECH pre-ionization is studied experimentally with the second harmonic 110 GHz EC beam at the upgraded power up to ~ 400 kW. Also, the fundamental harmonic 110 GHz ECH-assisted startup is attempted and its results are compared with those of the second harmonic 110 GHz ECH-assisted startup. This paper presents the overview of the startup ECH system and experimental results of 84 GHz and 110 GHz ECH-assisted startup from the first plasma campaign in 2008 to the 2010 campaign.

1. Introduction

KSTAR tokamak has used additional ECH power source for reliable plasma startup. Because the loop voltage ranged from 3 V to 4 V was too low to provide breakdown reliably since the KSTAR has a thick vacuum vessel wall and superconducting poloidal field coils. The ECH power injection before the onset of the toroidal electric field provide the localized plasma at the resonance region, which is called as pre-ionization that can reduce the loop voltage required to start the plasma current, reduce the startup runaway electrons, reduce the volt-second consumption, and allow the fast plasma current ramp-up. It also allowed the burn-through and sustained the plasma during the current ramp-up [1, 2, 3].

This paper reports on the second harmonic and fundamental ECH preionization and ECH assisted startup results obtained on KSTAR. In section 2 we will present the experimental setup such as KSTAR, ECH system, diagnostics, and so on. Section 3 summarizes the second harmonic and fundamental ECH preionization and ECH-assisted startup including parameter scans. Conclusions are given in section 4.

2. Experimental Setup

KSTAR is a superconducting tokamak with major radius R = 1.8 m, minor radius r = 0.5 m and designed for developing a steady-state advanced tokamak. The toroidal magnetic field is 3.5 Tesla. The superconducting magnets are composed of sixteen toroidal field (TF) coils and seven pairs of poloidal field (PF) coils with up-down symmetry. Figure 1 shows the KSTAR poloidal cross section and the locations of these coils. Except the outer PF6 and PF7 coils made of NbTi, four sets of Ohmic central solenoid (CS) coils, one set of PF5 coils, and all the sixteen TF coils were fabricated by using Nb_3Sn [4].

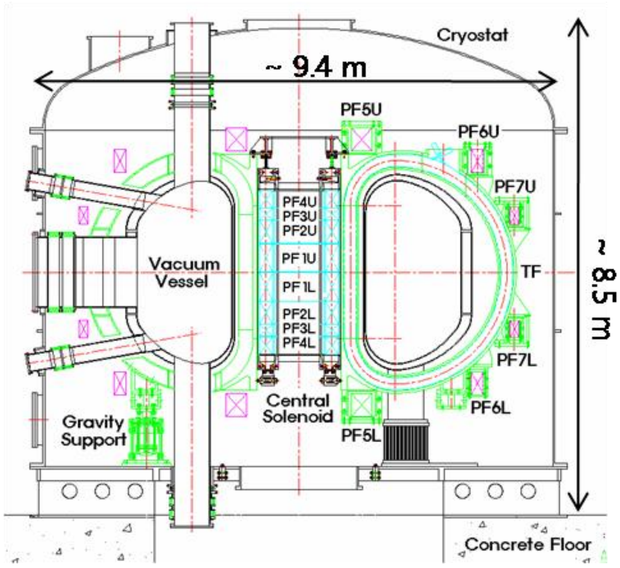

FIG. 1. *KSTAR poloidal cross section and superconducting magnet system configuration*

The loop voltage is measured by the innermost flux loop. The plasma current is measured by Rogowski coils. The line-integrated plasma density is measured by one channel microwave interferometer. The electron temperature is measured by electron cyclotron emission. The H_α emission and visible bremsstrahlung and fast visible camera are also measured. ICRF is used for wall cleaning and plasma heating besides EC heating.

KSTAR ECH system is composed of CPI gyrotron with frequency of 84 GHz and 110 GHz GYCOM gyrotron, one transmission line, and one launcher. In the 2008 KSTAR first plasma campaign, 84 GHz CPI gyrotron was used for plasma startup [5]. 84 GHz EC beam power of up to 350 kW was available and launched into the vacuum vessel. In the second campaign, 110 GHz GYCOM gyrotron was borrowed from GA due to the trouble of 84 GHz gyrotron. This 110 GHz GYCOM-made gyrotron was specified with an output power of 1 MW for 2 s pulse length and 0.5 MW for 5 s pulse length with the efficiency of about 38 %. However, the output of the existing high voltage power supply was limited by voltage of 63 kV and current of 20 A, because 84 GHz gyrotron was designed to the depressed potential collector and needed the cathode voltage of less than 60 kV. In the second campaign, available 110 GHz EC beam power was about 250 kW. Recently, we upgraded the high voltage power supply so that has the output voltage of 70 kV and the beam current of 30 A, respectively. In this campaign, the deliverable 110 GHz ECH beam power to the plasma will be more than 400 kW. RF beam with TEM_{00} mode outputted from the window of each gyrotron is transformed to HE_{11} mode by the MOU for 110 GHz gyrotron and by the L-box for 84 GHz gyrotron The EC beam is transmitted from the gyrotron to the antenna by the use of a circular corrugated waveguide with an inner diameter of 31.75 mm and about 40 m in length. This transmission line is evacuated by turbo-molecular pump and transmission efficiencies for 84 GHz and 110 GHz wave are estimated by about 15 % and about 25 %, respectively. Here to effectively transmit 110 GHz wave to the launcher, transmission line was modified by removing the diamond window and the mode mixtures at the miter bend [6]. The polarization of EC wave is controlled by using two grooved mirrors at the miter bends. EC wave is launched as Gaussian beam by the antenna located on the low field side at 25.2 cm far from the equatorial plane.

The EC wave can be steered poloidally from - 55 to - 90 degree and toroidally ± 38 degree by the steerable mirror of the antenna during and between pulses [7].

3. Experimental Results

In the KSTAR first plasma campaign as construction commissioning stage in 2008, KSTAR operated at a low toroidal magnetic field. For 2008 first plasma campaign, the KSTAR is operated with toroidal magnetic field of 1.5 T at the major radius which corresponds to the second harmonic resonant field with 84 GHz EC wave at 1.7 m. For 2009 plasma campaign, KSTAR is operated with TF field of 2 T at the major radius of 1.8 m which corresponds to the second harmonic resonant field with 110 GHz EC wave. For 2010 plasma campaign, the TF fields in the major radius are at 2 T and 3.5 T which give second harmonic EC resonance at the major radius and fundamental EC resonance at the radius of 1.6 m, respectively.

TABLE I. Injected ECH beam and KSTAR operation parameters

	2008	2009	2010	
Toroidal field	1.5 T	2 T	2 T	3.5 T
Gas species	H_2	D_2	D_2	D_2
EC Frequency	84 GHz	110 GHz	110 GHz	110 GHz
Injected power	~ 350 kW	~ 250 kW	~ 400 kW	~ 400 kW
EC resonance	R = 1.68 m	R = 1.8 m	R = 1.8 m	R = 1.6 m
Injection mode	X2, O2	X2, O2, X3	X2	O1
Beam radius	78 mm	60 mm	60 mm	67 mm
Power density	1.8 kW/cm^2	2.2 kW/cm^2	3.5 kW/cm^2	2.8 kW/cm^2

Figure 2 shows the successful ECH-assisted startups of the KSTAR first and second plasma campaign. The first plasma experiments were completed with the achievement of a plasma current larger than 100 kA and duration longer than 100 ms as seen in figure 2(a). The EC beam is applied at t = -30 ms before the onset of the toroidal inductive electric field with the perpendicular to the toroidal magnetic field intersecting the equatorial plane at the second harmonic EC resonance position R_{X2} ~ 1.8 m. H_α monitor signals shows that the pre-ionization occurred at about -23 ms before the onset of the toroidal inductive electric field. The line-averaged plasma density and three radiated ECE signals also starts almost at the same time as the H_α monitor signal. The second plasma experiments achieved a plasma current larger than 300 kA and duration longer than 300 ms as seen in figure 2(b). The experimental results during 2009 KSTAR campaigns showed the feasibility of the second harmonic 110 GHz ECH-assisted startup with the low loop voltage ranged from 3 V to 4 V, corresponding to an electric field E_φ ~ 0.26 V/m to E_φ ~ 0.35 V/m at R=1.8 m. Successful start-up was possible by the plasma breakdown in the ECH pre-ionization phase and additional EC heating during the plasma current ramp with a lower loop voltage of less than 4 V.

In the first campaign, the power threshold of the 84 GHz wave for plasma startup was observed and shown in figure 2. The minimum power for burn-through was 320 kW by the perpendicular injection of a linearly polarized pure X2 mode. As the ECH power is higher, the delay time, which is the onset of the H_α emission, the line integrated density, and ECE signal, becomes shorter. This result is also equal to the 110 GHz EC beam. In the case of 110 GHz wave, the power threshold was 250 kW and lower than in 84 GHz wave. This reason is that the power density of 110 GHz EC beam is 2.2 kW/cm^2 for the 250 kW and higher than 84 GHz EC beam with the power density of 1.8 kW/cm^2 (see Table 1). The power e-folding radius of 110 GHz EC wave at the second harmonic EC resonance position (R_{X2} = 1. 8 m) is about 6 cm by Gaussian beam optics in free space.

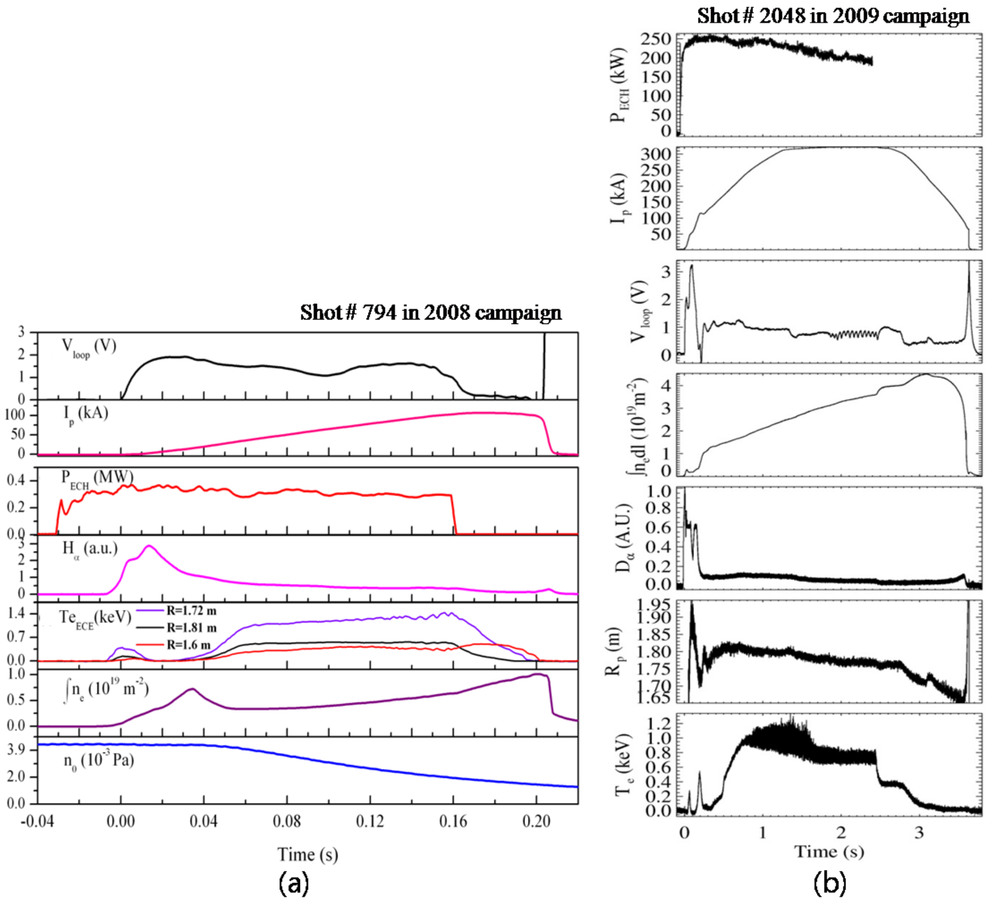

FIG. 2. The second harmonic ECH-assisted startups for the KSTAR first plasma (shot number 794) and second plasma (shot number 2048).

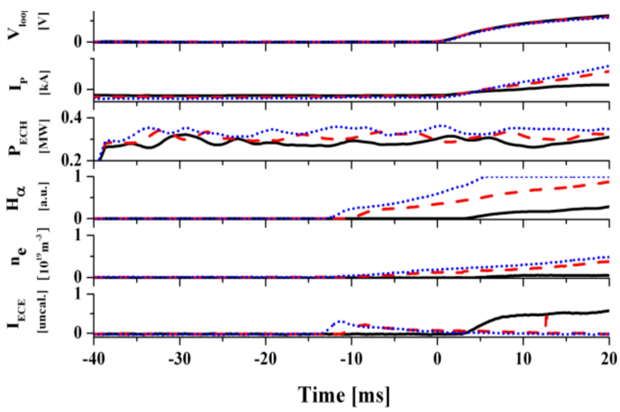

FIG. 3. Temporal evolution of loop voltage, plasma current, H_α emission, line integrated density, and electron cyclotron emission as ECH power. (Solid: 280 kW, dashed: 320 kW, dotted: 350 kW)

Figure 4 shows the effect of the prefill gas pressure for ECH perpendicular injection in the 110 GHz X2 mode with 240 kW power. The pressure changed from 0.75×10^{-5} mbar to 2.4×10^{-5} mbar and all shots had loop voltage of less than 3 V. Figure 4(b) shows the breakdown delay time as function of a prefill gas pressure. As the prefill gas pressure is increased, the breakdown delay time is decreased. The line integrated density and H_α emission are enhanced for higher prefill gas pressure as shown in figure 4(a). But at 2.4×10^{-5} mbar, the breakdown delay time was increased and ECH-assisted startup was failed.

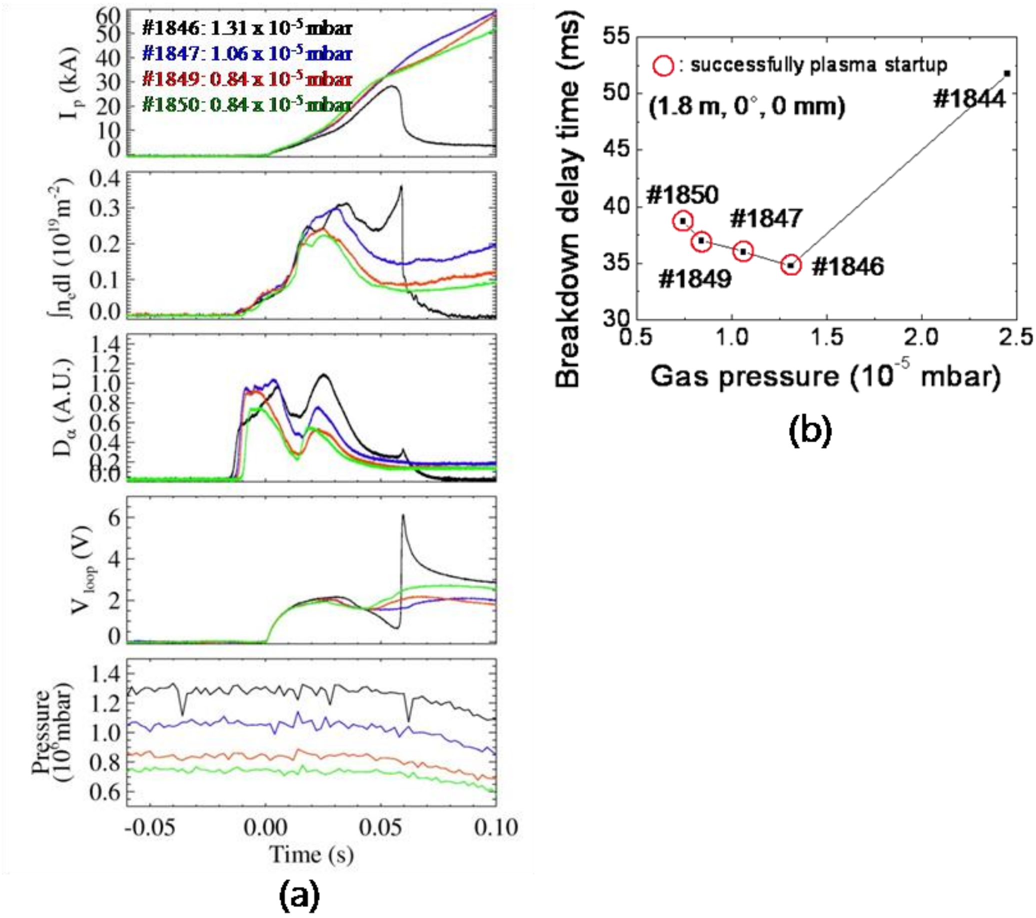

FIG. 4. Temporal evolution (a) and breakdown delay time effect (b) as prefill gas pressure for the second harmonic ECH-assisted startu with the 110 GHz X2 mode with 240 kW power. Black: 1.31× 10^{-5} mbar (#1846), blue: 1.06× 10^{-5} mbar (#1847), red: 0.84× 10^{-5} mbar (#1849), green: 0.75× 10^{-5} mbar (#1850)

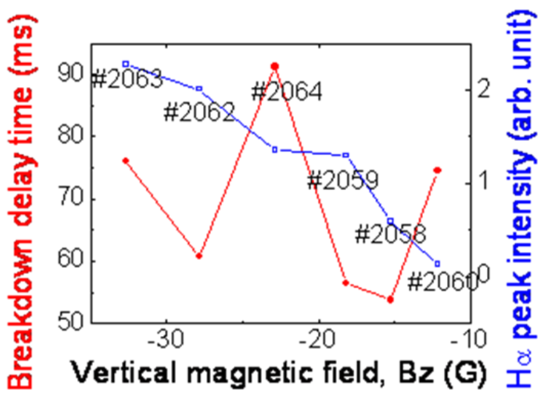

FIG. 5. Breakdown delay time and H_α emission as a function of vertical magnetic field.

The initial flat currents of the Ohmic coils and PF coils generate a poloidal magnetic error field with field null configuration which is very important to obtain the plasma breakdown. The effect of the vertical field in the field null configuration for ECH pre-ionization was measured in the preionization phase as seen in figure 5. The vertical magnetic field is changed in the range of -10 G to -40 G. DIII-D observed the optimum ECH-assisted breakdown with a vertical field of about - 50 G [8]. In KSTAR case, breakdown delay time is the smallest near the field null. The breakdown delay time was closely related with the plasma startup. However, all shots failed the plasma startup due to bad wall condition.

In 2010 plasma experiments, 110 GHz second harmonic and fundamental ECH preionization was performed. Figure 6 shows the typical preionization plasmas. Figure 6(a) and 6(b) are the field null configurations with the second harmonic resonance at R_{X2} = 1.8 m and the fundamental resonance at R_{O1} = 1.6 m, respectively. The second harmonic ECH preionization is much localized at the crossing position of the resonance layer and EC beam line. However, the fundamental ECH preionization is broadening at the resonance layer due to the large connection length.

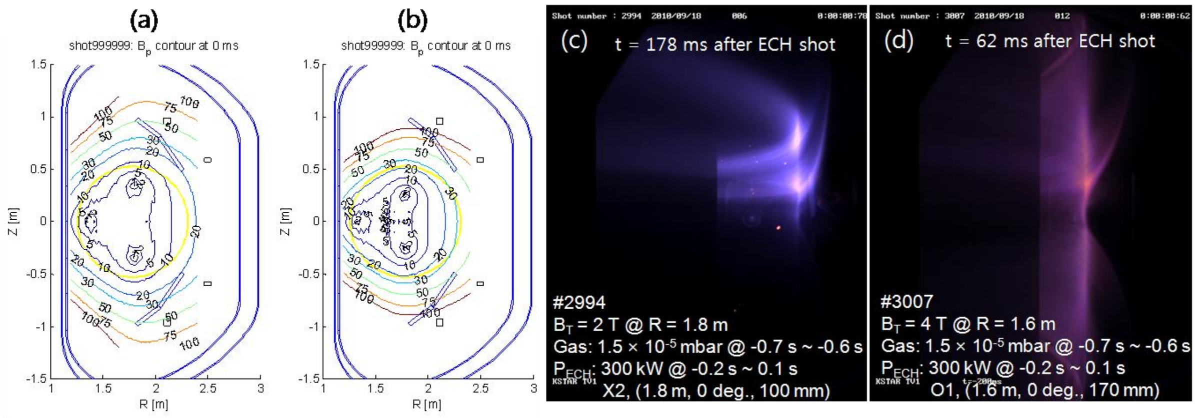

FIG. 6. 110 GHz second harmonic (c) and fundamental (d) ECH pre-ionizations in 2010 initial pre-ionization test in the initial magnetic field configurations (a) and (b), respectively

4. Conclusion

The experimental results during KSTAR 2008 and 2009 campaigns showed the feasibility of the second harmonic 84 and 110 GHz ECH-assisted startup with the low loop voltage ranged from 3 V to 4 V, corresponding to an electric field E_φ ~ 0.26 V/m to E_φ ~ 0.35 V/m at R=1.8 m. The application of the EC beam before the Ohmic provided a localized plasma, which is called as 'pre-ionization' as providing many hot electrons and thereby reduction of the resistive power consumption of the Ohmic flux, confined by the poloidal magnetic field null (FN) structure which is obtained by the initial magnetization in 7 pairs of the poloidal field coils. It also allowed the burn-through and sustained the plasma during the current ramp-up. The interesting thing is that there would not be pre-ionization with a pure toroidal field and no poloidal FN structure. Also, the small amount (~1 kA) of the toroidal plasma current was observed in the pre-ionization phase. It is considered that the vertical field component of the FN structure plays a role in confining the electrons during the pre-ionization phase. During the 2009 plasma campaign, the optimized condition of ECH pre-ionization was investigated with parameter scans of hydrogen and deuterium pre-fill gas pressure, resonance position, polarization, and vertical magnetic field without Ohmic discharge. The 2009 results showed that the breakdown was observed in most scanned conditions except X3 mode injection and the absence of initial FN configuration. The breakdown is increasingly delayed at the low pre-fill pressure, the inboard resonance position, O-mode injection, and the higher B_z at the FN center, as evidenced by the D_α emission and the central ECE signal. Despite optimized ECH pre-ionization, the plasma startup was not reproducible possibly due to the marginal ECH power, the poor wall conditioning, and the lack of the gas controllability during the phase change from the pre-ionization to the Ohmic phase. A second gas puff introduced just before the onset of the Ohmic pulse was shown to enhance the plasma startup. In the KSTAR 2010 campaign, the interrelationship between the reliable and reproducible plasma startup in Ohmic phase and the ECH pre-ionization is studied experimentally with the second harmonic 110 GHz EC beam at the upgraded power up to ~400 kW. The 2^{nd} harmonic and fundamental 110

GHz ECH-assisted startup is being carried out in 2010 campaign. And their results will be presented during the conference.

Acknowledgement

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