

Second Harmonic 110 GHz ECH-assisted Start-up in KSTAR

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Abstract. In KSTAR device, a 110 GHz ECH system has been a useful heating device for a stable plasma start-up because a pure ohmic discharge scenario with a limited loop voltage of about 4 V was sometimes not successful for burn-through and plasma current ramp-up due to inconsistent wall conditioning and density control. Even though a pure ohmic discharge also was successful, the application of X2-mode ECH could reduce the flux consumption of poloidal field coils, leading to long pulse discharges. The ECH power was injected at the time of the field null formation after the onset of the toroidal electric field in which the electron temperature significantly increased up to 100 eV so that burn-through is overcome. The ECH heating enabled the formation of close flux surfaces earlier, leading to the reliable plasma current ramp-up, but, it caused outward plasma movement and failure of the plasma control, resulting in loss of the discharge. Moreover, impurities from the plasma facing components caused by not fully absorbed ECH power had a detrimental effect on the H-mode transition. In ECH-assisted start-up in the ramp-up phase, ECH power was mainly used for central electron heating, leading to reduction of the flux consumption of the central coils by increasing the electron temperature along with a density increase in the ramp-up phase. When X2-mode ECH power of 350 kW was injected at the mid-plane with a toroidal angle of 10 degree for 1 sec after the onset of the loop voltage, the flux consumption was reduced by about 30% in comparison with the pure ohmic discharges.

1 Introduction

Present tokamaks and future reactor devices with superconducting poloidal field coils and thick vacuum vessel well have a limited toroidal electric field which is too low reliably to achieve ohmic start-up [1]. In addition, in-vessel structure generates considerable in-vessel poloidal magnetic stray fields [2]. In Townsend avalanche breakdown theory this stray field makes it difficult to initiate the plasma in the limited toroidal electric field. Therefore, ECH-assisted start-up, especially ECH pre-ionization, has been carried out for the past few years and was successfully achieved at a low toroidal electric field ($E_t \leq 0.3$ V/m). These results were reviewed in references [3, 4] and were shown that ECH can reduce the minimum toroidal electric field to breakdown the plasma as ECH assist can provide an additional margin in the operation range of pressure and magnetic stray field. KSTAR also had successfully conducted the second harmonic extraordinary(X) mode ECH-assisted start-up by using ECH pre-ionization in the first [5] and second campaign [6]. The field null formation and magnetic stray field were important factors to reproduce the plasma initiation. ECH-

assist start-up experiments in 2010 were shown helpful to breakdown the plasma in even pure ohmic discharge. This paper presents the experimental results of ECH-assisted start-up in the ohmic discharge scenario by changing ECH parameters such as onset time, power, and poloidal and toroidal launching angle of the ECH power. The plan for ITER-relevant experiments on ECH-assisted start-up planned in coming KSTAR campaign also will be presented.

2 Experimental Setup

2.1 ECH System

KSTAR 110 GHz ECH system is composed of 110 GHz gyrotron, matching optics unit (MOU), 31.75mm transmission line, and two mirrors antenna system and minutely represented in reference 6. GYCOM-made gyrotron loaned from General Atomics was specified with an output power of 1 MW for 2 sec pulse length, but could be outputted the RF power of about 760 kW from the window of the gyrotron by using the present power supply of 70 kV and 30 A. The ECH beam is transmitted about 40 m in length from the gyrotron to the antenna by the use of an evacuated circular corrugated waveguide with an inner diameter of 31.75 mm and eight miter bends included two polarizer miter bends. Two polarizers can change linearly polarized ECH beam into beam with arbitrary polarization. In this experiment ECH beam is injected to the plasma with X-mode. The diamond vacuum window and the mode mixture with the large transmission loss were removed for reducing the transmission loss. Transmission efficiency is measured by calorimetric method with two dummy loads where one is installed near the gyrotron and the other installed near the tokamak and about 25 %. This loss is almost agreed with the theoretically calculated value [6]. Total transmission loss included MOU and transition at the inlet waveguide of the antenna was about 45 % and the maximum RF power injected to the plasma was about 420 kW for 0.5 sec. The handling power of the ECH antenna is 1 MW pulse for 5 ~ 10 sec duration every 15 minutes because the antenna is passively cooled. Final steerable mirror of the ECH antenna is located at $R = 1.8$ m on the low field side at 25.2 cm down from the equatorial plane and can change the deposition position of ECH beam poloidally from - 55 to - 90 degree on the vertical axis and toroidally ± 20 degree between pulses.

2.2 Ohmic Start-up

Plasma start-up in KSTAR has been usually accomplished by ohmic discharge with a low loop voltage of about 4V since 2009. Ohmic discharge scenario in KSTAR which use the poloidal superconducting coils (PF) has the optimum conditions on Blip Resister Insertion System (BRIS), initial field null formation by large outer PFs, and magnetic error field by effect of Incoloy 908 which used in the jacket of PF coils and TF coils [7]. In this paper, plasma start-up includes raising the plasma current up to about 150 kA and ramping up the plasma current to flat top. In the first phase up to 150 kA, plasma is controlled by Plasma Control System (PCS) in pre-programmed (feed-forward) coil control and after that, PCS switched the control method to plasma feedback control. The loop voltage utilized for plasma breakdown is about 4 V which is corresponding to E_t of 0.35 V/m at major radius of 1.8 m. In the pre-programmed coil control, BRIS starts to generate the plasma breakdown at $t = 0$ s and the initial field null where the vertical magnetic field become low than 10 Gauss is formed at about $t = 30$ ms as shown in figure 1. We can see that plasma is generated at the time between 35 ms and 40 ms determined by the electron density and D_α emission signals. Figure 1(a) and 1(b) represent the time variation of B_p contour and breakdown contour ($=E_t \cdot B_r/B_p$) for 100 ms as a pure Ohmic discharge scenario used in 2011 KSTAR campaign. Plasma burn-through also occurs during this time. After the plasma burn-through succeed, the plasma current rises up to about 150 kA with the ramp rate of about 1 MA/s. We can also see the time evolution of the plasma formation by the visible fast camera in figure 1(c) for pure ohmic start-up and can compare with ECH-assisted start-up plasma in figure 1(b). These results are minutely described in section 3.

As mentioned, at the plasma current of about 150 kA, the Plasma Control System (PCS) switches the control method from pre-programmed coil control to plasma feedback control and the plasma current is ramped to the flat top with the different slope of about 0.2 MA/s. In KSTAR pure ohmic start-up could be successfully achieved the plasma current of up to 500 kA without assisting any heating source. However to control the plasma current well as expected and in order to increase the plasma current more than 600 kA, we need some additional heating source like ECH and NBI. Furthermore, sometimes pure Ohmic start-up is not successful in burn-through and the plasma current ramp-up because of inconsistent wall conditioning and density control.

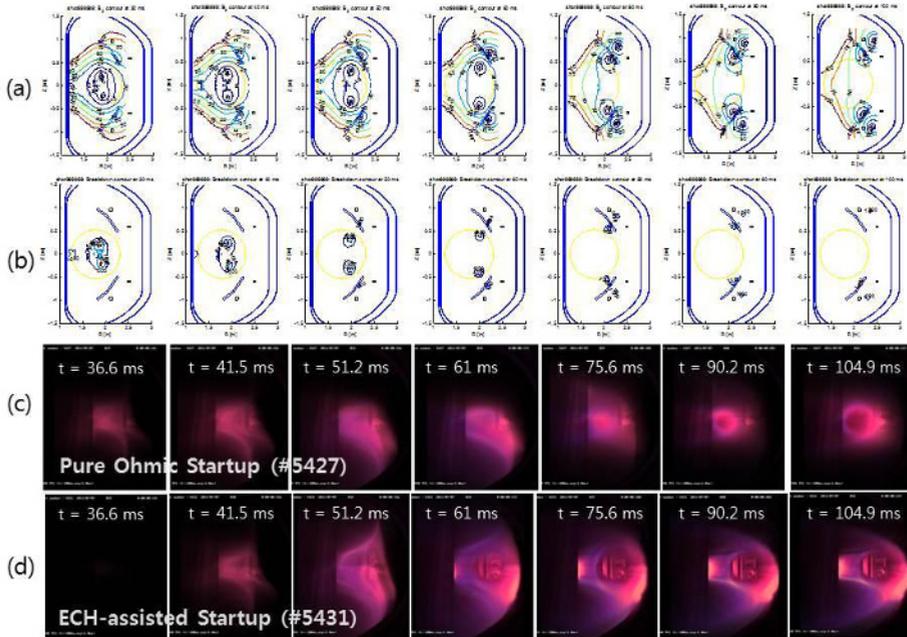


Figure 1. The time evolutions of Ohmic discharge scenario used in 2011 KSTAR campaign; (a) B_p contour and (b) breakdown contour used for pure Ohmic startup, (c) pure ohmic discharge plasma image, and (d) ECH-assisted plasma image measured by visible TV camera.

3 Experimental Results

In KSTAR, ECH-assisted start-up is utilized as a tool to help the plasma burn-through and the plasma current ramp-up because Ohmic power is enough to achieve the plasma breakdown. However, sometimes plasma breakdown by Ohmic start-up was failed due to limited loop voltage of about 4 V, inconsistent wall conditioning, and density control. At that time ECH power can help the breakdown, overcome burn-through and ramp up the plasma current as expected. Usually ECH heats the centre of the plasma at resonance position of $R = 1.8$ m and mid-plane with toroidal angle of $+10$ degree by second harmonic X-mode. Figure 2 shows a series of plasma discharges to succeed the plasma start-up with ECH when the Ohmic start-up is successful and failed by injection of Argon gas in the density control experiments. Plasma images of the same discharges for pure Ohmic discharge and for ECH-assisted start-up are shown in figure 1(c) and 1(d), respectively. ECH power is triggered at the time $t = -20$ ms. But in our system, ECH power has a delay time of about 30 ms and a long rising time of about 30 ms by cathode power supply which is inverter type. The ECH peak power is injected to the plasma at $t = 40$ ms after 60 ms. Additional ECH power generates the plasma at $t \sim 40$ ms when the field null configuration is formed and the close flux surface earlier than without ECH as shown in figure 1. In pre-programmed control phase, ECH increased the electron temperature T_e up

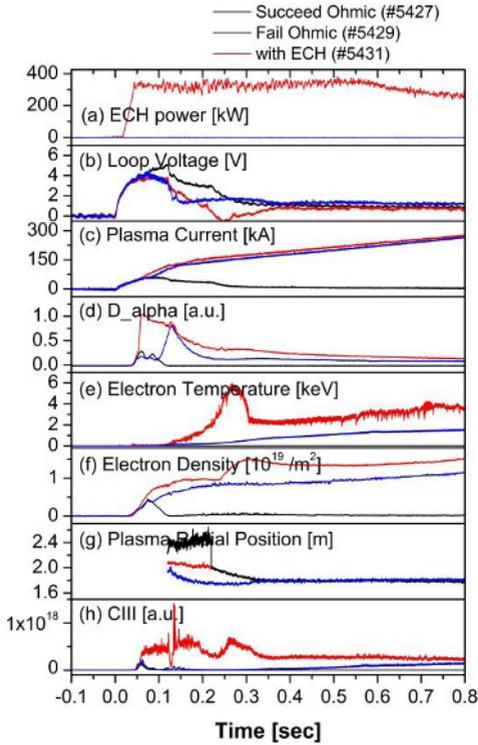


Figure 2. A series of plasma discharges to succeed the plasma start-up with ECH (red line) when the pure Ohmic start-up is successful (blue line) and failed (black line).

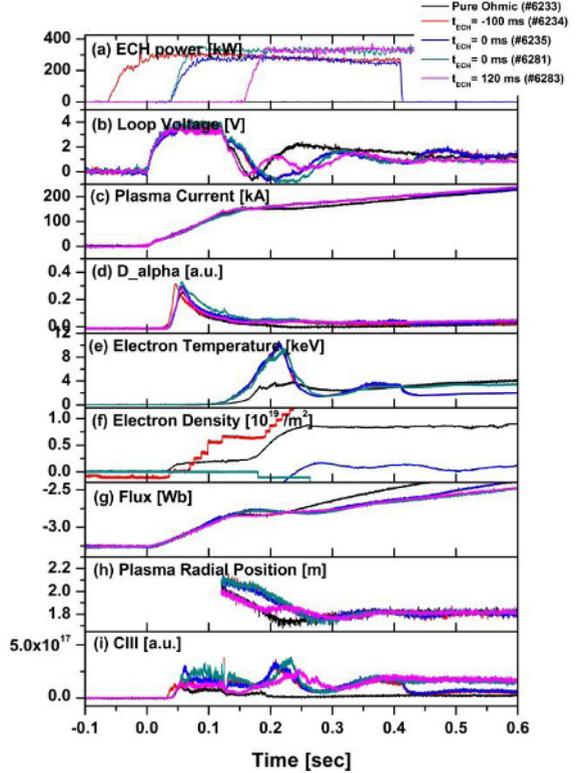


Figure 3. Time evolutions of plasma parameters as a function of ECH trigger times.

to about 100 eV compared to without ECH. During the plasma current ramp-up, ECH mainly increases T_e early and more, about 2 times and also D_α emission intensity, n_e , and I_p . In other words, ECH mainly plays a role of electron heating and it seems that the increase of T_e leads to the increase of n_e and in the end enhances the ramping ability of I_p . However, ECH shifts the plasma radial position outside by hoop force since the plasma is feed-forwardly controlled up to $t = 150$ ms and generates the impurities which make it difficult L-H mode transition.

ECH trigger time is varied to investigate the optimum ECH onset time at the same pure Ohmic start-up scenario with the same field null formation time. This experiment is accomplished at three different trigger times relevant to the field null formation time and the feedback control time, $t = -100$ ms before forming the field null configuration, $t = 0$ ms to inject ECH power at the field null formation, but not feedback control, $t = 120$ ms after feedback control and when Ohmic start-up is successful. ECH injection before blip ($t = 0$) increases T_e up to 100 eV, but isn't occurred the plasma breakdown because the field null configuration is not formed and the connection length is too short to confine the electron in the vessel. ECH injection after starting feedback position control decreases plasma movement by PCS control. If PCS controls plasma position well, optimal ECH injection time is the time that the field null configuration is formed and which is about 40 ms in KSTAR start-up scenario. ECH injection at that time can help plasma start-up and lead the flux saving.

During the plasma current ramp-up phase, ECH-assisted start-up is largely about the reduction of the flux consumption for high plasma current and long pulse and steady state operation. We have conducted the research on the flux consumption variation as function of ECH parameters; ECH power, toroidal launching angle, and poloidal launching angle. Figure 4 shows the time traces of the plasma parameters and the percentage of the flux consumption as a function of ECH power where

ECH trigger time is 120 ms due to the reduction of the effect of plasma movement. As ECH power is increased, T_e is increased and the flux consumption is reduced. However, the flux consumption in ECH-assisted start-up does not depend on ECH power of more than 200 kW and is about 70 % (about 0.45 Wb) to the flux consumption (100 %) in the pure Ohmic start-up. ECH power of less than 200 kW does not influence on T_e increase. At least 200 kW ECH power is required for the significant increase of T_e for the reduction of the flux consumption.

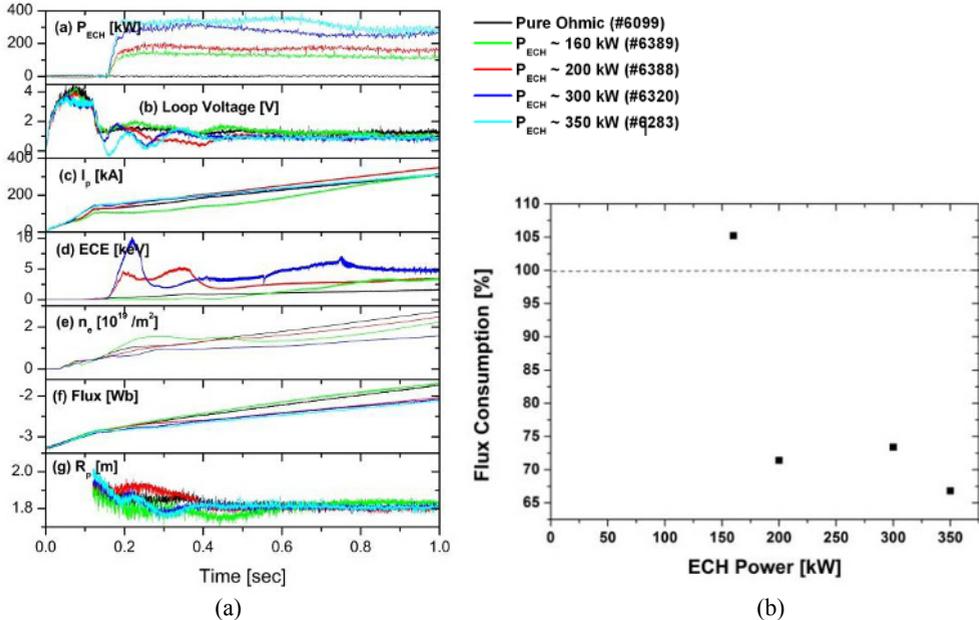


Figure 4. (a) Time evolutions of plasma parameters and (b) the flux consumption as a function of ECH power where ECH trigger time is 120 ms.

The dependence of ECH toroidal launching angle on the flux saving is investigated with the same ECH power at the trigger time of $t = 0$ ms. Figure 5 shows a series of plasma shots. The variation of ECH toroidal launching angle rarely affects the plasma current, D_α emission, plasma radial position, and CHI impurity. Electron temperature in co-current drive (Co-CD) injection to the plasma current is higher than in counter-current drive (CNT-CD) injection. In CNT-CD injection case, T_e is similar to in #6235 after 0.4 s when all additional heating sources are off and only Ohmic power exists. Unfortunately interferometer was not working well and we cannot get n_e data. We can see Co-CD injection of ECH power is more effective than CNT-CD injection to reduce the flux consumption since T_e increase. However we are necessary more analysis to investigate this difference of the flux saving which comes from the current drive effect or (and) ECH polarization effect. 110 GHz ECH cannot be injected with perpendicular angle to the magnetic field due to protect Thomson scattering device where installed at the upper position. 170 GHz ECH also is used for 2nd harmonic X-mode ECH-assisted start-up at $B_t = 3$ T and was perpendicularly injected and with toroidal angle of 20 degree. There results are shown in figure 5(b) and 170 GHz ECH toroidal angle effects correspond to 110 GHz ECH. ECH power injected to the plasma core is effectively increased the core electron temperature and then reduces the flux consumption of about 6 % compared to the lower deposition of -100 mm of ECH power.

4 Conclusions

Second harmonic X-mode ECH in the pure Ohmic start-up scenario is powerful tool to burn-through and plasma current ramp-up by T_e increase in superconducting Tokamak with a limited loop voltage and inconsistent wall conditioning and density control. The minimum ECH power for ECH-assisted start-up to burn-through and to save the flux is about 200 kW. The optimal ECH timing is field null formation time. ECH central heating is more effective for flux saving compared to the lower deposition of ECH power. The best ECH toroidal angle is 10 degree. Flux consumption can be reduced about 30% (0.3 Wb for 1 s) by using ECH power more than 200 kW with the toroidal angle of 10 degree. However, plasma position control is important due to plasma radial shift by additional heating and the impurities generated from ECH power tend to make it difficult L-H mode transition. In coming KSTAR campaign, we are planning for ITER-relevant ECH-assisted start-up to find the minimum loop voltage in pure Ohmic start-up, the minimum loop voltage and ECH effect on the breakdown in ECH-assisted start-up, and to investigate the ECH effect as a function of ramp-up rate during ramp-up phase.

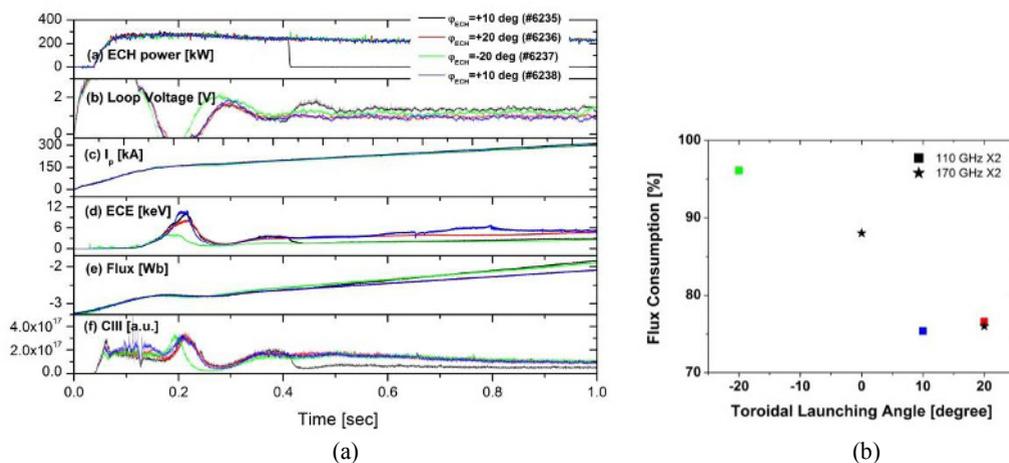


Figure 5. (a) Time evolutions of plasma parameters and (b) the flux consumption as a function of ECH toroidal launching angle where ECH trigger time is 0 ms.

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