Electron cyclotron heating assisted start-up experiments in J-TEXT

Junli Zhang[1], *Peter C de* Vries[2], *Kazunobu* Nagasaki[3], *Donghui* Xia[1,*], *Wei* Jiang[4], *Zhoujun* Yang[1], *Zhifeng* Cheng[1], *Xin* Xu[1], *Zhijiang* Wang[1], *Nengchao* Wang[1], *Li* Gao[1], *Yonghua* Ding[1], *Zhipeng* Chen[1], *Zhongyong* Chen[1], and *Pan* Yuan[1] and J-TEXT team[**].

[1]International Joint Research Laboratory of Magnetic confinement Fusion and Plasma Physics, Huazhong University of Science and Technology, Wuhan 430074, People's Republic of China
[2]ITER Organization, Route de Vinon sur Verdon, CS 90 046, 13067 St Paul Lez Durance, France
[3]Institute of Advanced Energy, Kyoto University, Uji, Japan
[4]School of Physics, Huazhong University of Science and Technology

Abstract. Electron cyclotron heating (ECH) breakdown and burn-through assist has been adopted to make the ITER start-up, which uses a low toroidal electric field of about 0.3 V/m, more robust. Related studies have been carried out on many fusion machines such as DIII-D, JT-60U, Tore Supra and FTU. However, the required ECH power to ensure an effective breakdown assist at ITER is not yet clear. Experiment was also performed in J-TEXT to determine the minimum ECH power requirements to assist breakdown and develop a better physics description of the process. The breakdown loop voltage for a successful shot was reduced from 34 to 3.7 V (corresponding to 0.56 V/m) by 300 kW X2-mode ECH power. The critical ECH power to assist the successful formation of a tokamak discharge is about 200kW, and below this value, ionization caused by ECH power is observed, however, the tokamak discharge start-up does not succeed. The effect of different loop voltages and ECH pulse-width on start-up was also studied. As injecting ECH power at a proper time, low ECH power can achieve a similar pre-ionization result as the case with high power. Extremely low breakdown voltage leads to a higher toroidal field later when putting a capacity to continue discharging in J-TEXT. The earlier shutdown of ECH power caused a failed discharge.

1 Introduction

Start-up is the first stage of the tokamak operation. However, until now, there are still a lot of questions urged to be answered. For example, there are concerns about whether a low toroidal electric field of 0.3 V/m is enough to support robust breakdown in ITER first plasma. Many tokamaks such as DIII-D[1][2], JT-60U[3], Tore Supra[4] and FTU[5] carry out related experiments to verify the feasibility of low toroidal electric field start-up with electron cyclotron heating (ECH) assisted. These experiments provided a scientific basis for ECH assisted ITER start-up. However, the required ECH power to ensure an effective breakdown assist in ITER is not yet clear [6].

J-TEXT has conducted the ECH assisted start-up experiments since 2019. These experiments aimed to determine the minimum ECH requirements to assist in the breakdown and develop a better physics description of the process. This paper is organized as follows: A brief introduction to the experimental setup is given in the next section. Section 3 shows the experimental results and some analysis. Finally, this paper concludes with a summary.

2 Experimental setup

J-TEXT is a conventional middle-size iron-core tokamak with a major radius of 1.05 m. It operated at a minor radius of 0.25-0.29 m with a movable titanium-carbide-coated graphite limiter. The typical J-TEXT discharge in the limiter configuration is done with a toroidal field B_t of 2.0 T, a plasma current I_p of 200 kA, a pulse length of 800 ms, plasma densities n_e of $1-7\times10^{19}m^{-3}$, and an electron temperature T_e of 1 keV.[7]

The Ohmic field begins acting with a reversed current first, corresponding to a reversed peak in loop voltage at the beginning. Then the pre-magnetic capacitor is triggered at t=0.0 ms, which is an artificially defined time series for discharge. The capacitor bank, including the ionization capacitor, capacitor one (C1) and capacitor two (C2), works successively to discharge to the Ohmic field coils. The ionization capacitor with a high voltage can achieve a successful breakdown. C1 and C2 can provide volt-seconds to the discharge after the breakdown. Figure 1 shows the top view of related diagnostics and the ECH system. Key diagnostics includes polarimeter-interferometer (named 'polaris')[8], photo-diode array (PDA), vacuum gauge. Polaris provides information on line-integrated plasma density at the core. PDA measures the hydrogen-alpha radiation, which is related to the ionization condition of working gas, namely

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[*] e-mail: xiadh@hust.edu.cn

[**] See the author list of "Y. Liang et al. 2019 Overview of the Recent Experimental Research on the J-TEXT Tokamak, Nucl. Fusion 59 112016"

hydrogen gas. The vacuum gauge measures the pressure in the vessel. Gas puffing was employed to inject hydrogen gas by giving an electric pulse before the application of a toroidal electric field. The pulse is constant for all shots shown in this paper. A 105 GHz/500 kW/1 s ECH system was developed in 2019[9]. Two polarizers on the miter bend can achieve arbitrary polarization, allowing X2-mode ECH assisted start-up to be applied. Its launcher has the capacity of injecting ECH power with a toroidal injection angle of ±20° and a poloidal injection angle of ±20°, respectively. The ECH power is injected with a poloidal injection angle of +3° and a toroidal injection angle of 0° in this paper.

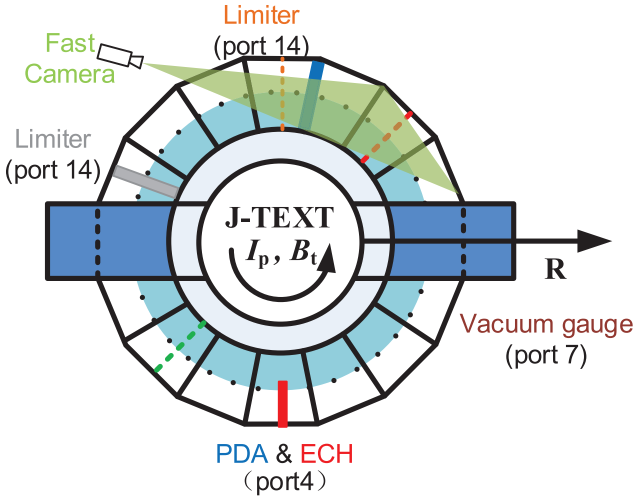

Figure 1. Distribution of related diagnostics and the ECH system on J-TEXT from a top view.

3 Experimental results and analysis

This is the first ECH assisted start-up experiment on J-TEXT. The error field was presented first to show the magnetic field configuration. A parameter scan of the voltage of the ionization capacitor was performed to explore the lower limit of breakdown voltage. The result of a typical ECH assisted start-up was given. Scanning of the ECH power and pulse-width showed its effect on start-up. The following parts give a more detailed description.

3.1 Error field

Prior to the plasma initiation, the magnetic field configuration is optimized to reduce the stray magnetic field and to obtain a favorable configuration for the tokamak start-up. It is expected to obtain a large enough field null structure, which will increase the effective connection length and achieve a robust start-up. Figure 2 shows the distribution of magnetic field configuration in cross section when t=0.0 s, which is calculated by EFUND code. The ECH resonance layer is around the center of the vessel (R=1.05 m) for a toroidal magnetic field of 1.87 T when 105 GHz ECH power is applied. In these experiments, the poloidal magnetic field is about 3 Gauss around the ECH resonance layer. The estimated connection length is 1590 m, which allows to achieve a successful breakdown in a large pre-fill pressure range [10].

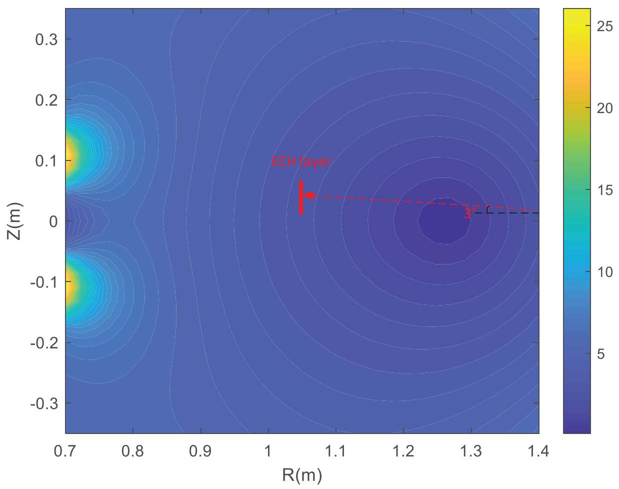

Figure 2. The magnetic field configuration (unit in Gauss) in cross-section When t=0 s. ECH resonance layer is around the center of the vacuum vessel (R=1.05 m, red square), where the stray-field is about 3 Gauss. The red dotted line is the schematic diagram of the EC propagation path

3.2 Typical ECH assisted start-up

For a reliable and robust start-up, J-TEXT usually discharges with a pre-magnetization and ionization capacitor of 1600 V. It will lead to an extremely high breakdown (loop) voltage of about 34 V (E=5.2 V/m). Scanning of the ionized capacitor with EC assisted was carried out to search for the limitation of breakdown voltage. Figure 3 illustrates the statistical results of the shots. It should be noted that the experiments were not carried out in one day. The pre-fill pressure is about 1.7 mPa. All the shots shown in figure 3 are assisted with 300 kW X2-mode ECH power. It can be easily observed that ECH power makes low loop voltage discharge possible, meaning expanding the operational space.

More details of typical temporal evolution are shown in Figure 4. The minimum breakdown voltage for a successful pure Ohmic heating start-up is about 14 V (E=2.1 V/m). Figure 4 presents the temporal evolution of a shot (#1065724) with this minimum breakdown voltage. However, the breakdown voltage can be as low as 3.7V (E=0.56 V/m) with 300 kW X2-mode ECH assisted. The temporal evolution of corresponding shot #1068924 is shown in Figure 4. At J-TEXT, the iron-core can cause variations in the loop voltage during breakdown. Besides that, there are no special wall conditioning but Taylor-type discharge cleaning (TDC) and baking at 150 °C, which make it possible to gather more impurities in the vessel. Although this toroidal field is higher than 0.3 V/m, it demonstrates the capability of ECH power in assisted start-up.

When ECH power is applied, the electron density and hydrogen-alpha increase, 15 ms after the application of ECH power (but before the loop voltage). The ionization caused by ECH power can be explained by non-linear wave-particle interaction [11] Pre-plasma density makes breakdown easier by generating more seed particles before the application of loop voltage. Less volt-seconds will be consumed for a lower breakdown voltage. However, low loop voltage also makes plasma current ramp up slowly, meaning more volt-seconds saved. As time goes by, volt-seconds tend to reach the same level. Note that when an extremely low breakdown voltage is applied, a higher loop voltage may be required later to achieve successful discharge, as shown in figure 4 at 0.012 s.

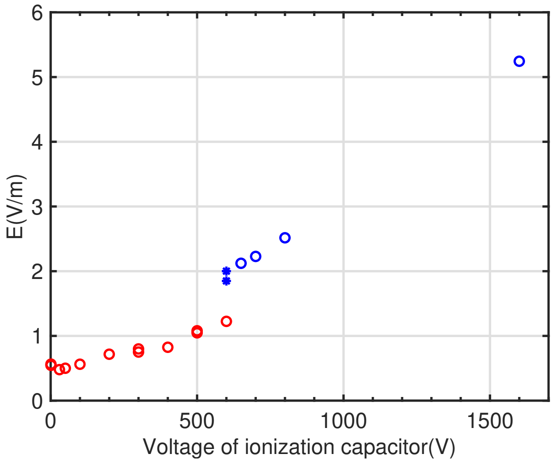

Figure 3. Operational space for pure Ohmic heating start-up and ECH assisted start-up on J-TEXT. A circle means the discharges were successful while an asterisk indicates the shot failed. The blue represents that it is a pure Ohmic heating start-up while the red represents EC assisted start-up

3.3 ECH power

Experiments with different ECH power on start-up were also conducted. It aims to search for the critical ECH power not just to achieve pre-ionization but for this ionization to be sufficient to effectively support the entire plasma initiation process.

Figure 5 shows the evolution of different signals during start-up with different ECH power assisted. It can be easily observed that high ECH power leads to quick and high-intensity ionization during pre-ionization phase, as shown in electron density and hydrogen-alpha radiation signals. It is not difficult to understand this effect. For an electron cyclotron beam with Gaussian-like profile, it results: $E \propto \sqrt{P}$, where P and E are the incident electron cyclotron power and the wave electric field amplitude, respectively. It indicates that high ECH power leads to a high electric field. When electrons travel through the wave electric field area, they will be accelerated in a shorter time to gain enough energy to achieve ionization or to higher energy, which will promote ionization in turn.

A more accurate expression, proposed by Farina, shows the maximum energy gain of an electron at second harmonic as $W_{max,n=2} \propto \sqrt{P}$ in non-linear interaction[11]. We can deduce the minimum required ECH power to achieve ionization. However, besides the ionization, if this energy is sufficiently large, in the trapping region, the energy transfer exceeds the energy needed to ionize the neutral particles in the pre-fill gas. The neutral can be well ionized. Several factors, for example, Coulomb collisions, play a role in order for this local ionization to support a high-quality pre-plasma[12][13].

ECH power is also important after the application of loop voltage. It can be easily observed from figure 5 that for shots #1073819 and #1073820, some parameters, such as plasma current, line-integrated density at the core and the loop voltage, are nearly the same before t= 7 ms. Plasma current of shot #1073820 ramps up smoothly toward the pre-set value of 180 kA. However, the plasma current of shots #1073819 drops down as it nearly reaches about 10 kA. These two shots indicates the critical power for assisted start-up is between 200 kW and 250 kW. As the plasma current of shot #1073819 ramps to about 10 kA, it is possible to achieve a successful start-up if the injected ECH power is larger, which can form a better pre-plasma at higher density and temperature and a wider area, and provide more power for tokamak plasma. Hence, the critical power for the ECH assisted start-up is 200 kW. Strictly, more shots with different ECH power can provide a more accurate value. Limited by shots, we estimate this value from physical characterizations.

Tokamak start-up usually experiences breakdown and burn-through. Burn-through will require enough energy to achieve ionization of main species and impurities[6]. ECH power will help a lot to experience such a process, which can be verified from other shots #1073825 and #1073820. Here is a preliminary quanlitative analysis. From the perspective of the energy balance equation, as shown in equation 1[10], enough Ohmic heating power density (P_{OH}) and electron cyclotron absorbed power density (P_{ECH}) is required to overcome the power loss density caused by equilibration (P_{equi}), bremsstrahlung (P_{brem}), impurity-related terms($\sum_I (P_{\mathrm{ion}} + P_{\mathrm{line}} + P_{\mathrm{RRE}} + P_{\mathrm{DRE}})$) and transport losses ($P^{\mathrm{e}}_{\mathrm{con}}$). The terms of P_{equi}, P_{brem} and $\sum_I (P_{\mathrm{ion}} + P_{\mathrm{line}} + P_{\mathrm{RRE}} + P_{\mathrm{DRE}})$ can be ignored because of no closed flux surface and low electron energy. When input power, including Ohmic heating and ECH power, is not enough, the electron will have the possibility of cooling down and recombination, which will lead to higher plasma resistance. That's the major reason that loop voltage increases around t=8 ms.

$$\frac{3}{2}\frac{\mathrm{d}}{\mathrm{d}t}(n_{\mathrm{e}}\kappa T_{\mathrm{e}}) = P_{\mathrm{OH}} + P_{\mathrm{ECH}} - (P_{\mathrm{Dion}} + P_{\mathrm{Drad}}) - P_{\mathrm{equi}} - P_{\mathrm{brem}} - \sum_I (P_{\mathrm{ion}} + P_{\mathrm{line}} + P_{\mathrm{RRE}} + P_{\mathrm{DRE}}) - P^{\mathrm{e}}_{\mathrm{con}} \qquad (1)$$

On the contrary, we can see that high power(#1073825 and #1073820) leads to an apparent higher electron density and a little higher plasma current. Enough power increases

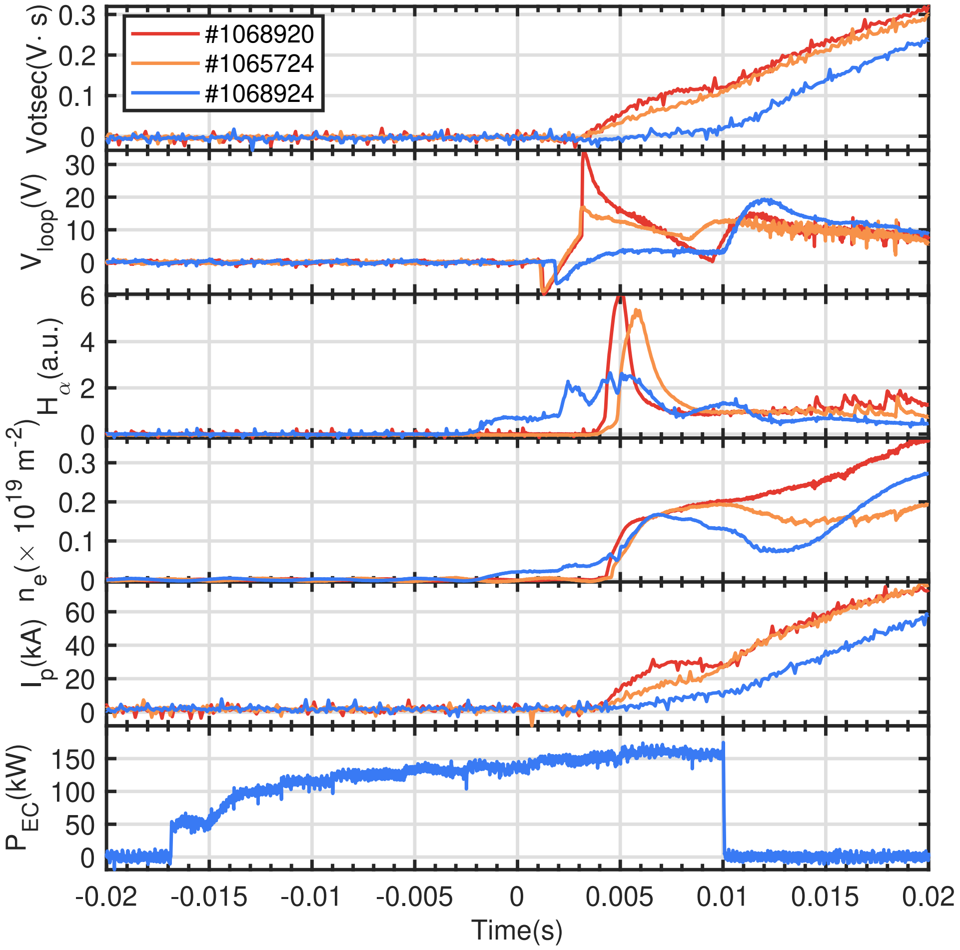

Figure 4. Evolution of different signals when discharging with ionization capacitor of 1600 V (red, #1068920), 800 V (orange, #1065724) and 1V (blue, #1068924). The last one is assisted with 300 kW ECH power while the two others are purely Ohmic heating. All the experimental densities presented in this paper are line-integrated densities.

electron density and energy, which promotes the increase of plasma current and electron density in turn. However, when another capacitor (C1) puts in use around t=10 ms, there will be a peak, which can be easily explained by the discharge characteristics of capacitors. Vol-second consumption is nearly the same, while plasma density is visibly different. As other conditions are the same or similar, these differences should be the contribution of different ECH power.

3.4 ECH pulse-width

ECH pre-ionization provides more seed electrons, which makes it easier to achieve a successful start-up. Hence, a proper ECH pulse-width, which provides a high initial plasma density and energy at the time of applying loop voltage, may achieve a reliable and robust start-up. Related experiments were conducted to preliminarily investigate this question.

Figure 6 illustrates the evolution of key signals at different ECH pulses. For shot #1068928, ECH power is the highest, and the ECH pulse lasts for 36 ms. Its density and hydrogen-alpha appeared first. However, the intensity, especially hydrogen-alpha, is not the highest. By contrast, ECH power of shot #1068924 is applied at a proper time, succeeding in a start-up with a lower ECH power than all the other cases shown in Figure 6, which makes it the ideal shot for ECH assisted start-up. A long pulse is not the best because there is no closed flux surface. Hence, the particles are not in good confinement. After ECH power is applied for enough time, PWI may happen or the distribution of electrons is out of expectation. The latter requires further investigation. Compared with the other shots presented in Figure 6, shot #1068928 has the highest ECH power and rather long pulse-width (36 ms). The electrons ionized by this power can expand quickly along the radial direction. Finally, they can interact with the wall and possibly introduce impurities from the wall.

Usually, a higher ECH power can achieve quicker ionization[13], corresponding to a quick ramp-up of hydrogen alpha after ECH power is applied. However, we also find a couple of shots different from the others. A

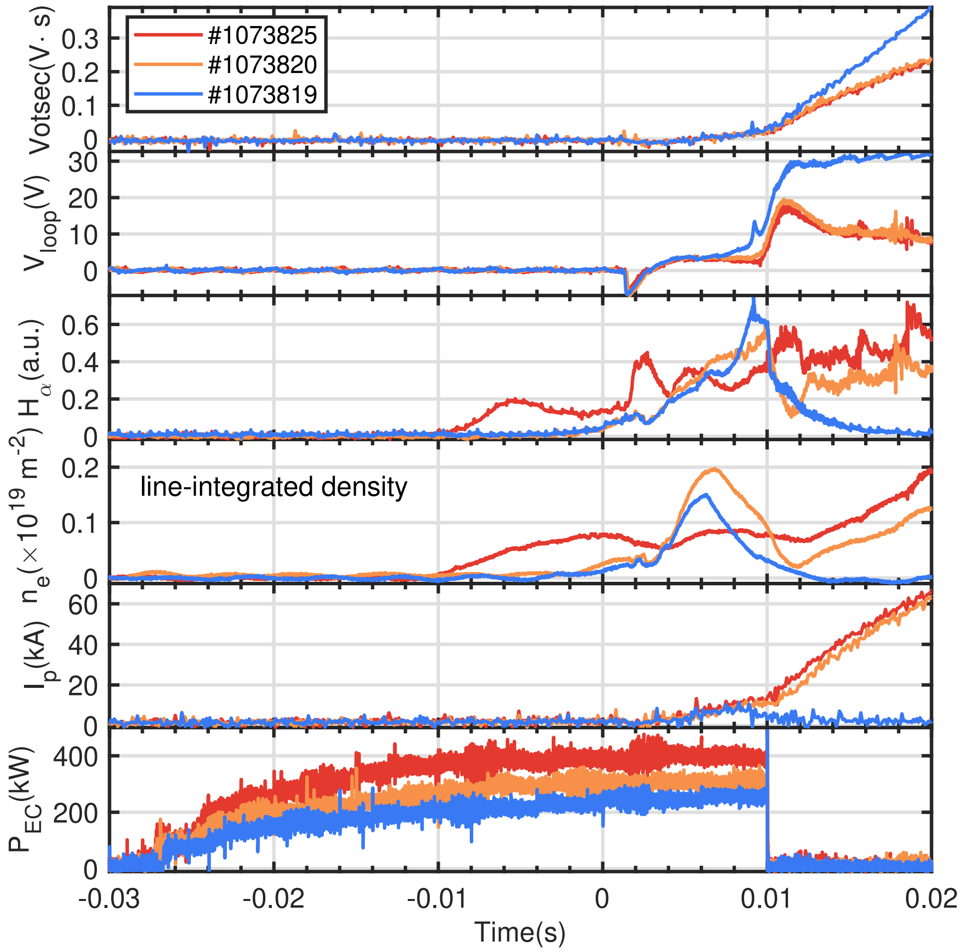

Figure 5. Evolution of key signals with different ECH power for assisted start-up.

slightly higher ECH power of shot #1068923 was injected earlier than that of shot #1068929. However, the hydrogen-alpha and electron density of shot #1068923 have appeared lately. It is different from most of our experimental results. There isn't any convincing explanation until now.

After switching off the ECH power of shot #1068928, electron density and plasma current begin decreasing while loop voltage starts increasing. The reason is insufficient energy to support burn-through, which has been analyzed qualitatively.

4 Summary

This paper shows some ECH assisted start-up experimental results on J-TEXT. An estimated rather long connection length of 1590 m indicates a good magnetic field configuration. Scanning the ionization capacitor learned the operational space for pure Ohmic heating start-up and a much wider operation region for ECH assisted start-up. The lowest breakdown field is 0.56 V/m. Scanning ECH power demonstrates that critical averaged ECH power is about 200 kW. High power of 200 kW to 400 kW leads to faster and stronger ionization. Lower ECH power (below critical power) will fail during burn-through because of a lack of input power. These results are similar to recent DIII-D studies on ECH pre-ionization.[13] . Proper ECH timing is important. High ECH power and long ECH pulse-width lead to failed discharge, while low ECH power and short ECH pulse-width (shot #1068924) succeed.

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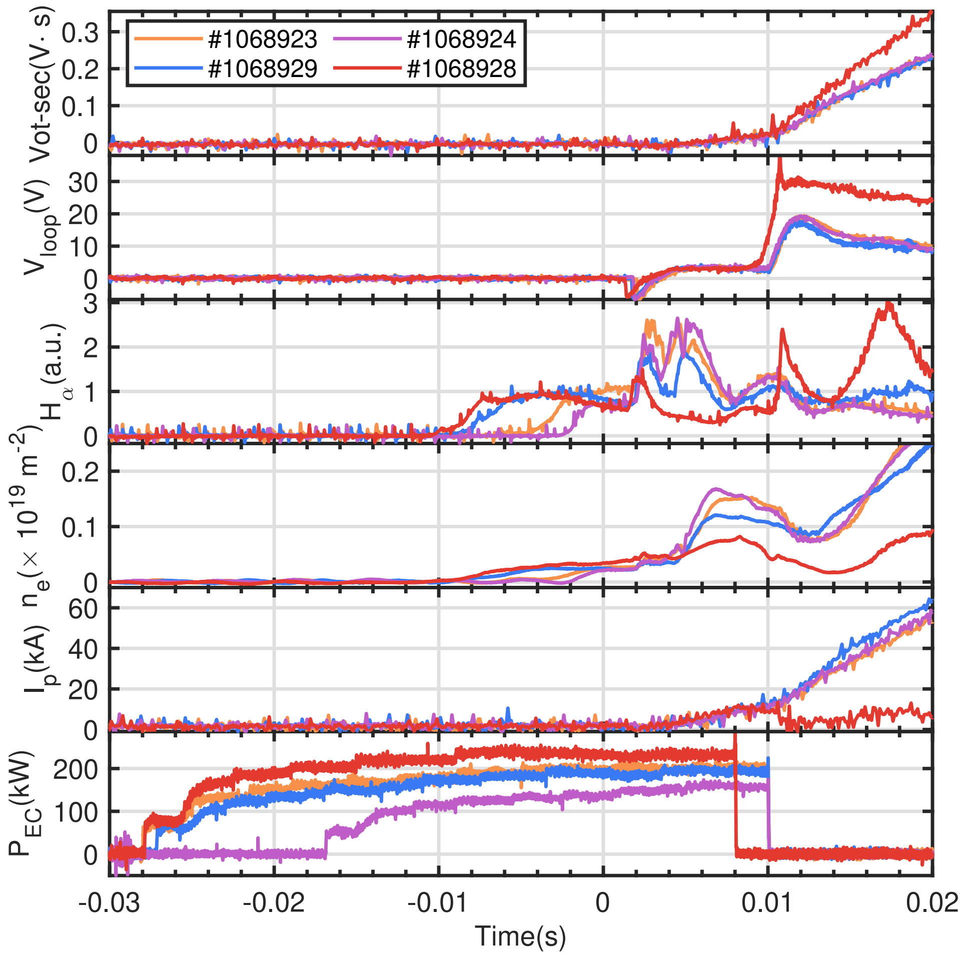

Figure 6. Evolution of key signals for different ECH pulse-width.

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