

# Solenoid-free current drive via ECRH in EXL-50 spherical torus plasmas

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**Article**

**Keywords:** spherical tokamak (ST), EXL-50, plasma

**Posted Date:** May 10th, 2021

**DOI:** <https://doi.org/10.21203/rs.3.rs-492727/v1>

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**Solenoid-free current drive via ECRH in EXL-50 spherical torus plasmas**

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**Abstract.**

As a new spherical tokamak (ST) designed to simplify engineering requirements of a possible future fusion power source, the EXL-50 experiment features a low aspect ratio ( $A$ ) vacuum vessel (VV), encircling a central post assembly containing the toroidal field coil conductors. Multiple electron cyclotron resonance heating (ECRH) resonances are located within the VV to possibly improve current drive effectiveness. The energetic electrons are observed via hard X-ray detectors, carry the bulk of the plasma current ranging from 50kA to 150kA, which is maintained for more than 1s duration. It is observed that over one Ampere current can be maintained per Watt of ECRH power issued from the 28-GHz gyrotrons. The plasma current with high line-density (approaching  $10^{19}\text{m}^{-2}$ ) has been achieved for plasma currents as high as 76kA. An analysis was carried out combining reconstructed multi-fluid equilibrium, guiding-center orbits, and resonant heating mechanisms. It is verified that in EXL-50 a broadly distributed current of energetic electrons creates smaller closed magnetic-flux surfaces of low aspect ratio that in turn confine the thermal plasma electrons and ions and participate in maintaining the equilibrium force-balance.

Great progress has been achieved in magnetic confinement fusion research based on the Tokamak since 50 years ago when the first stable high temperature plasma was observed in the T-3 tokamak [1,2]. The tokamak has been the most investigated and furthest advanced configuration among the magnetic confinement fusion systems. More recently, the spherical torus (ST) concept of aspect ratios around 1.5 [3, 4] has been experimentally (START [5], NSTX [6], MAST [7], and Globus-M [8]) tested to realize a substantially higher plasma beta compared to the tokamak of aspect ratios around 3, and is an attractive candidate for realizing a relatively compact fusion reactor.

The tokamak plasma current is required to insure a high plasma confinement capability to restrain transport losses from the core to the edge. The start-up and ramp-up of this current has been commonly driven by a toroidal electric field induced by current changes in a centre

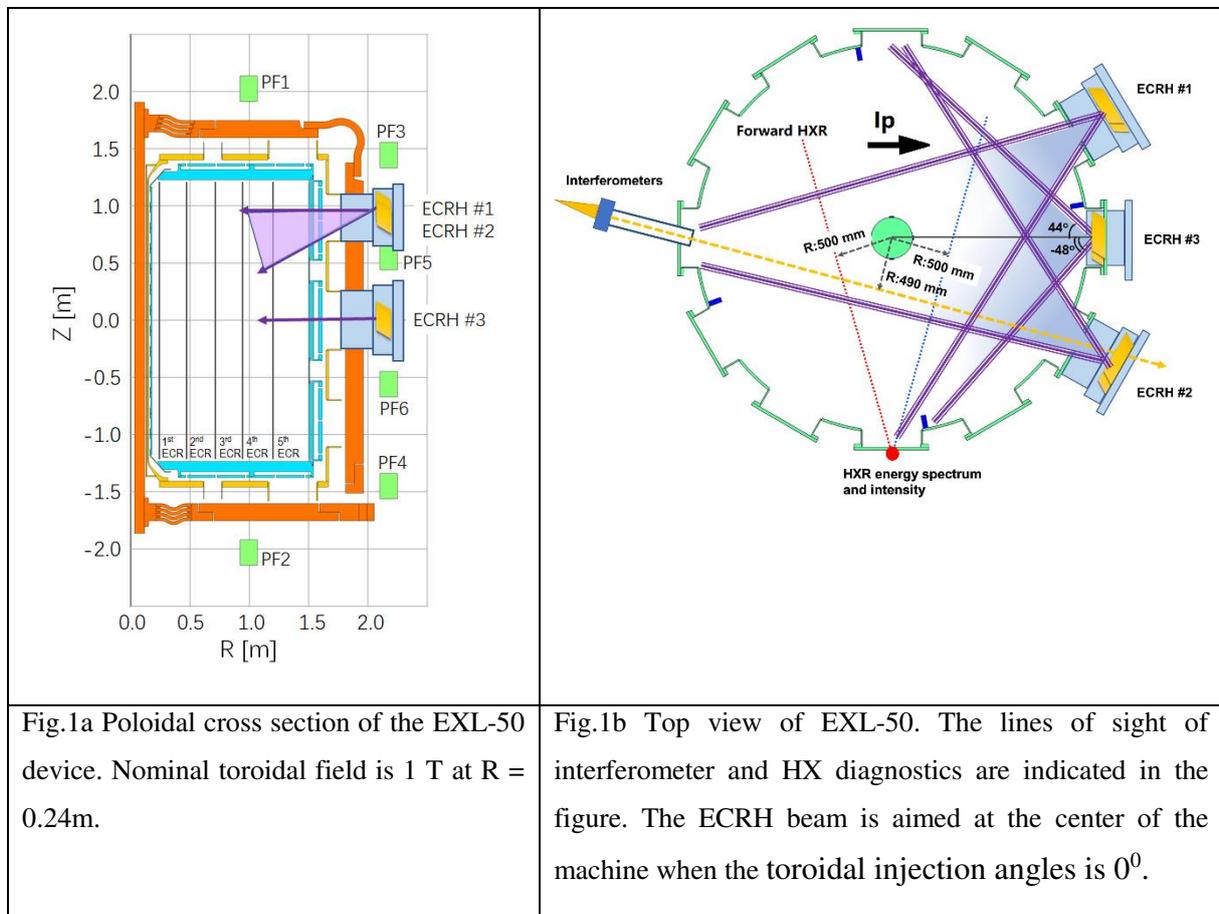
solenoid (CS) magnet. This however causes engineering difficulties for the ST due to the limited space available within a narrow centre column. Further, a CS magnet is capable of sustaining the plasma current over limited time periods, which is to be augmented by non-inductive methods in a future fusion reactor. To develop a solenoid-free current drive capability therefore has been an important research endeavour for the STs. On the positive side, removing the CS allows additional space to increase the toroidal field (TF), further improving compactness and economy.

The original physics concept and principle of the ENN Spherical Torus with a major radius 50 cm (EXL-50) in Energy iNNovation (ENN) Science and Technology Development Co. was recently proposed by Peng [9]. One of the key EXL-50 experimental goals is to test the efficacy of electron cyclotron resonance heating (ECRH) and current drive in the absence of an CS magnet. CS-free ECRH and current drive has been tested in several earlier ST devices (CDX-U [10], LATE [11-15], TST-2 [16-17], MAST [18-19], and QUEST [20-26]). A toroidal current of 1.05 kA was generated using about 8 kW of ECRH power on CDX-U [9], proving the possibility of current start-up by ECRH alone. Later, a 7kA plasma current was generated by about 30kW ECRH in LATE [11-12]. A current flattop with closed flux surface (CFS) plasma was sustained for 60ms in LATE, proving the potential for steady-state ECRH and current drive of the ST plasmas. In MAST, a plasma current of 73kA was produced by 60kW ECRH power with the help of the unique grooved mirror-polarizer installed on the central rod [18]. In QUEST, a plasma current of 90kA was obtained with about 200kW ECRH power through combined first and second harmonic resonances [24].

In this paper, we present the latest ECRH experimental results from EXL-50. Not only are the operational parameters of CS-free current drive by ECRH significantly expanded, but also observed are some remarkable plasma behaviour. Discharges with plasma currents substantially above 100kA are routinely obtained in EXL-50, with the current flat-top sustained for up to or beyond 2 seconds. More than 1A current per Watt of ECRH power issued from the gyrotrons, averaged over hundreds of discharges, have been accumulated. At line-densities approaching  $10^{19}\text{m}^{-2}$ , plasma currents as high as 76kA have been achieved.

The EXL-50 device is a medium-sized ST with a cylindrical vacuum vessel (see, Fig. 1). Six poloidal field (PF) coils are located outside the vacuum vessel and the TF coil conductors. Inner limiters on the center column and outer limiters on the vessel wall have leading edges at 0.186m and 1.512m in major radius, respectively. Two microwave frequencies have been utilized so far, 28-GHz from high power gyrotrons for higher toroidal field discharges and 2.45-GHz from

low power magnetrons for lower toroidal field discharges and wall cleaning. Fig.1 shows the poloidal cross section of the EXL-50 device. Two sets of 28GHz gyrotrons (50kW source power for ECRH1 and 400kW for ECRH2) are available to inject power through an outboard ports above the mid-plane. Another 400kW 28GHz gyrotron (ECRH3) and two sets of 2.45GHz magnetrons (30kW source power each) are available to inject power through the mid-plane ports. The toroidal injection angles of the ECRH systems can be adjusted over limited ranges (as shown in Fig.1b). Both the 2.45-GHz and the 28-GHz systems are arranged to inject primarily ordinary-mode (O-mode) wave in recent experiments on the EXL-50. When the electric current of a 12-turn TF coils per turn was set to about 100kA, the fundamental and higher ECR layers (up to five resonances) coexist within the EXL-50’s vacuum region within the limiters (as shown in Fig.1a). The electron density is measured by single-chord tangential microwave interferometer. Two CdTe detectors with energy resolution are applied to observe the forward and backward bremsstrahlung hard x-ray (HXR) emission.



Here, a simplified current drive effectiveness  $\eta_{AW}$  is defined as follows and utilized:

$$\eta_{A/W} = \frac{I_P}{P_{ECRH}},$$

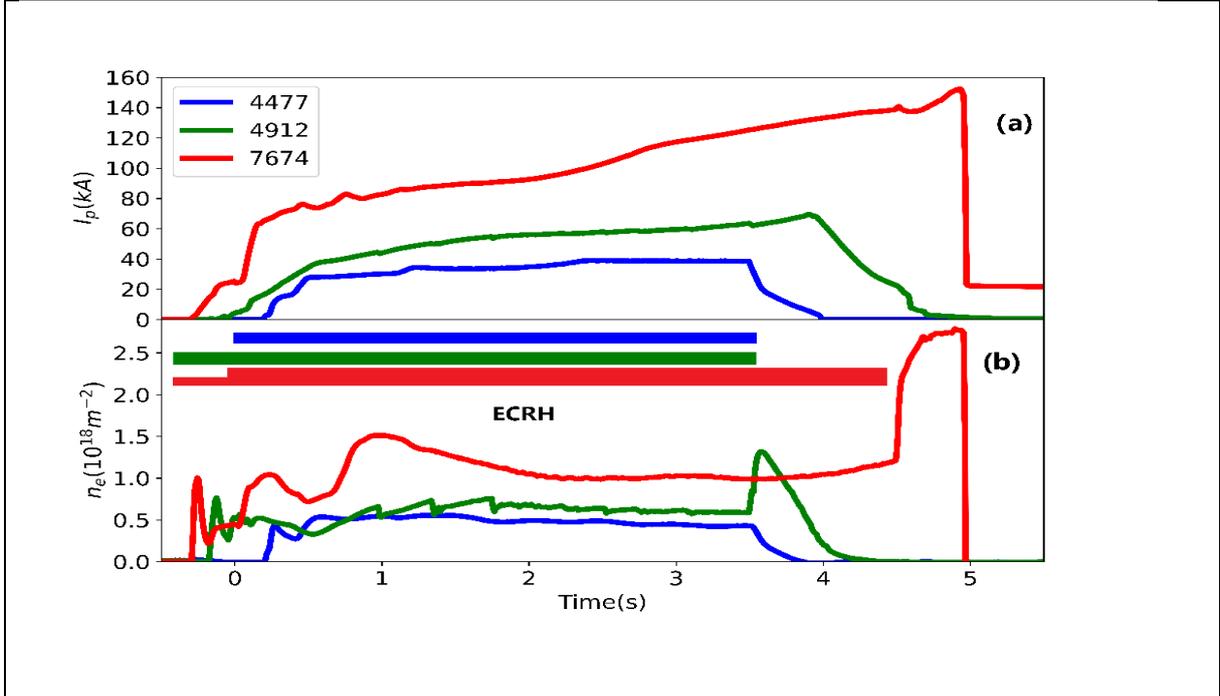


Fig.2 The discharge waveforms for different 28GHz ECRH heating power. (a) plasma current; (b) line integrated density.  $P_{ECRH}$  was 20kW in shot 4477 and 45kW in shot 4912. Two gyrotrons are used in shot 7674. One gyrotron injected 20kW from -0.3s to 0s and the other gyrotron injected 115kW from 0s to 4.5s.

where  $I_P$  is the plasma current,  $P_{ECRH}$  is the ECRH power issued from the gyrotrons. Fig.2 shows the typical discharge waveforms with different 28GHz ECRH heating power in EXL-50. The  $\eta_{A/W}$  can reach 2A/W (40kA/20kW) for low power ECRH plasma. The  $\eta_{A/W}$  is 1.55A/W (70kA/45kW) for moderate power ECRH plasma and 1.22A/W (140kA/115kW) for further increased power ECRH plasma. The  $P_{ECRH}$  in this paper is the power measured at the matching optical unit (MOU) which is close to the exit power of the gyrotrons. The power delivered from the antenna inside the vacuum vessel is unknown at present. The duration of high current ( $I_P > 100$ kA) for the higher power ECRH plasma in Fig.2 is more than 2s. The total pulse length for 28GHz ECR heating plasma is less than 6s limited by temperature rise at the top joints of the TF coils at 100kA electric current. One notable phenomenon as shown in Fig.2 is the density jumps as the ECRH power is turned off, indicating possibly a cessation of density pump-out by ECH [25], which is not addressed in this paper.

Fig.3 shows the relation of  $I_P$  v.s.  $P_{ECRH}$  for about 180 successful shots in EXL-50. The general trend in Fig.3 is that the  $I_P$  increases with  $P_{ECRH}$ . On the other hand, it is also can be seen in Fig.3 that the  $I_P$  varies in quite large range for the same  $P_{ECRH}$ . Notably, changes in the currents of PF coils has substantial effects on  $\eta_{A/W}$ . Fig.4 clearly shows that the  $I_P$  increases with the

current of PF5&6 coils for the same  $P_{\text{ECRH}}$  and density. More statistical information from 180 shots is shown in Fig.4b. It can be found that for fixed  $P_{\text{ECRH}}$  the  $I_p$  increases linearly with the external vertical magnetic field  $B_v$ . The force balance between the expansion of the plasma itself and external magnetic compress must be sustained for a stable equilibrium structure. So much potential for raising  $\eta_{A/W}$  further remains unexplored at present through optimization of PF coil current.

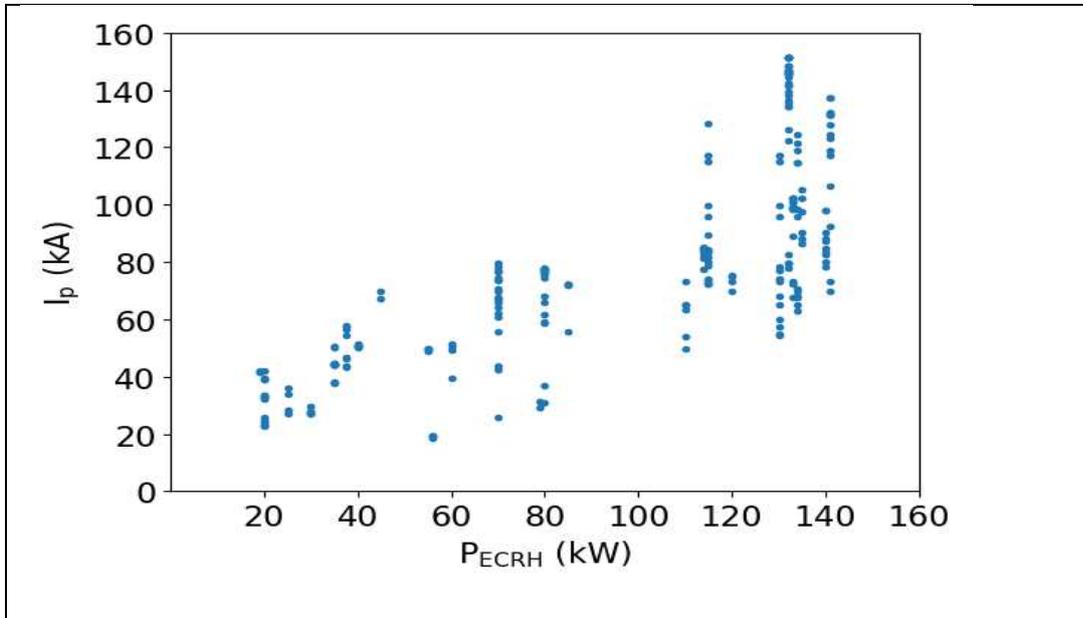


Fig.3  $I_p$  v.s.  $P_{\text{ECRH}}$  for 180 successful shots in EXL-50

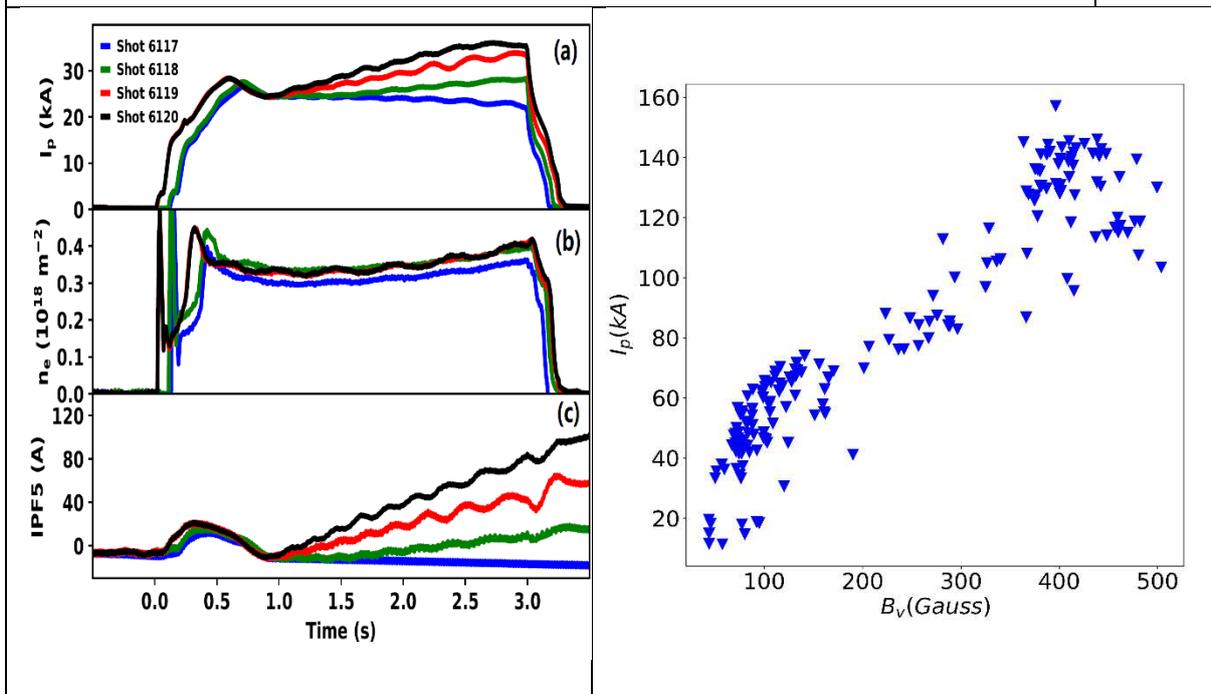
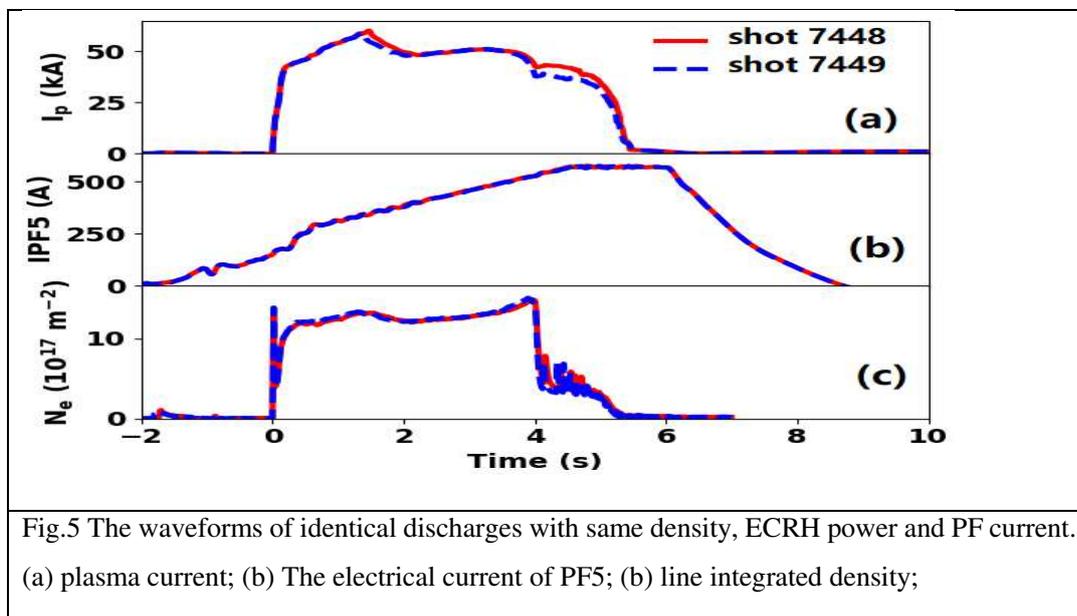


Fig.4a The waveforms of four discharges with similar density. (a) plasma current; (b) line

Fig.4b The plasma current at flattop phase versus external  $B_v$ .

integrated density; (c) The electrical current of PF5.  $P_{\text{ECRH}}$  was 25kW for these shots. The electrical current of PF1 and PF3 were kept constant during whole discharge phase.

The Pfirsch-Schluter (PS) current is a dominant component during the initial start-up phase, and drastically decreases with increasing  $B_v$  following the formation of CFS. The bootstrap current drive by the pressure gradient is at present estimated to be less than several percent for these EXL-50 plasmas. The conventional Electron cyclotron current drive (ECCD) via Fisch-Boozer mechanism [28] or Ohkawa mechanism [29] can also contribute to the non-inductive current. However, such ECCD effects have not been confirmed in EXL-50's experiments. Fig.5 shows the waveforms of two shots in EXL-50. Although the toroidal angle for the ECRH antenna was set at  $-16^\circ$  for count-current drive in shot 7448 and  $17^\circ$  for co-current drive in shot 7449, the plasma current remained largely unchanged.



QUEST and LATE's experiments have proven that the energetic electrons play a primary role for the CS-free current drive. EXL-50's experimental results confirm that the plasma current is mainly carried by such energetic electrons. The shot shown in Fig.6 is a very stable and well-controlled discharge, showing a nearly stationary plasma current, electron density, as well as a zero loop voltage from 1.5s to 4.5s. During the entire discharge, the plasma current, and hard x-ray intensity and its photon temperature (the average energy of energetic electrons) vary conjointly in magnitude. It is seen that both the number and the energy of energetic electrons contribute directly to the increase of ECRH plasma current.

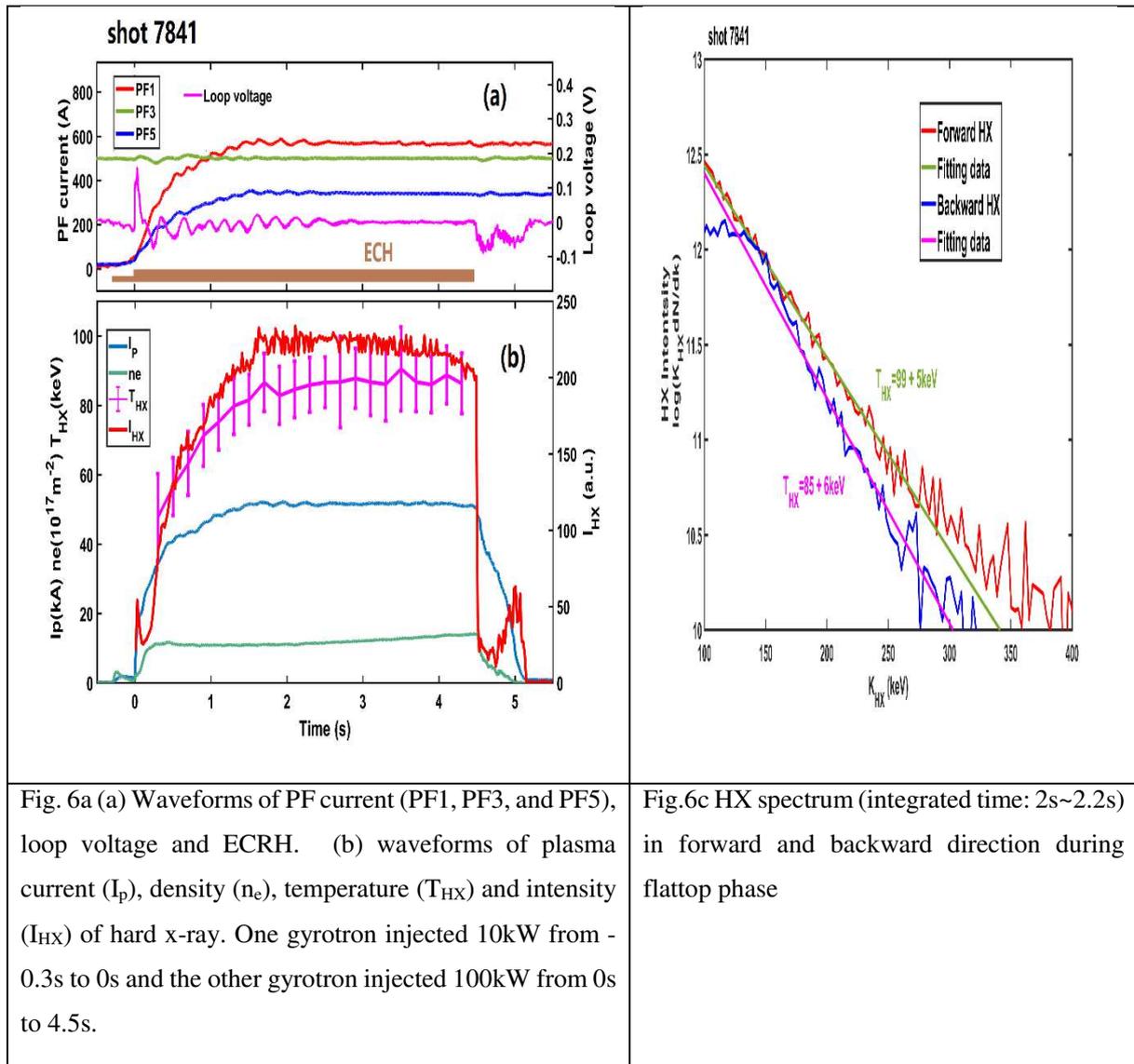
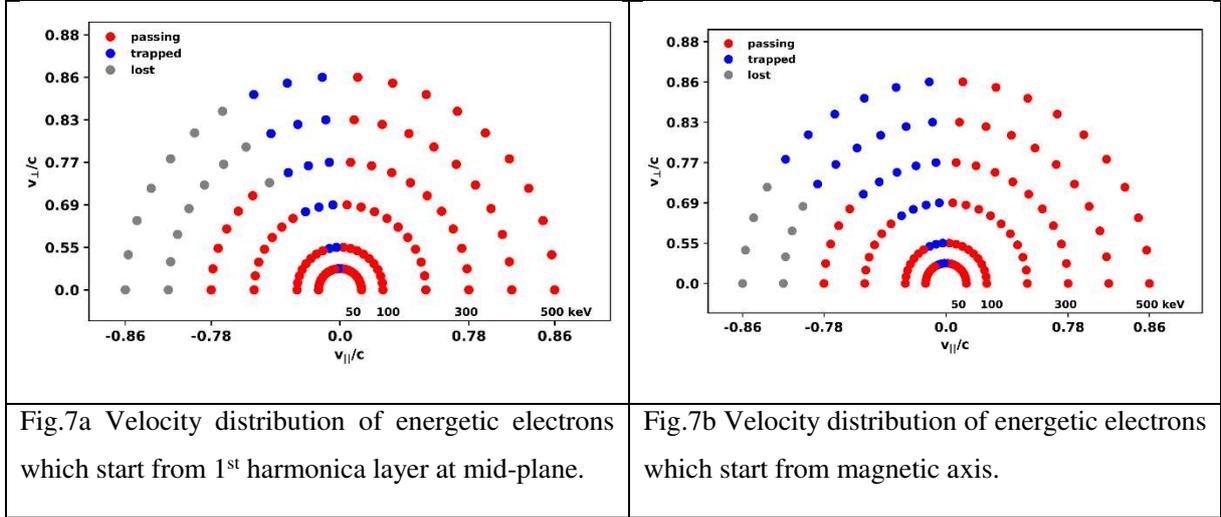


Fig. 6a (a) Waveforms of PF current (PF1, PF3, and PF5), loop voltage and ECRH. (b) waveforms of plasma current ( $I_p$ ), density ( $n_e$ ), temperature ( $T_{HX}$ ) and intensity ( $I_{HX}$ ) of hard x-ray. One gyrotron injected 10kW from -0.3s to 0s and the other gyrotron injected 100kW from 0s to 4.5s.

Fig.6c HX spectrum (integrated time: 2s~2.2s) in forward and backward direction during flattop phase

It should be noted that the role of induction in the CS-free ECRH driven current remains unresolved. That is, does the toroidal electric field induced by changes in the PF coil and plasma currents accelerate the already decoupled energetic electrons to even higher energies and carry a significant plasma current fraction during a discharge? Experiments dedicated to resolving this question were carried out. As indicated in Fig. 6a, the currents of PF3 and PF4 (not indicated) were kept constant during the entire discharge. The currents of PF1&2 and PF5&6 were ramped-up slowly until 1.5s and kept constant through to 6s. The loop voltage oscillated near zero between 1.5s and 2.5s and became zero between 2.5s and 4.5s. The largest value of loop voltage of +0.17V (counter-clockwise when viewed from top) appears at 0.037s, in the direction opposite to the plasma current (clockwise when viewed from top).. in addition, the velocity distribution of energetic electrons driven by ECRH is different from that of runaway electrons induced by a toroidal electric field. In the former case, the energetic electrons possess similar magnitudes of parallel and perpendicular velocities, while in the latter, the

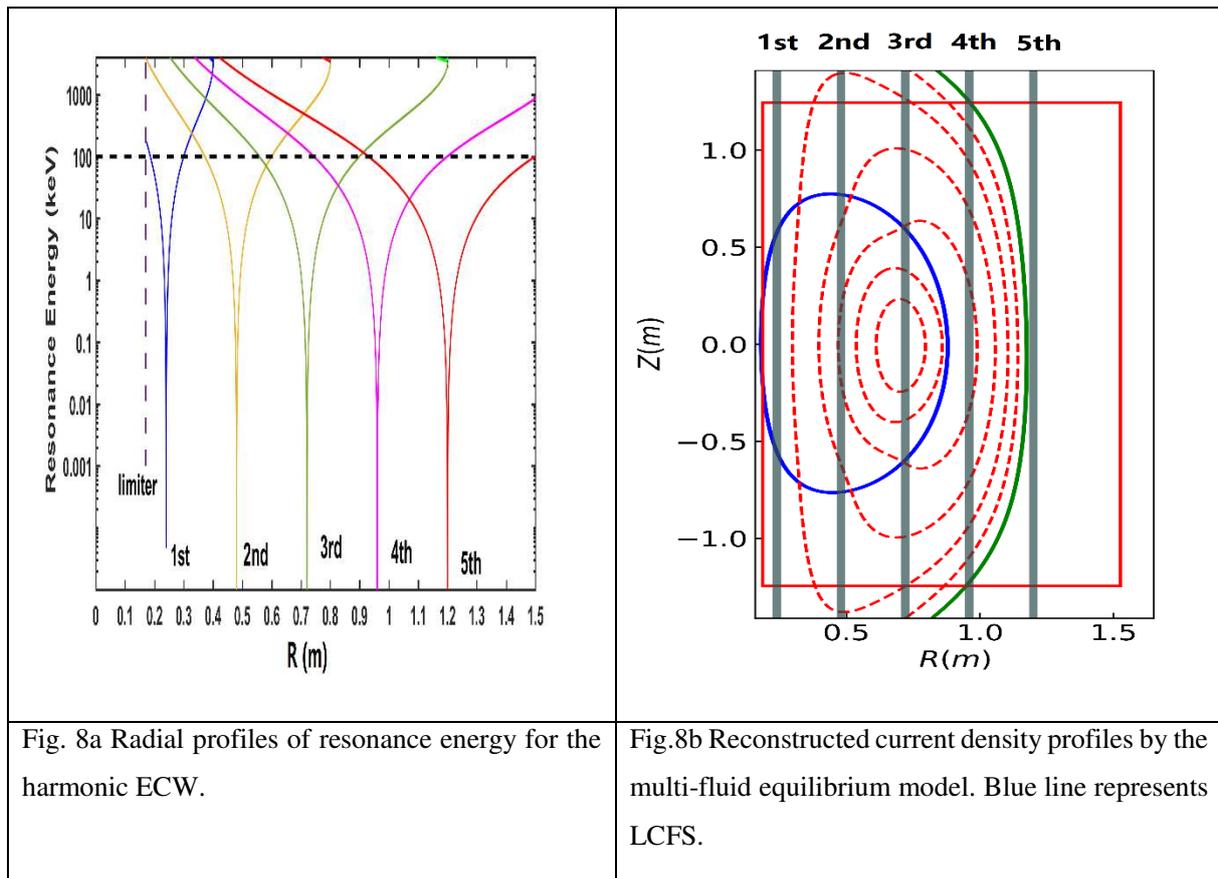
parallel velocities dominates. Fig.6c shows the hard x-ray intensity and energy spectrum in forward (count-current) direction and backward (co-current) direction, indicating relatively moderate differences. Further, the energetic electrons can be strongly accelerated in the parallel direction by the relative high loop voltage during current ramp-down after the ECRH is turned off. These experimental observations indicate that the inductive and runaway-like current drive mechanisms are not significant in the CS-free ECRH plasmas.



A key question regarding the very high current drive effectiveness ( $\eta_{A/W} = 1.2A/W \sim 2 A/W$ ) in EXL-50 via the energetic electrons may be addressed by analysing the asymmetric region of orbit containment of the energetic electrons. Fig.7 shows the orbit analysis for energetic electrons in velocity-energy space. A three-fluid equilibrium reproducing a 50kA EXL-50's plasma was obtained via the multi-fluid equilibrium model [30] for the computation for the guiding-center orbits [31]. A strongly asymmetric distribution in toroidal direction, in the  $v_{\parallel}$ ,  $v_{\perp}$ , and energy space, is obtained, accentuated as the electron energy increases toward the limiting energy of orbit containment. Further, the design of EXL-50 (as shown in Fig.1a) permits the coexistence of five ECR layers within the vacuum vessel. Considering the effect of relativistic Doppler shift [23], the resonance layers for energetic electrons broaden in major radius. Fig.8a shows the radial dependence of the characteristic resonant energies for the fundamental and harmonic ECW for EXL-50. For energy of electrons above 100keV, the width of a resonance upshifts to overlap with the downshifted resonance of the next higher harmonic. It can be seen that the individual resonance widths for the energetic electrons fill the entire space inside EXL-50's vacuum vessel.

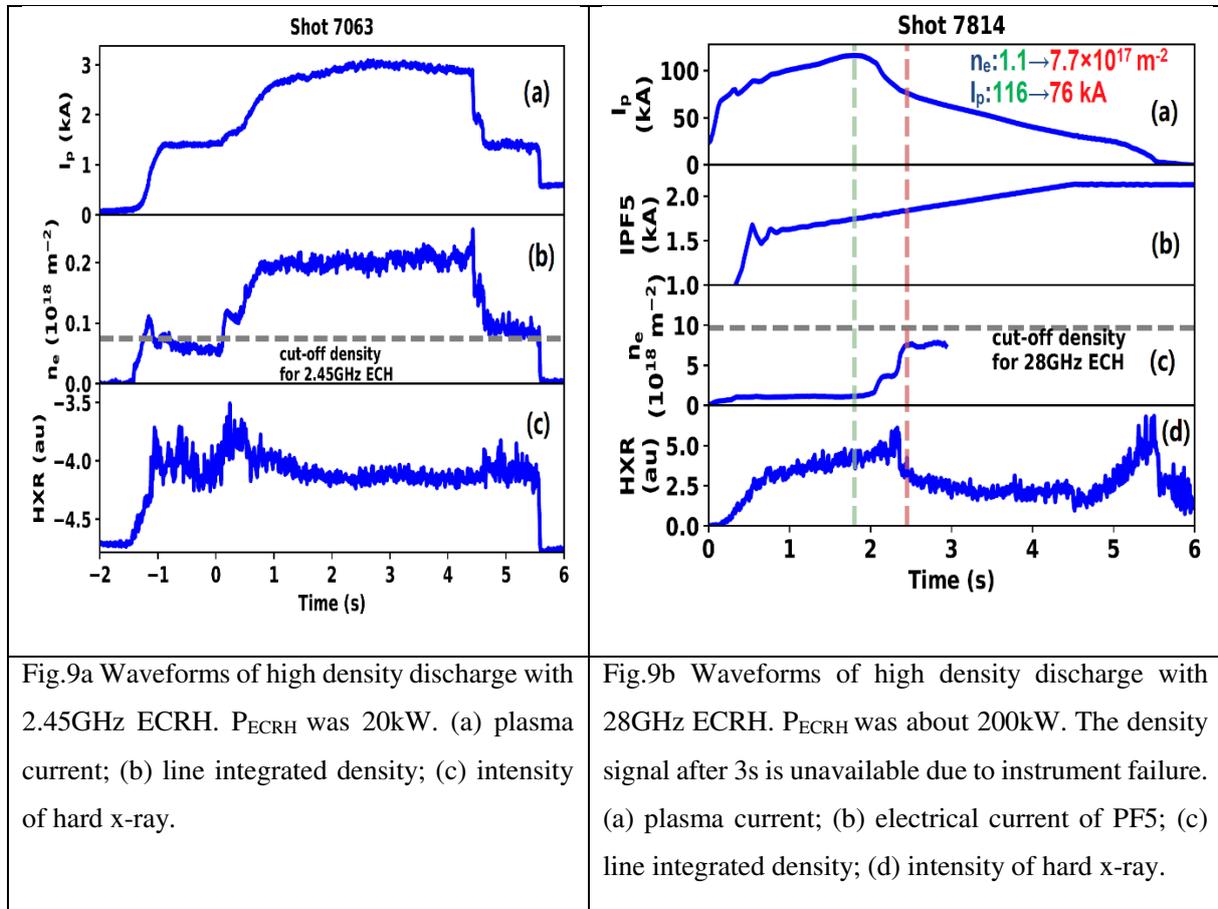
The single-pass absorption of ECW is estimated to be relatively low in EXL-50 for the present range of plasma densities. The smooth stainless steel vacuum vessel walls and limiters,

including those on the center column, assist in ensuring multiple reflected paths of the injected ECW back to the plasma. Wall-reflection further helps by converting O-mode wave to the X-mode and vice versa, thus taking advantage of the higher efficiency of X-modes by energetic electrons [26]. Another notable feature of EXL-50's plasma is that the cross section of the plasma current carried by the energetic electrons is much bigger than that of CFS during the flattop phase of plasma current. Fig.8b shows the current profile and last close flux surface (LCFS) for a 120kA discharge shown in Fig.2, computed via the multi-fluid equilibrium model [30]. A significant fraction of the plasma current (52% in this case) is flowing outside the LCFS.



High density ECRH discharges are also obtained in EXL-50. The line averaged density can be as higher as three times of the ordinary mode (O-mode) cut-off density in the 2.45GHz ECH discharges. In the 28GHz ECH discharges, the line average density near the O-mode cut-off ( $\sim 9 \times 10^{18} \text{m}^{-3}$ ) has been measured. The core density for shot 7814 in Fig.9 would exceed the cut-off density if the density profile within the LCFS has a parabolic shape. It is surmised that the electron Bernstein wave (EBW) has been excited and played key role to heat plasma and drive current for such high density discharges. In shot 7814, density ramp-up caused a decrease in plasma current. In fact, the continuous current decrease during the density flattop is mainly caused by the yet-to-be optimized PF current setting. After eliminating the influence of PF

current, the plasma current only decrease one third (from 116kA to 76kA) when the line density increases 6 times (from  $0.11 \times 10^{19}$  to  $0.77 \times 10^{19} \text{m}^{-2}$ ). The hard x-ray signal in Fig.9 indicates that the energetic electron can be still efficiently produced and maintain a dominant component of the plasma current in high density ECH discharges.



New records of driven plasma current and current drive effectiveness have been obtained during the CS-free ECRH-only operation on EXL-50. The energetic electrons play a unique and important role in EXL-50's plasmas. Metal wall of the vacuum vessel effecting multi-reflective absorption of high multi-harmonic resonances resulted in highly effective acceleration of the energetic electrons. The asymmetric distribution of the energetic electrons in velocity-energy space based on orbit analysis in a multi-fluid equilibrium is another key feature of the very high current driven effectiveness observed. However, the physics mechanism for the solenoid-free ECRH current drive is not yet well understood and quantifiable. Nevertheless, these results demonstrate an exceptional potential of ECRH to achieve and maintain highly efficient steady-state current drive under low and high densities in the CS-free EXL-50 device. Theory, modelling and simulation to better describe the full range

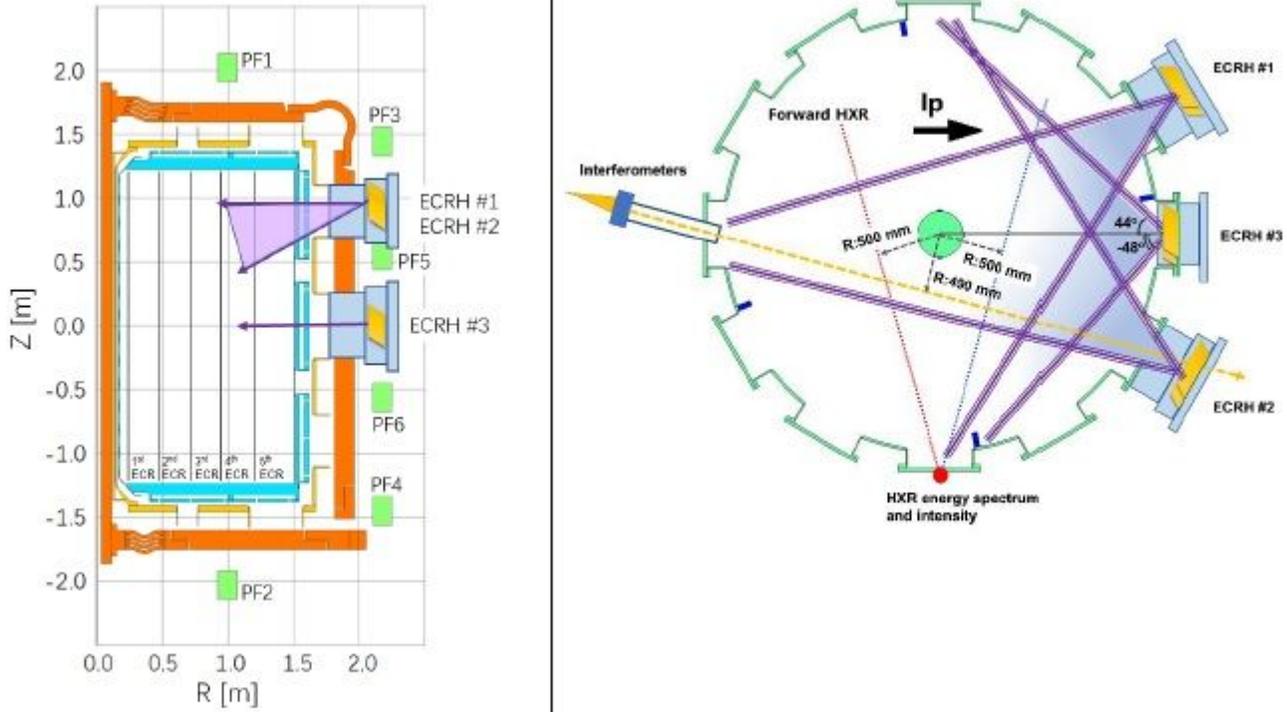
of mechanisms associated with the CS-free current drive observed will be systematically developed in the future. Steady-state high current and density experiments using high ECRH power on EXL-50 will continue to make additional physics contributions towards an eventual realization of a commercial fusion reactor.

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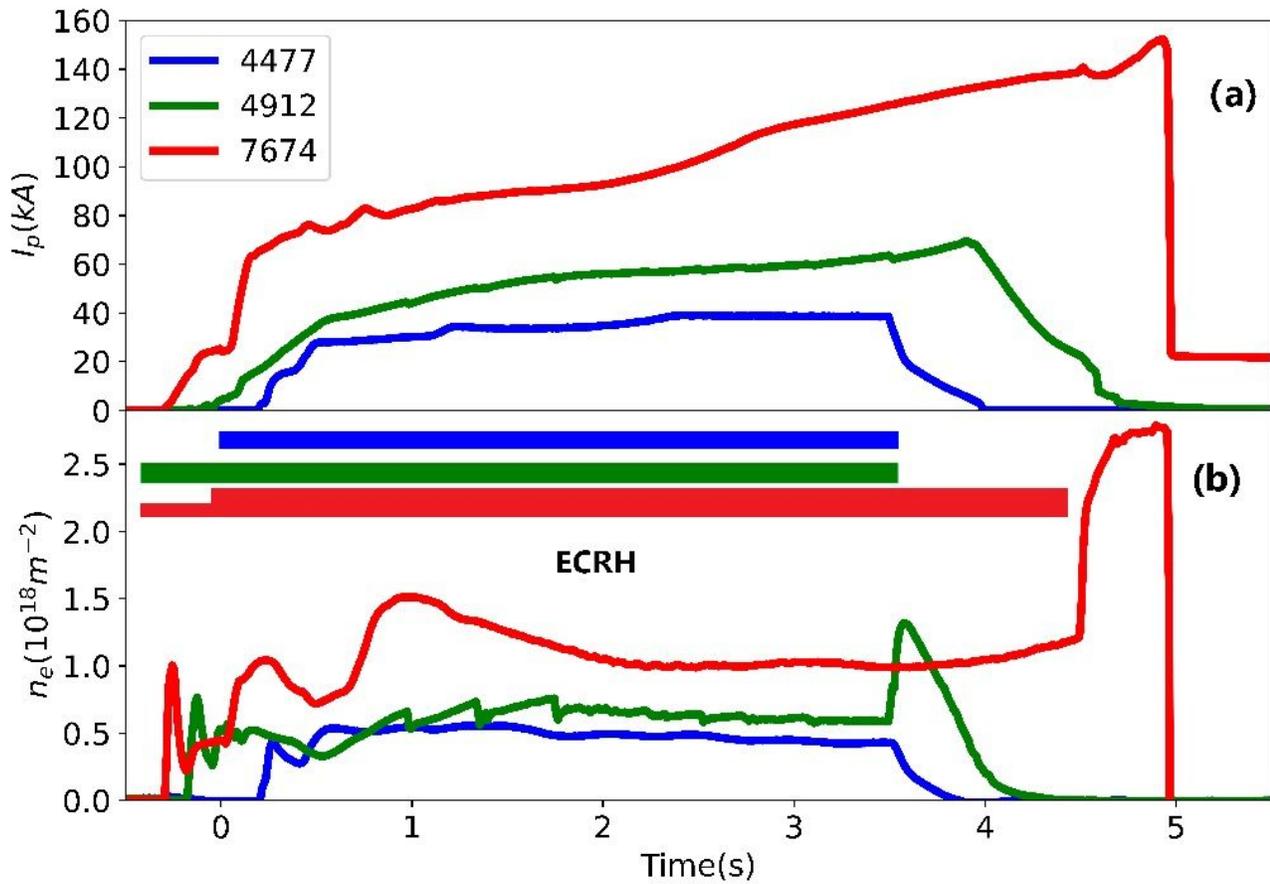
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# Figures



**Figure 1**

a Poloidal cross section of the EXL-50 device. Nominal toroidal field is 1 T at  $R = 0.24\text{m}$ . b Top view of EXL-50. The lines of sight of interferometer and HX diagnostics are indicated in the figure. The ECRH beam is aimed at the center of the machine when the toroidal injection angles is 00.



**Figure 2**

The discharge waveforms for different 28GHz ECRH heating power. (a) plasma current; (b) line integrated density. PECHH was 20kW in shot 4477 and 45kW in shot 4912. Two gyrotrons are used in shot 7674. One gyrotron injected 20kW from -0.3s to 0s and the other gyrotron injected 115kW from 0s to 4.5s.

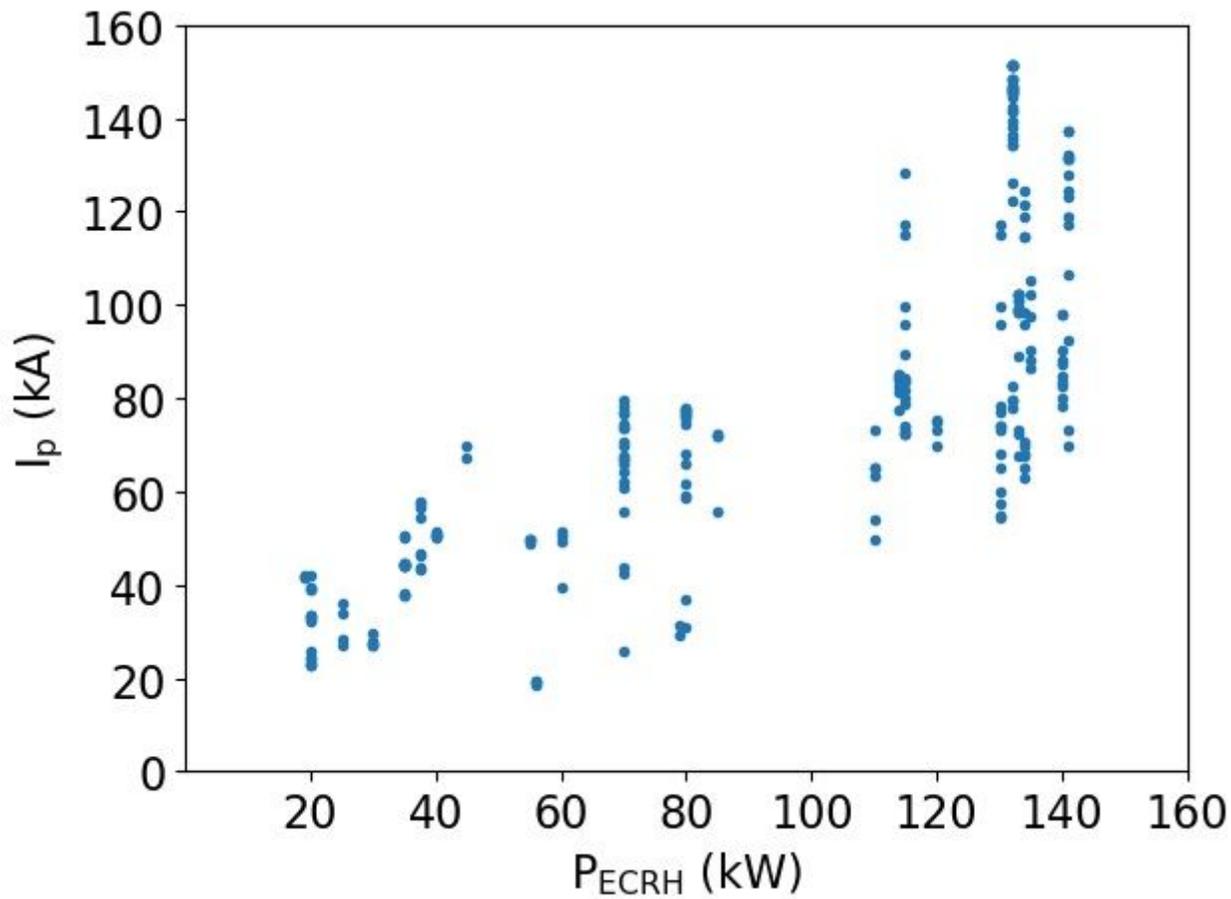


Figure 3

$I_p$  v.s.  $P_{\text{ECRH}}$  for 180 successful shots in EXL-50

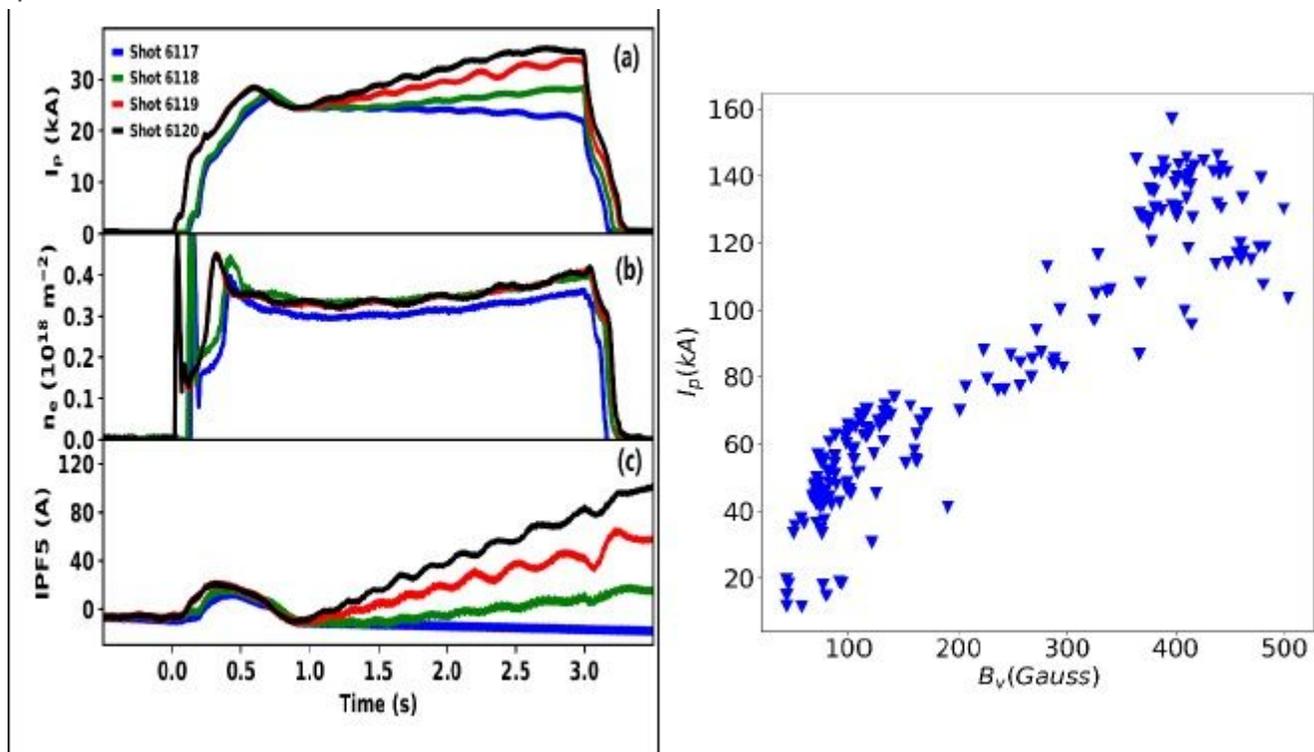


Figure 4

a The waveforms of four discharges with similar density. (a) plasma current; (b) line integrated density; (c) The electrical current of PF5. PECH was 25kW for these shots. The electrical current of PF1 and PF3 were kept constant during whole discharge phase. b The plasma current at flattop phase versus external Bv.

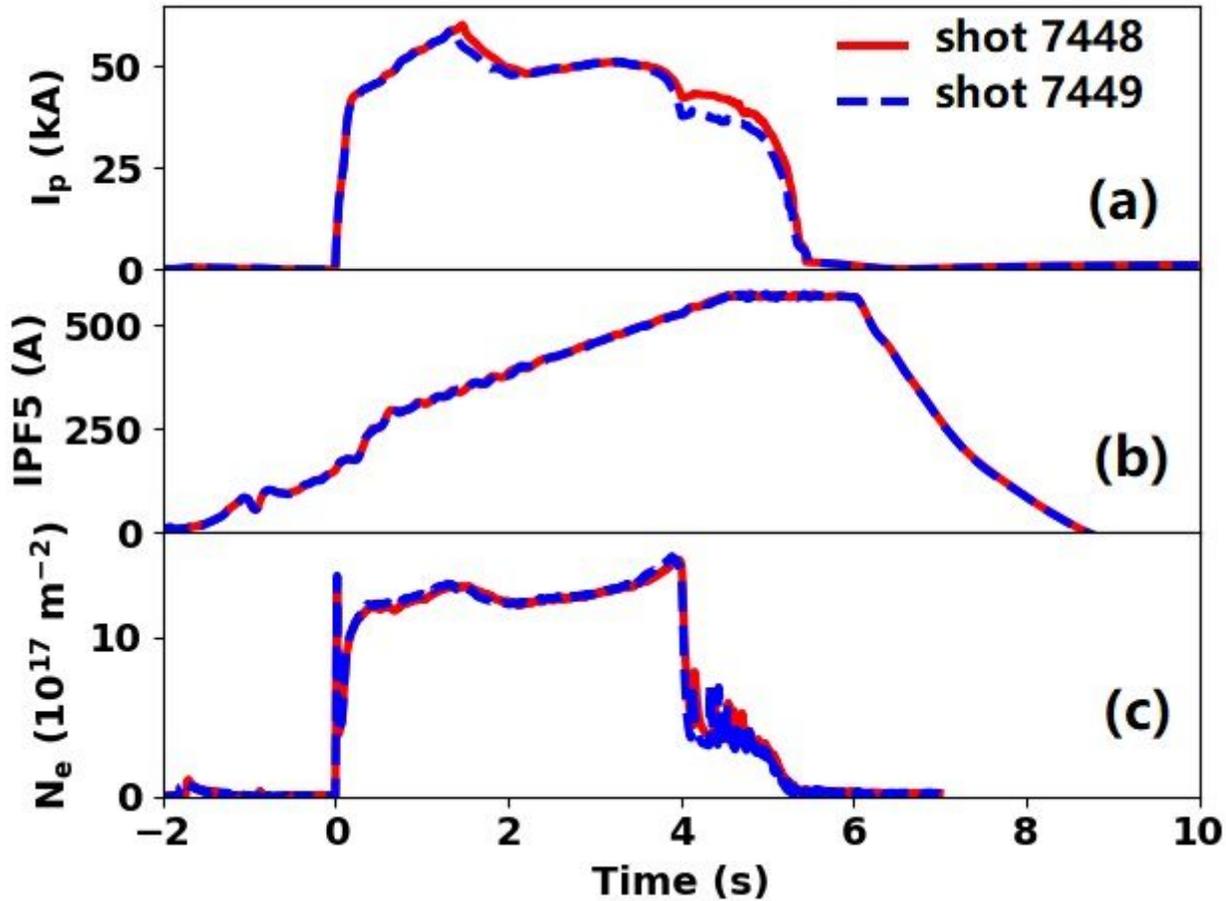


Figure 5

The waveforms of identical discharges with same density, ECRH power and PF current. (a) plasma current; (b) The electrical current of PF5; (b) line integrated density;

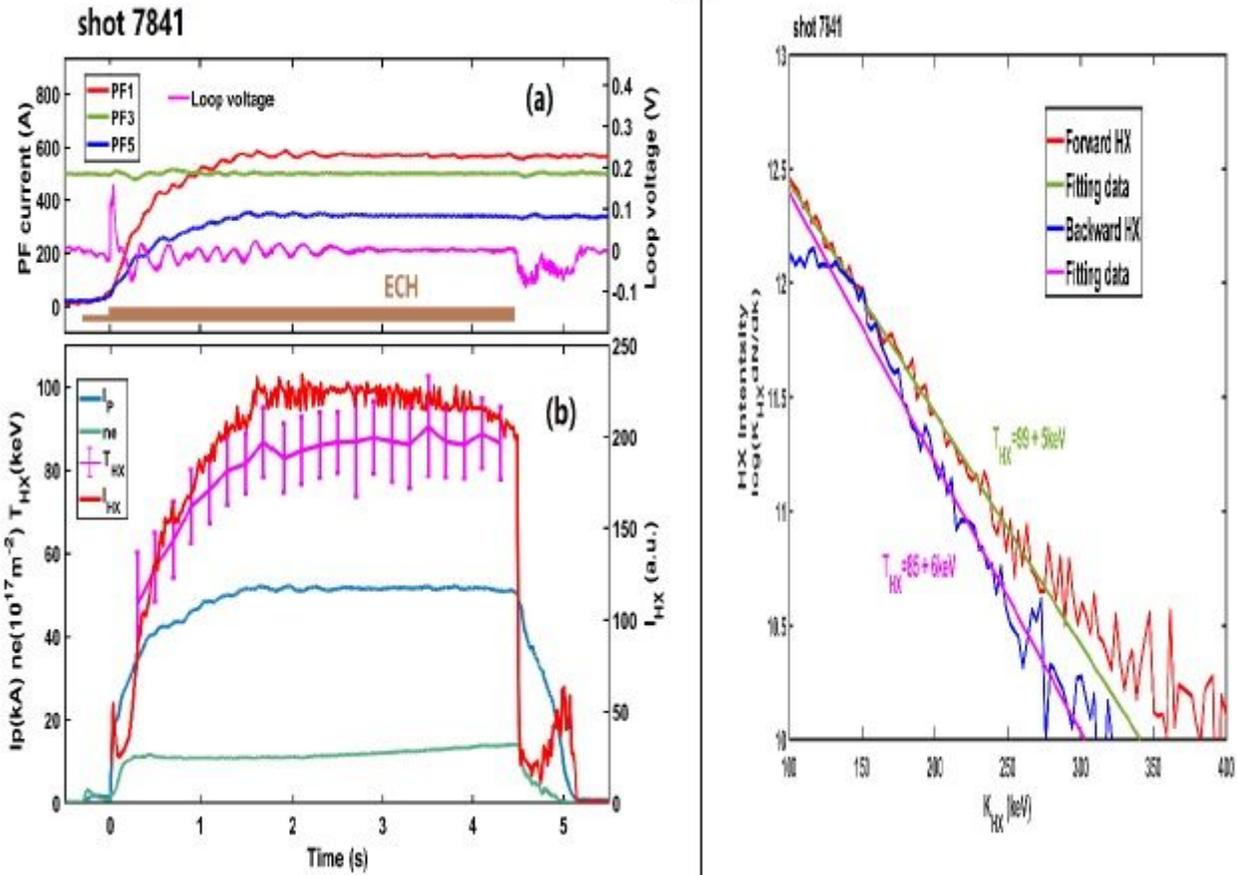


Figure 6

a (a) Waveforms of PF current (PF1, PF3, and PF5), loop voltage and ECRH. (b) waveforms of plasma current ( $I_p$ ), density ( $n_e$ ), temperature ( $T_{HX}$ ) and intensity ( $I_{HX}$ ) of hard x-ray. One gyrotron injected 10kW from -0.3s to 0s and the other gyrotron injected 100kW from 0s to 4.5s. c HX spectrum (integrated time: 2s~2.2s) in forward and backward direction during flat-top phase

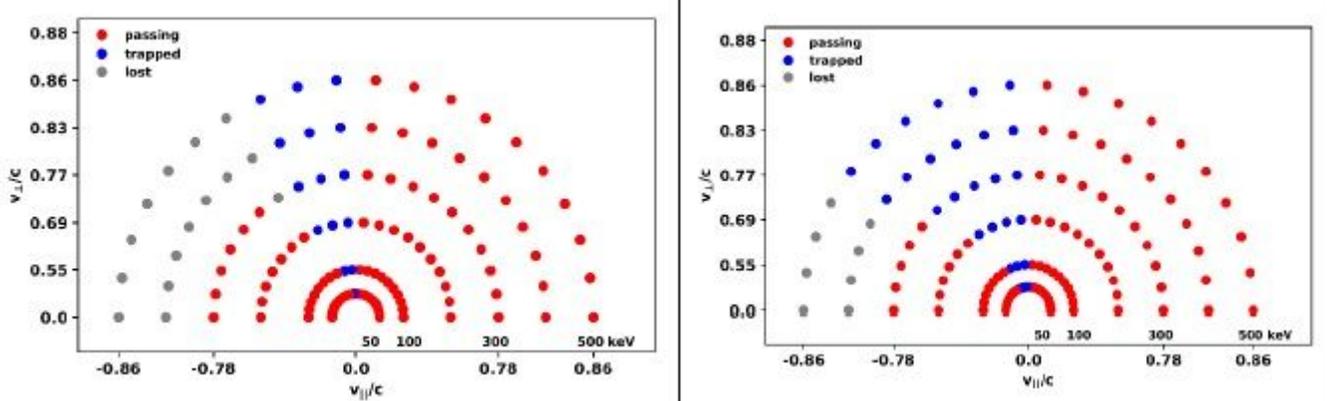


Figure 7

a Velocity distribution of energetic electrons which start from 1st harmonica layer at mid-plane. b Velocity distribution of energetic electrons which start from magnetic axis.

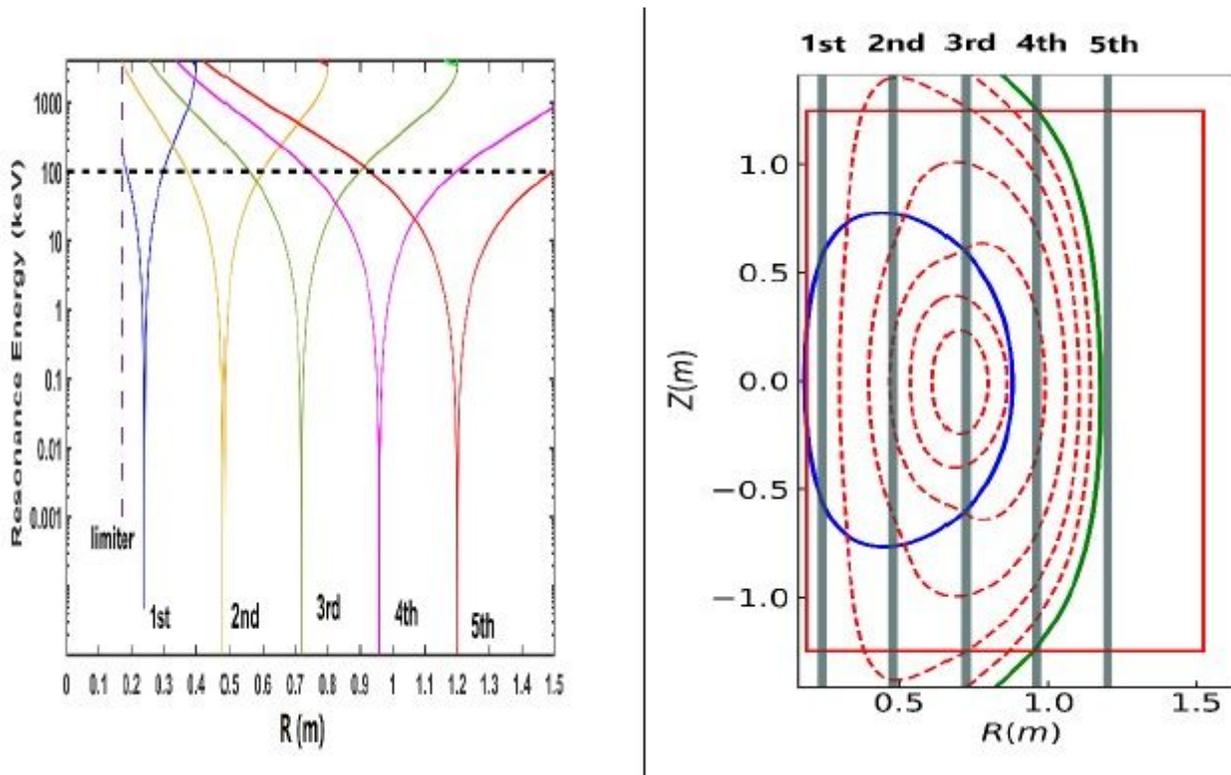


Figure 8

a Radial profiles of resonance energy for the harmonic ECW. b Reconstructed current density profiles by the multi-fluid equilibrium model. Blue line represents LCFS.

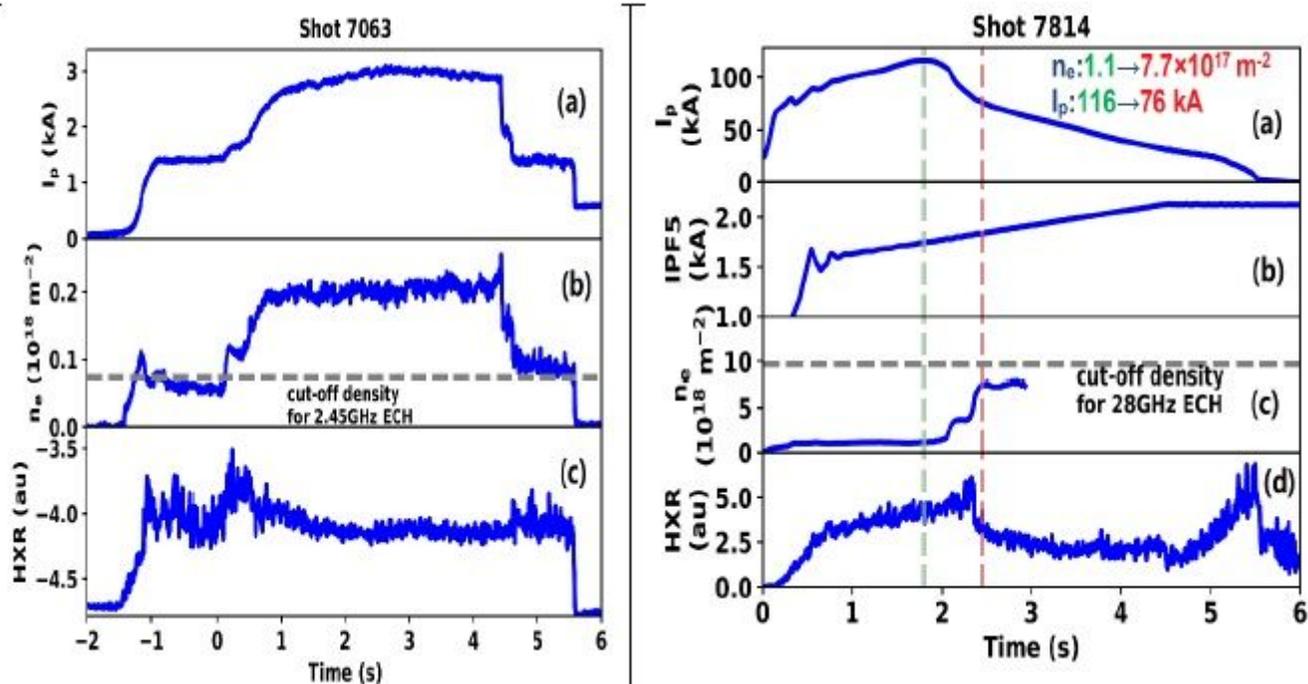


Figure 9

a Waveforms of high density discharge with 2.45GHz ECRH. PECRH was 20kW. (a) plasma current; (b) line integrated density; (c) intensity of hard x-ray. b Waveforms of high density discharge with 28GHz

ECRH. PECHRH was about 200kW. The density signal after 3s is unavailable due to instrument failure. (a) plasma current; (b) electrical current of PF5; (c) line integrated density; (d) intensity of hard x-ray.