Experimental study of the characteristics of energetic electrons outside LCFS in EXL-50 spherical torus

Dong Guo\textsuperscript{1,2,*}, Yuejiang Shi\textsuperscript{1,2,*}, Wenjun Liu\textsuperscript{1,2}, Yunyang Song\textsuperscript{1,2}, Tiantian Sun\textsuperscript{1,2}, Bing Liu\textsuperscript{1,2}, Yingying Li\textsuperscript{1,2}, Xiaorang Tian\textsuperscript{1,2}, Guosong Zhang\textsuperscript{1,2}, Huasheng Xie\textsuperscript{1,2,*}, Y-K Martin Peng\textsuperscript{1,2}, Minsheng Liu\textsuperscript{1,2}, and EXL-50 team\textsuperscript{1,2}

\textsuperscript{1} Hebei Key Laboratory of Compact Fusion, Langfang 065001, People’s Republic of China
\textsuperscript{2} ENN Science and Technology Development Co., Ltd, Langfang 065001, People’s Republic of China

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Abstract
Significant number of confined energetic electrons have been observed outside of the LCFS (last-closed flux surface) of EXL-50’s solenoid-free electron cyclotron resonance heating (ECRH) sustained plasmas. Several measurement technologies have been applied to verify the key characteristics of energetic electrons for the first time. Experiments reveal that the presence of high-temperature, low-density electrons can carry relatively large quantities of the stored energy. The boundary between the thermal plasma and the energetic fluid is clearly separated and the distance between the two boundaries can reach tens of centimeters (around the size of the minor radius of the thermal plasma). This implies that the Grad-Shafranov equilibrium is not adequate to describe the equilibrium of EXL-50 plasma and a multi-fluid model is required. Particle simulations of full orbits show that energetic electrons can be well confined outside the LCFS. This is consistent with the experimental observations.

Keywords: EXL-50, energetic electrons, LCFS, experiment, equilibrium

1. Introduction
Toroidal plasma current is essential in tokamaks to keep the plasma in equilibrium and to form nested magnetic surfaces for confinement. Usually, this magnetic equilibrium can be described by a single-fluid model and reconstructed from the plasma using the Grad-Shafranov formalism, with the assumption that the dominant plasma current is contained inside the last closed-flux surface (LCFS) \cite{1}. However, this assumption is no longer valid when a significant number of confined energetic electrons exist outside LCFS and carry considerable plasma current. Hard x-ray spectra showed that energy of the bulk of the energetic electron component inside LCFS range from 20 keV to 600 keV \cite{2}. Such electrons were collisionless and strongly decoupled from the low-temperature plasma ions and electrons that were also present. Orbit analysis shows the energetic electrons have a nearly isotropic velocity distribution in the parallel and perpendicular directions. It is therefore appropriate, as a first approximation, to describe these plasmas using a multi-fluid equilibrium model that includes a high-energy electron component in addition to a low-energy electron and ion component. In order to describe the equilibrium of such type of plasmas, some models have been developed \cite{3–5}. A three-fluid (two electron fluids and one ion fluid) axisymmetric equilibrium model with toroidal and poloidal flows was developed and first applied to the TST-2 spherical tokamak \cite{3}. It is found that the toroidal current density and pressure are dominated by the low-density high-energy electron fluid and the radial force balance for each

\* Authors to whom any correspondence should be addressed.
fluid species is quite different. The four-fluid axisymmetric plasma equilibrium model was prompted further consideration of the relativistic effects of energetic electrons [4]. There are also many experimental studies on energetic electrons. Electron cyclotron resonance heating (ECRH) power modulation experiments on TST-2 show that a large number of energetic electrons in SOL will cause the floating potential to go from negative to positive [6]. A co-directional toroidal flow of roughly 4 keV energetic electrons was detected on QUEST [7]. Such energetic electrons could carry significant currents of about 2–3 kA m$^{-2}$. However, few studies have been reported on the experimental observation of the multi-fluid equilibrium.

In order to study the characteristics of the energetic electrons in EXL-50, several different kinds of experiments were performed in this work. Firstly, considering the electron emission effect of Langmuir probe, two kinds of materials (stainless steel and tungsten) were applied in the measurement. In addition, boron powder injection experiments were conducted to study the relation between the main plasma boundary and the energetic electrons spatial distribution. Finally, from thermodynamic simulations, we give the edge threshold heat flux that causes the probe melting, and thus the energy range of energetic electrons for different density assumptions. Full orbit simulation based on the multi-fluid equilibrium reconstructed magnetic field were also performed to verify that energetic electrons could be confined outside the LCFS.

In section 2, a brief introduction of EXL-50 and experimental setups is introduced. Detailed experimental results and comparison with simulation results are presented in section 3. A discussion and a summary are presented in section 4.

### 2. Experimental setup

EXL-50 is a medium-size Spherical Torus (ST) experiment device [8] built in 2019 at the ENN Energy Research Institute. Its typical parameters are listed in table 1. One of the key EXL-50 experimental goals aims to test the efficiency of the electron cyclotron resonance heating and current drive (ECRH&CD) in the absence of a central solenoid [9]. The TF and PF coils are conventional copper conductors, which allow for a plasma discharge duration of $\sim$10 s. The vacuum vessel (VV) is made of 316L stainless steel with a major radius $R = 1.65$ m. At present, EXL-50 is equipped with two 400 kW ECRH heating systems at a frequency of 28 GHz and more than ten plasma diagnostics.

Generally, information of the energetic electrons inside the LCFS can be obtained by hard x-ray (HXR) diagnostic [2]. The Langmuir probe can give some quantitative measurements of energetic electrons outside the LCFS if secondary electron emission and electron reflection from the probe are taken into account [10]. The key diagnostics related to this paper are a mid-plane Langmuir probe and two high speed visible light cameras. The two monochrome cameras, Phantom V1212 model, are equipped with $1280 \times 800$ pixels watching plasma from different views. The spectral response curve ranges from 350 nm to 1050 nm with a peak response at 700 nm. As shown in figure 1, M120 camera installed on the mid-plane at 120 degrees can provide a full view of the plasma geometry. A D240 camera installed on the lower flange at 240 degrees provides an upside-view from the back. The reciprocating system is placed on the mid-plane of 150 degrees which can be observed by D240 camera if sufficient distance is penetrated. A set of boron powder injection apparatus is installed on the top of VV at 60 degrees. 70 $\mu$m diameter pure boron powders were introduced gravitationally in plasma discharges at rates of $8–10$ mg s$^{-1}$. In this application, full resolution is used at the frame rate of 300 frames per second. The Langmuir probe (shown in figure 2) is mounted on the reciprocating system with a maximum speed of 0.47 m s$^{-1}$ using a server motor and $\sim$1.5 m s$^{-1}$ using cylinder drive. In order to verify the effect of the secondary electron emissivity of different materials on the measurement signal, two adjacent probes spaced 10 mm from each other, are made of stainless steel and tungsten respectively. In order to penetrate deeper into the plasma position without affecting the plasma discharge, the probe head is set to 1 mm diameter and 3 mm height out of the $\text{Al}_2\text{O}_3$ insulation tube. The total length of the thin tube is about 210 mm. A Boron nitride support is placed in the middle of the long $\text{Al}_2\text{O}_3$ tube to guarantee that the two tubes are parallel.

### 3. Experimental result

#### 3.1. Observation of energetic electrons outside the main thermal plasma region

Figure 3 shows the time evolution of typical parameters of shot 9695. This shot is a hydrogen plasma discharge with 120 kW ECRH power input from $t = 0$ to 4.5 s. The absolute power of the ECRH is obtained at the matching optical unit close to the gyrotron by daily calibration of the water load before normal discharge. The probe is triggered at $t = 1.8$ s and penetrates into the plasma with an average speed of 0.23 m s$^{-1}$ from R$_{R_{\text{LCFS}}} = 10$ cm. At 3.3 s, the probe penetrates to the deepest position of the plasma R$_{R_{\text{LCFS}}} = -20$ cm. The probe still stays at about 0.1 s from 3.3 to 3.4 s as marked by the blue shadow area. The probe is then returned back to the original position at the same speed. During the whole process, the probe penetrates in and out with less impact on the plasma current IP. It changes slowly from 90 kA to 130 kA with the variation of PF coils current. As shown in figure 3(b), the line-integrated plasma density changes not much during the phase of probe penetration before 3.3 s. After that, it increases

| Table 1. EXL-50 device design parameter. |
|-------------------------------|------------------|
| EXL-50 Design Parameters      |                  |
| Plasma current (kA)           | 500              |
| Major radius R$_0$ (m)        | 0.6              |
| Minor radius a (m)            | 0.4              |
| Toroidal field (T)            | 0.46             |
| Plasma elongation             | 1.8–2.2          |
| Plasma triangularity          | 0.1–0.4          |
| Plasma duration (s)           | 5                |
Figure 1. Different views of EXL-50 VV and the installation positions of the key diagnostics used in this paper. Left is the poloidal projection of installed cameras and their FOV (field of views). Right is the bird-view of the diagnostics used in this paper. Reciprocating system were installed on the mid-plane of 150 degrees. Boron powder injection port is on the top of the VV at 60 degrees.

Figure 2. Photograph of the Langmuir probe with different material tips. The zoomed-in area shows the burned probe tip after the experiment (left is tungsten and right is stainless steel).

Figure 3. Time evolution of plasma parameters: (a) plasma current, $I_P$ (b) plasma integral density, (c) plasma impurity concentration, (d) hard x-ray intensity, and (e) floating potential.

-exponentially from 8 to $12 \times 10^{17} \text{ m}^{-2}$. The hard x-ray in this shot changes synchronously with the probe data. With larger areas (probe tips and its support structure) exposed to plasma, the higher counts of hard-x-ray detector will be. This is due to thick-target bremsstrahlung caused by high-energy electron bombardment of the probe material. When high energy electrons interact with the probe-material, it is generally necessary to consider the effect of electron emission from the probe on the measurement. The measured current of the probe is the difference between the current entering the surface of the probe and the electron current emitted from the probe. The floating potential $V_f$ can be expressed finally by the following expression

$$V_f - V_{\text{plasma}} = \frac{T_e}{2e} \ln \left[ \frac{1 - \xi}{2 \pi m_e m_i} \frac{T_e + T_i}{T_e} \right]$$

where $V_{\text{plasma}}$ is the plasma potential, $m_i$, $m_e$, $T_i$ and $T_e$ are the mass and temperature of plasma ions and electrons, respectively. From equation (1), it can be seen that the measured value $V_f$ will be more positive when the electron emission coefficient $\xi$ is nonzero. The total emission coefficient $\xi$ is defined to be $\xi = \delta + \eta$, where $\delta$ is due to the true secondary electrons and $\eta$ represents reflected or backscattered electrons. The total emission coefficient of tungsten is larger than that of stainless steel.
velocity of boron atoms $6.87 \text{ m s}^{-1}$. In this equation, the injection depth $d = 0.5 \text{ m}$. Thus, we can estimate the boron atom flux injection depth of boron powder in this discharge is about 0.5 m. This indicates that there exists a large number of energetic electrons outside the main plasma boundary, causing the probe to be burned and melted during its reciprocating process.

Another experiment was conducted to verify the relation between the main plasma boundary and the energetic electrons region. Figure 5 shows the injection process of boron powder observed by the M120 camera at different phases. A clear bright light can be observed at the injection port of boron powder. Then, the plasma shape is gradually compressed by adjusting the PF coils current as to distinguish between the boundary of the main plasma and energetic electrons. The images indicate that with a certain injection rate, the boron powder is completely ionized before reaching the maximum injection depth shown in the green dash line. The white dotted line means the injection rate. The injection depth of boron powder in this discharge is about 0.5 m. Thus, we can estimate the boron atom flux $\Gamma$ within the injection depth

$$\Gamma = \frac{d}{v \cdot r / M_B \cdot N_A}. \quad (2)$$

In this equation, $d$ is the injection depth 0.5 m, $v$ is the mean velocity of boron atoms $6.87 \text{ m s}^{-1}$, $r$ means the injection rate. $M_B$ is the molecular mass of boron and $N_A$ being Avogadro constant. Under such conditions, the boron atoms flux is about $4 \times 10^{19}$ and its density is larger than $4 \times 10^{19} \text{ m}^{-3}$ with the volume less than 1 m$^3$ within the injection depth. This is much larger than the value of the main plasma density $8 \times 10^{17} \text{ m}^{-3}$. Low temperature and low-density plasma outside LCFS cannot ionize such a large number of boron atoms. Therefore, we can infer that the ionization of the boron atoms is due to the numerous collisions of energetic electrons, a mechanism which needs further study.

3.2. Reconstruction of the plasma equilibrium

In tokamaks, the LCFS position is routinely calculated using a Grad–Shafranov MHD equilibrium solver, such as EFIT, if adequate plasma information is supplied. But it fails when a significant plasma current exists outside of LCFS. Recently, a multi-fluid equilibrium reconstruction model [4] has been developed considering the special scenario of plasma. And the calculated results match well with the experimentally measured data, such as plasma density $n_e$, temperature $T_e$, current $I_p$, magnetic flux $\Phi$ and so on. In addition, the high-speed visible light camera can give us a clear boundary of the main plasma. Many researches indicate that the optical boundary can reflect the real LCFS numerically, and the error is generally less than 10 cm [12, 13]. Such technology is also applied to determine the LCFS in EXL-50 [14].

Figure 6 shows the plasma geometry of shot #9695@3 s. The boundary threshold of the plasma-emitting region can be obtained by fitting the brightness histogram of the image, which is shown as the red line. Assuming that the plasma is a spherical luminous body, the CCD image is its projection in the two-dimensional plane, so a coordinate transformation is required to reflect the true coordinates of the plasma [15]. The coordinate-transformed curve is shown in cyan line which can tell us the rough estimation of plasma major radius. Further, given the boundary of the central post, we can then give the long and short axes of the plasma by ellipse fitting. The optical reconstruction of plasma geometry is shown in the right of the CCD image and left is the simulation result obtained by multi-fluid code. The blue solid line is the LCFS with its major radius 0.96 m. The dotted line out of the LCFS represents the open flux surface. Figure 7 shows the plasma density and temperature profile obtained by multi-fluid simulation. The result shows that energetic electrons exist both inside and outside the LCFS. The temperature of energetic electrons is almost three orders of magnitude larger than that of main plasma. The density of energetic electrons is about $2 \times 10^{16} \text{ m}^{-3}$, which is two orders-of-magnitude below that of the thermal plasma contained within the LCFS. The boundary of thermal plasma (LCFS) in the middle plane is around $R = 0.96 \text{ m}$ while the boundary of energetic electrons is about $R = 1.2 \text{ m}$.

A particle orbit simulation could provide a ‘first-principle’ physical picture of the energetic electrons produced in the EXL-50 experiment. As shown in figure 8, the contour plot is the equilibrium magnetic flux with the white dashed line representing the open flux surface and the green solid line means the LCFS. The black dashed line shows the position
Figure 5. The injection process of boron powder captured by M120 camera of shot #12094. The white dashed line is the start position of boron powder atoms drop due to gravity and the green dashed line is the stop position.

Figure 6. Optical reconstruction and multi-fluid simulation results of shot #9695@3 s. The left of the center post shows the flux surface and the right shows the fitting result. The red circle means plasma boundary brightness threshold contour and its coordinate transformed result is shown in cyan line. Ellipse fitting result of transformed data is shown in magenta line.

Figure 7. Plasma density and temperature profile obtained by multi-fluid simulation. (a) Temperature of thermal electrons and energetic electrons. (b) Density of thermal electrons and energetic electrons.

Figure 8. Simulation of a confined-orbit region of the energetic electrons using the equilibrium magnetic field calculated for a plasma from discharge #9695@3 s. The white dashed line means the flux surface and the green line means the LCFS. The black dashed line is an illustration of the limiter wall of EXL-50. The brown solid line is the orbit simulation of energetic particles.

3.3. Experimental evaluation of energetic electrons temperature

Despite some uncertainties involved with probe data analysis, the Langmuir probe is one of the primary means of diagnosing the plasma boundary. The plasma facing the surface of the probe will be suffered with large heat flux. The parallel heat flux $q_{\parallel}$ to the target surface is given by [16, 17]
The relation between the heat flux on probe tip \( q_t \) and \( q_\parallel \) is expressed as following

\[
q_t = q_\parallel \cdot \sin \theta = q_\parallel \cdot B_p / B_T.
\]

where \( q_t = \gamma n_e C_i T_i \) and \( q_\parallel = n_e C_s \varepsilon_{pot} \) are the kinetic and potential powers respectively. \( C_i \) is the ion speed. \( T_i \) and \( J_s \) are the plasma temperature and ion saturation current that can be measured by a set of triple probes. \( \varepsilon_{pot} \) is the potential energy deposited on the surface per incident ion which can be negligible compared with the kinetic power when \( \varepsilon_{pot} / \gamma T_i \ll 1 \). \( \gamma \) is the sheath transmission coefficient relating \( q_\parallel \) to the electron temperature \( T_e \) and the particle flux \( \Gamma_s = n_e C_s \) at the sheath edge.

Experimental results show that a single discharge can cause the melting of the tungsten needles when the reciprocating system is scanned from R-R_CFS = 0.20 cm. The melting point of tungsten is 3410 °C. Assuming no thermal convection between the plasma and the probe, the temperature rise induced by the heat load of the probe surface can be calculated by heat conduction. Figure 9(a) shows the simulation results of the maximum temperature time evolution of the probe tip under 4.2 MW m\(^{-2}\) heat irradiation. With a continuous thermal load of 4.2 MW m\(^{-2}\), the temperature of the tungsten probe rises to the melting point within 5 s. The temperature rise of stainless steel can reach as high as 5000 °C, which is much higher than its melting point 1850 °C. The photograph of the extracted probe shown in figure 2 also shows that the melting of stainless steel is stronger than that of tungsten. Figure 9(b) shows the temperature distribution along the probe. The calculation results show that the temperature of the probe decays exponentially from the top downwards, and after more than 5 cm, the temperature has dropped to room temperature. Therefore, the melting situation in figure 2 could happen when the heat load of the probe tip is higher than 4.2 MW m\(^{-2}\).

The relation between the heat flux on probe tip \( q_t \) and \( q_\parallel \) is expressed as following

\[
q_t = q_\parallel \cdot \sin \theta = q_\parallel \cdot B_p / B_T.
\]

In this formula, \( \theta \) represents the angle between the poloidal magnetic field \( B_p \) and toroidal magnetic field \( B_T \). The multi-fluid simulation results show that in the radial region where probe scan form \( R = 1.525 \) m to \( R = 1.325 \) m, the ratio of \( B_p \) to \( B_T \) is about 0.24. The density and temperature of thermal plasma at LCFS of EXL-50 are less than \( 10^{17} \) m\(^{-3}\) and 30 eV, which should be lower outside the LCFS. Even though the parameters of thermal plasma can reach such a high level, with the assumption \( T_s = T_i \), we can estimate the heat flux of the main plasma as \( q_\parallel = \gamma n_e C_s T_i \approx 0.155 \cdot ne \cdot 10^{19} \text{m}^{-2} \cdot T_e^{1.5} \) with its unit MW m\(^{-2}\). Under this condition, the heat flux of the main plasma acting on the probe tip \( q_t = 0.06 \) MW m\(^{-2}\), which is much smaller than the threshold value for melting tungsten or stainless steel. Since there are no measurements of the temperature and density of energetic electrons outside of the LCFS, we can reasonably estimate the parameters of energetic electrons based on the heat flux from the melting probe. Figure 10 shows the heat flux threshold acting on the probe tip to cause the melting of the probe tip with different density and temperature. According to the results of equilibrium calculations, the density of energetic electrons is within the range of \( 10^{15} - 10^{16} \) m\(^{-3}\), it is reasonable to deduce that the minimum temperature of energetic electrons is in the range of 2–45 keV.

4. Summary and discussion

In this paper, several experiments have been performed to verify the existence of confined energetic electrons outside the LCFS of EXL-50 spherical tokamak. Considering the electron emission effect of Langmuir probe, two kinds of materials (stainless steel and tungsten) were applied in the measurement. The floating potential measured by tungsten and stainless-steel probe tips shows that the existence of energetic electrons would cause the floating potential to be more positive. And the probe tips of both materials were subjected to different degrees of ablation. Simulation results show that the
probe tips have been subjected to a minimum heat load of 4.2 MW m\(^{-2}\) which is caused by the energetic electrons with its energy ranging from 2 keV to 45 keV with the assumption that energetic electron density is about \(10^{14} \text{--} 10^{16} \text{ m}^{-3}\). In addition, a boron powder injection experiment was conducted to study the relation between plasma boundary and energetic electrons. Finally, the confined-orbit energy of the energetic electrons was simulated using the multi-equilibrium magnetic field. This indicates that energetic electrons can be confined within the region of \(R = 1.3 \text{ m}\), which is far from the boundary of the main plasma.

Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

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ORCID iDs

Dong Guo https://orcid.org/0000-0001-6562-8841
Yuejiang Shi https://orcid.org/0000-0002-9572-3310
Huasheng Xie https://orcid.org/0000-0001-9204-135X

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