PLASMA CURRENT RAMP-UP WITH 28 GHZ SECOND HARMONIC ELECTRON CYCLOTRON WAVE IN THE QUEST SPHERICAL TOKAMAK

T. ONCHI
Kyushu university
Kasuga, Japan
Email: onchi@triam.kyushu-u.ac.jp

Kyushu university
Kasuga, Japan

T. KARIYA
University of Tsukuba
Tsukuba, Japan

A. EJIRI, K. MATSUZAKI, Y. OSAWA, Y. PENG, Y. TAKASE
The University of Tokyo
Kashiwa, Japan

N. BerTElli, M. ONO
Princeton University Plasma Physics Laboratory (PPPL)
Princeton, USA

A. FUKUYAMA, S. MURAKAMI
Kyoto University
Kyoto, Japan

Abstract

Plasma current ramp-up experiment with 28 GHz second harmonic electron cyclotron (EC) wave has been in progress in the QUEST spherical tokamak. Through the oblique injection of the EC wave, the observation presents that the highest level of plasma current $I_p$ as non-inductive EC ramp-up is attained with small loop voltage, $V_{loop} < 0.1\, \text{V}$. As a result of quasi-normal beam injection and finely adjusted gas fuelling, bulk electrons are heated efficiently, and hence the electron temperature reaches $T_e > 500\, \text{eV}$ at the density $n_e \sim 1 \times 10^{18}\, \text{m}^{-3}$ with the incident RF power of no more than 150 kW. Auxiliary ohmic heating after EC current ramp-up increases $I_p$ reaching 100 kA with $V_{loop} < 0.5\, \text{V}$. Modulation of toroidal electric field with the quasi-normal RF injection increases the bulk temperature by nearly 80%, where $T_e$ reaches 830 eV transiently.

1. INTRODUCTION

High plasma pressure at lower toroidal field has been pursued under the concept of spherical tokamak [1]. The non-inductive current start-up is an essential technique to realize a compact and slim central stack for future spherical tokamaks. Coaxial helicity injection [2,3] and local helicity injection [4] are powerful methods, but plasmas generated by them are terminated transiently. Radio frequency (RF) can heat plasma in a long-time scale [5]. Electron cyclotron heating (ECH) is employed in spherical tokamak machines to start up plasma current [6-9]. The antenna to inject RF is not exposed to high temperature plasma, and hence its heat load can be sufficiently low.

Plasma current ramp-up experiment with 28 GHz second harmonic electron cyclotron (EC) wave has been explored in the QUEST spherical tokamak [10,11]. The third and fourth harmonic resonance layers also locate in the plasma confinement region. These harmonics are less effective than the second one but are not negligible. Through the oblique injection of the EC wave in QUEST, the observation presents that high plasma current $I_p > 80\, \text{kA}$ as non-inductive EC ramp-up is attained with near zero loop voltage, $V_{loop} \sim 0$, solely by ECH [12].

Effect of relativistic Doppler shift is essential to drive plasma current when parallel (to toroidal magnetic field) refractive index of the incident beam $N_0$ is large. The EC power is absorbed into energetic electrons, which owns the energy of tens of kilo electron volts, over the plasma core region owing to the multiple harmonic resonances [13]. The second harmonic resonance layer stays close to the inward limiter on the central post. Practically, the down-shifted resonance for such energetic electrons is cut out by the central post. Furthermore, these harmonic resonance layers locate close each other per 0.16 m. The area of the $n$th upshifted
resonance overlaps with that of the \((n+1)\)th down-shifted resonance. Here, it is straightforward that the absorption of the \(n\)th harmonic resonance is higher than that of the \((n+1)\)th resonance. Therefore, symmetry of the EC resonance is broken so that forward electrons resonate more effectively than ones moving backward due to the effect of relativistic Doppler shift. Consequently, net toroidal current flows. Although high plasma current as non-inductive start-up can be obtained, the electron temperature through Thomson scattering is quite low.

To ramp up current and heat bulk electrons simultaneously, quasi-normal RF injection has been conducted in QUEST. Turning the steering antenna, the RF is injected with \(N_r = 0.11\) and \(0.26\). In the case of normal RF injection with \(N_r = 0\), there is no Doppler shift theoretically. In the experiment, EC wave resonates both energetic electrons and bulk electrons effectively at the same time. Bulk electrons are heated as the temperature increases to \(T_e > 500\) eV.

In the paper, experimental setup is described in Sec. 2. In Sec. 3, the experimental results are described. The paper is summarized briefly in Sec. 4.

2. EXPERIMENTAL SETUP

**FIG. 1.** A top view of QUEST. Directions of \(I_p\) and \(B_t\) are clockwise and anti-clockwise, respectively. The inner limiter locates at \(R = 0.23\) m. The second, third, and fourth harmonic resonance layers are shown by red, green, and blue half circles, respectively. The RF beam is injected from the steering antenna consisting of (1) the beam expanding mirror and (2) the focusing mirror.

The major and minor radii of QUEST are \(R_0 = 0.68\) m and \(a_0 = 0.40\) m, respectively. The gyrotron generating high power 28 GHz-RF is used for the ECH [14]. In the experiment, the RF power is limited to lower than 250 kW. The 28 GHz-RF is injected from the low field side, where the steering antenna consists of two mirrors has been set up. The first mirror receives HE11 mode from the end of the waveguide, and the RF beam is expanded toward the second mirror. This large mirror focuses the RF beam on the position of the second harmonic resonance layer, \(R_{res2} = 0.32\) m. The waist of the focused beam is about 5 cm diameter examined at the low power test [12]. The beam is sharply-focused as the power density reaches nearly 20 MW/m² when the RF power is 150 kW, and its polarization is optimized as extra-ordinary: X-mode. Owing to the steering function, the incident angle can be controlled. At \(R_{res2}\), the parallel refractive index has wide range of \(N_r < 0.9\). Turning the steering antenna, the beam can be injected obliquely or normally to the toroidal magnetic field.

As presented in Fig. 1, multiple harmonic resonance layers locate together. The major radius of the second, third and fourth layers are \(R_{res2} = 0.32\) m, \(R_{res3} = 0.48\) m and \(R_{res4} = 0.64\) m, respectively in this experiment. The field at \(R_{res2}\) is \(B_t = 0.5\) T, where the total toroidal field coil current in the central stack is 800 kA. All data in this paper have been obtained with the same setting of toroidal field.

3. ELECTRON CYCLOTRON HEATING AND CURRENT DRIVE USING THE STEERING ANTENNA

3.1. RF injection normal to magnetic field

Power absorption of EC wave into electrons depends on the incident angle to magnetic field. Accordingly, performance of EC heating and current drive can be adjusted by the index \(N_r\). Oblique injection with high \(N_r\) is suitable for current drive. In the QUEST experiment, efficient current ramp-up has been achieved by the oblique...
injection as such tendency [13]. Instead, the steering antenna can set the incident angle normal to toroidal magnetic field. The waveforms at a discharge with \( N_e = 0.11 \) at \( R_{res} \) are presented in Fig. 2(a) – (d). 28 GHz-RF with the power of 120 kW is injected for longer than 0.9 s. The rays of the RF beam injected quasi-normally are traced as shown in Fig. 2(e). Here, the rays were analysed by TASK/WR code. The paths of the O- and X-mode are approximately same. In the experiment, the polarization of the RF is set as X-mode is dominant.

Plasma current is ramped up to \( I_p \approx 25 \text{ kA} \). Loop voltage is as low as \( V_{loop} = 0.1 \text{ V} \) measured on the central post, \( R = 0.18 \text{ m} \), and hence this start-up is slightly inductive. As shown in (c), line-integrated electron density ranges \( 0.5 < n_e < 1 \times 10^{18} \text{ m}^{-2} \) by multiple Hydrogen gas injections. Hard X-ray (HXR) pulse signal counted by Cadmium Telluride detector is also observed concurrently with plasma ramp-up. The energy range of HXR shown here is \( 50 < E_{HXR} < 100 \text{ keV} \). This time evolution of the HXR signal indicates that energetic electrons are generated through ECH and they contribute to the plasma current even though RF is quasi-normally injected. In addition, \( T_e \) and \( n_e \) through Thomson scattering measurement at \( R = 0.34 \text{ m} \) are presented in (d). Electrons are heated as \( T_e \approx 500 \text{ eV} \) with \( I_p < 30 \text{ kA} \). The RF power is absorbed in both bulk and energetic electrons effectively, therefore moderate current drive and bulk electron heating occur simultaneously.

![FIG. 2. The waveforms of discharge 41176: (a) plasma current \( I_p \), loop voltage \( V_{loop} \) at \( R = 0.18 \text{ m} \), and 28 GHz-RF power monitor signal measured in the middle of the waveguide. (b) line-integrated density and \( H_a \) line emission with gas injection timing. (c) Count number of hard X-ray which the energy range is 50-100 keV. (d) Electron temperature and density measured at \( R = 0.34 \text{ m} \) through Thomson scattering measurement at \( R = 0.34 \text{ m} \). (f) Single pass power absorption rate out of total ECW power. The grey and red bars show absorptions of O- and X-mode, respectively.](image)

Relativistic Doppler shift is weak with this quasi-normal RF injection. Therefore, the plasma current does not increase compared to the experiment of oblique injection. When initial bulk electron heating is achieved, ECH can be more efficient. TASK/WR code analysed power absorption of EC wave. As shown in (f), electrons with higher bulk \( T_e \) absorb EC power more. When the wave is X-mode and \( E_e = 500 \text{ eV} \) at the central peak of tokamak, 7 % of the 28 GHz-RF is absorbed through single pass. Instead, absorption of O-mode is low. To simplify the model and estimate the effect of single pass absorption, this ray tracing has ended at the central post. In the experiment, the EC wave may be absorbed and heat electrons after the reflection at the central post and further multiple reflections at the walls.
3.2. Temperature, density and pressure of electrons

As results of many observations, there are tendencies that high $I_p$ is achieved at oblique injection, and that high $T_e$ is obtained at quasi-normal injection. In Fig. 3, relationships between $I_p$ and $(T_e, n_e)$ out of 754 data points are presented. Red dot, green up-pointing triangle, yellow down-pointing triangle, and blue square represent data with $N_\parallel = 0.11, 0.26, 0.45$ and $0.75$, respectively. These statistic data points are listed under the condition that $|I_p| > 20$ kA, $T_e > 5$ eV, $n_e > 1.0 \times 10^{17}$ m$^{-3}$. Furthermore, a data point is picked up as $P_e$, the product of $T_e$ and $n_e$, is the highest in the radial profile. It is noted that $T_e$ and $n_e$ in Fig. 3(a) and (b) represent the parameters of bulk electron, because they are estimated through Thomson scattering. From these plots, $T_e > 200$ eV is observed when $|I_p| < 40$ kA. High $T_e$ is not expected when $|I_p| > 50$ kA. Quasi-normal injection ($N_\parallel = 0.11$ and 0.26) tend to achieve higher $T_e$ than that by oblique injection ($N_\parallel = 0.75$). According to Fig. 3(b), high $n_e$ may be obtained by quasi-normal injection. However, the tendency is less obvious than that of $T_e$ as shown in (a). $n_e$ may not depend on $I_p$ or $N_\parallel$ even though $T_e$ decreases with high $n_e$. Further investigation is required to understand the dependences of $n_e$ in detail.

FIG. 3. (a) $I_p$ vs $T_e$ and (b) $I_p$ vs $n_e$ plotting 754 data points obtained in an experimental campaign. $T_e$ and $n_e$ are measured through Thomson scattering. Data points of $N_\parallel = 0.11, 0.26, 0.45$ and 0.75 are represented by Red dot, green up-pointing triangle, yellow down-pointing triangle, and blue square, respectively.

FIG. 4. $I_p$ vs $P_e$, which is product of $T_e$ and $n_e$, plotting 754 data points obtained in an experimental campaign.

The relationship between $I_p$ and bulk electron pressure $P_e$ is presented in Fig. 4. $P_e$ decreases logarithmically with $I_p$. High $P_e$ is achieved with $N_\parallel = 0.11$. Increasing $N_\parallel$, obtained $P_e$ decreases. It would be difficult to obtain high $P_e$ by oblique injection with $N_\parallel = 0.75$. To maintain the equilibrium, according to Ref. 10, plasma pressure of 200-300 Pa is required, where pressure made of ions is low enough in these discharges. Therefore, pressure of
energetic electrons contributes to the equilibrium when $I_p$ is high. This interpretation is consistent with previous experimental results [10-13].

4. AUXILIARY OHMIC HEATING OF EC-HEATED PLASMA

![Waveforms of the discharge 40527: (a) the 28 GHz-RF power monitor signal, (b) $I_p$, (c) $V_{loop}$, (d) line-integrated $n_e$. (e) Two-dimensional map of magnetic flux surfaces, obtained by an equilibrium reconstruction, with $I_p = 100$ kA.](image1)

![$E_{\phi}$ measured at $R = 0.18$ m, vs $I_p$. Blue down-pointing triangles represent non-inductive discharges, and orange up-pointing triangles represent discharges that medium loop voltage is added.](image2)
An option after EC current ramp-up is the auxiliary OH. The power supply can save the coil current through the central solenoid owing to the EC current ramp-up. The loop voltage can be applied additionally by changing the solenoid current rapidly. After the plasma current is ramped up to $|I_p| \approx 50$ kA, $V_{\text{loop}} \approx 0.5$ V was applied as the waveforms presented in Fig. 5(a)-(d). Here, 28 GHz-RF was injected for 1.1 s, where $N_e$ at $R_{\text{eez}} = 0.75$. As a result, the plasma current reaches $I_p > 100$ kA. Such value of $I_p > 100$ kA has not been achieved non-inductively so far, and hence toroidal electric field by the loop voltage performs effectively to drive current. The line-integrated density $n_e$ also increases concurrently with $I_p$-increase. Owing to the toroidal electric field, it is likely that electrons moving forward are accelerated and those moving backward are decelerated. In this situation, distribution function may be distorted as there are more forward electrons than backward ones. More forward energetic electrons tend to resonate 28 GHz RF than backward electrons due to the effect of relativistic Doppler shift [13]. Thus, it can be presumed that the additional toroidal electric field advances the asymmetry of the EC resonance. Fig. 5(e) presents a two-dimensional map of the magnetic flux surfaces at $I_p \approx 100$ kA, which is obtained by an equilibrium reconstruction. Closed surfaces stretch out over the vacuum vessel. There are two X-points, but the last closed flux surface touches the inward limiter. Thus, this is not the divertor configuration. Such $I_p$ increase has been observed in multiple discharges. In Fig. 6, the relationship between the $I_p$ and $E_{\phi}$, which is measured at $R = 0.18$ m, is presented. This auxiliary OH increases $I_p$ by 30-40 %.

**FIG. 7. The waveforms of discharge 41194:** (a) plasma current $I_p$, electric field $E_{\phi}$ at $R = 0.18$ m. (b) $H_a$ line emission with gas injection timing. (c) $T_e$ and $n_e$ measured at $R = 0.40$ m through Thomson scattering.

Furthermore, a toroidal electric field was modulated when the bulk electrons were heated through the quasnormal RF injection with $N_e = 0.11$ at $R_{\text{eez}}$. Discharges without $E_{\phi}$-modulation end up, for example, as shown in Fig. 2. As presented in Fig. 7, the central solenoid current started changing to modulate $E_{\phi}$ at $t = 2.69$ s. Here, $E_{\phi}$ estimated from $V_{\text{loop}}$ is measured at $R = 0.18$ m. Before the swing of $E_{\phi}$, electron temperature at $R = 0.40$ m is $T_e \approx 458$ eV, where $|I_p| \approx 22$ kA. At $t = 2.70$ s when is the laser timing of Thomson scattering, the temperature reaches $T_e \approx 830$ eV. From $t = 2.6$ s, the increasing rate is estimated at approximately 80 %. This value of bulk $T_e$ is the record high since QUEST operation started in 2008. It is not easy to obtain such value $T_e > 800$ eV without such $E_{\phi}$-modulation so far. ECH may perform effectively with $E_{\phi} \approx 0$ at the moment. It is likely that the balance of bulk-$T_e$, $I_p$, and $E_{\phi}$ is required to obtain the $T_e$-increase. Additionally, change of the central solenoid current influences the tokamak equilibrium. Further experiment is required to understand the mechanism of the efficient heating. This $T_e$-increase is transient as $T_e < 200$ eV at $t = 2.80$ s although the loop voltage is kept applied for the purpose of auxiliary OH. Increase of $I_p$ occurred already at the moment. It is presumed that the toroidal electric field accelerates energetic electrons, and EC power is absorbed into them. Moreover, the auxiliary OH power proportional to $(T_e)^{3/2}$ may be low due to the $T_e$ increase. In other multiple shots, the features analogous to this shot have been observed. It is easy to gain $I_p$ by this auxiliary OH with high $V_{\text{loop}}$, but resultant $T_e$ decreases by 90 % or higher percentages.
5. SUMMARY

Experiments in the QUEST spherical tokamak have advanced EC current ramp-up. Recently, bulk electron heating without OH has been achieved by the quasi-normal EC wave injection, where the temperature reaches $T_e > 500 \text{ eV}$. Statistic data presents that the pressure of bulk electrons decreases considerably with high $I_p$. Oblique injection may not heat bulk electrons, while energetic electrons contribute to non-inductive current ramp-up. After the current increases high enough as $I_p > 50 \text{ kA}$, energetic electrons own most of pressure to maintain tokamak equilibrium. Auxiliary OH was applied after $I_p$ was ramped up by oblique EC wave injection. The plasma current exceeded $I_p = 100 \text{ kA}$ with moderate loop voltage. Besides, bulk electrons can be heated by the $E_z$ modulation when $I_p$ is relatively low as $I_p < 30 \text{ kA}$. As a result, $T_e \approx 830 \text{ eV}$ was observed transiently.

ACKNOWLEDGEMENTS

The authors are most thankful to the QUEST team for technical support. This work was performed under the auspices and support of the NIFS Collaboration Research Programs (NIFS19KUTR136/NIFS17KUTR128). This research was partially supported by the Ministry of Education, Science, Sports and Culture, under Grant-in-Aid for Scientific Research (B) (No. 15H04231).

REFERENCES

