Noninductive Electron Cyclotron Heating and Current Drive with Dual Frequency (8.2/28 GHz) Waves in QUEST

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By means of dual 8.2 GHz and 28 GHz waves, the over dense 25 kA plasma with central high energetic-electron pressure was noninductively built up and sustained for 0.4 s by Electron Bernstein Wave Heating (EBWH) effect between 8.2 GHz fundamental and 2nd harmonic electron cyclotron (EC) layers. Spontaneous Density Jumps (SDJs) have been clearly observed at a few times in a shot, and the electron density became over dense for the 8.2 GHz injection. The bulk electron temperature or pressure increased in the over dense region being fundamentally Doppler-shifted resonant with the parallel refractive index \(N_\parallel > 4\) for the 8.2 GHz injection. Current-carrying energetic electrons with more than 200 keV were remarkably observed in the over dense region due to the 8.2 GHz EBWH effect.

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Abstract:
By means of dual 8.2 GHz and 28 GHz waves, the over dense 25 kA plasma with central high energetic-electron pressure was non-inductively built up and sustained for 0.4 s by Electron Bernstein Wave Heating (EBWH) effect between fundamental and second harmonic electron cyclotron resonance layers at 8.2 GHz. Spontaneous density jumps have been clearly observed at a few times during a discharge, and the electron density became over dense for 8.2 GHz. The bulk electron temperature or pressure increased in the over dense region where was the fundamentally Doppler-shifted resonant area for the large parallel refractive index (>1). Current-carrying energetic electrons with more than 200 keV were observed in the over dense region due to the 8.2 GHz EBWH effect. A new 28 GHz transmission line with polarizer and launcher systems was introduced for local EC heating and current drive, and high non-inductive plasma current of 70 kA has been attained.

1 Introduction

The Q-shu University Experiments with Steady-State Spherical Tokamak (QUEST) have proposed to conduct basic studies on a steady-state operation in the spherical tokamak (ST) configuration under controlled plasma wall interactions [1]. Plasma current drive methods should be considered for the steady-state tokamak operation. Electron Bernstein Wave Heating and Current Drive (EBWH/EBWCD) is a promising candidates for sustaining high-β ST plasmas in the steady state [2,3]. Non-inductive plasma start-up and sustainment experiments by 8.2 GHz injection have expanded the plasma current up
to 35 kA, but the density was normally lower than the cut-off density $n_{e}^{\text{cut}}$ [4]. On the other hand, the EBWH/EBWCD effect for the 8.2 GHz injection was observed in over dense Ohmically heated plasmas of 30 kA [5].

In order to expand the EBWH/EBWCD experiments to higher density region, Kyushu University, University of Tsukuba and the National Institute for Fusion Science started a collaborative research on Electron Cyclotron Heating and Current Drive (ECH/ECCD) using a high-frequency power tube, gyrotron. University of Tsukuba has developed a 28 GHz gyrotron with 1MW output [6], and the high voltage power supplies for the gyrotron were prepared in Kyushu University. A simple transmission line with no polarizer and launcher systems was adopted for the initial experiment to form an over dense plasma for 8.2 GHz [7]. The O-mode wave was injected into the plasma from a corrugated waveguide (WG) of a 2.5-inch diameter without the launcher system. The incident power was the 250 kW level. The incident wave from the WG was expanded, and single pass absorption was not expected in the O-mode 2nd harmonic ECH/ECCD scenario. Major and minor radii, $R_0$ and $a$, are 0.64 m and 0.42 m at the QUEST torus device, and maximum toroidal magnetic field $B_t$ is 0.25 T at $R = R_0$, respectively. The 2nd harmonic electron cyclotron resonance (ECR) layer was located at a high-field side off-axis position of $R=0.32$ m, close to the inboard limiter position at $R=0.22$ m. The single pass absorption was only considered in the fundamental Doppler-shifted ECH/ECCD scenario for high energy electrons between the limiter and the 2nd harmonic ECR layer. Despite the off-axis ECH/ECCD by poor single pass absorption, the ECH/ECCD effect of a re-charging phenomenon was clearly observed in superposed injection into the Ohmically heated plasma. Fully non-inductive plasma current was started up and sustained at 54 kA for 0.9 s by the 28 GHz injection, and the current was successfully built to 66 kA by the vertical field ramp-up. The line-averaged density $\langle n \rangle$ increased to the cutoff density $n_{e}^{\text{cut}}$ for 8.2 GHz with no additional gas fueling in the superposed 8.2 GHz injection to the 28 GHz plasma. The plasma current was kept at the 40 kA level if the stable plasma shaping was obtained. Simultaneous 8.2 GHz and 28 GHz injections were also conducted, and a spontaneous density jump (SDJ) was observed with no additional gas fueling in the simultaneous injections. In this paper, the SDJs at a few times during a discharge is discussed in detail.

This paper is organized as follows. Section 2 describes the SDJ phenomena with the dual frequency injections. In order to conduct the local ECH/ECCD with sufficient single pass absorption, a new 28 GHz transmission line with polarizer and launcher systems has been designed and fabricated. In Section 3, the new 28 GHz system is introduced and preliminary results are described. The summary is finally given in Section 4.

## 2 Spontaneous Density Jump Phenomena with Dual Frequency Injections

Dual frequency powers of 8.2 GHz and 28 GHz have been simultaneously injected to conduct fully non-inductive plasma current start-up and sustainment in the QUEST. The 28 GHz 2nd harmonic and 8.2 GHz fundamental ECR layers were located at $R=0.32$ m
and 0.55 m, respectively. The 270 kW power at 28 GHz was injected at \( t = 1.6 \) s with the 8.2 GHz injection of 60 kW. Figure 1 (a) shows time evolution of differential pressure \( \Delta P \) at a fueling hydrogen reservoir, \( \bar{n}_\ell \) and \( H_\alpha \) intensity. Gas-fueling timings could be marked with the \( \Delta P \) increments (\( t = t_{g1}, t_{g2}, t_{g3} \) and \( t_{g4} \)). The \( H_\alpha \) intensity increased at the fueling timings, while \( \bar{n}_\ell \) sometimes increased without the fueling. Such spontaneous \( \bar{n}_\ell \) increments, namely SDJs, were observed twice (\( t = t_{SDJ,1} \) and \( t_{SDJ,2} \)) in the discharge. The density \( \bar{n}_\ell \) finally exceeded the cutoff for the 8.2 GHz injection. Figure 1 (b) shows time evolution of the plasma current \( I_p \), the minor plasma radius \( a \), the outmost major radius of closed flux surfaces at the mid-plane \( R_{out} \), and \( \beta_p^* \) (sum of the averaged poloidal beta \( \beta_p \) and half plasma internal inductance \( \ell_i \)). The plasma current \( I_p \) rapidly built up by the 28 GHz injection at \( t = 1.6 \) s. The radius \( a \) became large with the \( I_p \) build-up. The maximum \( R_{out} \) seemed to be clamped at the 2nd harmonic ECR position of \( R = 1.1 \) m. Some events such as the first SDJ and the rapid density decrement before the 2nd SDJ were occurred at the maximum \( R_{out} \) of 1.1 m. When the 8.2 GHz injection was superposed into the 28 GHz plasma enlarging beyond \( R = R_{out} \), the plasma could not be sustained notably with a stable configuration due to 2nd harmonic EC coupling at \( R = 1.1 \) m. Rather strong vertical field was required to push the plasma inward and to obtain the stable plasma configuration in the superposed injection [7]. The \( \beta_p^* \) value was relatively large (\( > 1.5 \)), and roughly changed in inverted relation to the \( I_p \) evolution.

Figure 2 (a) shows magnetic flux surfaces \( t = 1.85 \) s and 2.25 s after the 1st and 2nd SDJs. The equilibriums were analyzed by the EFIT code. The equilibrium electron pressure profile was bell-shaped with the maximum pressure of 400 Pa. Large Shafranov-shifts \( \Delta \) could be seen at both of the times in the figure. The magnetic axes \( R_{axis} \) were around 0.8 m, and the dense flux surface structures were appearing between \( R_{axis} \) and \( R_{out} \). Figure 2 (b) shows a plasma toroidal current density profile \( J_{\phi}^{\text{EFIT}}(R) \) for the equilibrium analyzed by the EFIT code. The current density profile was also peaked around \( R_{axis} \), where was between fundamental and 2nd harmonic ECR layers at 8.2 GHz. The electron temperature \( T_{e}^{\text{TS}} \) and density \( n_e^{\text{TS}} \) and pressure \( P_e^{\text{TS}} \) for the dual frequency experiments were measured by Thomson Scattering (TS) diagnostics. Figure 3 shows radial profiles of \( T_{e}^{\text{TS}}(R) \), \( n_e^{\text{TS}}(R) \) and \( P_e^{\text{TS}}(R) \) at times before and after the 1st SDJ (\( t = 1.75 \) s and 1.85 s) and after the 2nd SDJ (\( t = 2.25 \) s and 2.55 s). High \( T_{e}^{\text{TS}} \) were observed near the 2nd
harmonic ECR at 28 GHz, while a local $T_e^{TS}$ peak was observed near the fundamental ECR at 8.2 GHz only before the 1st SDJ at $t=1.75\ s$.

The measured bulk pressure $P_e^{TS}$ profiles were hollow-like, resulting from the off-axis 2nd harmonic heating and the radiation cooling after the SDJs. Measured bulk electron pressure was one order less than the equilibrium pressure, indicating large pressure contribution from energetic electrons. The large pressure components of the energetic electrons resulted in the large $\beta_p^*$ and $\Delta$. Since the equilibrium pressure was so large and its profile was center-peaked, some heating mechanisms should exist to generate the energetic electrons in the central region. Figure 4 shows Hard X-ray (HX) energy spectra measured at forward tangential viewings for current-carrying electrons at $t=2.25\ s$. The midplane measured tangential radii were $R_{tan}=0.714\ m$ and $0.341\ m$. The spectrum for $R_{tan}=0.714\ m$ included the HX radiation from the central region near $R_{axis}$ with large equilibrium pressure and current density. The HX spectrum for $R_{tan}=0.341\ m$ contained the HX radiation from the high-field off-axis region near the 2nd ECR layer at 28 GHz as well as the central region.

**FIG. 2:** (a) Magnetic flux surfaces analyzed by the EFIT code at $t=1.85\ s$ and $2.25\ s$ after first and second SDJs and (b) plasma toroidal current density profile $J_{EFIT}^\phi(R)$ for the equilibrium analyzed by the EFIT code at $t=2.25\ s$.

**FIG. 3:** (a) Electron temperature profile $T_e^{TS}(R)$, (b) density profile $n_e^{TS}(R)$, and (c) pressure profile $P_e^{TS}(R)$ by Thomson Scattering diagnostics before and after first SDJ ($t=1.75\ s$ and $1.85\ s$) and after 2nd SDJ ($t=2.25\ s$ and $2.55\ s$).
The HX radiation temperature was $507 \pm 35$ keV for $R_{\text{tan}}=0.714$ m, but it was $231 \pm 10$ keV for $R_{\text{tan}}=0.341$ m. There were abundant energetic electrons rather in the over dense region, while the bulk electron pressure $P_{eTS}$ was large in the high-field off-axis region near the 2nd ECR layer at 28 GHz. The energetic electrons would be generated in the over dense region due to the 8.2 GHz EBWH effect, resulting in the center-peaked electron pressure and current density distributions. Bulk electron temperature or pressure in the over dense region also increased after the 2nd SDJ. It should be noted that the over dense region was the fundamentally Doppler-shifted resonant area for the large refractive index $N_{\parallel}$ in parallel to the magnetic field.

![FIG. 4: Hard X-ray energy spectra measured at tangential radii of $R_{\text{tan}}=0.714$ m and 0.341 m at $t=2.25$ s.](image1)

![FIG. 5: Photograph of a corrugated $\lambda/4$ plate to be installed at a miter bend. It is fabricated with careful attention to reduce Ohmic losses by means of milling, not wire-electrical discharge machining.](image2)

### 3 New 28 GHz Transmission and Launcher Systems for Local ECH/ECCD

A new 28 GHz transmission line with polarizer and launcher systems has been designed and fabricated for local ECH/ECCD experiments. To realize the local 28 GHz ECH/ECCD, there were two aspects. One is polarization control into a desired X-mode to obtain good single pass absorption, and the other is focusing of the launched field to obtain a narrow beam. The elliptical polarization control was required for the X-mode oblique injections. Two corrugated $\lambda/4$ and $\lambda/8$ plates were designed and fabricated with careful attention to reduce Ohmic losses by means of milling, not wire-electrical discharge machining [8]. Figure 5 shows a photograph of a corrugated $\lambda/4$ plate to be installed at a rectangular miter bend. The corrugations were fabricated with rounded top corners by some milling processes, as shown in the figure. Orthomode-field directional couplers for the transmitting HE$_{11}$-mode and arc sensors were installed at another miter-bend after the polarizers. The elliptical polarized-wave excited at the polarizers can be monitored...
at the couplers.

**FIG. 6**: A new focusing mirror system for 28 GHz injection. The two mirror system is adopted.

Firstly, the focusing mirror system was designed conceptually in Gaussian optics. The 2nd ECR position at \( R=0.32 \) m is far from the QUEST vessel port; the focal length to the ECR position became larger than 1.2 m. Here two mirror system was adopted. A first convex mirror was prepared to obtain a large diameter beam for strong focusing at a second mirror. The second mirror diameter was 0.37 m. Figure 6 illustrates the focusing mirror system. The mirror surfaces were designed to match the propagating-wave phase front. The developed Kirchhoff integral code [9] was used for the mirror design to simulate beam propagation of the HE\(_{11}\) mode properly, radiating from the corrugated WG. The large focusing mirror had a second surface designed for for the 8.56 GHz injection. Some WG components were shown at the bottom side of the launcher vacuum vessel in Fig. 6. The 8.56 GHz system will be reported elsewhere. Mirror performances of the 28 GHz injection were checked by three-dimensional full-wave simulation using a moment method simulator, the Wip-d software. Figure 7 shows intensity and phase patterns of the horizontal wave-field \( E_x \) evaluated at the 2nd ECR position in the perpendicular injection case. A sharply focused beam with a small beam size of 0.052 m was reasonably obtained. The phase in the beam was almost flat, indicating the evaluation point actually corresponded to the beam waist point as designed. The focussed beam was measured to check the mirror system performance at low power test bench. Figure 8 shows a measured \( E_x \) intensity pattern at the 2nd ECR position in the perpendicular injection case. The sharply focused beam was also confirmed at the low power level experiments. The focussing mirror system was installed on the QUEST vessel as shown in Fig. 9. The system was set with the 0.07 m offset so that the tangential beam could transmit the QUEST vessel port with no interruption. The directions of the toroidal magnetic field \( B \) and the plasma current \( I_p \) are also shown in the figure. The 2nd focusing mirror could steer the beam in the toroidal direction. The 2nd harmonic ECH/ECCD experiments in
FIG. 8: An intensity pattern of the horizontal field $E_x$ at the 2nd ECR position of the perpendicular injection in the low power test.

FIG. 9: Top view of the 28 GHz mirror launcher installed on the QUEST. The directions of the toroidal magnetic field $B$ and the plasma current $I_p$ are also shown in the figure.

The various incident toroidal angles (from perpendicular $[N_\parallel \sim 0]$ to tangential $[N_\parallel \sim 1]$ injections) could be conducted using the developed mirror launcher. Figure 10 shows the horizontal-field intensity profiles $E_x(x)$ measured at the low power test bench in the incident toroidal angle scanning. Here the $x$ direction is defined to be normal to the beam direction of the perpendicular injection in Fig. 9. The beam profiles became broad in the oblique injections because the $x$ direction was not normal to the oblique propagations. The focused beams were correctly steered using the mirror launcher system, as shown in Fig. 10.

FIG. 10: Horizontal-field intensity profiles $E_x(x)$ in the incident toroidal angle scanning. The $x$ direction is defined in Fig. 9.

FIG. 11: Time evolution of plasma current by means of the 28 GHz injection with the incident power of 140 kW.

Fully non-inductive plasma start-up experiments using the new 28 GHz system have been begun in this year. The high plasma current could be built up to 70 kA for 0.9 s, following the vertical field ramp-up, as shown in Fig. 11. The incident power and $N_\parallel$ of
the 28 GHz injection were 140 kW and 0.78, respectively. The elliptically polarization for the oblique injection was set at the very beginning, but the incident polarization should be optimized more together with the $N_y$ scanning.

4 Summary

The over dense 25 kA plasma with central high energetic-electron pressure was non-inductively built up and sustained for 0.4 s with the dual frequency (8.2 GHz and 28 GHz) injections. The abundant energetic electrons were generated, and the bulk electron temperature or pressure increased in the over dense region for 8.2 GHz where was fundamentally Doppler-shifted resonant area for the large $N_y$ ($>1$). A new 28 GHz transmission system with polarizers and a mirror launcher has been developed. The incident polarization can be controlled by means of corrugated $\lambda/4$ and $\lambda/8$ polarizers. The beam was properly focused and steered by the launcher with two quasi-optical mirrors designed by the developed Kirchhoff integral code. The 2nd harmonic local ECH/ECCD experiments have been conducted, and high non-inductive plasma current of 70 kA has been preliminary attained.

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