OBLIQUE LAUNCHING EXPERIMENT FOR ECH AND ECCD IN HELIOTRON E

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1. Introduction

Oblique launching experiment of high power millimeter waves in the toroidal direction have been performed in tokamaks and helical systems for electron cyclotron current drive (ECCD) and second harmonic O-mode heating [1]. In Heliotron E, one of helical devices, the magnetic field structure is three dimensional, and the magnetic field strength along the wave beam path is dependent on the launching angle. The propagation and absorption of electron cyclotron waves are affected by such a field structure. The plasma profile closely related to the power absorption profile can be changed as observed in off-axis electron cyclotron heating (ECH) at the perpendicular launching case [2], and the density limit can be a function of the launching angle. There is also a possibility of measuring the non-inductive current in Heliotron E. Since Heliotron E inherently has strong poloidal magnetic field, a small plasma current does not greatly change the rotational transform. In this paper, we show the experimental results of toroidally oblique launching experiment in Heliotron E, especially, the density limit at high density and the electron cyclotron current drive at low density.

2. Launching system and magnetic field structure

The 106.4 GHz perpendicular launching system [3] has been modified into the toroidally oblique launching system by installing a movable mirror additionally in the Heliotron E vacuum chamber. A focused Gaussian beam is launched from the outside of the torus, and its focal point is located around the magnetic axis when the beam is perpendicularly launched. The measured e-folding beam power radius is 14 mm, which is smaller than the plasma minor radius. Low power (several mW) and high power (300 kW) transmission tests showed that the launching angle, φ, widely ranged from 0° to 50° at the injection port, corresponding to the angle between the magnetic axis and the beam ranging from 90° to 25°. The polarization of launched waves should be controlled for obtaining the good single pass absorption. The polarization is adjusted so as to couple the beam to the second harmonic X-mode at the plasma edge as much as possible. The maximum launched power is 370 kW, and the maximum pulse length is 200 msec in the experiment reported here.

The magnetic field along the beam path depends on the launching angle. The parabolic profile of total magnetic field strength at the perpendicular launching case is modified into the

flat profile as the launching angle is steeper. At $\varphi \sim 20°$, the magnetic field strength increases inside the torus like tokamaks because the beam approaches the helical coil.

3. Density Limit

The ECH plasma suffers from radiation collapse when the electron density increases due to wall recycling or additional gas puffing. The density limit is related to the radiation collapse in helical system. Once the radiation collapse happens, the electron temperature does not recover to the high temperature state even during the ECH pulse. Figure 1 shows the time evolution of averaged electron density and total radiation power. The radiation power increases almost linearly with the electron density (t = 280-360 msec), and then its increasing rate suddenly grows up when the electron density reaches a critical value (t = 360-367 msec). A seven-channel far-infrared interferometer measurement shows that the density rise firstly stops at the edge region 20 ms before the final radiation collapse, then it proceeds inwardly. The time scale of radiation collapse event is the same order of global energy confinement time, $\tau_E \sim 20$ msec, and weakly depends on the launching angle.

The maximum density is nearly the cut-off of the second harmonic X-mode in the perpendicular launching case ($\varphi = 0°$), and it is a decreasing function of toroidal injection angle as shown in Fig. 2. A ray tracing calculation has been performed to investigate the relation between the density limit and the wave propagation and absorption. At the density below the cut-off, the power absorption profile of second harmonic X-mode is centrally peaked at $\varphi = 0°$ and it becomes broader with steeper angle due to Doppler broadening, refraction and flattening of the magnetic field profile. As the density increases, the refraction effect is more enhanced especially at steeper launching case, making the absorption move toward the edge. There is a critical density for the single pass absorption rate. The total
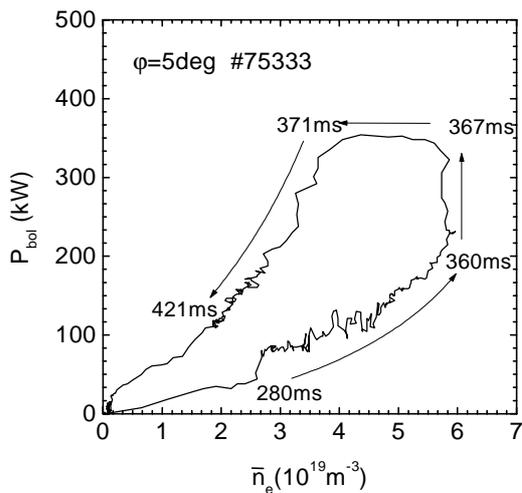

Fig. 1. Time evolution of total radiation loss as a function of electron density. The injection angle is $\varphi = 5°$.
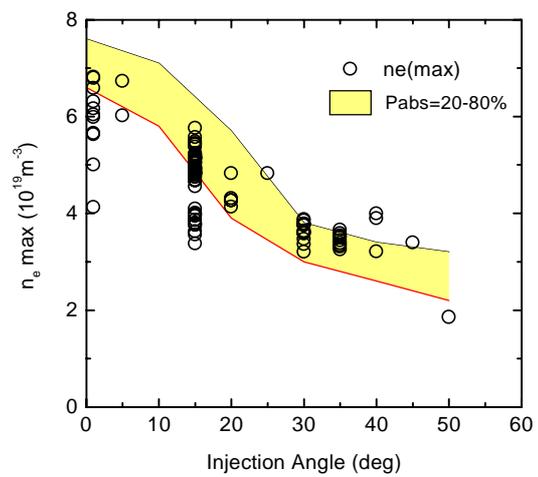
Fig. 2. Dependence of maximum electron density on toroidal injection angle. The critical density (shaded region) calculated by ray tracing code is also plotted.

absorption rate, P_{abs}, is kept nearly 100 % at low density, but it drastically decreases at the critical density. The density range for P_{abs} = 20-80 % is found to be narrow, $\Delta n_e/n_e \sim 15$ %. The existence of the critical density for the single pass absorption may explain the sudden increase of radiation loss and the density limit. The absorption range, P_{abs} = 20-80 %, is plotted in Fig. 2. The accessible density is in agreement with the numerical results, implying that the density limit of second harmonic X-mode ECH plasma may be determined mainly by the wave refraction.

4. Electron Cyclotron Current Drive

In tokamaks, the EC driven current has been measured by evaluating the difference of loop voltage between co- and counter-injection, because the plasma can not be sustained only by ECCD due to insufficient EC power. In contrast to tokamaks, helical system does not require the ohmic current in principle, and the sensitivity limitations for the measurement of small non-inductive current are much lower. The driven current has been measured in the accuracy of several kA at the W7-AS stellarator with shearless configuration [4]. The Heliotron E device inherently has strong poloidal magnetic field produced by external coils. A simple calculation shows that the on-axis current of 5kA total with Gaussian profile changes the rotational transform only by 0.05 and it does not change the magnetic shear, meaning that the EC current less affects the global confinement.

Figure 3 shows the measured plasma current as a function of launching angle. The averaged electron density is $\bar{n}_e = 1 \times 10^{19}$ m^{-3}. The time evolution of plasma current is fluctuated due to the ohmic current caused by the small ripple in external coil currents. Since this ohmic current is non-negligibly large, the non-inductive current is evaluated by taking the relation between the loop voltage and the plasma current. The finite current flows at the perpendicular launching condition, $\varphi = 0°$, which is considered to be the bootstrap current driven by density and temperature gradients. According to the neoclassical theory, the bootstrap current in the $1/\nu$ regime flows in the direction to increase the rotational transform, corresponding to the negative direction in Figs. 3 and 4, and it is on the order of several kA in Heliotron E plasma parameters [5]. If the offset is attributed to the bootstrap current, the EC current is positive and has a peak around $\varphi = 15°$. This flow direction is opposite to that from a simple current drive theory, and its magnitude is small. Figure 4 shows the dependence of the plasma current on the magnetic field strength. When the magnetic field strength is 1.90 T, the resonance, $\omega = 2\Omega_{ce}$, is located at on-axis. The current tends to be positive with a decrease of the magnetic field strength. This tendency may be due to the change of the EC driven current, because the n_e and T_e profiles are not so changed that the bootstrap current is constant. The current drive efficiency is rather low, less than 0.01 A/W (2×10^{17} A/Wm^2). This efficiency is not enhanced at lower density, $\bar{n}_e = 0.5 \times 10^{19}$ m^{-3}. A possible candidate to explain the low current drive efficiency is the existence of trapped electrons [6]. Detailed theoretical analysis and comparison with the experimental results are left for future.
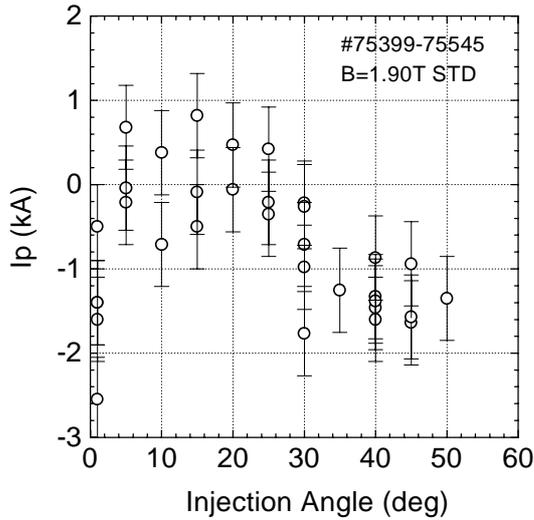
Fig. 3. Dependence of plasma current on toroidal injection angle. The electron density is fixed as $n_e = 1.0 \times 10^{19} \, \text{m}^{-3}$.
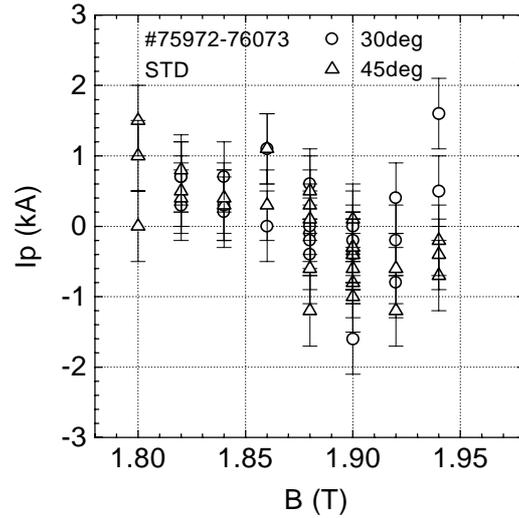
Fig. 4. Dependence of plasma current on magnetic field strength. The launching angles are 30° and 45°.

5. Conclusion

The oblique launching experiment of high power millimeter waves in the toroidal direction were made to investigate the density limit and ECCD in the Heliotron E helical device. The ECH plasma is subject to radiation collapse at high density, and the accessible density decreases with an increase of launching angle. The density limit may be determined by the wave refraction of the second harmonic X-mode. Another heating scenario such as second harmonic O-mode would be required to extend the accessible density regime at the oblique launching case. The EC driven current was measured at low density, and its dependence on toroidal launching angle and magnetic field strength was investigated. The experimental results showed that the current drive efficiency was rather lower than that of tokamaks, and its direction contradicted a simple linear theory.

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