Performance of Electron Cyclotron Harmonic Heated Plasmas in Large Helical Device

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1. Introduction

High harmonic heating of the electron cyclotron (EC) resonance is an attractive method to extend a heating regime of plasma parameters by reducing the density limitation due to some cutoffs of the EC wave propagation. The second harmonic heating by an extraordinary (X) mode injection from a low field side antenna has been used for a plasma production and heating in Large Helical Device (LHD). From the third experimental campaign, six gyrotrons (two 82.6GHz/one 84GHz gyrotrons and three 168GHz gyrotrons) could be operated to inject over 1 MW power into the LHD vacuum vessel.

In the LHD launching geometry, the magnetic field strength has a saddle point in the position of the magnetic axis where the ray path launched from top antenna crosses. Under this condition, the ray can keep resonant with the plasma over a considerable length. So good absorption is predicted over a wide density range even for the 3rd harmonic heating by the linear theory[1]. In the experiments of the 3rd harmonic resonance heating, obvious heating of the bulk plasma (ΔTe=200eV around the plasma center by 340kW power injection) was observed.

In this paper we will describe the ECH system for harmonic heating and the experimental results of the 3rd harmonic heating in special, and compare with the calculation based on the linear theory.

2. ECH System

The ECH system consists of 0.5 MW, 84 GHz range and 168 GHz gyrotrons, high voltage power supplies, long distance transmission lines, and in-vessel quasi optical antennas. It has been improved step by step. At the third campaign of LHD experiments (from July to December, 1999) three 84 GHz range and three 168 GHz gyrotrons are operated and ECH power can be injected from four antennas vertically and two horizontally.

At the third campaign in which the magnetic field was raised to around 2.75-2.9T, three 0.5 MW/1 sec. 168 GHz gyrotrons were joined for higher plasma temperature and density for second harmonics heating[2]. Table 1 summarizes the total ECH system for the third campaign of LHD experiments, including power supplies, gyrotrons, transmission lines and antenna system.

Each gyrotron is operated by two different kinds of high voltage power supplies shown in Table 1. One is a solid-state power supply for 168GHz gyrotrons with depressed collector and/or diode type 82.6GHz gyrotrons. The other is a conventional power supply which regulates the beam voltage precisely by a regulator tube and equipped with a crowbar system for fast turn-off against gyrotron faults. This power supply is used for the 84GHz gyrotron.

The transmission lines are composed of a matching optics unit (MOU), corrugated waveguide (>100m in length, 88.9mm in diameter) with at most 17 miter bends, a waveguide switch, polarizer, DC break, and vacuum window. The transmission lines are not evacuated and some arcings in the line have limited higher power and longer pulse operation so far. High power transmission test shows about 60% total efficiency on average, though it depends on the lines. Main power loss is due to low coupling efficiency from the gyrotron to the waveguide. Many miter bends also attenuate the transmitted power to the LHD. The coupling efficiency will be improved by replacing the MOU mirrors designed and optimized on the basis of a phase retrieving method. The transmission efficiency could be also improved by reducing the number of the miter bends, which requires reconsideration of the transmission line path.

Two kinds of antenna systems for ECH are installed in the LHD vacuum vessel. The vertical injection antenna system consists of four millimeter beam focusing and steering mirrors. Low power measurement of this system shows a good agreement with the designed beam waist size of 15 mm in radial and 50 mm in toroidal direction. The beam can be steered radially and toroidally without degrading the quality over 150 mm toroidally and 200 mm radially in both sides. For horizontal injection, the antenna system consists of 2 mirrors, one is fixed and another is steerable. Movable range covers the whole plasma cross section for perpendicular injection and can change about –30 degrees toroidally.

Gyrotrons

Frequency	Number	Max. Power	Max. pulse duration	Depressed collector
82.6GHz (GYCOM)	2	0.45MW	2sec.	-
84GHz (CPI)	1	0.5MW	CW(at 80kW)	-
168GHz (Toshiba)	3	0.5MW	1sec.	with SDC

High Voltage Power Supplies

	Number	Collector PS	Body PS	Anode PS
Solid-state PS	5	<65kV,42A	<90kV,100mA	<50kV,50mA
Regulator tube PS	1	<80kV,50A	-	<40kV

Transmission lines

Number	Total length	MOU mirrors	Miter bends	Other components	Injection window	Antenna
6 lines	~100m ϕ88.9mm	4 mirrors	<17	Waveguide SW,polarizer Dummy load	BN or SiN single disk	Top or out injection

Table 1 Summary of ECH system for LHD

3. Third Harmonic Heating Experiments

Several experiments were performed for the different frequency heatings at the different strength of the confinement magnetic field, for example, the second harmonic heating by 84GHz power injection at 1.5T and 168GHz injection at 2.5 - 2.9T. The target plasma was produced by an EC fundamental or second harmonic resonance heating.

The most attractive trials are the third harmonic heatings by both 82.6GHz/84GHz and 168GHz power injection into a plasma with the center field of 1T and 2T, respectively. This could be realized by a successful target plasma production by only neutral beam injection (NBI). Proper gas puffing makes plasma built up to electron density over 10^{19} m^{-3} level[3]. Wide range of the electron density ($0.5\text{-}3 \times 10^{19}$ m^{-3}) can be obtained on the electron temperature of about 1.5keV. Figure 1 shows a configuration of a 168GHz millimeter wave launch from the top antenna on a poloidal cross section. A direction of the RF injection and the 3rd harmonic resonance are indicated on the plane together with the equi-magnetic field strength contours and the magnetic flux surfaces for the magnetic field of about 2T on the magnetic axis. Total power of 340kW, which was launched from two top-antennas and one side-antenna, was injected into the NBI plasma produced by about 120keV, 1.7MW port through power. The electron temperature and average density of the target plasma were 1.5keV and $1.5\times10^{19}m^{-3}$, respectively.

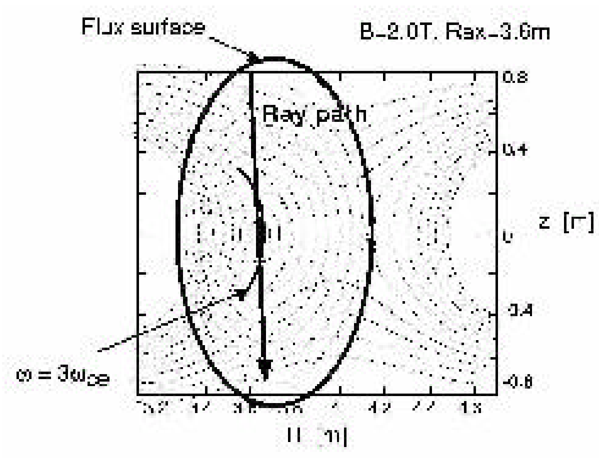

Fig. 1 Configuration of 168GHz RF injection. 3rd harmonic resonance, equi-B contours, and magnetic flux surfaces are also shown.

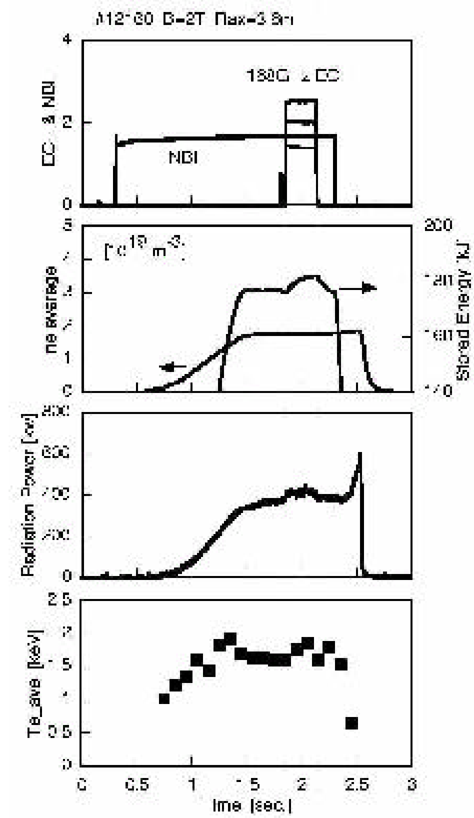

Fig. 2 Time evolution of plasma parameters during 3rd harmonic ECH.

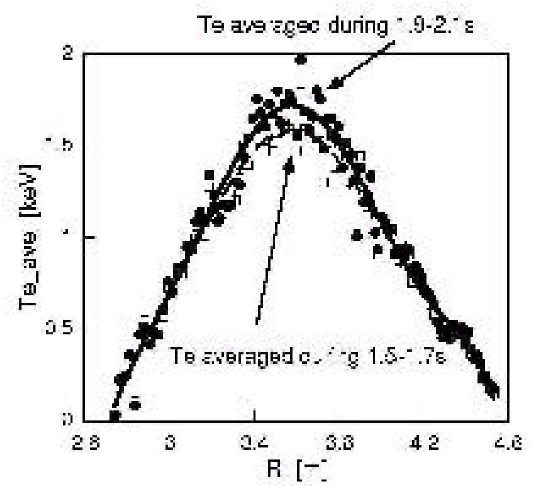

Fig. 3 Electron temperature profiles averaged over 0.2s before (t=1.5-1.7s) and during (t=1.9-2.1s) RF pulse.

The time evolution of main plasma parameters are plotted in Fig. 2. RF power of 168GHz is injected into a NBI produced plasma from 1.85 sec. to 2.1 sec. The stored energy, Wp, measured diamagnetically increases during the pulse, though the line averaged electron density is kept constant. The time evolution of the electron temperature around R=3.6m range measured by Thomson scattering is also plotted in the figure. The data are averaged over 0.1s time period. The increase of the temperature is noticed during the ECH pulse. The electron temperature profiles averaged over 0.2s before ECH (t=1.5-1.7s) and during ECH (t=1.9-2.1s) are compared in Fig. 3. Localized heating of about 200eV increment is observed around the magnetic axis (R=3.6m). The absorbed power in the plasma is estimated by the difference of dWp/dt between before and after the RF turn-on time. In this case it achieved about 65kW of the injected power of 340kW. Figure 4 shows a density dependence of power absorption rate Pabs/Pin for several electron densities and two injection powers (210 and 340kW). The absorption rate gradually increases with the increase of target plasma density. In this density range, the electron temperature of the NBI plasma linearly decreases with the density as shown in Fig. 4. The saturation of the absorption at high density regime is due to the temperature decrease, because the efficiency of the higher harmonic heating is very sensitive to the plasma temperature.

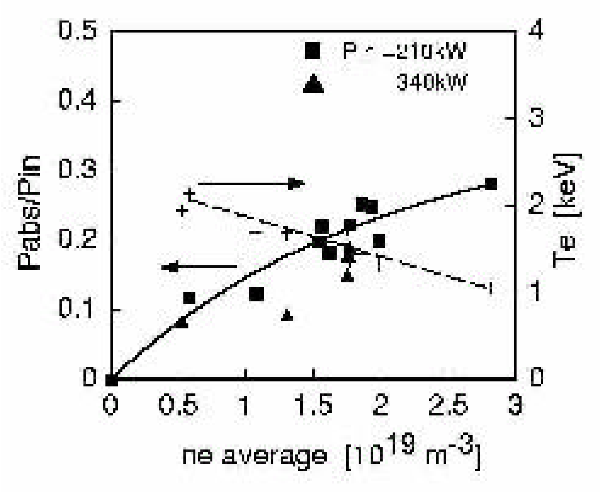

Fig. 4 Experimentally obtained RF absorption rate is plotted to line averaged electron density The electron temperature of target plasma is also indicated.

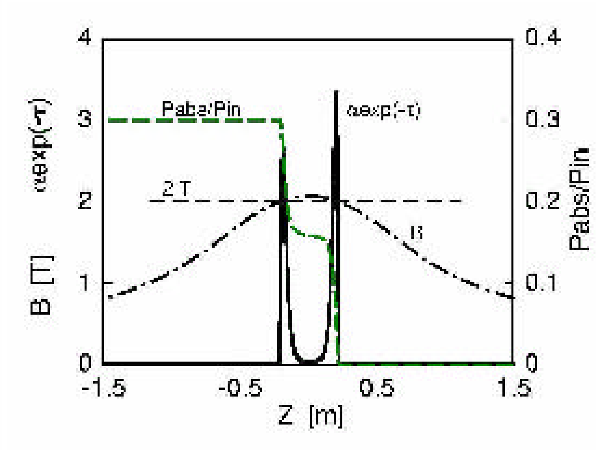

Fig 5 Profiles of magnetic field B(z), weighted absorption coefficient $\alpha exp(-\tau)$ and absorption rate Pabs/Pin along a straight ray path launched from top position (positive Z side).

4. Discussion

In order to estimate the absorption rate, optical thickness of given electron temperature and density is calculated along a straight ray path in the LHD magnetic field configuration as Fig. 1. An extraordinary (X) mode is assumed to be perpendicularly injected from top antenna focused on the magnetic axis. In Fig. 5 magnetic field strength B(z), weighted absorption coefficient αexp($-\tau$) and absorption rate $P_{abs}/P_{in}=1-\exp(-\tau)$ are plotted as a function of z coordinate of the ray, where α is an absorption coefficient and τ is an optical thickness. The electron density n_0 is assumed to be constant of 1.5×10^{19} m^{-3} in the whole plasma cross section. On the other hand, the profile of the electron temperature is assumed $T_{e0} \times (1 - \rho^2)^2$ and T_{e0}=1.5keV. The absorption is localized near the 3rd harmonic resonance (B=2T) and the absorption rate reaches 0.3 in a single transit. This value is fairly good agreement with the experimental results, although the model is very simple. Multi reflection effect for the absorption seems to be weak due to the large port area of the opposed side of the antenna, to the RF absorption by many graphite divertor plates on the wall, to polarization scrambling and to the small absorption volume of the 3rd harmonic resonance. Calculation results show that the optical thickness scales as $\tau \sim n_0 T_{e0}^2$ in this low temperature range. This temperature scaling corresponds to '∇B dominated' absorption[1]. Higher temperature and optimization of the magnetic configuration will be required for much better absorption.

5. Summary

During the third campaign of LHD experiment, 2nd and 3rd harmonic electron cyclotron additional heating experiments were performed. Especially, because of the addition of three 168GHz gyrotrons and successful plasma production by only NBI, the good heating results were obtained for the 3rd harmonic resonance. During the ECH pulse of 0.3sec. stored energy of the plasma increased several percents. The central electron temperature raised about 200eV. The absorption rate increases gradually with the electron density and the maximum absorbed power reaches 30% of the injected power. Calculated results of the optical thickness based on the simple model show a fairly good agreement with the experiment. These calculations suggest optimization of both RF focal point and magnetic field configuration will be needed for the better absorption.

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