Recent studies of ECH methods for expanding applicable parameter ranges on LHD

Presented by K. Saito


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Outline of this presentation

- Recent ECH system on LHD
  - A new 77GHz, 1MW-3sec/300kW-CW gyrorotoron was installed.
- EBW heating experiments by slow X-B and O-X-B method.
- High Te experiment by use of higher magnetic field .
- Third harmonic ECH in low magnetic field (1T) configuration
- Summary
The Large Helical Device

- Major radius: 3.6~4.1m
- Minor radius: ~0.63m (at $R_{\text{axis}}=3.6m$)
- Plasma volume: 30m$^3$ (at $R_{\text{axis}}=3.6m$)
- Aspect ratio: 6~8
- Magnetic field: $< 2.75T \rightarrow 2.85T$ (at $R_{\text{axis}}=3.6m$)

Sub-cooling of the superconducting helical coils was carried out. Expansion of the upper limit of the coil current.

- 1 pair of twisted helical coils
- 3 pairs of poloidal coils
- 10 pairs of Local Island Divertor coils
Recent ECH System in LHD

- 6-88.9mm Waveguides
- 4-Dry Air(#1,3,11,12)
- 2-Evacuated (#2, 8)

- 82.7GHz 500kW 2s
- 84GHz 200kW CW
- 84GHz 800kW 3s
- 168GHz 500kW 1s

- New 77GHz 1MW 5s / 300kW CW
- 82.7GHz 500kW 2s

- 77GHz, 1MW/5sec or 300kW/CW, gyrotron was newly installed.
- Transmission lines with 88.9mm waveguides will be evacuated sequentially to avoid arcing in high power transmission.
- Aiming for 5MW short pulse and 3MW CW operation.
Installation of a new 77GHz gyrotron

- New gyrotron
- Installation to the tank
- Matching Optics Unit (MOU)
800kW, 800ms operation was achieved with CW Dummy Load before injection to LHD

Development of Conditioning

Achieved Parameters up to 2007 Oct. 12

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<td>Pulse [ms]</td>
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During the LHD experiment, the conditioning is carried out with injection to LHD every 3 minutes.  
0.81MW, 3.3s operation (631kW injection to LHD) has been achieved.
Preliminary experimental result with 77GHz gyrotron (Rax=3.6 m, Bt=-1.375 T Second harmonic)

Deposited power was estimated from the time change of the plasma stored energy (dWp/dt) at power turn on/off.

R_{foc} (beam focal point) dependence is same as the expectation from ray-tracing calculation.

Polarization near $\alpha =-45$ deg. (X-mode) optimum is as expected. Deposition at $\alpha =+45$ deg. (O-mode) might indicate O2 mode absorption?
Arcing and cracking at the output diamond window

During the injection into LHD at 800kW, 3.7s operation at #79642, arcing was detected at the output diamond window and the high voltage was shut off at 3.5s.
Vacuum leakage occurred at the output diamond window.
Detailed checking is now carrying at TOSHIBA factory.
The purposes of studying EBW heating in LHD

Using electron Bernstein waves (EBWs), electron cyclotron heating (ECH) and current drive (ECCD) can be applicable in extremely high density region.

- In LHD, development of the high density operation requires the study of ECH by electron Bernstein waves (EBWs) in over-dense plasmas.
  - Super dense core (SDC) regime has been found in LHD.
  - EBW-ECH in the SDC plasma will be call for in the high density operation of LHD-type demo reactor.
The scenario of EBW excitation via slow X-B mode conversion

X-mode waves can approach the UHR layer from the high field side. Injection of X-mode from the bottom port.

Diagram showing the interaction of waves and the location of the ECR (X-B access window) within the tokamak geometry.
In a relatively low density plasma \( (n_e < n_c) \), perturbation of ECE signals and stored energy are observed coincidentally with ECH pulse.

X-mode launching in manner of X-B heating.

\[ P_{\text{ECH}} \sim 235 \text{kW} \]

H. Igami et. al., Plasma and Fusion Research 1, 52-1 ~ 52-3 (2006)
Power absorption occurred in the low field side of the ECR layer.

Speculations about these power absorption profiles.

(a): EBWs excited via X-B mode conversion are absorbed.
(b): X-waves are absorbed in the Doppler shifted ECR layer before they reach the UHR layer.
(c): X-waves are reflected at the right handed cutoff.

H. Igami et. al., Plasma and Fusion Research 1, 52-1 ~ 52-3 (2006)
Parametric decay spectrum is observed in the LH frequency range when the X-mode waves launched toward the UHR layer.

ECH and ICRF pattern

ECH 82.7, 84, 168GHz
1sec. ECH 84GHz #6 (#5 antenna)
CW, ICRF ~10sec. (Low power)

Spectrum in the LH frequency range (~1GHz).
X-mode wave launching.

Plasma and #5 beam cross sections

For O-mode wave launching, such spectrum was not observed.
In the super dense core plasma, the central electron density reaches several times of the plasma cutoff density.

Typical electron density and temperature profiles in the SDC plasma.

The central $n_0$ has achieved $1 \times 10^{21} \text{m}^{-3}$ in the last experimental campaign.

Plasma cutoff density for 84GHz EM wave

For ECH, electron Bernstein wave (EBW) excitation via O-X-B mode conversion is required. The slow X-B method is not available.

N. Ohyabu et. al., PRL 97, 055002 (2006)
Antenna setting for exciting EBWs by O-X-B method

Antenna setting parameter (Rf, Tf) is defined as the beam position on the midplane.

An example of contour plot of OXB mode conversion rate

Sniffer probes are used for monitoring the stray radiation for searching the “mode conversion window”
Increment of the electron temperature was observed by O-mode launching. 

Waveforms of the discharge:

47Hz, ECE perturbation amplitude profiles obtained by FFT analysis.

Roughly estimated absorbed power suggests 100% mode conversion ($P_{\text{abs}} \sim 300kW$)
Achievement of high central electron temperature in new operational regime

• Achievement of high electron temperature by ECRH is important in view of not only obtaining high performance plasmas, but studying fusion relevant low collisionality plasmas.

• Recently, ECRH system in LHD has been upgraded, aiming at higher and stable power injection. Total injection power is over 2MW with 84GHz, 168GHz gyrotrons.

• In the last experimental campaign, sub-cooling of the helical coils extended operational regime of magnetic configuration.
Magnetic axis should be placed on the high-field side of ECR layer

ECRH absorption layer moves to high-field side due to relativistic down-shift of ECR.

This is a preferable magnetic configuration, which realized by sub-cooling of the helical coil.

Magnetic field profiles around the axis
Higher field configuration ($R_{ax}=3.5\text{m}, B_0=2.931\text{T}$) realizes high $T_e$ plasmas

The magnetic axis has been able to set the higher field side of the non-relativistic ECR layer by the accomplishment of the sub cooling. In ECR discharge with $P_{ECH}=1.58\text{MW}$, the highest $T_{e0}$ over $10\text{keV}$ was obtained.

magnetic field configuration at $R_{ax}=3.5\text{m}, B_{ax}=2.931\text{T}$

Electron temperature profiles

$n_{e\text{\_bar}}=0.3\times10^{19}\text{m}^{-3}$

$n_{e\text{\_bar}}=0.2\times10^{19}\text{m}^{-3}$

![Graphs showing electron temperature profiles](image)
Third harmonic ECH in low magnetic field (1T) configuration

• High harmonic heating of the electron cyclotron resonance (ECR) is an attractive method to extend a heating regime of plasma parameters by alleviating the density limitation due to some cutoffs of the EC wave propagation.
• In the LHD launching geometry, the magnetic field strength is almost constant along the ray paths launched from upper- and lower-port antennas which cross near the magnetic axis. 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.
Plasma core was efficiently heated by 3rd ECH

- Although in a low electron temperature ($T_e$) and low electron density ($n_e$) plasma, rising of $T_e$ and stored energy ($W_p$) was observed.
Absorbed power was evaluated by the increment of the plasma stored energy $dW_p/dt$ before and after ECH on-timing.

The maximum absorption rate was obtained on $R_{foc}=3.7\, \text{m}$. However, on $R_{foc}=3.75\, \text{m}$ (position of ECR layer), the absorption rate is rather low, because the temperature and density of the target plasma was fairly low.

The absorption rate for the other antennas were about 8%.

The maximum heating efficiency of 82.7GHz EC wave is 20%.
Summary

• A 77GHz new gyrotron was installed. The conditioning run smoothly and the preliminary experimental result was obtained. However, its running was stopped because of clacking of the output diamond window.

• EBW heating in relatively low density plasmas by slow X-B method and in an over dense plasma by O-X-B method has been demonstrated.

• In a preferable magnetic field configurations, the highest central electron temperature over 10keV was achieved.

• The 3rd harmonic electron cyclotron resonance heating experiments were performed.