Central Deuteron Temperature Derived from Total Neutron Emission Rate in Electron Cyclotron Heated LHD Plasmas

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Total neutron emission rate from Large Helical Device plasmas is measured by using a neutron flux monitor newly installed for deuterium operations. Deuteron temperature is derived from the total neutron emission rates in electron cyclotron heated Large Helical Device plasmas. Time evolution of central deuteron temperature obtained by the neutron flux monitor approximately agrees with central impurity ion temperature measured by the EUV spectrometer.

Keywords: neutron diagnostics, total neutron emission rate, deuteron temperature, LHD

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Deuterium operation on Large Helical Device (LHD) was initiated in March 2017 in order to achieve higher temperature and higher density plasmas [1]. In deuterium experiments, fusion reaction products such as neutrons become newly available as a signal to diagnose compared with hydrogen experiment. Total neutron emission rate ($S_{\rm n}$) measurement on thermal plasmas has been used to determine the central deuteron temperature ($T_{\rm d0}$) in tokamaks and middle sized stellarators/helical devices [2–6]. Recently, a neutron flux monitor (NFM) composed of three fission chambers, a ^{10}B counter, and two ^{3}He proportional counters was installed [7] and working successfully for measurement of $S_{\rm n}$ in LHD. As a result, we are able to obtain the time-resolved deuteron temperature in electron cyclotron (EC) heated deuterium plasmas by means of the NFM.

Figure 1 shows the typical time evolution of the deuterium plasma discharge with EC heating. Total EC heating power ($P_{\rm ECH\_total}$) was reduced in two steps from 3 MW to 1 MW and line-averaged electron density ($n_{\rm e\_avg}$) was gradually increased to $2 \times 10^{19}\,{\rm m}^{-3}$ throughout the discharge. Deuterium ratio {D/(H + D)} evaluated by Hα and Dα diagnostics was around 0.9. Maximum total neutron emission rate ($S_{\rm n}$) and total neutron yield measured by the NFM are 0.7×10^{11} neutrons per second, and 1.0×10^{11} neutrons per shot, respectively. Radiation power ($P_{\rm rad}$) and the central electron temperature ($T_{\rm e0}$) were measured by a resistive bolometer and a Thomson scattering diagnostics (TSD), respectively.

In EC heated plasmas, S_n can be expressed by

$$S_{\rm n} = \frac{1}{2}\int_{r=0}^{a} n_{\rm D}(r)^2 \langle\sigma v\rangle_{\rm DD\text{-}n}(T_{\rm d}(r)){\rm d}V(r). \qquad (1)$$

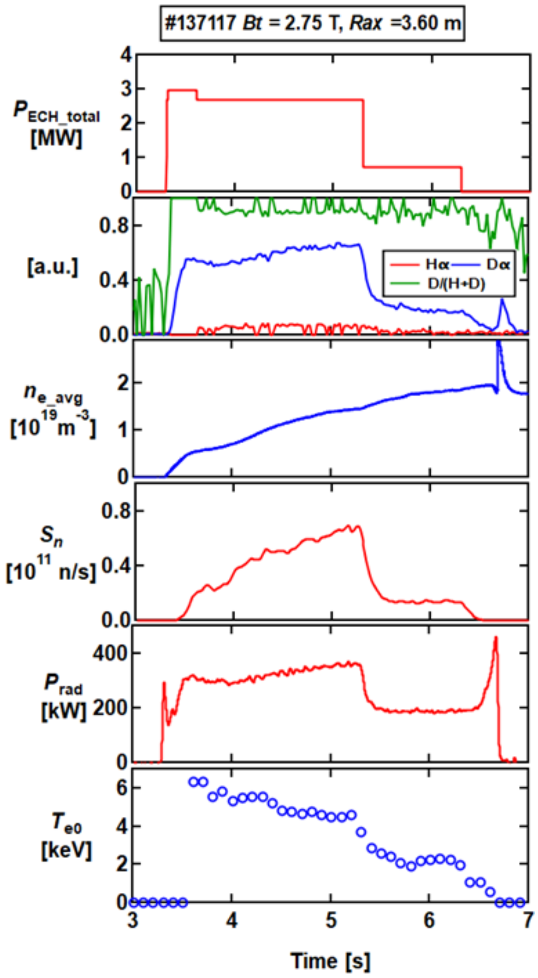

Fig. 1 Typical time evolution of EC heated plasma.

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Here r, a, n_D, $\langle\sigma v\rangle_{DD\text{-}n}$, T_d, and V are minor radius, averaged plasma minor radius, deuteron density, reaction rate of the $D(d,n)^3He$ reaction when deuterons form the Maxwellian velocity distribution, deuteron temperature, and the volume of each flux surface, respectively. In this ion temperature derivation, S_n is measured by ^{10}B counter with the conversion factor derived by in-situ neutron calibration. The profile of n_D is deduced from n_e profile with assuming the Z_{eff} range from 1.5 to 2.5 and main impurity of C^{6+} [8], and $D/(H+D)$ obtained by $D\alpha$ and $H\alpha$ measurement. $D(d,n)^3He$ reaction rate is given from the analytic model [9]. Deuteron temperature profile is assumed to be in the parabolic shape, $T_d(r) = T_{d0}\times\{1-(r/a)^2\}$. The intervals of T_{d0} in this calculation is 0.05 keV. Volume of each surface is given from the equilibrium reconstructed using VMEC2000 [10].

Figures 2 (a) and (b) show the profiles of electron temperature (T_e) and n_e measured by TSD, and estimated ion density profile at t of 5.01 s. We calculated

$$\Delta = \left| S_n - \frac{1}{2}\int_{r=0}^{a} n_D(r)^2 \langle\sigma v\rangle_{DD\text{-}n}(T_d(r))\,dV(r) \right|^2,$$

for each T_{d0} to find appropriate T_{d0} to minimize Δ in each time bin. Here, the calculated neutron emission density rate profile at T_{d0} of 1.40 keV, at t of 5.01 s is shown in Fig. 2 (c). Figure 3 shows the time evolutions of T_{d0} and

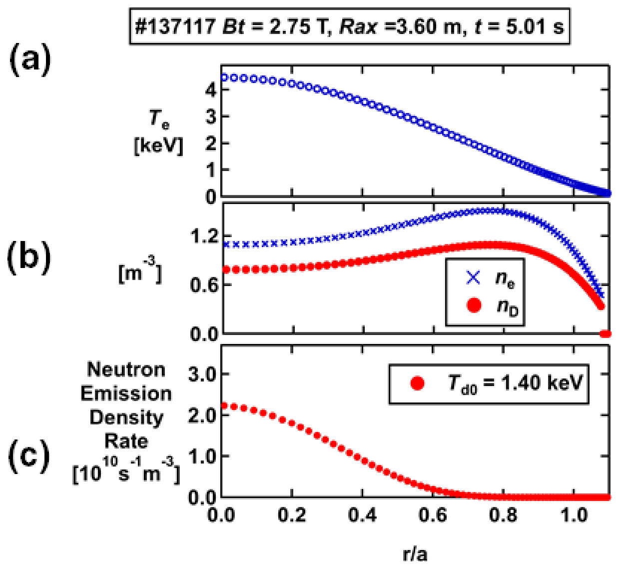

Fig. 2 Radial profiles of a) T_e, b) n_e and n_D. c) Neutron emission density profile calculated at T_{d0} of 1.40 keV and Z_{eff} of 2.

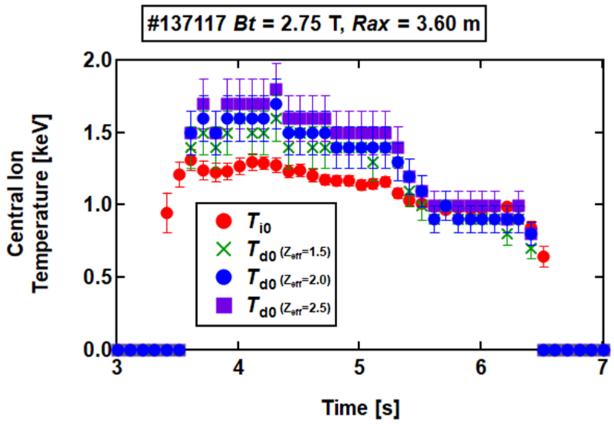

Fig. 3 Time evolutions of T_{i0} and T_{d0}.

central impurity ion temperature measured by EUV spectrometers (T_{i0}) which is basic diagnostics for measuring ion temperature in EC heated LHD plasmas. The error bar of T_{d0} is mainly from the error of in-situ neutron calibration of NFM. Time evolution of T_{d0} approximately agrees with that of T_{i0}.

In summary, time evolution of deuteron temperature is derived from the total neutron emission rate measured by the neutron flux monitor in electron cyclotron heated deuterium LHD plasmas. Appropriate time evolution of central deuteron temperature is derived by total neutron emission rate measured using the neutron flux monitor.

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[1] Y. Takeiri *et al.*, "Extension of Operational Regime of LHD towards Deuterium Experiment" in Proceedings of 26th IAEA Fusion Energy Conference, Kyoto, Japan, 17-22 October (2016).
[2] K.M. Young *et al.*, Plasma Phys. Control. Fusion **26**, 11 (1984).
[3] O.N. Jarvis, Plasma Phys. Control. Fusion **36**, 209 (1994).
[4] C.L. Fiore and R.L. Boivin, Rev. Sci. Instrum. **66**, 945 (1995).
[5] S. Besshou *et al.*, Nucl. Instrum. Methods **A237**, 590 (1985).
[6] M. Isobe *et al.*, Rev. Sci. Instrum. **68**, 532 (1997).
[7] M. Isobe *et al.*, Rev. Sci. Instrum. **85**, 11E114 (2014).
[8] X. Huang *et al.*, Plasma Fusion Res. **10**, 3402036 (2015).
[9] H.S. Bosch and G.M. Hale, Nucl. Fusion **32**, 611 (1992).
[10] S.P. Hirshman and J.C. Whitson, Phys. Fluids **26**, 3353 (1983).