*29th EPS Conference on Plasma Phys. and Contr. Fusion Montreux, 17-21 June 2002 ECA Vol. **26B**, P-1.073 (2002)*

# Global Electron Energy Confinement of Neon Plasmas in LHD

J. Miyazawa, H. Yamada, S. Morita, Y. Takeiri, M. Osakabe, K. Narihara, K. Tanaka, S. Sakakibara, M. Goto, S. Murakami, R. Sakamoto, B.J. Peterson, K. Ida, O. Kaneko, K. Kawahata, A. Komori, Y. Nakamura, N. Ohyabu, and LHD experimental Group

*National Institute for Fusion Science, 322-6 Oroshi-cho, Toki, Gifu 509-5292, Japan*

Neon gas puff experiment has been performed on the Large Helical Device (LHD), to investigate the effect of electric charge and mass of plasma ions on the energy confinement property. Here, we focus on the global energy confinement of electrons in the plasmas heated by the neutral beam (NB) injection. The major radius of the magnetic axis, $R$, and the plasma minor radius, $a$, are fixed to 3.6 m and 0.62 m, respectively. Meanwhile, the magnetic field strength at the plasma center, $B_0$, is changed from 1.5 T to 2.893 T.

The relation between the electron (ion) temperature at the plasma center, $T_{e0}$ ($T_{i0}$), and the volume averaged electron density, $\langle n_e \rangle$, is plotted in Fig. 1 (a) (Fig. 1 (b)). Only the hydrogen (or the neon) gas is puffed into plasmas denoted as 'hydrogen' (or, 'neon') plasmas. The highest $T_{e0}$ is obtained in the neon plasmas, although the difference from the hydrogen data is not remarkable. As for the $T_{i0}$, which is plotted in Fig. 1 (b), there is a significant difference between the hydrogen plasmas and the neon plasmas; i.e. $T_{i0}$ of the neon plasmas is more than 1.5 times higher than that of the hydrogen plasmas, in the high $B_0$ case. In Fig. 1 (c), drawn is the $\langle n_e \rangle$ dependence of the electron-stored energy, $W_{e\_kin}$, which is estimated from the profiles of $T_e(\rho)$ and $n_e(\rho)$, where $\rho = r/a$ is the normalized radius. The energy confinement time of the helical plasmas usually exhibits the positive dependence on density as summarized in the international stellarator scaling 95 (ISS95) [1]. In the experiment, the positive density dependence of $W_{e\_kin}$ can be recognized only in the low-density regime of $\langle n_e \rangle < 2 \times 10^{19}$ m$^{-3}$ (see Fig. 1 (c)). This 'saturation' of the global confinement in the high-density regime is not fully understood at this moment. In this study, however, our interest lies in the difference between the hydrogen plasmas and the neon plasmas. Therefore, we restrict the density range as $\langle n_e \rangle < 2 \times 10^{19}$ m$^{-3}$ in the analysis below, to eliminate the saturated data.

In LHD, negative-ion based NB injection systems are adopted and the energy of the beam ions, $E_{NB}$, is much larger than $T_e$ (typically, $E_{NB} > 150$ keV). This results in the large fraction of the electron heating power, $P_{NB\_e}$, of about 0.8 $P_{NB}$. Here, 'pure' plasmas are assumed for both of the hydrogen ($Z_{eff} = 1$) and the neon ($Z_{eff} = 10$), to give $P_{NB\_e}$. As seen in Fig. 1 (a) and (b), $T_{i0} < T_{e0}$ is observed in the low-density hydrogen plasmas, and therefore

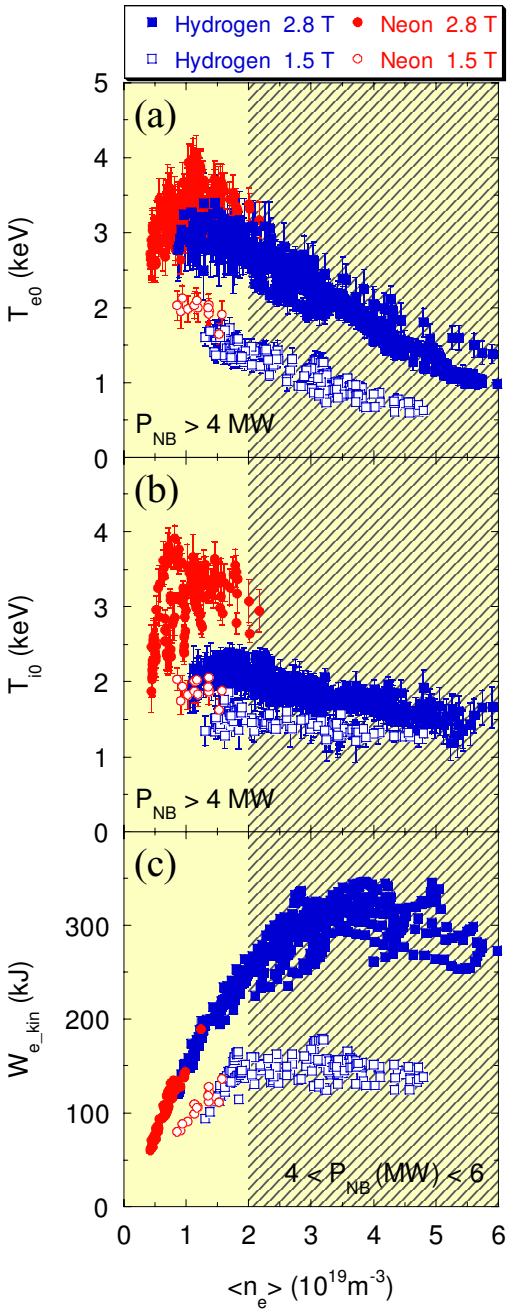


Fig. 1. Distributions of (a) $T_{e0}$, (b) $T_{i0}$, and (c) $W_{e\_kin}$, with respect to <$n_e$>.

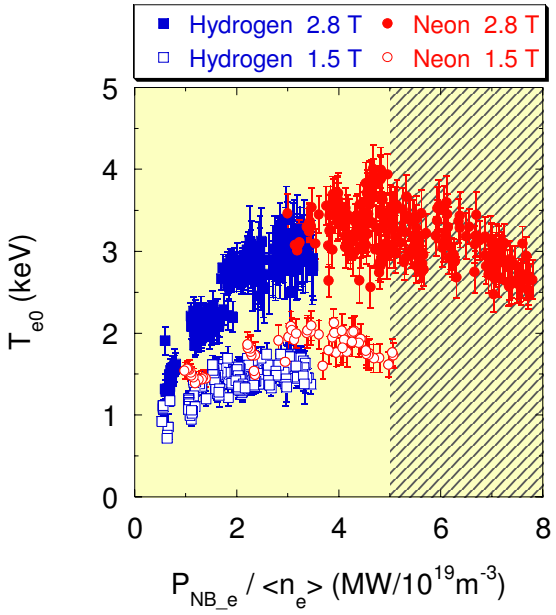


Fig. 2. Dependence of $T_{e0}$ on $P_{NB\_e}$ / <$n_e$>. Plotted are the data that satisfy the two criteria; <$n_e$> < $2 \times 10^{19}$ m$^{-3}$, and $P_{ei}$ / $P_{NB}$ < 0.1.

the heat transfer from the electrons to the ions, $P_{ei}$, should be considered carefully. The maximum $P_{ei}$ reaches to 1 MW at <$n_e$> < $2 \times 10^{19}$ m$^{-3}$ and is not small enough to be neglected. Hereinafter, we eliminate the data that has $P_{ei}$ / $P_{NB}$ > 0.1, and neglect $P_{ei}$ to reduce its influence.

The relation between $T_{e0}$ and the electron heating power per an electron, $P_{NB\_e}$ / <$n_e$>, is plotted in Fig. 2. In the range of $P_{NB\_e}$ / <$n_e$> < 5 MW / $10^{19}$ m$^{-3}$, $T_{e0}$ increases with $P_{NB\_e}$ / <$n_e$>, and any particular differences between the hydrogen and the neon plasmas can be recognized. The maximum $T_{e0}$ obtained in the neon plasmas can be attributed to the increased heating power due to the small fraction of the NB shine-through power at the low-density regime. Above $P_{NB\_e}$ / <$n_e$> > 5 MW / $10^{19}$ m$^{-3}$, however, $T_{e0}$ gradually decreases. The reason why this kind of deterioration occurs is not solved to date. Hereinafter, we adopt one more criterion to eliminate the deteriorated data; i.e. $P_{NB\_e}$ / <$n_e$> < 5 MW / $10^{19}$ m$^{-3}$.

Next, we compare the global energy confinement of the electrons in the hydrogen and

the neon plasmas. The non-dimensional regression analysis of the experimental electron energy confinement time, $\tau_{E\_e}^{exp}$ ($\equiv W_{e\_kin} / P_{NB\_e}$) is examined. In the non-dimensional form, $\tau_{E\_e}^{exp}$ can be expressed as

$$\tau_{E\_e}^{exp}\,\Omega_e \propto B_0\ \tau_{E\_e}^{exp} \propto (\rho_e^*)^{\phi}(\nu^*)^{\gamma}(\beta_e)^{\eta}, \tag{1}$$

where $\Omega_e$ is the electron gyro frequency, $\rho_e^* = \rho_e / a$ is the normalized electron gyro radius, $\nu^*$ is the collisionality, and $\beta_e$ is the normalized electron pressure [2]. For the hydrogen data, however, the linear correlation coefficients of each components are 0.89, 0.35 and 0.54 for $\rho_e^*$, $\nu^*$, and $\beta_e$, respectively. Here, we neglect the dependence on $\nu^*$ and $\beta_e$, since these are not strongly correlating with $\tau_{E\_e}^{exp}$. Regression analysis with $\rho_e^*$ alone gives;

$$B_0\ \tau_{E\_e}^{exp}\,(\mathrm{H}) = 3.57 \times 10^{-13}\ (\rho_e^*)^{-2.74\pm0.07}. \tag{2}$$

As for the neon data, the linear correlation coefficients for each components are 0.91, 0.49 and 0.27 for $\rho_e^*$, $\nu^*$, and $\beta_e$, respectively. Again, $\nu^*$ and $\beta_e$ are not strongly correlating with $\tau_{E\_e}^{exp}$. Regression analysis with $\rho_e^*$ alone results in

$$B_0\ \tau_{E\_e}^{exp}\,(\mathrm{Ne}) = 1.15 \times 10^{-12}\ (\rho_e^*)^{-2.61\pm0.09}. \tag{3}$$

In both of the hydrogen and the neon plasmas, $B_0\ \tau_{E\_e}^{exp}$ is strongly related to $\rho_e^*$ and the exponents are identical within the standard deviations. These relations are plotted in Fig. 3 (a). This suggests that both plasmas have similar parameter dependence of the global electron energy confinement. The difference in the coefficients between Eqs. (2) and (3) is possibly due to the small $\rho_e^*$ of ~ $10^{-4}$ (note that even the small difference of 0.1 in the exponents causes an error of factor 2.5 in the coefficients). To compare the coefficients more accurately, we assume a model equation with the exponent of – 2.7;

$$\tau_{E\_e}^{fit}\,\Omega_e \propto B_0\ \tau_{E\_e}^{fit} \propto (\rho_e^*)^{-2.7}. \tag{4}$$

In the gyro-Bohm model, where micro-turbulences are considered as the cause of the anomalous energy transport [3, 4], the exponent of – 3 is assumed, while it is – 2 in the Bohm model, for example (note that $\rho_i^*$ is used instead of $\rho_e^*$, in these models). Equation (4) can be rewritten using the conventional terms as below;

$$\tau_{E\_e}^{fit} = C_0\, a^{2.30} R^{0.574} B_0^{0.723} P_{NB\_e}^{-0.574} \langle n_e \rangle^{0.574}, \tag{5}$$

where $C_0$ is the fitting parameter, and the units of each terms are; m, m, T, MW, and $10^{19}$ $m^{-3}$, for $a$, $R$, $B_0$, $P_{NB\_e}$, and $\langle n_e \rangle$, respectively. Fitting the data with Eq. (5), the distributions of

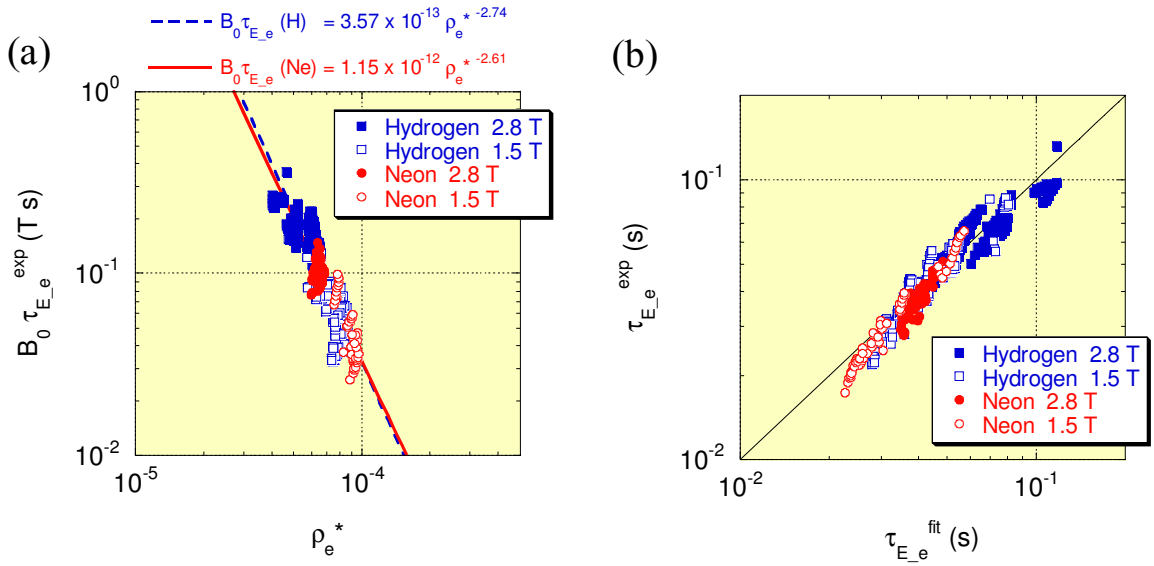


Fig. 3. (a) Dependence of $B_0\ \tau_{E\_e}^{exp}$ on $\rho_e$*, and (b) the comparison of $\tau_{E\_e}^{exp}$ and $\tau_{E\_e}^{fit}$. Plotted are the data that satisfy the three criteria; $\langle n_e \rangle < 2 \times 10^{19}$ m$^{-3}$, $P_{ei} / P_{NB} < 0.1$, and $P_{NB\_e} / \langle n_e \rangle < 5$ MW / $10^{19}$ m$^{-3}$.

$\tau_{E\_e}^{exp}$ in the plasmas with different ion species can be compared. Using hydrogen dataset, $C_0 = 0.060 \pm 0.007$ is obtained, while $C_0 = 0.056 \pm 0.004$ is obtained with the neon dataset. In both cases, $C_0$ is identical within the standard deviations. Assuming $C_0 = 0.06$, $\tau_{E\_e}^{exp}$ and $\tau_{E\_e}^{fit}$ are compared in Fig. 3 (b). As is seen in the figure, $\tau_{E\_e}^{fit}$ well reproduces $\tau_{E\_e}^{exp}$, and its absolute value is similar in both of the hydrogen and the neon plasmas.

These results are contrastive to the Z-mode [5] and the RI-mode [6] in tokamaks, where a reduction of the electron thermal diffusivity induced by the impurity (including the neon) gas puff has been observed. In this study, however, parameter region is limited. Especially, the confinement deterioration at $P_{NB\_e} / \langle n_e \rangle > 5$ MW / $10^{19}$ m$^{-3}$ is observed only in the neon plasmas. Whether this deterioration will also occur in the hydrogen plasmas, or not, should be examined in the future experiment. The energy confinement of the ions has not been treated in this study. To carry out the conclusive discussion on this, it is necessary to measure the ion temperature profile and the ion density profile.

**References**

[1] U. Stroth et al., Nucl. Fusion **36**, 1063 (1996).

[2] H. Yamada et al., Plasma Phys. Control. Fusion **43**, A55 (2001).

[3] R. J. Goldston et al., Bull. Am. Phys. Soc. **34**, 1964 (1989).

[4] M. Murakami et al., Phys. Fluids B **3**, 2261 (1991).

[5] E. A. Lazarus et al., Nucl. Fusion **25**, 135 (1985).

[6] G. R. McKee et al., Phys. Plasmas **7**, 1870 (2000).