Observation of non-collisional ion heating in helical plasmas under dominant electron heating condition by neutral beam injection on LHD

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In LHD, significant increases in the central ion temperature T_{io} are observed in low density plasmas having a non-monotonic rotational transform profile produced by high energy neutral beam current drive (NBCD). The phenomena realize $T_{io} \sim T_{eo}$ (central electron temperature). The T_{io}-increases disappear by a factor of two increase of electron density. During the T_{io}-increase, turbulent density fluctuations in the core plasma region are not suppressed but are enhanced. The T_{io}-increases are realized by the addition of non-collisional ion heating, but not confinement improvement by suppressed turbulence. The ion heating power estimated from the T_{io} evolutions is considerably higher than the collisional ion heating. The additional ion heating power agrees well with the ion heating power by damping of energetic ion driven geodesic acoustic modes (EGAMs) through the fundamental Landau resonance with passing bulk protons.

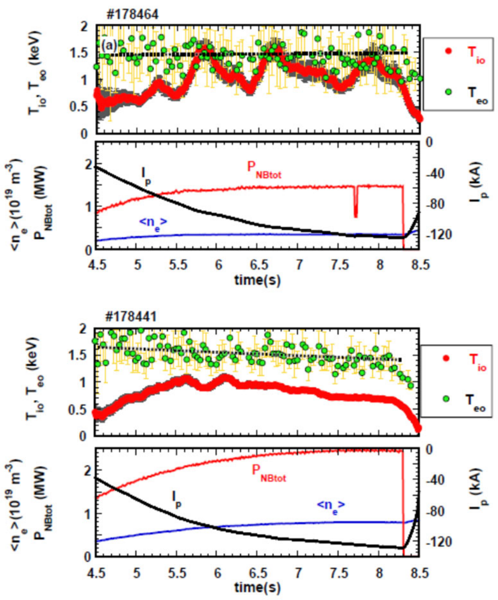

Fig.1 Time evolutions of the central ion and electron temperatures, the line averaged electron density, total absorbed NBI power and NB-driven plasma current in low density (a) and higher density (b) plasmas. The dotted thick line on T_{eo} data points indicates the time averaged T_{eo}.

Bulk ion heating by various mechanisms is critically important for future D-T burning plasmas under dominant electron heating by alpha particles. In LHD, significant increases of bulk ion temperature T_{io} measured by an argon line ArXVII broadening are observed in the reversed magnetic shear (RS-) plasmas having a non-monotonic rotational transform (ι-) profile produced by NBCD of the order of 100 kA. The temperature of Ar^{16+} ion reflects the proton one in the RS-plasmas. The initial beam energy (~115-140 keV) is much higher than the critical beam energy. The RS-plasmas are under a condition of dominant electron heating by the high energy proton beams. Time evolutions of T_{io} are compared in Fig.1 for low and higher density RS-plasmas. The T_{io} reaches about 1.6 keV in the low density plasma with ~1.5 MW total absorbed NBI power, while the T_{io} reaches in ~ 1.1 keV and gradually decreases in the higher density plasma with ~ 2.4 MW input. The collisional ion heating power is less than 20% of total NBI input. An important observation is that T_{io} increases significantly and intermittently during a constant $<n_e>$ and absorbed power phase, and $T_{io} \sim T_{eo}$ is realized, under dominant electron heating condition. Turbulent density fluctuations in the core region (normalized minor radius ρ ≲ 0.5) is not suppressed but clearly enhanced during the increase phases, as shown in Fig.2. The T_{io} -increases are not caused by confinement improvement due to turbulence suppression but by non-collisional ion heating. In the RS-plasmas, the EGAM fluctuations are clearly detected by magnetic probes (MPs) and a heavy ion beam probe (HIBP). The EGAM magnetic fluctuations have an n=0 and m=2 standing wave structure, where n and m are toroidal and poloidal mode number respectively. The fluctuations indicate the EGAM characters. In addition, n=0 global Alfven eigenmodes (GAEs) as well as n=1 reversed shear AEs (RSAEs) are also destabilized. The local minimum of the ι-profile, ι_{min} is estimated from the RSAE frequency [1]. Moreover, the central value ι(0) is accurately predicted from the GAE frequency. The T_{io}-increase starts just after the time that ι_{min} passes the rational values 1/2 and 1/3 (Figs.3(a) and (c)). The EGAM frequency in the RS-plasma is about 60% of the standard GAM frequency and is nearly independent of T_{io} (Figs.3(c)). The non-collisional ion heating power is estimated from a ion power balance using the T_{io} data, on the assumption of power degradation in ion energy confinement time as ${P_{itot}}^{-\alpha}$. For the cases of α=0.6 like the ISS04 scaling and 0.3 in a mild degradation, the non-collisional ion heating P_{iadd} is noticeably higher than ~10 kW/m^3 collisional ion heating power (Fig.3(b)). It is noteworthy that the EGAM potential amplitude is obviously suppressed during the T_{io} increase (Fig.3(b)). With the radial wave number obtained from the EGAM profiles in Fig.3(e) and other experiment data, the expected ion heating power by EGAM P_{EGi} is estimated as shown in Fig.3(d), with the help of ref. [2]. The magnitude and temporal evolution agree well with those of P_{iadd} obtained for α=0.3 in Fig.3(b), except the initial increase phase. The deviation may be due to enhanced radial transport of bulk ions by destabilized MHD modes related to ι_{min}=1/2.

In conclusion, the observed T_{io}-increase is realized by ion Landau heating of EGAM through the fundamental resonance with passing bulk protons.

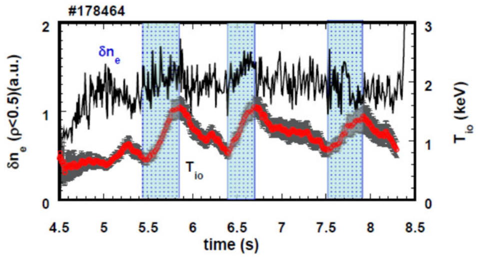

Fig.2 Temporal behaviors of turbulent density fluctuation amplitude and T_{io}. Each T_{io}-increase phase is emphasized with a shaded zone.

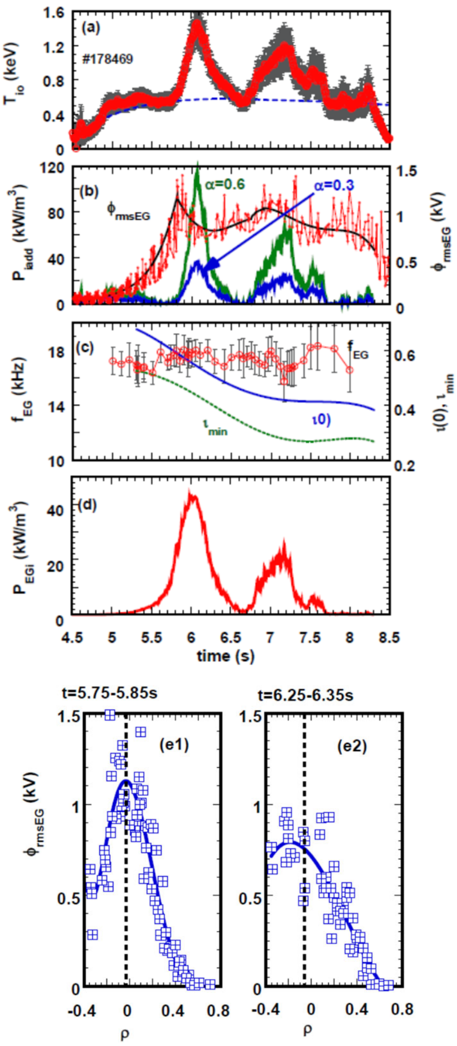

Fig.3 Time evolutions of (a) Tio with Tio by collisional ion input only (broken curve), (b) additional ion heating inputs for α=0.6 and 0.3, and the root-mean squared amplitude of EGAM near the plasma center and its fitted curve, (c) EGAM frequency, ι(0) and ι_{min} from the AE frequencies, (d) calculated ion heating input by EGAM damping, and (e) the EGAM potential profiles just before and after the T_{io}-increase.

[1] K. Toi et al., Phys. Rev. Lett. **105** (2010) 145003.

[2] H. Sugama and T.H. Watanabe, Phys. Plasmas **13** (2006) 012501 and **14** (2007) 079902.