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

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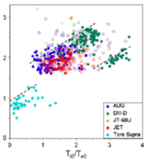
Introduction
High ion temperature required for a D-T burning Plasma under dominant electron heating condition

DT-burning plasma:
Dominant electron heating by energetic alpha particles
Ion heating via Coulomb collisions with electrons
=> Plasmas of $T_e > T_i$ => Not favorable for fusion output.

Burning plasmas having $T_i \gtrsim T_e$ is required for improved plasma confinement, so auxiliary ion heating is also applied.

- Easy access to improved plasma confinement regimes in $T_i \gtrsim T_e$ plasmas was confirmed in many tokamaks.
- Many theories and numerical simulations show ITG turbulence suppression on $T_i \gtrsim T_e$.



E.J. Doyle et al, *Chap.2: Plasma confinement and transport,* Nucl. Fusion (2007).

In LHD plasmas under strong electron heating condition by high energy tangential NBIs, strong T_{io}-increases are often observed, leading to T_i~T_e plasmas.
This paper will present the details of the observations and clarify the physics mechanisms.

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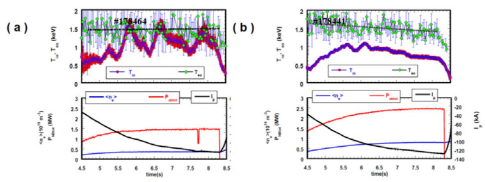
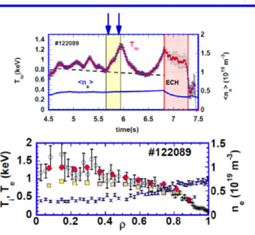
1. Experimental setup and plasma behaviors in LHD



Counter NBCD with E_{b1}=140 keV, E_{b3}=118 keV
I_p~100-120 kA, $\beta_{bulk}(0)$~0.13 %, P_h~$10P_{bulk}$
$E_b/T_{eo} \gtrsim 80$ => Dominant el. heating More than 80 % of total NBI absorbed power is deposited on electrons.
In a low density shot #178464 (a), T_{io}~T_{eo}, while in a higher density shot #178441 (b) $T_{eo} > T_{io}$.

Time evolutions of ion temperature profiles



The T_{io}-increase corresponds to the increase in ion temperature in the plasma central region, and realizes a parabolic profile.
Yellow squares: initial phase of T_{io}-increase
Red diamonds: at the T_{io}-max

The profiles of electron temperature and density remain unchanged during the T_{io}-increase.
Open circles: T_e profile
Crosses : n_e profile

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2. Possible physics mechanisms of the observed T_{io}-increases

Likely candidate mechanisms for the T_{io}-increases:

◆ Transition in neoclassical transport to "electron root" => Ruled out!

- Reduction of ion transport by transition from "ion" to "electron" root is predicted in a helical plasma.
  Theories and simulations: H.P. Furth & M.N. Rosenbluth, 3rd IAEA conf.(1968), S.P. Hirshman & D.J. Sigmar, Nucl. Fusion (1981).
  Experimental observations in LHD: K., Ida et. al., Phys. Rev. Lett.(2001).
  However, in the plasmas of this experiment, the $E_r \lesssim 0$ in $r/a \lesssim 0.5$ is observed.
  => No transition to "electron root" ($E_r > 0$), because the plasmas are in the "ion root".

◆ Suppression of microturbulence in the plasma core region

◆ Ion Landau damping of EGAM

➢ *Discussed below.*

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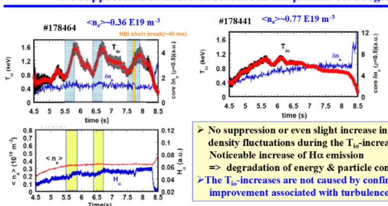
No suppression of microturbulence in the plasma core region



- No suppression or even slight increase in microturbulence density fluctuations during the T_{io}-increase phases. Noticeable increase of Hα emission => degradation of energy & particle confinement.
- The T_{io}-increases are not caused by confinement improvement associated with turbulence suppression.

A typical example of the T_{io}-increase due to turbulence suppression in LHD => Strong E_r-shear generation by energetic ion losses due to energetic ion driven resistive interchange modes (EICs).
X. Du, K. Toi et al., PRL(2015), NF(2015)

3. Studies of correlation between EGAMs and the observed T_{io}-increases

The energetic ion driven GAM (EGAM) strongly destabilized in this experiment can play an essential role in the observed T_{io}-increases.

Characteristic features of the EGAM are as follows:
@Confirmation of n=0 mode in the coherent poloidal magnetic fluctuations (High coherence between the n=0 mode of ~17 kHz in poloidal magnetic fluctuations and potential fluctuations)
@ The mode frequency is ~ 50 % of the standard GAM frequency.
@ The frequency has a dependence of $\sqrt{T_e}$ (confirmed by ECH experiment) but has no dependence on T_i.
@ Large amplitude of electrostatic potential fluctuations in the order of kV.

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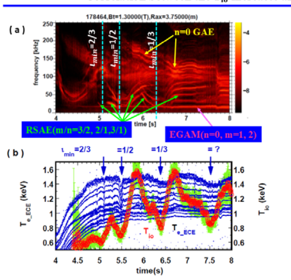
Correlation between the T_{io}-increases and the ι_{min} evolution



- Accurate prediction of ι_{min} from the RSAE frequency sweep K. Toi et al, Phys. Rev. Lett. (2010)
- T_{io}-increase is initiated by the time ι_{min} passes a rational value, 1/2 or 1/3. Noticeable changes of T_{e_ECE} signals take place at ι_{min}=1/2 and 1/3.
- T_{io} increases last for about 0.3 s, and then is suddenly terminated.

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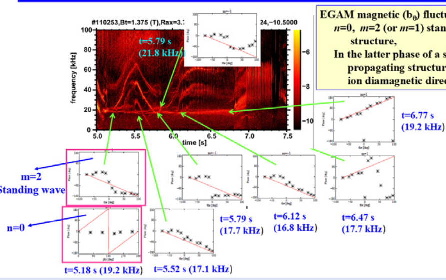
Characteristics of EGAM magnetic fluctuations



EGAM magnetic (b_θ) fluctuations:
n=0, m=2 (or m=1) standing wave structure,
In the latter phase of a shot, m=1 propagating structure in the el. or ion diamagnetic direction appears.

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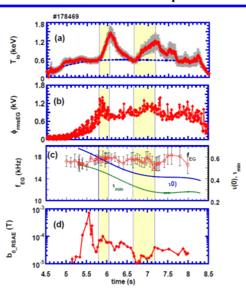
Obvious reduction in EGAM potential fluctuations during the T_{io}-increase phase



- Obvious decrease in the EGAM potential fluctuation amplitude, responding to the first increasing phase of T_{io} has been observed (Figs.(a) & (b)).
- The EGAM frequency is nearly constant in time. The frequency does not depend on the T_{io}-increases.
- The ι(0) derived from the n=0 GAE frequency slowly evolves from ~ 0.65 to ~0.40.
- The 2nd T_{io}-increase seems to correlate well with the reduction phase of n=1 RSAE activities. When the activities are re-enhanced, the T_{io}-increase is quenched.
- While the 1st T_{io}-increase is started just after the strong suppression of the RSAE activities, the quench does not show any clear correlation with the RSAE activities. In the quench phase, a harmful m=2 double tearing mode becomes unstable.

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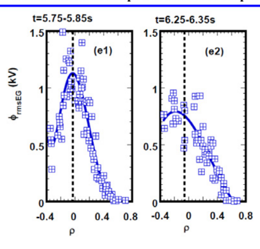
Correlation between the radial profiles of the EGAM potential amplitude and the T_{io}-increase



- The radial profile of the EGAM potential amplitude (r.m.s. values) is centrally peaked at the beginning of the T_{io}-increase phase. The radial wave number is estimated to be small (~ 8 m^{-1}).
- The profile in the decay phase following the T_{io}-increase broadens, reducing the central peak to about two-thirds.
- In both phases, the EGAM well localizes near the plasma central region of $\rho \lesssim 0.5$.

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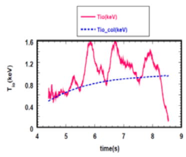
4. Estimation of additional ion heating power from the T_{io} evolutions

Additional ion heating power density $\langle p_{iadd}\rangle$ can be approximately estimated from a simple power balance equation of ions, on the assumption of a possible power degradation.



$$\langle\frac{dw_i}{dt}\rangle + \langle\frac{w_i}{\tau_{Ei}}\rangle = \langle p_{NBi}\rangle + \langle p_{ei}\rangle + \langle p_{iadd}\rangle$$

$$\langle\frac{dw_{icol}}{dt}\rangle + \langle\frac{w_{icol}}{\tau_{Eicol}}\rangle = \langle p_{NBi}\rangle + \langle p_{eicol}\rangle$$

$$\tau_{Eio}/\tau_{Eicol} = \left(\frac{<p_{nbi}>+<p_{eicol}>}{<p_{nbi}>+<P_{ei}>+<p_{iadd}>}\right)^{\alpha}$$

where <F> =F(0)f_{prof} with the profile shape factor for T_e, T_i, ne and P_{NB}.

T_{io} evolution will be expressed as a sum of the collisional and non-collisional increases, where T_{io_col} stands for the increase by collisional ion heating alone.

Estimation of <P_{iadd}> depends on the degradation index α sensitively, but nearly independent of f_{prof}.

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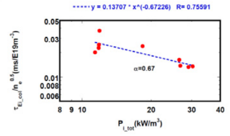
Estimation of power degradation index of τ_{Ei_col} in the cases with collisional ion heating alone on LHD

Power degradation in various empirical scaling laws of global energy confinement time is ubiquitous in toroidal plasma confinements.

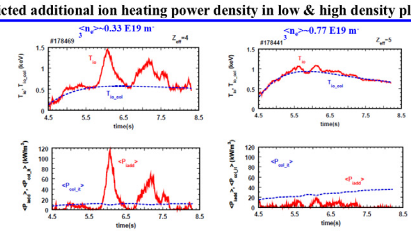
International stellarator scaling, ISS04 [1] : $\tau_E \propto n_e^{0.5} P_{tot}^{-0.6}$ (n_e-dependence is also included.)
ITER H-mode scaling, IPB98(y,2) [2] : $\tau_E \propto n_e^{0.4} P_{tot}^{-0.7}$ (n_e-dependence is also included.)

[1] H. YAMADA et al., *Nucl. Fusion (2005).*
[2] E.J. Doyle et al., Nucl. Fusion (2007).

The power degradation in ion energy confinement time for the cases with collisional ion heating alone was investigated and found to be nearly same as that in the ISS04 scaling.



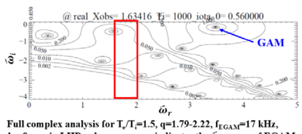
Predicted additional ion heating power density in low & high density plasmas



The ion heating power density <P_{iadd}> are obtained with the α=0.6, based on the study of τ_{Ei_col} scaling.
In low density plasma, <P_{iadd}> is much higher than the collisional one indicated with the broken curve.
In high density plasma, <P_{iadd}> can be ignored for the collisional one.

5. Possibility of ion heating by ion Landau damping of EGAM

- From the obvious correlation of the EGAM potential fluctuations to the T_{io}-increase, ion heating power density by ion Landau damping of EGAM is the most likely in the this experiment.
  $P_{i\_EGAM} = 2\gamma_{d\_EG} W_{EG}$, where the EGAM wave energy density $W_{EG} = \frac{m_i n_i k_r^2 \phi_{rms EG}^2}{2B_t^2}$
  => To explain the observed <P_{iadd}>, large damping rate of the EGAM is required , i.e., $\frac{\gamma_{d\_EG}}{\omega_{EG}} = 2-3$!
  (A scenario of the EGAM damping via a standard GAM is unrealistic, because of $\frac{\gamma_{d\_GAM}}{\omega_{GAM}} << 1.$)
- EGAM persists during the T_{io}-increase, so the EGAM growth rate should be comparable to γ_{d_EG}.



Full complex analysis for T_e/T_i=1.5, q=1.79-2.22, f_{EGAM}=17 kHz, k_r=8 m^{-1} in LHD, where a square indicates the $\hat{\omega}_r$ range of EGAM.

- For the GAM dispersion relation $F_{GAM}(\hat{\omega})$, the electric field fluctuations is expressed as the response to the external radial current by EGAM:
  $$\frac{d\hat{\phi}}{dr} = \frac{\varepsilon_o}{F_{GAM}(\hat{\omega})} J_{ext}(\omega_{EG})$$
  $1/F_{GAM}(\hat{\omega})$: plasma response to J_{ext}
- Many mode having large damping rates may interact with EGAM and absorb the wave energy. The absorbed energy will be transferred to bulk ions.

6. Summary

- Observation of strong increases in T_{io} and realization of T_{io}~T_{eo} plasmas in LHD under dominant electron heating condition, similar to a D-T burning plasma
- The ion temperature increases are not associated with suppression of microturbulence. No transition to "electron root" in the neoclassical transport of the helical.
  => Observed ion temperature increases caused by an addition of non-collisional ion heating, instead of confinement improvement !
- The additional ion heating power estimated in the range of 50-80 kW/m³ is much higher than collisional ion heating
- The ion heating occurs intermittently just after the ι_{min} passes the rational values, 1/2 and 1/3.
- EGAM potential fluctuation amplitude clearly decrease, responding to the T_{io}-increase. Ion Landau damping of EGAM is thought to be the most likely candidate mechanism of strong non- collisional ion heating observed in the present experiment.
- Quantitative interpretation is left for the future important and interesting research target.

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