24th FEC IAEA, San Diego, USA, 2012/10/9, EX/2-5

Extension of Operational Regime in High-Temperature Plasmas and the Dynamic-Transport Characteristics in the LHD

H. Takahashi, M. Osakabe, K. Nagaoka, S. Murakami[1], I. Yamada, Y. Takeiri, M. Yokoyama, H. Lee[2], K. Ida, R. Seki, C. Suzuki, M. Yoshinuma, T. Ido, A. Shimizu, M. Goto, S. Morita, T. Shimozuma, S. Kubo, S. Satake, S. Matsuoka, N. Tamura, H. Tsuchiya, K. Tanaka, M. Nunami, A. Wakasa[1], K. Tsumori, K. Ikeda, H. Nakano, M. Kisaki, Y. Yoshimura, M. Nishiura, H. Igami, T. Seki, H. Kasahara, K. Saito, R. Kumazawa, S. Muto, K. Narihara, T. Mutoh, O. Kaneko, H. Yamada
and the LHD experiment group

E-mail: *takahashi.hiromi@LHD.nifs.ac.jp*

National Institute for Fusion Science, Toki 509-5292, Japan
[1] Department of Nuclear Engineering, Kyoto University, Kyoto 606-8501, Japan
[2] Department of Nuclear Fusion and Plasma Science, University of Science and Technology (UST), Gajungro 217, Daejeon 305-350 Korea

Outline

1. Extension of High-Temperature Regime in the LHD

- Upgraded heating property and the new scenario with ICRF-wall conditioning

2. Characteristics of High-T_i Plasmas with ion ITB

- Centre-peaked T_i, reduction of χ_i, energy-confinement improvement, and the negative E_r formation

3. Dynamic Transport Analyses for High-T_i Plasmas

- Temporal change of the heat/momentum-transport state

4. Future Prospect

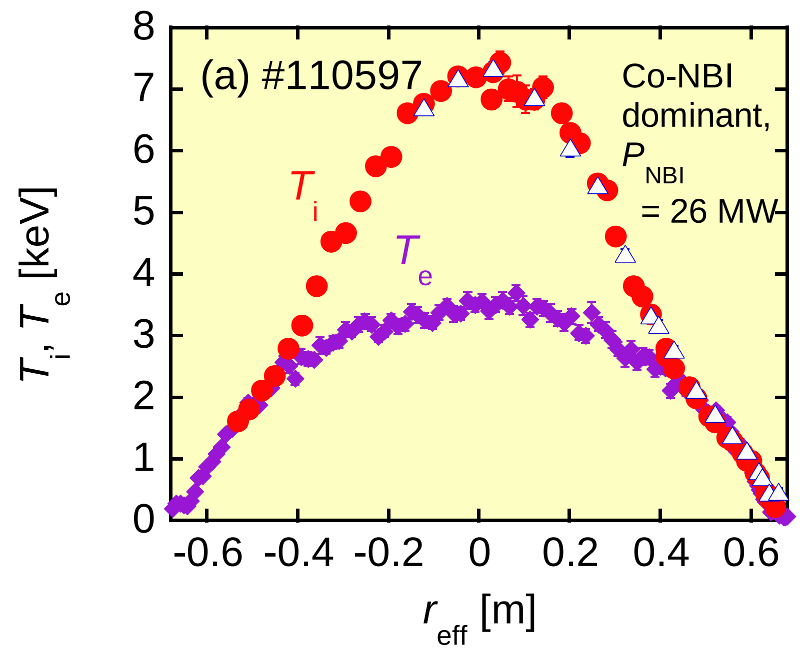
- Toward the quasi steady state operation

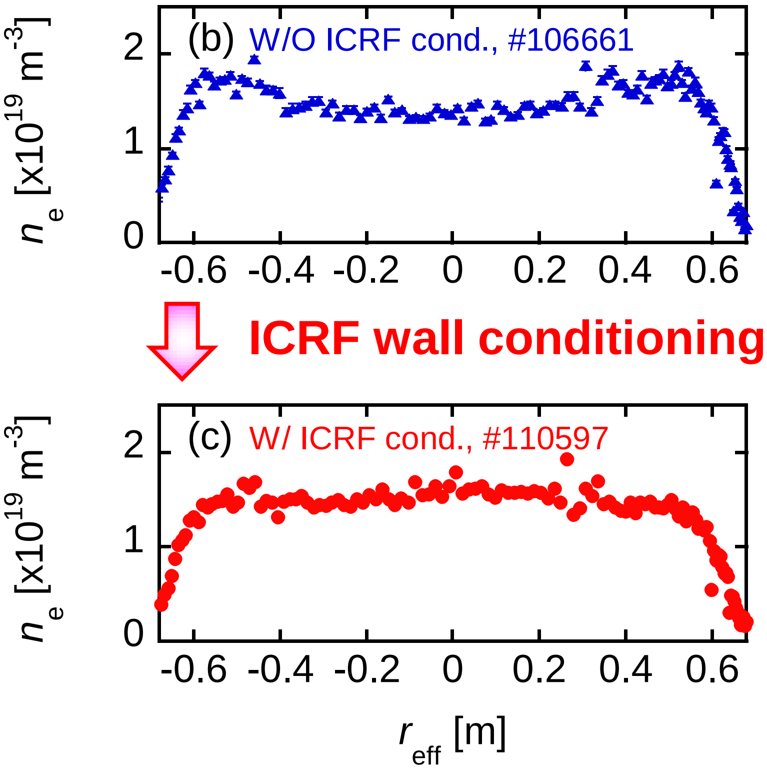
5. Summary

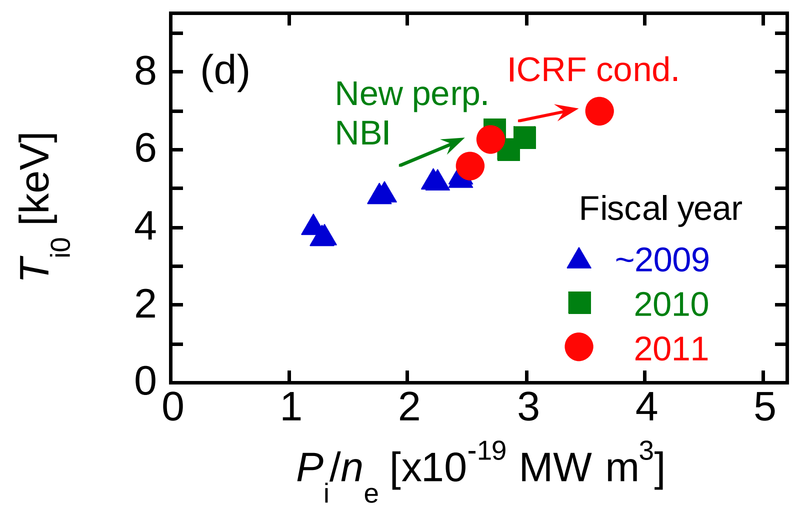
Extension of High-Temperature Regime with Upgrade Heating Property

Achievement of T_i = 7 keV

- **Installation of a new perp. NBI (6 MW/40 keV).**
- **New operation with ICRF wall conditioning.**
  - -> n_e profile: hollow -> flat/parabolic,
  - -> Increase of P_i/n_e in the core, -> **T_{i0} of 7 keV.**
- **High T_i regime has been extended.**







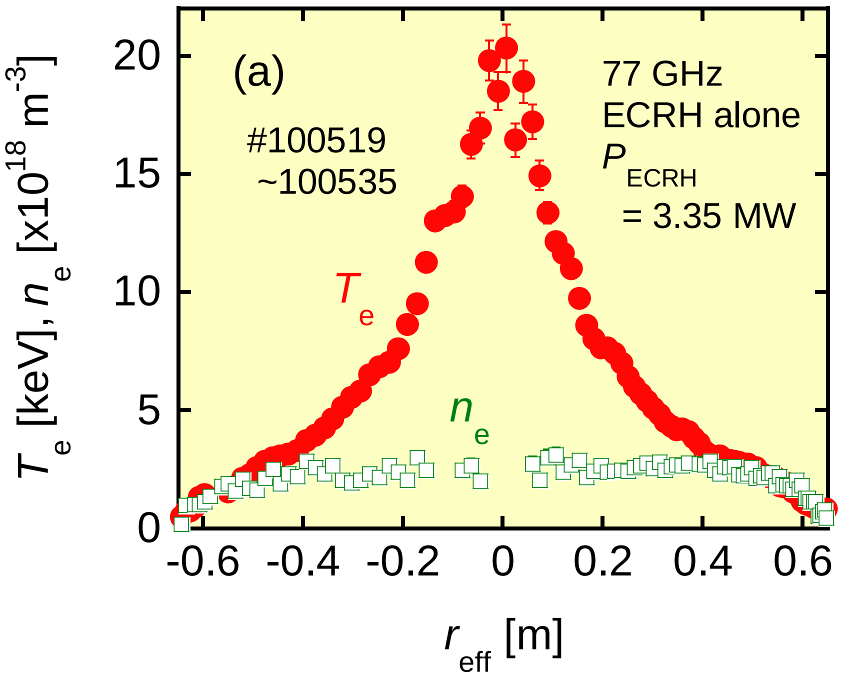
Extension of high-T_e regime

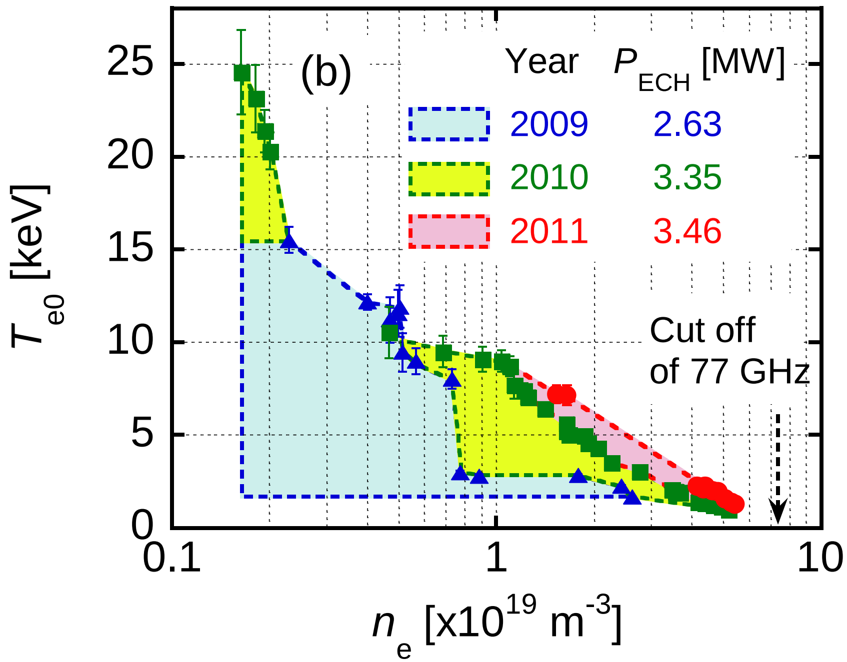
- **Since 2007, Gyrotron x3 (Over 1 MW each/ 77 GHz).**
- Increase of P_{ECH} -> **Extension of high T_e regime**.

(1) Achieved highest temperature -> **T_{e0} = 20 keV** (n_{e_fir} = 0.20x10^{19} m^{-3}).

(2) High density condition,

-> **T_{e0} = 8.7 keV (n_{e_fir} = 1.1x10^{19} m^{-3})**, T_{e0} = 1.3 keV (**n_{e_fir} = 5.4x10^{19} m^{-3}**).



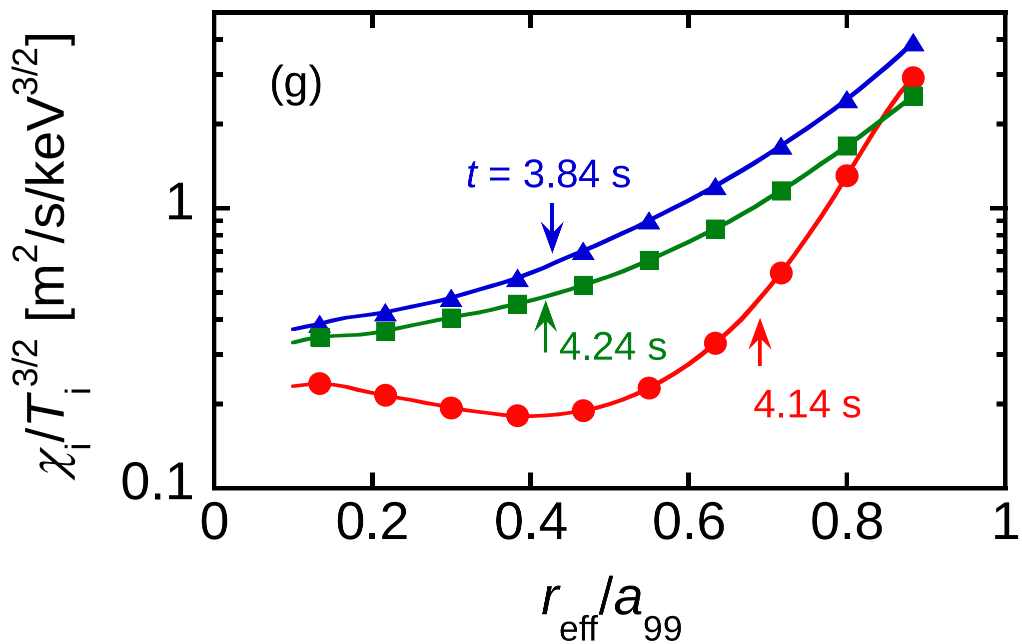


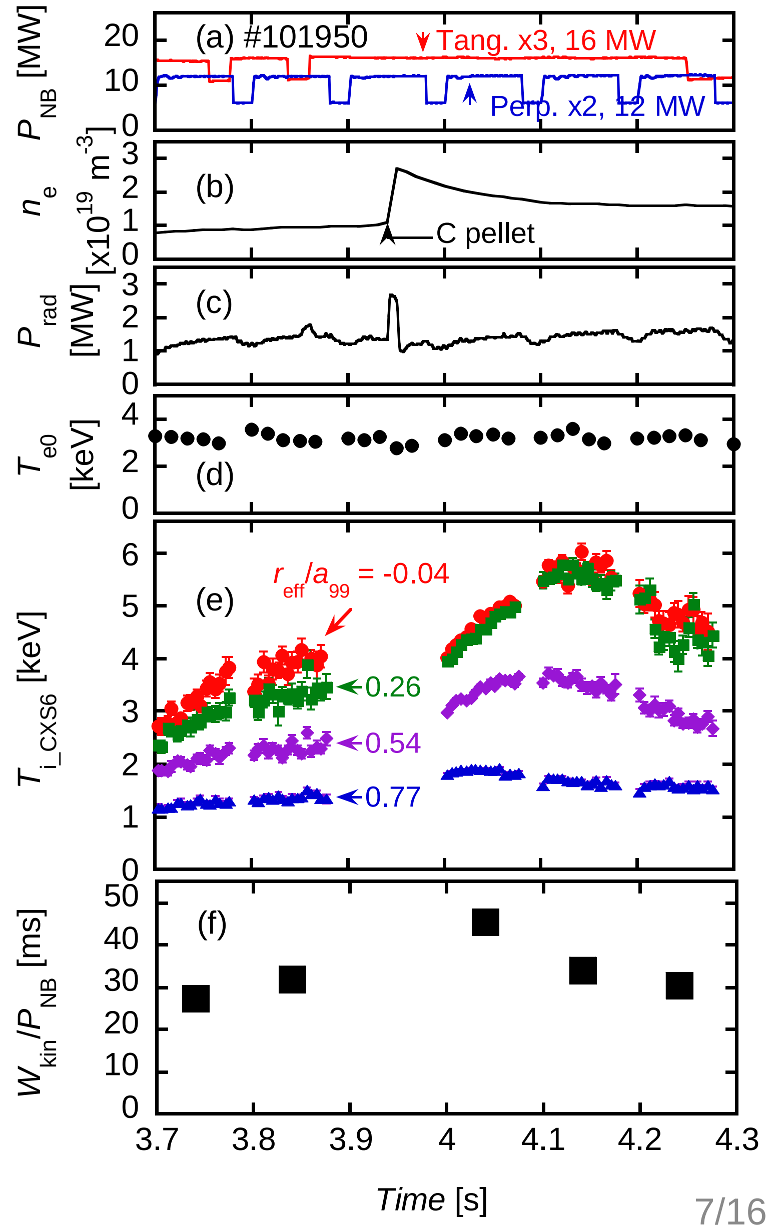
Characteristics of High-T_i Plasmas with Ion ITB

Typical time evolution in a carbon pellet discharge

<u>**In the C-pellet discharge,**</u>

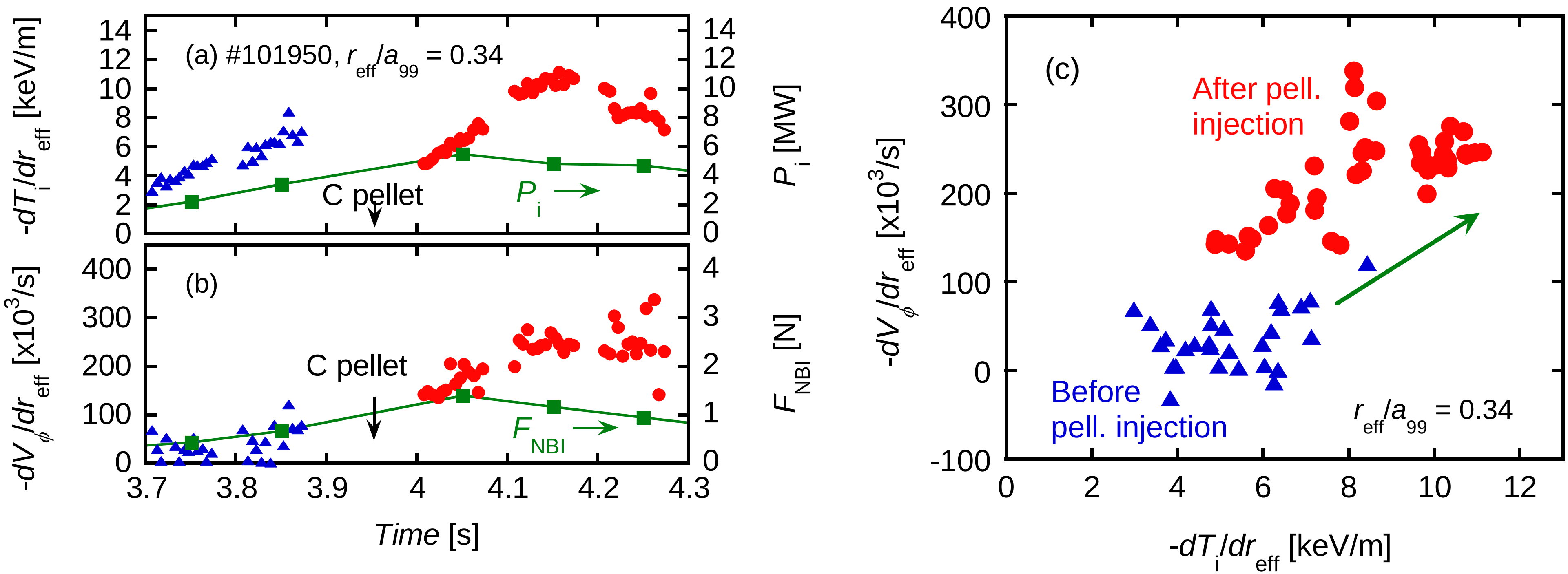
- **T_i and dT_i/dr_{eff} increased in the core** -> **ion-ITB**
- T_e was not improved -> T_e/T_i dropped to 0.5.
- The energy confinement improved **by a factor of 1.5**.
- **χ_i reduced in the entire region**.
- **The improved confinement was transient**.





Relation between grad-T_i and V_ϕ shear

- Centre-peaked profile of V_ϕ was formed.
- **V_ϕ shear clearly increased with increase of T_i gradient.**



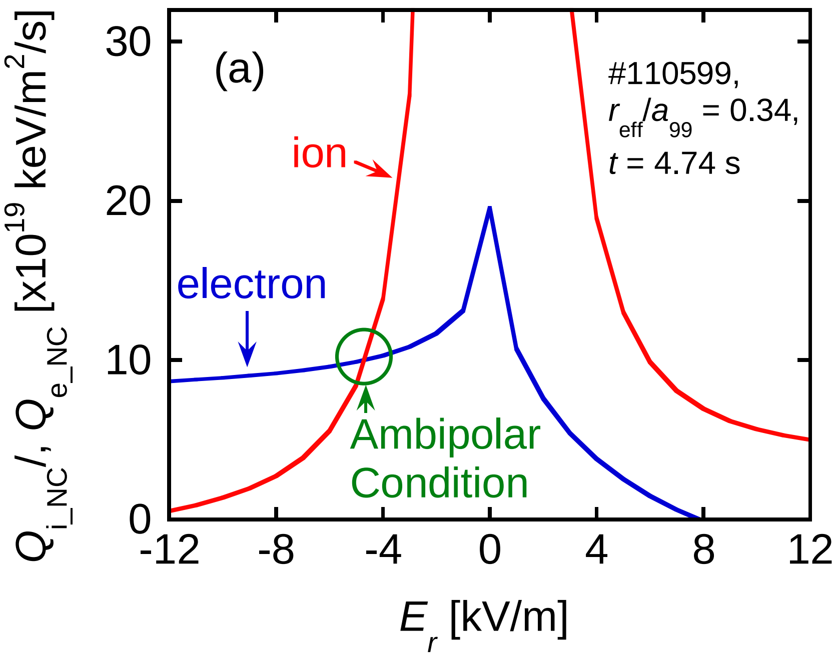
Radial electric field in ion ITB plasma

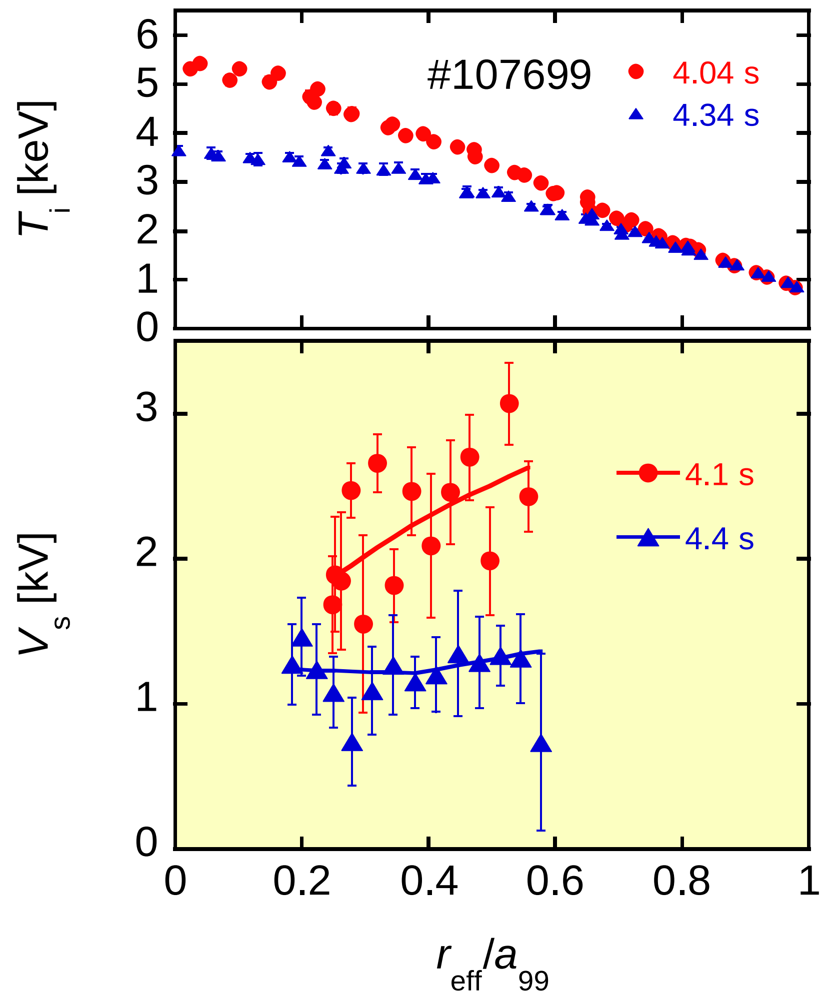
Neoclassical transport,

- **Huge if E_r = 0**.
- **Significantly reduced due to E_r**.

E_r was measured using HIBP,

- Low T_i -> **E_r ~0**
- Ion ITB -> **Negative E_r** ↔ **grad T_i**





Dynamic Transport Analyses for High-T_i Plasmas

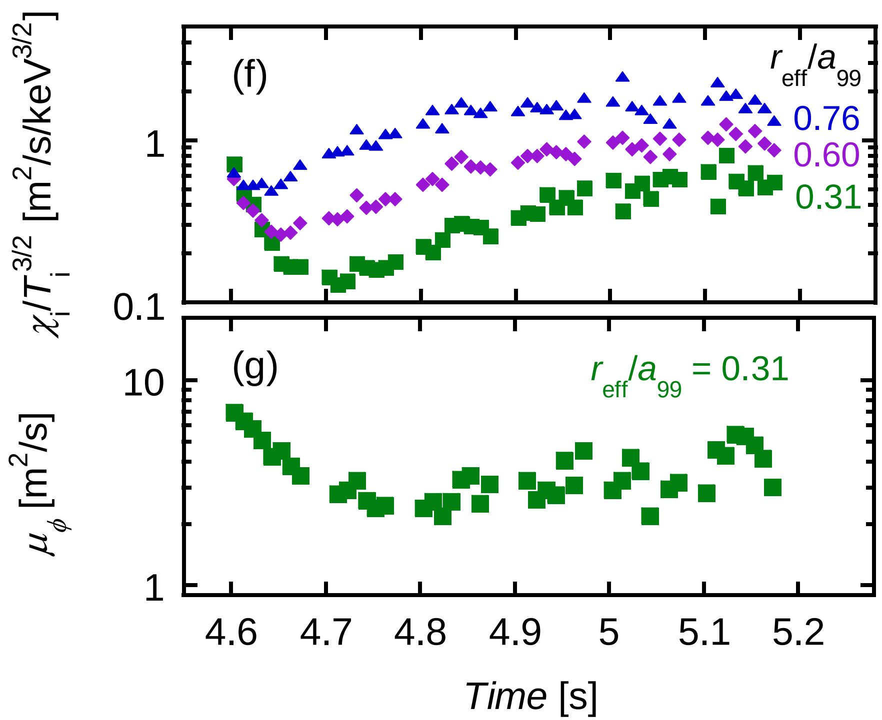
Temporal change of χ_i and μ_ϕ

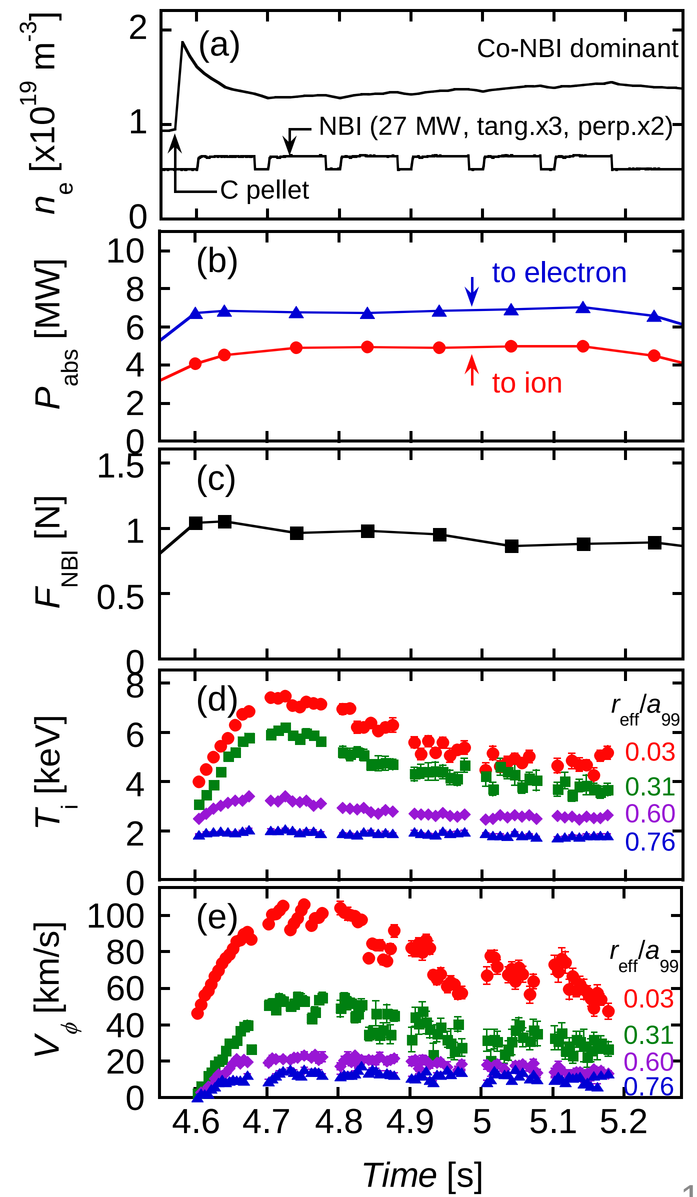
- Temporal behaviour of χ_i

  Plasma Core -> Slow change, **great decrease**.

  Peripheral -> Fast change, **small decrease**.

- **Toroidal-momentum transport was also improved.**

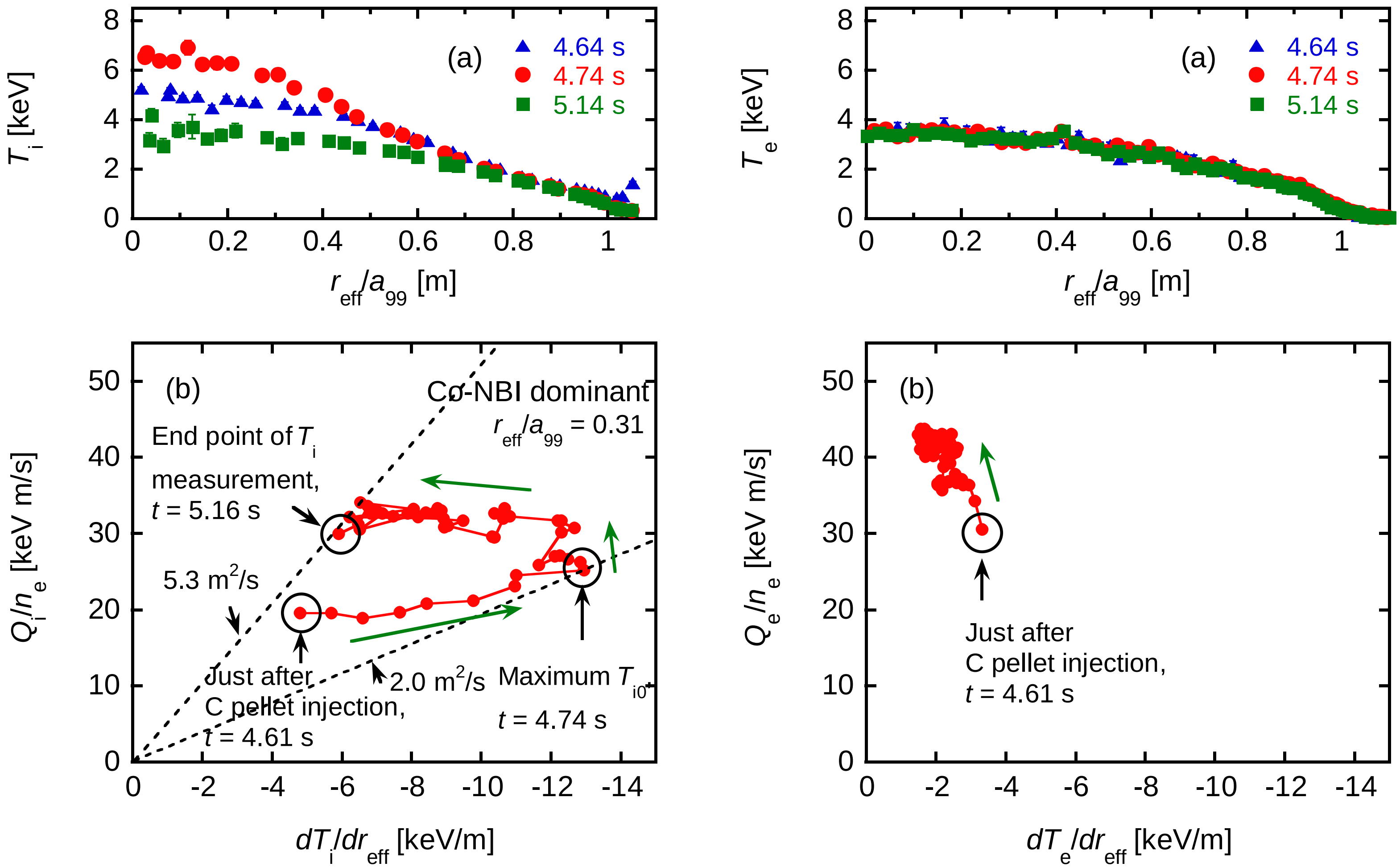




Flux-gradient relation ~Heat transport~

The slope in the flux-gradient relation -> χ_i, χ_e

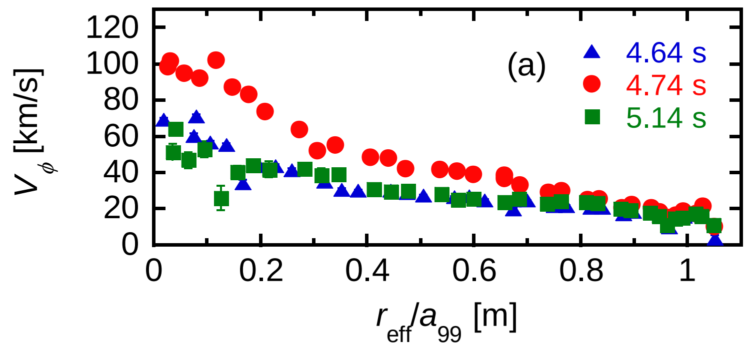
- **Improvement of the Ion-heat transport** -> **Back to low confinement branch**.
- The electron-heat confinement was not improved.

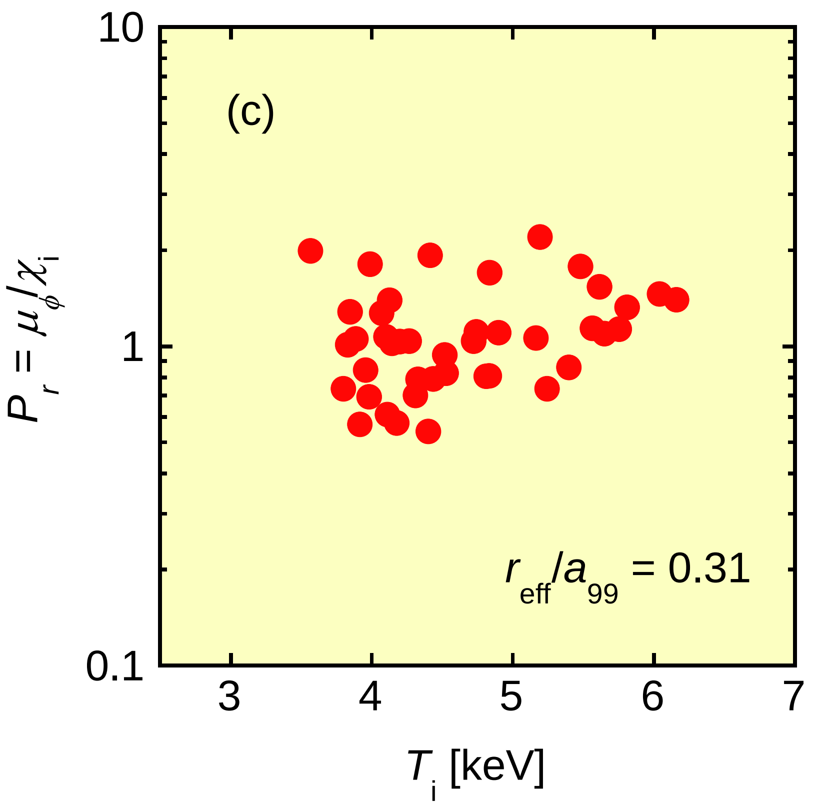


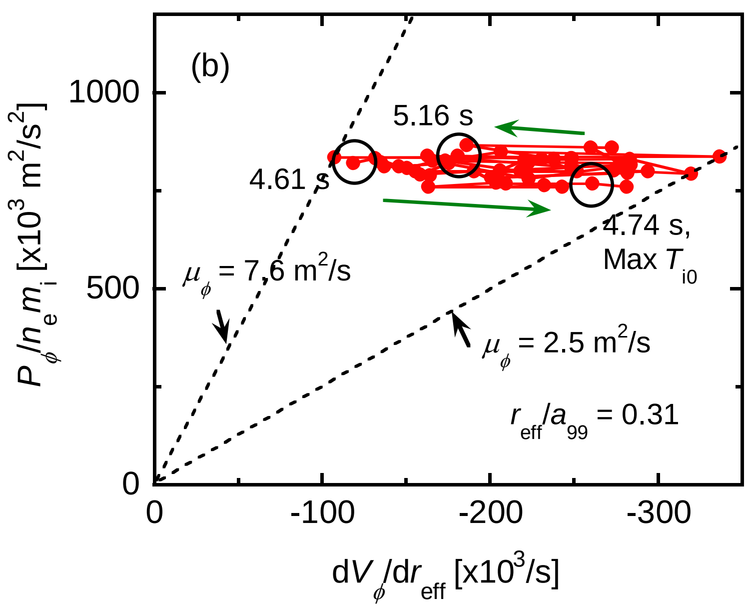
Flux-gradient relation ~Momentum transport~

The slope in the flux-gradient relation -> μ_ϕ

- (1) **Decrease of μ_ϕ**, (2) Increase of the intrinsic rotation.
- **Back to low-confinement branch**.
- $P_r = \mu_\phi / \chi_i$ kept unity.







Future Prospect and Summary

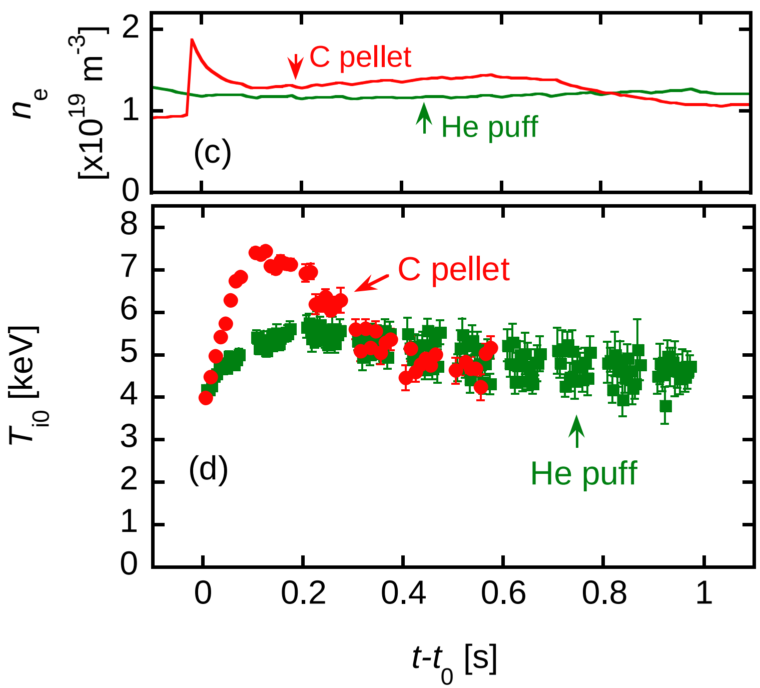
Toward quasi-steady-state operation

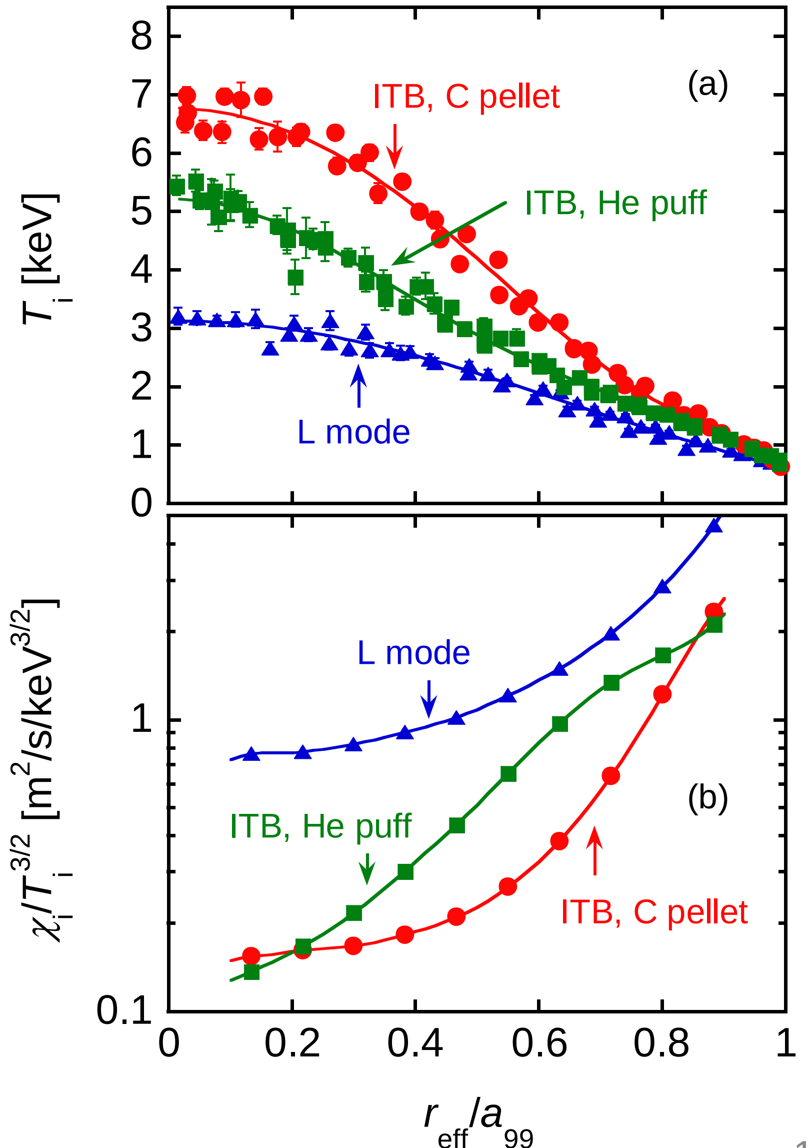
Strategy of high-T_i operation in the LHD

- Verification how high T_i is realized.
- **Long pulse operations toward a reactor.**

In the He-puffing discharge

- **Steep T_i gradient** and **reduction of χ_i**.
- T_{i0} ~5 keV/ 1 sec. was achieved.
- T_i degradation was considerably smaller.





Summary

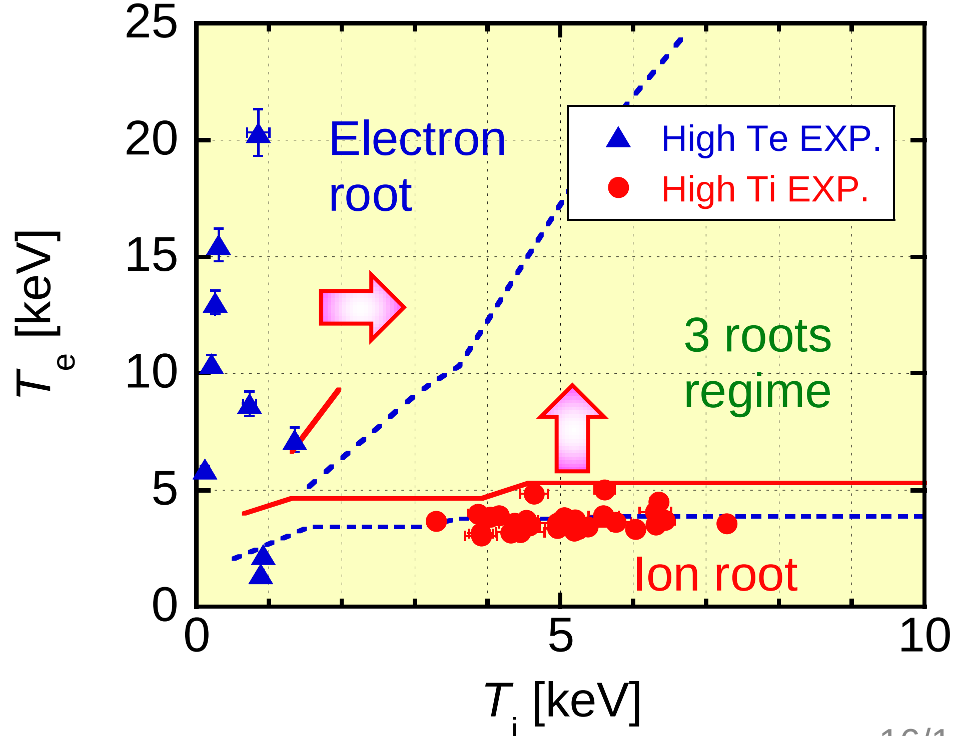
Progress of the extension of the high-temperature regime

- **High-temperature regime was successfully extended** due to the upgraded heating system and the optimization of discharge scenario.

High T_i characteristics with ion ITB

- **Centre-peaked T_i and V_ϕ, energy-confinement improvement** , **reduction of χ_i and μ_ϕ** and the **negative E_r** were observed.

- Ion thermal transport and momentum transport **moved to high confinement branch** by the ITB formation.



Future works

- Investigation of the off-diagonal-terms effects.

- Performance integration of high-T_i, high T_e and long-time sustainment.

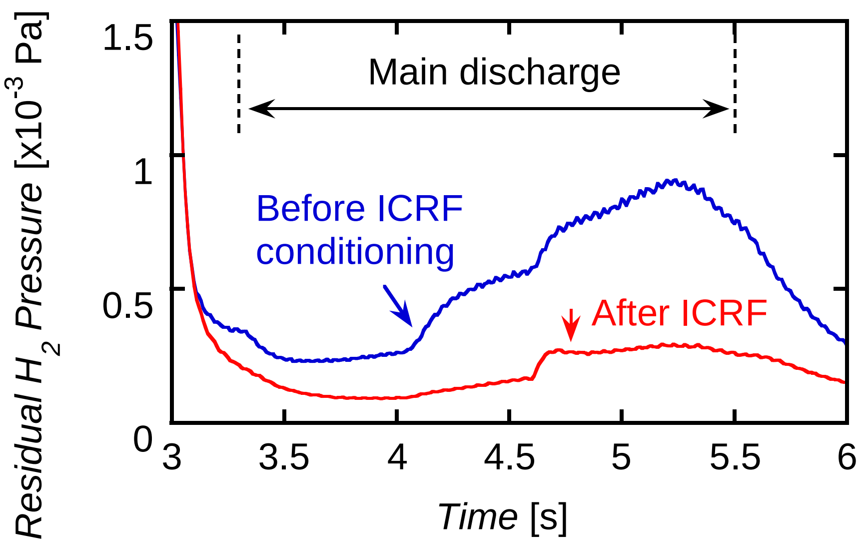
ICRF-conditioning effect on the high-T_i discharge

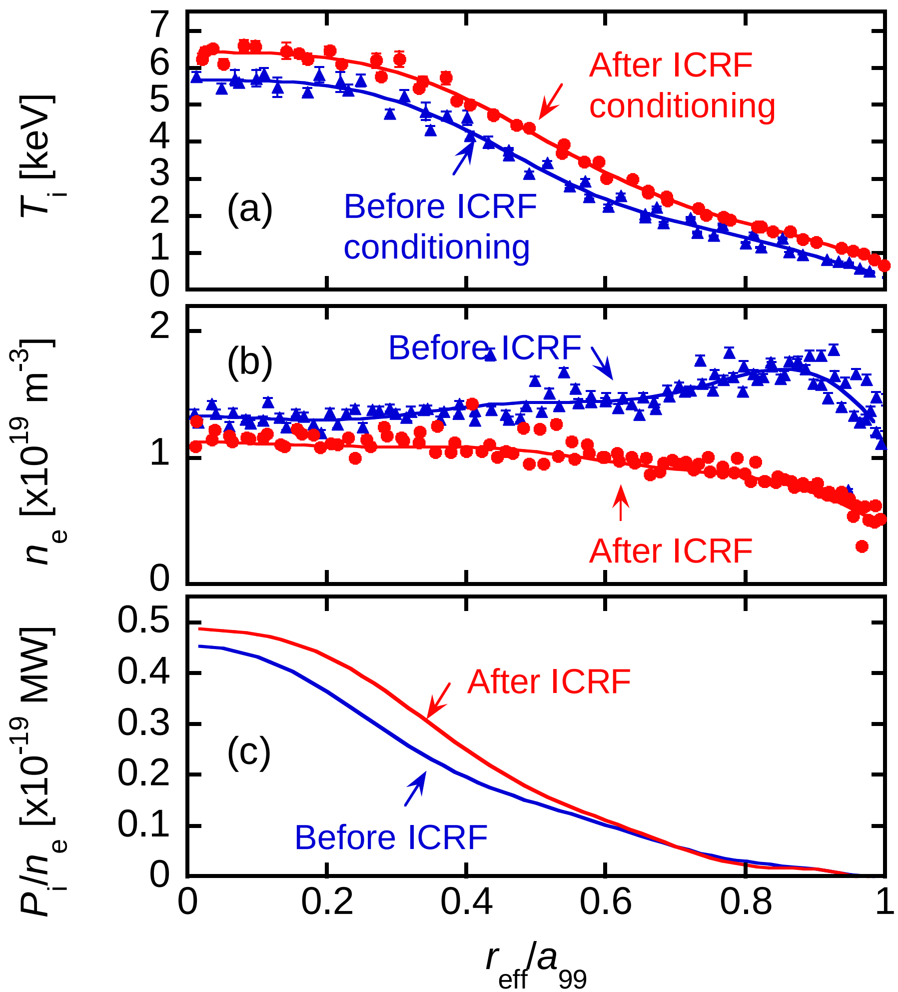
<u>**Before the ICRF conditioning,**</u>

- ➢ **T_{i0} below 6 keV,** hollow n_e profile.

<u>**After 30 discharges of ICRF conditioning,**</u>

- ➢ **Residual pressure significantly decreased,**
  - -> Decrease of neutral recycling,
  - -> Lower n_e with the parabolic profile,
  - -> P_i/n_e increased in the plasma core,
  - -> **T_{i0} exceeding 6 keV.**





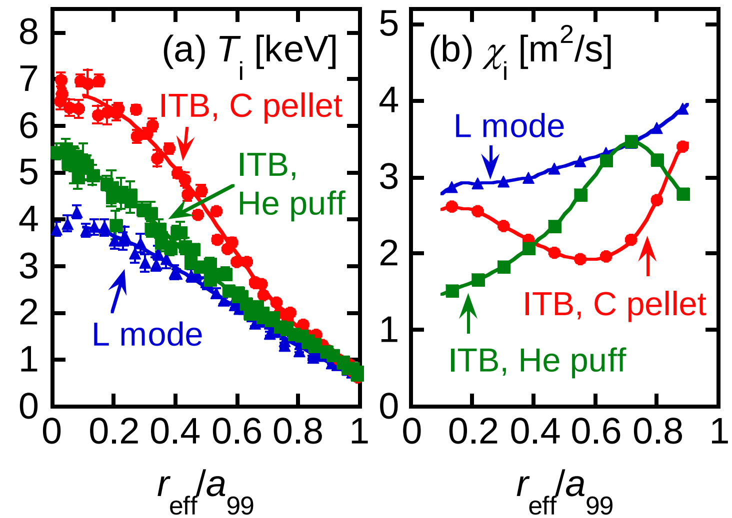
Toward quasi-steady-state operation

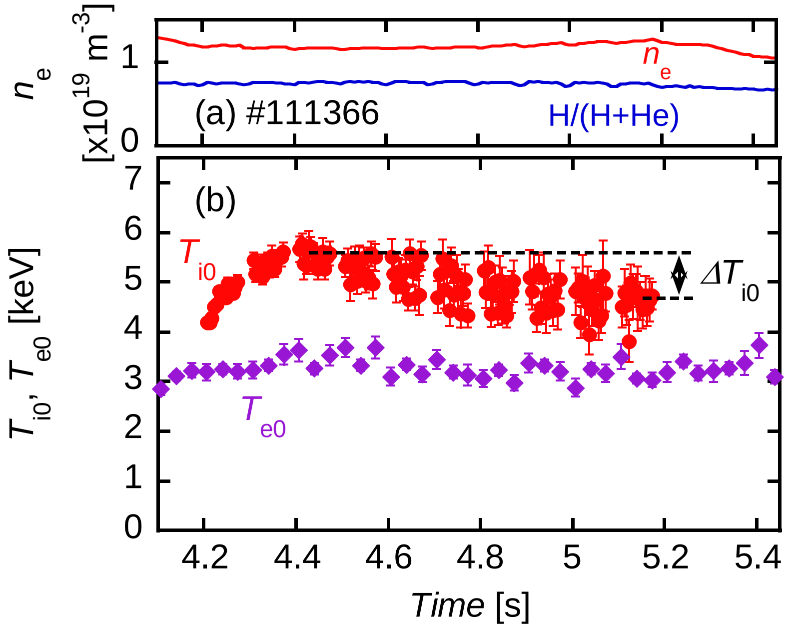
Strategy of high-T_i operation in the LHD

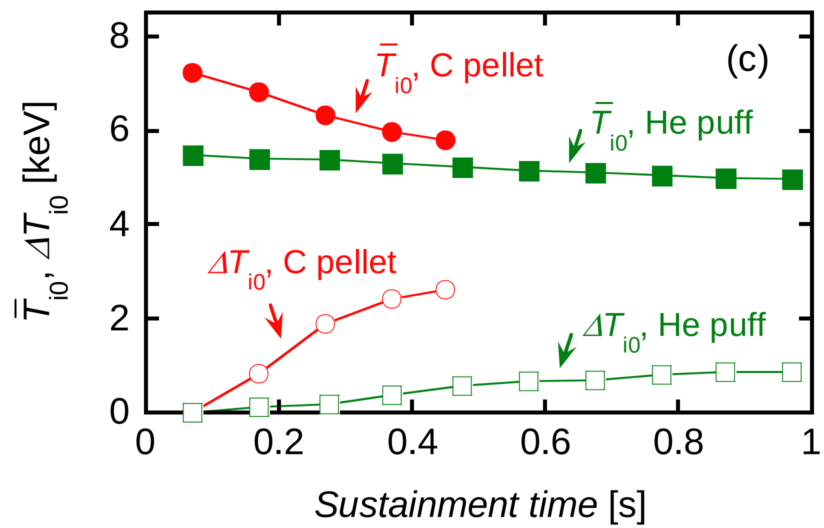
- Verification how high T_i is realized in helical system.
- **Long pulse operations toward the fusion reactor.**

In the He-puffing discharge (H/(H+He) ~0.75),

- **Steep T_i gradient** and **decrease of χ_i**.
- T_{i0} ~5 keV/ 1 sec. was achieved.
- T_i degradation was quite smaller.







Newly installed NBI and gyrotrons

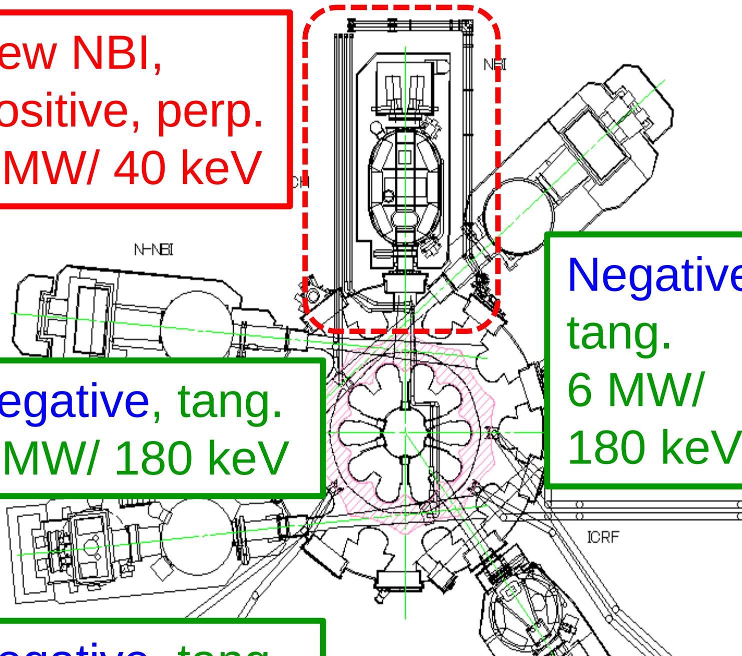
- Recent upgrade of heating system:

  Since 2007, **Gyrotron x3** (**Over 1 MW** each/ 77 GHz)

  2010, **Perpendicular NBI** (**6 MW**/ 40 keV)

- Total PT power, **NBI: 28 MW, ECRH: 3.7 MW**

New NBI,
Positive, perp.
6 MW/ 40 keV



Negative, tang.
6 MW/
180 keV

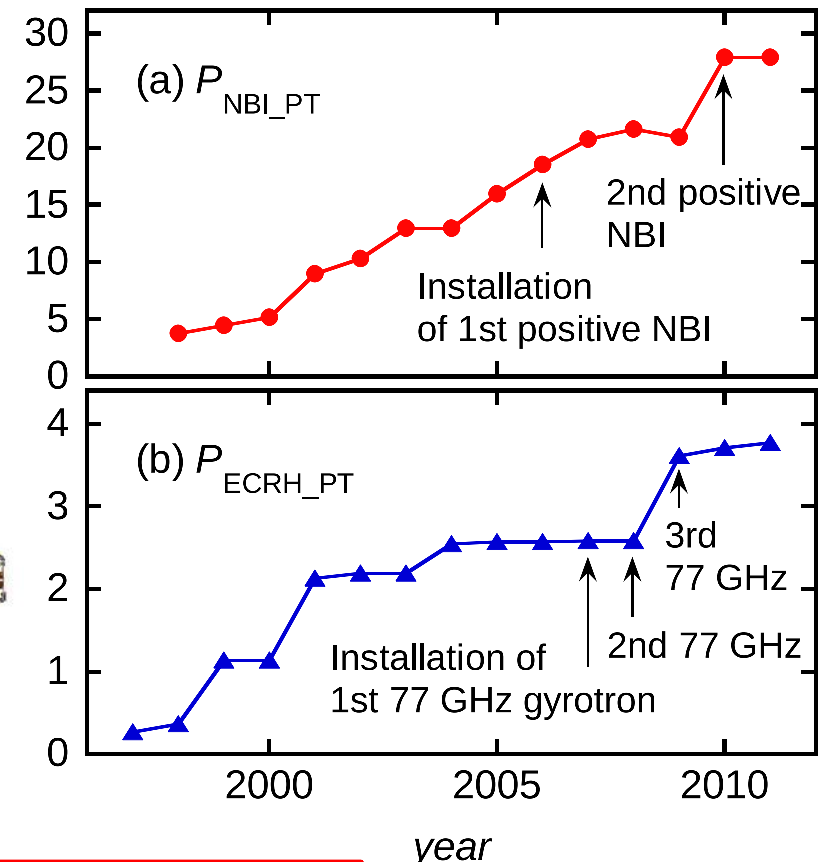
Negative, tang.
5 MW/ 180 keV

Negative, tang.
5 MW/ 180 keV

Positive, perp.
6 MW/ 40 keV

77 GHz gyrotron
Over 1 MW

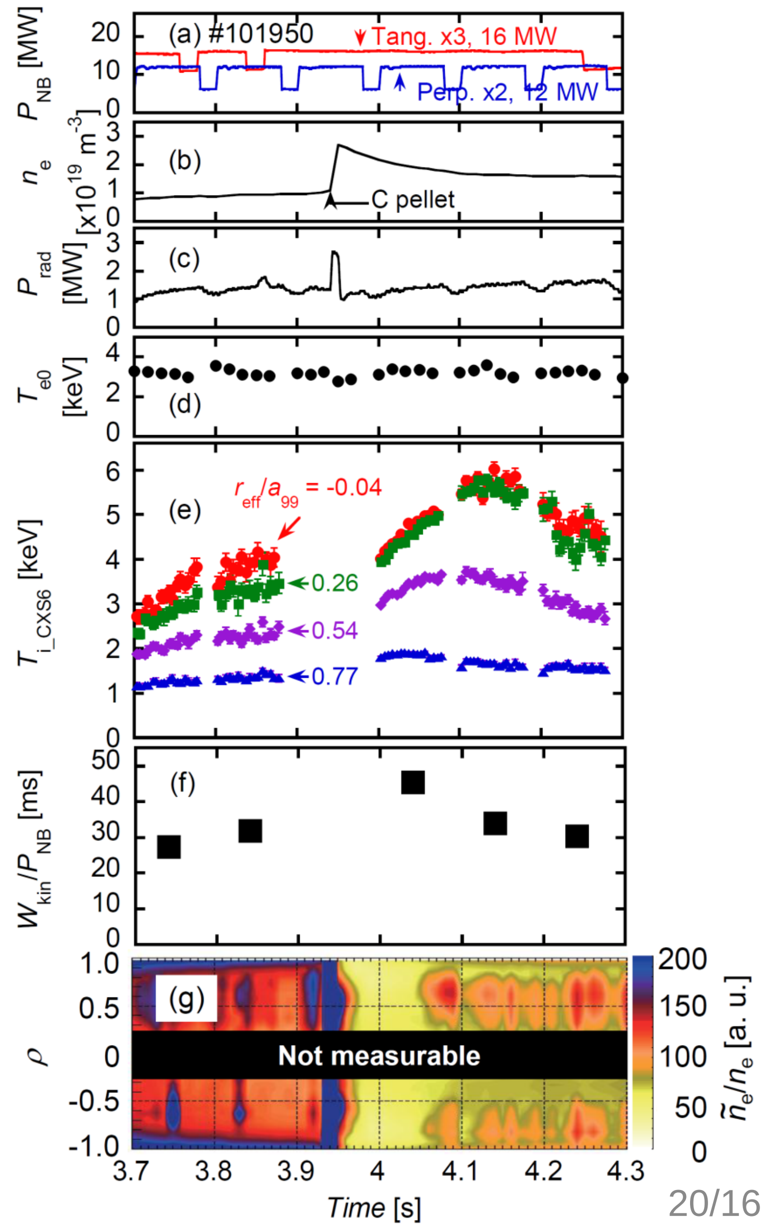
History of total injection power to LHD



Typical time evolution in a carbon pellet discharge

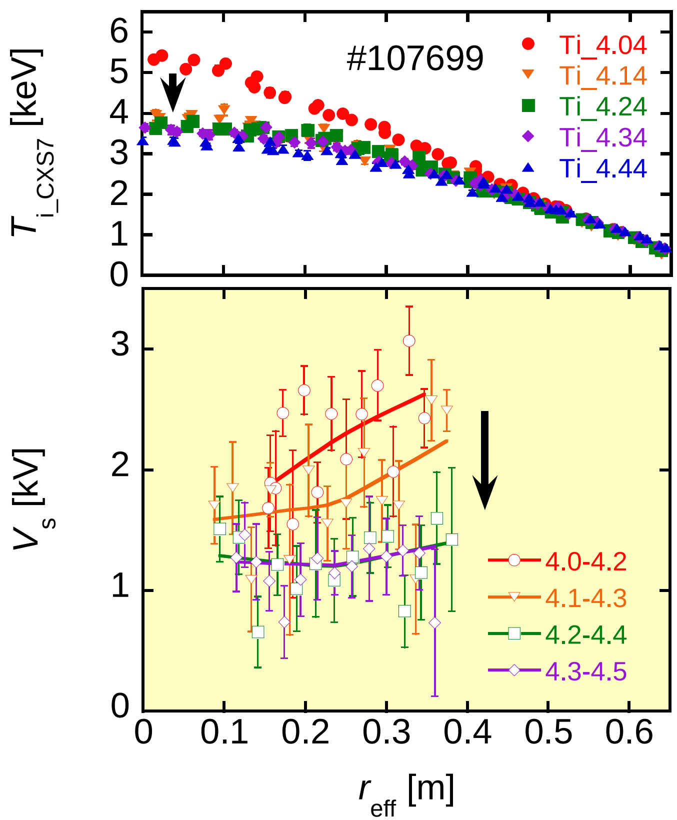
<u>In the C-pellet discharge,</u>

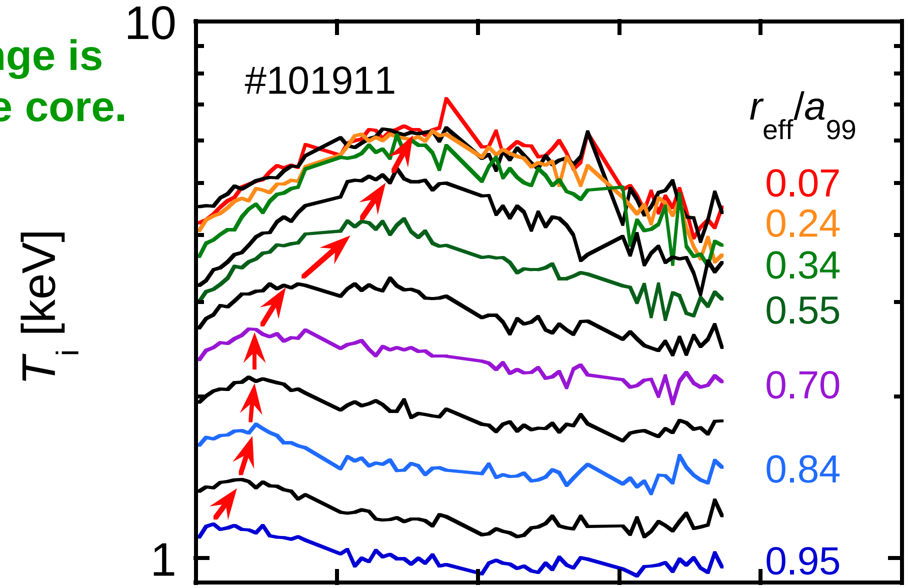
- **T_i and dT_i/dr_{eff} clearly increased in the core** -> **ion-ITB**
- T_e was not improved and T_e/T_i dropped to 0.5.
- The energy confinement improved **by a factor of 1.5**.
- **n_e fluctuation significantly suppressed**.
- **χ_i reduced in the entire region**.
- **The improved confinement was transient**.

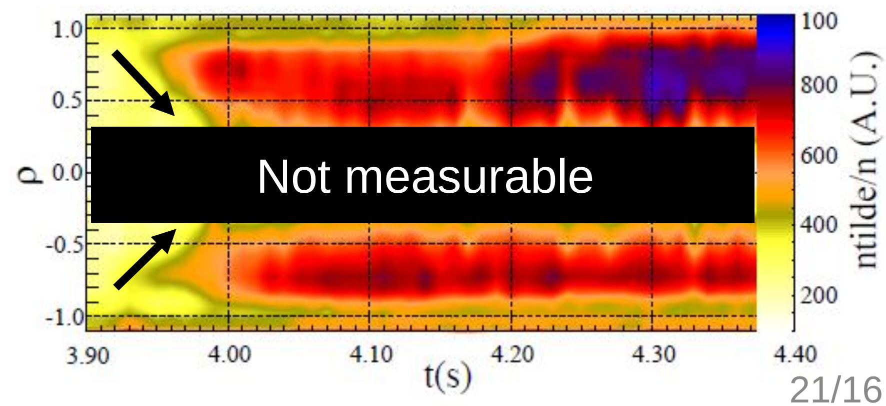


Behavior of E_r and turbulence in high-T_i plasmas

- Negative E_r was formed in the core and was gradually decreased with T_i degradation.
- **n_e fluctuation started to increase from the peripheral region to the core**.
- **T_i also decreased from the edge**.
- **The difference of the time constant of T_i change is considered to form the steep T_i gradient in the core.**





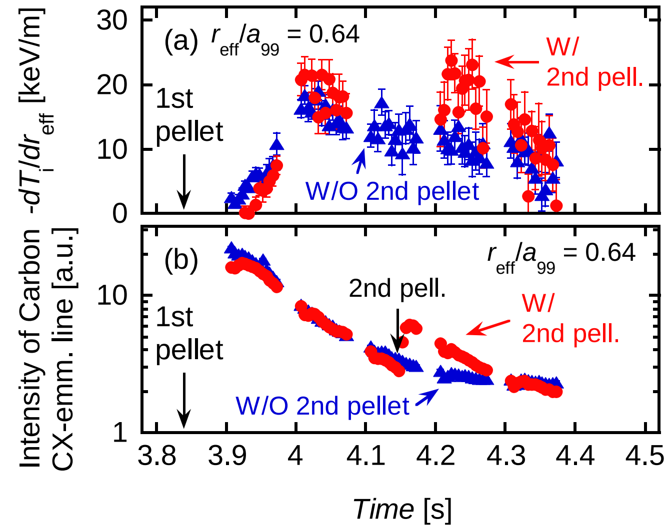


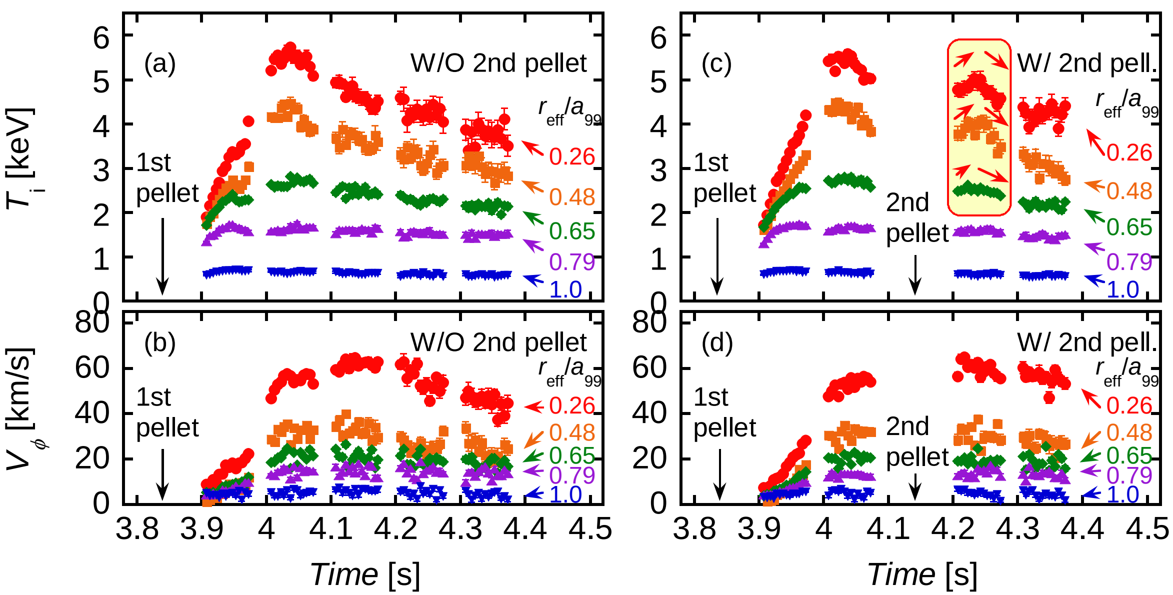
Recovery of T_i by an additional impurity pellet

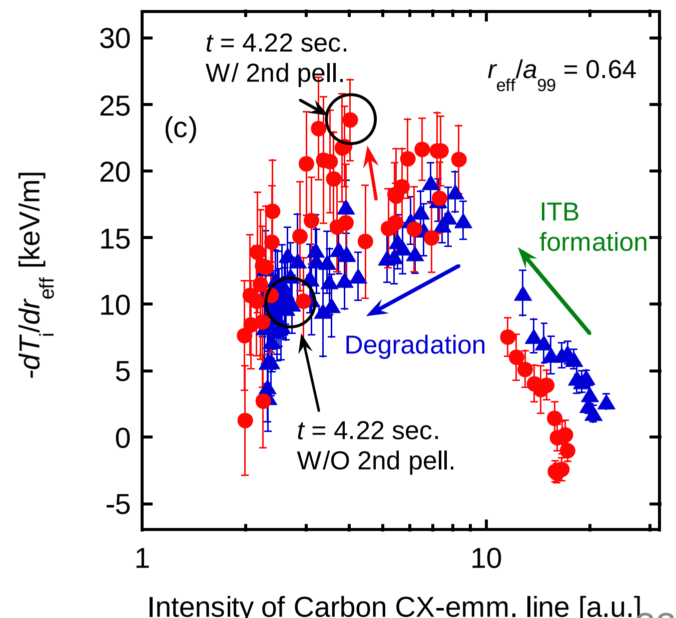
<u>Additional C pellet was injected in the T_i degradation phase</u>

- Increase of V_ϕ was not observed but the time constant of the degradation became longer.
- **Clear recovery of T_i and grad T_i.**

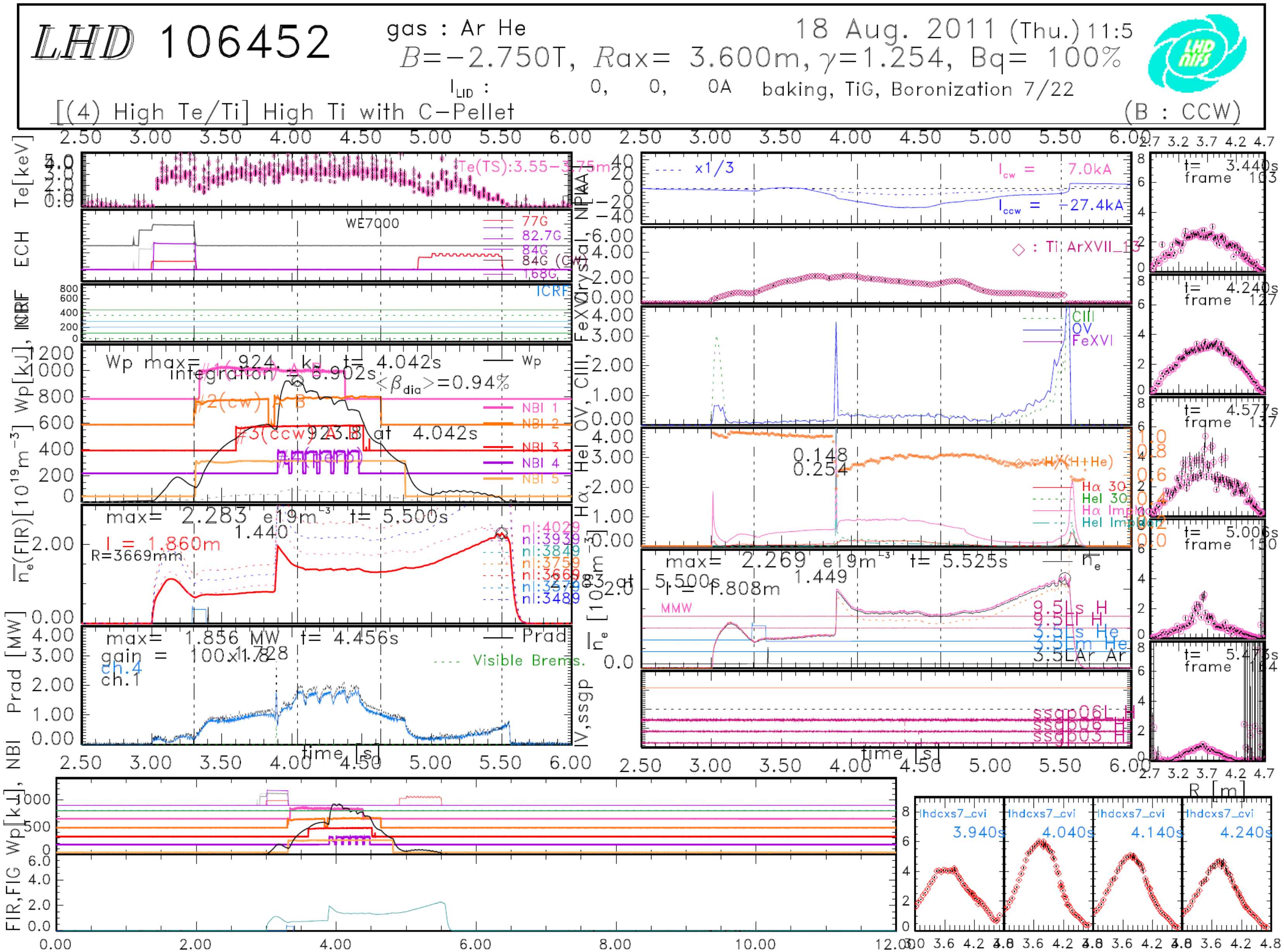
<u>**Impurity effect is one of the candidate for the confinement improvement due to the suppression of turbulence.**</u>



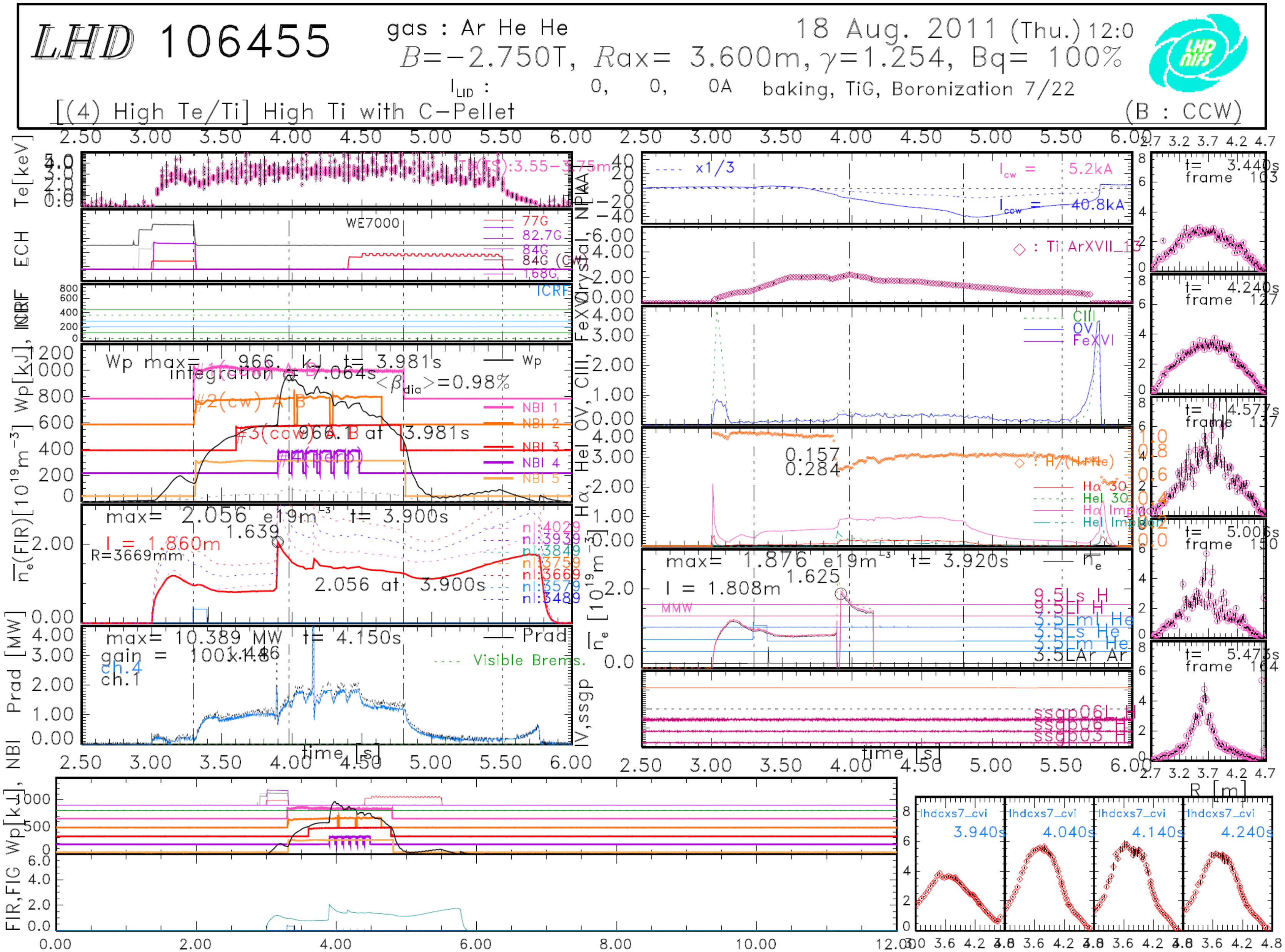




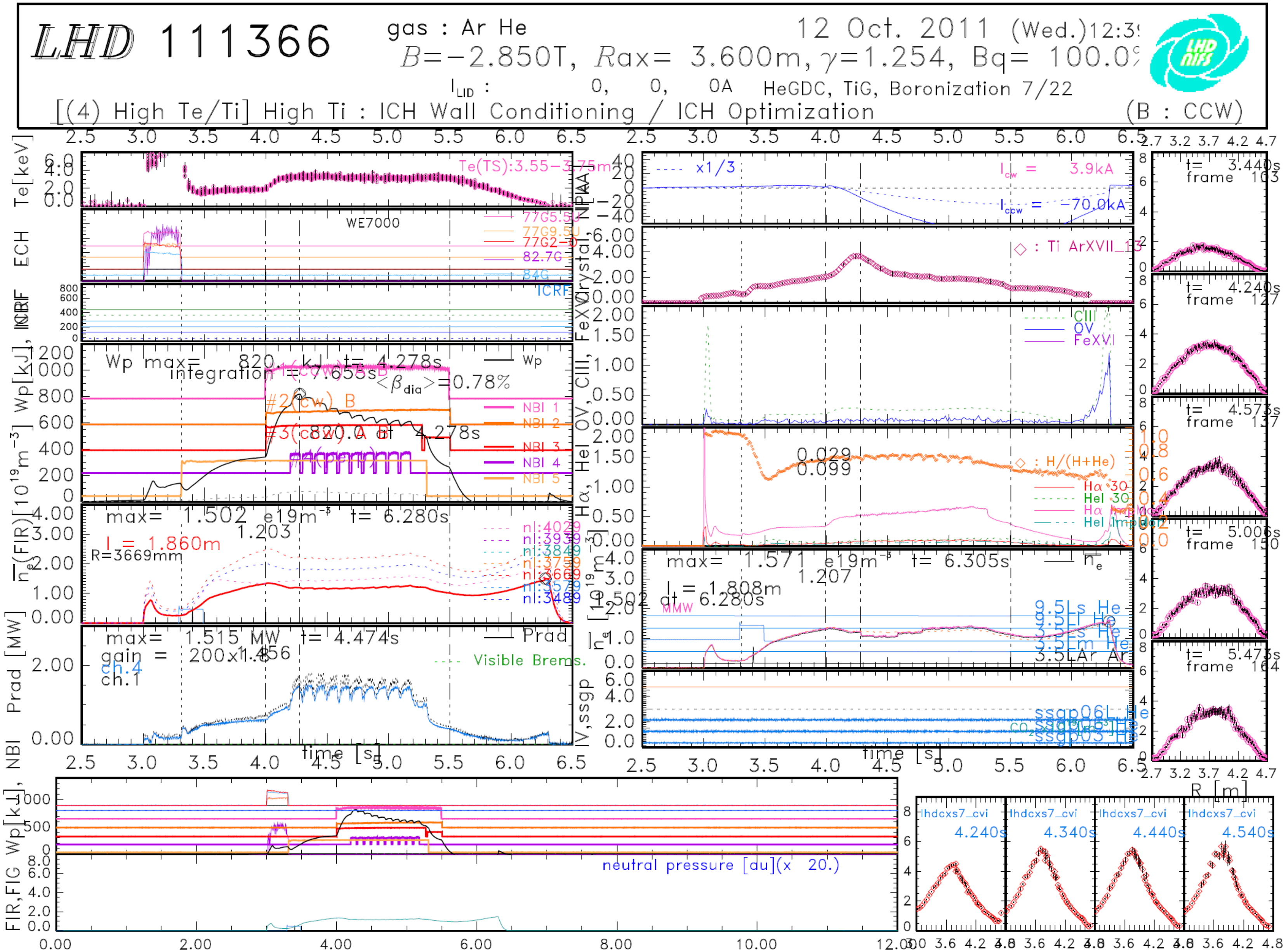
2nd pellet reference #106452



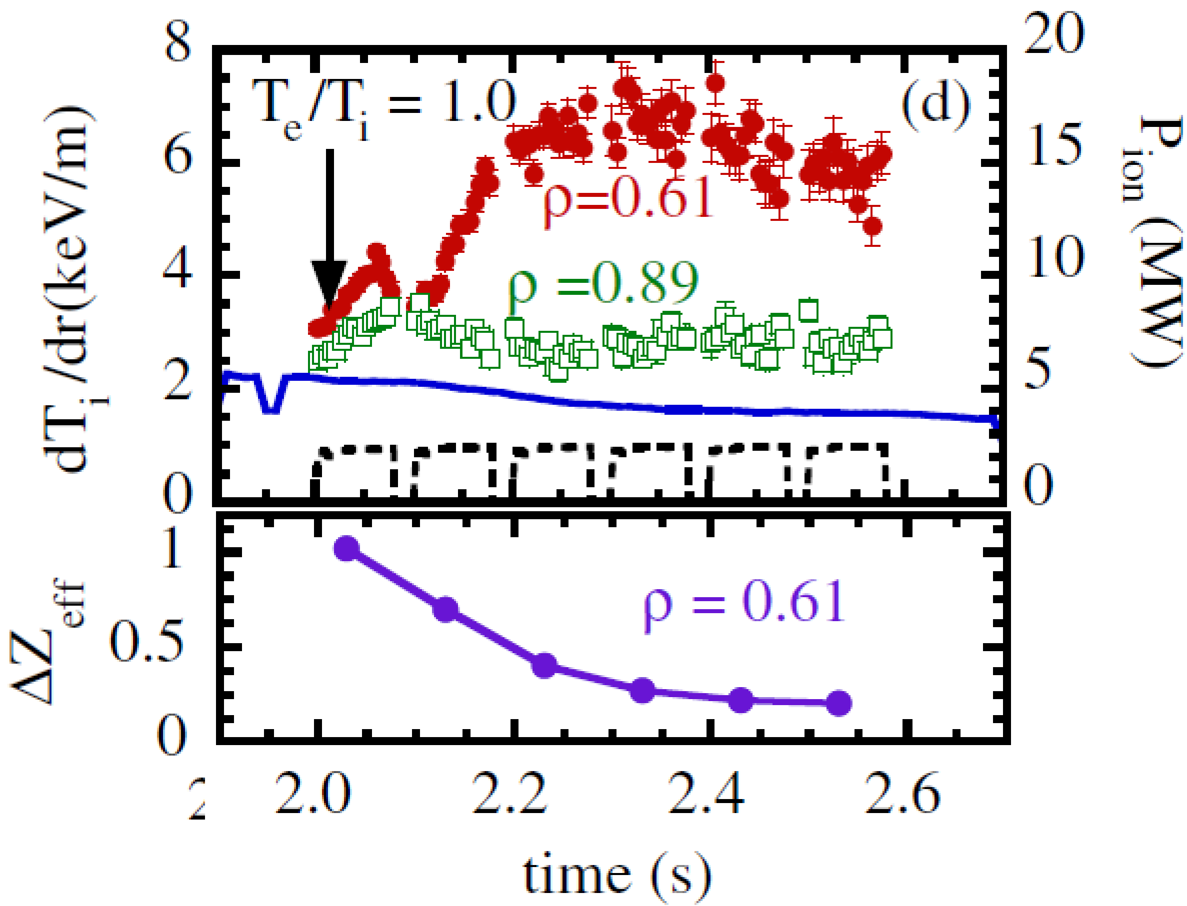
2nd pellet #106455



Quasi steady state_#111366



Temporal change of Zeff



IDA K. et al., "Dynamics of ion internal transport barrier in LHD heliotron and JT-60U tokamak plasmas", Nucl. Fusion, **49** (2009) 095024.

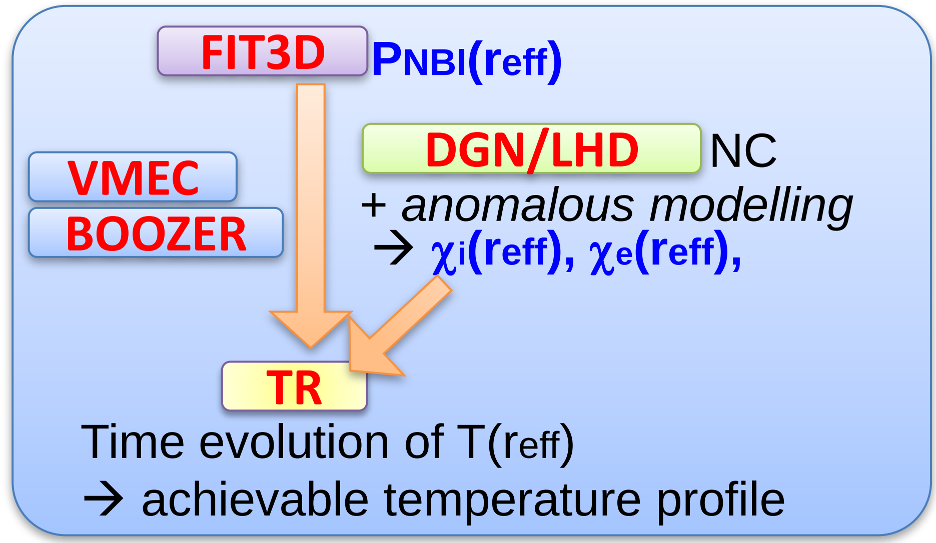
TASK3D for quasi-steady-state plasma

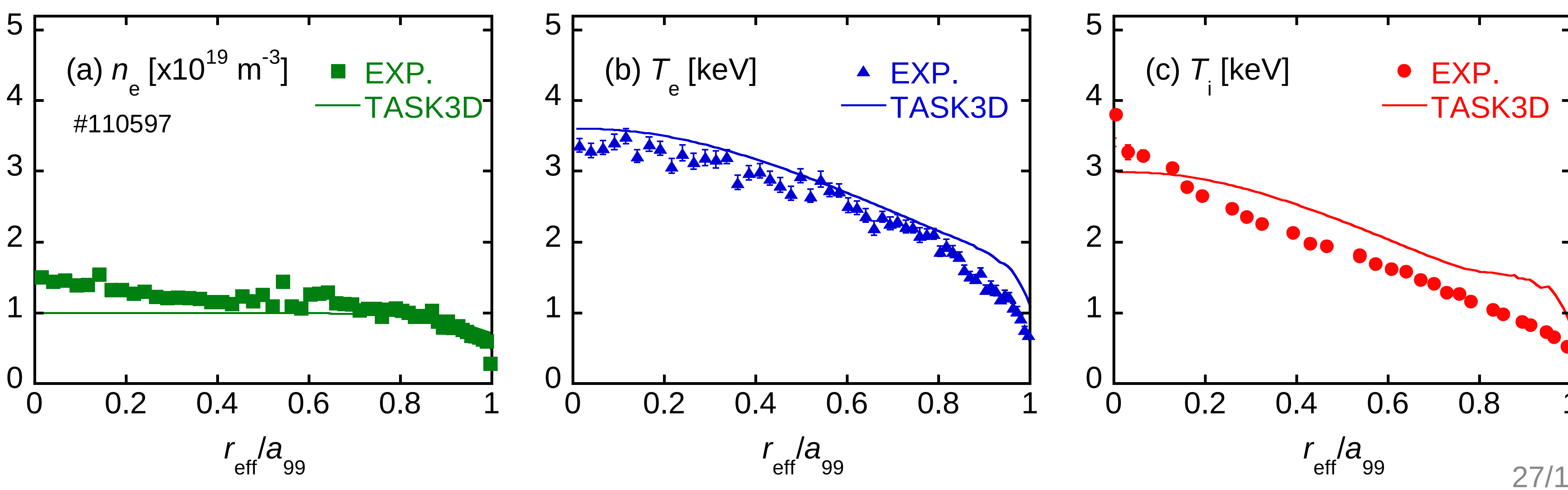
Prediction of achievable temperature

→ **survey for “anomalous” modeling**

→ **Increased accuracy of prediction**

- **TASK3D simulation qualitatively reconstructed the experimental results.**



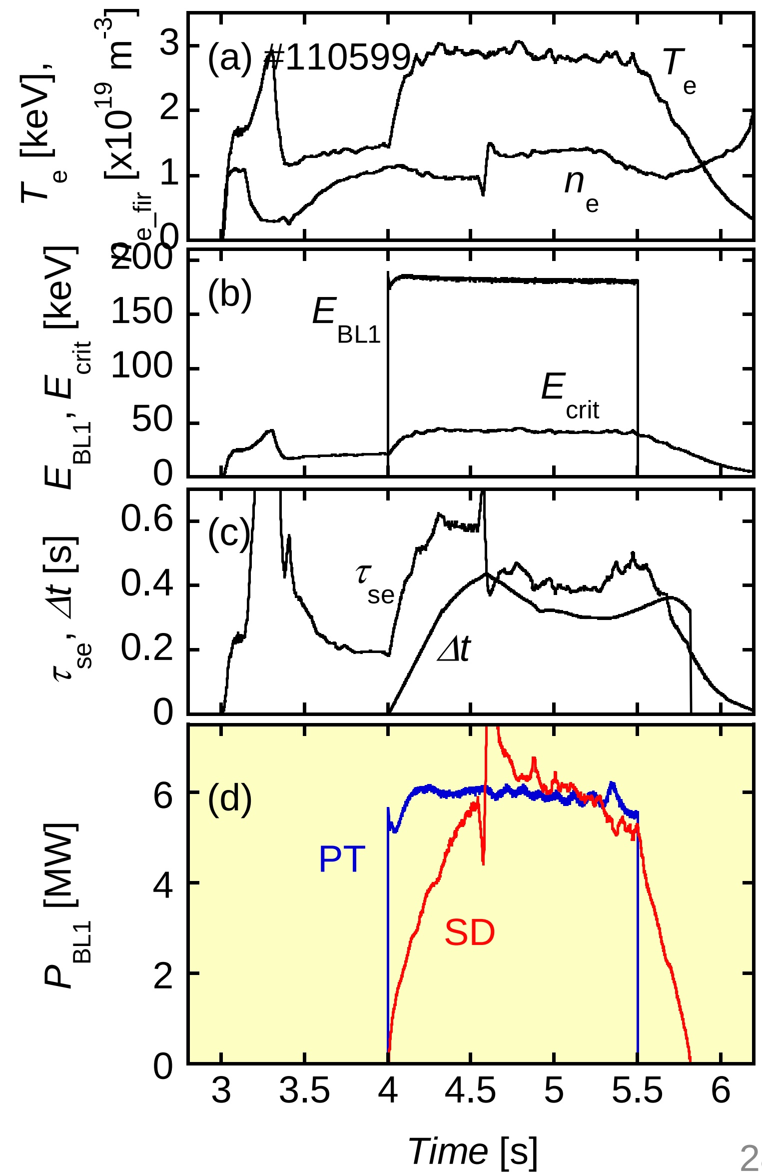


TASK3D for C-pellet discharges -> in progress

Time-transient P_{NB} was evaluated taking account of E_C and τ_{se}.

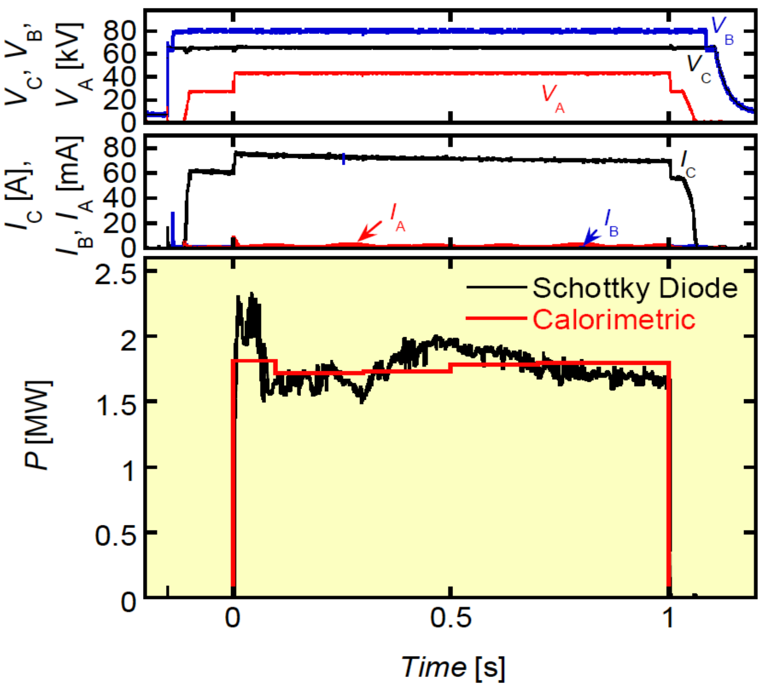
- Temporal change of the energy of the beam particle, which is produced every 0.1 ms, was calculated.
- Plasma is heated by the particles with $E > T_i$ (T_e).
- Heating contribution of the particles at $t = t_j$ was calculated and the temporal P_{NB} was evaluated from the summation of $\Delta E = E_j - E_{j+1}$.

$$E_{j+1} = \left(E_j^{3/2} \exp\left(-\frac{3\Delta t}{\tau_{se}}\right) - E_c^{3/2}\left(1 - \exp\left(-\frac{3\Delta t}{\tau_{se}}\right)\right)\right)^{2/3}$$

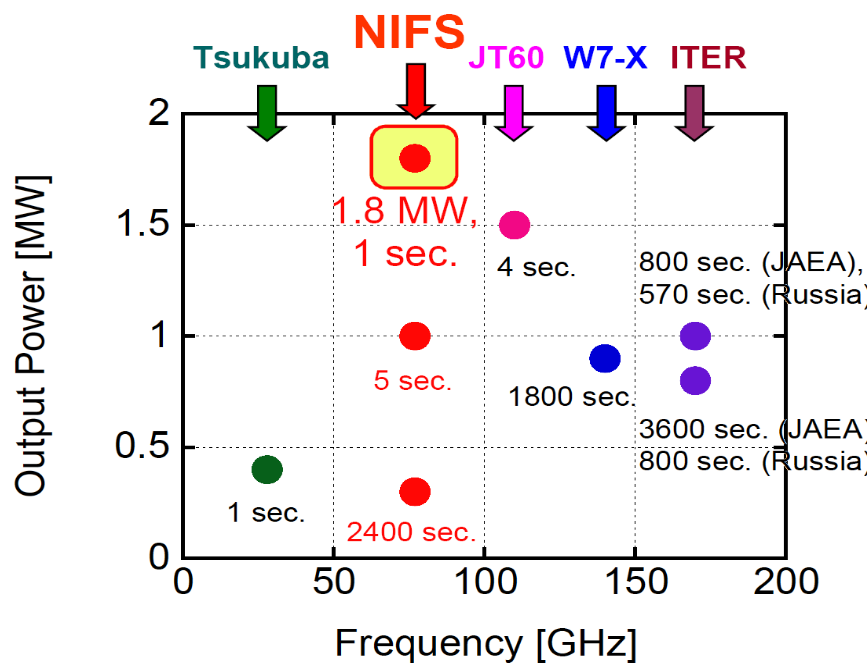


High-power gyrotron has been successfully developed

- **Output power of 1.8 MW was obtained for one second** in a 77 GHz-gyrotron, which was developed in collaboration with University of Tsukuba.



Stationary operation for 1 sec



World's highest output power (>1sec) was achieved.

77 GHz-Gyrotron