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Improved Performance of ECRH by Real-Time Deposition Location Control and Perpendicular Injection in LHD

Toru Tsujimura[1]

R. Yanai[1], K. Tanaka[1], Y. Yoshimura[1], T. Tokuzawa[1,2], M. Nishiura[1], R. Sakamoto[1,2], G. Motojima[1,2], S. Kubo[1], T. Shimozuma[1], H. Igami[1], H. Takahashi[1,2], M. Yoshinuma[1], S. Ohshima[3], LHD Experiment Group[1]

[1]National Institute for Fusion Science, [2]The Graduate University for Advanced Studies, [3]Kyoto University

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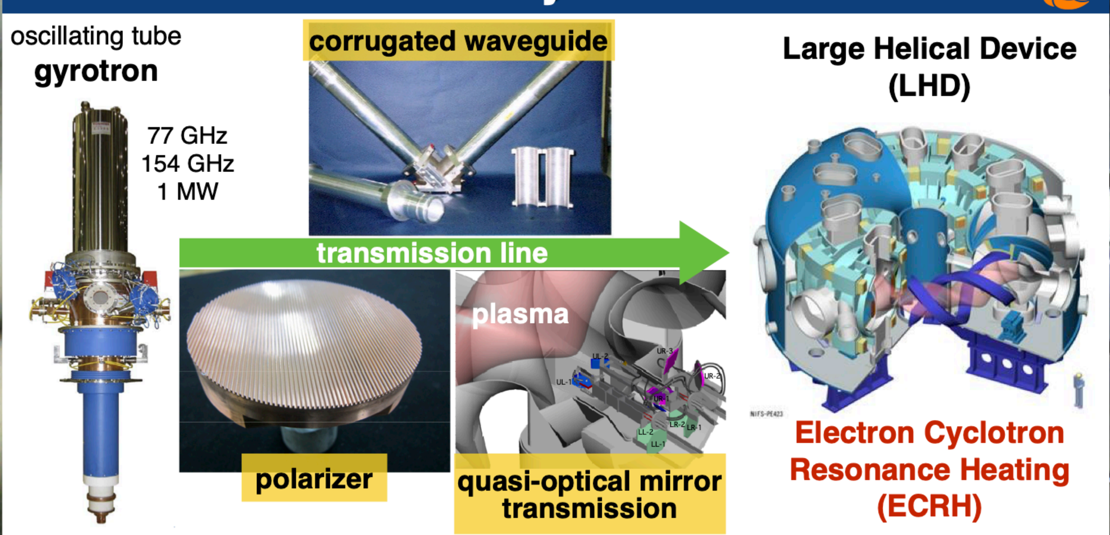
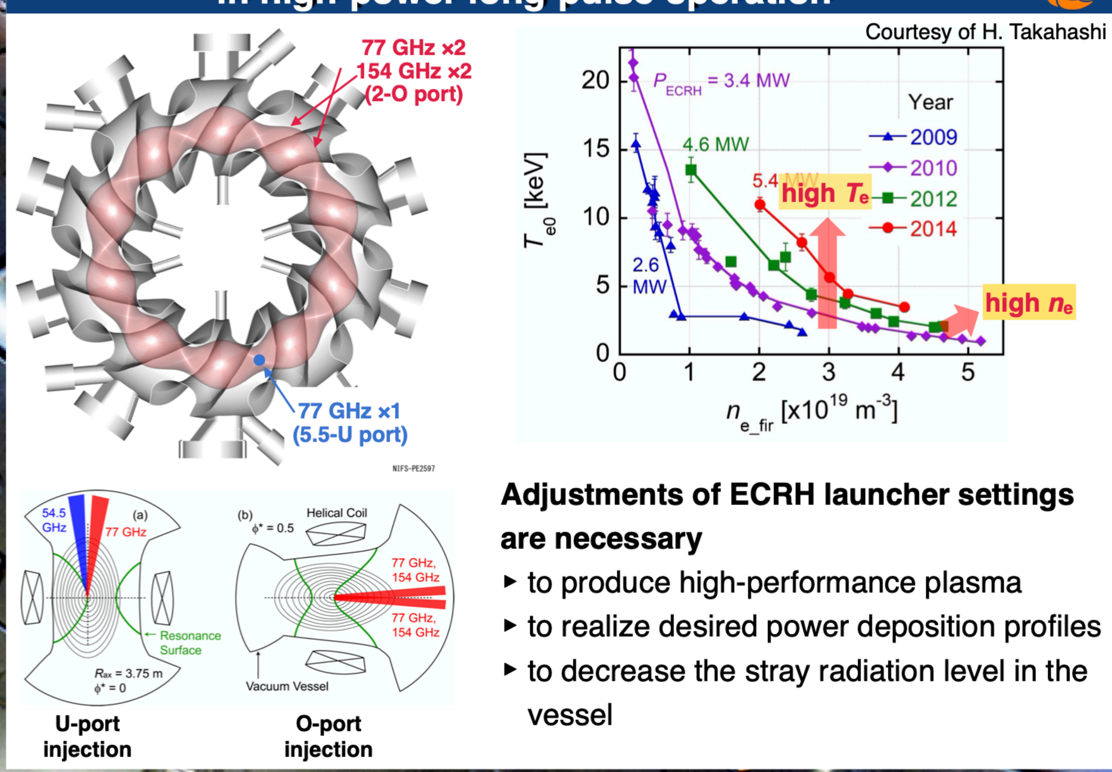
ECRH system



- Inject mm wave to heat plasma electrons through cyclotron resonance
- Produce high-temperature plasma almost without plasma currents
- Local heating to control pressure profiles and current density profiles
- Contribute to transport physics
- Candidate of external heating sources for reactors, but dependent on developments of gyrotrons

Maximizing single-pass absorption is important in high-power long-pulse operation

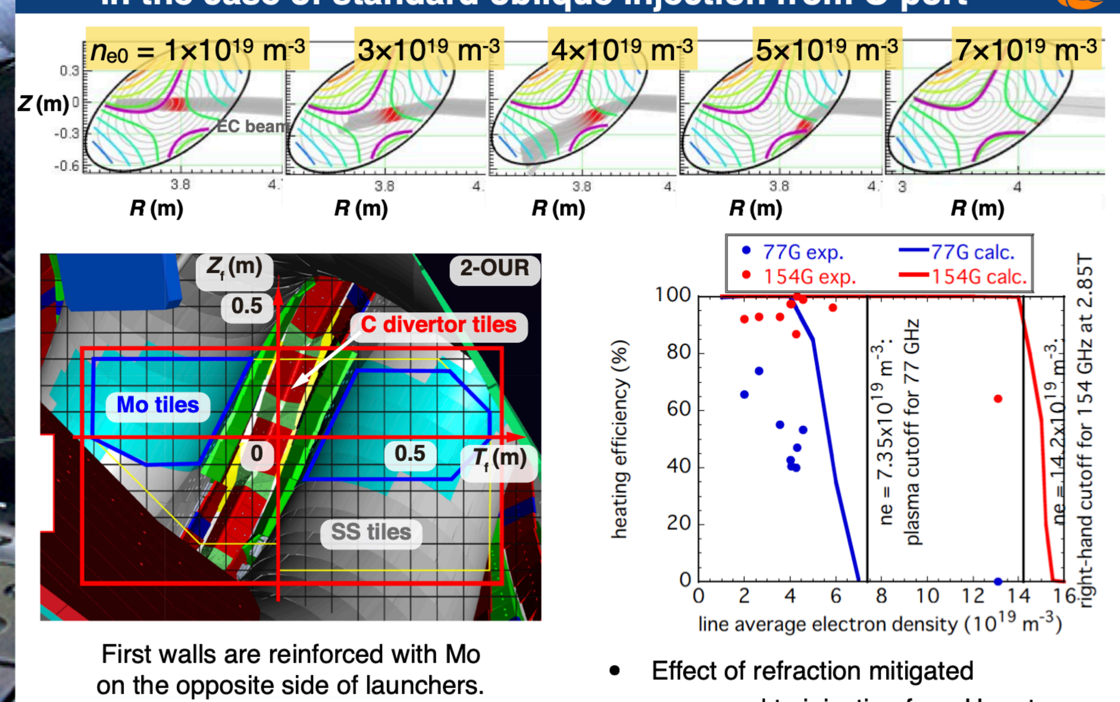


Courtesy of H. Takahashi

Adjustments of ECRH launcher settings are necessary

- to produce high-performance plasma
- to realize desired power deposition profiles
- to decrease the stray radiation level in the vessel

Heating efficiency decreases as density increases in the case of standard oblique injection from O port



First walls are reinforced with Mo on the opposite side of launchers.

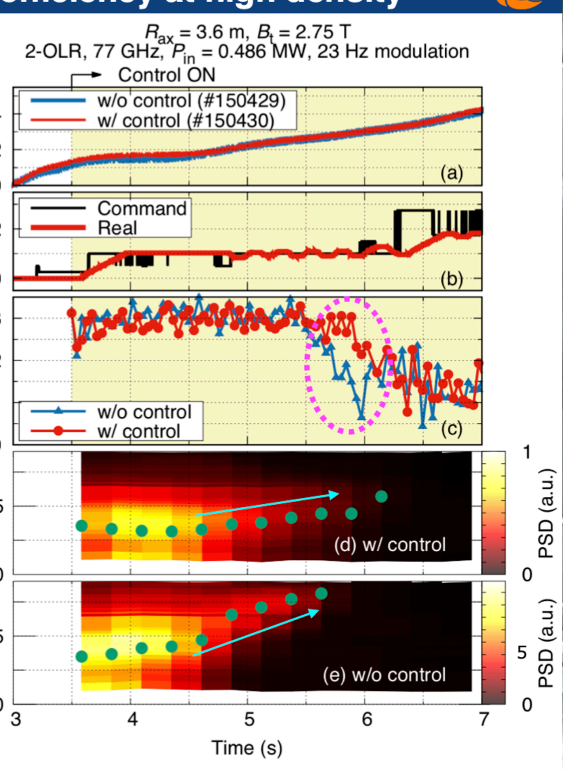
Courtesy of Y. Yoshimura

- Effect of refraction mitigated compared to injection from U port
- Contribution to ECCD experiments

Real-time control of the deposition location of ECRH functioned properly to improve heating efficiency at high density

- Needs of transport studies for isotope effects of high-n_e ECRH plasma
- 77 GHz rarely used for transport studies at high n_e compared to 154 GHz
- Standard obl. injection from 2-O
  - sensitive to the effect of refraction
  - higher absorption successfully maintained longer due to the real-time deposition location control up to 3×10^{19} m^{-3} *
  - deposition location kept in the plasma core region
  - dominant multi-pass absorption above 3×10^{19} m^{-3}

➡ Leading to the necessity of perpendicular injection in the LHD



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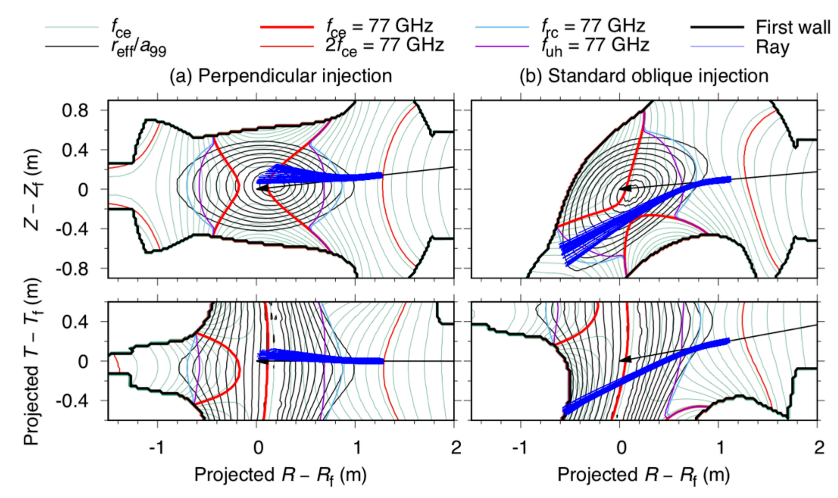
Perp. injection can be an efficient heating method



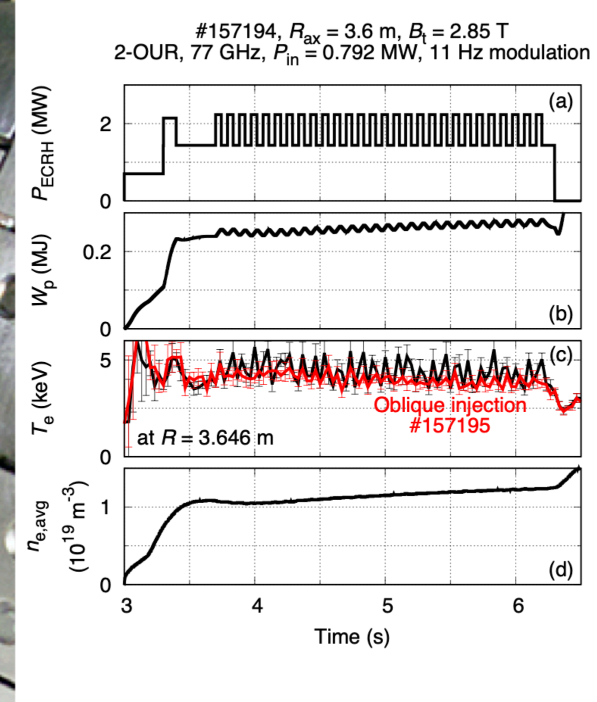
$n_{e,max} = 3\times10^{19}$ m^{-3}

Ray-tracing calculations by LHDGauss code*

*T. Ii Tsujimura *et al.*, NF **55** (2015) 123019

- Standard obl. injection is sensitive to refraction by high-n_e plasma.
- Perp. injection is more insensitive to the effect of refraction to be verified with experiments
  - Unabsorbed transmitted waves to divertor regions are expected to be minute in principle.
  - Similar heating method in tokamaks and W7-X, or FFHR-c1
  - Available only in the increased B field with sub-cooled helical coils

O1-mode ECRH perp. injected from 2-O port



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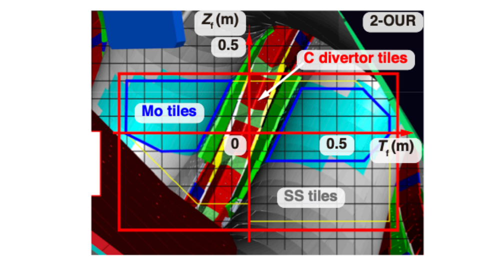
- Plasma was sustained with 154 GHz gyrotrons.
- The interlock for power injection only to plasma sustained by other ECRH functioned correctly to make no unfavorable sparks from the divertor tiles in $n_e > 0.5\times10^{19}$ m^{-3}.
- Higher modulated T_{e0} was observed.



The real-time interlock system was developed with FPGA in a CompactRIO controller.

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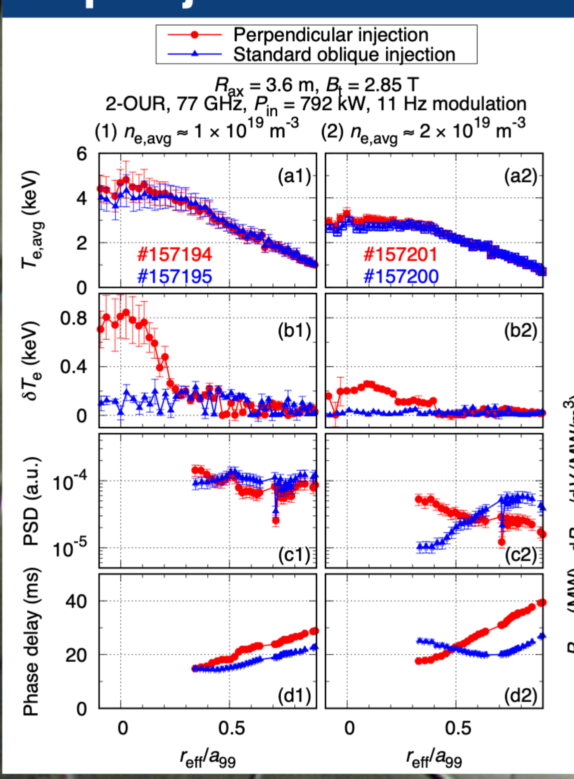
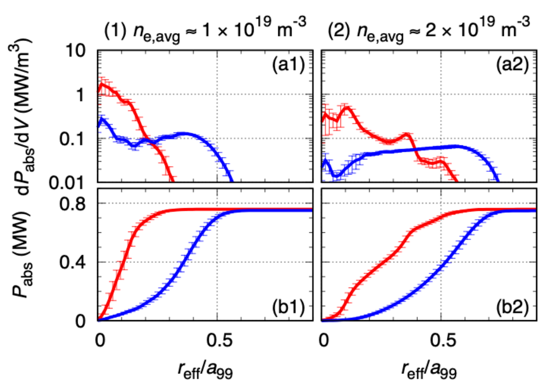
Perp. injection showed better central heating



- Refraction and Doppler-shifted absorption in oblique propagation cause broadened deposition.
- Analysis of modulation ECE showed the deposition shifted outward to $r_{eff}/a_{99} \sim 0.7$ in the case of 2×10^{19} m^{-3} and obl. injection.
- Calculation of deposition profiles by the LHDGauss code shows better central heating in the case of perp. injection.



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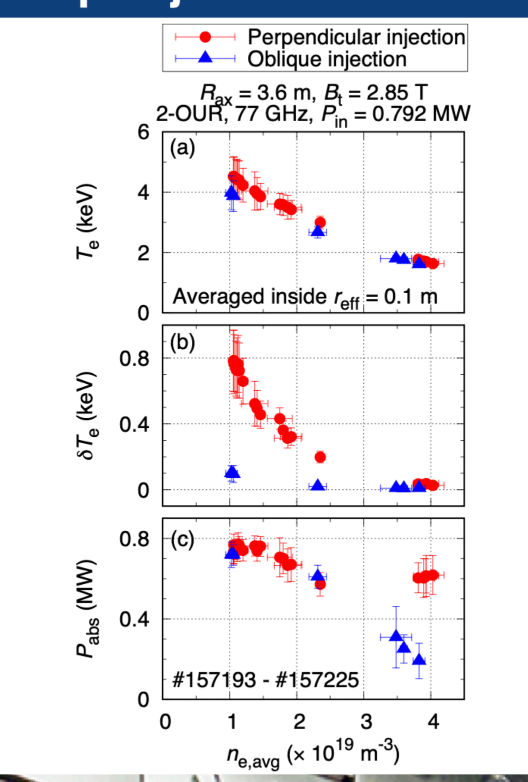
Perp. injection showed better heating efficiency



Absorbed power is higher by perp. injection for $n_e > 3\times10^{19}$ m^{-3}.

➡ Contribute to transport studies in $n_e < 5\times10^{19}$ m^{-3} by gas puffing

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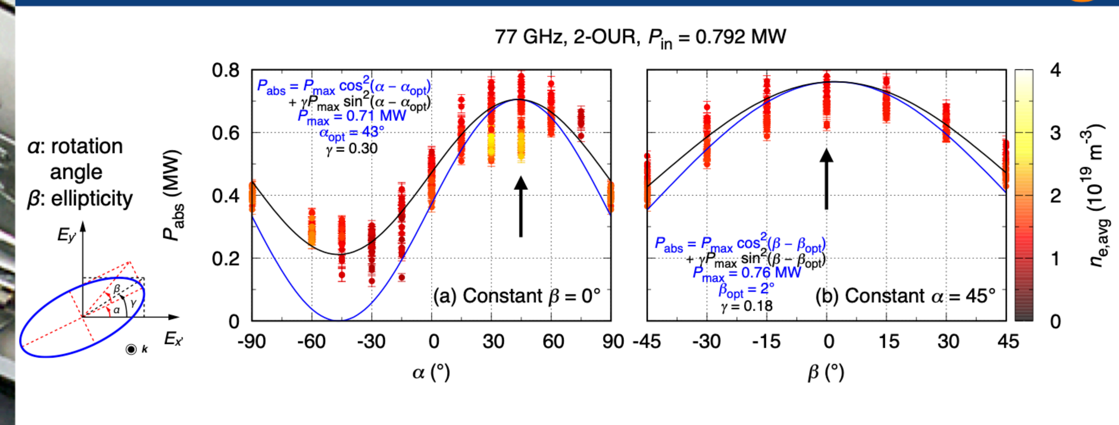
Polarization optimized for perp. injection



- Incident mm wave couples to EC waves with O and X modes under their orthogonality
- Mode purity: $\eta_\sigma = \cos^2(\alpha-\alpha_\sigma)\cos^2(\beta-\beta_\sigma)+\sin^2(\alpha-\alpha_\sigma)\sin^2(\beta+\beta_\sigma), \quad \sigma = \mathrm{O, X}$
- Linear polarization of $(\alpha, \beta) \sim (45°, 0°)$ was optimum to excite the pure O mode in low density plasma of $\sim1.5\times10^{19}$ m^{-3}, as expected from mode content analysis using the LHDGauss code.

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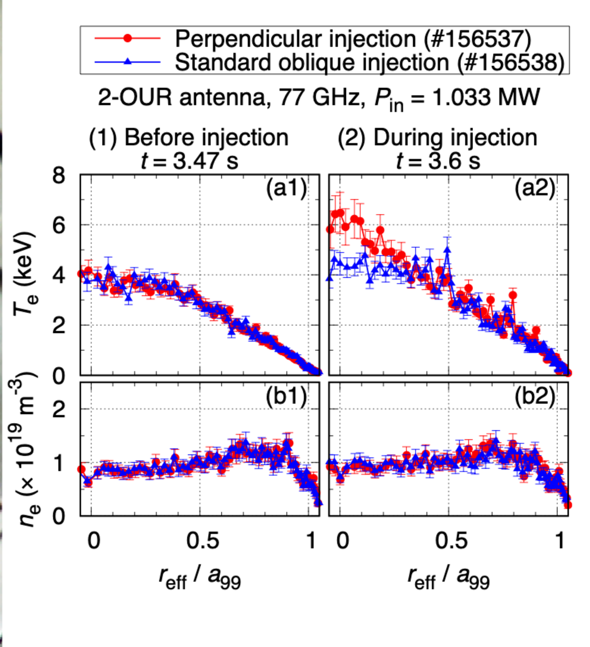
Higher T_{e0} achieved by perp. injection



- 1 MW injection without modulation
- Plasma sustained by other two 154 GHz gyrotrons with 1 MW each
- T_{e0} increased from 4 keV to 6 keV by perp. injection
- Approx. 2 keV increment compared to oblique injection

➡ Contribute to extending high T regime

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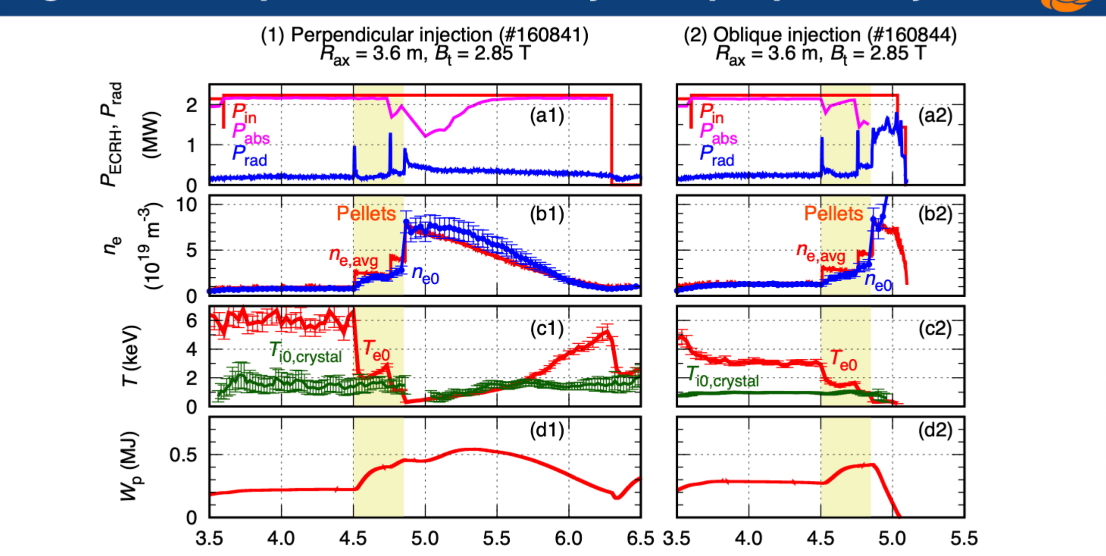
High n_e ECRH plasma obtained by multiple pellet injection



- ECRH plasma with $n_{e0} \sim 8\times10^{19}$ m^{-3} was successfully sustained after injection of three consecutive hydrogen pellets for the first time in LHD.
- Hollow n_e profiles by gas puffing changed to rather peaked ones.
- Equipartition heating is significant in high n_e regime: $T_{i0} \sim T_{e0} \sim 1$ keV
- Contribute to comparative studies in transport between W7-X and LHD and to helical reactor designs

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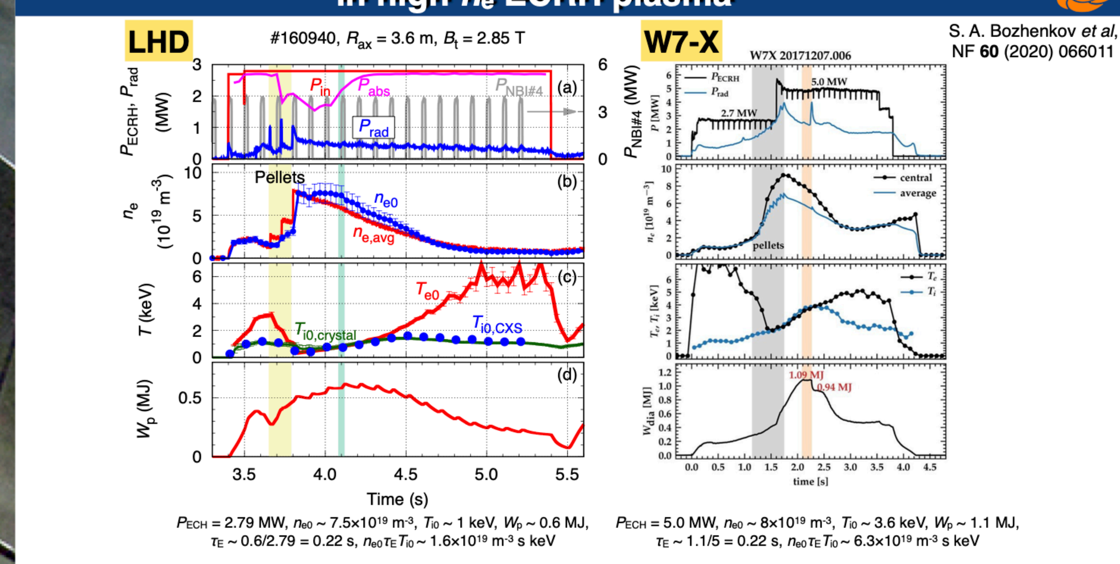
Promotion of comparative studies between devices in high n_e ECRH plasma



High n_e ECRH plasma with $T_{e0} = T_{i0}$ was compared with W7-X high n_e plasma as a reference:

- ~half heating power, ~same density, ~1/3 ion temperature, ~half plasma stored energy
- ~same energy confinement time
- ~1/4 triple product

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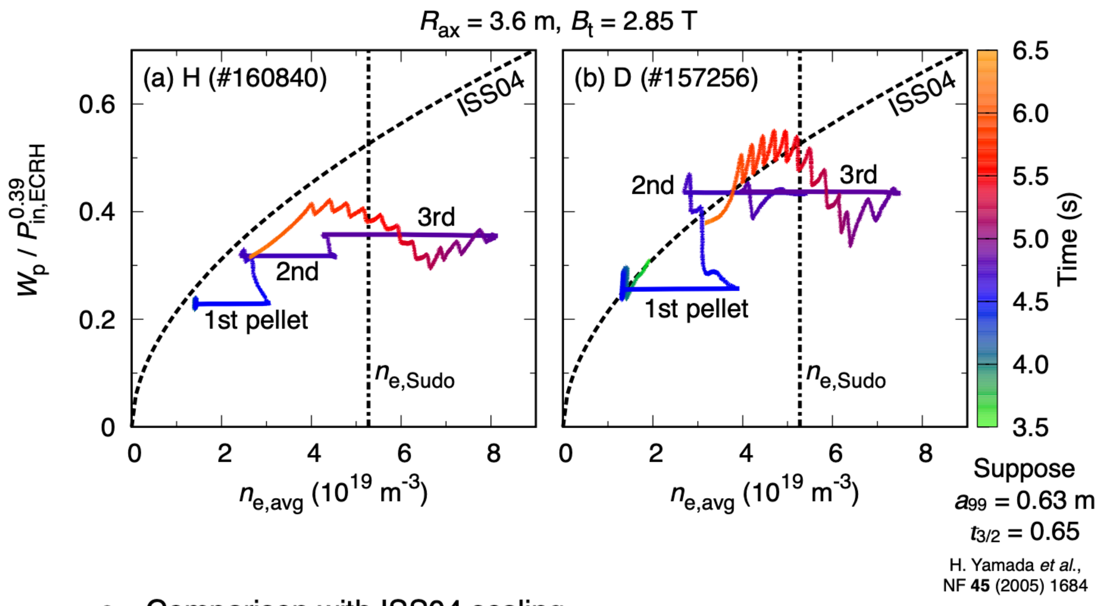
Promotion of isotope effect studies in high-n_e ECRH plasma



Suppose $a_{99} = 0.63$ m, $\iota_{2/3} = 0.65$

H. Yamada *et al.*, NF **45** (2005) 1684

- Comparison with ISS04 scaling
- Discharges over the density limit transiently after pellet injection
- Experiment data in high n_e ECRH plasma will be expanded.

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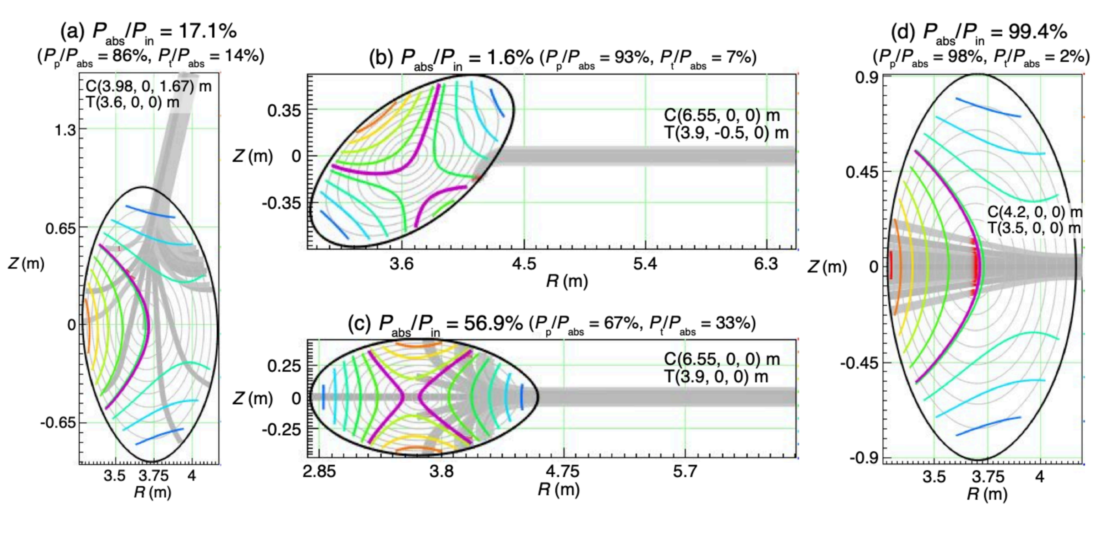
Future plan: proposal of O-mode perpendicular injection on the vertically-elongated cross section



- Comparison of ray-tracing calculations at $n_{e0} = 7\times10^{19}$ m^{-3}
- New perp. injection heating on the vertically elongated cross section can be available up to plasma cutoff density of 7.4×10^{19} m^{-3}.
- Peripheral heating of obliquely-injected X-mode can be available up to left-hand cutoff density.

Summary

- A method of perp. injection was developed in order for the EC wave to be more insensitive to the effect of refraction in LHD.
- The achieved T_{e0} in the case of perp. injection was about 2 keV higher than that in the case of oblique injection for $n_{e0} \sim 1\times10^{19}$ m^{-3} by 1 MW injection.
- With such improved performance of ECRH, high density ECRH plasma of $n_{e0} \sim 8\times10^{19}$ m^{-3} was successfully sustained after multiple hydrogen pellet injection.
- This method as well as the real-time deposition location control for efficient first-pass absorption in the plasma core region are beneficial not only for preventing damages of in-vessel components during long-pulse operations but also for extending high T operational regimes and precise transport studies.
- Further improvement of ECRH performance up to plasma cutoff n_e is envisaged by perpendicular injection on the vertically-elongated cross section.

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