Recent Results of High temperature mode, EC/ICRF heating and Steady state operation in LHD

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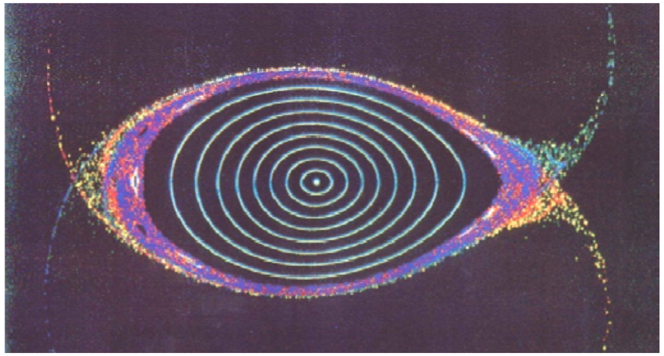
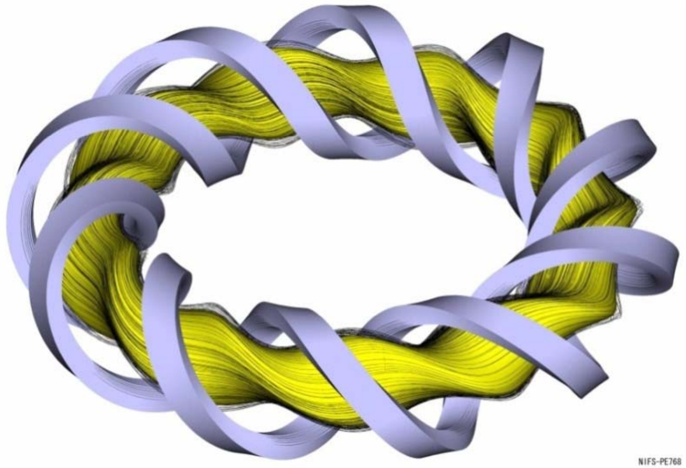
the 7th Integrated Operation Scenarios Topical Group Meeting
Kyoto University, Kyoto, Japan, 18th – 21st October 2011

Outline

- Introduction of LHD Project
- High temperature mode experiment
- ECH experiment
- ICRF Heating and Steady State Operation
- Future plan

LHD is a unique and excellent confinement device





Heliotron : Net-current free plasma suited to Steady State Reactor
Originally developed by K. Uo (Kyoto Univ.)

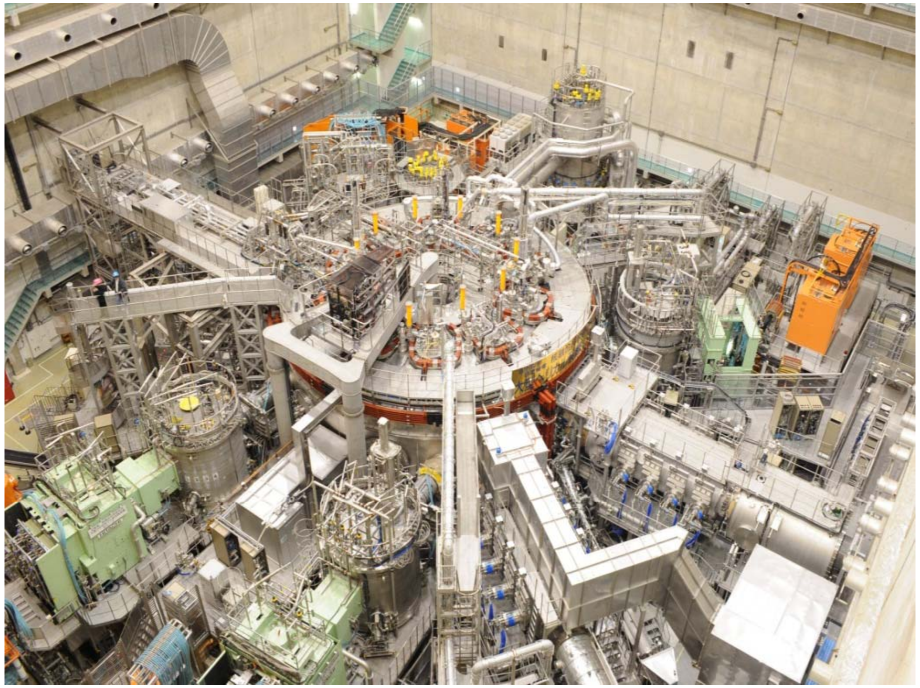
Goals of the LHD Program

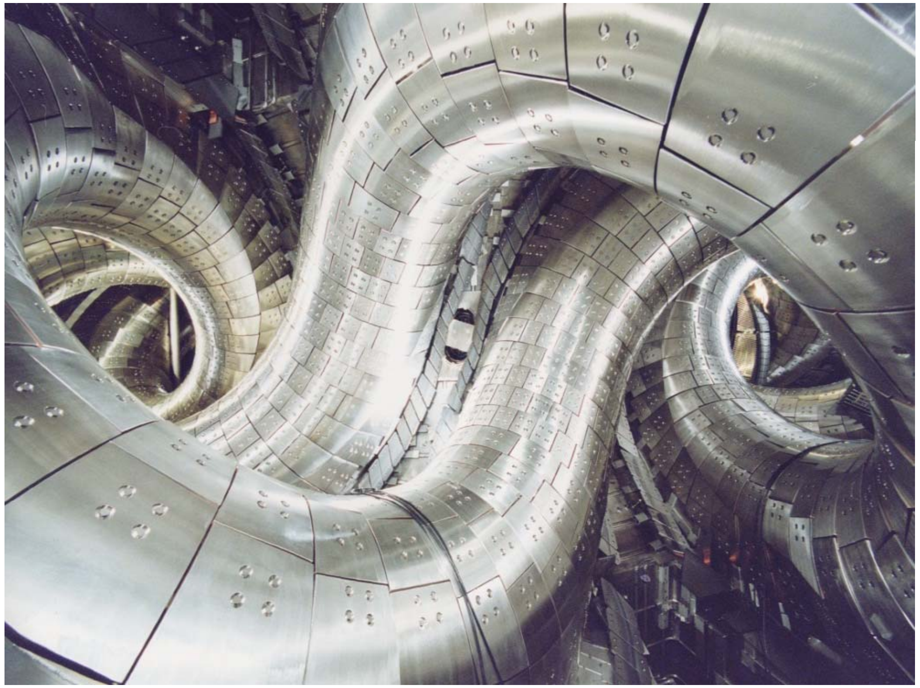
1. Clarification of physics of fusion relevant plasmas in heliotron configuration
2. Demonstration of scientific feasibility of steady state helical reactor
3. Comprehensive understanding of toroidal plasmas
   ==> complementary approach to tokamaks

Summary of recent achievements in LHD

• T_e: 20 keV, • T_i: 7 keV, • n_e: $1.2\text{x}10^{21}\text{m}^{-3}$, • $n\tau T_i$: $5.2\text{x}10^{19}\text{m}^{-3}$skeV

The Large Helical Device (LHD)





World largest heliotron

External diameter	13.5 m
Plasma major radius	3.9 m
Plasma minor radius	0.6 m
Plasma volume	30 m^3
Magnetic field	3 T
Total weight	1,500 t

Superconducting coil system

magnetic energy	1 GJ
Cryogenic mass (-269 degree C)	850 t
Tolerance	< 2mm

Construction 1990-1998

First plasma 1998(March)

Plasma generated in LHD shows steady progress
- LHD supports ITER operation by complementary research -

-- LHD results ---
Long pulse : > 1 keV plasma for 1 hour

High beta : $\beta = \frac{\text{plasma kinetic pressure}}{\text{pressure of magnetic field}}$

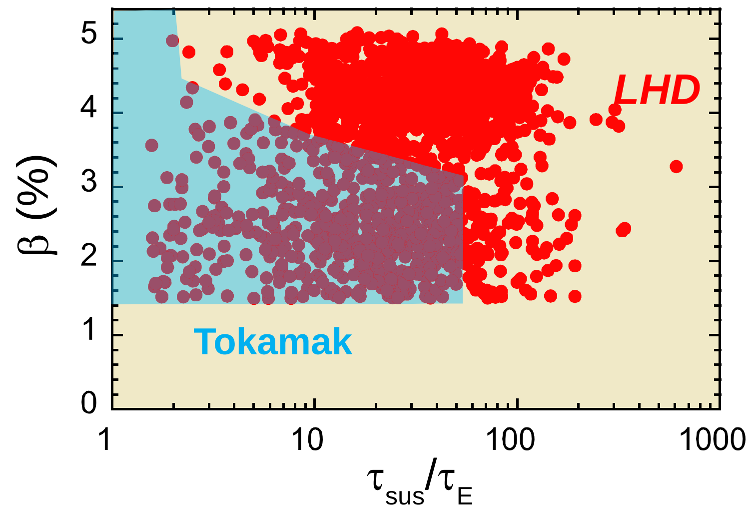
$\langle\beta\rangle = 5.1\ \%$ at B = 0.425 T
$\langle\beta\rangle \approx 5\ \%$ is maintained for more than 100 energy confinement time τ_E

High density
$n_e(0) = 1.2\times10^{21} m^{-3}$
1.5 atmospheric pressure at B = 2.5 T
➔ an innovative concept of ignition at T(0) = 6-7 keV

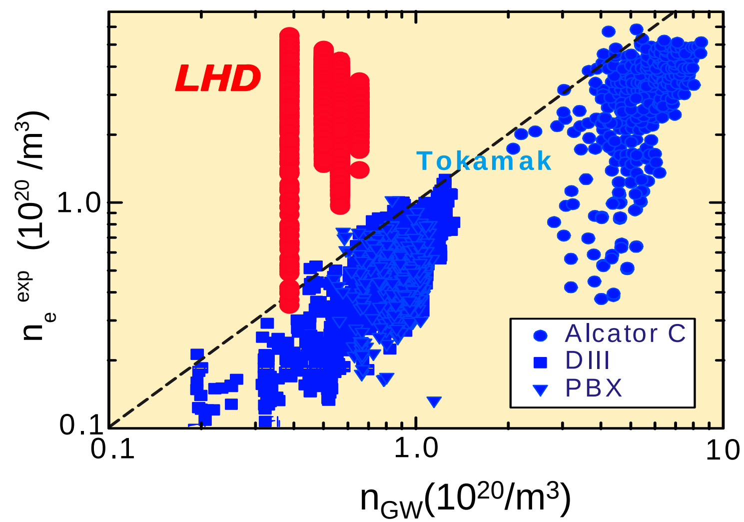
High ion temperature
$T_i = 6.4$ keV at $n_e = 1.6\times10^{19} m^{-3}$
accompanied phenomena to expel impurities

$n\ \tau_E\ T = 5\times10^{19}\ m^{-3}$ s keV

Quasi-steady state high beta



Very high density operation



High-*Ti,Te* mode experiments are helpful for comprehensive understanding of toroidal plasma in low collision regime

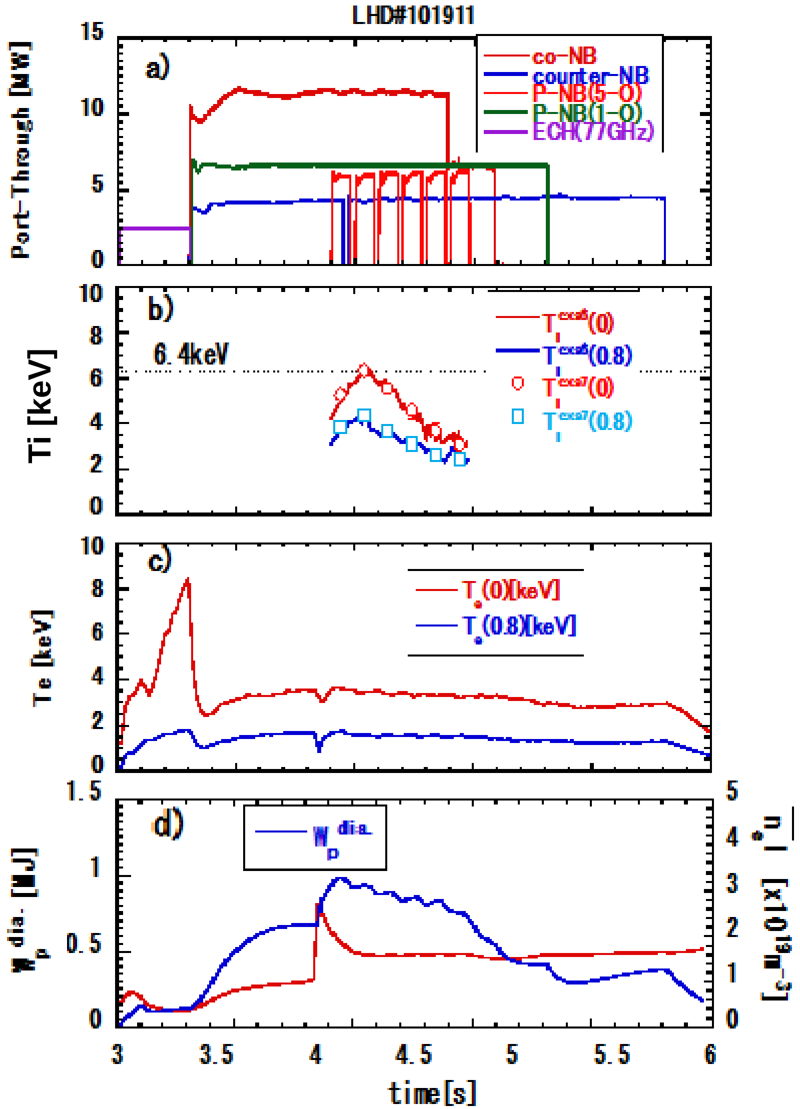
◆ Ion ITB with expelling of high Z ions

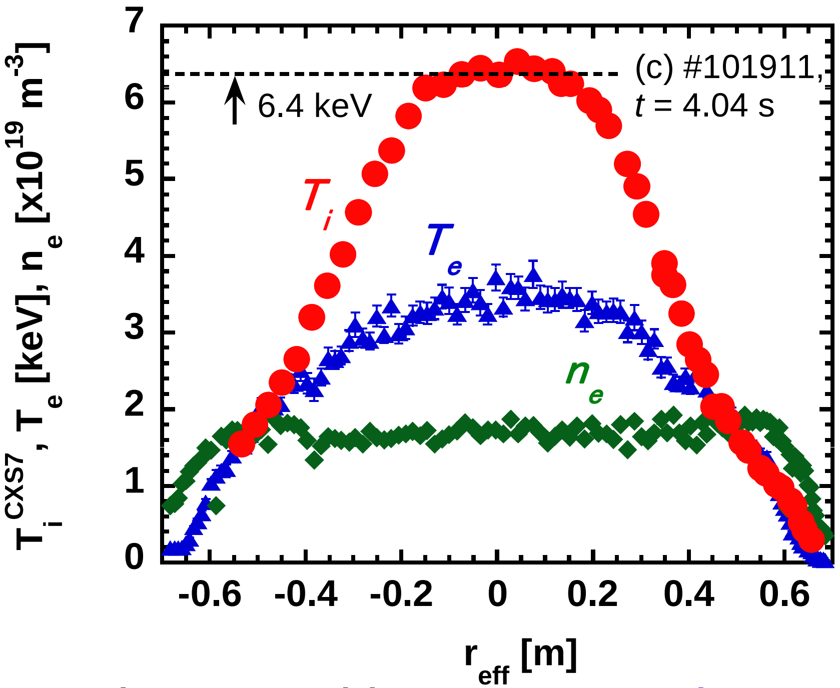
- T_{i0} > 6 keV and improved confinement
- Low thermal conductivity with low viscosity
- Impurity hole formation

◆ Electron ITB with NC electron root (CERC)

- High-power gyrotron development
- Extended high-T_e regime

Ion ITB is formed in wide area of NBI heated plasmas and T_{i0} > 6 keV is achieved





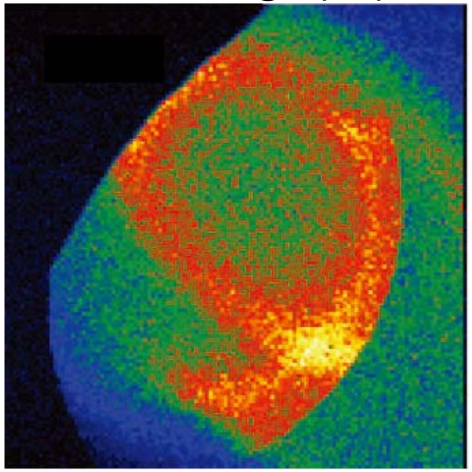
- An ion ITB with a steep gradT_i and flat density profile is formed after carbon pellet injection.
- T_{i0}=6.4 keV is achieved. (2010)
- The carbon density of n_C/n_e less than1% is achieved (Impurity hole formation)

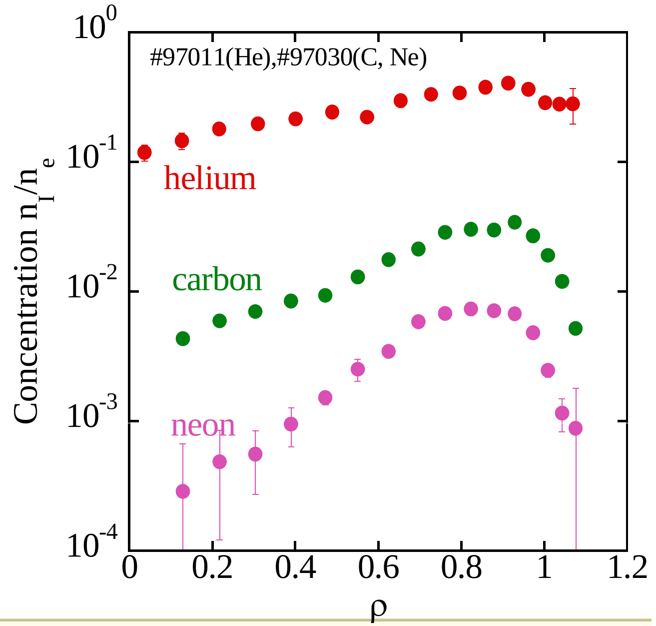
M. Yoshinuma, NF, 49, 002002 (2009),
K. Ida, PoP 16, 056111 (2009)

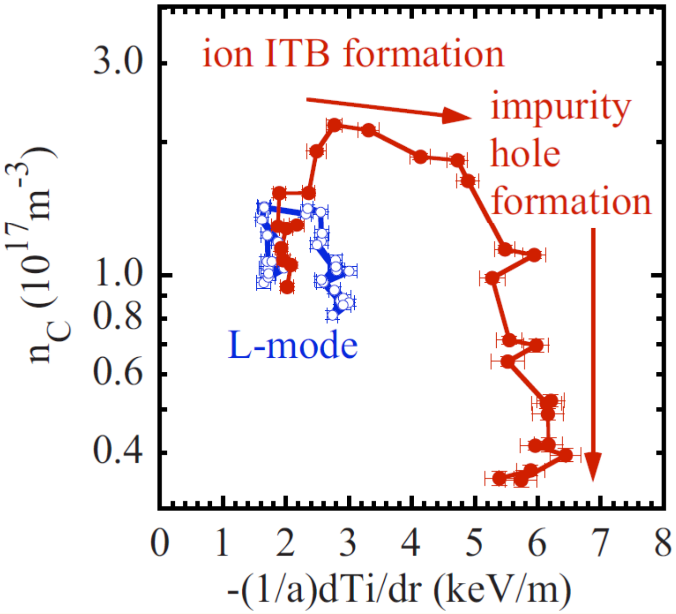
Impurity Hole is formed with ion ITB

M. Yoshinuma, NF, 49, 062002 (2009), K. Ida, PoP 16, 056111 (2009), T. Ido, PPCF, 52, 124025 (2010)

SX image (Fe)





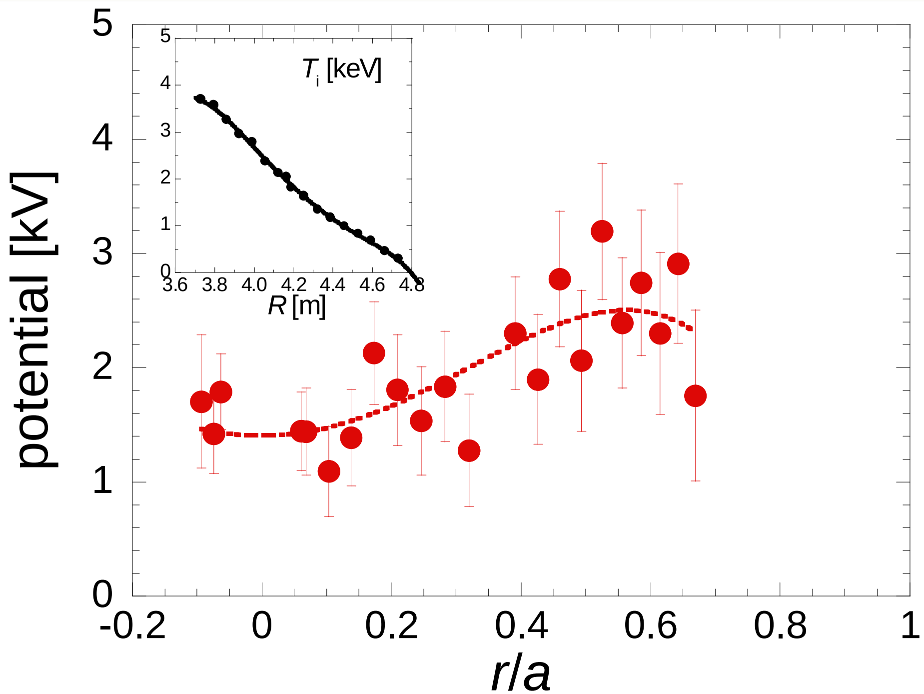


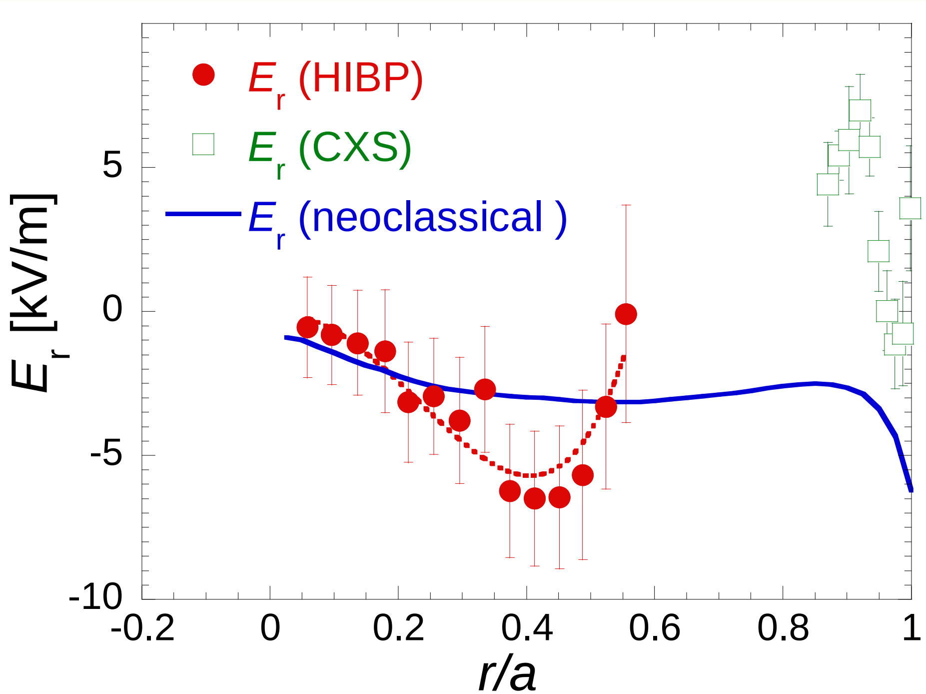
- Extremely hollowed profile of impurities (**Impurity Hole**) forms in ion ITB plasmas.
- **Heavier impurity ions** form steeper impurity hole profile.
- Impurity hole forms after ion ITB formation (enhancement of T_i gradient)
- Outward convection of impurity is considered to be driven by turbulence, but still an open question.

Simultaneous realization of Good energy confinement and Poor impurity confinement is not obtained in tokamak plasmas yet.

Negative Er during ITB was Confirmed by HIBP

K. Nagaoka, NF, 51, (2011)





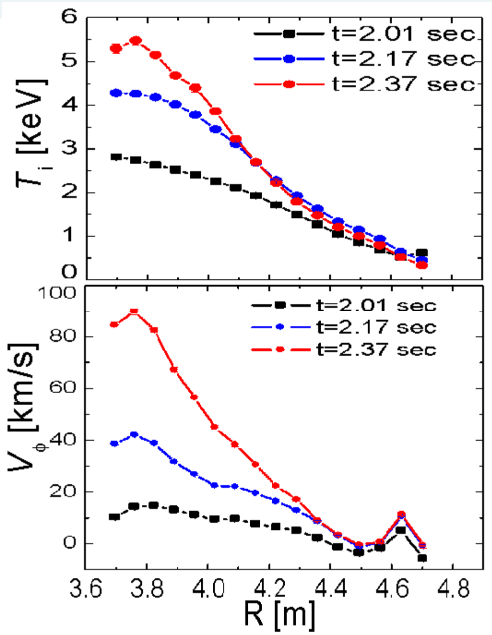
- Weakly hollowed profile of electrostatic potential in the core is observed by HIBP
- Observed negative E_r in the ITB region is consistent with neoclassical theory.
- Positive E_r appears at periphery, which is marginal in neoclassical calculations.

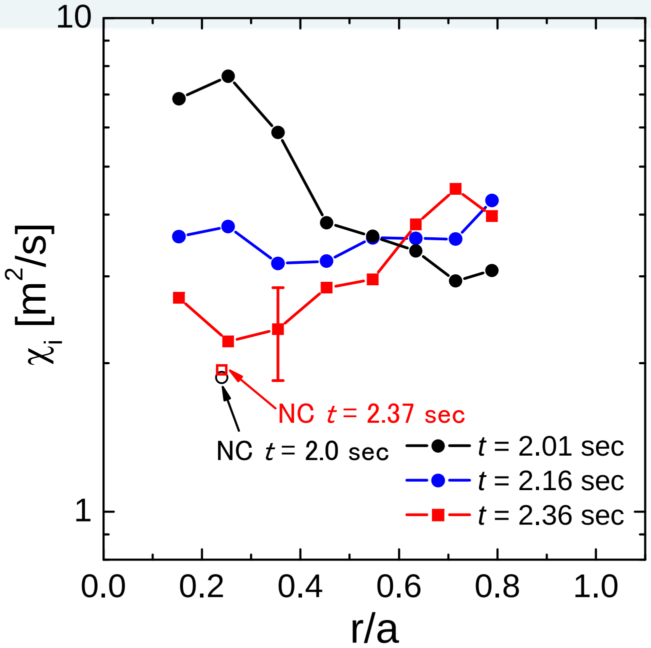
Ion ITB == > Improved confinement with negative E_r without significant E_r shear like observed in tokamak ITB.

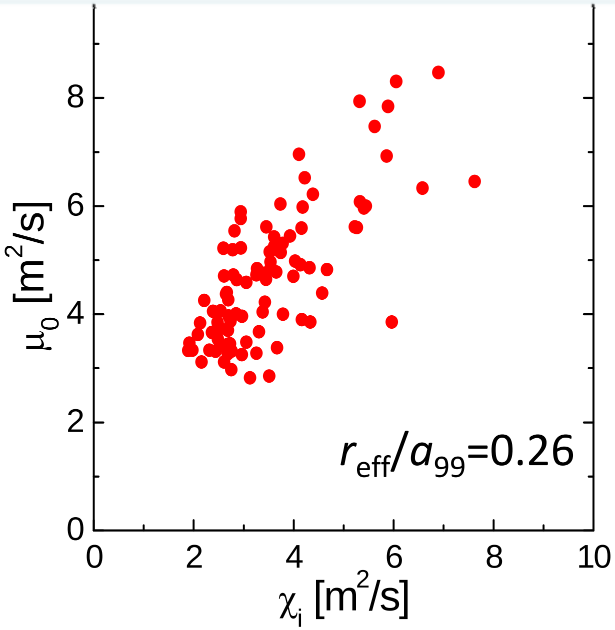
cf. electron ITB (CERC) forms with the transition to positive E_r from negative E_r

Peaked Profiles of T_i and V_ϕ in ion ITB Plasma on LHD

K. Nagaoka, NF, 51, 083022 (2011)







- The peaked T_i and V_ϕ profiles are simultaneously formed in ion ITB plasmas.
- χ_i decreases down to neoclassical level in ion ITB plasma, indicating significant reduction of anomalous transport.
- Momentum transport (viscosity) was analyzed with the neoclassical damping effect (collision with ripple trapped particles) taken into account.
- The viscosity (μ_0) decreases with a good correlation to thermal diffusivity (χ_i).
- Although spontaneous rotation is not taken into account in this analysis, a spontaneous rotation driven by grad-T_i was also identified in the ion ITB core.

M. Yoshinuma, NF 49, 075036 (2009). K. Ida, NF 50, 064007 (2010)

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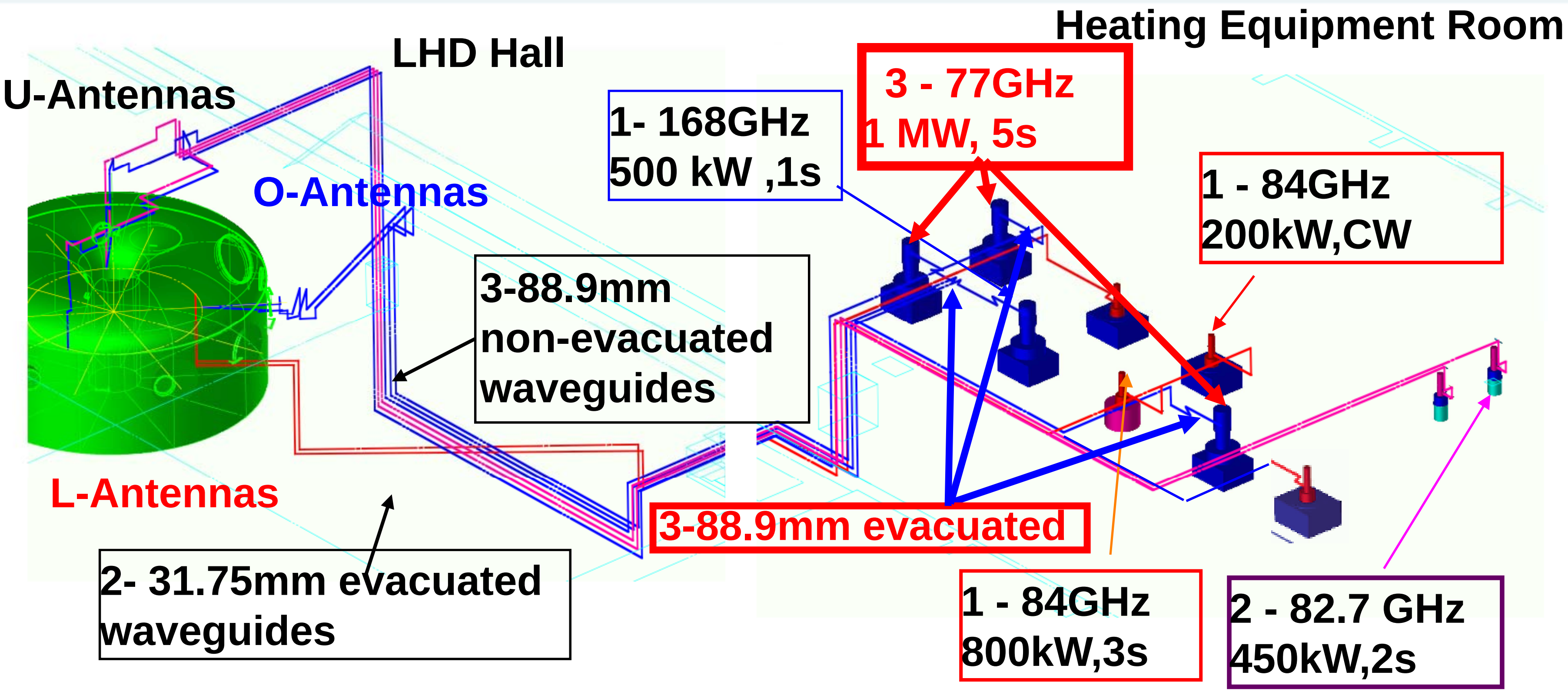
ECH system for LHD (2006->2011)



9 gyrotrons, transmission Lines, antennas are operated.
1-168GHz(Toshiba), 1-84GHz CPD (GYCOM), 1-82.7GHz non CPD (GYCOM)
3-168GHz is replaced by 3- 77 GHz(NIFS-Tsukuba Collaboration)
1-84GHz CPD (GYCOM) 200kW 1000 s (diamond window)
2- evacuated 31.75mm corrugated waveguide system.
3 non-evacuated 88.9mm corrugated waveguide system.
3- 88.9mm evacuated, corrugated waveguide upgraded for 77 GHz.

Achievement of 1.8 MW/ 1 s with new 77GHz gyrotron

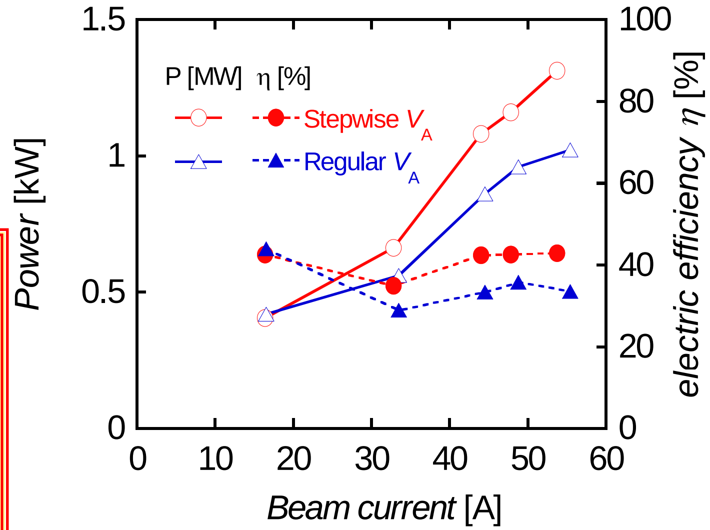
T. Imai, IAEA-FEC 2010

- **New technique of anode bias voltage ramp up**

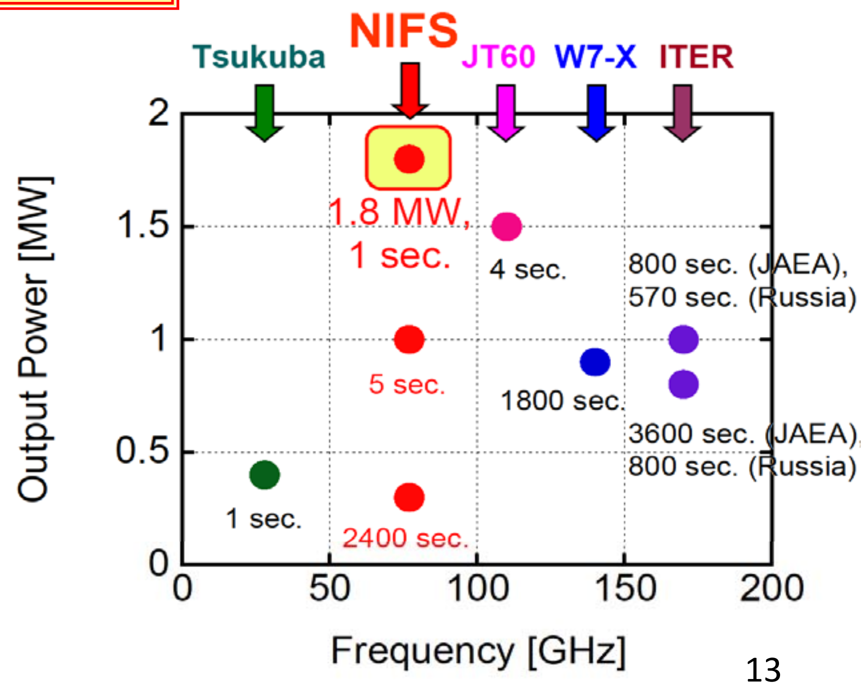
-> Stable and high power operation!

1.8 MW/ 1 s

World's highest output power (>1s)



Beam Current	Pulse Width	MOU Out	Gyrotron Out
77.4 A	0.1 s	1.87 MW	1.97 MW
72.2 A	1 s	1.77 MW	1.86 MW



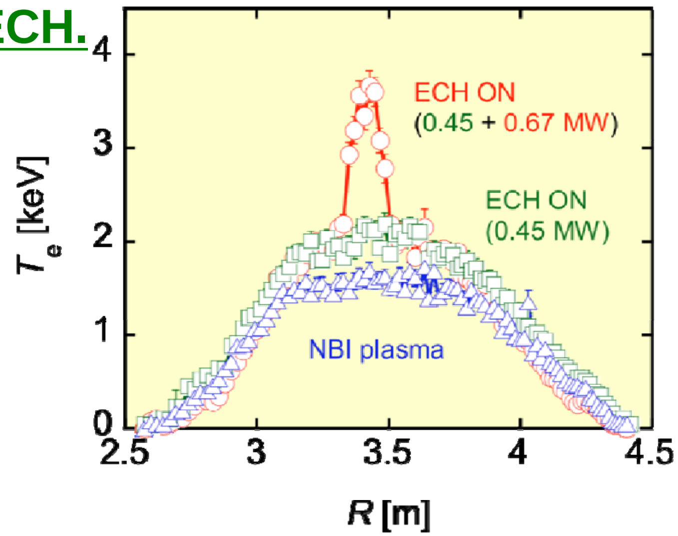
Electron Internal Transport Barrier (e-ITB) formation

e-ITB formation was attained by centrally focused ECH.

- The foot point locates near the rational surface of $\iota/2\pi = 1/2$.

  -> **Lower-order rational surface** may trigger ITB.
- There is the threshold in ECH power.

  -> **Local parameter control** plays a key role for ITB formation.



Prospective effect by 77 GHz heating

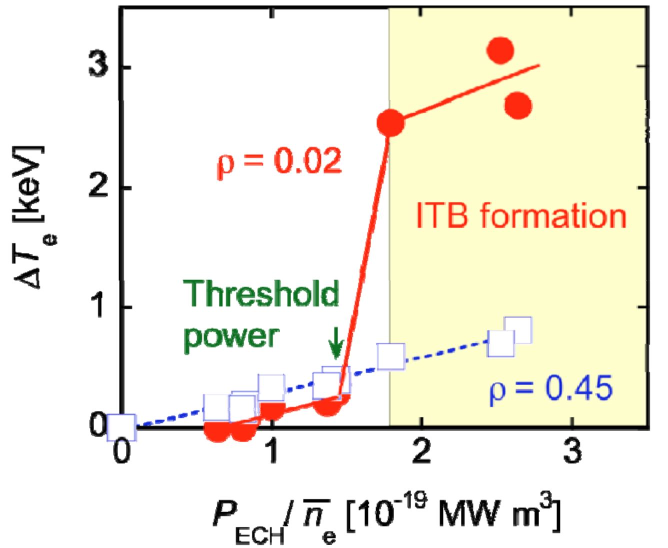
- Expansion of central heating source.

  -> **Improvement of core temperature/ pressure**.
- Different frequency from those of existing gyrotrons.

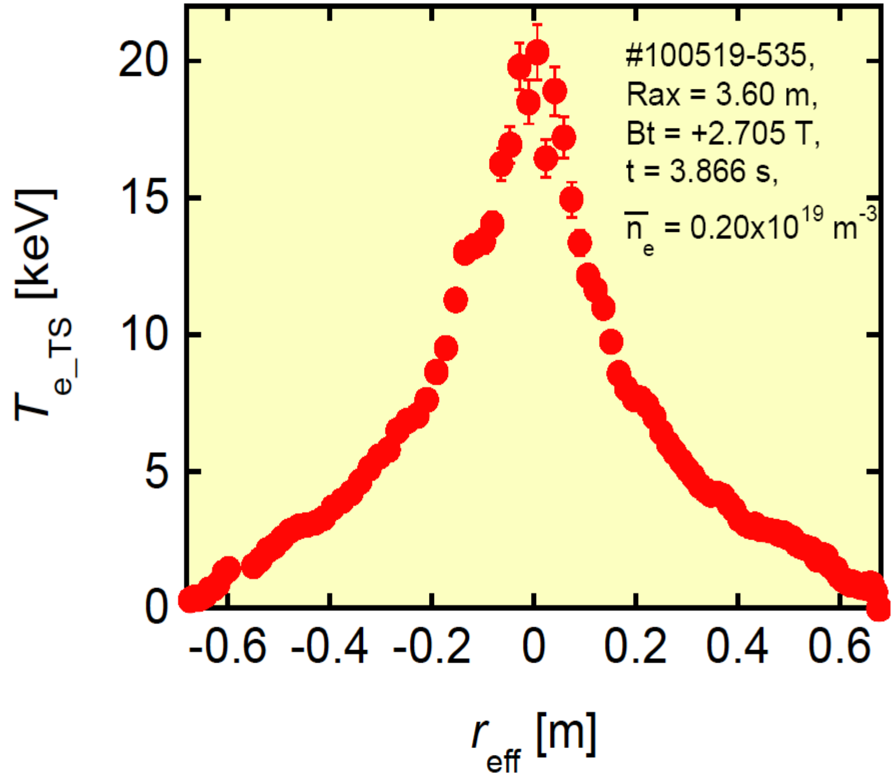
  -> simultaneous-multi-point heating of plasma

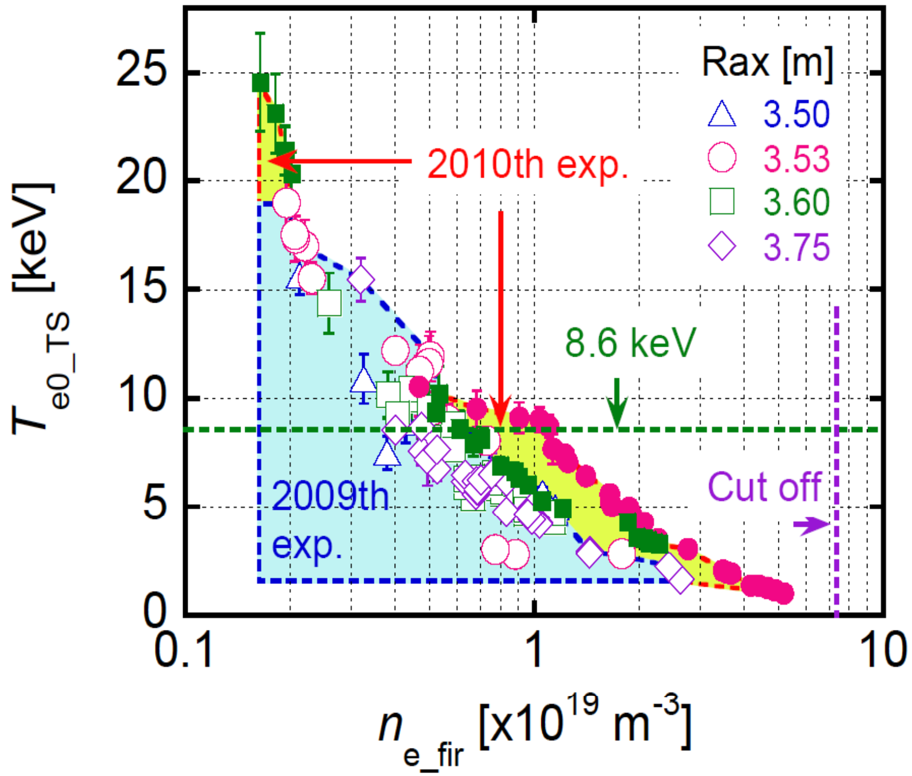
  -> **Local control of radial electric field/ radial transport** by local collisionality control.

  -> Influence of **deposition power/ position** on the ITB formation.



Achievement of T_{e0} = 20 keV by increased ECRH power





- 3.7 MW of ECRH power was injected for plasma generation and sustainment.
- T_{e0} = 20 keV was successfully achieved using centre focused ECRH.
- Electron temperature increases in higher density regime.

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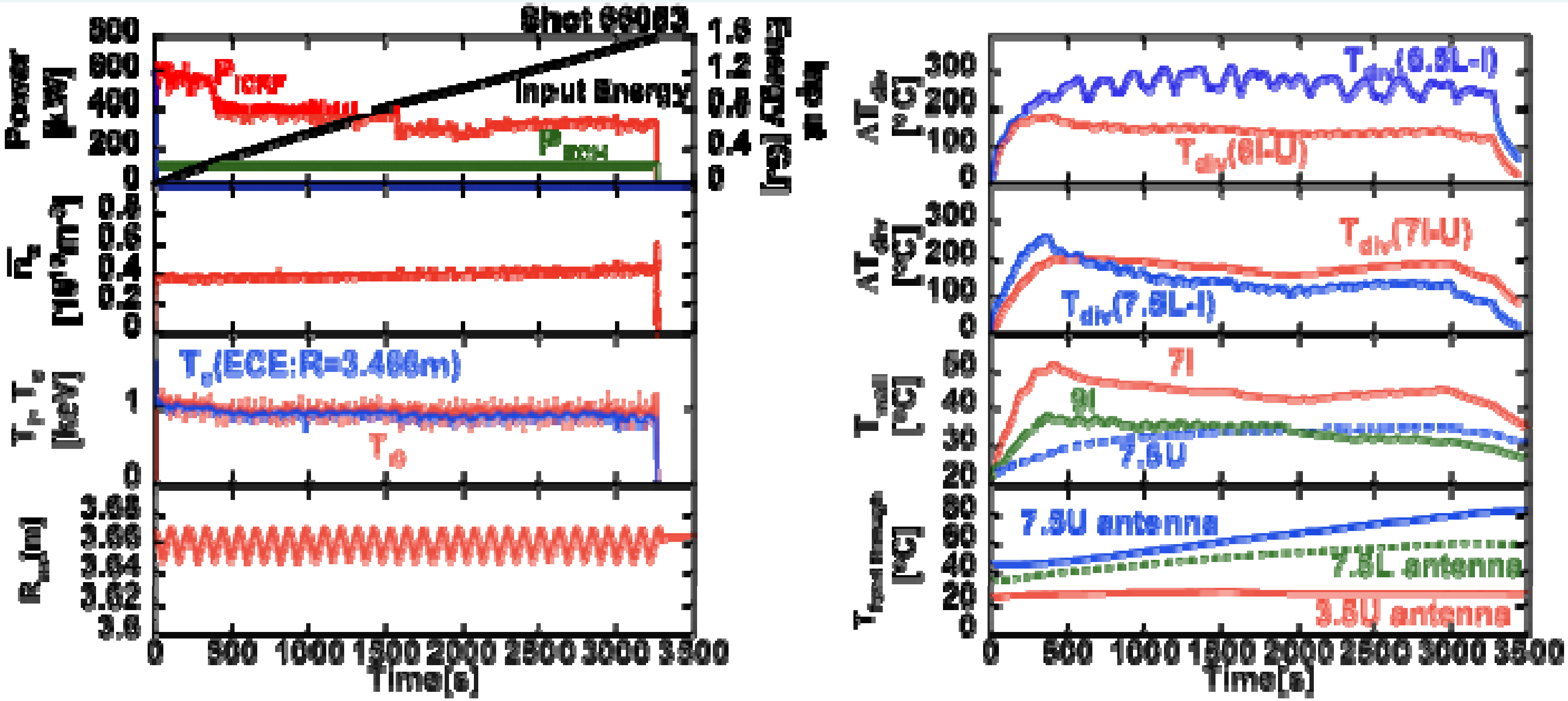
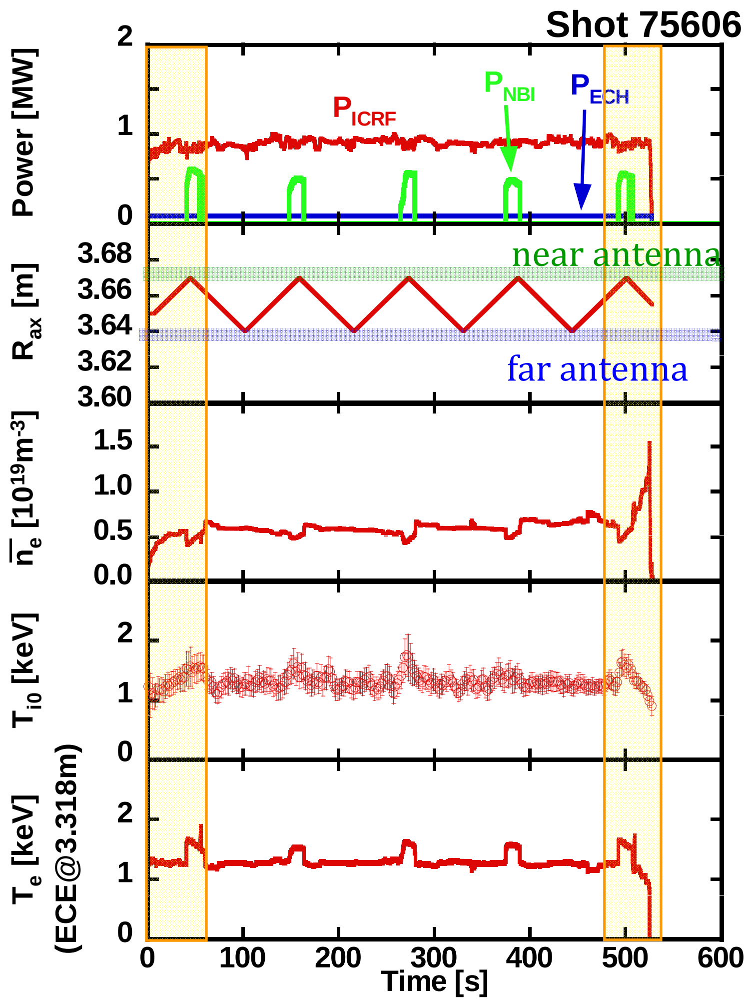
SSO by H minority in He majority ions

Experiment condition is same with ITER non-activated half B, case 4 (^4He)



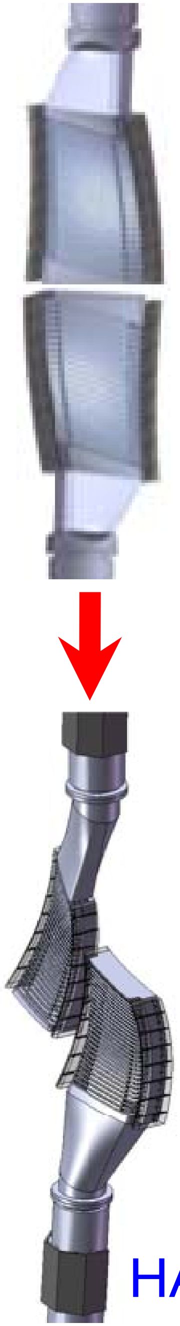
- **Power control during plasma discharge with watching sparks in vacuum vessel**
- **R_{ax} = 3.64- 3.67 m, $n_e \sim 0.4 \times 10^{19}$ m^{-3}, $T_e \sim T_i \sim$ 1 keV**
- **Plasma was terminated by sudden increase of density caused by influx of iron impurity**

Higher power operation (P > 1MW) for SSO



B=2.85T(@R=3.6m)
P_{ICRF}=894kW (freq = 38.47MHz)
(3.5U, 7.5UL antenna)
P_{NBI}=75kW
P_{ECH}=90kW
P_{total}=1059kW
$T_{duration}$=525sec

HAS antenna is installed to suppress edge heat loss by controlling of $k_{//}$

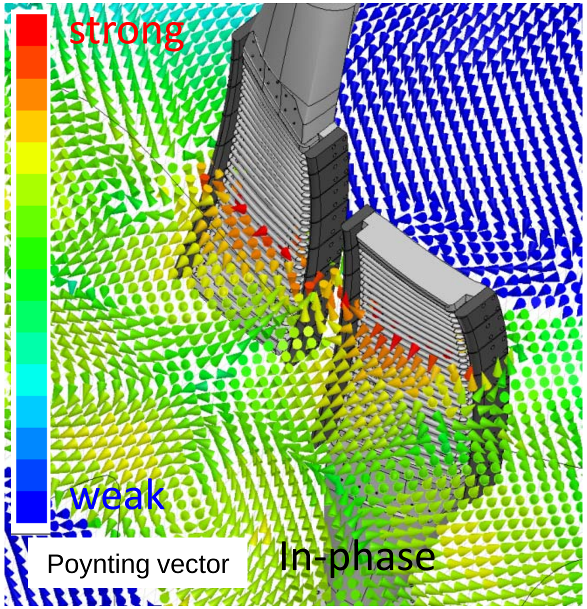


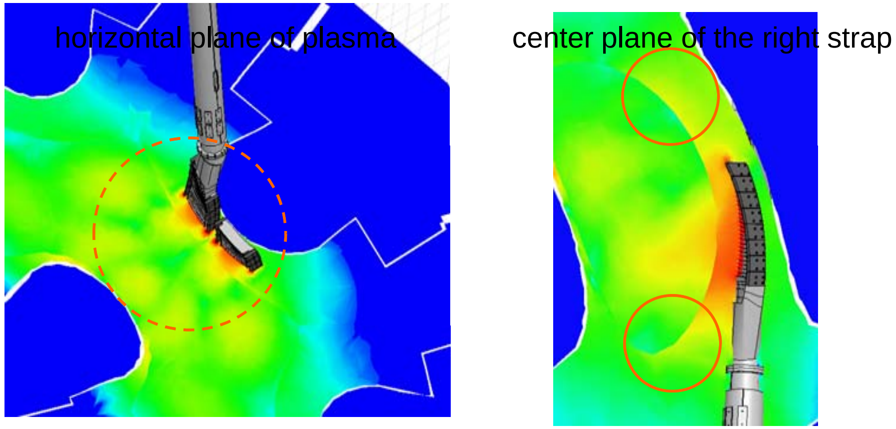
previous Poloidal antenna

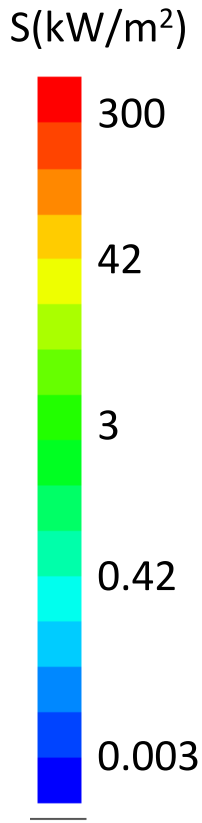
HAS antenna

- strap width : 20cm
- strap length : 75cm
- antenna width : 54cm
- water-cooled strap and backplate
- Faraday shield is made by Cu-SUS clad
- Side protector is made by CFC
- Movable in horizontal direction

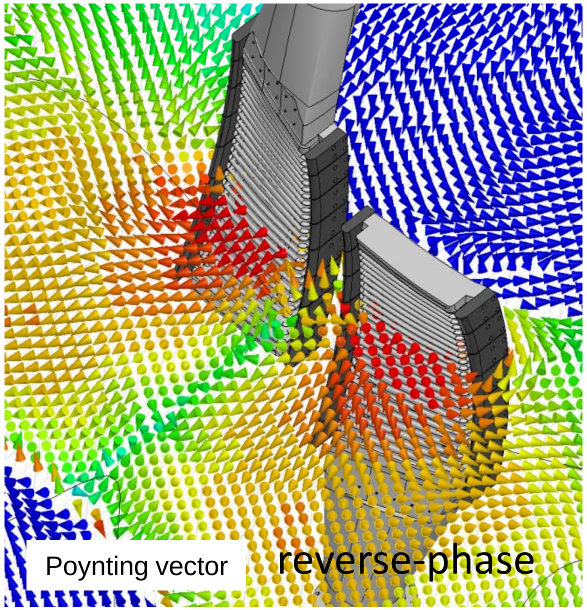
RF power is strongly concentrated in front of the antenna with reverse phase

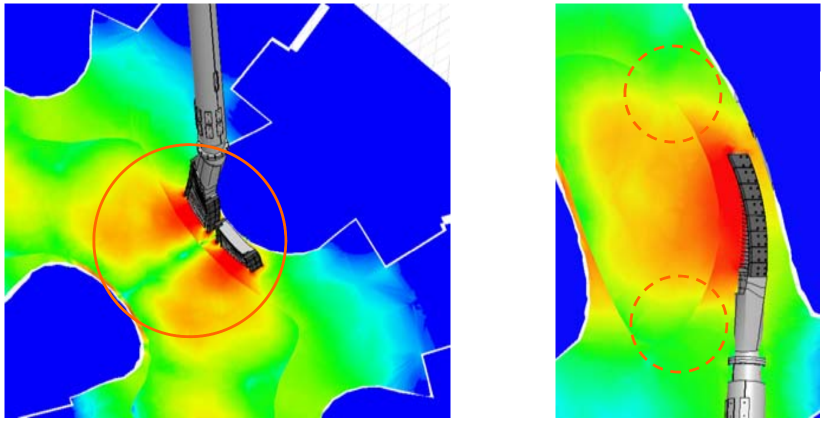






Antenna loading is approximately same, and so the Poynting vector is widely scattered.

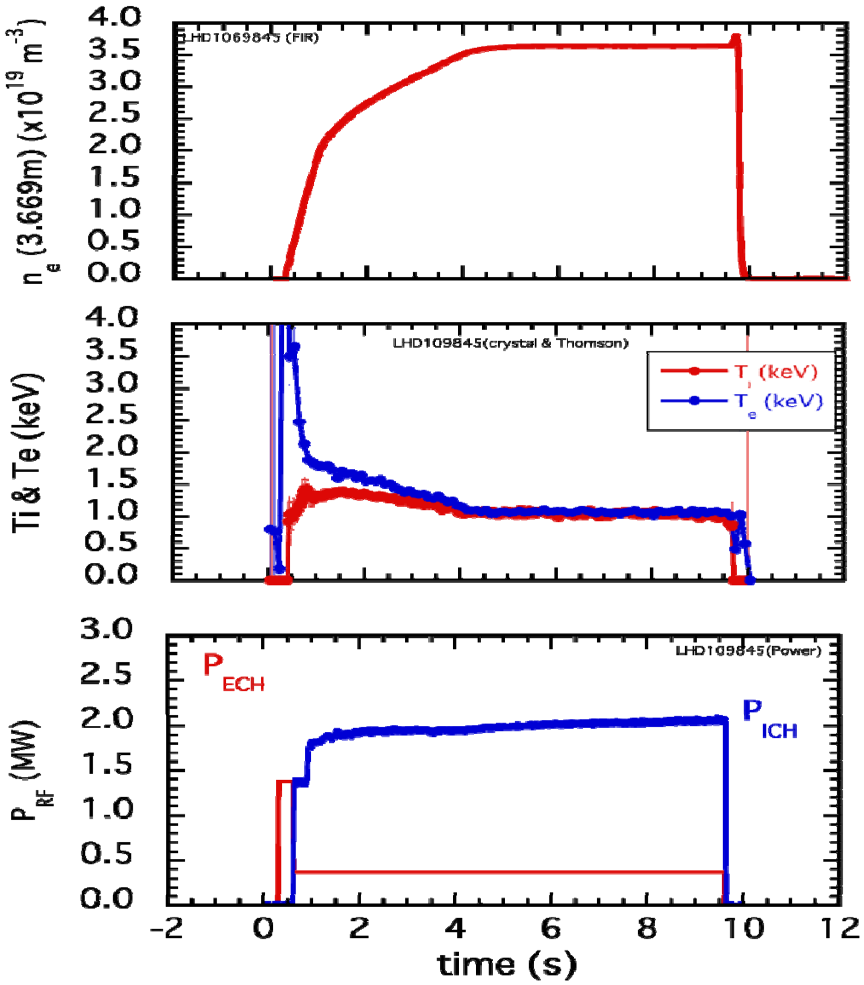


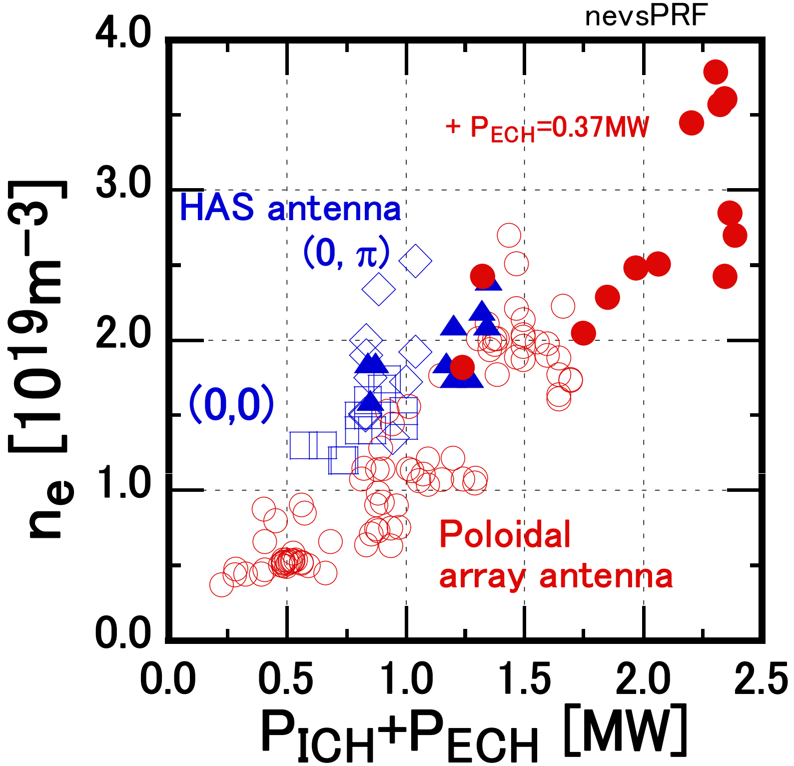


The Poynting vector is strongly concentrated in front of the antenna in the reverse-phase.

Higher density and long pulse operation is on-going

High performance plasma of steady state is required as mission plan





By using four antennas (a pair poloidal array antenna, a pair of HAS antenna), n_e of 3.7x10^{19} m^{-3} and T_i ~ T_e ~ 1 keV is stably sustained.
Pulse length can be elongated in this experimental campaign.

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- ECH/ECCD/EBW experiment
- ICRF Heating and Steady State Operation
- Contribution to ITER operation
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Future Research Plan in LHD

Extension of operation regime

- ◆ DD experiments
  - Confinement improvement due to isotope effects
  - High ion temperature
  - Investigation of high energy particle behavior
- ◆ Closed divertor operation
  - Confinement improvement
  - Steady state operation
- ◆ Steady state operation
  - Increase of heating power of ICRF and ECH

Researches for physics understanding support an ITER operation

- ◆ Further understanding of 3-D plasma physics
  - Transport
  - MHD
  - High energy particles
  - --