Recent Development in the Operational Regime of Large Helical Device Toward a Steady-State Helical Fusion Reactor

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on behalf of the LHD Experimental Group
National Institute for Fusion Science

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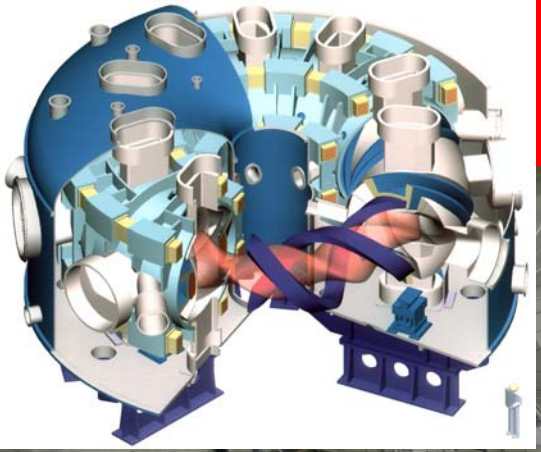
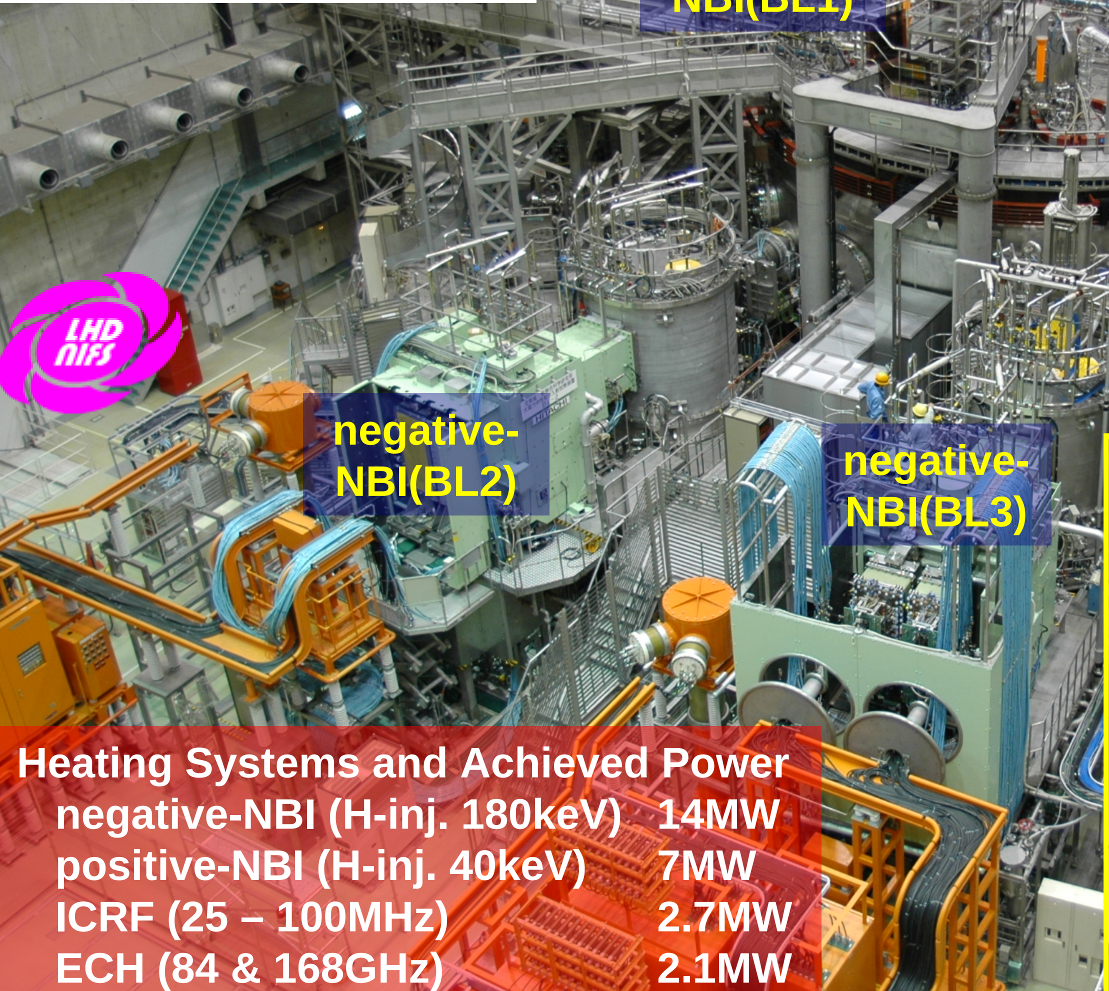
Large Helical Device (LHD)



Heliotron configuration of
l=2/m=10 field period
All superconducting coil system

Plasma major radius	3.42-4.1 m
Plasma minor radius	0.6 m
Plasma volume	30 m^3
Toroidal field strength	3 T

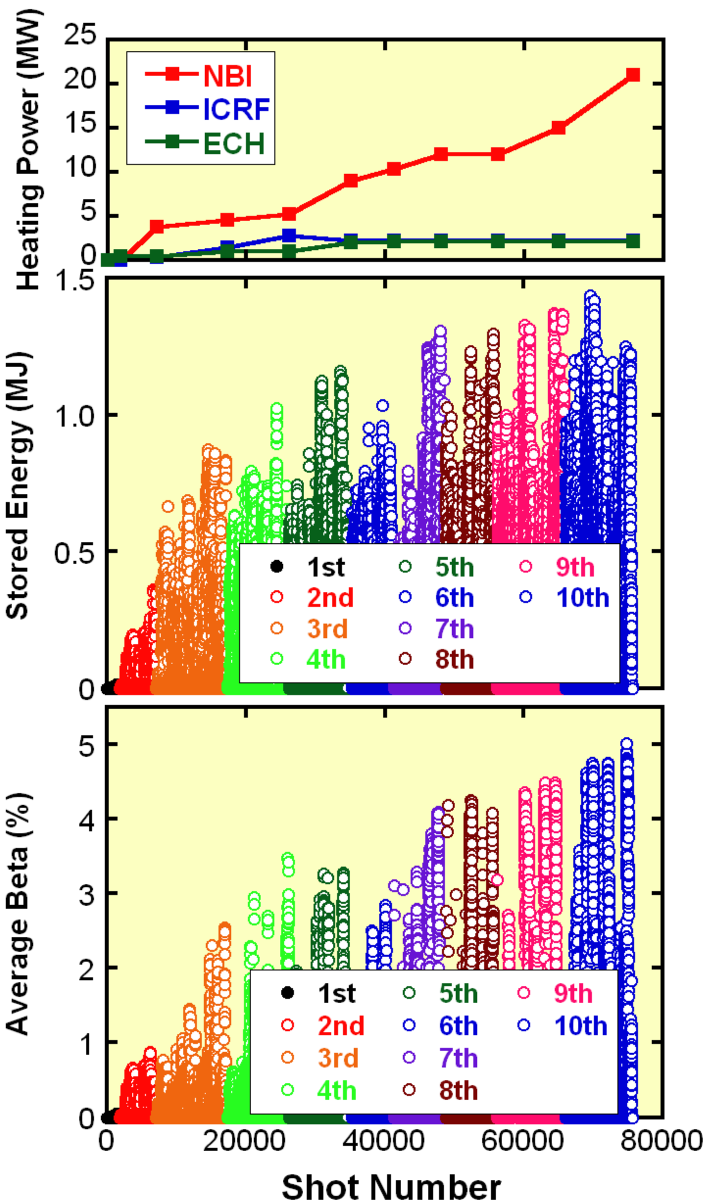


Heating Systems and Achieved Power

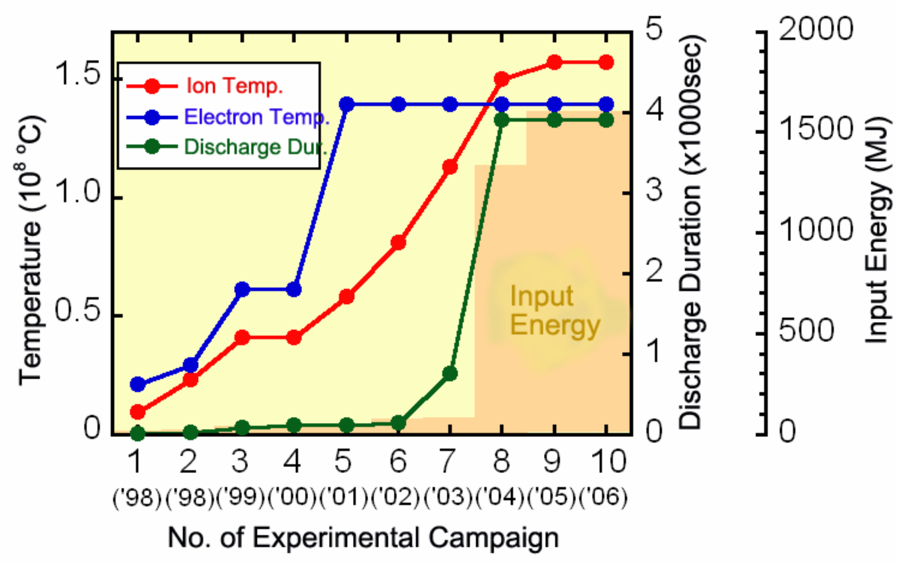
negative-NBI (H-inj. 180keV)	14MW
positive-NBI (H-inj. 40keV)	7MW
ICRF (25 – 100MHz)	2.7MW
ECH (84 & 168GHz)	2.1MW

Plasma vacuum vessel

LHD plasma performance has progressed together with improvement of heating devices.



- Plasma stored energy is beyond 1.4 MJ, comparable to large tokamaks.
- Ion and electron temperatures exceed 10 keV, respectively.
- Plasma discharge duration is extended to around 1 hour.



Increase in heating power is a major contribution to the steady progress.

N-NBI : 14 MW P-NBI : 7 MW
ECH : 2.1 MW ICRF : 2.7 MW

Highlights in the 10th Campaign (FY2006: After the IAEA Conference)

- High β : Achievement of the reactor-relevant value
  - $<\beta>$=5.0% (transient by pellet)
  - $<\beta>$=4.8% (stationary by gas-puffing)
- High n_e : Extension of the parameter regime in HD configuration
  - $n_e(0)=1 \times 10^{21} m^{-3}$ with IDB
  - P(0)>130kPa (above an atmospheric pressure)
- High T_i : Achievement in the hydrogen plasma
  - $T_i(0)$=5.2keV at $n_e=1.2 \times 10^{19} m^{-3}$ (H-plasma)
- Other achievements
  - W_p=1.44MJ (with high-power NBI heating)
  - $T_e(0)$=15keV at B=2.931T (Sub-cooling of the helical coil)
  - Observation of 2.5MeV of the ICRF-accelerated ions
  - Long-pulse plasma sustainment of 1MW-500sec

Outline

- Characteristic features with regard to the magnetic axis position
- High-β plasma characteristics relevant to the helical reactor
  - High β : $<\beta>$=5.0% (transient by pellet)
    $<\beta>$=4.8% (stationary by gas-puffing)
- Plasma confinement of the IDB plasmas formed in the helical divertor configuration
  - High n_e : $n_e(0)=1\times10^{21}m^{-3}$ with IDB
- Ion transport in the high-T_i plasmas
  - High T_i : $T_i(0)$=5.2keV at $n_e=1.2\times10^{19}m^{-3}$ (H-plasma)
- New approach to ignition
  - High-density scenario to the ignition based on the SDC/IDB plasma
- Summary and Future project

LHD plasma characteristics depend strongly on magnetic axis position.

Good particle orbit

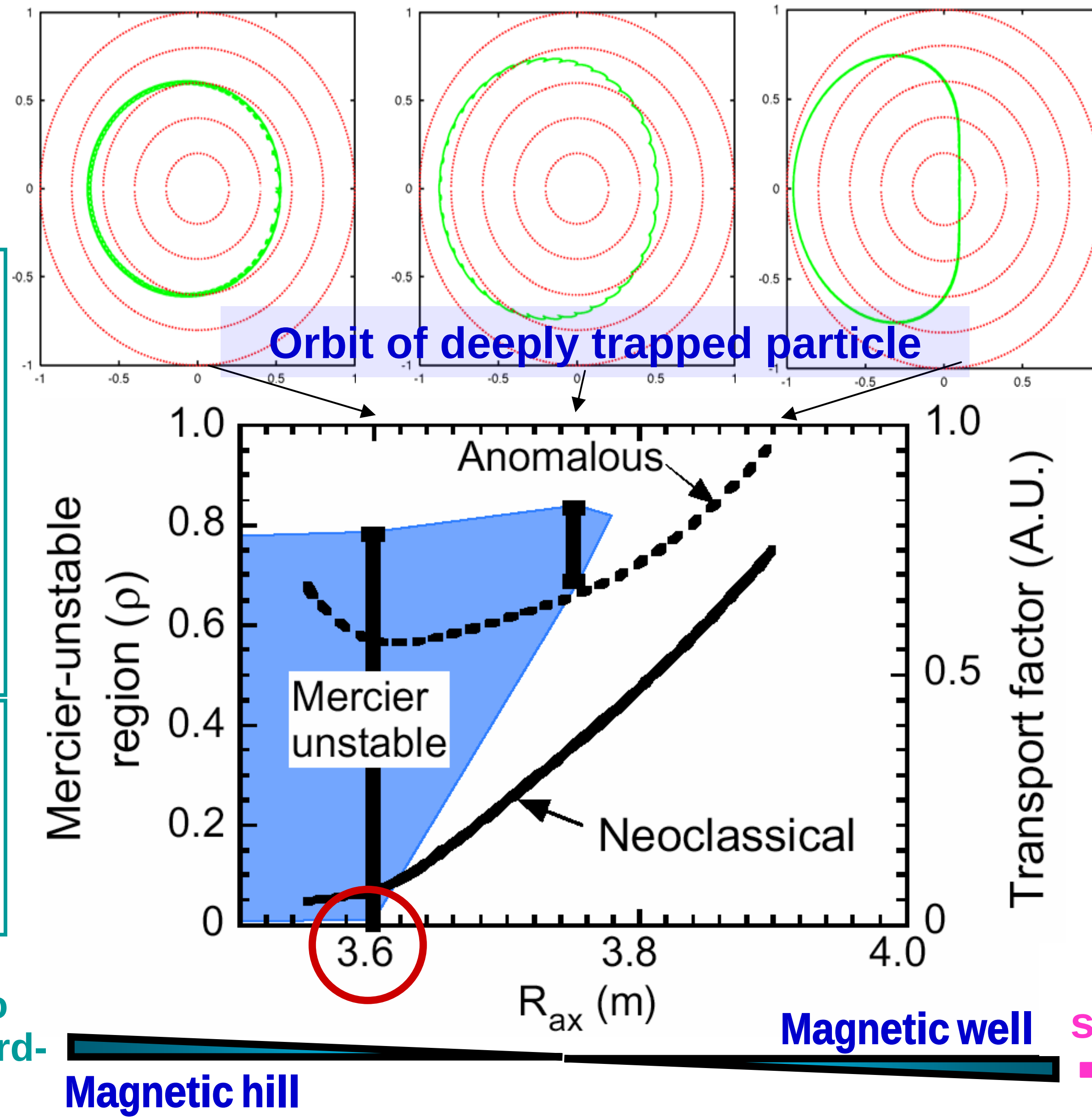
Theoretical prediction

In **the inward-shifted configurations**, the particle orbit and the transport are better although the ideal linear MHD mode (interchange mode) is unstable due to the presence of the magnetic hill region.

In **the outward-shifted configurations**, the MHD mode is stable although the particle orbit and the transport are worse.

Compatibility between stability and confinement is resolved in the inward-shifted configuration.

Amplitudes of MHD instabilities were found to be small even in the inward-

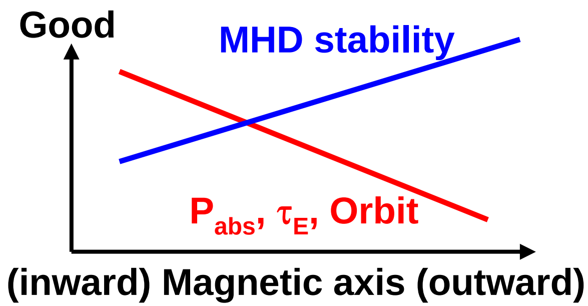


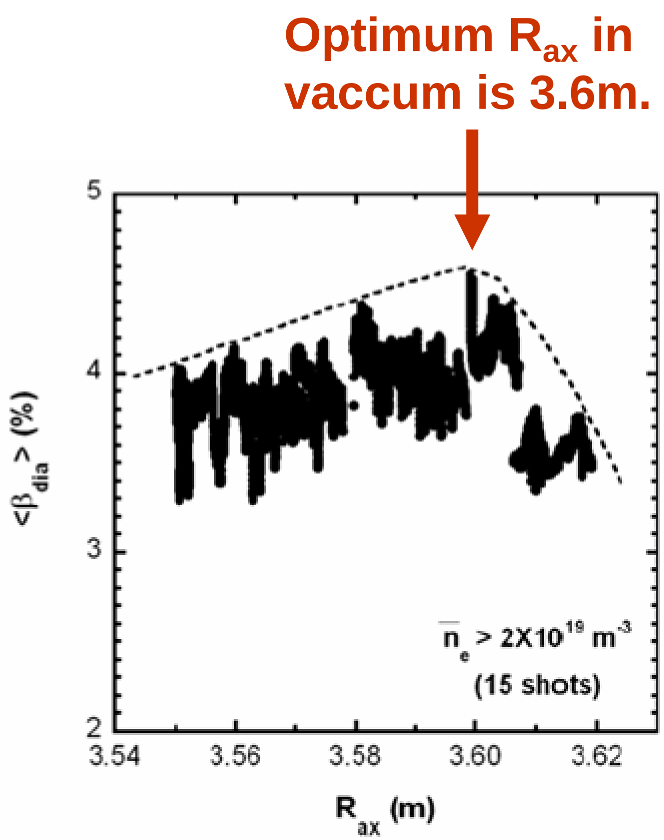
Good stability

Strategy for the access to high-β plasmas.
Control of magnetic axis and plasma aspect ratio

Shafranov shift is better for stability due to the spontaneous well formation while it deteriorates the transport and the NBI heating efficiency.

Control of magnetic axis position



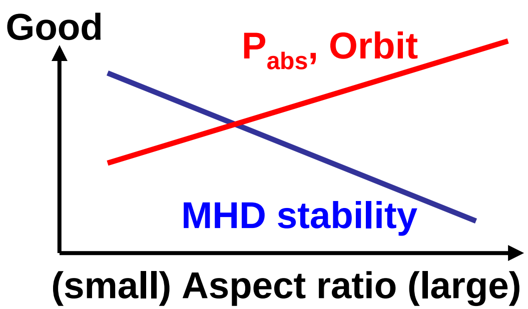


- In outward-shifted configuration, MHD stability is better while transport and NBI heating efficiency are degraded.
- Magnetic axis is shifted outward by Shafranov shift as the β increases.

Strategy for the access to high-β plasmas.
Control of magnetic axis and plasma aspect ratio

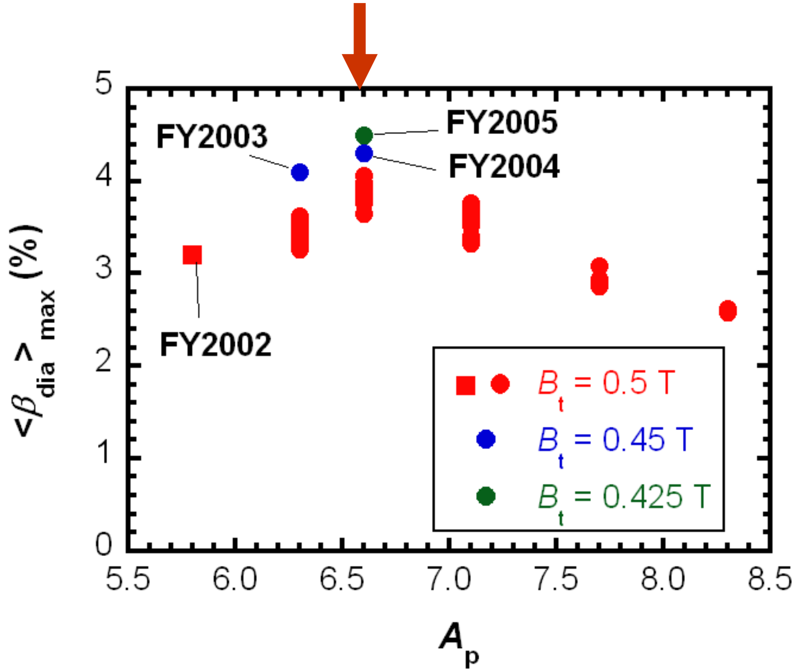
Shafranov shift is better for stability due to the spontaneous well formation while it deteriorates the transport and the NBI heating efficiency.

Control of plasma aspect ratio

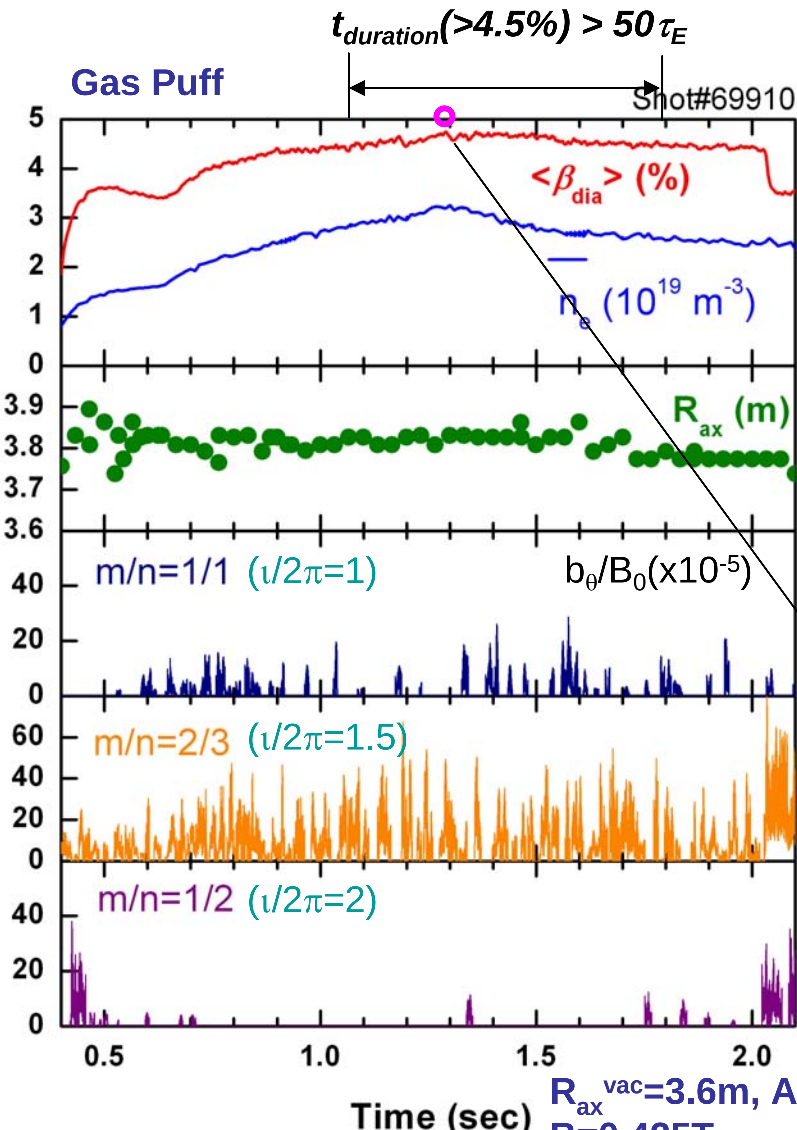


- Shafranov shift is restricted with an increase in the plasma aspect ratio.
- Restricted Shafranov shift suppresses the spontaneous formation of magnetic well.

Optimum A_p is 6.6.

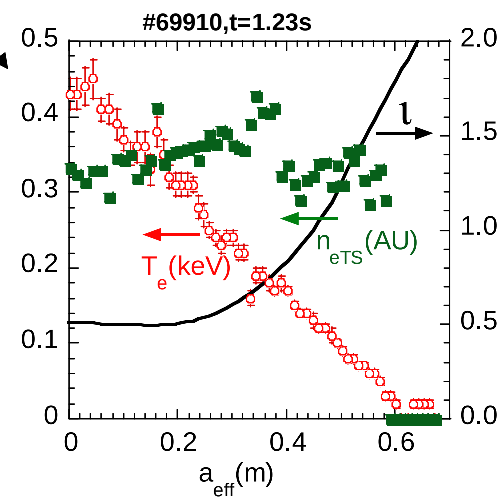


Plasma of <β>=4.8% is stationary sustained without any disruptive phenomena



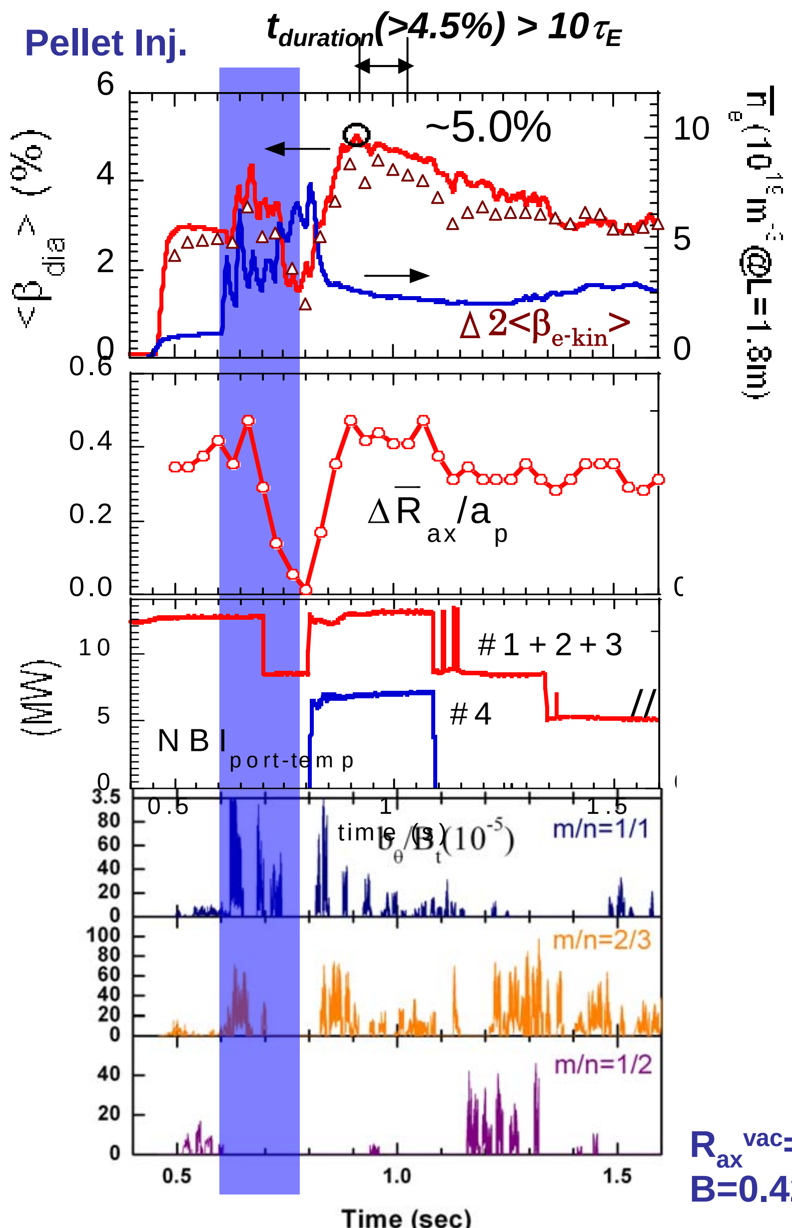
R_{ax}^{vac}=3.6m, A_p=6.6
B=0.425T
P_{abs}=11MW

- No crucial MHD instability is observed in a period of 50 times the confinement time during which <β> is over 4.5%.
- Shafranov shift normalized by the effective plasma minor radius, Δ/a_{eff}, is as large as around 40%, near the equilibrium beta limit of 50%.
- Dominant MHD modes are moving outward as β increases, and peripheral MHD modes (ρ>0.9), resonated with m/n=2/3 and 1/1, are only observed.



- Flattening of the T_e profile causing the instability is not observed.

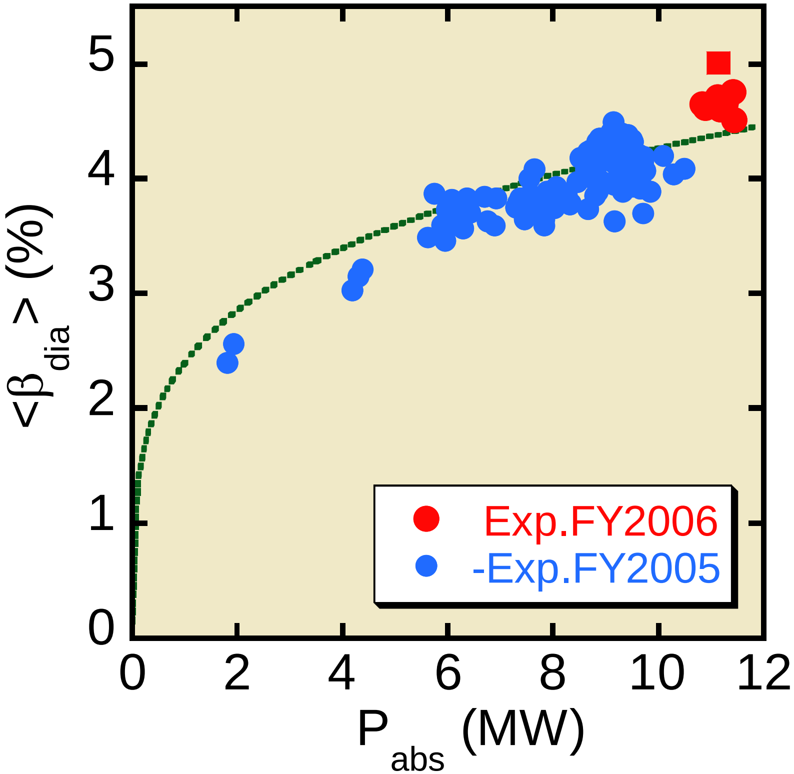
Reactor-relevant <β> value of 5% is achieved transiently by pellet injection.



- Tangential NBI power is reduced at the pellet injection for effective penetration of the pellets.
- Shafranov shift is rapidly reduced at that time, followed by the perpendicular NBI together with the restoration of the tangential NBI.
- Due to the reduction of the Shafranov shift, the perpendicularly injected beam effectively heats the plasma, and the <β> is rapidly increased, then, reaching 5%.
- High-β plasma greater than 4.5% of <β> is maintained for 10τ_E without crucial MHD instability.
- T_e and n_e profiles are nearly the same as those in the gas-puffing shot.

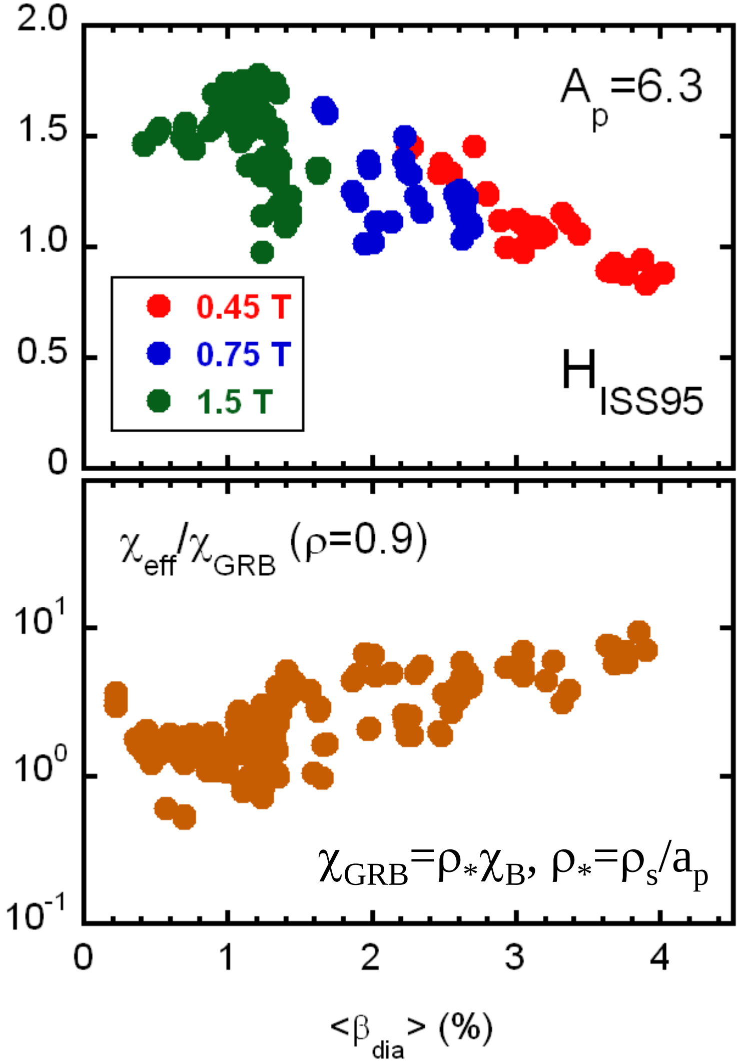
R_{ax}^{vac}=3.6m, A_p=6.6
B=0.425T, P_{abs}=11MW

<β> is still increased with an increase in the heating power without saturation.



- <β> is increased as $P^{0.25}$, and is not limited by the MHD instabilities.
- Considering the energy confinement scaling of W_p depending on $P^{0.4}$, confinement degradation caused by the β increase is suggested.
- It is thought that the core MHD mode is not correlated with the possible confinement degradation, because of no observation of it.

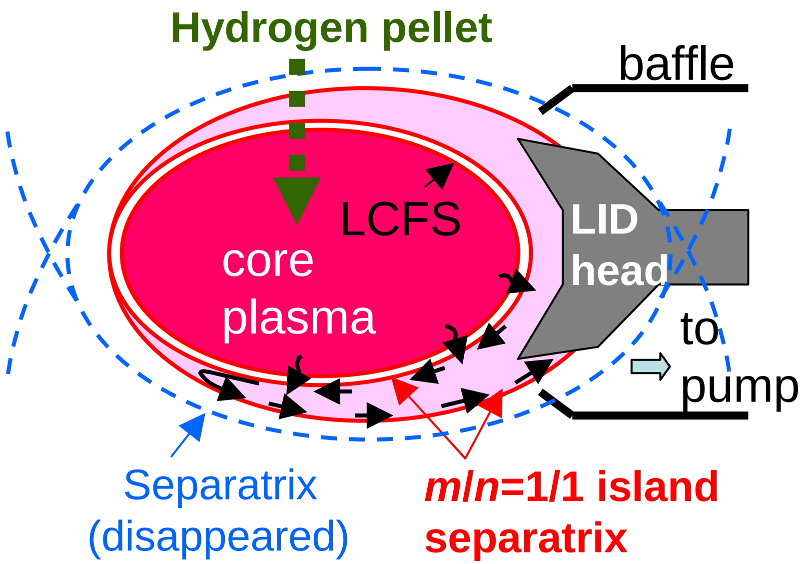
Transport enhancement in the peripheral region seems to be responsible for the confinement degradation in high-β plasmas.



- Global energy confinement is gradually degraded with increasing β.
- Accordingly, the peripheral transport is also degraded with increasing β.
- Observed MHD modes in the peripheral region are resistive interchange mode, and the resistive g-mode turbulence would cause the transport degradation.
- Analysis with magnetic Reynolds number, S, indicates that the amplitude of resistive interchange modes is expected to be reduced at higher temperature and at higher magnetic field.

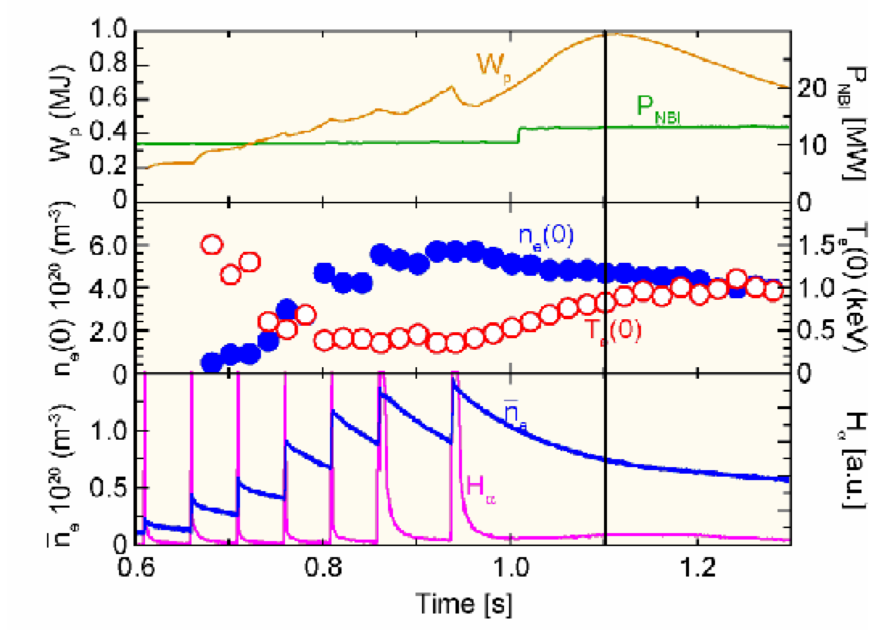
K.Y. Watanabe, I-13 on Thursday

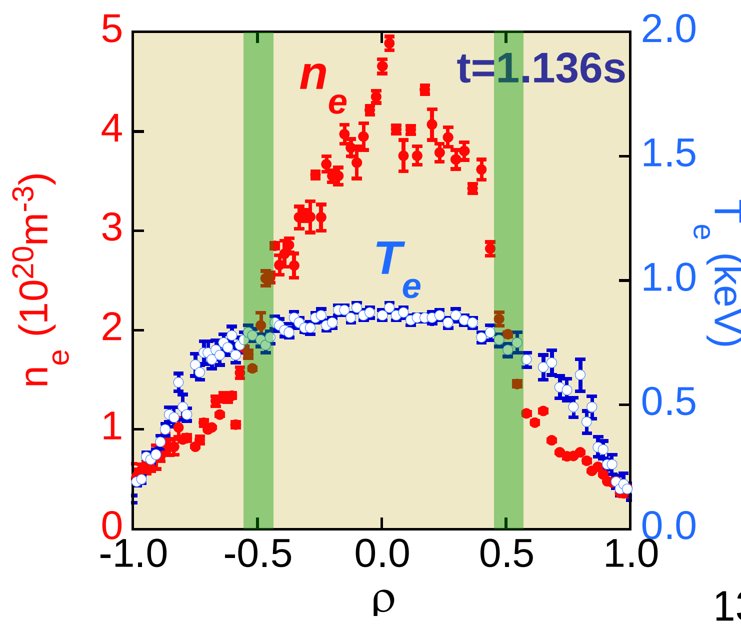
Internal Diffusion Barrier (IDB) is formed in LID-controlled plasmas core-fueled by pellets.



Previously observed in FY2005

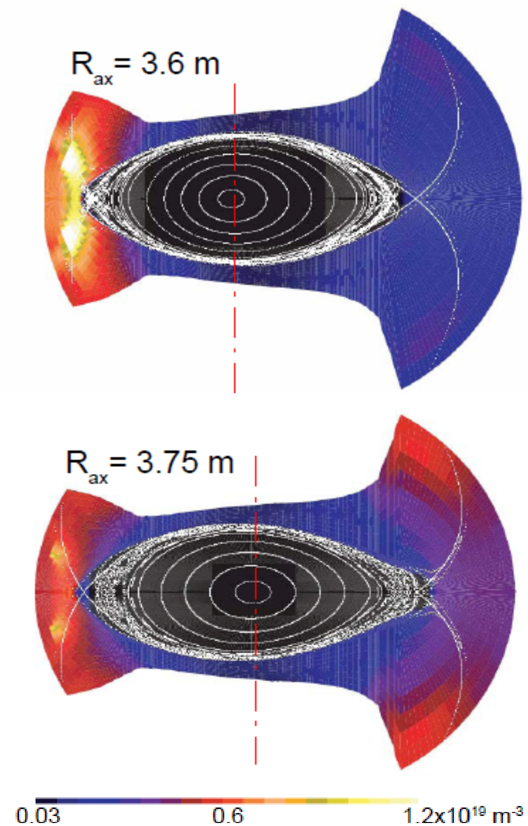
- LID realizes a low recycling plasma condition by strong particle control at plasma edge.
- Direct core fueling by repetitive pellet injection results in a super-dense-core (SDC) plasma of $n_e(0)=5\times10^{20}m^{-3}$, accompanied by formation of IDB.

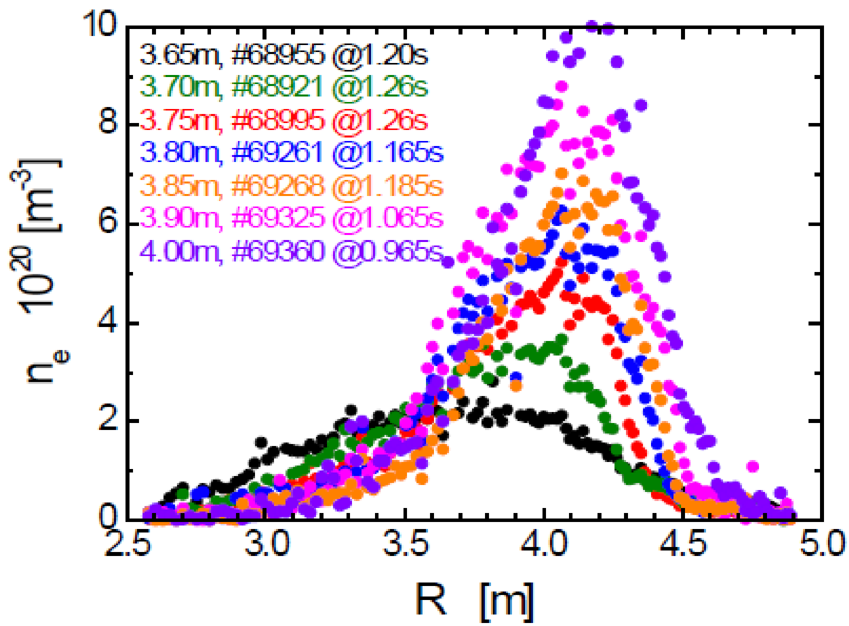




IDB is realized even in helical divertor (HD) configuration with well-conditioned wall.

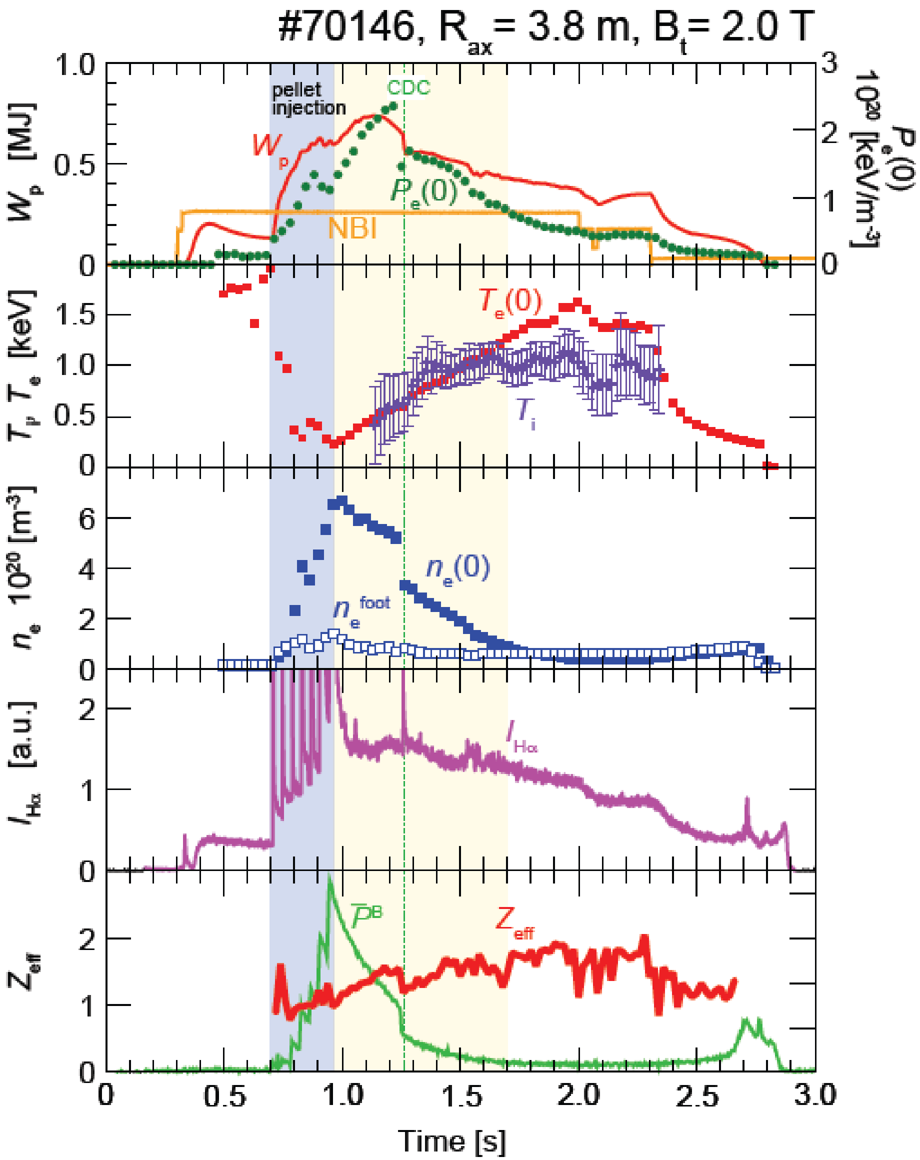
- Edge plasma control is a key issue to form the SDC/IDB plasmas.
- In the outward-shifted configuration, localization of neutrals is small, and the recycling is suppressed due to weaker plasma-wall interaction.
- Since the low edge-density can be maintained by the wall-pumping effect in the outward-shifted configuration, the SDC/IDB plasma is realized without the LID at R_{ax}^{vac} > 3.7m.





M. Kobayashi, I-07 on Tuesday

SDC/IDB plasma formed in HD configuration with core density collapse (CDC).

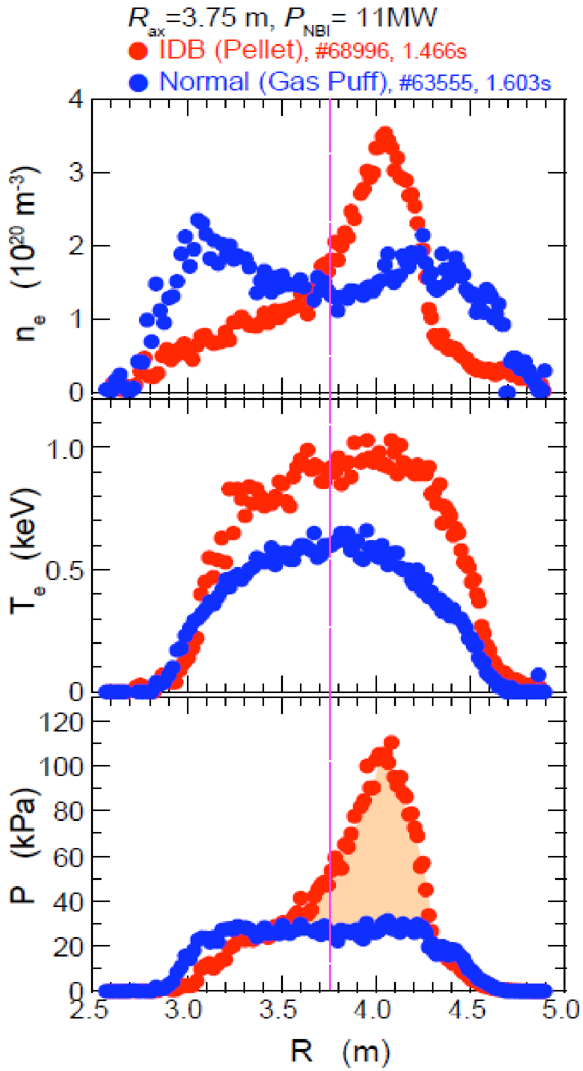


- **Density is rapidly increased by the core fueling with repetitive pellet injection.**
- **After the pellet injection, the peripheral density in 'mantle' region is rapidly decreased during the density relaxation with the recovery of temperature, and then the SDC/IDB plasma is formed.**
- **Central pressure continues to be increased and, occasionally, the core density collapse (CDC) occurs with an abrupt decrease in the central pressure.**

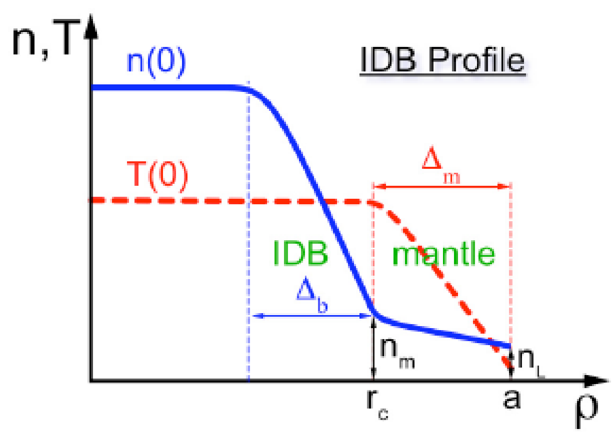
  J. Miyazawa, P1-087 on Tuesday

- **Impurity accumulation is not observed, and Z_{eff} is around 1.5 during the discharge.**

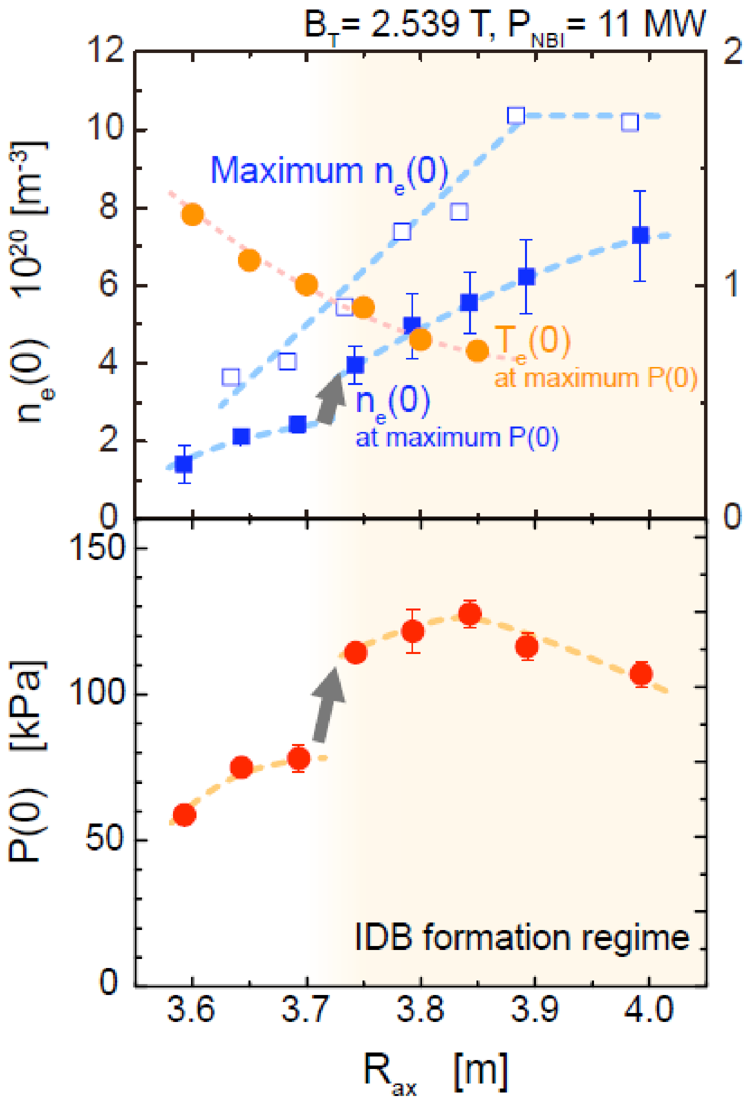
Large Shafranov shift with a steep pressure profile is observed in SDC/IDB plasmas with improved confinement.



- SDC/IDB plasma has a peaked density profile in the core region while a low density is maintained with a steep T_e-gradient in the 'mantle' region.
- Compared with the normal gas-puffing discharge, the peripheral T_e rises toward the core due to the low density in the 'mantle' region, and, as a result, the core T_e is higher.
- Central pressure is extremely high with a steep gradient, and large Shafranov shift is observed, approaching the equilibrium limit of Δ=a/2.
- Confinement improvement is suggested in the SDC/IDB plasmas.



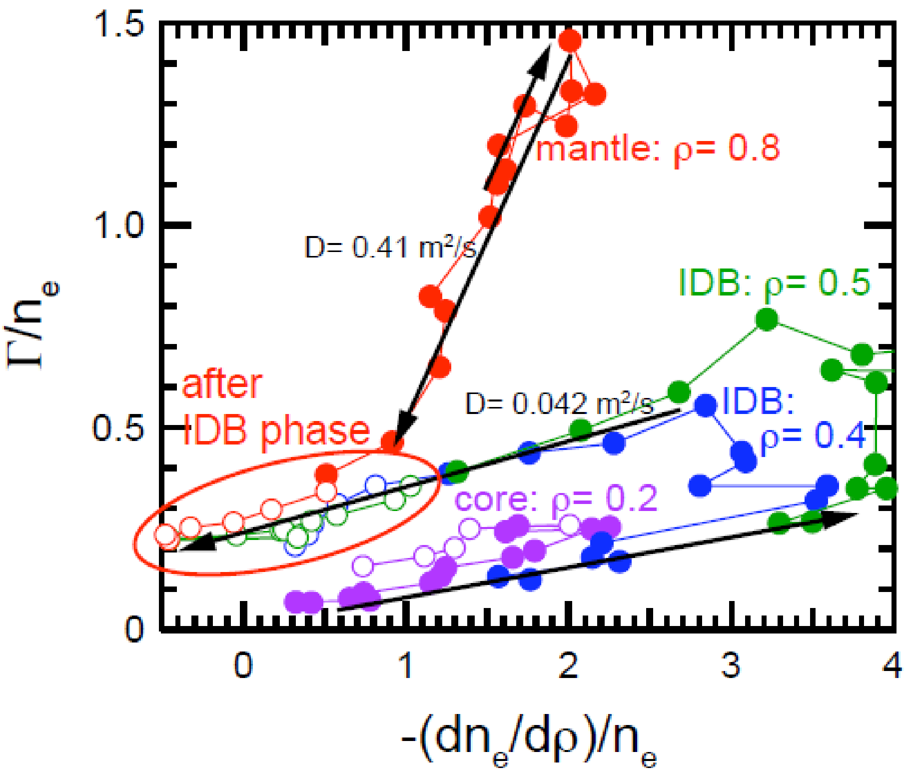
Central pressure exceeds an atmospheric pressure, and reaches 130kPa.



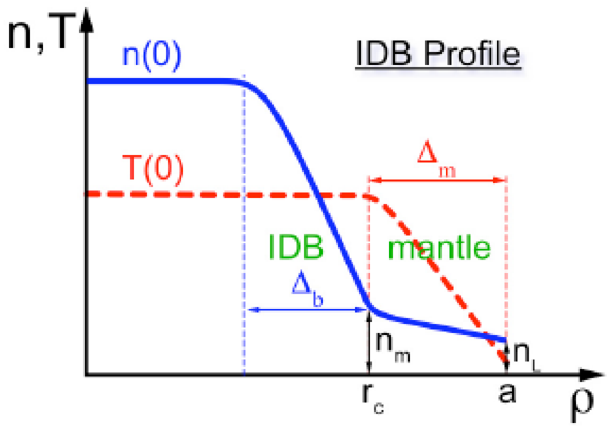
Preset vacuum R_{ax}

- Formation of the IDB in the HD configuration is observed in outward-shifted configuration at R_{ax}^{vac}>3.7m.
- Achieved $n_e(0)$ is increased as the R_{ax}^{vac} is shifted more outward, and the maximum $n_e(0)$ is $1\times10^{21}m^{-3}$ obtained at R_{ax}^{vac} = 3.9m.
- Peripheral density in the mantle region is maintained low, independent of the R_{ax}^{vac}.
- Central pressure, P(0), jumps up at the IDB formation, and the maximum P(0) is 130kPa observed at R_{ax}^{vac}=3.85m.
- High P(0) and the steep pressure gradient cause large Shafranov shift near the equilibrium limit, and, occasionally, the core density collapse (CDC) occurs.

Particle confinement is maintained well in core region while it is degraded in peripheral region.

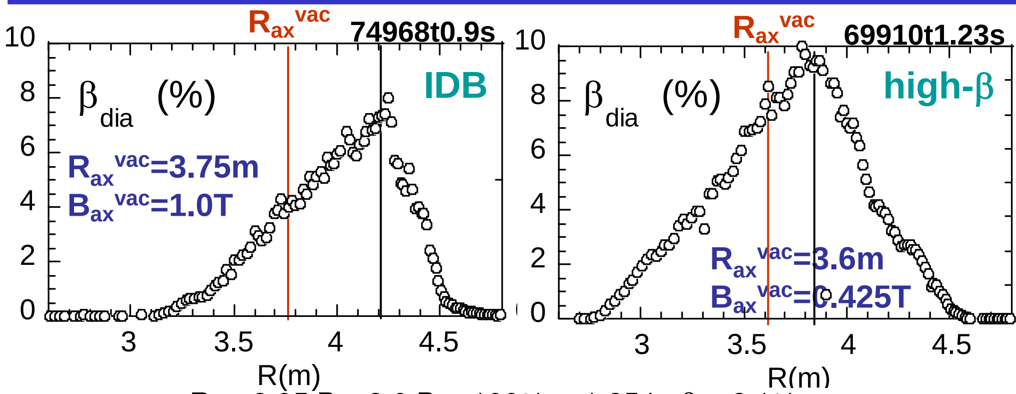


- Core particle diffusion is maintained low for the steep density gradient in the IDB formation.
- On the other hand, peripheral particle diffusion in the 'mantle' region is enhanced with an increase in the density gradient.
- As a result, the SDC/IDB plasma is formed with an extremely high core density and a low peripheral density.

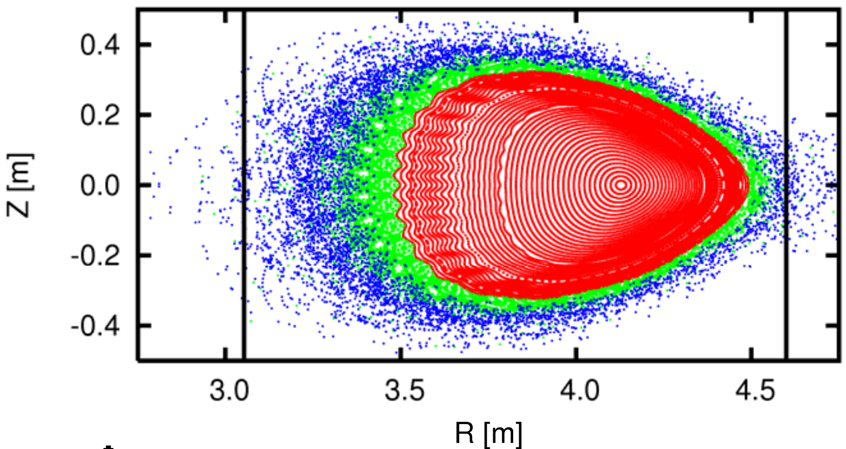


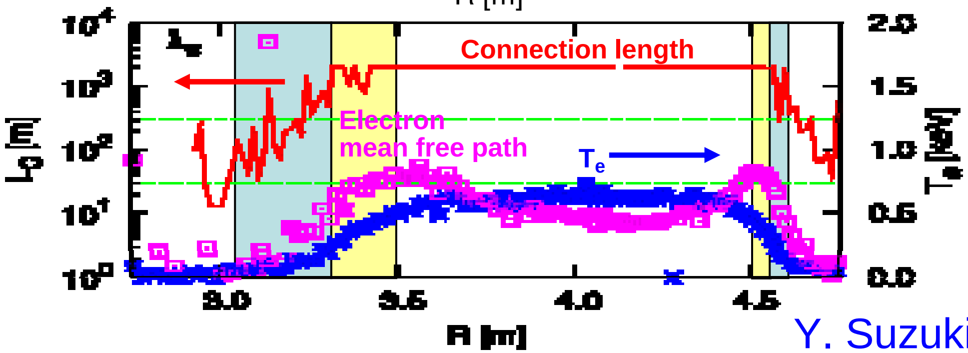
R. Sakamoto, I-04 on Tuesday

T_e-gradient can exist in the magnetic surfaces distorted by the large Shafranov shift.



R_{ax}=3.85,B_T=3.0,B_Q=100%,γ=1.254 <β>=2.1%

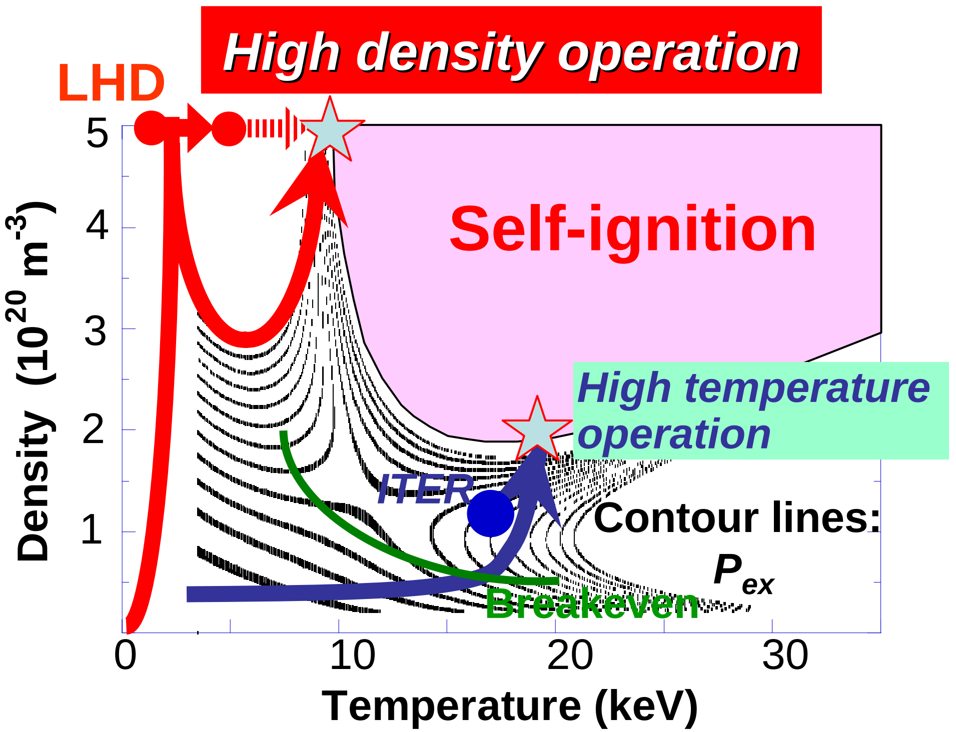




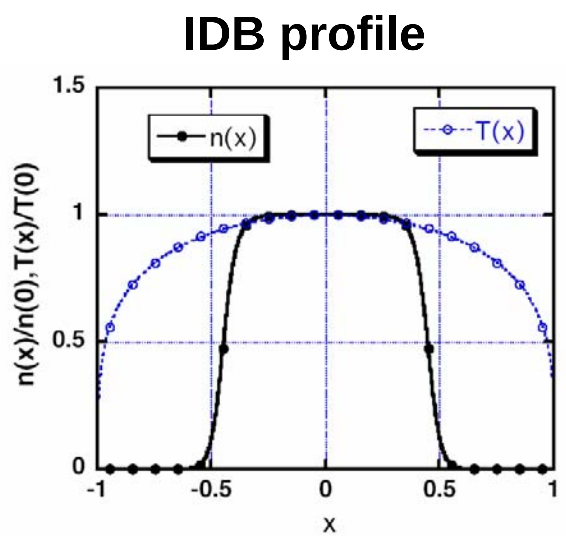
- Compared with the high-β plasmas at low B, the SDC/IDB plasma has a similar β(0), a steeper pressure gradient, and a larger Shafranov shift.
- Finite β equilibrium obtained with HINT2 code shows distorted magnetic surfaces in the ‘mantle’ region in the SDC/IDB.
- Connection lengths of the magnetic field lines are longer than the electron mean free paths.
- Thus, T_e profile in the ‘mantle’ region has a gradient even in the distorted region of the magnetic surfaces.
- SDC/IDB plasmas should be compatible with high-β plasma.

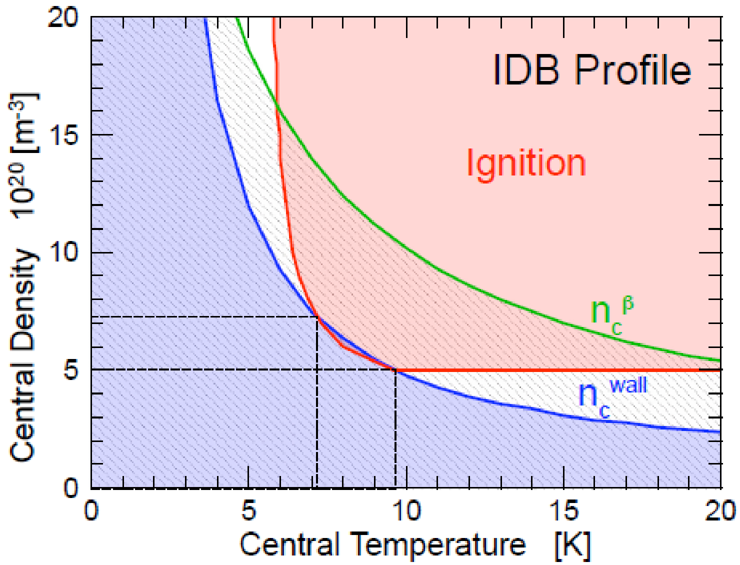
SDC/IDB plasmas pioneer a new approach to the ignition with a high-density scenario.

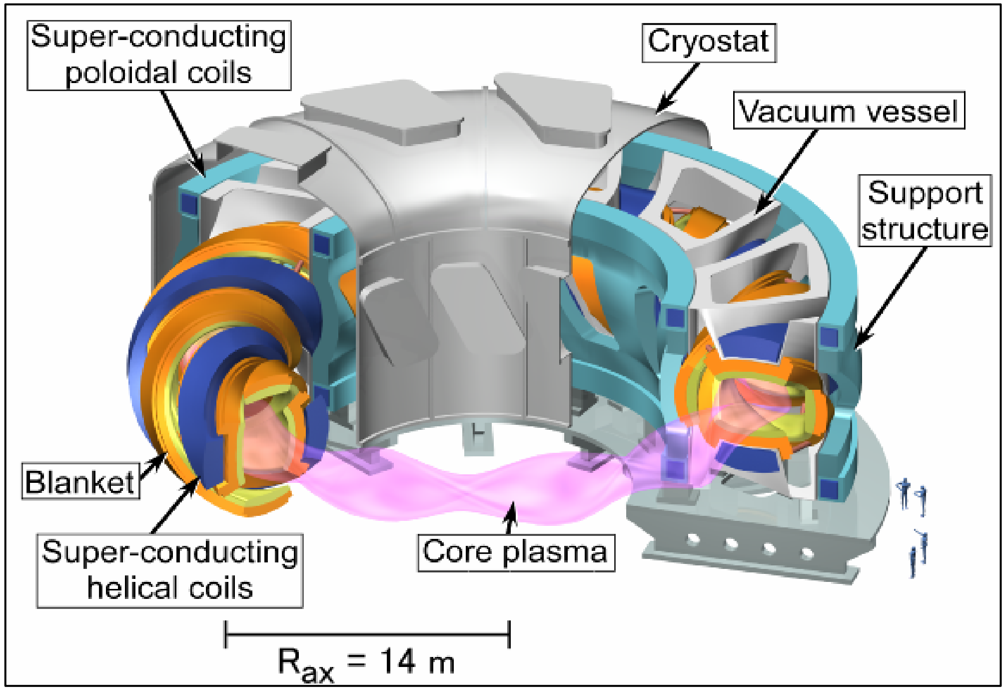
- Based on the SDC/IDB plasma parameters, high-density ignition scenario is proposed.
- Compared with the high-temperature ignition scenario, the engineering demand is much reduced, due to a moderate operational temperature.
- Helical system, in which the current drive is not required, can access the high-density operation, and the neoclassical ripple transport is mitigated.



LHD-type helical fusion reactor is being designed based on the high-density ignition scenario.







FFHR

1,000 MW

6Tesla

25,000 ton

Ignition condition:

$n(0) = (5 - 7) \times 10^{20}\ m^{-3}$

$T(0) = 7 – 10\ keV$

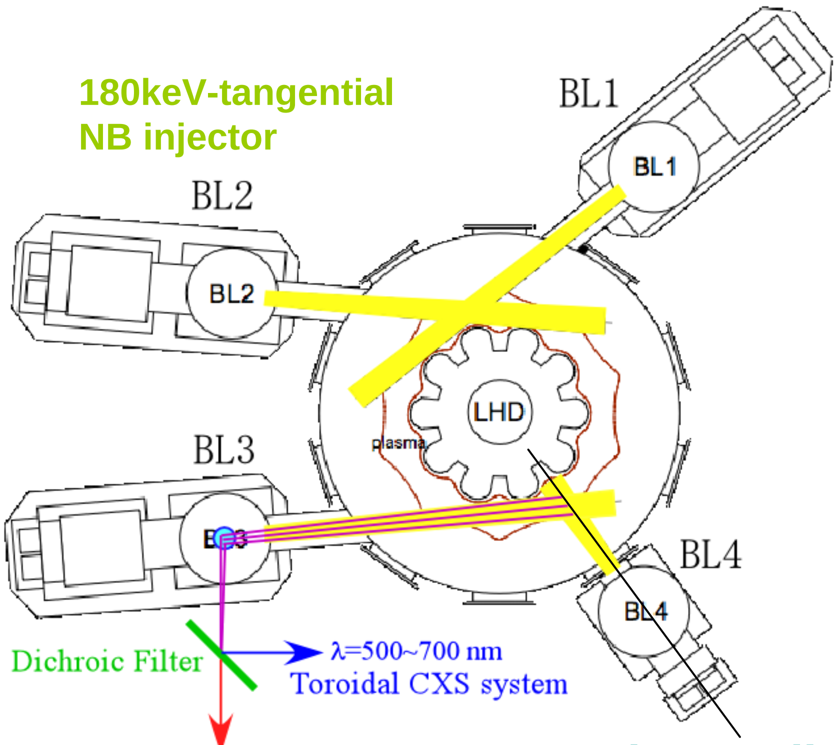
$\tau_E = 1.2\ \tau_E^{ISS95}$

A. Sagara, I-22 on Friday

Low-energy NBI system with perpendicular injection has been installed for the ion heating.

Also used for the T_i-profile measurement along a toroidal line of sight with CXRS

180keV-tangential NB injector



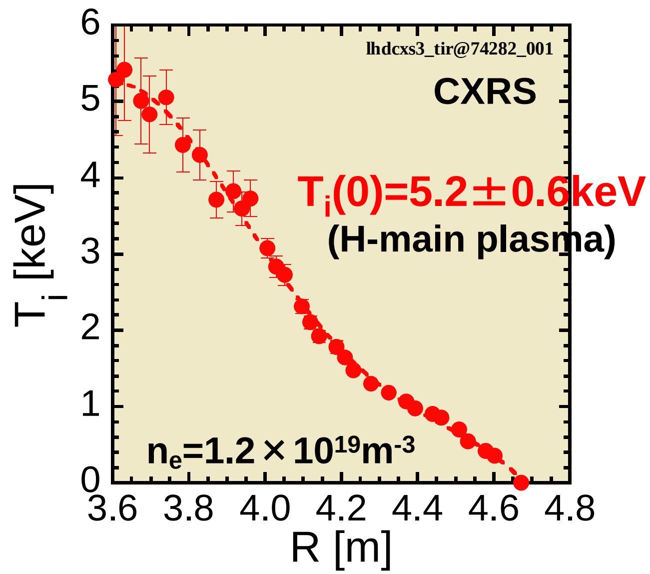
Toroidal line of sight for CXRS

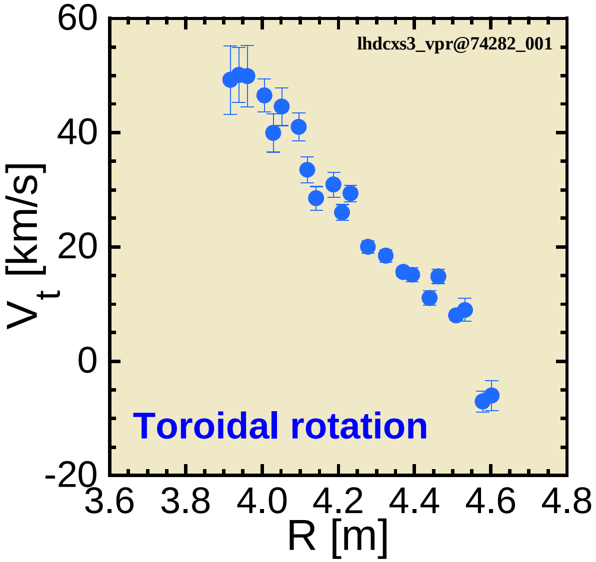
40keV-radial NB injector

- Ion heating is dominant with low-energy NBI.
  - Electron heating is dominant with present high-energy NB injectors.
- Particle fueling into core plasma
- Profile measurement of T_i and E_r (CXRS)
- Confinement study of perpendicular injected high-energy particles

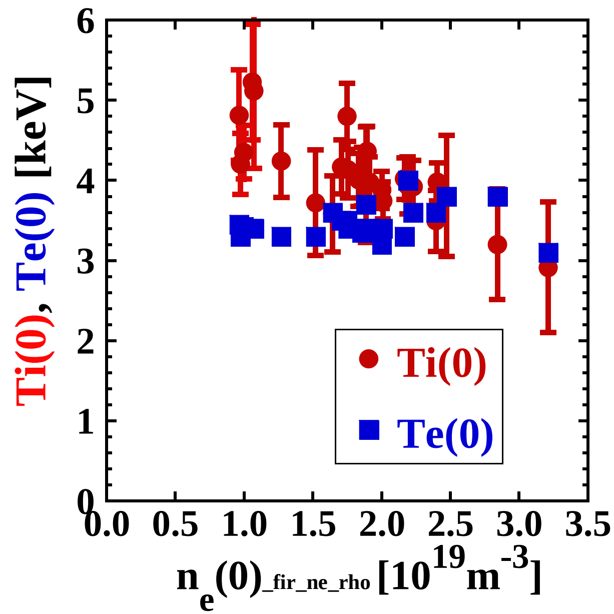
- Injection energy : 40keV
- Injection power : 6MW (with 4 positive-ion sources)
- Perpendicular hydrogen injection

Ion temperature exceeds 5keV in H-main plasmas by combination of low- and high-energy NB injections.





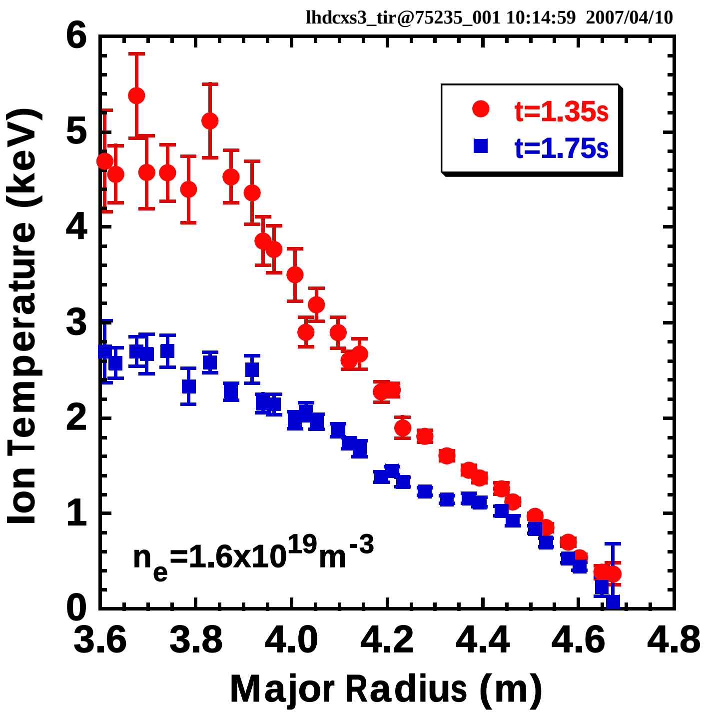
- High ion-temperature of 5.2keV has been achieved in H-main plasma at $1.2\text{x}10^{19}m^{-3}$, and high-T_i regime has been extended toward higher density plasmas.
- Large toroidal rotation and its shear is observed in association with the T_i rise.

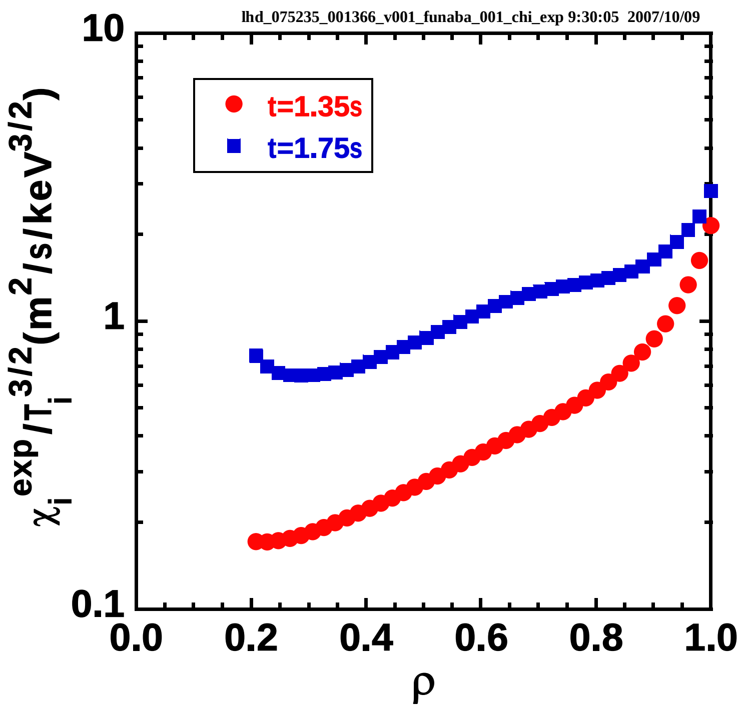


K. Nagaoka, O-11 on Thursday
M. Yoshinuma, O-12 on Friday
M. Yokoyama, P1-036 on Tuesday

Ion transport is improved in the high-T_i plasma with a reduction of the anomalous transport.

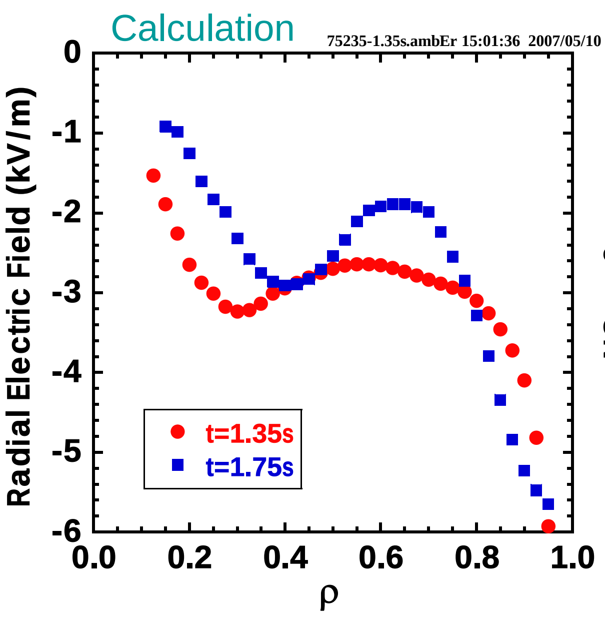
- Ion thermal diffusivity divided by the gyro-Bohm factor, $\chi_i / T_i^{3/2}$, is reduced with the T_i rise.
- Anomalous transport should be reduced in the high-T_i plasma.
- Electron transport is not changed.

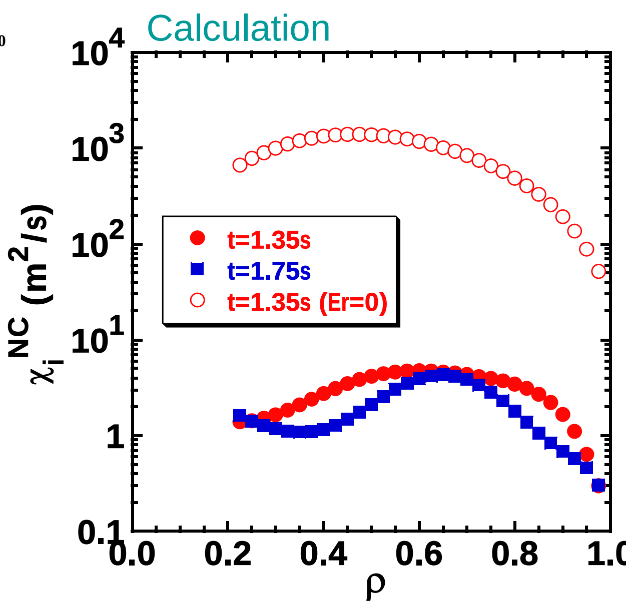


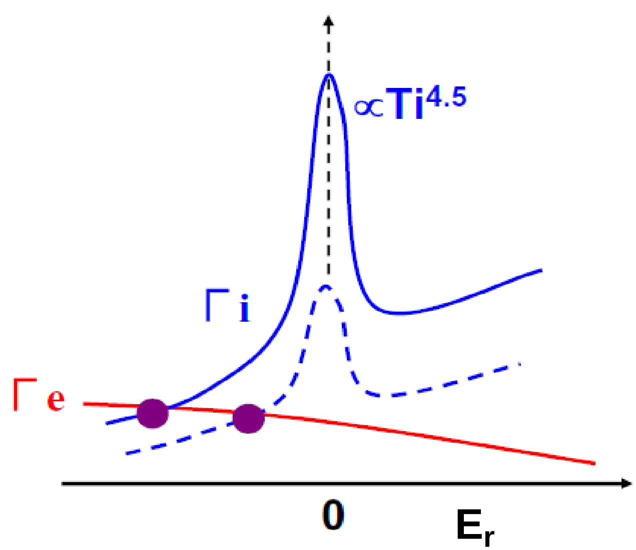


Enhanced ripple transport is suppressed in ion root with negative E_r in the high-T_i plasma.

- Neoclassical ambipolar calculation indicates negative E_r in the T_i rise.
- Ripple transport of ions would be greatly enhanced by the T_i-rise without consideration of the E_r effect.
- With strong reduction of the ripple transport by the negative E_r, neoclassical χ_i is not so changed with the T_i rise.
- Considering the experimental results, the improvement of ion confinement is due to reduction of the anomalous transport in the ion root.







Achieved plasma parameters are approaching to the final targets in LHD.

	Final Targets	*Achievements*	
Fusion triple product: $n\tau T$	5×10^{19} keVm^{-3}s	4.4×10^{19} keVm^{-3}s	
Ion temperature (average)	2.5 keV : $\langle T_i \rangle$	0.8 keV : $T_i(0)$	
Density	1×10^{20} m^{-3}	5×10^{20} m^{-3}	
Energy confinement time	0.1 - 0.2 s	0.11 s	
Electron Temperature: T_e			
Central T_e	10 keV	10 keV	15 keV
Density	2×10^{19} m^{-3}	5×10^{18} m^{-3}	2×10^{18} m^{-3}
Ion temperature: T_i			
Central T_i	10 keV	13.5 keV	5.2 keV
Density	2×10^{19} m^{-3}	3×10^{18} m^{-3} (Ar gas)	1.2×10^{19} m^{-3} (H gas)
Beta: β	β = 5 %	β = 5.0 %	
Magnetic field strength	1 - 2 T	0.425 T	
Steady state operation			
Pulse length	3600 s at 3 MW	3900 s at 110 kW 1905 s at 680 kW 3268 s at 490 kW (Input Energy: 1.6GJ)	

Now, proposing the next experimental stage.

Deuterium experiments with upgrading the heating facilities

- Plasma performance is expected to be improved by a factor of 1.5 – 2 in deuterium experiments.
- Plasma parameters are also pushed up by increasing the heating power.
- By systematic investigations of high-performance plasmas with plasma parameters of the LHD goal, the helical fusion reactor can be designed.

Achievements [Final target]

Ion Temperature

Central T_i 5.2 keV [10 keV]
Density $1.2\times10^{19}m^{-3}$ [$2\times10^{19}m^{-3}$]

Central T_i 13.5 keV
Density $3\times10^{18}m^{-3}$ (Ar gas)

Electron Temperature

Central T_e 10 keV [10 keV]
Density $5\times10^{18}m^{-3}$ [$2\times10^{19}m^{-3}$]

> 10 keV : reactor condition

Volume Averaged β

5.0 % (B=0.425T) [≥ 5 % (1-2 T)]

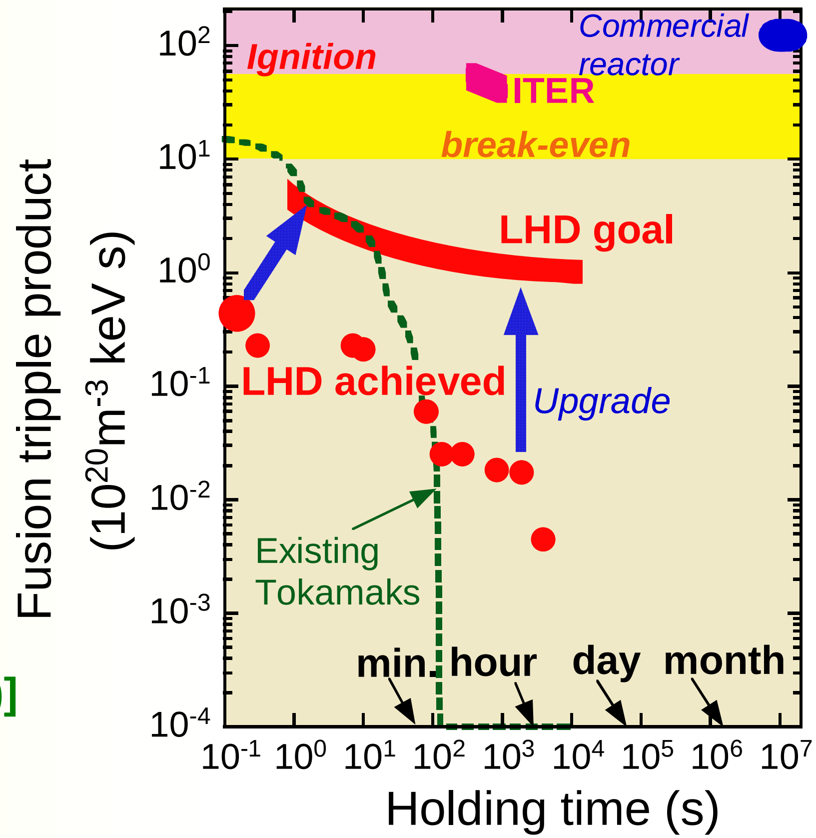
Steady State Operation

31min.45sec. (680 kW) 1.3GJ [1 hour (3,000 kW)]
54min.28sec. (490 kW) 1.6GJ

Largest input energy

High Density

$1\times10^{21}m^{-3}$



Summary

- LHD has much progressed for the 9 year's operation, and extended the parameter regime toward a helical fusion reactor.

- Reactor relevant <β> value of 5% was achieved without any disruptive MHD instabilities.

- IDB plasmas were formed in the helical divertor configuration, and high central density of $1 \times 10^{21} m^{-3}$ was observed.

- High-T_i of 5.2keV was obtained in H-plasmas at $n_e = 1.2 \times 10^{19} m^{-3}$., and the ion transport improvement was observed with a reduction of the anomalous transport in the neoclassical ion root.

- High-density ignition scenario based on IDB/SDC plasmas is proposed for the helical fusion reactor, which reduces the engineering demand and mitigates the helical ripple transport.

- Upgrade of LHD is proposed, including deuterium experiments and power-up of the heating systems to the further extension of the operational regime for designing the steady-state helical fusion reactor.