Confinement and MHD Stability in the Large Helical Device

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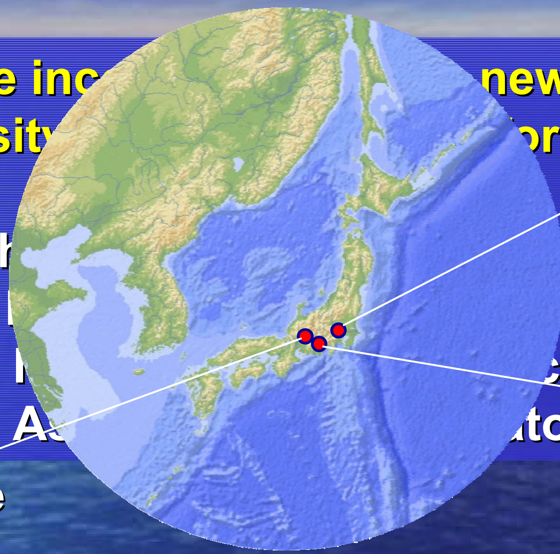
Content of my paper

- 1. Change of NIFS Organization
- 2. MHD study
- 2.1. High beta experiment
- 2.2. Healing of magnetic island
- 3. Extended operation regime in LHD
- 3.1 Edge control by Local Island Divertor
- 3.2 Control of radial electric field by shift of magnetic axis
- 3.3 Density limit and radiation collapse
- 3.4 Achievement of high ion temperature with NBI
- 3.5 Long pulse operation with ECH
- 4 Transport study
- 4.1 Properties of particle and heat transport
- 4.2 Electron transport
- 5 Summary

Big Challenge!
National Institute for Fusion Science (NIFS) joined a new organization in April, 2004
"National Institutes of Natural Sciences (NINS)"

NIFS will be inc... new academic agency, as an inter-university ... or universities all over Japan

Together with ... arch Institutes (Institute for ... onal Institute for Basic Biology and National ... cal Sciences) and National A... tory of Japan



Fusion, Astronomy, Materials, Biology, etc.

- **Increase the activities of mutual collaboration and exchange program with domestic and international universities and institutions to develop individual research areas and new science categories**
- **Provide adequate research opportunities for scientists**
- **Work with Universities to educate graduate students**

Objectives of NIFS/LHD Project

National Institute for Fusion Science

- Established in May, 1989

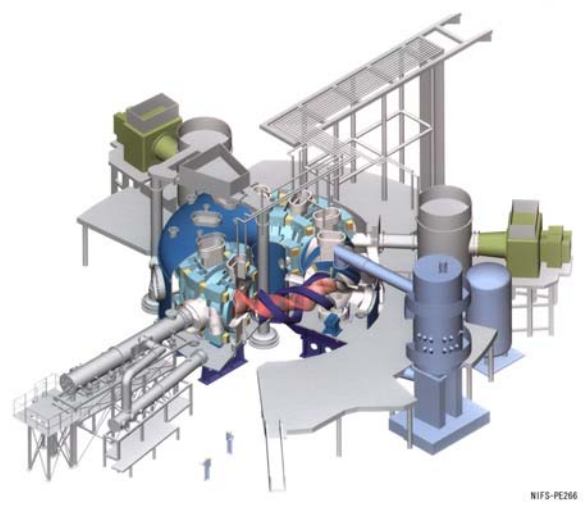
  An inter-university National Institute to promote scientific research of fusion plasmas and their application

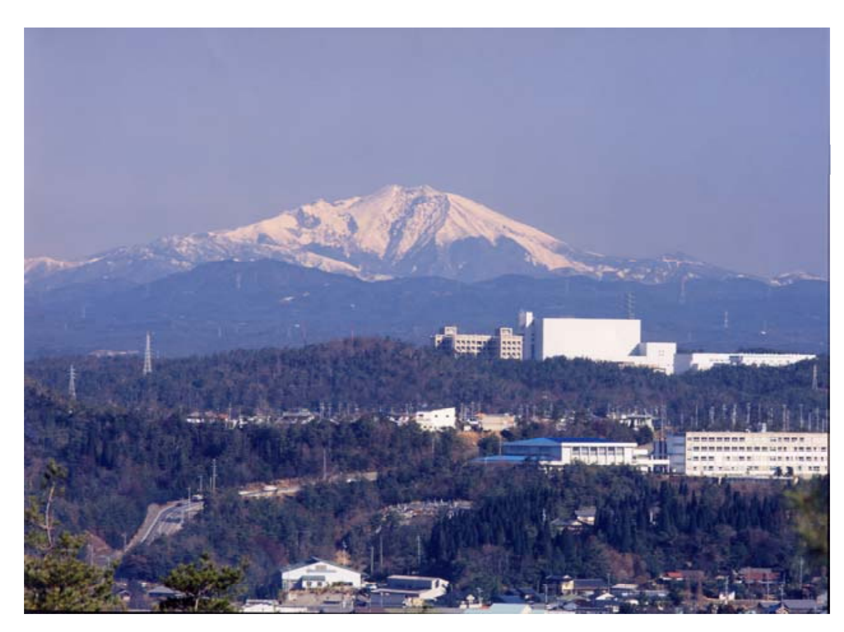
  ← Report of National Council for Science and Technology in 1984

- NIFS promotes experimental and theoretical research into fusion and plasma physics using the world's largest superconducting helical experiment, the Large Helical Device (LHD) and by means of theoretical and simulation studies

  → Based on the Heliotron, an original Japanese concept

- Increased effort in fusion technology



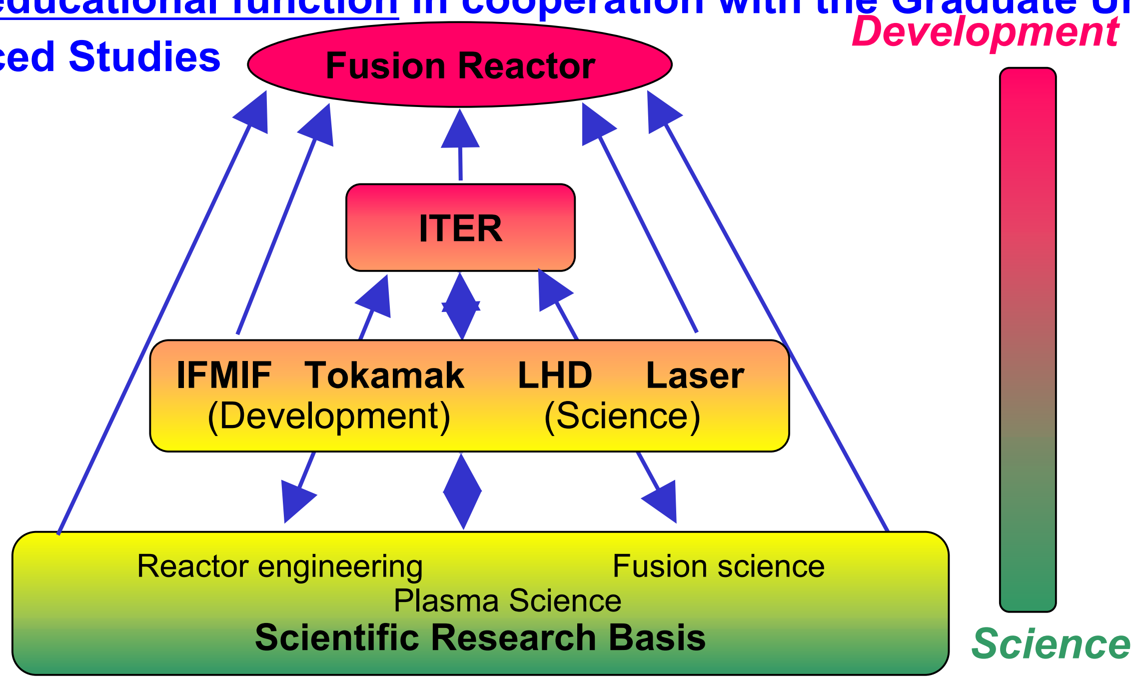


Ground Design of Japanese Fusion Research

Now, role of NIFS is clear

- **Keep a close relation with universities**
- **Increase collaboration as a center of excellence of fusion research**
- **Increase educational function in cooperation with the Graduate University for Advanced Studies**

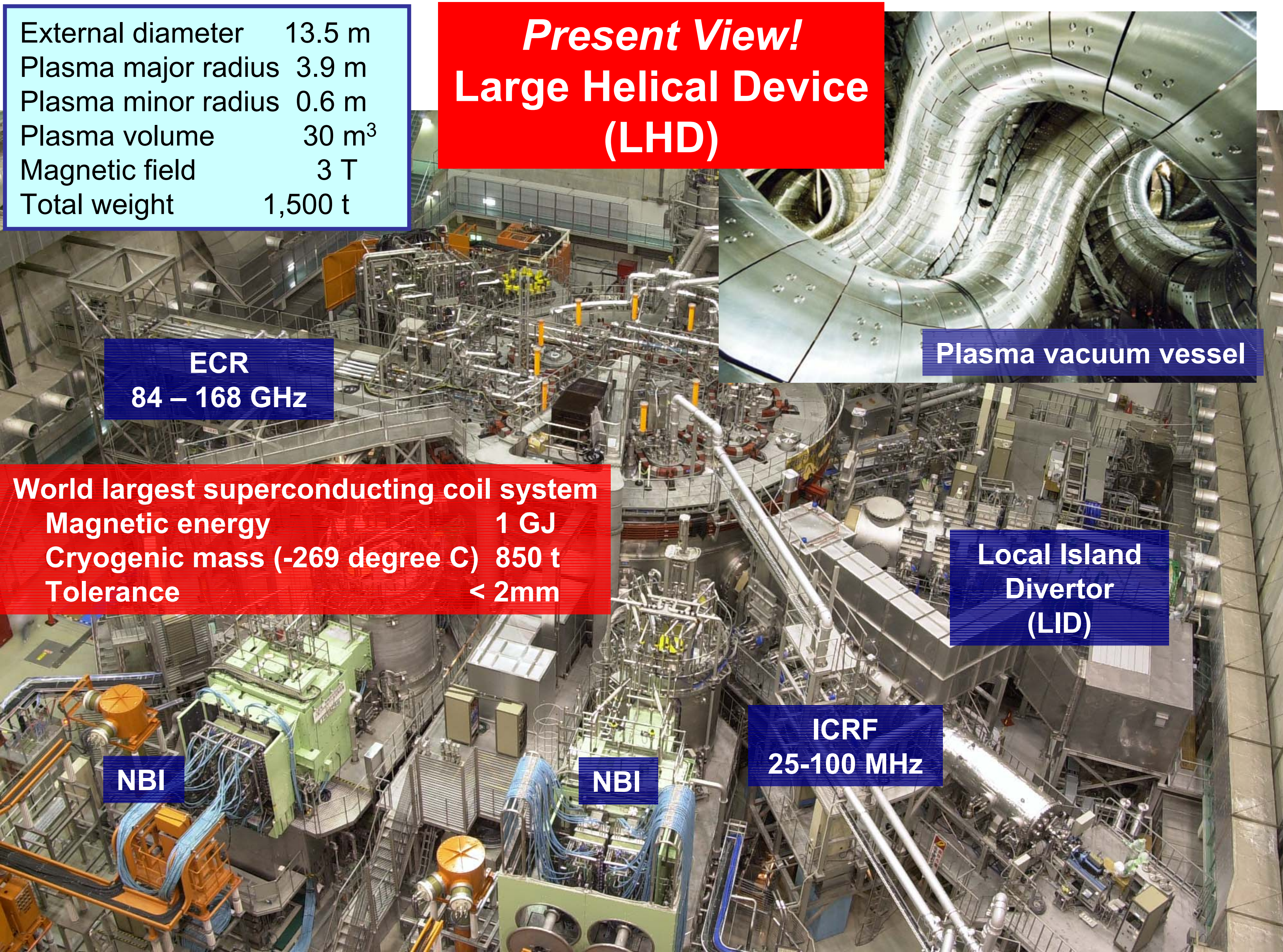
Stratified Structure of Research towards Fusion Reactor



Working Group on Fusion Research
Future Direction of National Fusion Research
Special Committee on Basic Issues
Subdivision on Science Council for Science and Technology

Present View!
Large Helical Device (LHD)

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



World largest superconducting coil system

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

Mission of LHD

Physics Issues Contributing to Fusion Research

(a) To realize high $n\tau_E T$ plasmas and to study transport physics applicable to fusion plasmas,

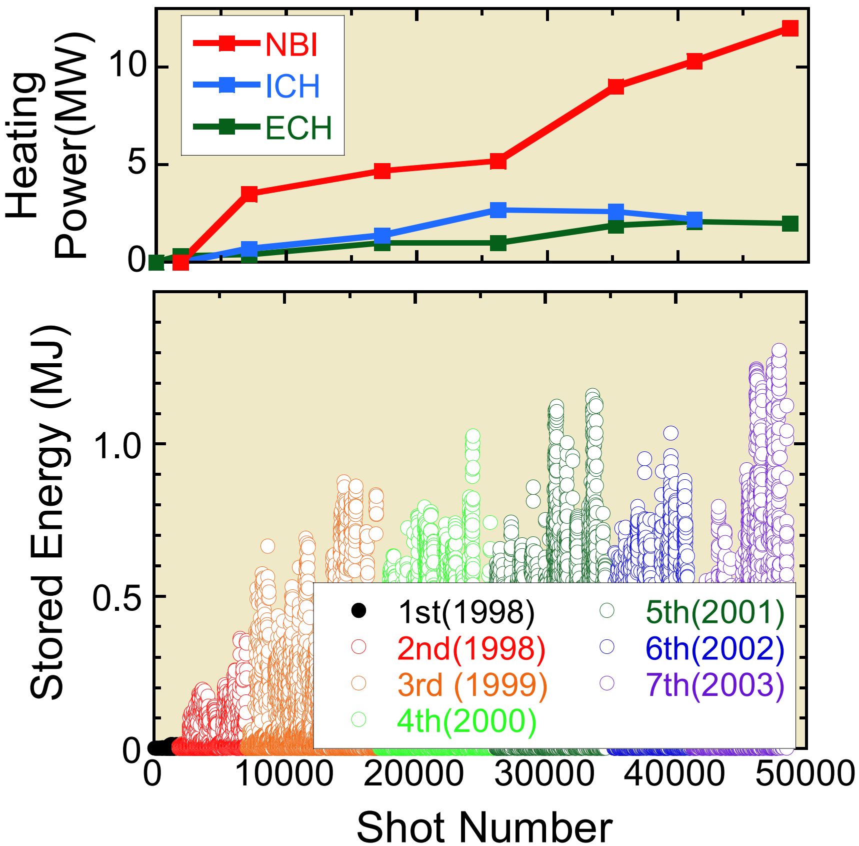
(b) To demonstrate high β stable plasmas (<β> ≥ 5 %) and to study related physics,

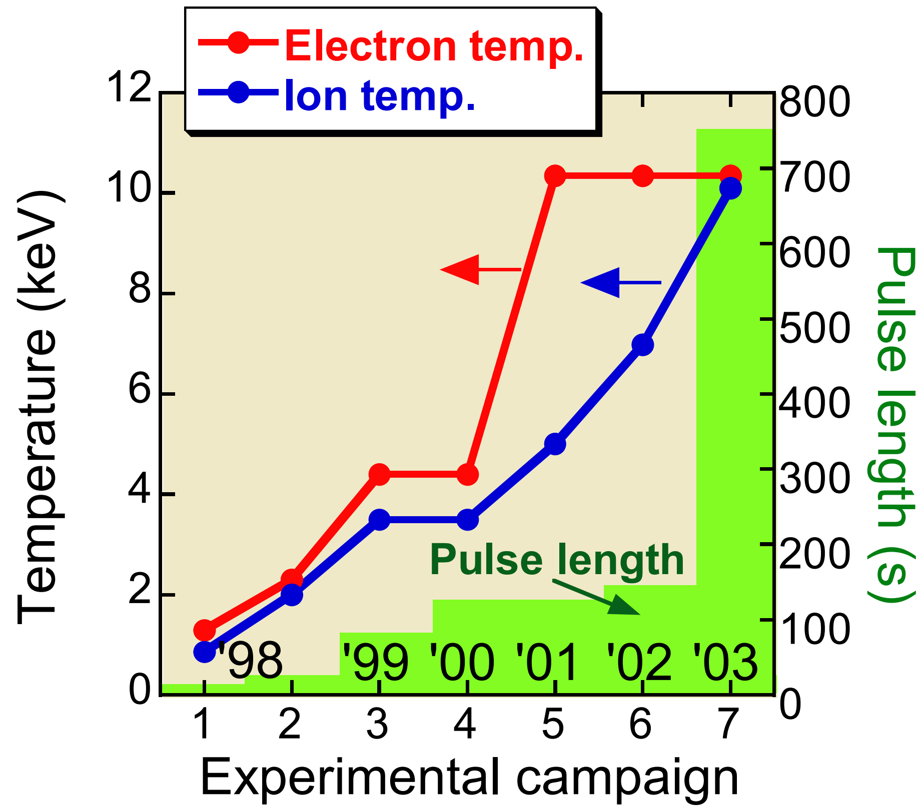
(c) To develop physics and technology for long pulse or steady state operation and control using divertor,

(d) To study energetic particle behaviors to simulate a particles in fusion plasmas,

(e) To increase the physics understanding of toroidal plasmas by an approach which is complementary to tokamaks

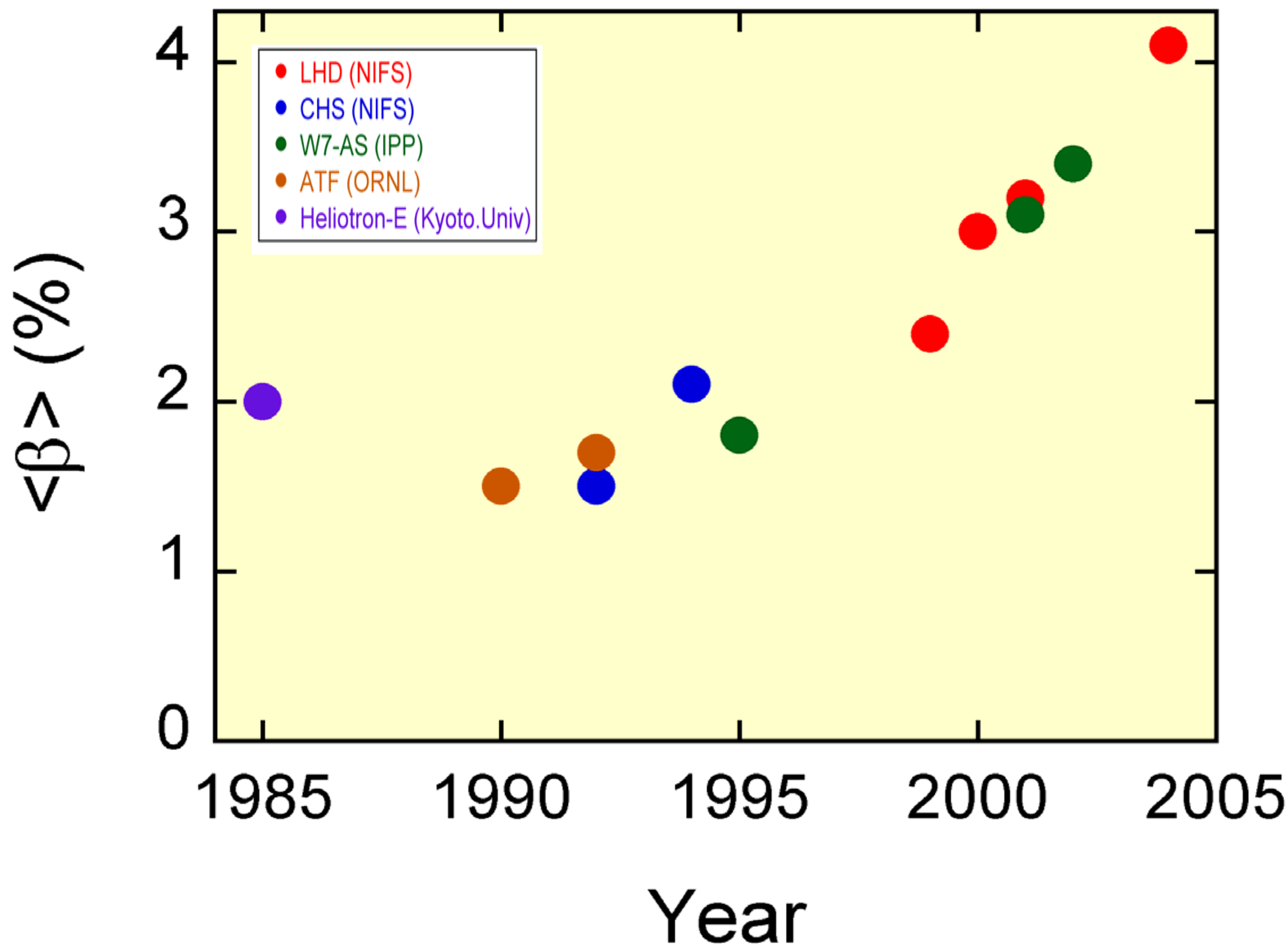
Steady progress of plasma parameters





- Stored energy has reached 1.3MJ comparable to big tokamaks.
- Electron temperature 10 keV
- Ion temperature 10 keV
- Beta 4.1 %
- Density 2.4x10^{20} m^{-3}
- Pulse length 756 s

Beta value has reached 4.1%



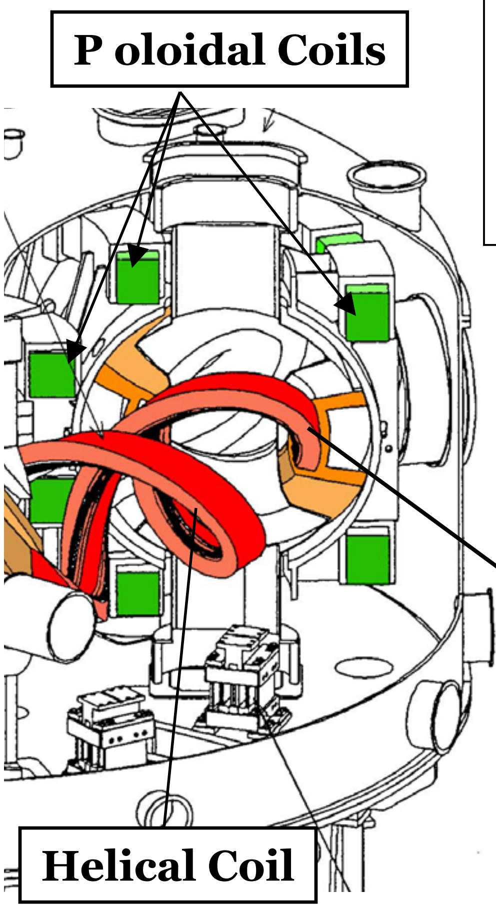
- LHD has been pushing beta

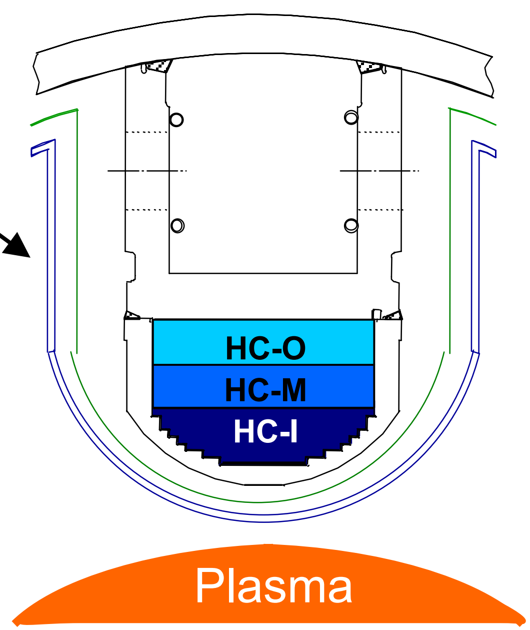
Aspect-ratio (γ=n/m·a_c/R=$\kappa\varepsilon$) Control in LHD

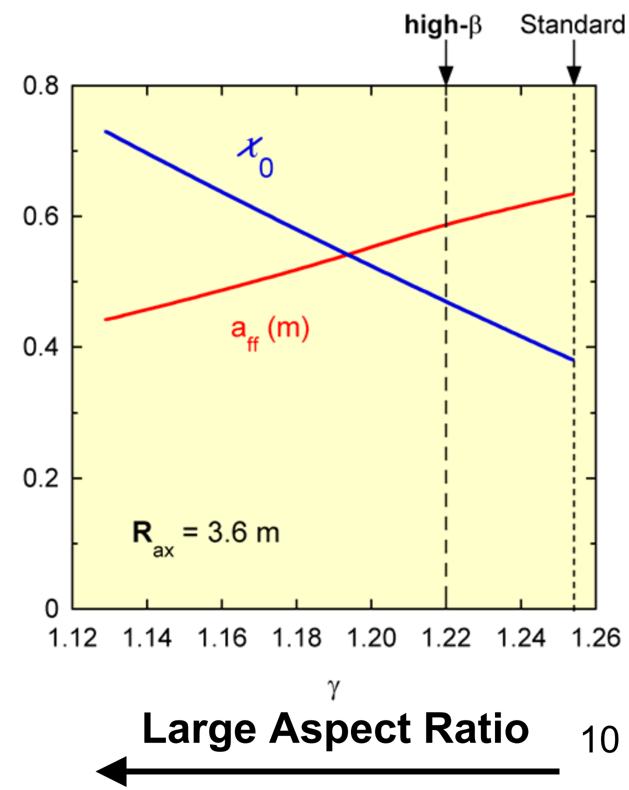
- Aspect ratio of plasma is optimized by controlling the central position of HC current

- Aspect-ratio of 5.8 ~ 8.3 is available in the R_{ax} = 3.6 m configuration

- High aspect-ratio configuration has high rotational transform which restrains the plasma shift

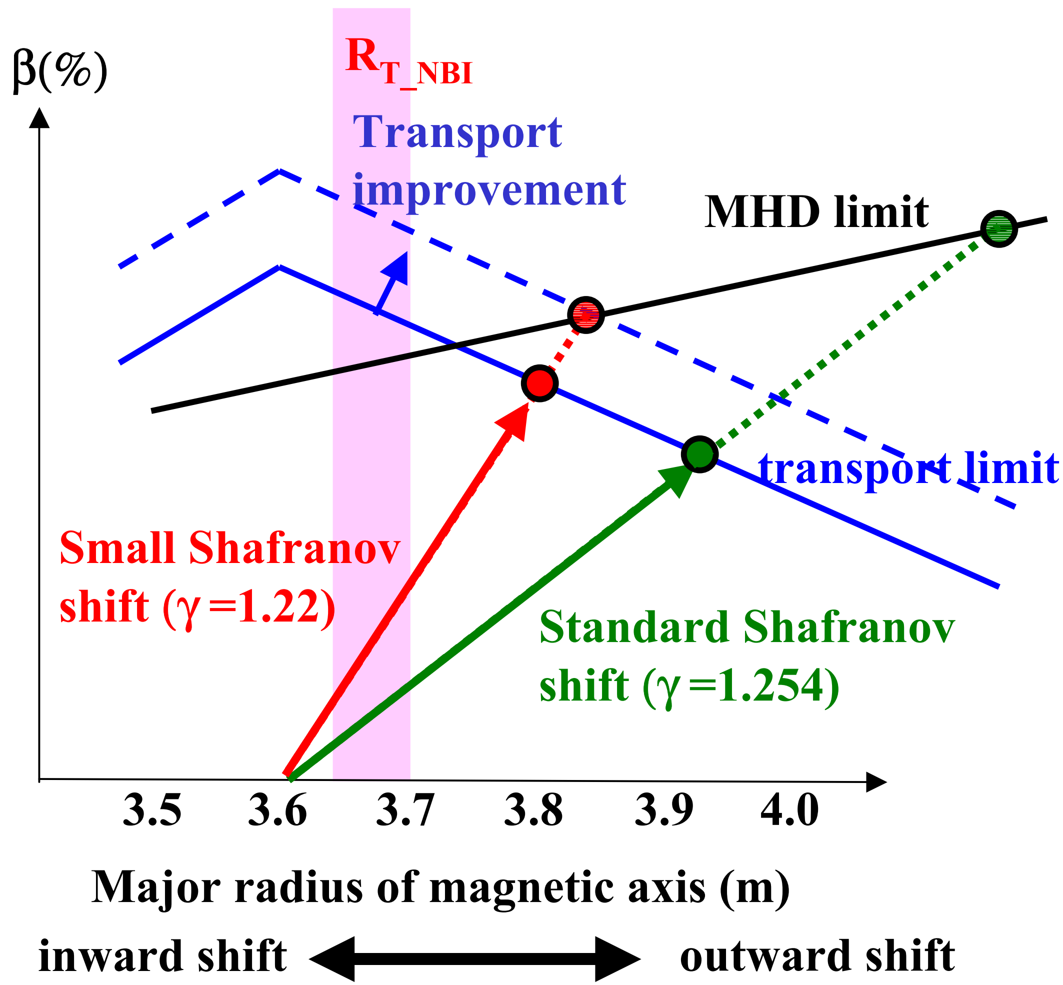


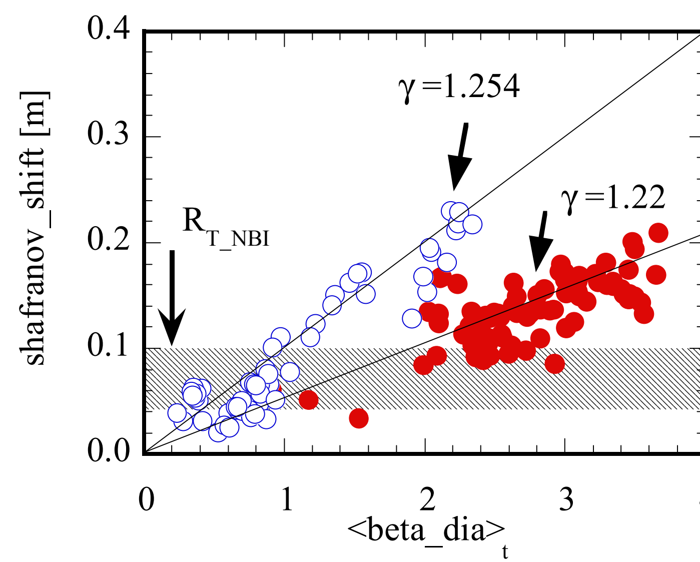




Scenario to achieve high β plasma in LHD

• γ optimization to minimize Shafranov shift is a key

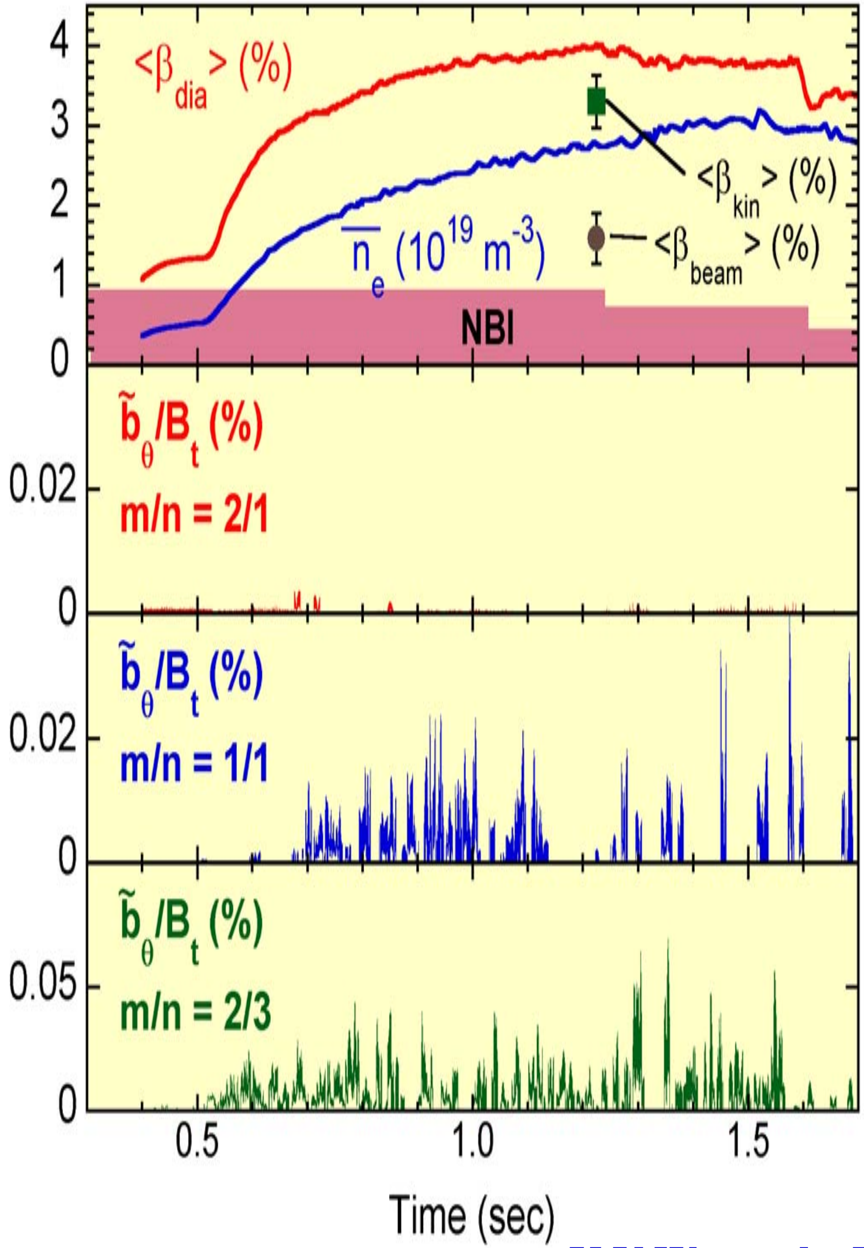




Smaller Shafranov shift (γ=1.22) has higher transport limit for a given heating power and better heating efficiency

Although it has lower beta limit than the standard configuration (γ=1.254)

High beta discharge at B=0.45T



Beta value has reached 4.1%

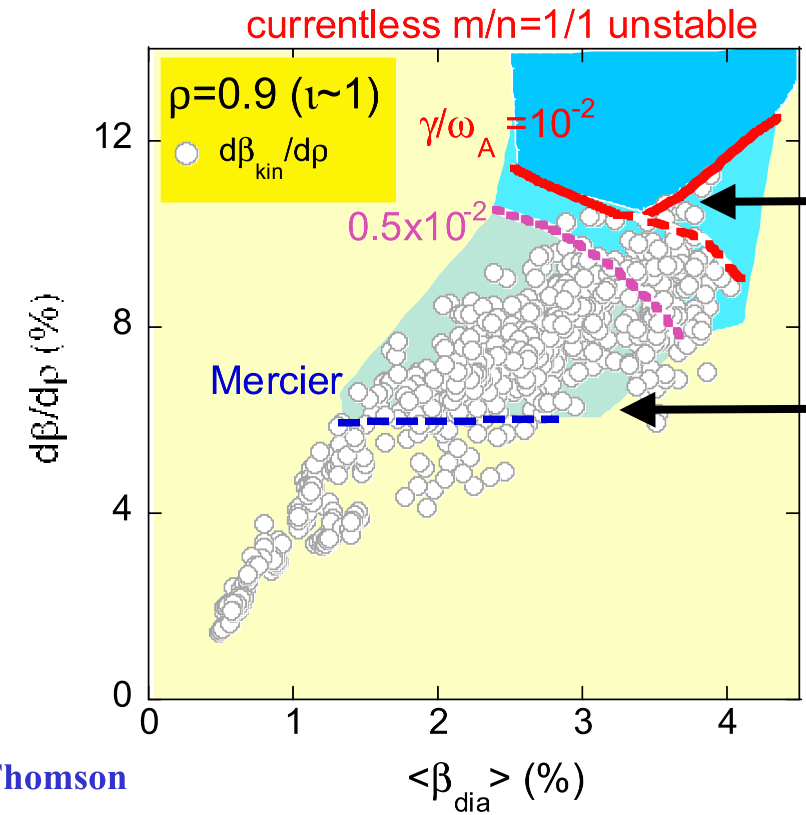
· The core fluctuation (ex.*n*/*m*=1/2) disappears because of spontaneous generation of magnetic well

· Even edge fluctuation (*n*/*m*=1/1) is mitigated because of flattening of pressure gradient

→ Further progress expected

Study on MHD stability limit of high beta plasma

Role and Function of Boundary



Achieved beta is close to the m/n=1/1 ideal mode limit

Achieved beta significantly exceeds the Mercier limit

γ=1.22

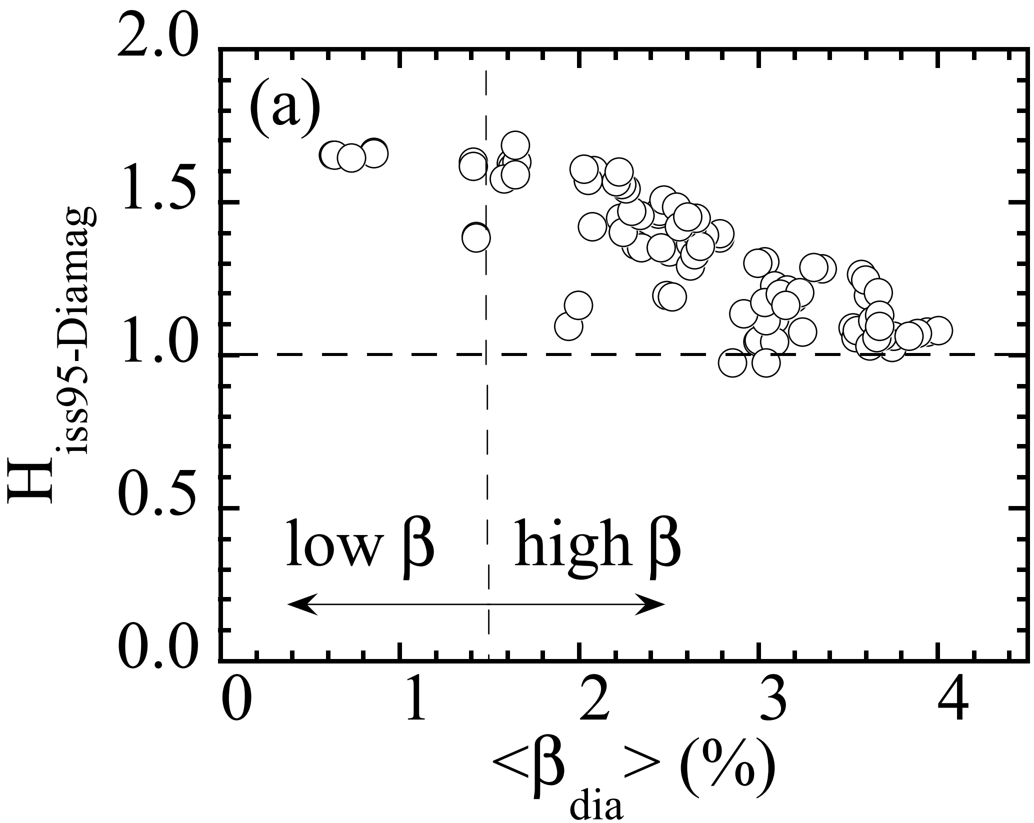
(γ=n/m·a_c/R=$\kappa\varepsilon$)

T_e(T_i): Thomson
n_e:FIR

· β values achieved significantly exceeds the Mercier limit and increases up to m/n=1/1 ideal MHD limit

kinetic beta gradients at ρ=0.9 (ι/2π = 1) in <β>-dβ/dρ diagram.

Confinement property of high β regime



- **H-factor with respect to the ISS95 scaling decreases as the β is increased**
- **This decrease is due to the possible reduction of ISS95 scaling at higher collisionality**

- **Degradation of energy confinement due to high β is not observed**

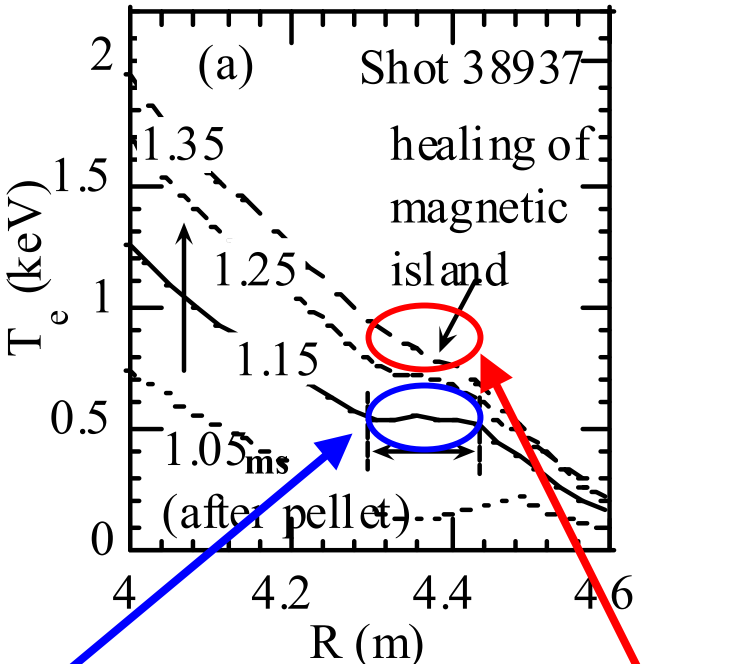
The improvement factor of effective energy confinement as a function of
(a) beta value for the plasma with R_{ax}=3.6m, B=0.45-1.75T and γ = 1.22 and

K.Y.Watanabe EX/3-3
B.J.Peterson EX/6-2

Healing of magnetic island

- **Magnetic island appearing after the pellet injection is healed by itself as the collisionality decreases**

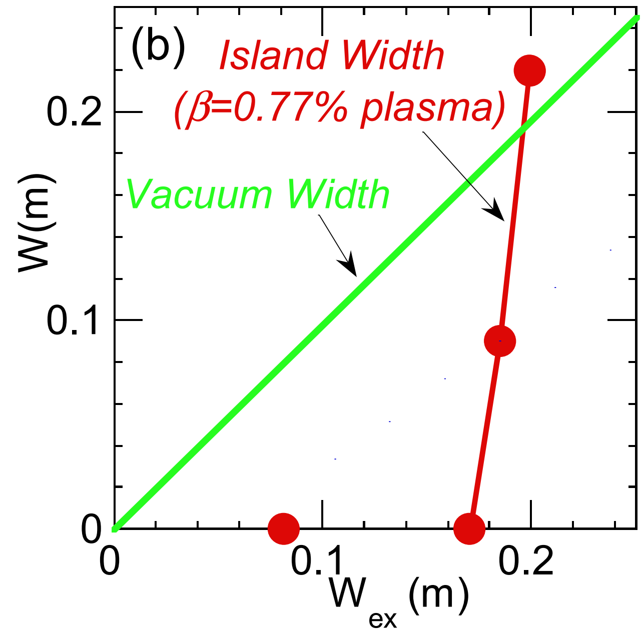
- **Positive shear(ι/2π) plays an important role on MHD property of LHD**



high ν_b^* → **Low ν_b^***

Magnetic island is growing

Magnetic island is healed



- **Magnetic island existing in the vacuum field is healed, when the size of magnetic island is small (w<0.3a)**

(a) Time evolution of the *Te* profile with the *n*=1 external field.
(b) Normalized coil current vs. island width (*w*) in vacuum (open circles) and in plasma (closed circles).

Y.Nagayama EX/P5-14

Extended operation regime in LHD

- Edge control by Local island divertor (LID)
- Control of radial electric field by shift of magnetic axis
- Density limit and radiation collapse
- Achievement of high ion temperature with NBI
- Long pulse operation with ECH

Transport study

- Properties of particle and heat transport
- Electron transport

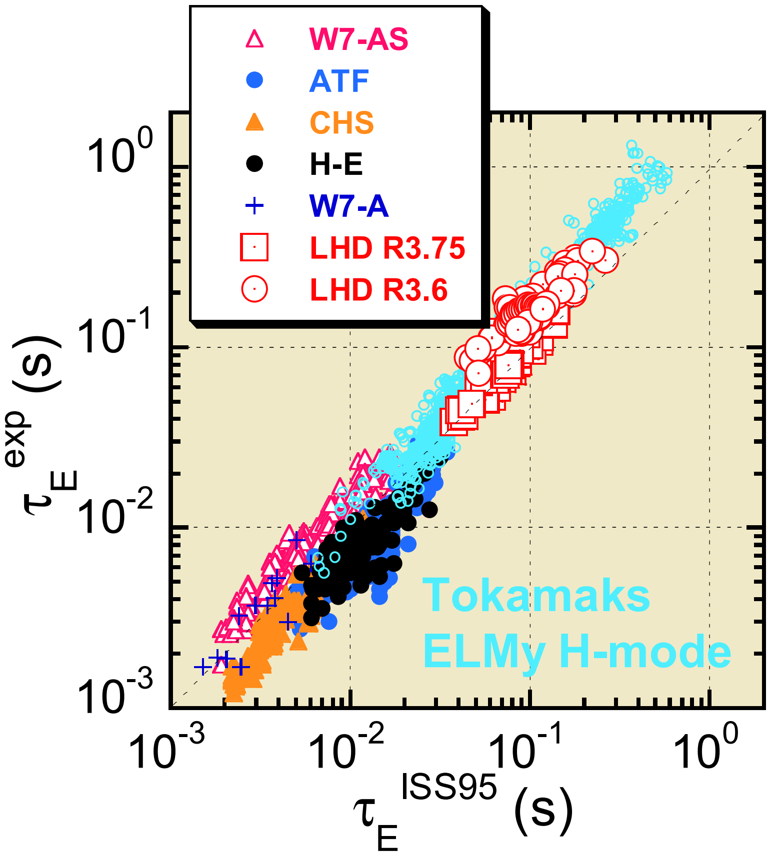
Energy Confinement and Targets of LHD

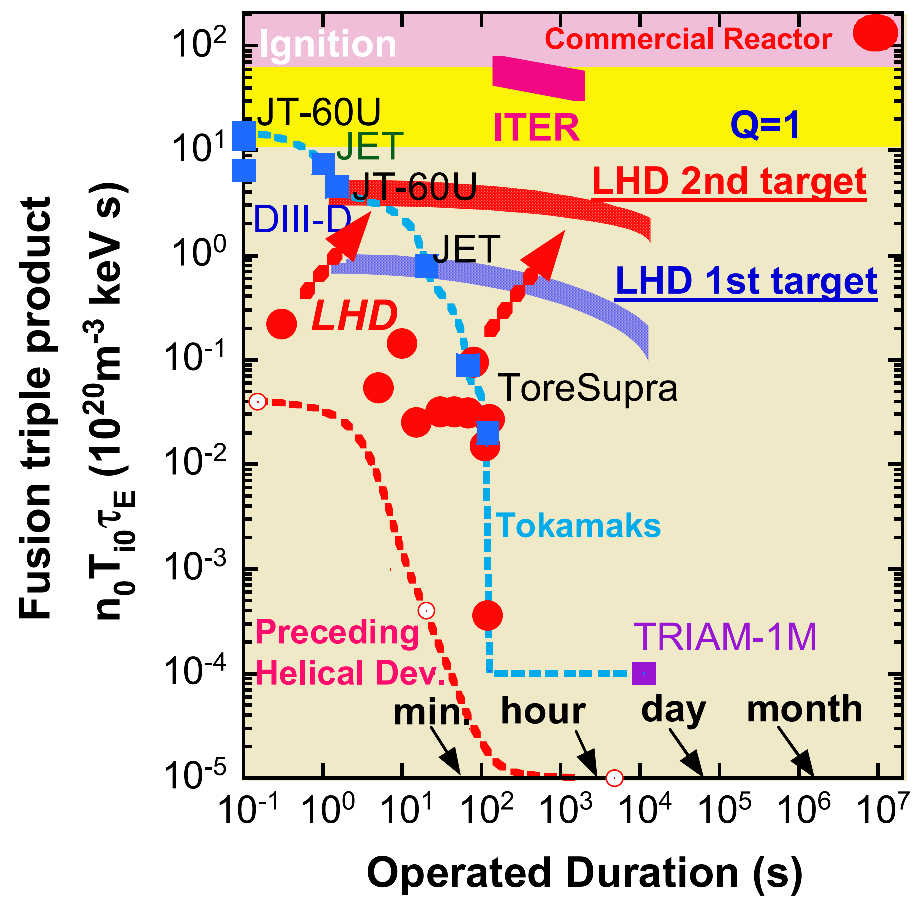
A factor of 1.5 improvement of the energy confinement time τ_E over the ISS95
Comparable to ITER ELMy H-mode

International Stellarator Scaling 95 (ISS95)

$$\tau_E^{ISS95} = 0.26 B^{0.80} P^{-0.59} \bar{n}_e^{0.51} R^{0.65} a^{2.21} q_{2/3}^{-0.40}$$

$$\propto \tau_B \rho_*^{-0.71} \beta^{-0.16} \nu_*^{-0.04}$$

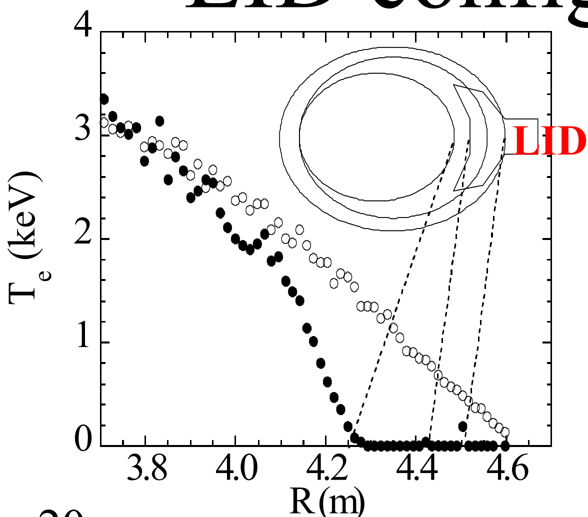




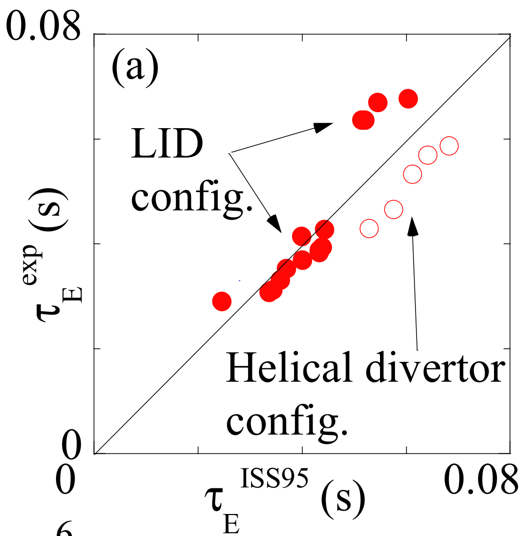
H.Yamada EX/1-5

LID configuration

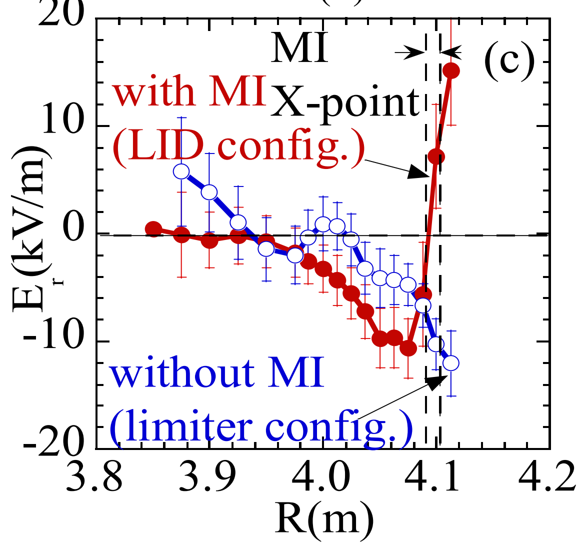
Create sharp edge (large Te gradient)



Confinement improvement

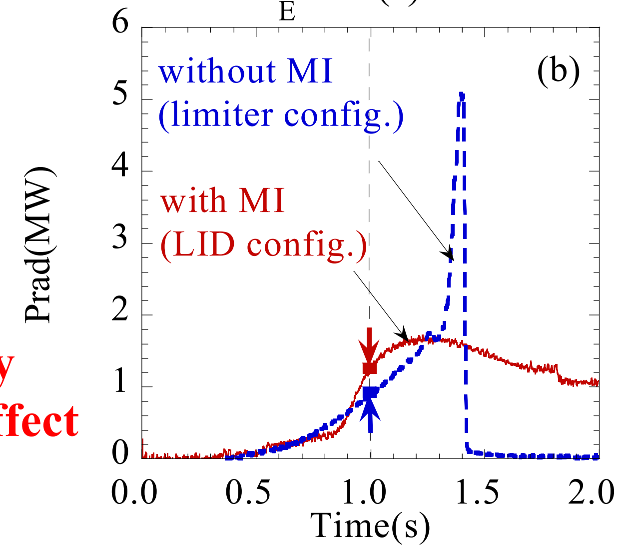


Produce edge Positive E_r



Prevent radiation collapse

by impurity shielding effect

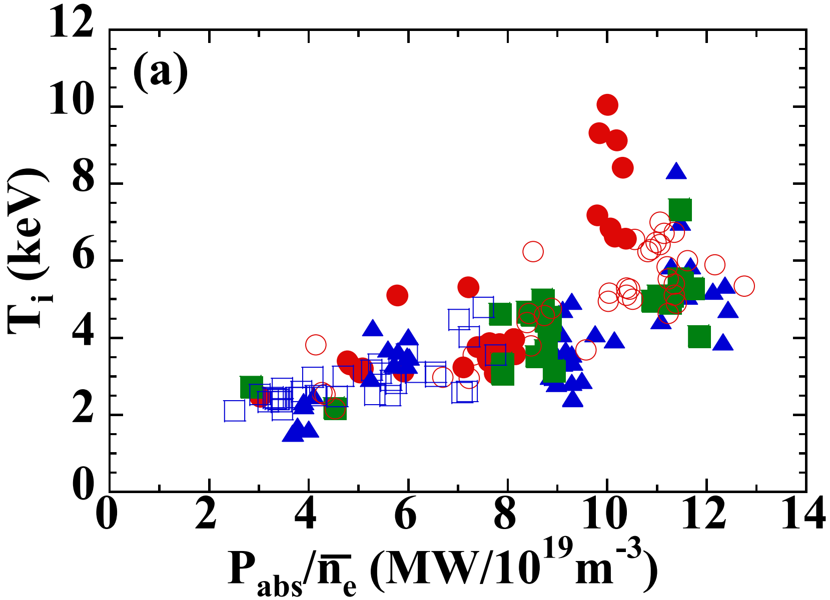


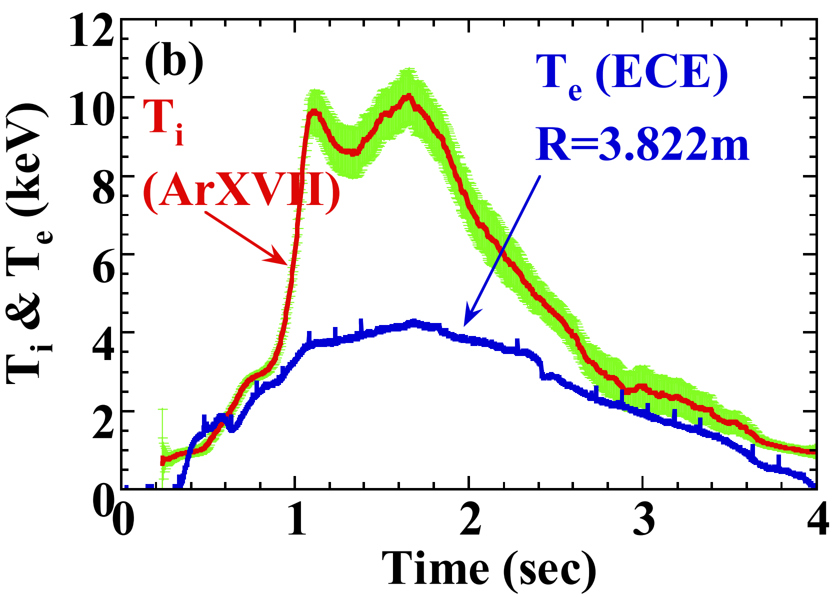
- **Basic function of LID demonstrated**
  1) **confinement improvement**
  2) **prevent radiation collapse**

A.Komori EX/10-4, K.Ida EX/P4-6

Study on high ion temperature

- **Central ion temperature increases up to 10keV with strong impurity puff**





at present: 3 tangential beam lines with 180keV/14MW

H: electron heating → Ar, Ne: ion heating

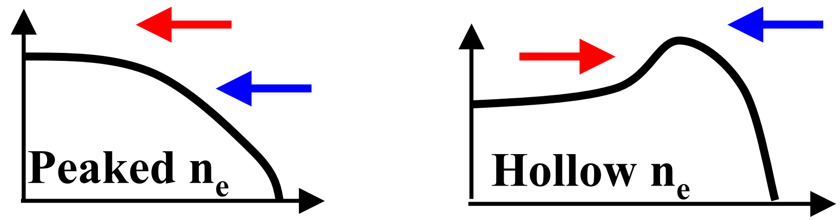
next year: one perpendicular beam line added with 40kev/3MW

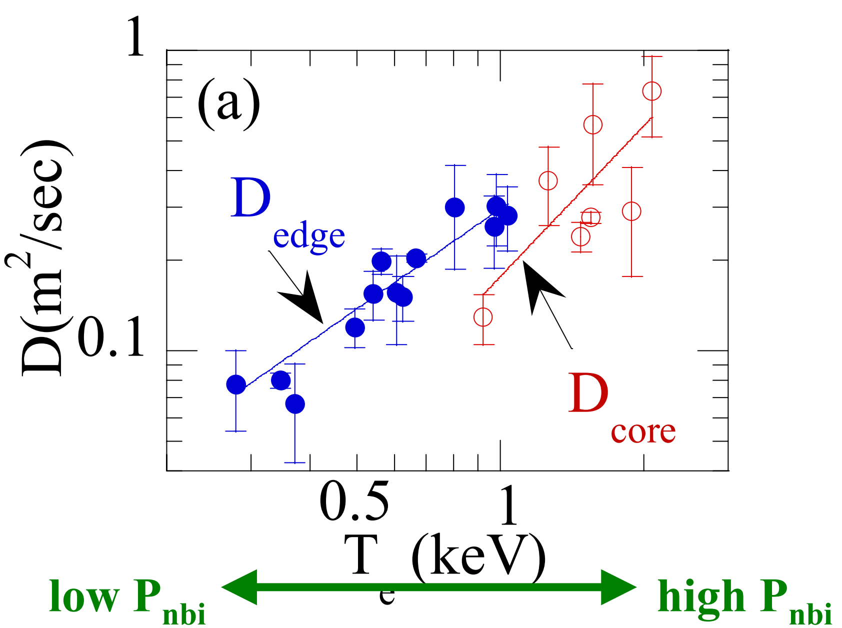
→ more efficient central ion heating

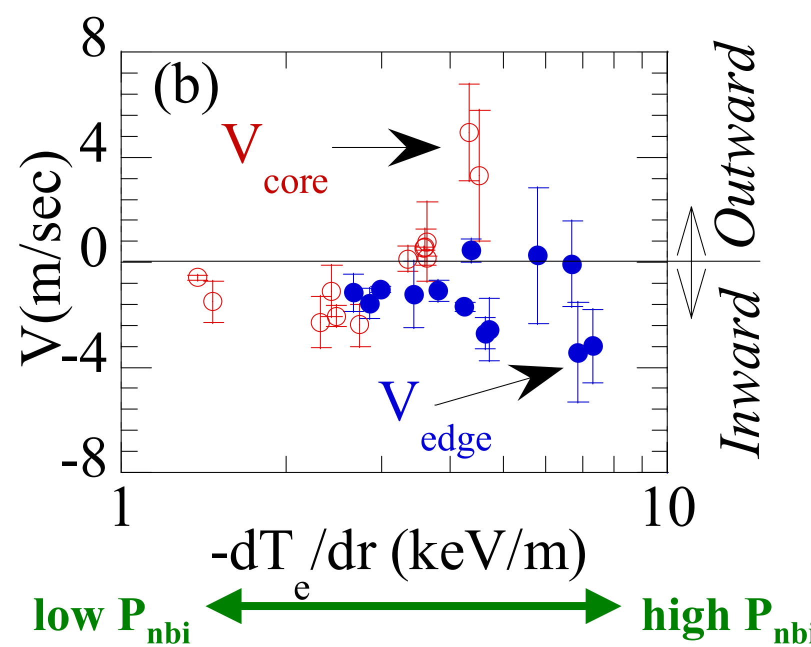
(a) Ion temperature as a function of the direct ion heating power normalized by the ion density in the plasma with Ar- and Ne-puff and
(b) time evolution of electron and ion temperature in a low-density high-Z plasma.

Particle transport in L-mode plasmas

Density profile is flat in the core region in LHD
→ Transient transport analysis with gas puff modulation is required to derive diffusion coefficient in the core







$D_{core} \sim T_e^{1.7+-0.9}$

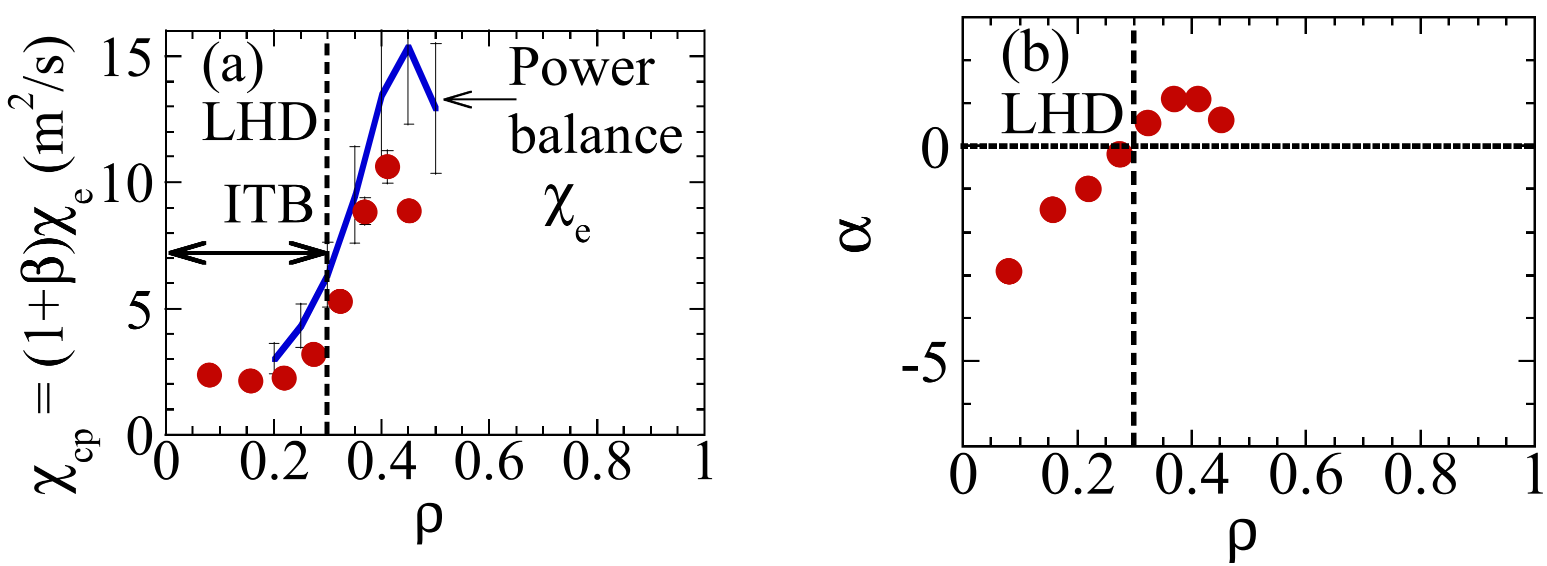
$D_{edge} \sim T_e^{1.1+-0.14}$

- **Consistent with Gyro Bohm**
- **Consistent with density profile measured in the steady state**
- **T_e dependence ($T_e^{1.5}$)**

(a) Electron temperature dependence of diffusion coefficient
(b) convective velocity as a function of the temperature gradient

Heat transport in ITB plasma

Steady-state transport analysis ← Power balance → χ_e
Transient transport analysis ← Cold pulse propagation → χ_e and $d\chi_e/dT$



Temperature dependence
$\alpha = (T_e/\chi_e)(d\chi_e/dT_e)$

- **Significant reduction of thermal diffusivity inside the ITB is observed both in steady-state and transient transport analysis**

Inside ITB : $\alpha < 0$ → negative T_e dependence
Outside ITB : $\alpha > 0$ → positive T_e dependence

(a) The radial profiles of the electron heat diffusivity
(b) T_e dependence factor of χ_e, α, estimated by cold pulse propagation. The heat diffusivity estimated by power balance is also plotted

S.Inagaki EX/P2-12, T.Shimozuma EX/P3-1

Obtained Physics and Achieved Parameters of LHD Experiments

1. Plasma performance was improved remarkably through 7 experimental campaigns in these 6 years
2. Quality and amount of database increased remarkably for MHD and transport study
3. With NBI of 12MW, T_e=4.5keV and T_i=10.1keV were obtained at $<N_e>=3.5 \times 10^{18} m^{-3}$
4. With ECRH of 1.2MW, T_e=10.2keV and T_i=2.0keV were obtained at $<N_e>=5.0 \times 10^{18} m^{-3}$
5. A maximum volume averaged β value of 4.1% was achieved without any serious MHD instability
6. Good confinement time of τ_E=0.36sec, large plasma energy of W_p=1.36MJ, and long plasma operation of 756sec were obtained, which showed the good capability of LHD plasmas
7. The global confinement characteristics show better properties than the existing empirical scaling ISS95
8. The knowledge of transport, MHD, divertor and long pulse operation etc. is now rapidly increasing, which comes from the successful progress of physics experiments
9. The advantage of an SC device is becoming clearer especially when we try to perform the steady state experiments → 50 thousand shots

- **steady state operation**
- **advanced plasma regimes (higher normalized plasma pressure: β)**
- **control of power fluxes to walls**

Joint Report of EU/JA Expert Group Meeting
18th / 19th April 2004, Culham
on
A Broader Approach to Fusion Power

ITER/DEMO oriented

Strong accompanying physics programmes are needed in the parties during ITER construction and operation. Their functions should include, in particular, to directly support ITER and to complement ITER outputs in the preparation of DEMO.

The main functions in support to DEMO will be to explore operational regimes and issues complementary to those being addressed in ITER. In particular these will include:

Contributor

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