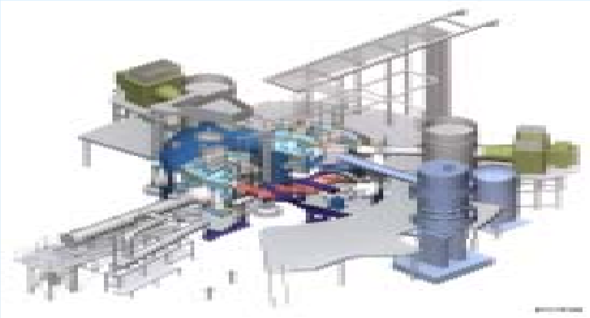
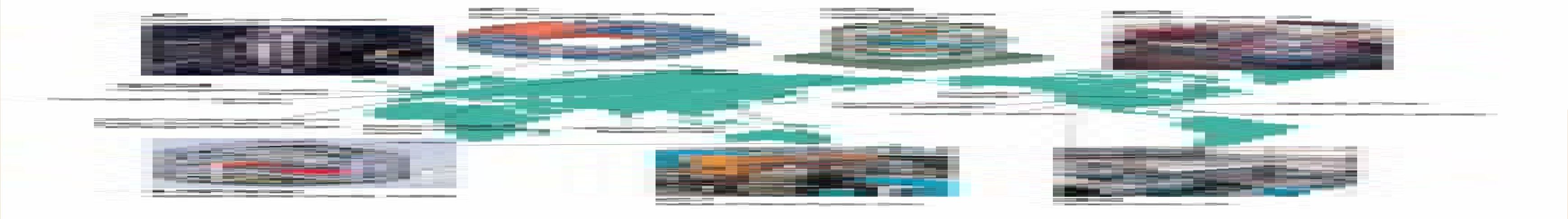


Extended Steady-State and High-Beta Regimes of Net-Current Free Heliotron Plasmas in the Large Helical Device

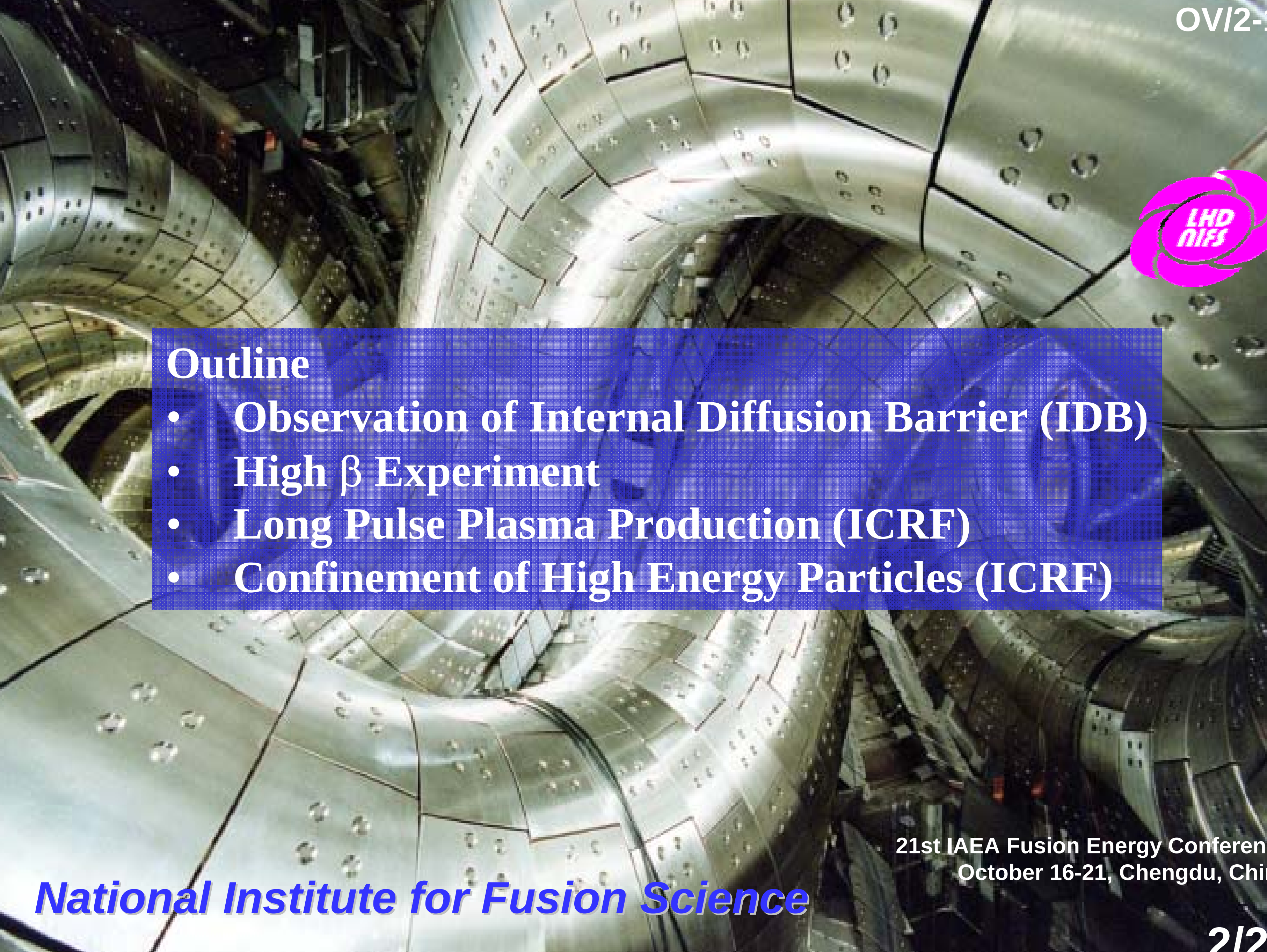


IAEA in Chengdu, 17 October, 2006

for LHD Experimental Group and all of Contributors

O.Motojima

Director General and Professor
National Institute for Fusion Science, NIFS, Japan

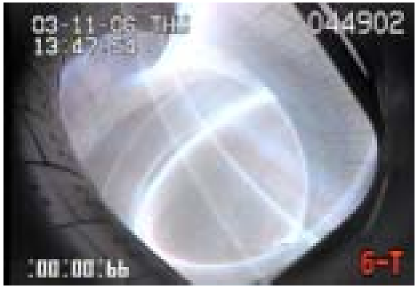


Outline

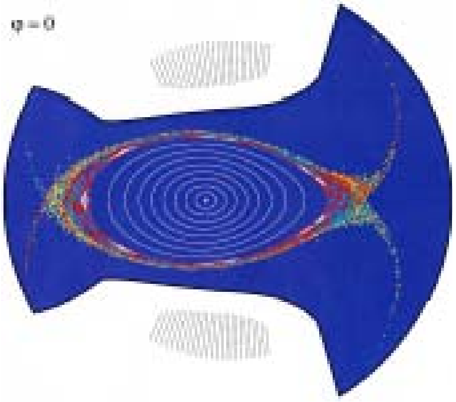
- Observation of Internal Diffusion Barrier (IDB)
- High β Experiment
- Long Pulse Plasma Production (ICRF)
- Confinement of High Energy Particles (ICRF)

Characteristics of Heliotron Magnetic Field

Outlook from outside
(Stochastic Structure)
↓



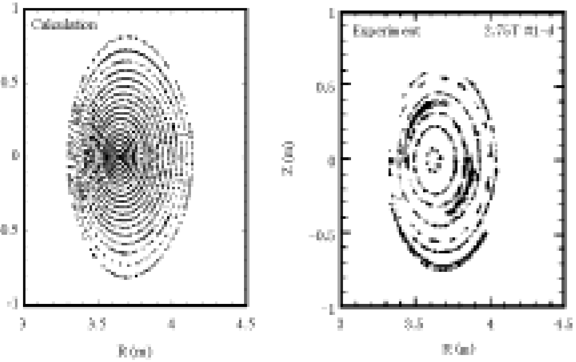
Cross section
(Well Nested Magnetic Structure)
↓



B=2.75 (T), R_{ax}=3.6 (m)

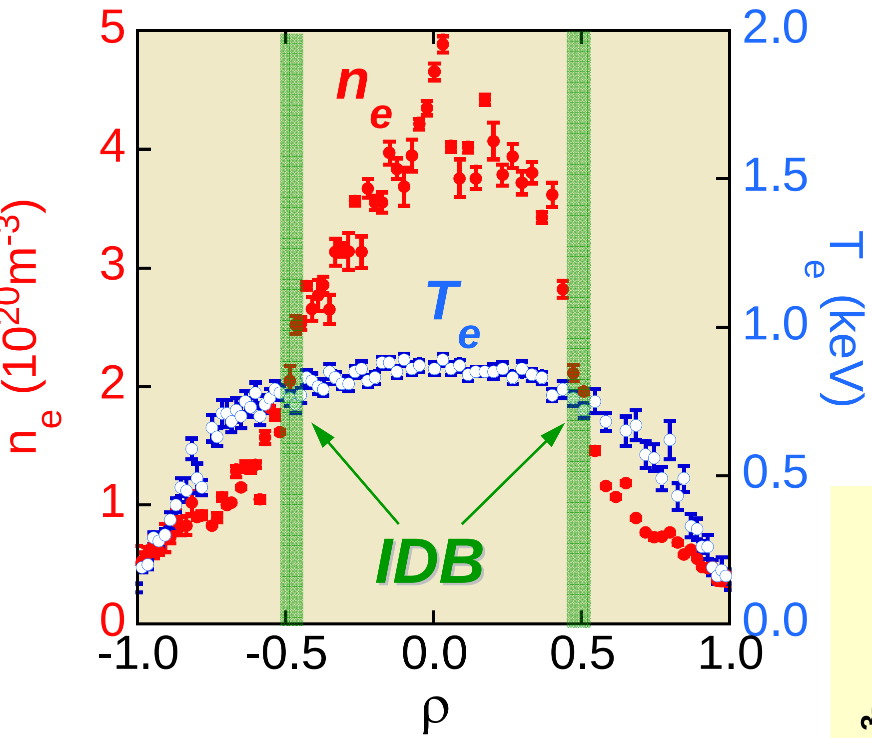
Observable
(Beam Mapping)

Complex at first sight, but can be simplified by understanding the principle



Beautiful order of field lines predicts the presence of high quality of equilibrium, stability and transport of LHD plasmas
LHD is providing an opportunity to investigate new physics of 3 D plasmas

Observation of Internal Diffusion Barrier (IDB) Enabling New Scenario of Super Dense Core Reactor



N.Ohyabu, Phys.Rev.Lett. 97 (200
N.Ohyabu(EX/8-1) on Fri.

Central density : 5×10^{20}m^{-3}
Central temperature : 0.85 keV
➔ exceeding 1 atmospheric pressure

Magnetic field : 2.64 T
➔ Central beta : 4.4 %
: > 5 % at B of 1.5T

Reduce engineering demand and neoclassical ripple transport

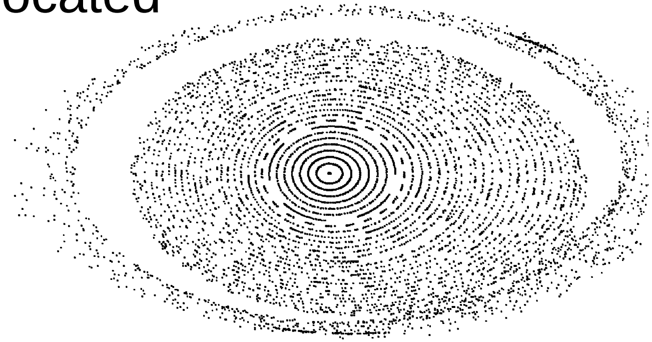
FFHR
1,000 MW
6Tesla

. Mitarai (FT/P5-24) on Thu.

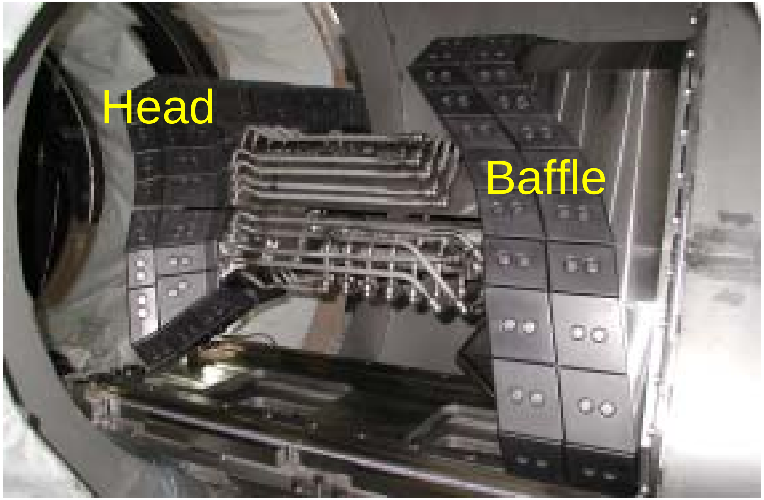
Efficient Particle Control Is Realized by Local Island Divertor (LID)

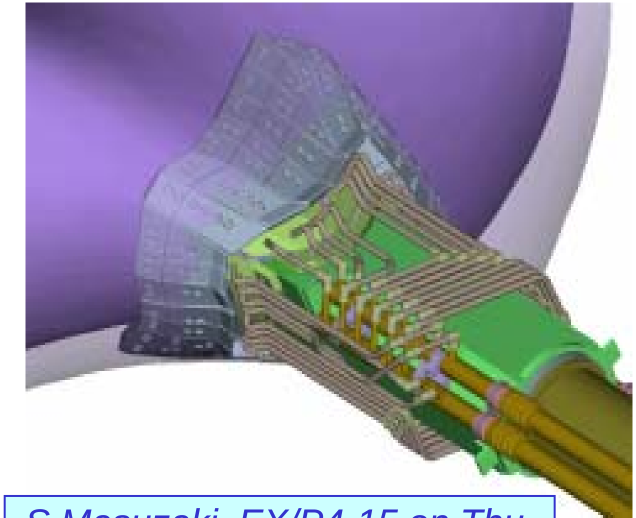
A.Komori, Nucl. Fusion 45 (2005)

10 pairs of perturbation coils produce
m/*n*=1/1 island located
at the edge



LID head is inserted into the island
Particle flux is guided backward on to the head of LID
➔ Efficient pumping speed of several×10^{21} particles/s



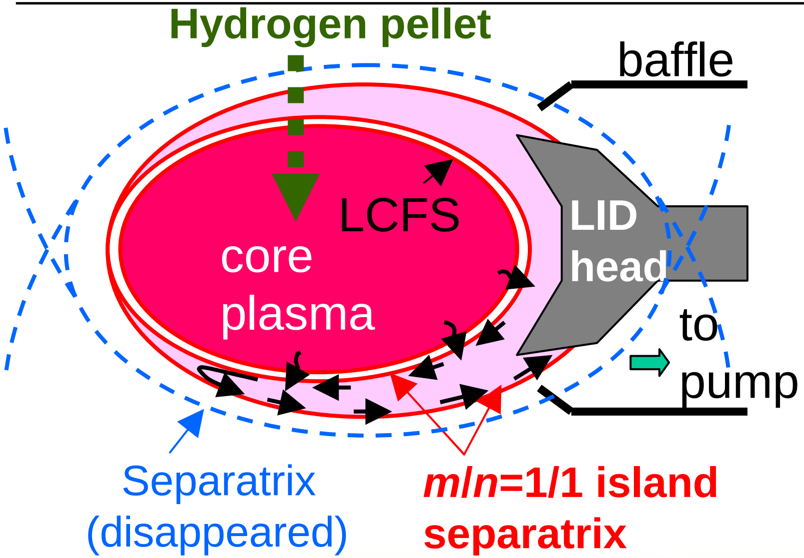


S.Masuzaki, EX/P4-15 on Thu

Formation of IDB

Effective Core fueling by pellet injection is combined with Local Island Divertor (LID)

R.Sakamoto, Nucl. Fusion 46(2006)
N.Ohyabu(EX/8-1) on Fri.



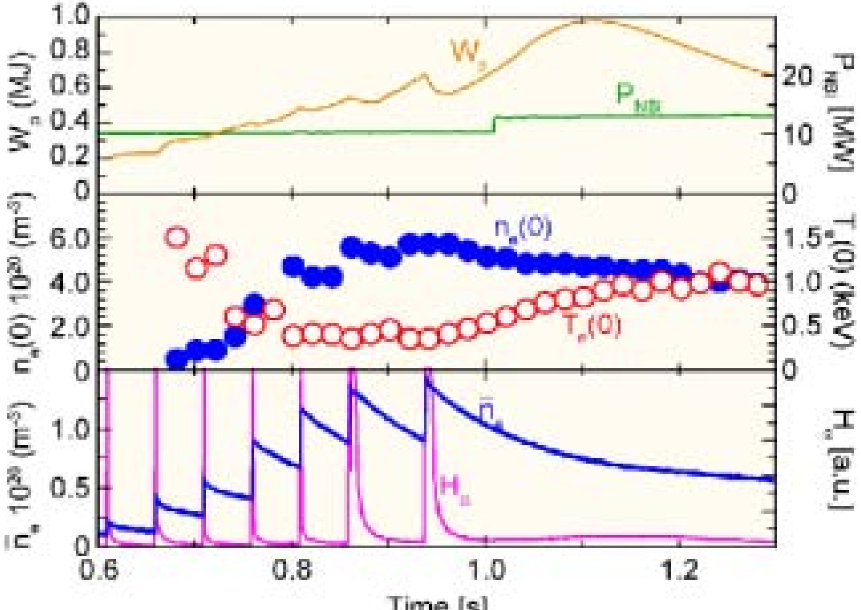
W_p =1.1MJ, P_{abs}=10MW

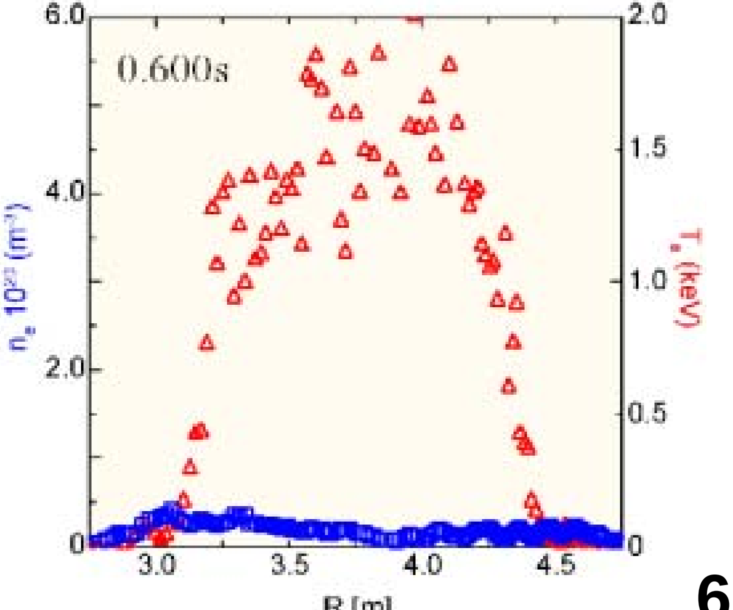
$n\tau_E T$ =4.4×$10^{19}$$m^{-3}$ s keV

$\beta(0)$ =4.4 %, $<\beta>$=1.5 %

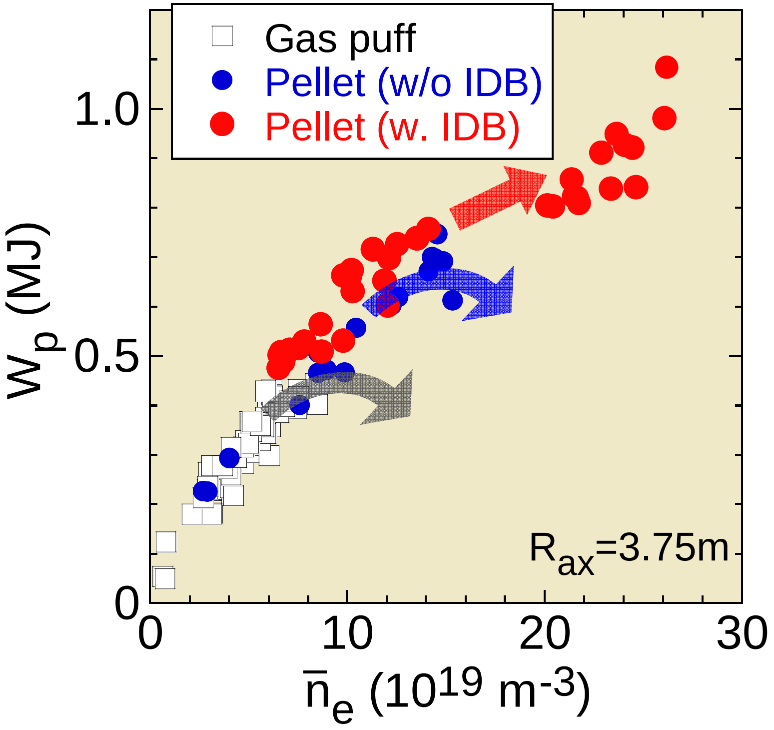
R_{ax} =3.75m, B=2.64T

Time constant of n(0) decay is 1sec, indicating that D is 0.02 m²/s, a very low value

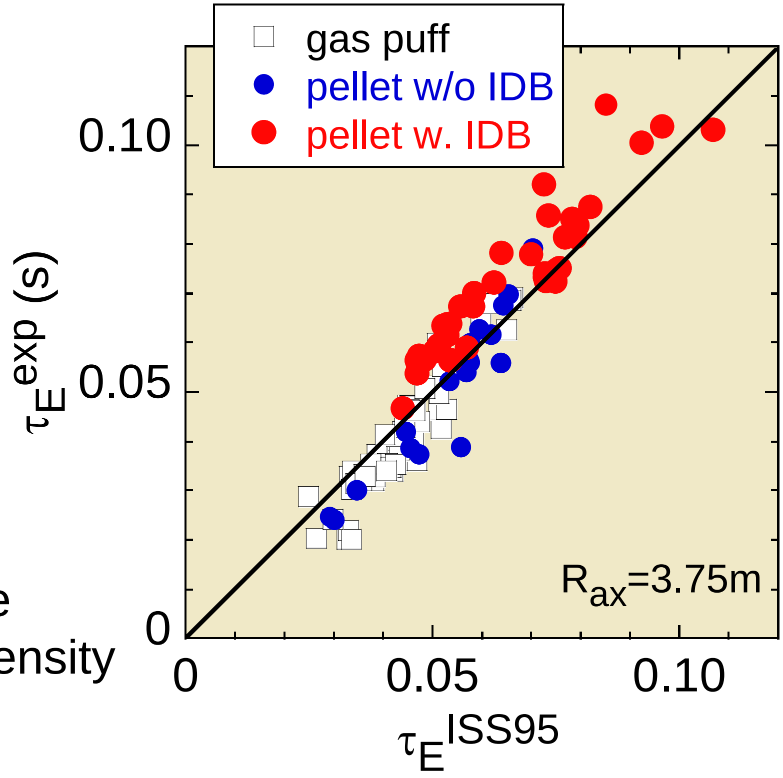




Key to understand IDB
Control Scenario of Edge Density and Core Fueling



- LID operation with pellet injection extends the density regime
- Capability of improved confinement (IDB) appears in high density regime

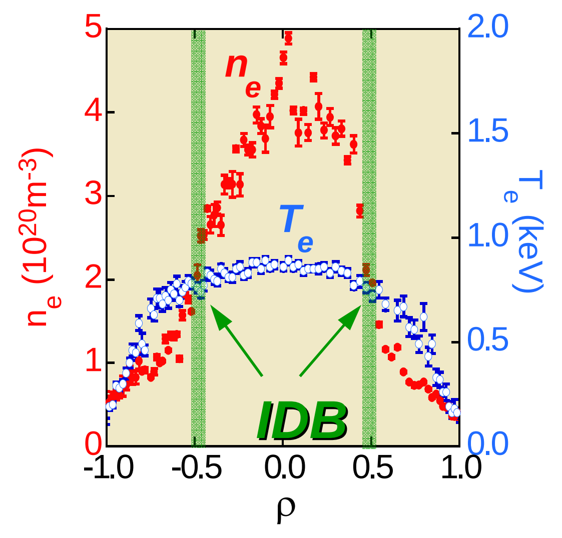


Energy confinement time exceeding the ISS95 scaling is achieved in the high density regime by IDB

J.Miyazawa(EX/3-2) on Wed.

$$\tau_E^{ISS95} = 0.079 a^{2.21} R^{0.65} P^{-0.59} \bar{n}_e^{0.51} B^{0.83} \iota_{2/3}^{0.4}$$

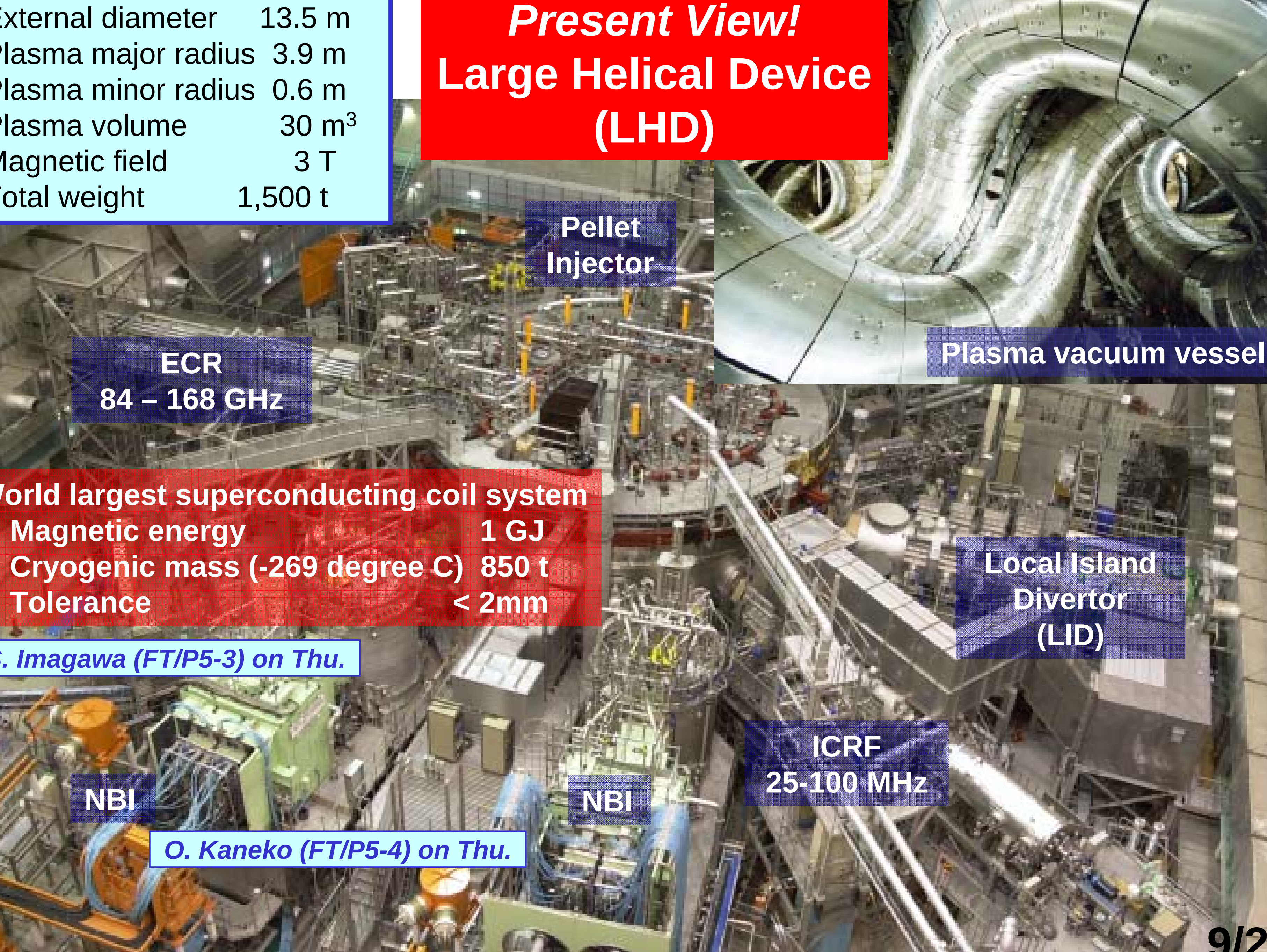
IDB Scenario and Super Dense Core Reactor (SDCR)



- Edge Control
  - Core fueling by pellet injector
  - Particle pumping by LID
    - ➔ Low edge density
- Confinement Improvement (IDB)
  - Present Interests
    - Position sensitivity of IDB foot
    - MHD stability
- New Ignition Scenario (SDCR)
  - High Density and Lower Temperature Core
  - Parameters (n, T, beta) obtained are encouraging

Present View!
Large Helical Device (LHD)

xternal diameter	13.5 m
lasma major radius	3.9 m
lasma minor radius	0.6 m
lasma volume	30 m^3
agnetic field	3 T
otal weight	1,500 t



orld largest superconducting coil system

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

. Imagawa (FT/P5-3) on Thu.

O. Kaneko (FT/P5-4) on Thu.

Target and Achievements in LHD

Achievements [Final target]

Ion Temperature

Central T_i 13.5 keV [10 keV]

Density $3\times10^{18}m^{-3}$ (Ar gas) [$2\times10^{19}m^{-3}$]

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

4.5 % (magnetic field of 0.425T) [$\geq$ 5 % (1-2 T)]

High β in steady state

Steady State Operation

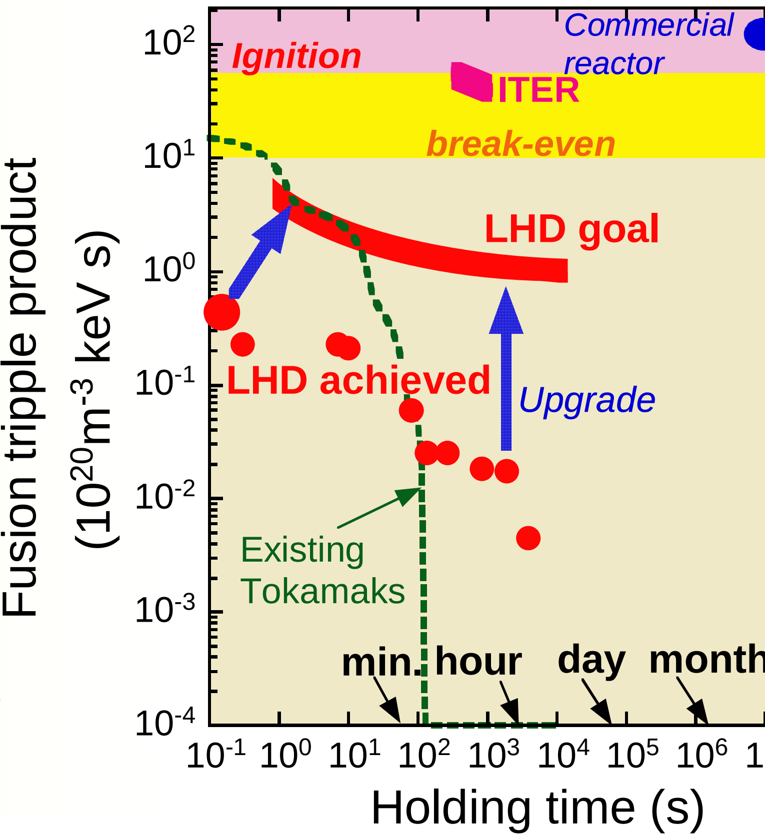
31min.45sec. (680 kW) 1.3GJ [1 hour (3,000 kW)]

54min.28sec. (490 kW) 1.6GJ

Largest input energy

High Density

$5\times10^{20}m^{-3}$



Highlighted progress in Steady State, High β, and High Density by discovery of *Internal Diffusion Barrier* (IDB)

Accumulation of physical data

Systematic investigations become possible

➔ increase of heating power, deuterium experiment, etc.

Takeiri(EX/P4-42) on Thu., M.Yokoyama(EX/5-3) on Thu.
Sakakibara(EX/7-5) on Fri. T.Mutoh(EX/P1-14) on Mon.

For use of EU/JA ITER negotiator

Joint Report of EU/JA Expert Group Meeting

18th / 19th April 2004, Culham
on
A Broader Approach to Fusion Power

Basic Activities and Functions in a Broader Approach

The group of experts identified three main classes of activities/functions within a broader approach, as follows:

1 Primarily ITER oriented

Joint implementation of ITER (including a possible remote data centre)

2 ITER/DEMO oriented

Satellite tokamak function – ITER/DEMO Physics support function

3 Primarily DEMO oriented

DEMO Concept Definition, Design and Co-ordination of R&D Activities in Physics and Technology, IFMIF

The overall assumption is that strong domestic programmes will continue, which support and complement the above activities and functions

ITER/DEMO oriented

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:

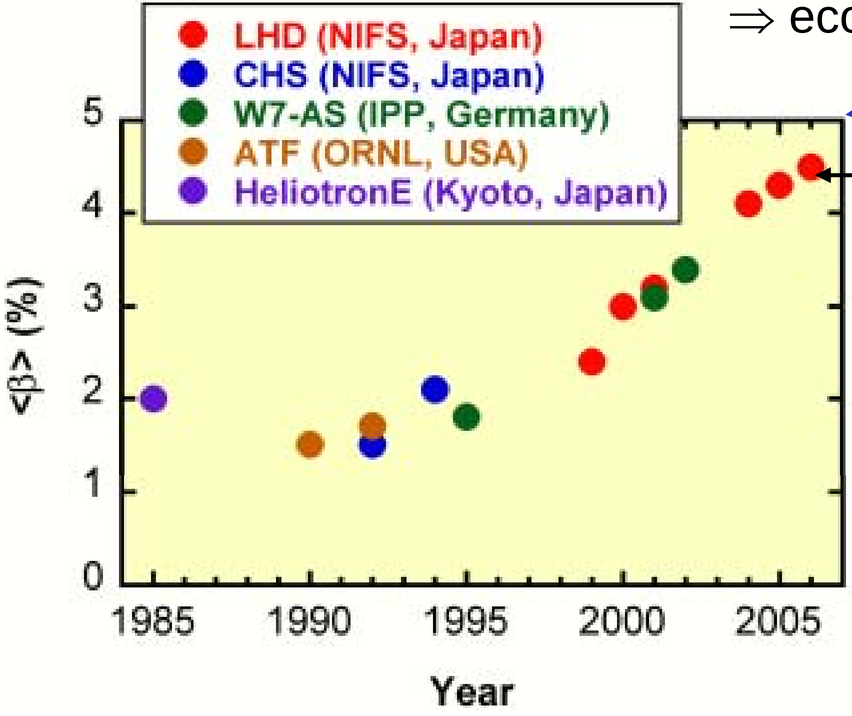
- **steady state operation**
- **advanced plasma regimes (higher normalized plasma pressure: β)**
- **control of power fluxes to walls**

The LHD project addressed these issues from the begging in 1989!

Progress of Achieved Beta

H.Yamada, PPCF 43 (2001

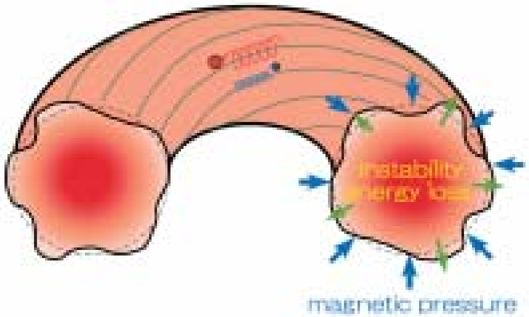
Beta : ratio of plasma pressure to magnetic pressure
⇒ economic index of fusion reactor

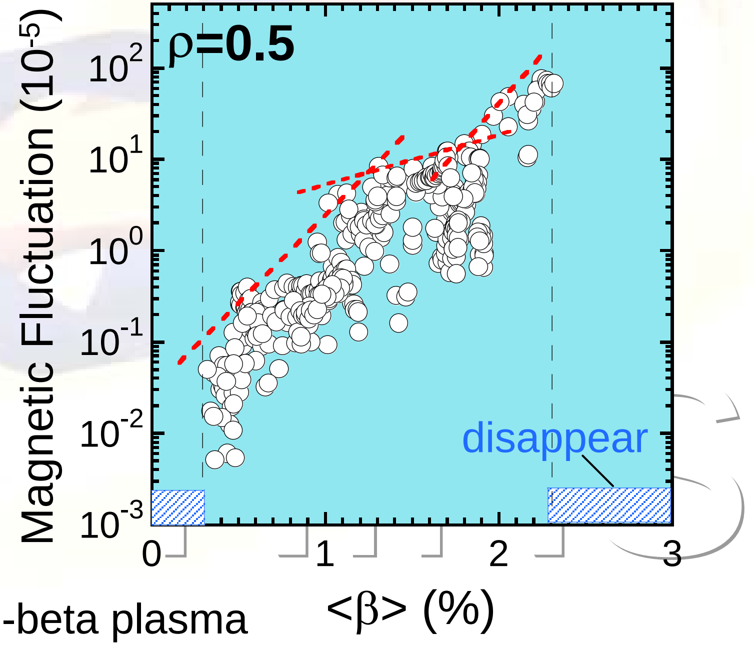


Goal : 5 %

4.5 % achieved in 9th experimental campaign

<β> > 4 % was sustained for >> 10τ



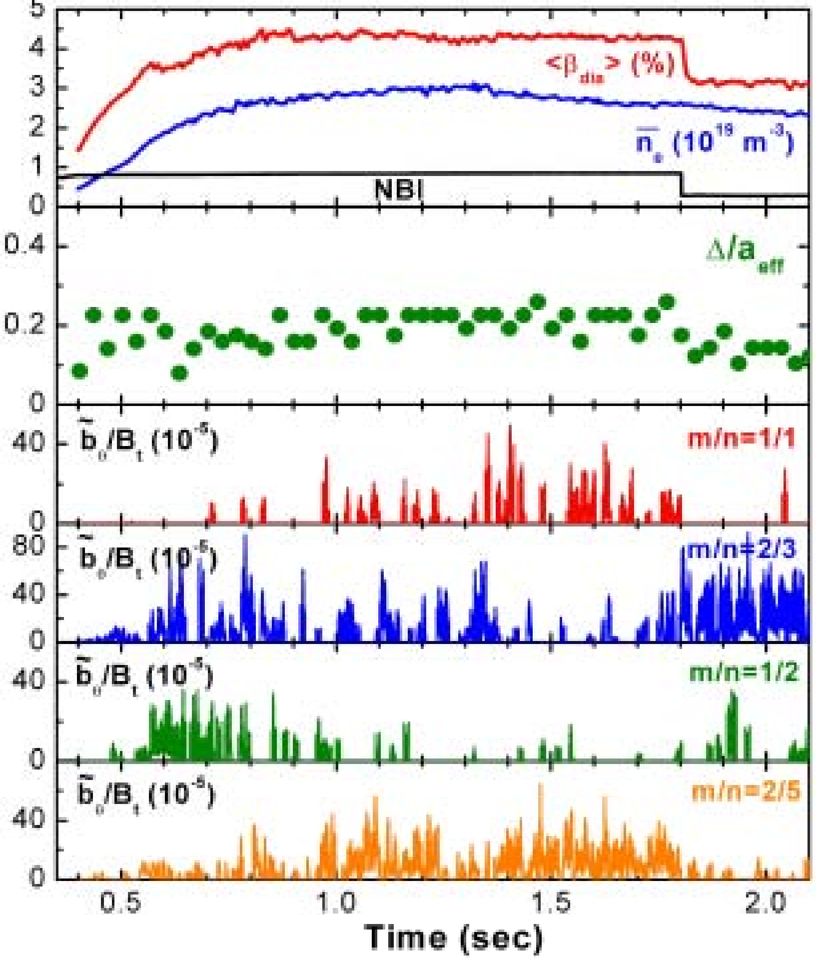


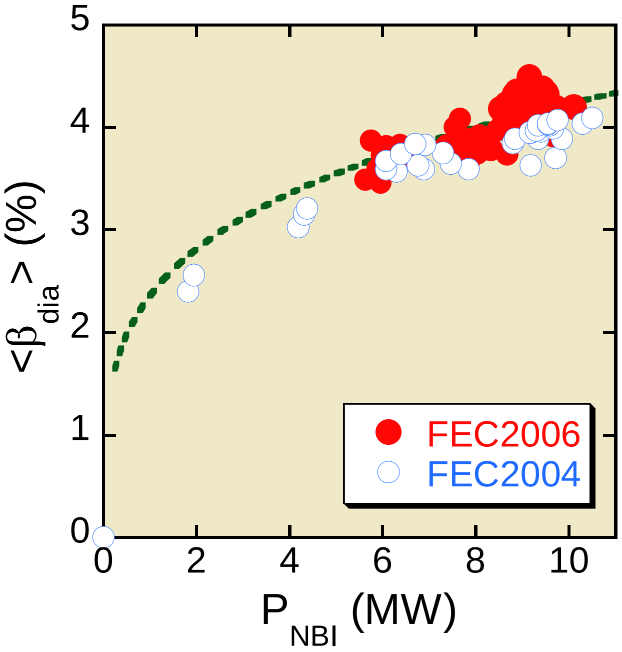
Verification of self-stabilization ⇒ realization of high-beta plasma

S.Sakakibara(EX/7-5) on Fri

β~4.5% is maintained for 10 τ_E in LHD

R_{ax}=3.6m, A_p=6.6, B=0.425T, P_{abs}=6.4MW





β can be pushed up by increasing the heating power like $P^{0.25}$

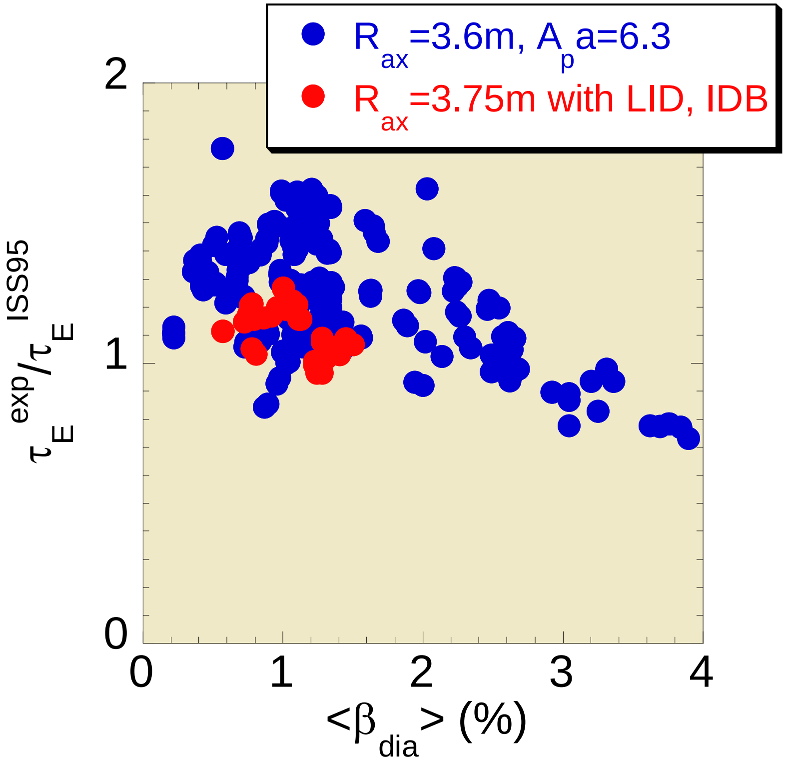
Increase of A_p enhances magnetic fluctuations with resonances at the edge

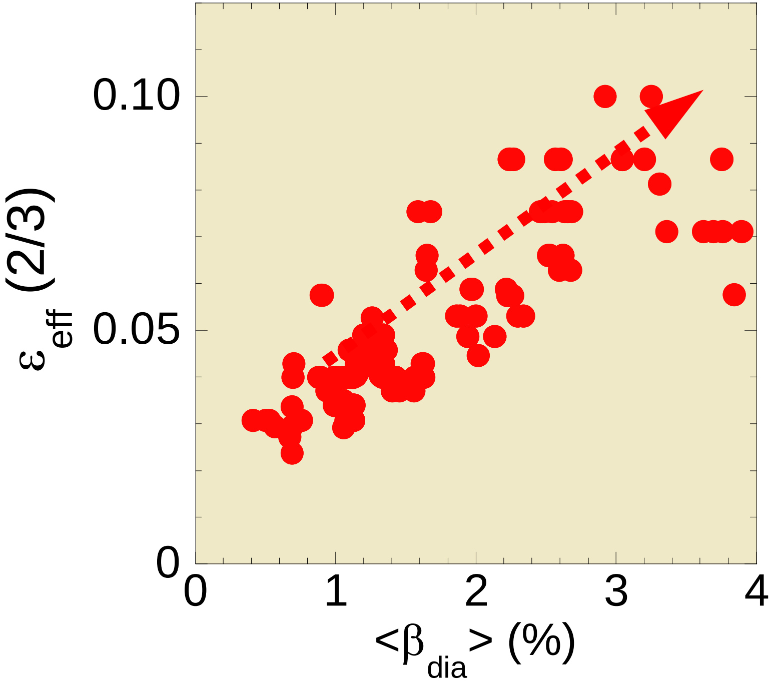
➔ resistive interchange mode

S.Sakakibara(EX/7-5) on Fri

Study on the Confinement in High-β Regime

H.Yamada, Nucl.Fusion 45 (2005)





Outward shift of plasma by Shafranov shift causes an increase of the effective helical ripple

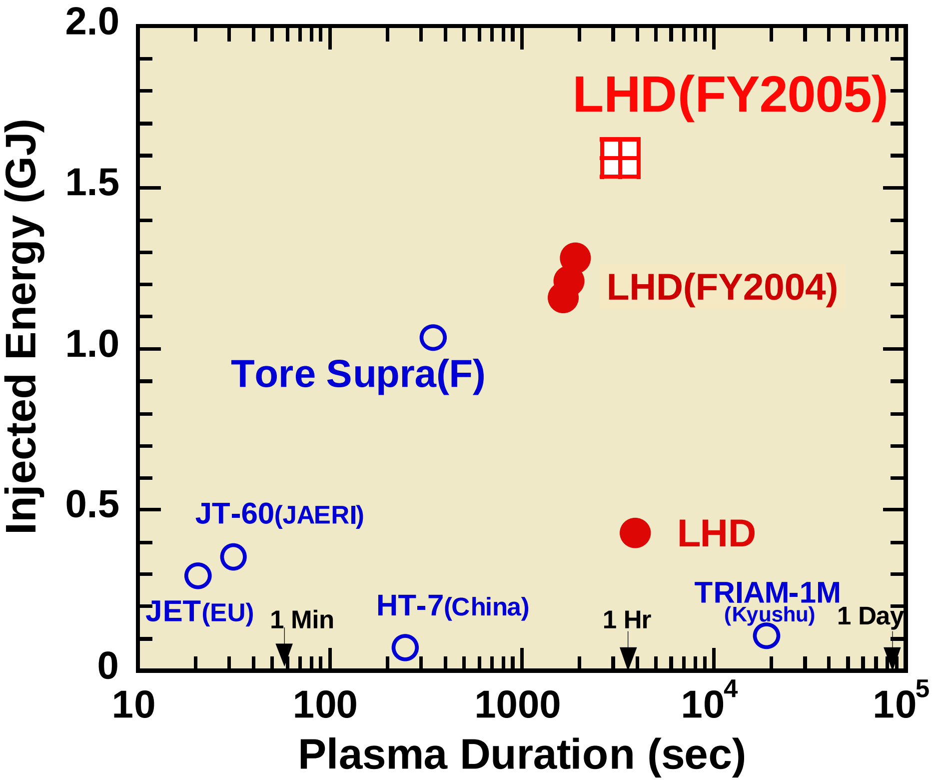
Degradation can be attributed to global dependence on effective helical ripple to the neoclassical transport

not on MHD effect

➔ Degradation in high β regime will be improved by dynamic R_{ax} control by vertical field in nearest future

T.Watanabe (EX/5-4) on Fri.

Extended Steady State Operation by ICRF



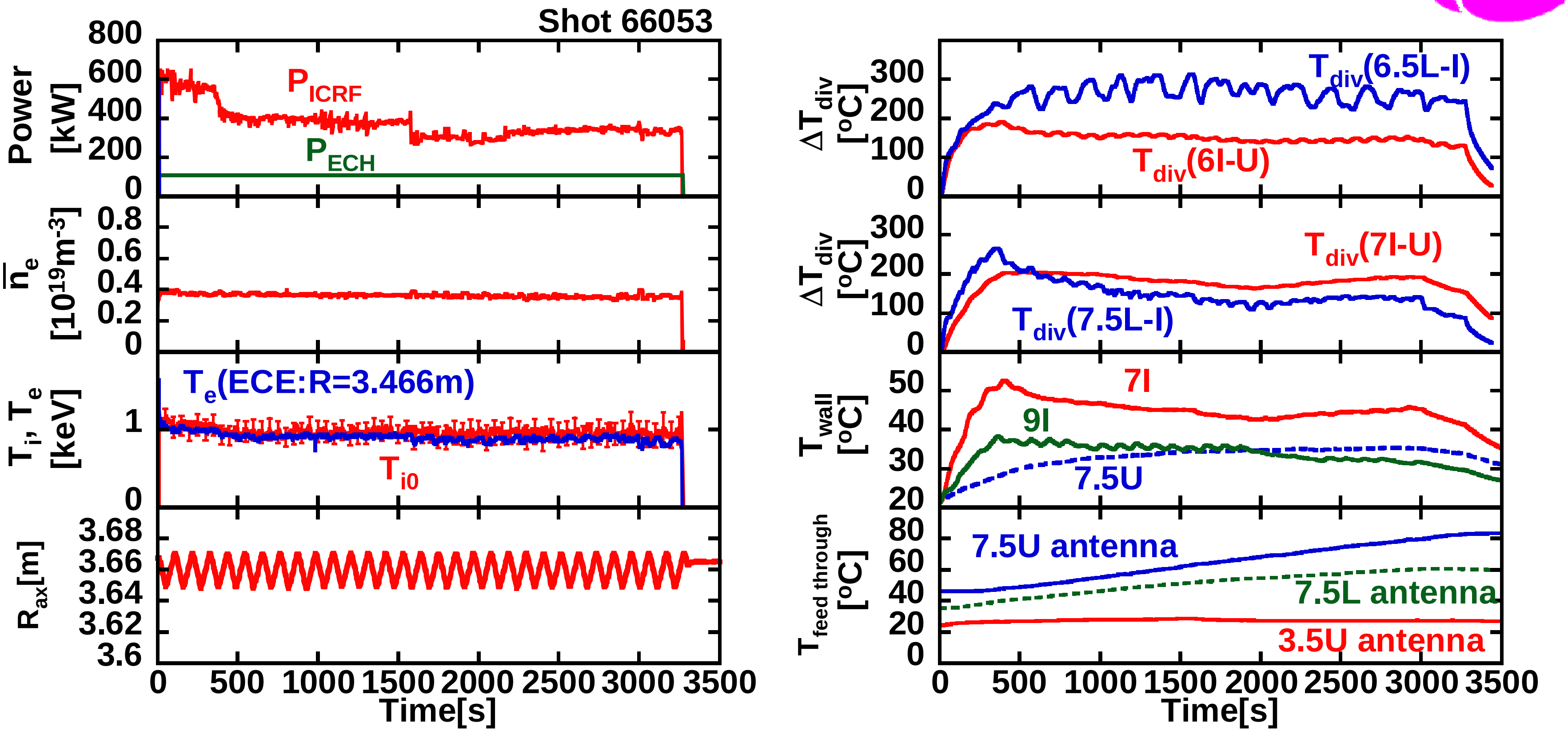
- **Record of input energy to high temperature plasmas in 2005**
  1.6GJ : New record
  490kW × 3268s
  Tokamak record : 1.07GJ (ToreSupra)
- **Extended the achievements in 2004 (1.3GJ)**
  680kW × 1905s
- **Planning longer pulse with higher heating power**
  3 MW for 1 hour

◆ **Steady state experiment by ICRF demonstrates the high potential of helical systems towards a currentless steady state reactor**

◆ **Minority heating by ICRF accelerates perpendicular component of ion velocity effectively up to MeV range. This experiment demonstrates the high capability of LHD to confine high energy ions**

T.Mutoh(EX/P1-14) on Mon

54-Minute Long Operation with 500 kW



R_{ax}= 3.67-3.7m, B=2.75T,
P_{ICRF}= 600-380 kW, P_{ECH}=110 kW

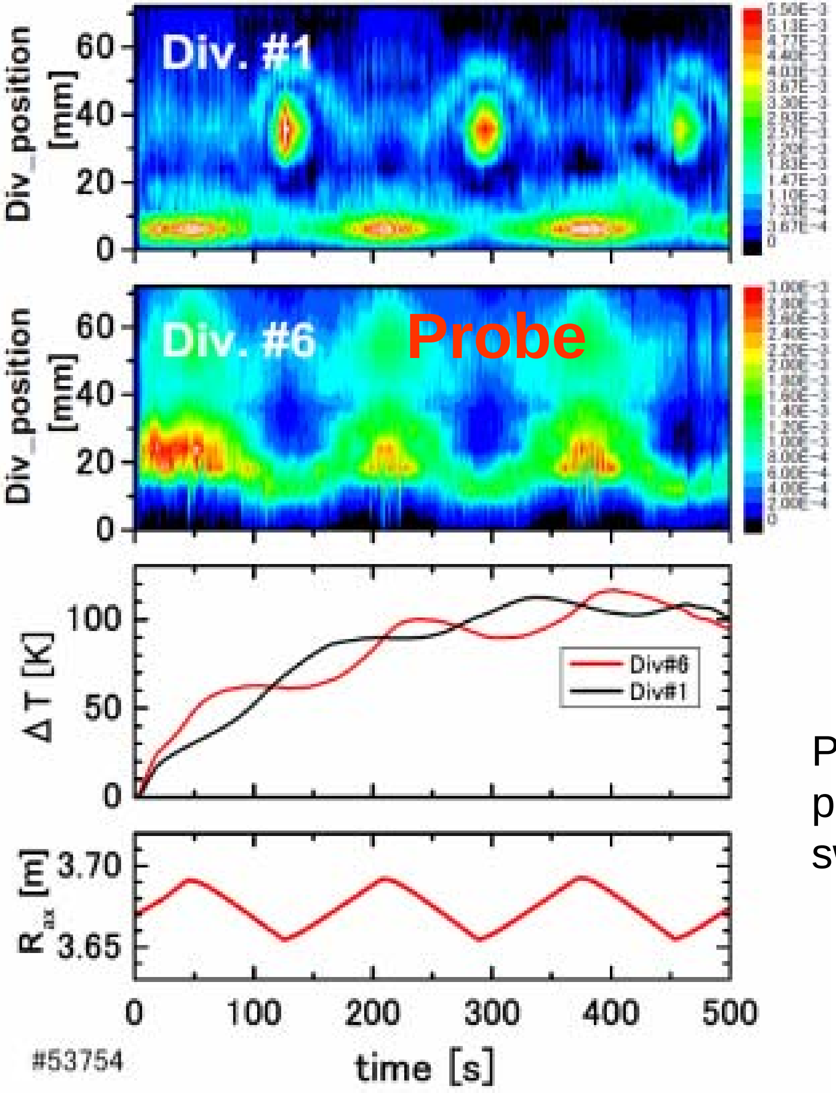
Record of input energy 1.6 GJ was achieved

Key elements: 1) heat dispersion control by R_{ax} sweeping,
2) confinement capability of high energetic trapped ions

31-minute long discharge was achieved with $T_e(0)$ and T_i (0) of 2 keV at n_e of $0.8\times10^{19}m^{-3}$ by the power of 680 kW

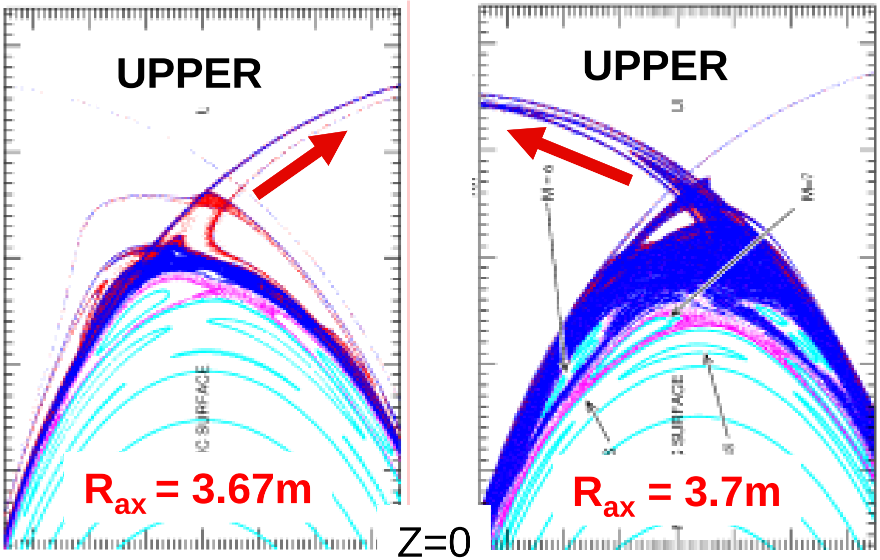
T.Mutoh(EX/P1-14) on Mon

R_{ax} sweeping by ΔR/R=0.8% Disperses Heat and Particle Loads on Divertor Plate

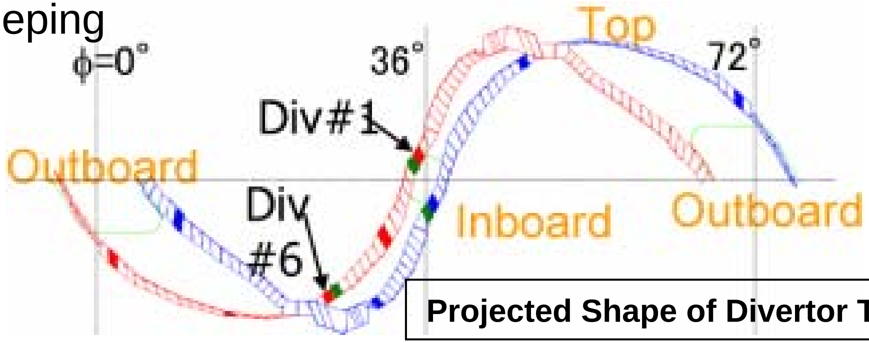


Temperature of divertor tiles saturates at tolerable level

Divertor traces are switched by a tiny shift of R_{ax}



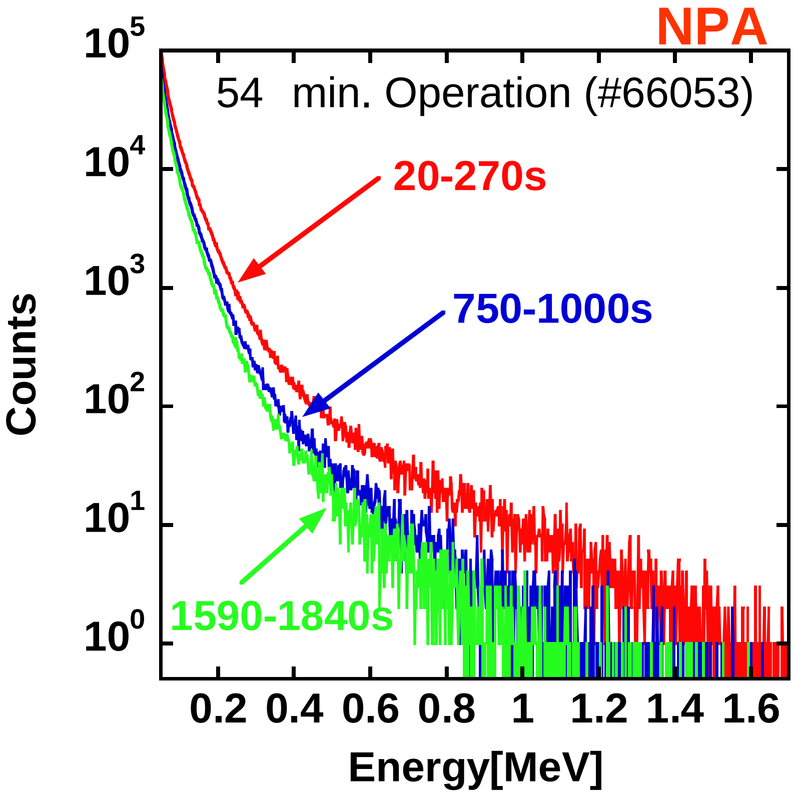
Particle flux profiles as well as heat deposition profile on divertor plates are dispersed by R_{ax} sweeping

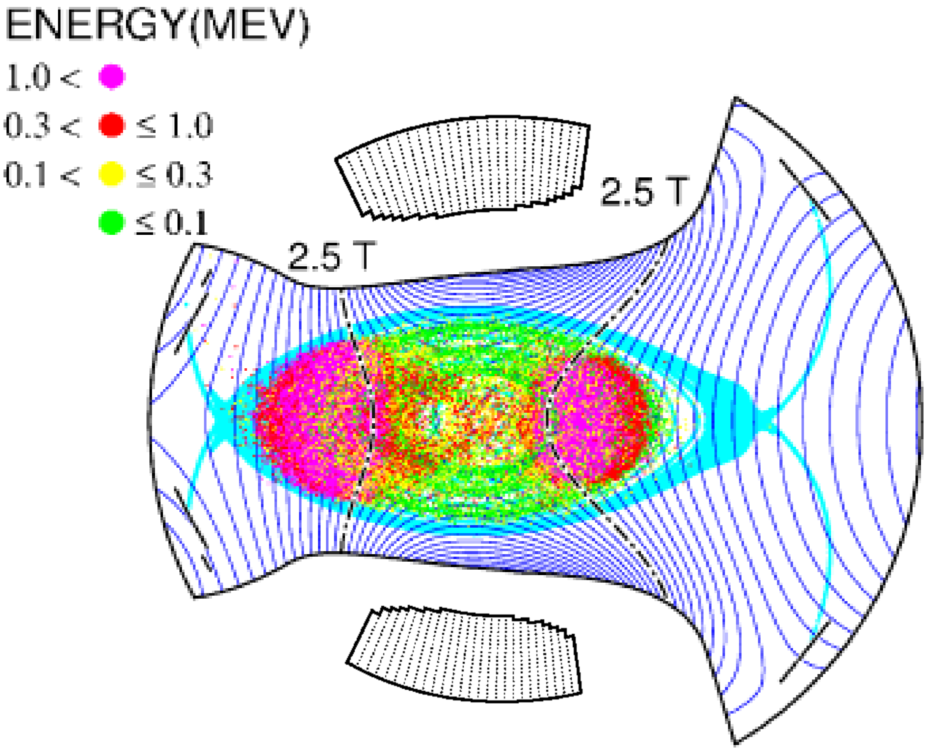


Projected Shape of Divertor Tile

High Energy Ion Tail Obtained with Energy Range up to 1.6 MeV

Fundamental heating (38MHz) of H minority and He majority plasma at B=2.64T, R_{ax}=3.7m





Particle Orbit Calculation

NPA measurement and full orbit calculation indicate that significant loss or confinement degradation is not observed in the high energy range of MeV

T.Mutoh(EX/P1-14) on Mon., K.Saito(EX/P6-17) on Fri.

Future Plan of LHD Project

Present experimental campaign (Oct.2006-)

- Improvement of helical field capability by sub-cooling system

  Coil temperature is lowered from 4.4K (saturated) to 3.5K (sub-cooled)

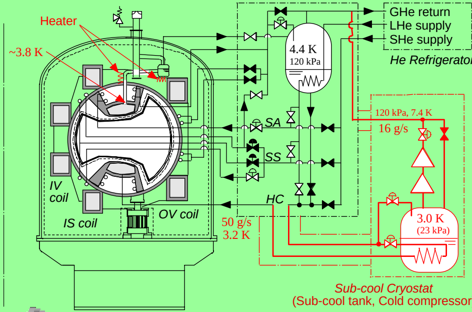
  ➔ Operational magnetic field : 2.8 T to 3.0 T (at R_{ax}=3.6m)
- NBI heating capability

  17 MW ➔ 20 MW (additional 3MW of 40 keV perpendicular beam)

Next year

- ICRF heating capability

  3 MW ➔ 4.5 MW (pulse), 1MW ➔ 1.5 MW (steady state)



Next step in the nearest future

- **Dynamic control of vertical field**

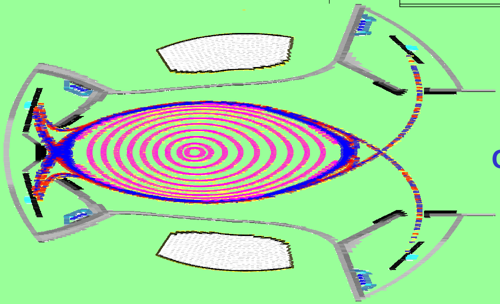
  Improvement of high-β performance
- **Deuterium**

  Clarification of isotope effect

  α particle simulation

  Upgrade of NBI power >30 MW
- **Closed helical divertor**

  Extension of steady state performance



Cross Section of Plasma
Helical Coils
Vacuum Chamber, and
Divertor

S. Imagawa (FT/P5-3) on Thu.

Summary

1. Potential of net-current-free plasmas is enhanced in the **Large Helical Device (LHD)**
2. In particular, very high density up to $5\times10^{20}\mathrm{m}^{-3}$ has been achieved and maintained in quasi steady state by the combination of **Local Island Divertor (LID)** and repetitive pellet injection. This was successfully produced by an **Internal Diffusion Barrier (IDB)**
3. This new finding of IDB enables a new scenario of a **Super Dense Core Reactor (SDCR)** which reduces engineering demands and a concern of neoclassical helical ripple transport
4. Unique operational regimes have been expanded, i.e., long pulse steady state operation (1.6GJ, 1 hour) and high-beta (up to 4.5%)
5. Intensive studies on characterization of edge plasmas, control scheme of heat and particle flux on divertor, analysis of turbulence and MHD properties, physics of diffusion barrier, high energy particle confinement, steady state experiment etc., are elucidating the advantages of net-current-free heliotron plasmas

➔ Developing an alternative path to an attractive fusion reactor