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

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for LHD Experimental Group and all of Contributors

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Outline

- Observation of Internal Diffusion Barrier (IDB)
- High $\beta$ Experiment
- Long Pulse Plasma Production (ICRF)
- Confinement of High Energy Particles (ICRF)
Characteristics of Heliotron Magnetic Field

Outlook from outside
(Stochastic Structure)

Cross section

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 3D plasmas.
Observation of Internal Diffusion Barrier (IDB) Enabling New Scenario of Super Dense Core Reactor

Central density  : $5 \times 10^{20} \text{m}^{-3}$

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

6 Tesla

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

40m

N. Ohyabu (EX/8-1) on Fri.
Efficient Particle Control Is Realized by Local Island Divertor (LID)

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
\( \Rightarrow \) Efficient pumping speed of several \( \times 10^{21} \) 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)

Hydrogen pellet

baffle

LCFS

LID

head

to

pump

Separatrix (disappeared)

m/n=1/1 island separatrix

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

Wₚ = 1.1MJ, Pₚₐₛₚ = 10MW

nᵣₑₑₜ = 4.4×10¹⁹ m⁻³ s keV

β(0) = 4.4 %, <β> = 1.5 %

Rₚₓ = 3.75m, B = 2.64T

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

\[ \tau_E = 0.079 a^{2.21} R^{0.65} P^{-0.59} n_e^{-0.51} B^{0.83} t_{2/3} \]

J. Miyazawa (EX/3-2) on Wed.
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
External diameter 13.5 m
Plasma major radius 3.9 m
Plasma minor radius 0.6 m
Plasma volume 30 m³
Magnetic field 3 T
Total weight 1,500 t

Present View!
Large Helical Device (LHD)

Pellet Injector
Plasma vacuum vessel
Local Island Divertor (LID)

ECR
84 – 168 GHz

World largest superconducting coil system
Magnetic energy 1 GJ
Cryogenic mass (-269 degree C) 850 t
Tolerance < 2mm

S. Imagawa (FT/P5-3) on Thu.
O. Kaneko (FT/P5-4) on Thu.
Achievements [Final target]

- **Ion Temperature**
  - Central $T_i$: 13.5 keV [10 keV]
  - Density: $3 \times 10^{18} \text{m}^{-3}$ (Ar gas) [$2 \times 10^{19} \text{m}^{-3}$]

- **Electron Temperature**
  - Central $T_e$: 10 keV [10 keV]
  - Density: $5 \times 10^{18} \text{m}^{-3}$ [$2 \times 10^{19} \text{m}^{-3}$]

- **Volume Averaged $\beta$**
  - 4.5% (magnetic field of 0.425T)
  - $[\geq 5 \% (1-2 \text{ T})]$ in steady state

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

- **High Density**
  - $5 \times 10^{20} \text{m}^{-3}$

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

Accumulation of physical data
Systematic investigations become possible
- increase of heating power,
deuteron experiment, etc.

Y. Takeiri (EX/P4-42) on Thu., M. Yokoyama (EX/5-3) on Thu.
S. Sakakibara (EX/7-5) on Fri., T. Mutoh (EX/P1-14) on Mon.
N. Ohyabu (EX/8-1) on Fri., J. Miyazawa (EX/3-2) on Wed.
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

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: $\beta$)
- control of power fluxes to walls

The LHD project addressed these issues from the begging in 1989!
Progress of Achieved Beta

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 >> 10τE

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

S. Sakakibara (EX/7-5) on Fri.
$\beta \sim 4.5\%$ is maintained for $10 \tau_E$ in LHD

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

Increase of $A_p$ enhances magnetic fluctuations with resonances at the edge ➔ resistive interchange mode

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

S.Sakakibara(EX/7-5) on Fri.
Study on the Confinement in High-β Regime

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
54-Minute Long Operation with 500 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 $0.8 \times 10^{19} \text{m}^{-3}$ by the power of 680 kW

$R_{ax} = 3.67-3.7 \text{m}$, $B = 2.75 \text{T}$,
$P_{ICRF} = 600-380 \text{ kW}$, $P_{ECH} = 110 \text{ kW}$
Particle flux profiles as well as heat deposition profile on divertor plates are dispersed by $R_{ax}$ sweeping.

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

$R_{ax} = 3.67m$  
$R_{ax} = 3.7m$

Temperature of divertor tiles saturates at tolerable level.
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, \( R_{ax}=3.7 \) m

NPA measurement and full orbit calculation indicate that significant loss or confinement degradation is not observed in the high energy range of MeV.
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-$\beta$ performance
- Deuterium
  Clarification of isotope effect
  $\alpha$ particle simulation
  Upgrade of NBI power >30 MW
- Closed helical divertor
  Extension of steady state performance
Summary

1. Potential of net-current-free plasmas is enhanced in the Large Helical Device (LHD)

2. In particular, very high density up to $5 \times 10^{20} \text{m}^{-3}$ 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