I-04

ITC18, Seratopia in Toki(Jpn), Dec. 9, 2008

Recent study of the high performance confinement and the high beta plasmas on the Large Helical Devices

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Special Thanks the LHD technical staff for their support of the experiments.

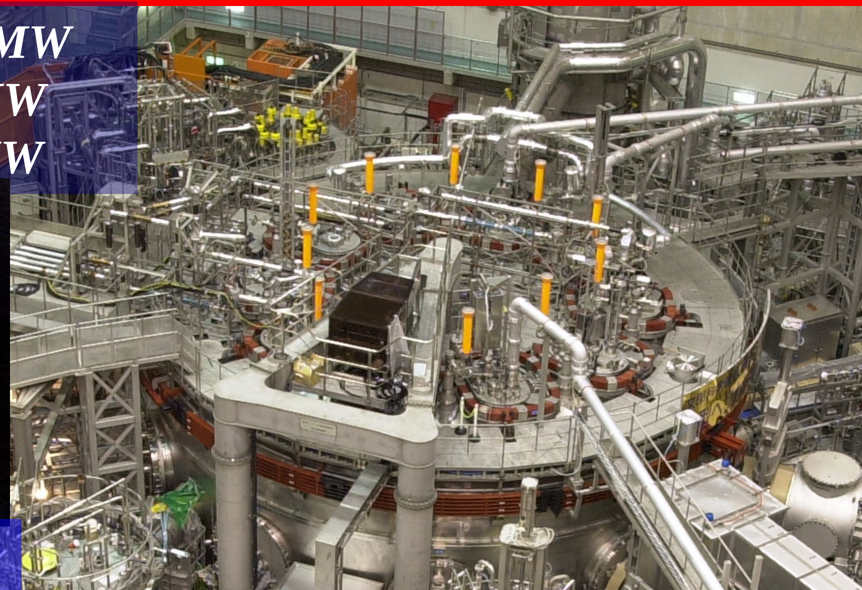
Exp. started at F.Y.1998
Shot *# 90426*
(Up to Dec.5/2008)

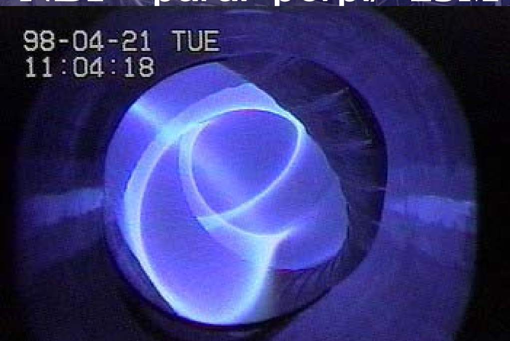
Largest helical and super conducting machine in the world

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

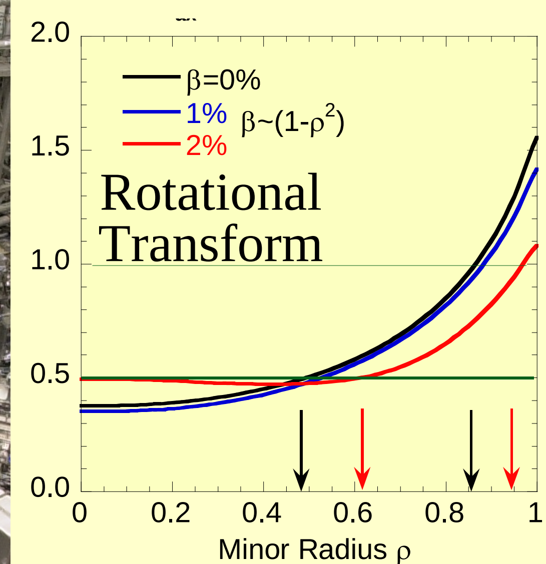
External dia.	**13.5 m**
Plasma Maj. R.	**~3.7 m**
Plasma Min. R.	**~0.6 m**
Plasma Vol.	**~30 m^3**
Magnetic field	**3 T**
Total weight	**1,500 t**

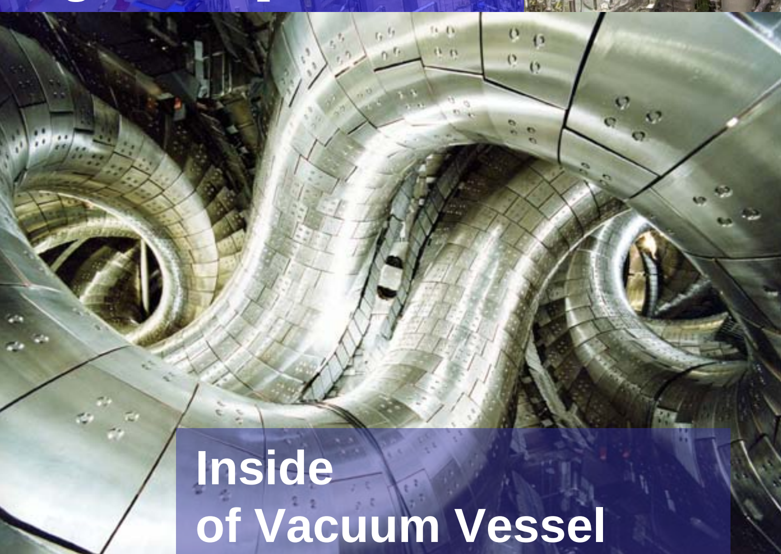
ECH 77 – 168 GHz/*~3MW*
ICH 25-100 MHz/*~3MW*
NBI para.+perp./*~23MW*



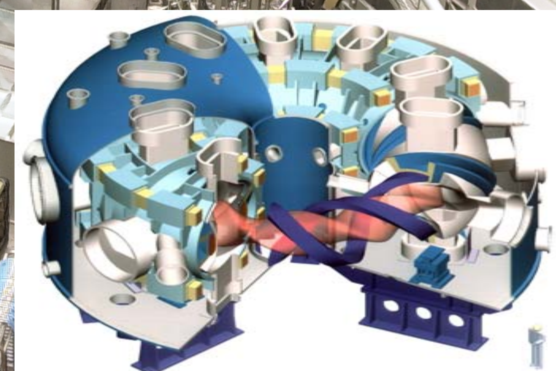


Light from plasma

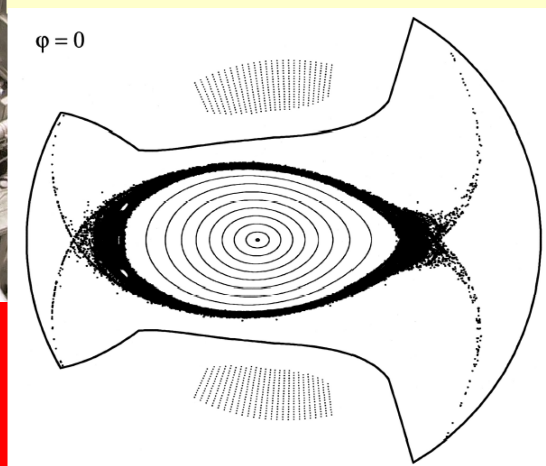




Inside of Vacuum Vessel



Large Helical Device (LHD, NIFS, Japan)



Recent achievements and Designed target in LHD

Achievements [Designed target]

Ion Temperature

Central T_i 5.2 keV (Low Z) [10 keV]

Density $1.6\times10^{19}m^{-3}$ [$2\times10^{19}m^{-3}$]

Electron Temperature

Central T_e 10 keV [10 keV]

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

> 10 keV : reactor condition

Volume Averaged β

5.1 % transient, 5% quasi-steady

(B_0=0.425T) [≥ 5 % (1-2 T)]

Economical reactor

Steady State Operation

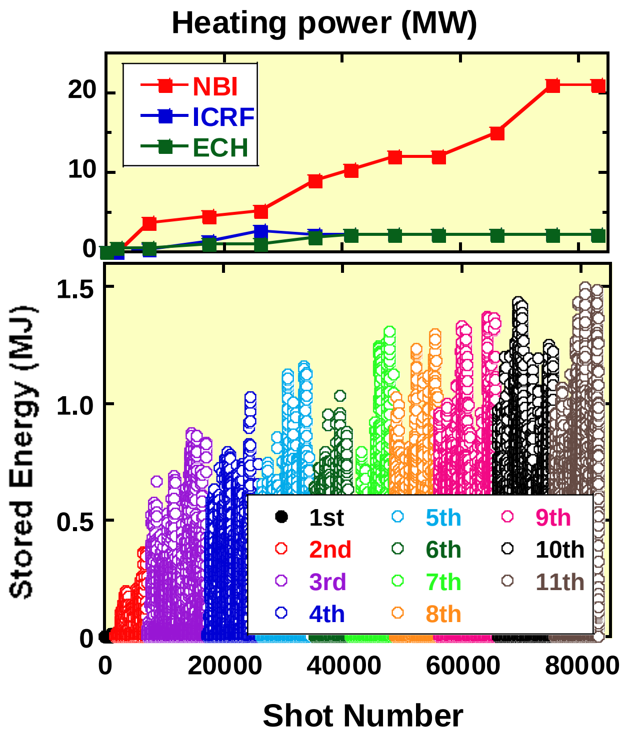
54m28s (490 kW) 1.6 GJ

800s (1.1 MW) [1 hour (3 MW)]

Largest input energy

High Density

$1.1\times10^{21}m^{-3}$ (Super high density with Peaked prof.)



High stored energy comparable to big tokamaks

In the large plasma parameter space systematic investigations become possible → *Accumulation of physical data*

Outline

1. High ion temperature with confinement improvement similar to *Internal Transport Barrier (ITB)*

2. High density n_e (0) > $10^{21}m^{-3}$ with *Internal Diffusion Barrier (IDB)*

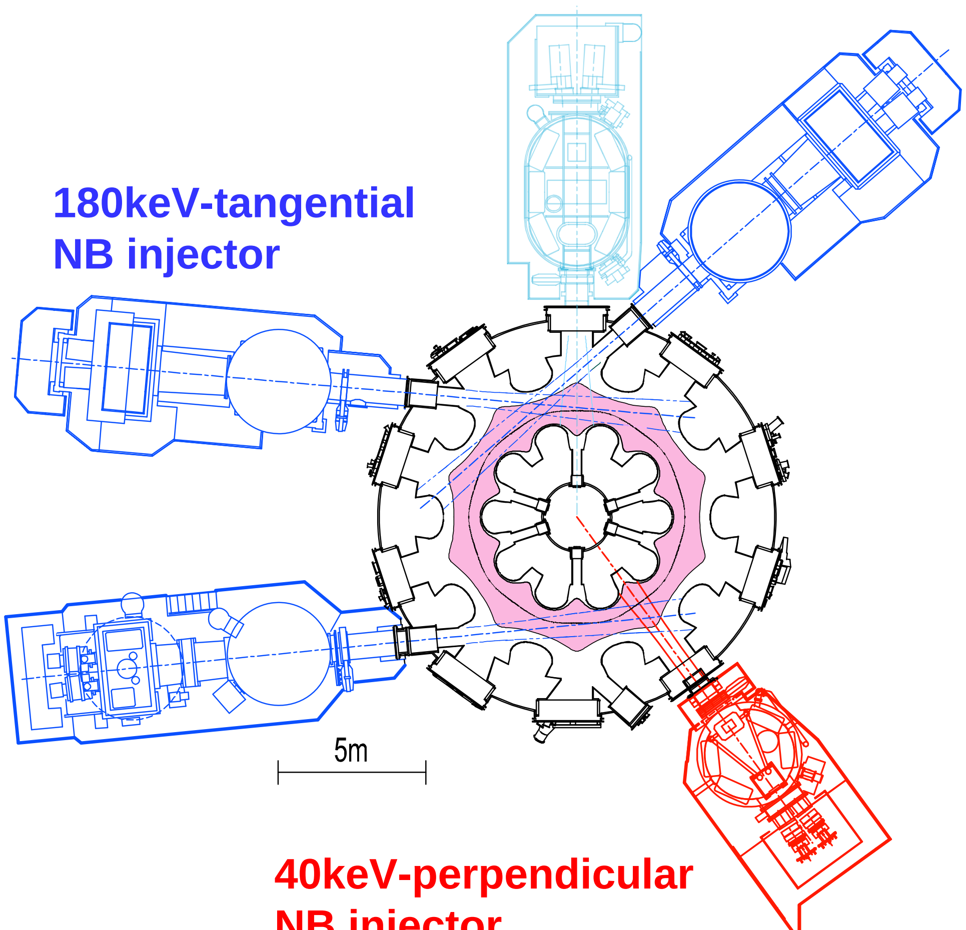
3. High beta <β> = 5 % in quasi-steady state

4. Steady state operation with high input power and high heat load

5. Summary

Update of NBI heating system *to improve ion transport study*

✓ 4 beam lines of NBI (at present)
= 3 tangential + 1 perpendicular (+ 1perpendicular in 2010 ; *in plan*)



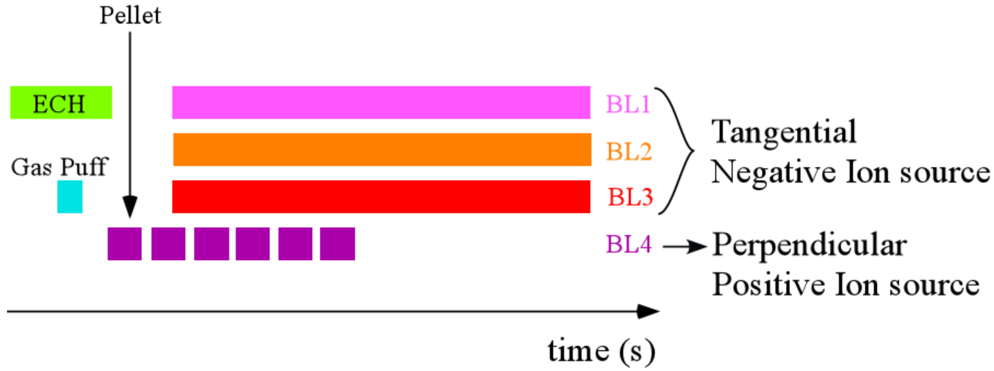
Tangential beams
- 16 MW in total, E_{NBI} = 180 keV with negative-ion sources
- Primarily electron heating
- Good heating efficiency

Perpendicular beam; updated
- 7 MW, E_{NBI} = 40keV with positive-ion sources
- **Ion heating**
- works as a diagnostic beam for **CXRS (T_i, V_ϕ, V_θ, E_r)**

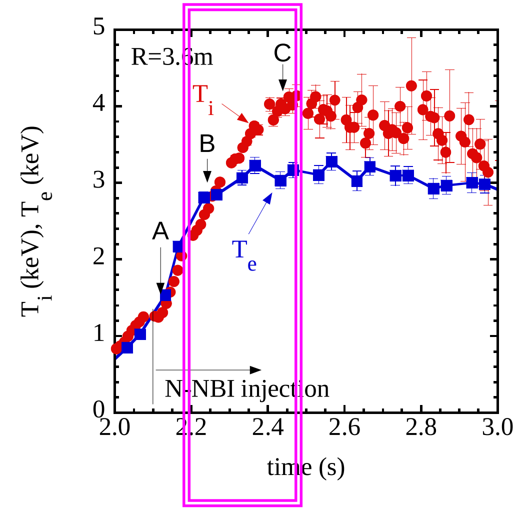
Total input power; 23 MW

Schematic view for High Ti Discharge

Schematic View of discharge



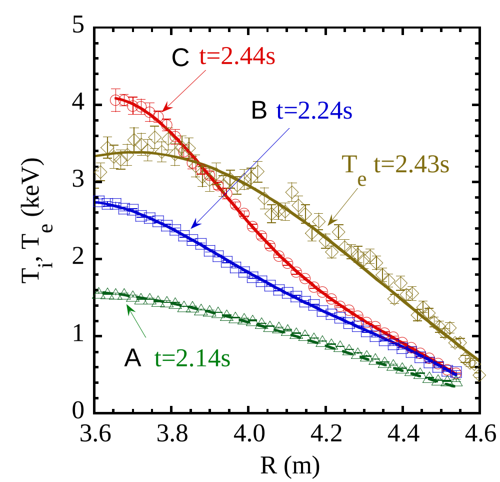
Ti, Te Time Trace



\# Plasma produced with ECH and sustained with NBI.

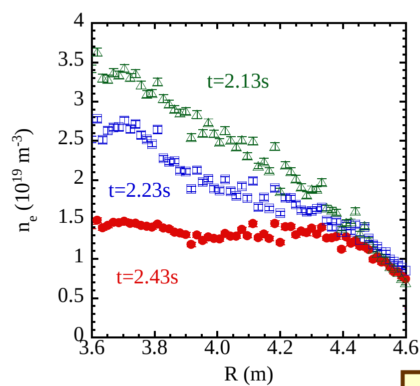
\# Particles are fueled with Gas puffing or pellet injection and NBI.

\# NBI with positive ion sources is modulated on and off with 5Hz for CXRS.



Typical density at high T_i phase

$n_e = 1 \sim 2 \times 10^{19}\ m^{-3}$

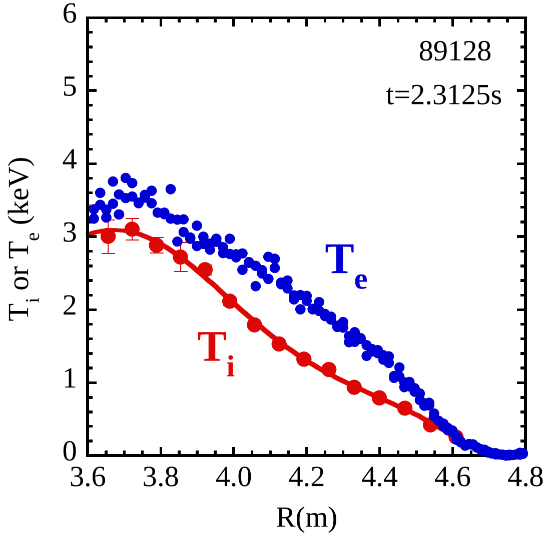


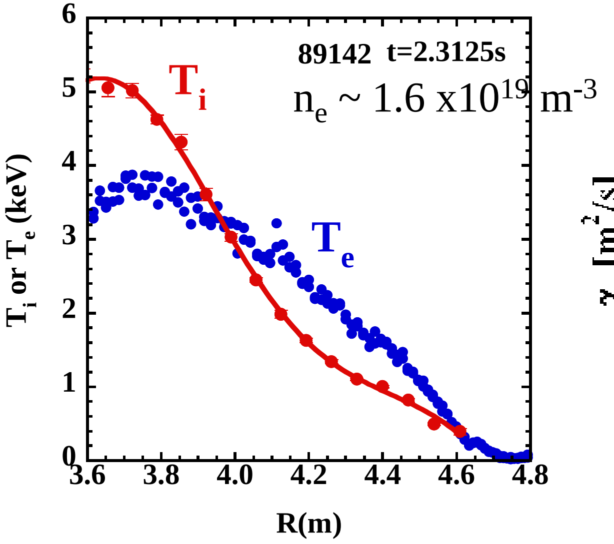
➔ **(Wed) I-11 by M.Yoshinuma**

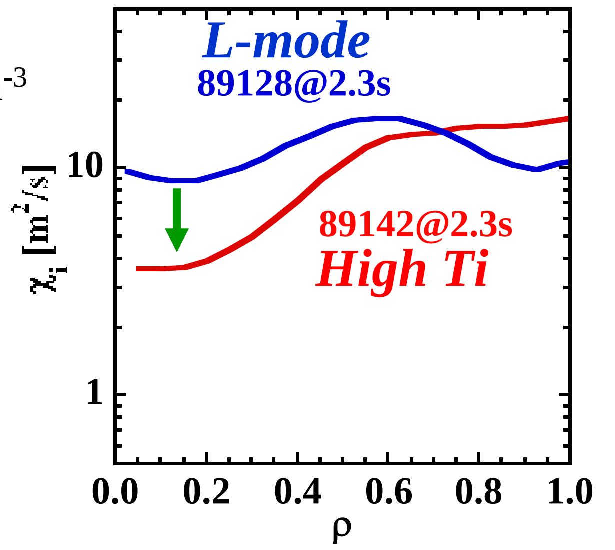
High Ti discharge with confinement improvement

L-mode

Improved confinement with Internal Transport Barrier







$T_i < T_e$

$\nabla T_i \sim \nabla T_e$ at $\rho < 0.5$

$T_i > T_e$

$\nabla T_i >> \nabla T_e$ at $\rho < 0.5$

Improvement of ion transport in Core

Mechanism of the Ion ITB formation; under investigation

What is the key parameter?

Ratio of Te/Ti, Deposition power, Er, Vt and so on?

Extension of the high density operation regime with good energy confinement in IDB plasmas

Achievements of high n and high p in *Internal Diffusion Barrier* plasmas

\# Super high density with peaked prof. is obtained just after the multi-pellet injection.

Maximum $n_e(0)$ exceeds 1×10^{21} m^{-3}

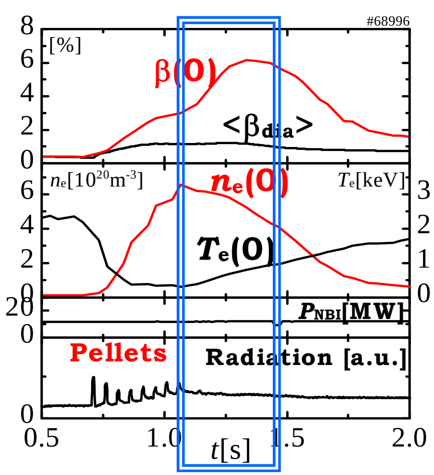
\# High central pressure is obtained during the density decay phase.

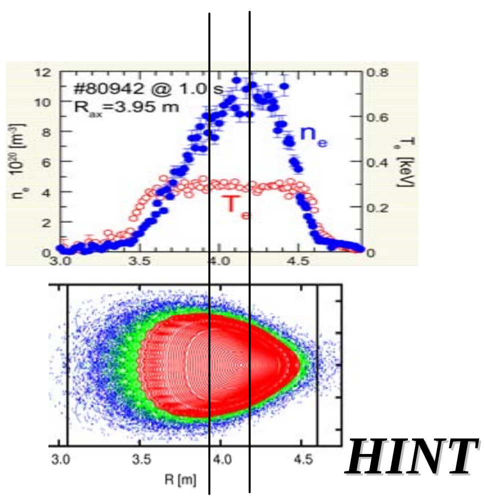
Maximum P(0) ~150 kPa

Large Shafranov shift;

reaches to half the radius

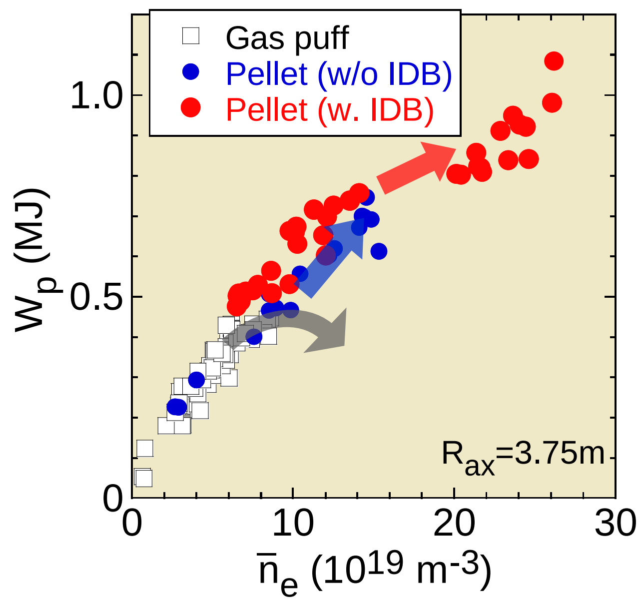
predicts large stochastic region.





\# Confinement capability rolls over in high density regime w/o IDB

\# IDB plasmas extend the high density regimes with the good energy confinement (ISS95 scaling).



→ (Wed) I-12 by T.Morisaki

Operational limit of IDB plasmas

Limitation of central pressure by Core Density Collapse

\# Core density is abruptly expelled at high central pressure phase

\# Sometimes MHD events are observed around CDC.

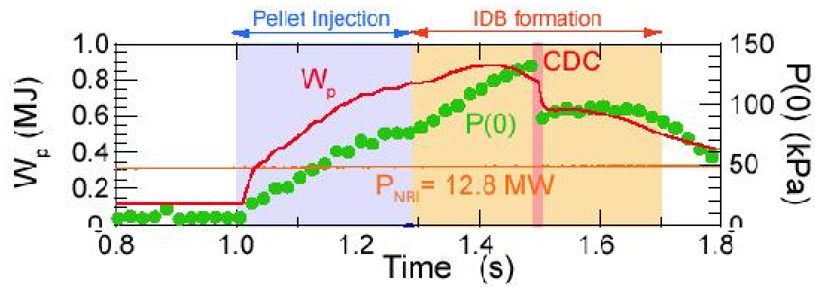
Driving mechanism;
under investigation
(MHD insta. and/or equil. limit)

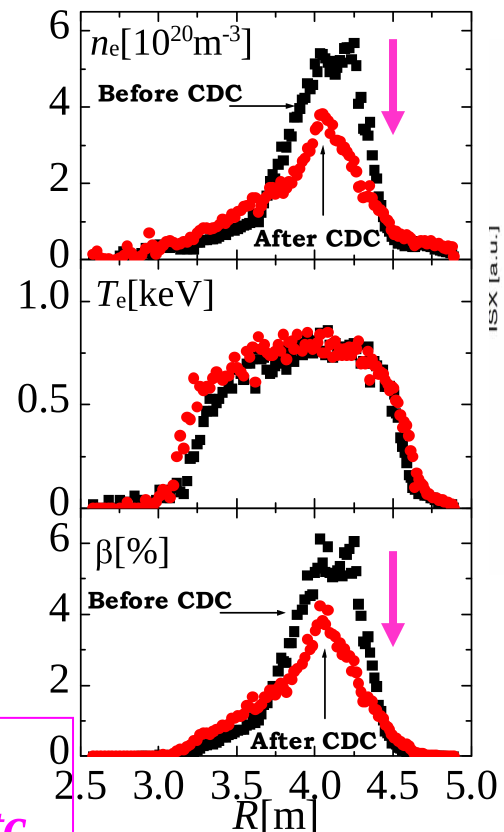
Limitation of central density by lack of central heating power

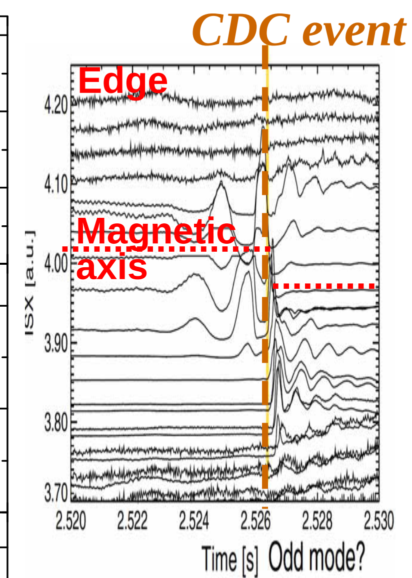
\# High density plasma inhibit NB penetration to the core

\# Density rise by pellet is limited

Central heating efficiency is a key issue
=> ***high energy NBI. Bernstein Wave etc.***

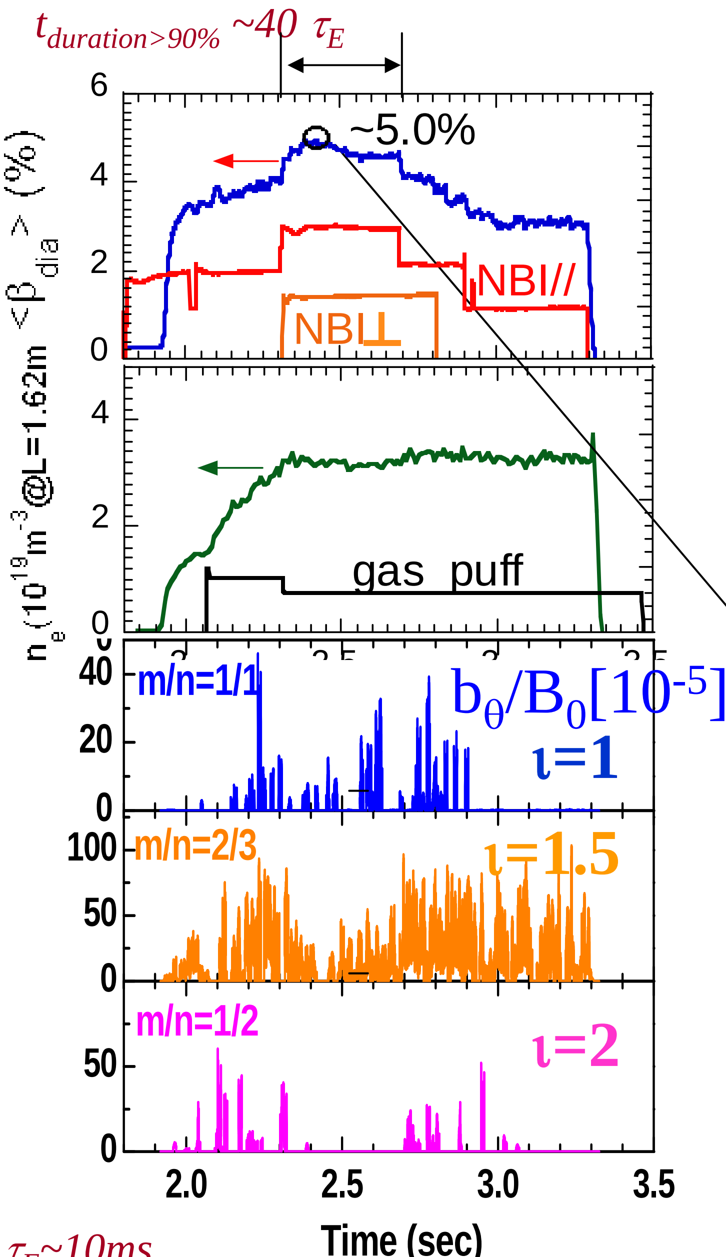






SX fluctuation

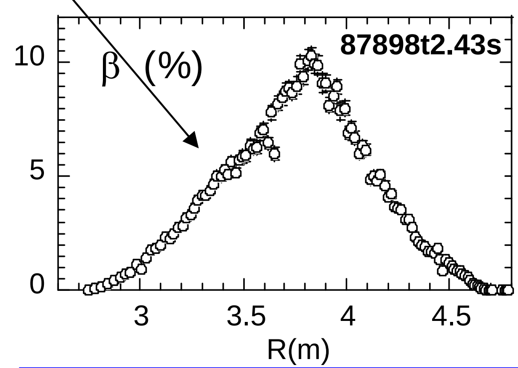
Quasi-steady high-β discharge <β>=5.0 %



τ_E~10ms

B_0~0.425T, R~3.7m, a_p~0.55m, V_p~22m^3
Mainly tangential NB heats plasmas

 # No disruptive high beta plasma is maintained during around 40τ_E
 # Large shafranov shift Δ/a_p ~ 40%
 # Low-n,m MHD activities
- **No observation of core resonant modes.**
- **Only resonating mode with peripheral surf. (m/n = 2/3 and 1/1) appear**



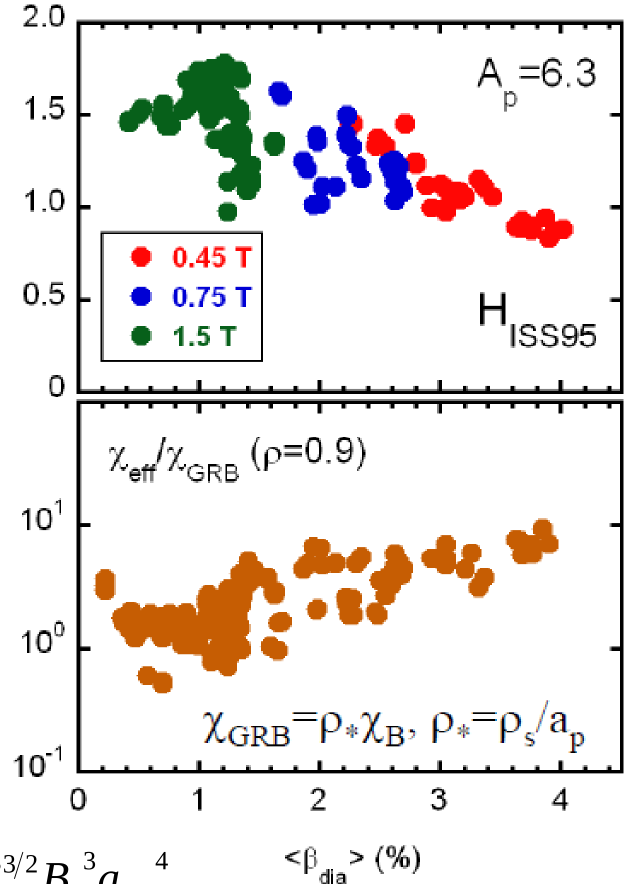
Some fine structures are observed.

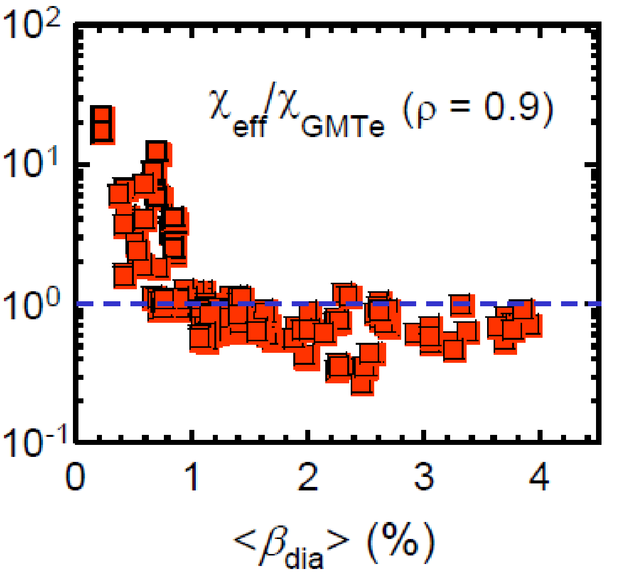
Theoretically;
Low-n MHD insta. with narrow radial mode width are predicted.

Fine structure (flattening and asymmetry) effect on a global confinement looks small

Effect of MHD instability on the confinement

Global confinement and peripheral local transport degrading with beta





 # χ dependence on β is similar with a prediction based on MHD (resistive interchange mode) driven turbulence.

$$\chi_{GMTe} \propto \beta^1 \nu_{p*}^{0.67} \rho_*^{0.33} \chi_B \propto S^{-\frac{2}{3}}$$

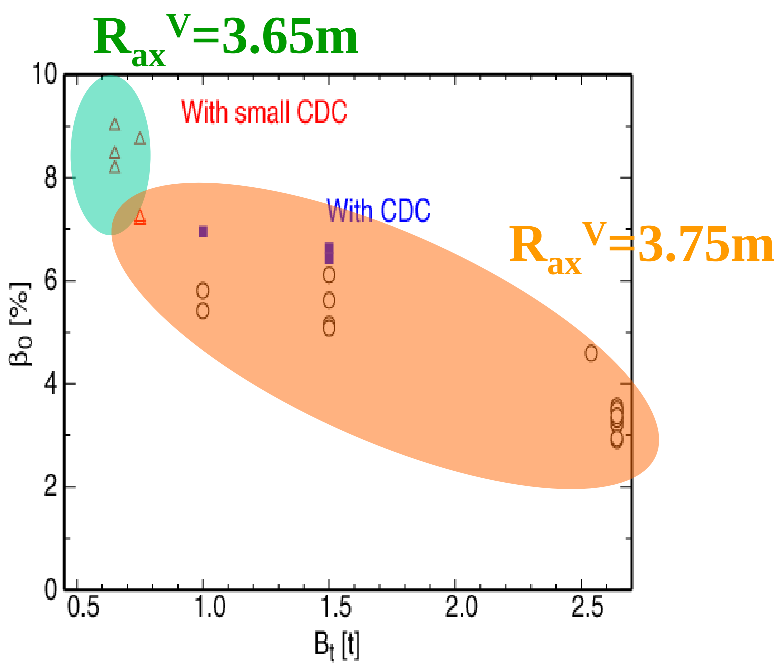
proposed by Carreras et al. (PoF B1 (1989))

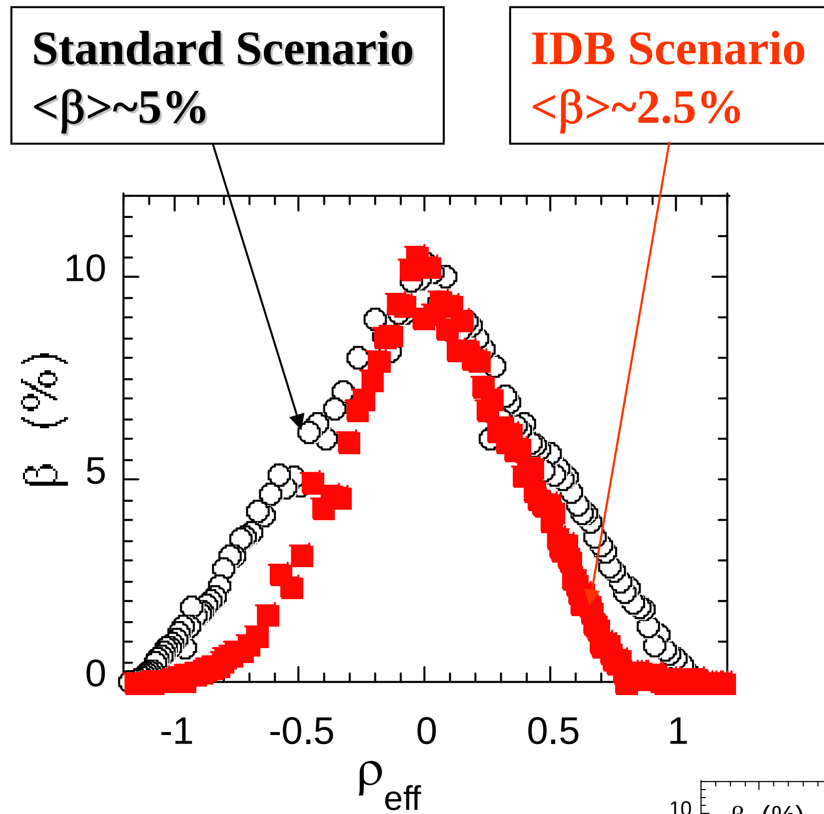
$$S \propto \frac{\beta^{3/2} B_0^{\ 3} a_{eff}^{\ \ 4}}{P}$$

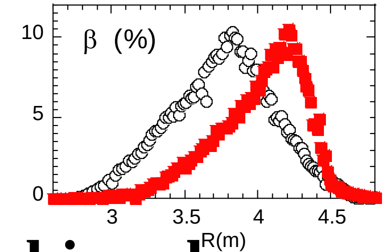
Present LHD < β >~5% is obtained in 0.42T, 1T, <β>~4% plasma => S ; 10 times larger

Magnetic Reynolds number, S, is a key parameter for resistive MHD insta.

High central beta plasmas by IDB formation







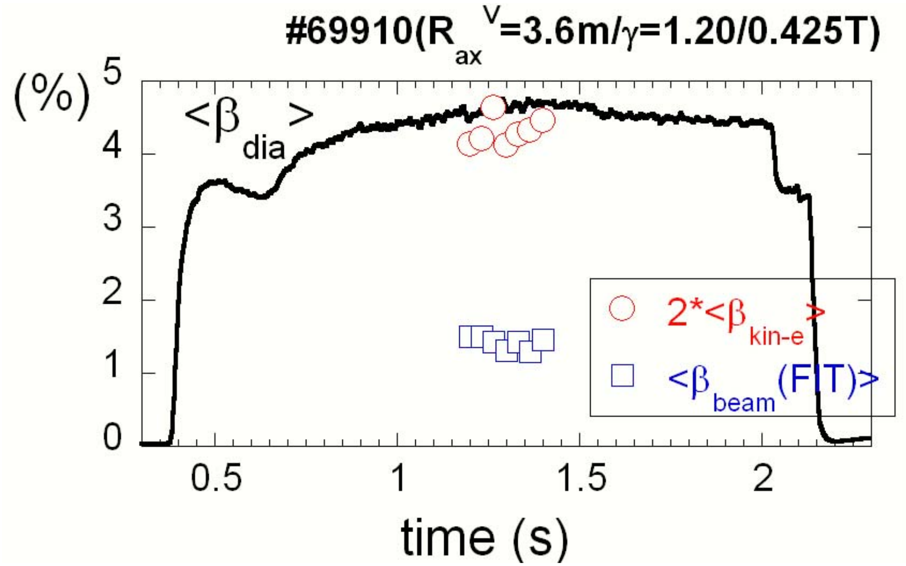
As B_t decreases,
CDC effect on confinement becomes small
=> Achieved β_0 increases

Reason not clear yet!!

β_0 comparable with standard high beta operation has been achieved by IDB formation

Large beam pressure component is predicted in high β

$<\beta_{kin}>$; 3.6% (Z_{eff}=2.5), $<\beta_{beam}>$; 1.5% (Cal.)



Port-through power //NBI *13.8MW*

$<\beta_{dia}>$; 4.8% (β_{perp}~3.2)

$<\beta_{kin}>$; *3.6%* (Z_{eff}=2.5)

(2x$<\beta_{kin-e}>$; 4.3%)

$<\beta_{beam}>$; *1.5%* (Cal. by FIT code)

Beam pressure effects on MHD;To be resolve

Relatively low n_e and low B_0 leads to large ratio of p_{beam}.

$<\beta_{dia}>$; based on the diamagnetic measurement.

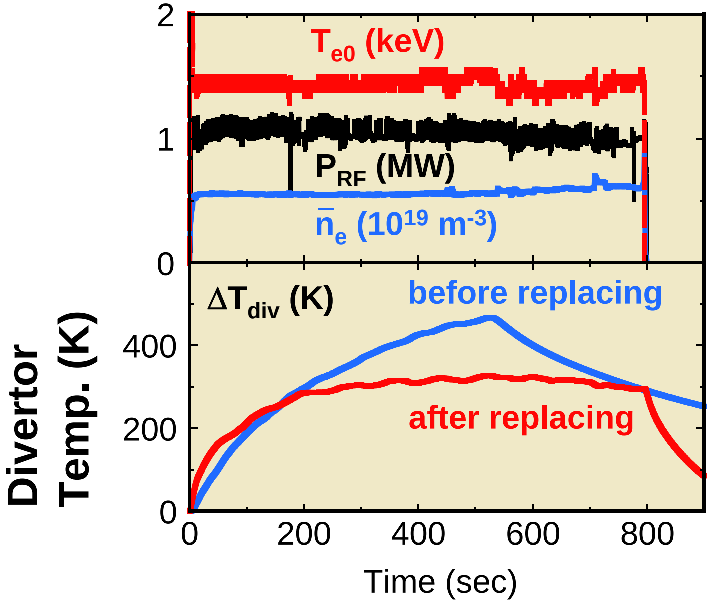
$<2x\beta_{kin-e}>$; based on the T_e and n_e profile measurements Z_{eff}=1 and T_i=T_e are assumed.

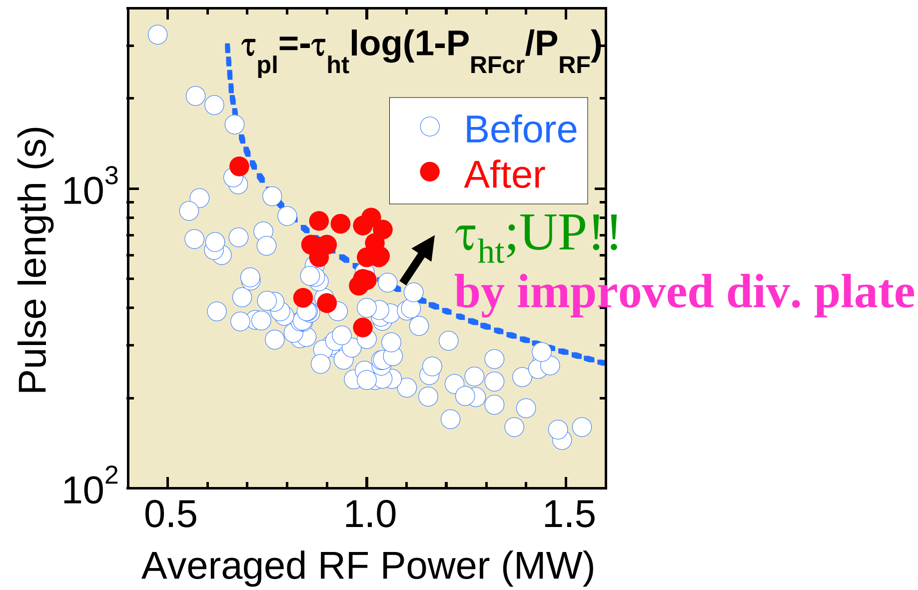
(When Z_{eff}=2.5, $<\beta_{kin}>$~3.6%(β_{perp}~2.45), $<\beta_{beam}>_{perp}$~0.75%, $<\beta_{beam}>_{ara}$~0.75%)

$<\beta_{beam}>$; based on the calculation with Monte Carlo technique.

Demonstration of high input power and high heat load in Steady state

A scaling relation of the pulse length to the injected RF power was derived defining the critical temperature of divertor plates.





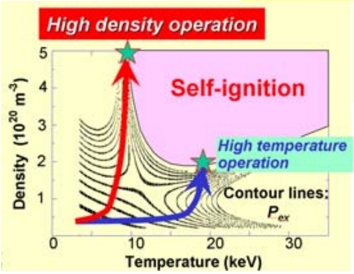
P_{RF} = 1.1 MW (ICH;1 MW, ECH; 0.1 MW) **for 800s**

 # Divertor temperature is a key parameter of the observation of intensive spark.

 # Replacement of the improved divertor plates with good heat conductivity reduces the increment of divertor plate temperature.

➔ (Thu) I-21 by T.Seki

Subjects on LHD Experiment to Reactor



Two reactor operation scenario

; High T /High n

LHD designed target
[Achievements]

Ion Temperature
T_{i0} 10 keV@ 2×10^{19}m^{-3}
[5.2 keV@ 1.6×10^{19}m^{-3}]

Electron Temperature
T_{e0} 10 keV@ 2×10^{19}m^{-3}
[10 keV @ 5×10^{18}m^{-3}]

Volume Averaged β
≥ 5 % (1-2 T) [5.1 % (0.425T)]

Steady State Operation
1 hour (3MW)
[54m28s(490 kW)1.6GJ,
800s(1.1MW)0.88GJ]

High Density
[1.1×10^{21}m^{-3} (with IDB)]

For high T scenario (conventional)

 # Reduction of neoclassical transport in low ν
(Demonstrate electron root under Ti~Te)

 # High performance confinement in low ν and high β, under low beam pressure
(Confirm small effects of low-n MHD insta. & resistive g turbulence in low S and high β)
<β>>4% with B_0~1T and/or <β>~5% with B_0>0.8T

For high n scenario (innovative)

 # Development of particle fueling method in the core with high n and relatively high T repeatedly

 # Understandings of CDC mechanism to avoid it
(Study of ballooning, resistive MHD insta. and MHD equil. limit and so on)

 # Study of transport property in stochastic regime

Under steady state operation

 # Study of impurity transport (including development of He exhaust scenario)

 # Development of suppression method of heat load to divertor

Summary

1. **Demonstration of high ion temperature with confinement improvement similar to *Internal Transport Barrier* (*ITB)* accompanied by Impurity hole**

2. **Achievement of high density n_e (0) > $10^{21}m^{-3}$ with *Internal Diffusion Barrier (IDB)* and Extension of the high density operation regime with good energy confinement**

3. **High beta <β> = 5 % is maintained in quasi-steady state and Demonstration of the high beta scenario consistent with high density reactor scenario**

4. **Demonstration of high input power and high heat load in Steady state; 1.1MW for 800s**

LHD exp. related contributions (I/3, O/2, P/20)

I-11 M.Yoshinuma

Characteristic of an impurity hole in Large Helical Device

I-12 T. Morisaki

Topological Changes in Magnetic Flux Surfaces during IDB-SDC Discharge in LHD

I-21 T. Seki

Progress of Steady State Experiment in LHD

O-6 S.Murakami

Energetic ion confinement and lost ion distribution in heliotrons

O-7 A. Shimizu

The observation of potential fluctuation with 6 MeV Heavy Ion Beam Probe in LHD

P1-4 J. Miyazawa	Heating power dependence of the fusion triple product in high-density internal diffusion barrier plasmas in LHD
P1-9 S. Sakakibara	Effect of external magnetic perturbation on MHD characteristics in the Large Helical Device
P1-26 H.Yu. Zhou	Zeff Profile Analysis from Visible Bremsstrahlung Measurement under Different Density Profiles inl LHD
P1-30 Y. Nobuta	Hydrogen Concentration and Crystal Structure of Carbon Films produced at the duct of Local Island Divertor in Large Helical Device
P1-32 E.A. Veshchev	Influence of Neutral Beam Injection Direction on Fast Ion Distribution Function in Large Helical Device (LHD)
P1-36 T. Ozaki	Comparison of neutral particle flux decay times on the NBI plasmas in Large Helical Device
P2-8 H. Takahashi	Development of 77 GHz-1 MW ECRH system for LHD
P2-10 Y. Yoshimura	2nd Harmonic ECCD experiment using 84 GHz EC-wave in LHD
P2-13 T. Oosako	Fast wave electron heating experiments focusing on competition between damping mechanisms on Large Helical Device
P2-17 G. Motojima	Spectroscopic diagnostics for spatial density distribution of plasmoid by pellet injection in Large Helical Device
P2-23 H. Chikaraishi	Voltage enhancement of the dc power supplies for dynamic current control of LHD superconducting coils
P2-28 M. Takeuchi	Development of a High Speed VUV Camera System for 2-Dimensional Imaging of Turbulent Structures in LHD
P2-31 S. Kubo	Collective Thomson Scattering Study using Gyrotron in LHD
P2-32 S. Muto	Observation of space and energy distributions of high-energy electrons produced in ECH plasmas of LHD
P2-33 M. Goto	Simultaneous measurement of electron and ion temperatures with heliumlike argon spectrum for LHD
P2-40 T. Yoshinaga	Fluctuation observation by the microwave imaging reflectometry in LHD
P2-41 D. Kuwahara	Development of 2-D Antenna Array for Microwave Imaging Reflectometry in LHD
P2-42 T. Oishi	Development of beam emission spectroscopy system for the measurement of density fluctuations in LHD
P2-43 C. Suzuki	Extension of the energy-resolved soft X-ray imaging system using two CCD cameras in LHD
P2-46 T. Minami	Development of in-situ Density Calibration for Thomson Scattering Measurement by Microwave Reflectometry on LHD