Summary of LHD Project: FY2004 Results and FY 2005 Plan

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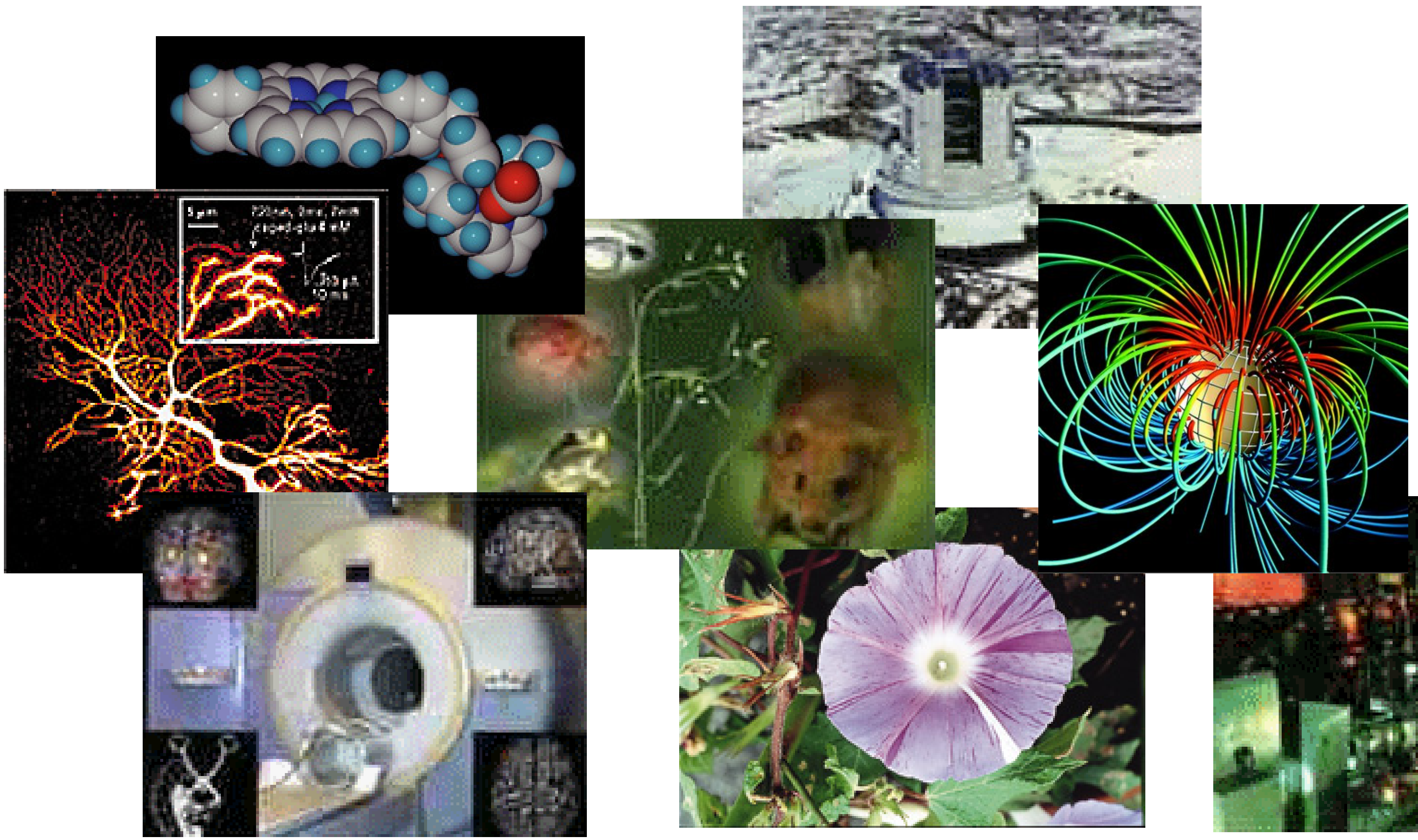
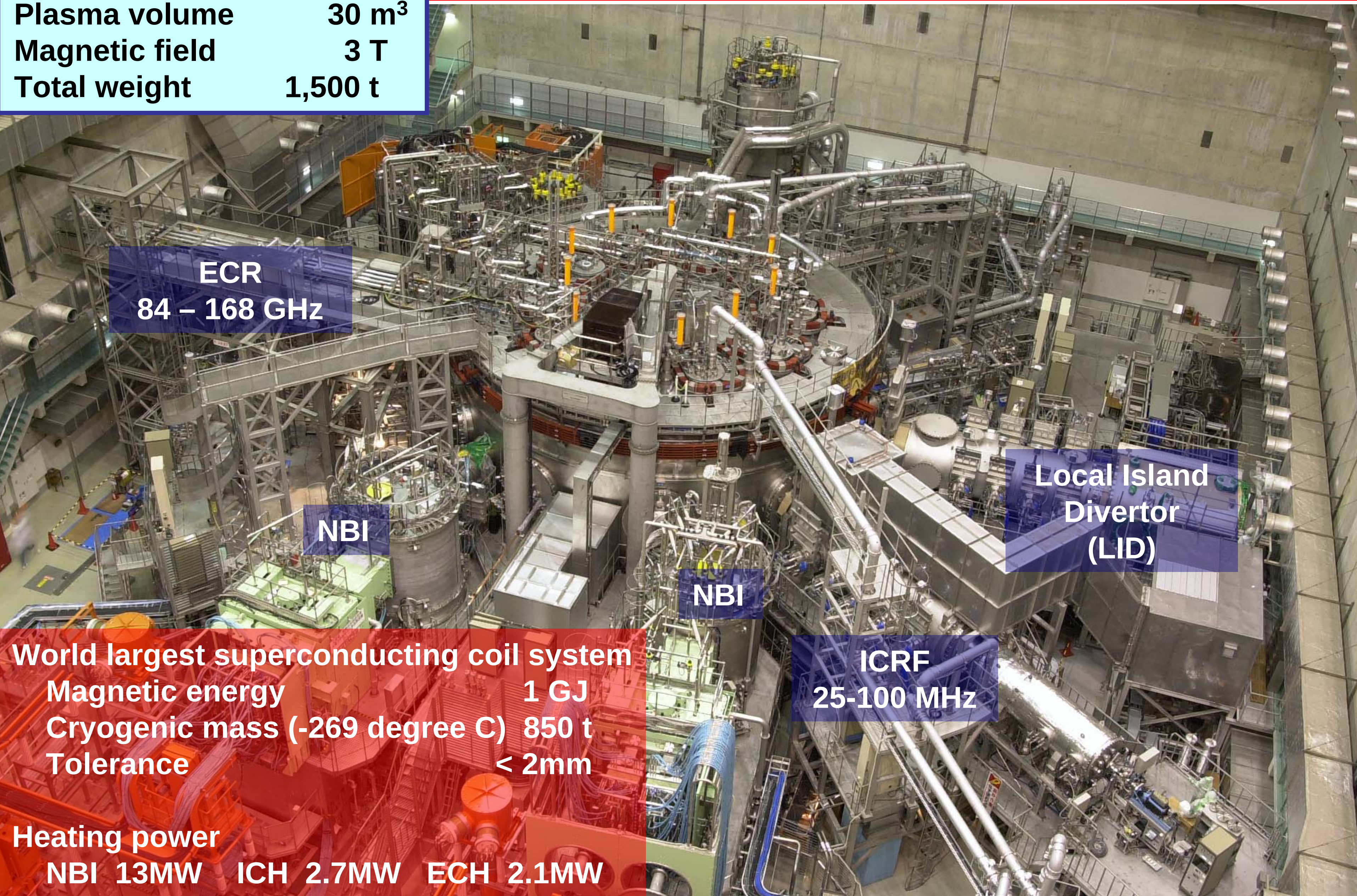


Large Helical Device (LHD)

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



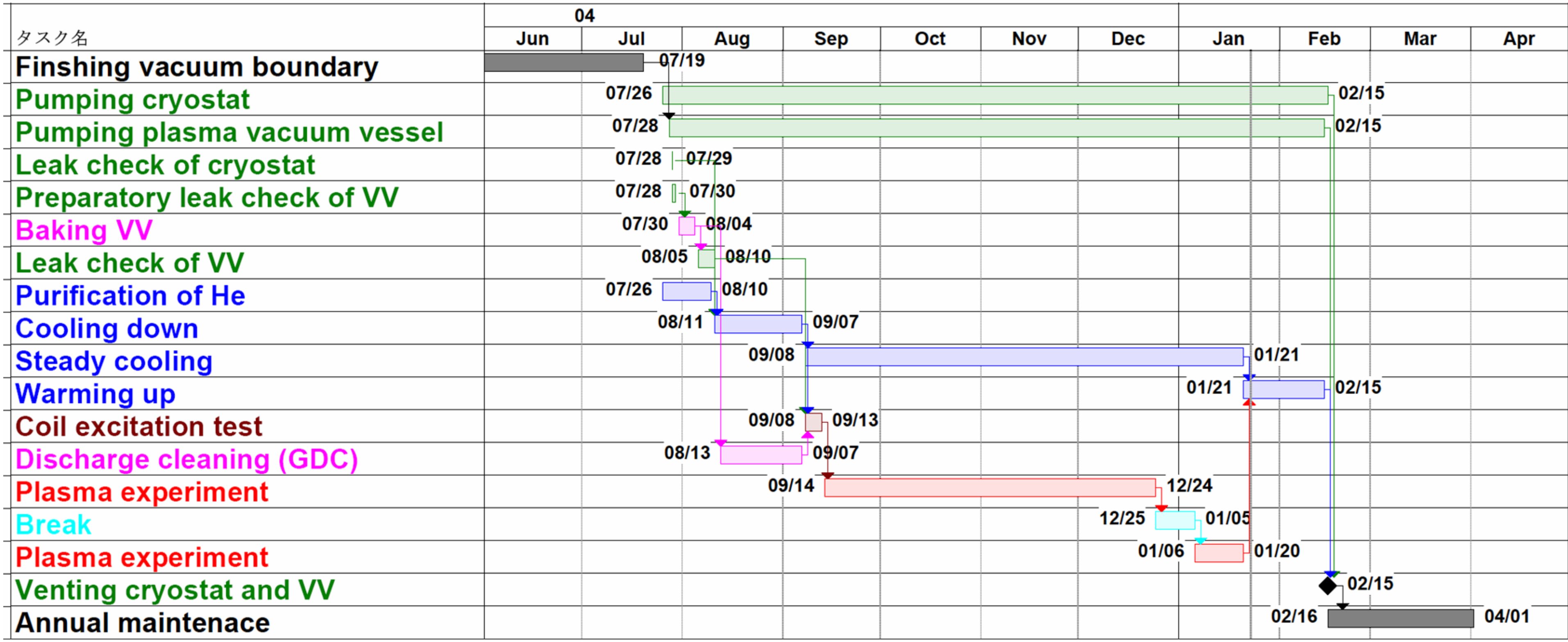
World largest superconducting coil system

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

Heating power

NBI 13MW   ICH 2.7MW   ECH 2.1MW

The 8th experimental campaign (FY2004)



Plasma experiment (57 days in 17 weeks) has been completed by Jan.20.
Number of coil excitation : 87 (891 in total for 8 campaigns in 7 years)
Number of plasma shot : 7398 (56220 in total)

Plasma discharge is available every 3 min.

- ➔ **High reliability in highly repetitive operation**
- ➔ **Leading to steady-state operation**

Steady state operation at LHD

Goals

- **Extension of plasma parameter regime : ~1 MW for a few min**
  (extended to 1 MW for 1000s (= 1 GJ of input energy) in a few years)

Results

- **Long pulse operation with 1 MW for 2 min. has been achieved.**
- **Long pulse operation with 680 kW for 1905 s has been achieved.**
  ➔ Input energy is 1.3 GJ
  (exceeded the previous world record 1.07GJ of ToreSupra)
- **Pulse length extended to over 1 hour (65 min.) by 100 kW of ECH.**

Major elements for these results

- **Improvement of performance of steady-state heating facility**
  Systematic integration of ICRF facility
  Modification of gyrotron and transfer tube
  Stable long pulse operation of NBI
- **Improvement of heat removal efficiency of divertor plates**
- **Dispersing heat load on divertor plates by real-time magnetic axis sweep**

Next step

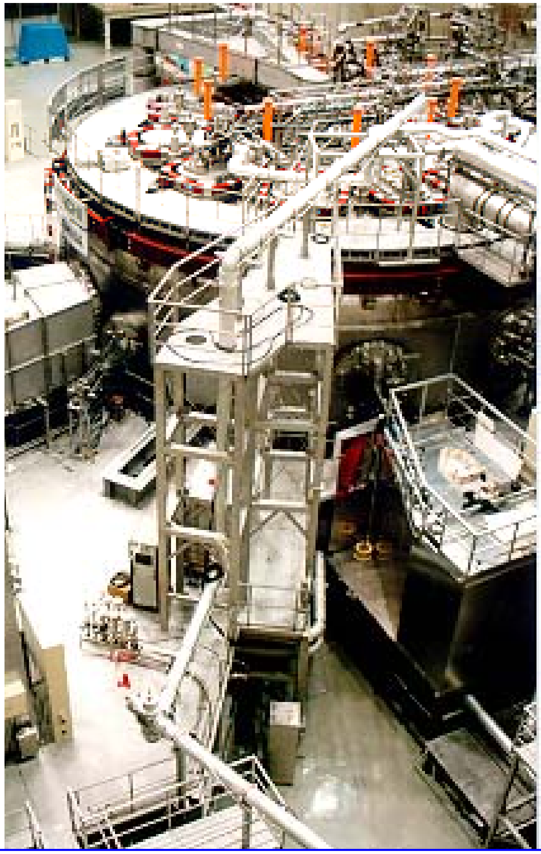
Input energy of more than 1.3 GJ with heating power of ~1 MW

Systematic improvement of ICRF facility has enabled stable injection of heating power in steady state

Radio-frequency Oscillator

Drastic remodeling for stability & reliability

- DC power supply
- Control system
- Circuit breaker

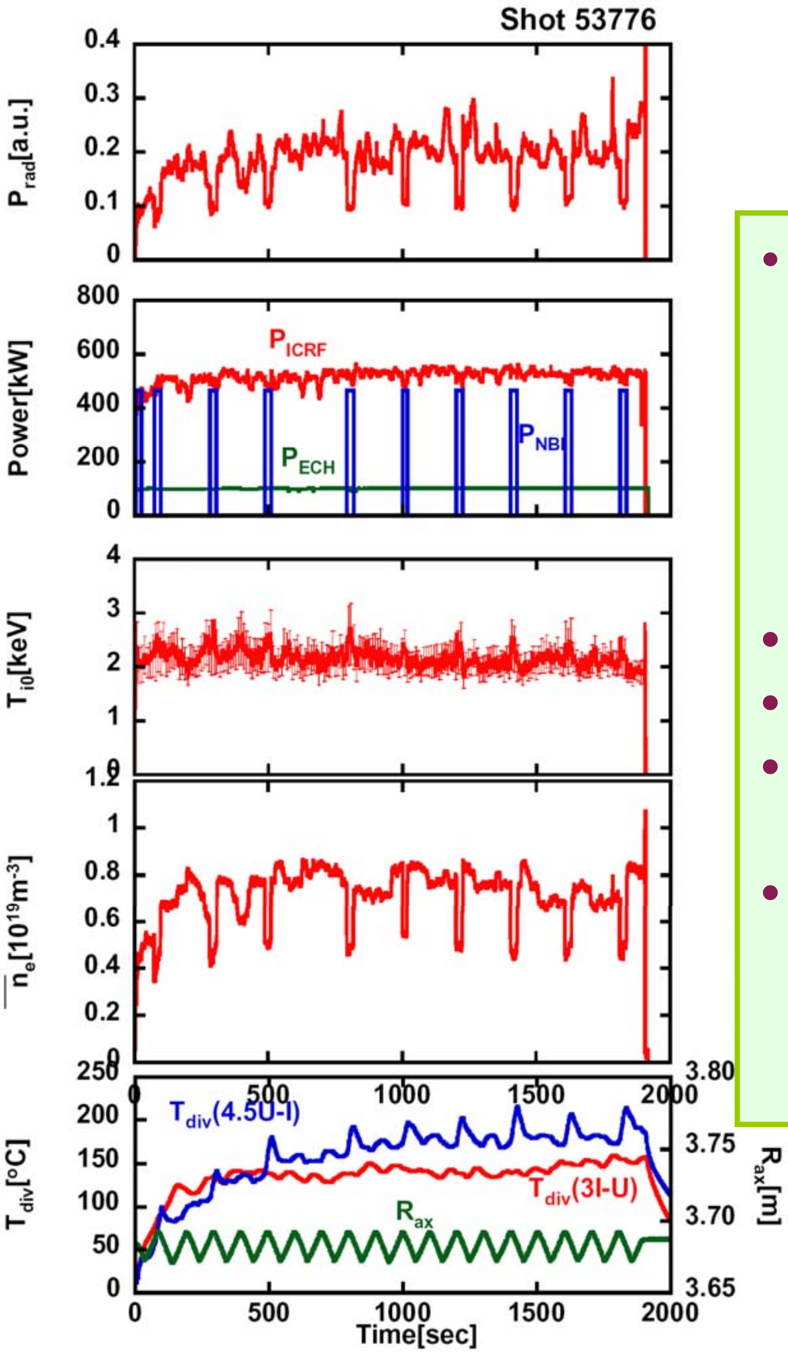


ICRF antenna modification to prevent arcing and water leak

- **Faraday shield**
- **Carbon side-protector**
- **Inner conductor**
- **Grounding plate**

Coaxial transfer line to LHD

- **Upgrade of cooling facility for transfer line and impedance matching unit**
- **Feedback control against change of loading becomes available**

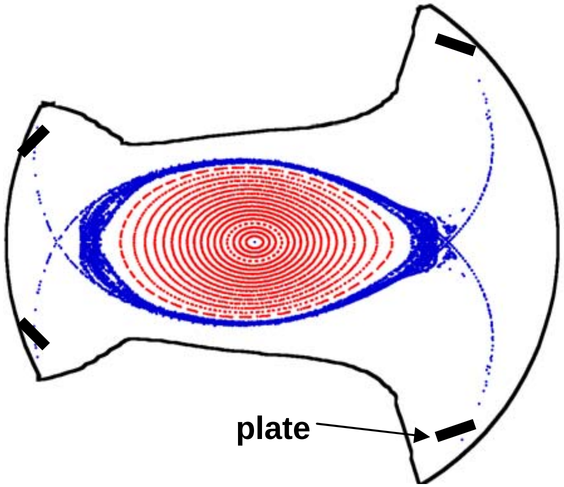


31 min 45 sec long pulse discharge

- Combination of three heating schemes
  Average power is 680kW.
  Steady state injection of ICRF(520 KW) and ECH(100 kW)
  25s pulse of NBI at intervals : 60 kW
  (averaged for one duty cycle)
- Ion temperature 2.0keV
- Electron temperature 1.3-1.7keV
- Line averaged electron density $7\text{-}8\times10^{18}\ m^{-3}$
  Density drops during NBI pulses.
- Sweep of magnetic axis (one round of 3cm for 3min. 18 rounds between R_{ax}= 3.67-3.7m)
  ➔ maintain the temperature of divertor plates close to antenna at moderate level.

(B = 2.75T at R=3.6m, #53776, Helium)

Key subjects for long pulse operation



Divertor : heat removal capability and reduction of heat load

- **Modification of carbon divertor plate to suppress spouting of gas due to temperature increase.**
- **Real-time magnetic axis sweep prevents concentration of heat load to the specific position and consequently suppresses spouting of gas.**

Upgrade of heating facilities

- **Stabilization of ICRF heating source**
  - **Avoidance of arcing in antenna**
  - **Increase of the number of steady-state oscillator, which reduces the power per one antenna and consequently more stable operation is available.**
  - **Upgrade of cooling capability of transfer lines**
- **Combination of three heating schemes**
  - **ICRF（520kW） Primary heating source（He majority and H minority）**
  - **ECH(100kW) Improvement thermal stability of plasmas by electron heating**
  - **NBI (60kW : averaged for one duty cycle) Improvement thermal stability of plasmas by electron heating and core fueling**

Wall conditioning

- **Boronization suppresses influx of both metal and light impurities.**

Parameters in steady state plasma discharge (ICRF, ECH, NBI)

Parameter of LHD operation

Magnetic field	2.75 T
Major radius	3.67~3.70 m（18 rounds）
Minor radius	0.6 m

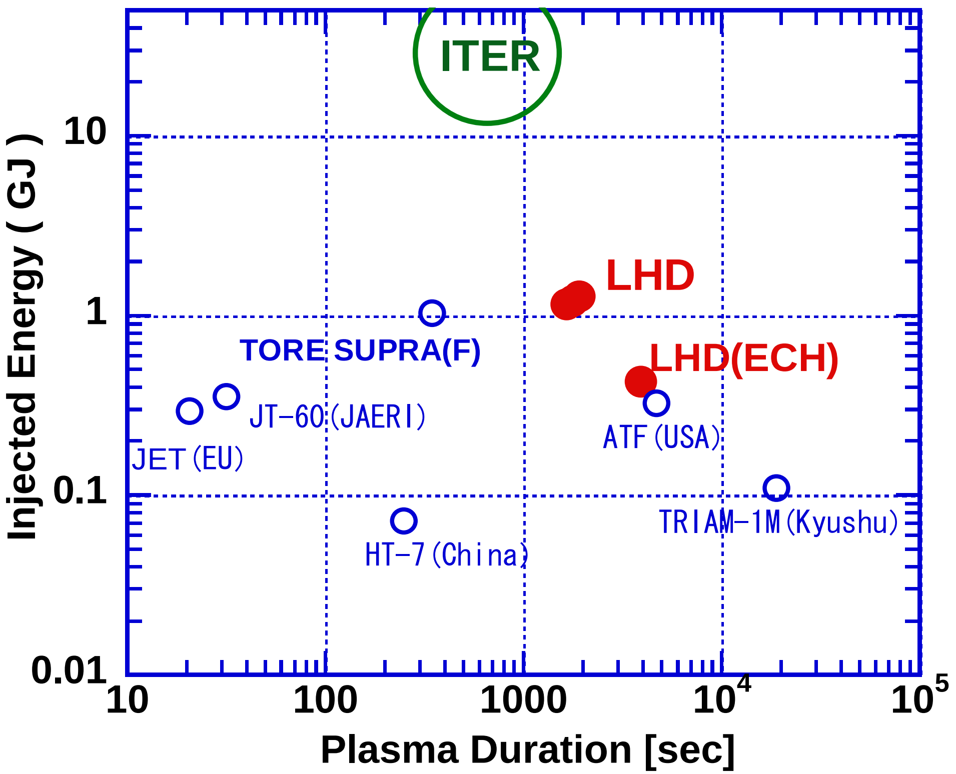
Plasma parameters

Electron density	$7 \sim 8 \times 10^{18}/m^{-3}$
Central ion temperature	2.0 keV
Central electron temperature	1.3-1.7keV

Averaged input power :	**680kW**
ICRF (38.5MHz)	520kW
ECH (84GHz)	100kW
NBI	60kW

Discharge pulse length :	**31min. 45 sec.**（1905 s）
Total input energy :	**1.3 GJ**

LHD has extended the regime of the long pulse plasma experiments

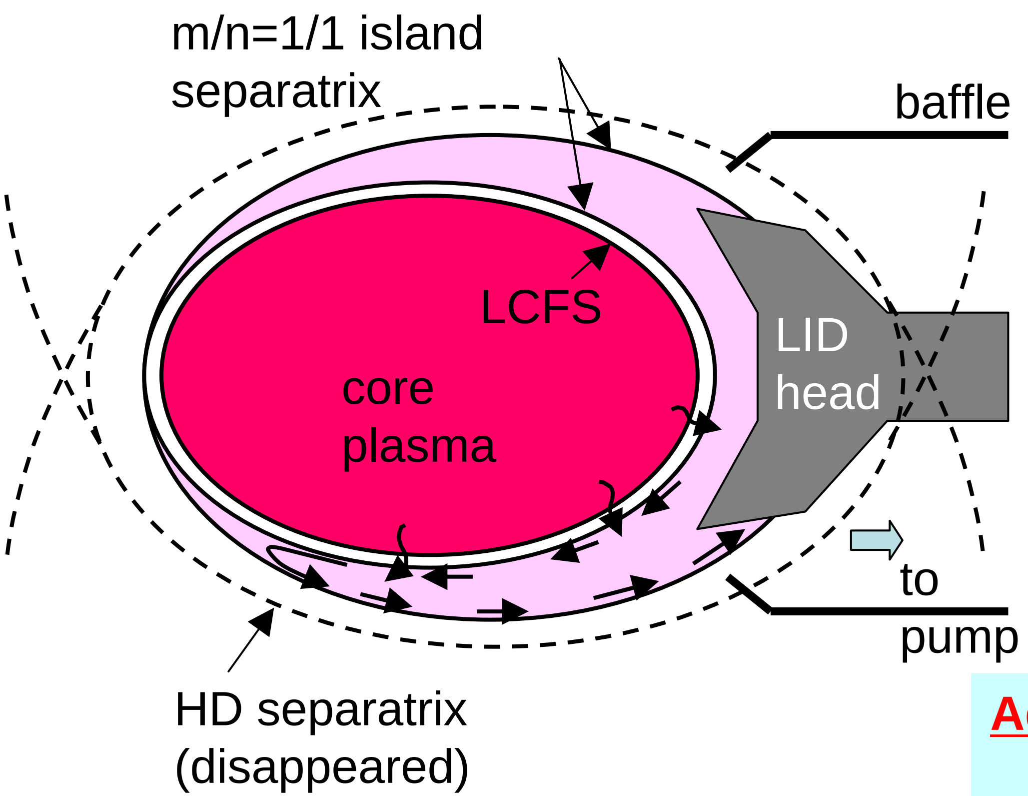


- ◆ Record of input energy to high temperature plasmas
  1.3GJ : World record
  Previous record : 1.07GJ
  （Tore Supra）
- ◆ Beyond achievements in super-conducting tokamaks
- ◆ Planning longer pulse with more heating power

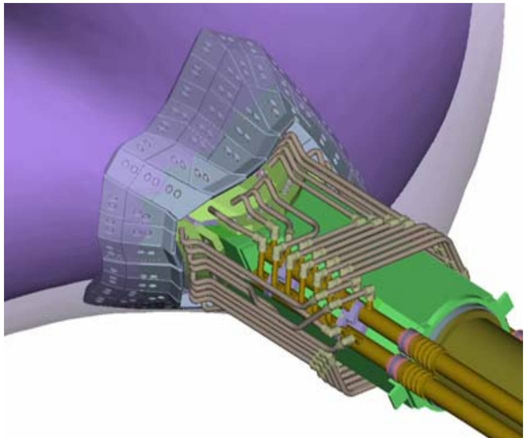
- Successful demonstration of potential of helical system towards steady state reactor
- Minority ion heating by ICRF which produces ions accelerated perpendicularly to magnetic field is successful : indicating high performance of high energetic ion confinement of LHD.

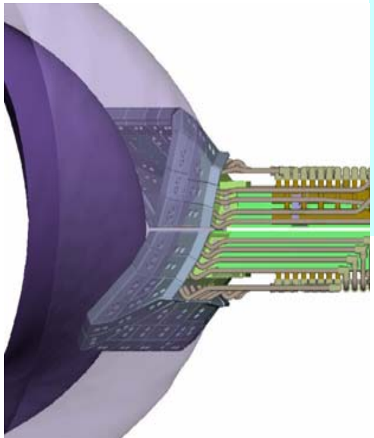
Particle control & confinement improvement

Local Island Divertor (LID)



<u>Features</u>
* Utilize m/n=1/1 island.
* Insert a divertor head locally.
* LCFS defined by island separatrix
* No leading edge problem
* Closed system
* High efficient pumping
* No ergodic layer
* L_c=~250m





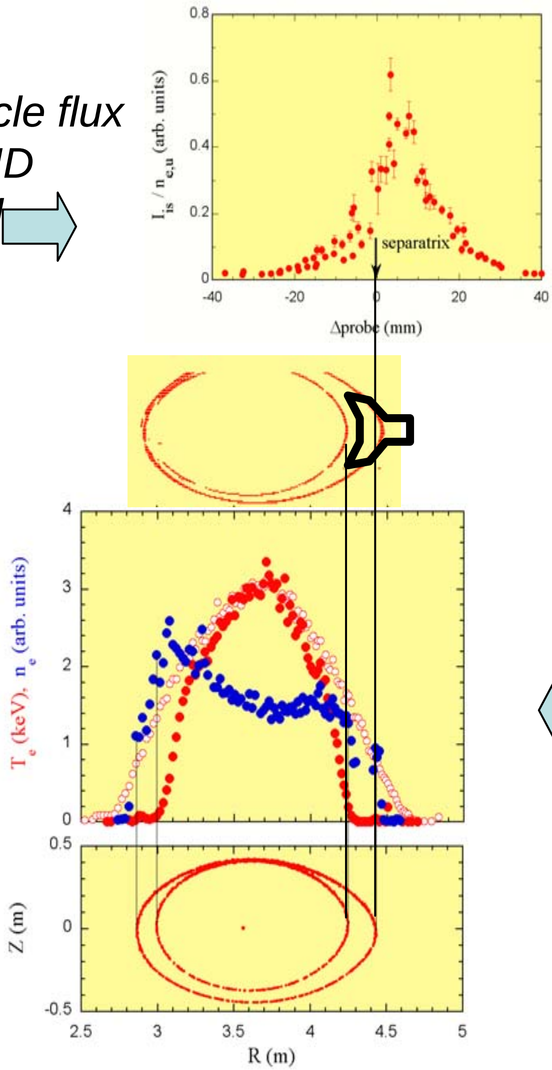
<u>Advantage</u>
* high efficient pumping
* easy to realize closed system
  ➔ *superior cost performance*
* compact and integrated
  ➔ *favorable for blanket, diagnostics*

<u>Disadvantage</u>
* small wetted area
  ➔ *high heat load*

Basic LID functions

LID has been confirmed to function as a divertor.

particle flux on LID head



(1) Particle flow

*** Particles are well guided to the back side of the LID head by island separatrix.**

(2) Edge profile control

*** Steep T_e gradient is formed at inner separatrix.**

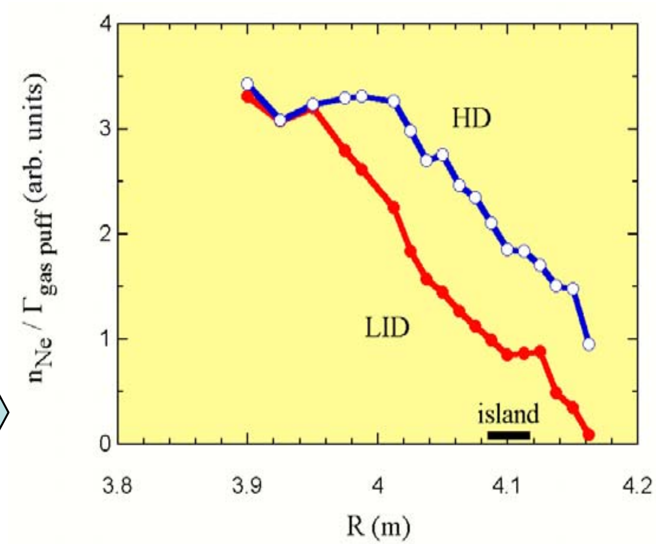
(3) Impurity control

*** Impurities are screened or pumped out.**

Te and ne profiles.

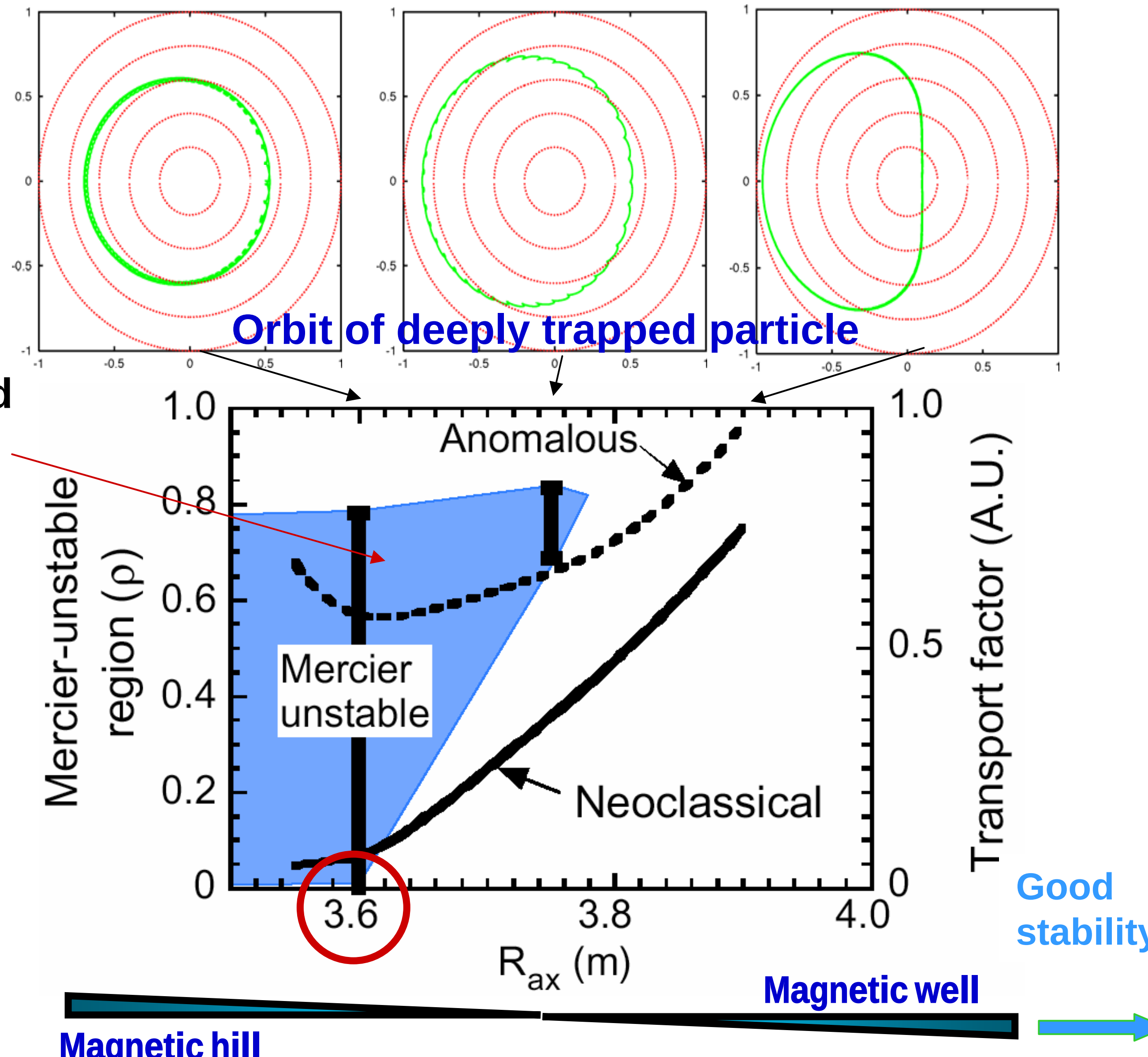
Small peaks at outer separatrix can be seen.

Ne (injected by gas puff) profiles



Performance of LHD plasma depends on magnetic axis position

Good particle orbit



Amplitudes of MHD instabilities were found to be small even in the unstable regime, so that almost no degradation of confinement was observed.

↓

The potential conflict between stability and confinement was favorably resolved.

Changes of Dominant Modes as a function of β

Suppression of $\iota/2\pi < 1$ modes → $\beta\uparrow$ → Suppression of $\iota/2\pi \leq 1$ modes → $\beta\uparrow$ → Suppression of $\iota/2\pi \leq 2$ modes

$<\beta_{dia}>$, n_e

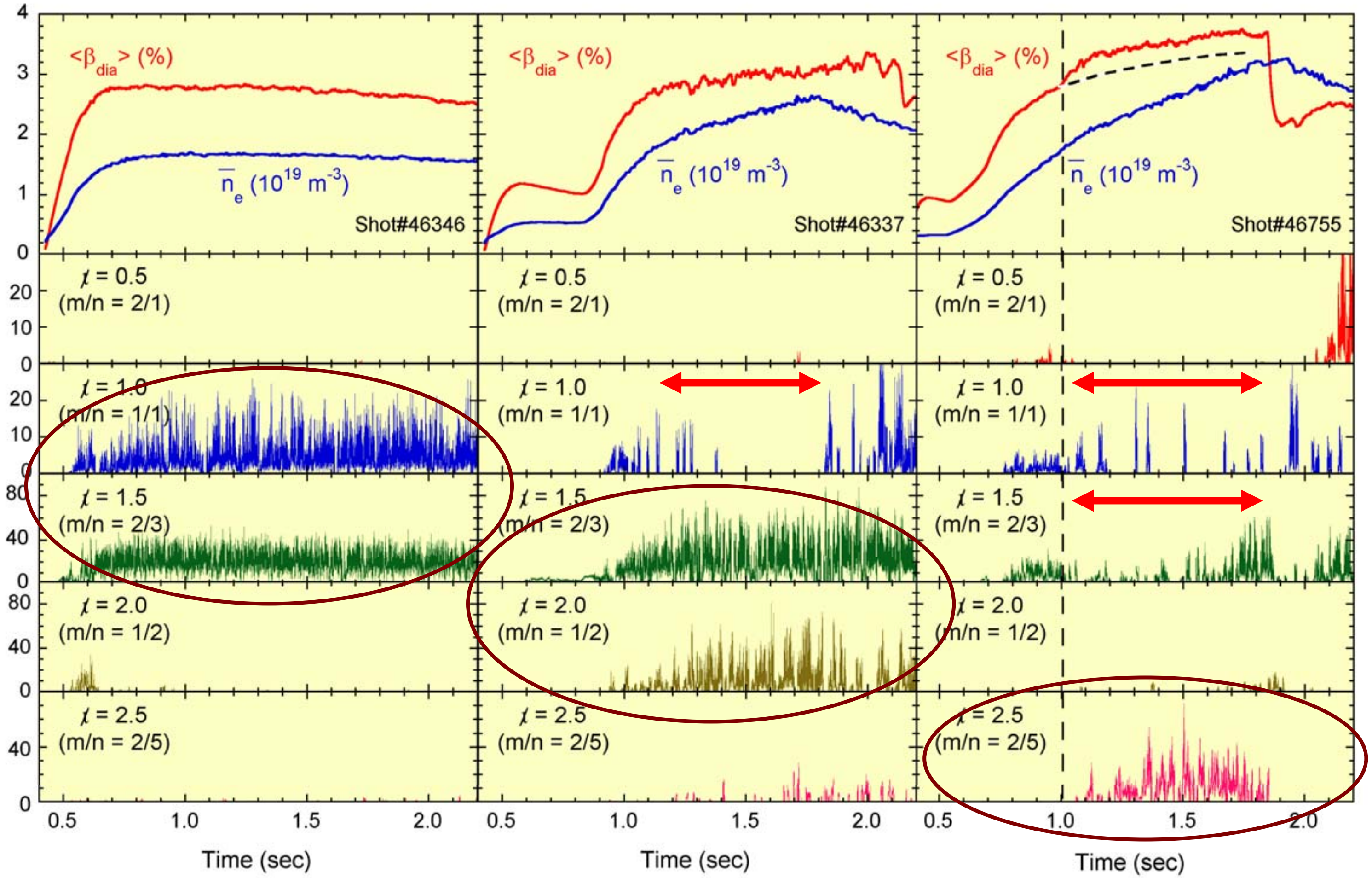
$\iota/2\pi = 0.5$

$\iota/2\pi = 1.0$

$\iota/2\pi = 1.5$

$\iota/2\pi = 2.0$

$\iota/2\pi = 2.5$

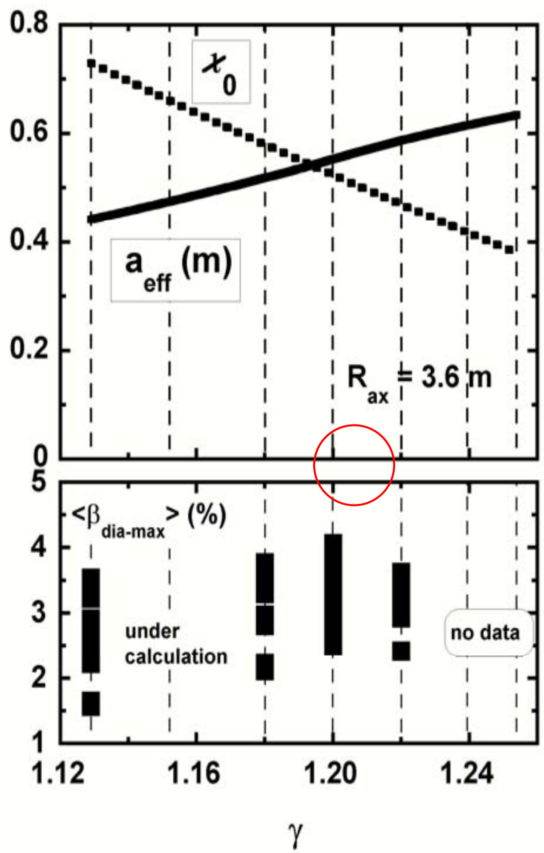


γ optimization for high β

- Increase of plasma aspect ratio suppresses Shafranov shift consequently reduces degradation of NBI heating efficiency.
- However simultaneously MHD stability could become danger.

➔ promotes γ optimization for high β.

Optimum point : $\gamma = 1.20$ ➔ $\langle\beta_{dia}\rangle = 4.3$ % at $B_t = 0.45$T

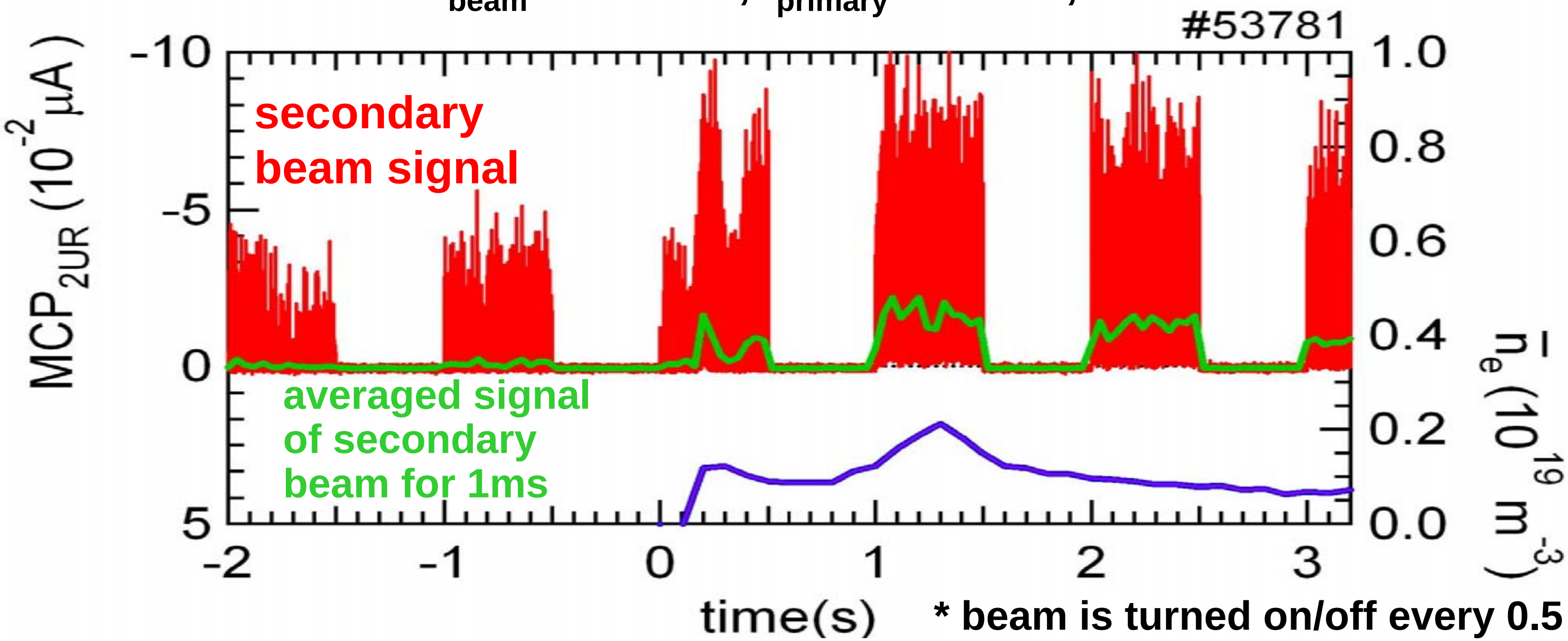


$$\gamma = \frac{m}{n} \cdot \frac{a_c}{R}$$

$\gamma = 1.254 \rightarrow 1.200$

HIBP diagnostics: started

HIBP : W_{beam}=5.04MeV, $I_{primary}$~ 0.1mA, Gain=10^5x10^8



* beam is turned on/off every 0.5 s

- Development of sensor employing MCP
- Stabilizing ion source
- Improvement of beam line

- Secondary beam was successfully detected.
- Substantial output for potential measurement and physics related to electric field is expected in the nearest future.

Plasma Parameters Achieved at LHD

	Achieved (~2003)	*Achievements in FY2004*
Fusion triple product	**2.0×10^{19}keVm^{-3}s**	**2.3×10^{19}keVm^{-3}s**
Ion temperature	**1.1 keV: $T_i(0)$**	**0.8 keV : $T_i(0)$**
Density	**$4.8\times10^{19}m^{-3}$**	**$8\times10^{19}m^{-3}$**
Energy confinement time	**0.36 s**	**0.37 s**
Electron Temperature T_e		
Central electron temperature	**10 keV**	**10 keV**
at Density	**$5\times10^{18}m^{-3}$**	**$5\times10^{18}m^{-3}$**
Ion temperature T_i		
Central ion temperature	**10 keV**	**13.5 keV**
at Density	**$3.5\times10^{19}m^{-3}$**	**$3\times10^{18}m^{-3}$**
Beta β	**β = 4.1% at B = 0.45 T**	**β = 4.3% at B = 0.45 T**
Pulse length (Steady state operation)		
Pulse length	**756 s**	**1 hr 5 min 110kW** **31min 45 sec 680kW** **(Input energy 1.3GJ)**

Main subjects for LHD 2005 Plan

1. **Particle control & confinement improvement**
   Improvement of plasma confinement by **LID**
2. **High beta**
   Realization of higher beta plasma using a **new perpendicular NBI**
   Evolution of MHD instabilities
3. **Effect of magnetic configuration on MHD & confinement**
   Ion transport study
4. **Steady-state operation**
   Long pulse discharge with **higher ICRF heating power** of ~1 MW
5. **High ion temperature**
   Realization of higher hydrogen ion temperature using a **perpendicular NBI**
   High fusion triple product, **Ion temperature profile measurement** by CXRS
6. **Electric field & transport barrier**
   Electric shear control by a **perpendicular NBI**
   Electric field measurement by **CXRS and HIBP**
7. **High energy particle confinement**
   Behavior of **high-energy ion tail**, Energetic-ion driven instability

Low-energy NBI system with perpendicular injection is being prepared for the 9th campaign

Objectives

- Ion heating (cf. Electron heating in the present high-energy NBI)
- Particle fuelling
- Diagnostics for the ion temperature profile (CXRS)
- Investigation of the high-energy particle confinement

Specification

- 40keV – 3MW
  (Upgrade to 6MW in future)
- Perpendicular H injection
- 2 large positive-ion sources

Targets

- High-T_i in H plasmas
- Peaked density profile
- Ion transport study by measuring T_i profile