Recent Development of LHD Experiment

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for the LHD team
National Institute for Fusion Science

Primary goal of LHD project

1. **Transport studies in sufficiently high $n\tau_E T$ regime relevant to reactor condition.**

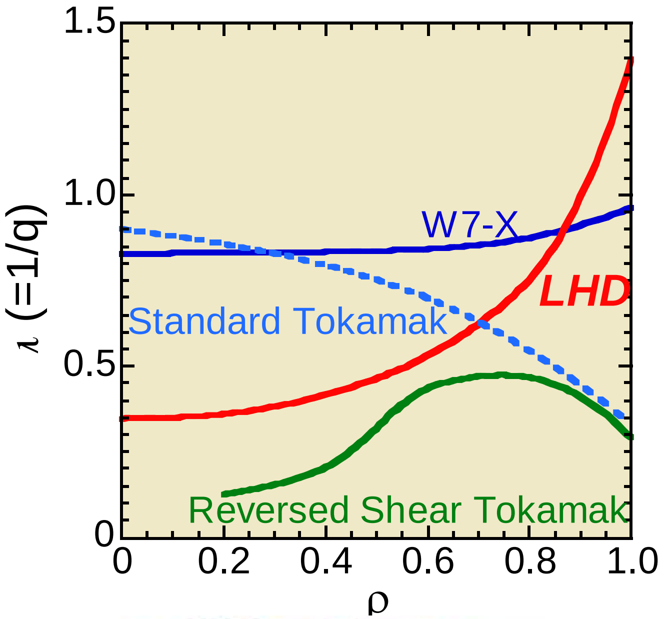
2. **MHD studies beyond β of 5%.**

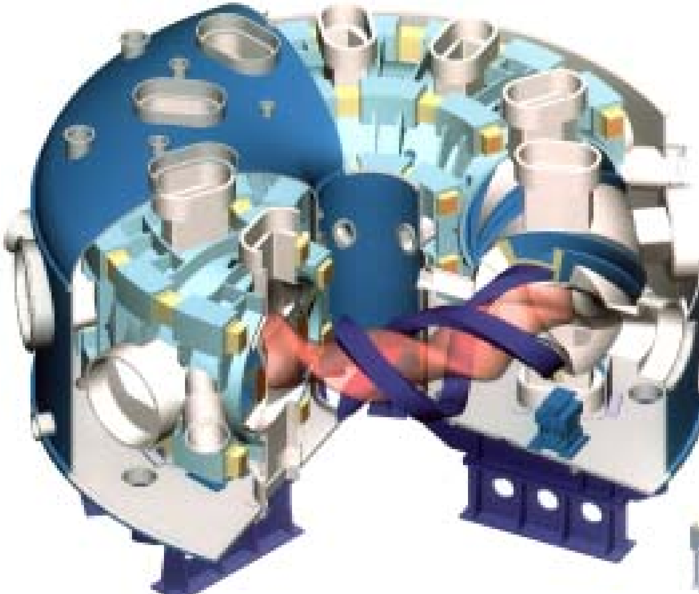
3. **Fundamental research for steady-state operation with employing divertor.**

4. **Confinement studies on high energetic particles and simulation experiments of alpha particles**

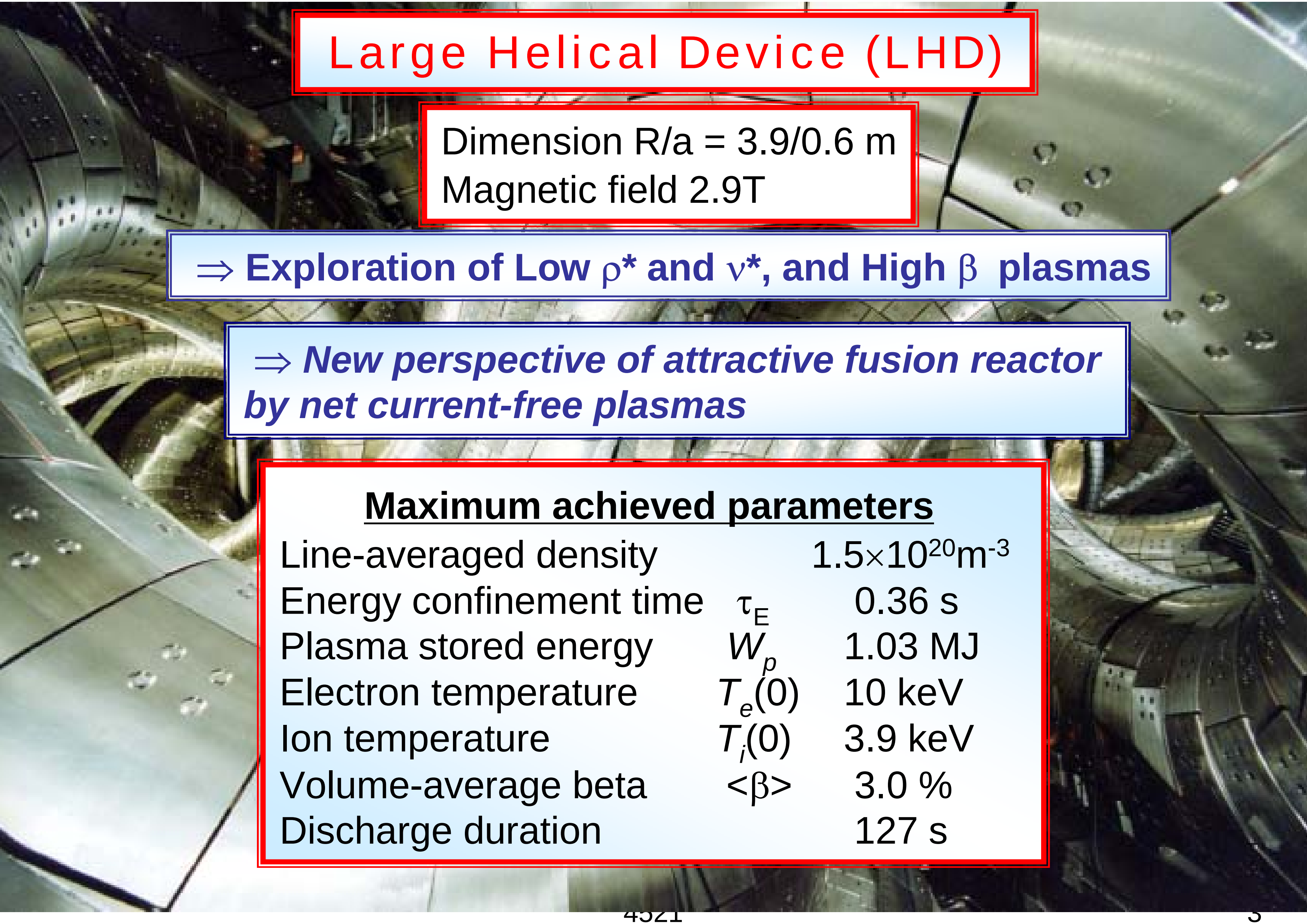
5. **Complimentary study to tokamaks leading to comprehensive understanding of toroidal plasmas.**

6. **Reactor technology, in particular, superconducting system, high heat flux components, and structural material.**





Heliotron configuration with employing full superconducting manget system



Large Helical Device (LHD)

Dimension R/a = 3.9/0.6 m
Magnetic field 2.9T

⇒ Exploration of Low ρ^* and ν^*, and High β plasmas

⇒ New perspective of attractive fusion reactor by net current-free plasmas

Maximum achieved parameters

Line-averaged density		$1.5\times10^{20}\mathrm{m}^{-3}$
Energy confinement time	τ_E	0.36 s
Plasma stored energy	W_p	1.03 MJ
Electron temperature	$T_e(0)$	10 keV
Ion temperature	$T_i(0)$	3.9 keV
Volume-average beta	$<\beta>$	3.0 %
Discharge duration		127 s

Present experimental specifications of LHD

Major radius

3.4 ~ 4.1 m

Minor radius

~ 0.63 m (at R_{ax}=3.6m)

Plasma Volume

~ 30 m^3 (at R_{ax}=3.6m)

Magnetic field

2.98 T (at R_{ax}=3.5m)

Heating power

ECH (84 /168 GHz)

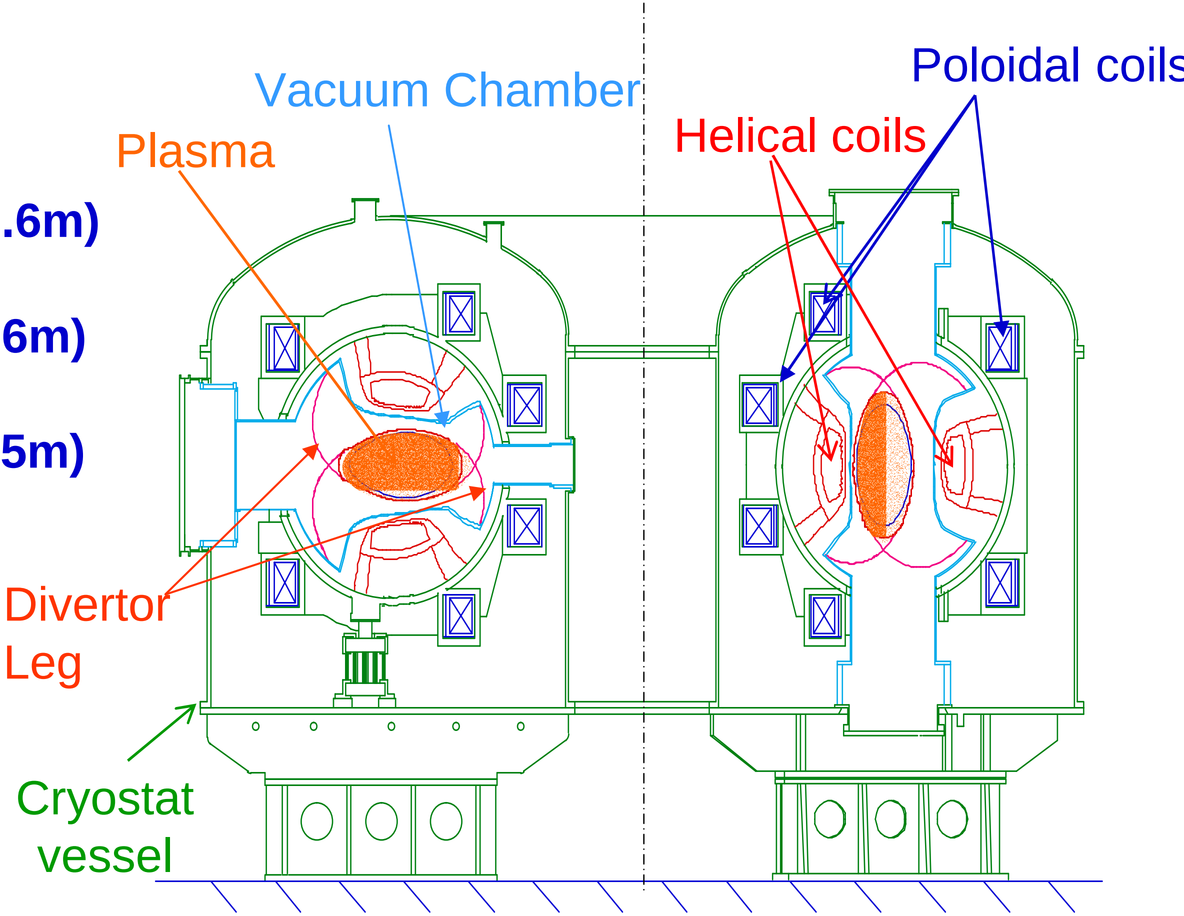
1.7 MW

N-NBI (<170keV, H)

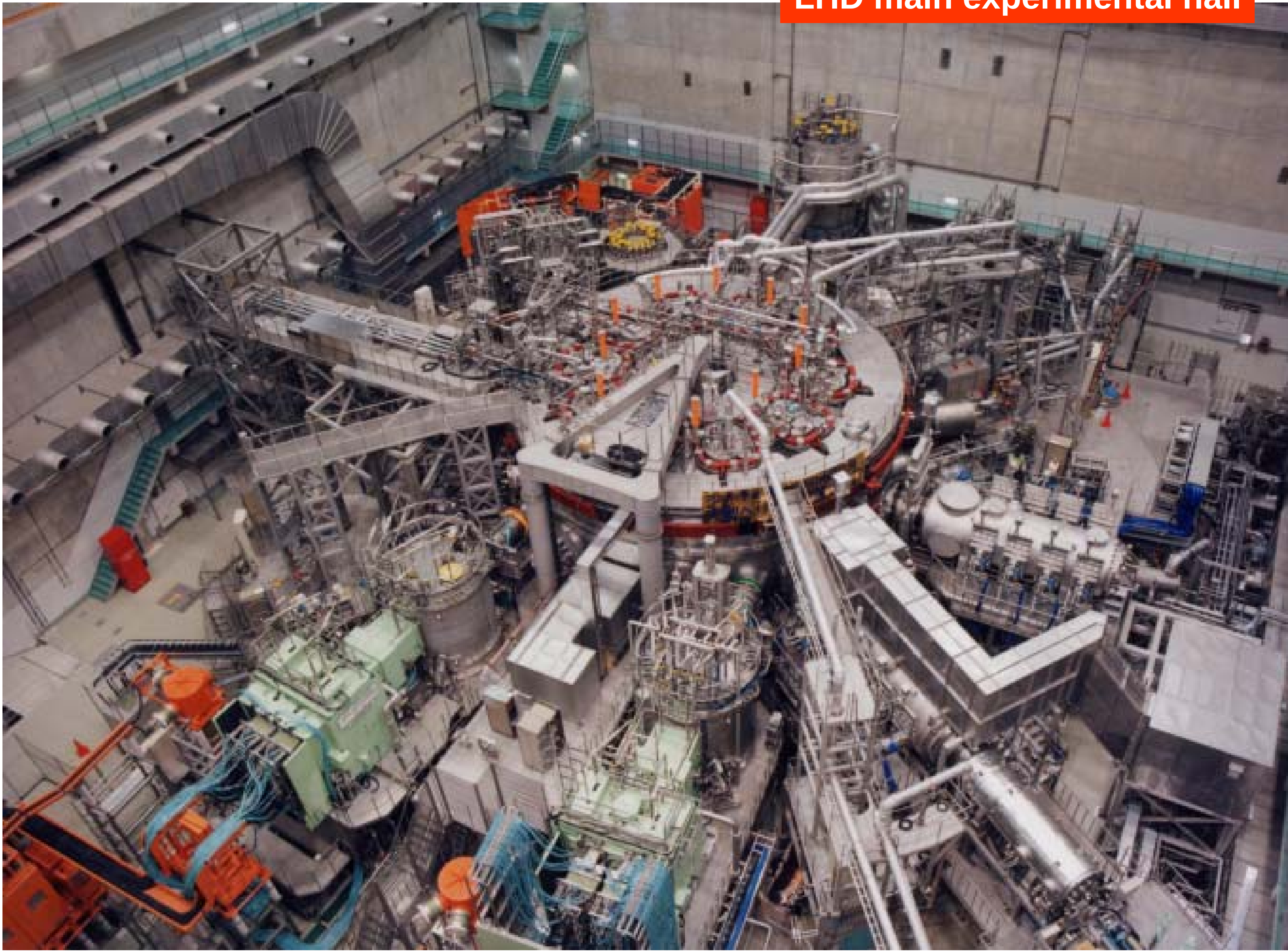
7.0 MW

ICRF (25-100MHz)

2.7 MW

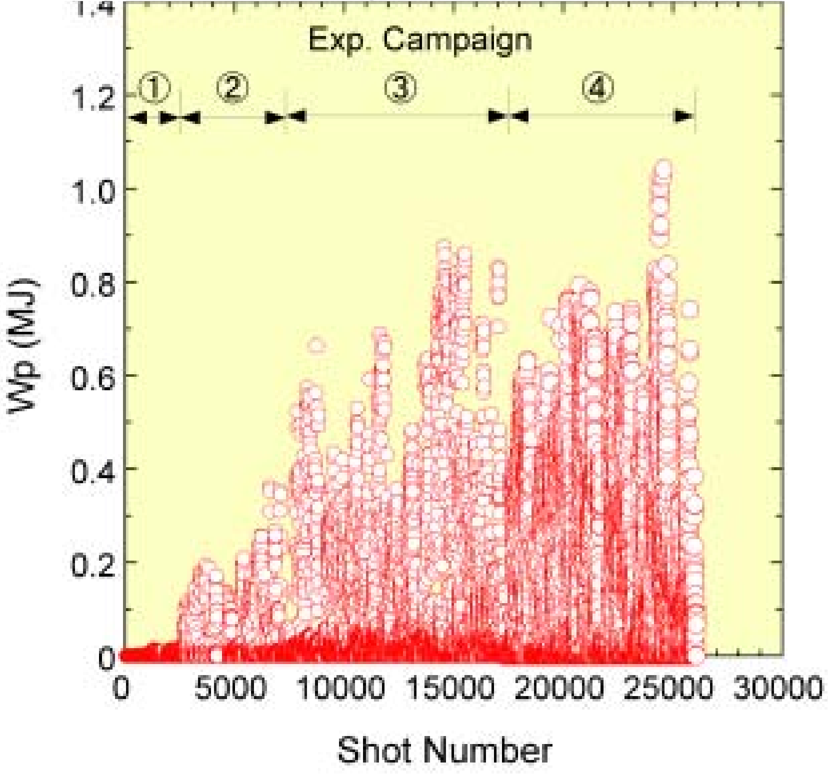


LHD main experimental hall

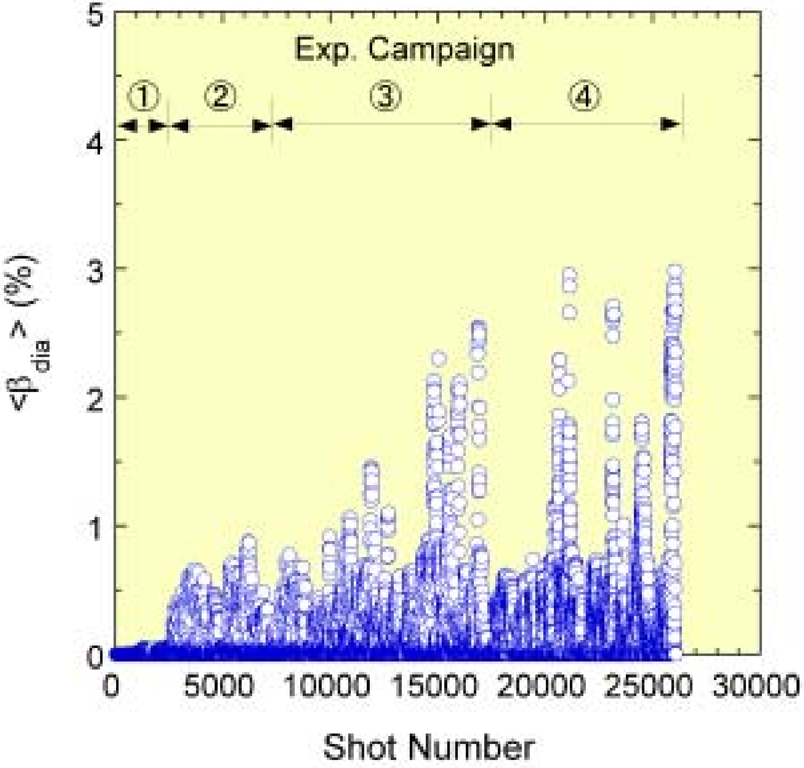


Steady Progress of Plasma Performance (I)

Stored energy exceeds 1MJ.



Beta reaches 3%

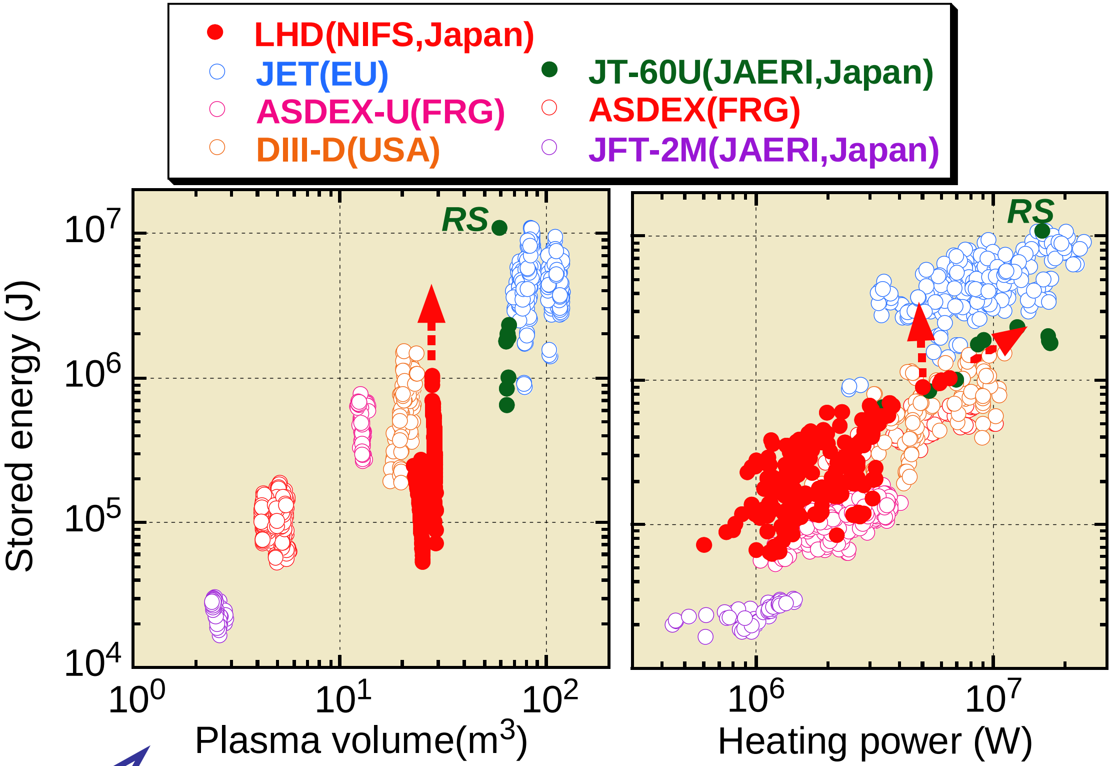


First plasma

Present plasma

Progress of experimental condition has been enhancing performance of plasmas.

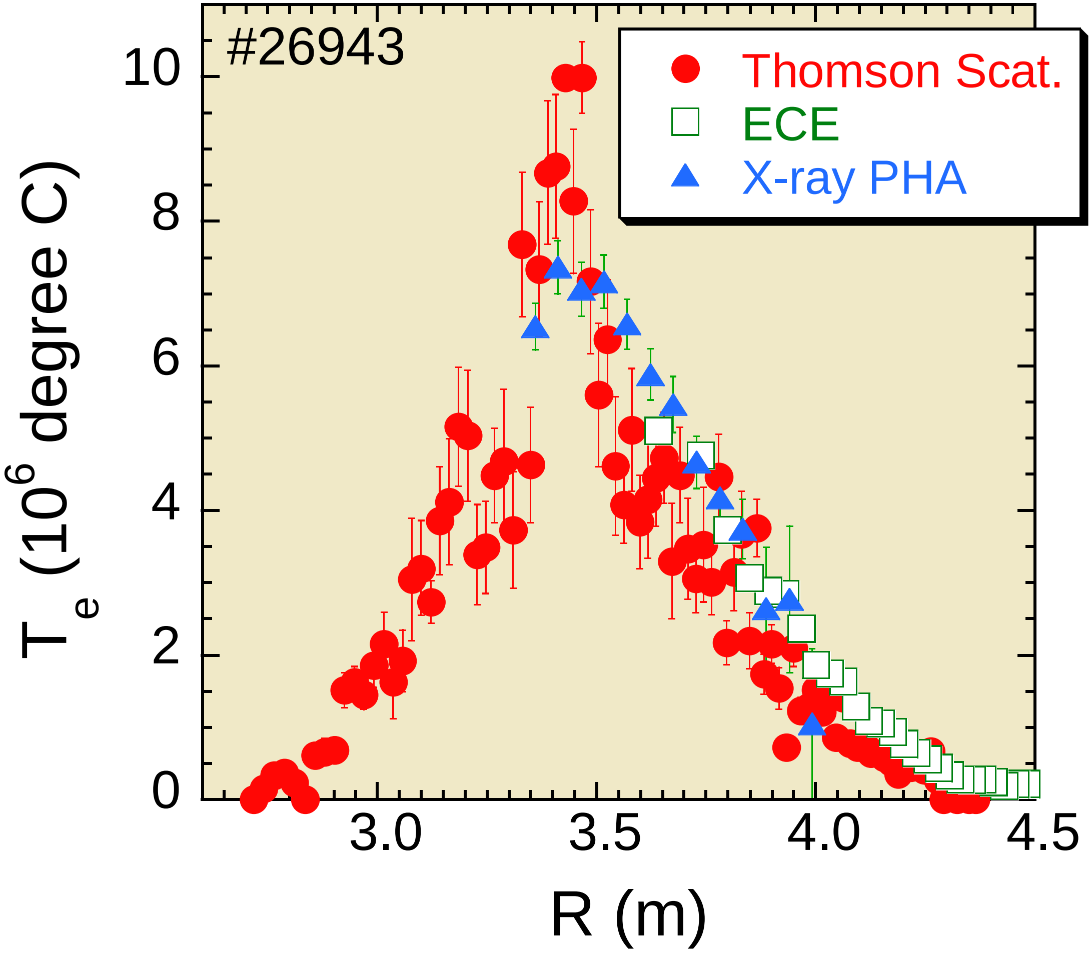
Progress of LHD experiment(2)



LHD is entering the operational regime of large tokamaks.

Tokamak data extracted from ITER H-mode DB.

Electron temperature has reached 10 keV



Achieved parameters

$T_e(0)$ 10 keV

$T_i(0)$ 2 keV

$<n_e>$ 5×10^{18} m^{-3}

τ_E 0.05 s

Discharge duration 0.4s

Experimental conditions

ECRH 1.2 MW

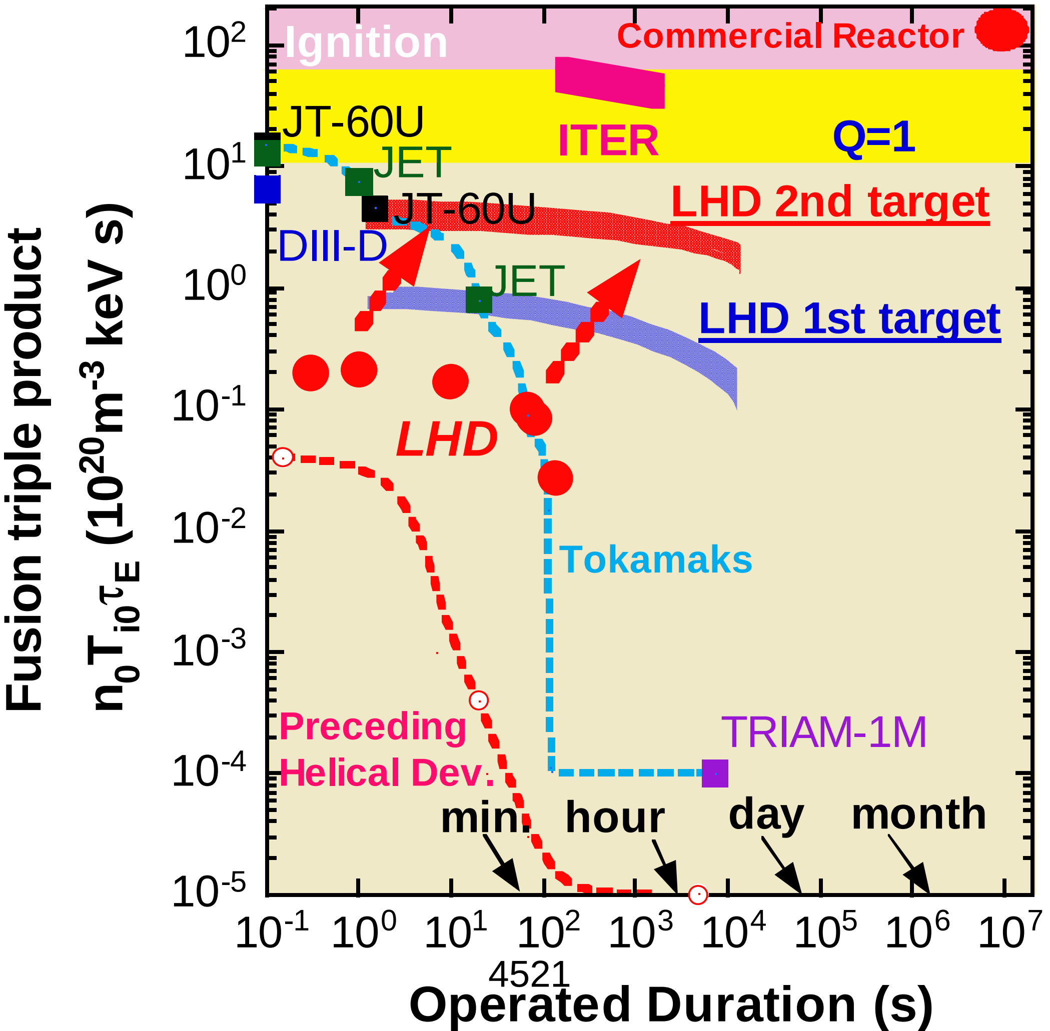
B 2.976 T

R_{ax} 3.5 m

Comparison of achieved maximum parameters

	Tokamaks	Helical systems other than LHD	**LHD**
Ion temp. (keV)	45 (JT-60U・J)	1.6 (Heliotron E・J)	**3.9**
Electron temp. (keV)	25 (ASDEX-U・FRG) 15 (JT-60U・J)	6.1(W7-AS・FRG)	**10**
Density ($10^{20}m^{-3}$)	20 (AlcatorC・US) 2.7 (JT-60・J)	3.0 (W7-AS・FRG)	**1.5**
Beta (%)	40 (START・UK)	3.0 (W7-AS・FRG)	**3.0**
Energy conf. time (s)	1.2 (JET・EU) 1.1 (JT-60U・J)	0.055 (W7-AS・FRG)	**0.36**
Fusion triple product ($10^{20}m^{-3}$・s・keV)	15 (JT-60U・J)	0.035 (W7-AS・FRG)	**0.22**
Stored energy (MJ)	11 (JET・EU) 10.9 (JT-60U・J)	0.015 (W7-AS・FRG)	**1.03**

LHD is extending the frontier on steady-state plasmas



Accumulation of Database for Stellarators (1)

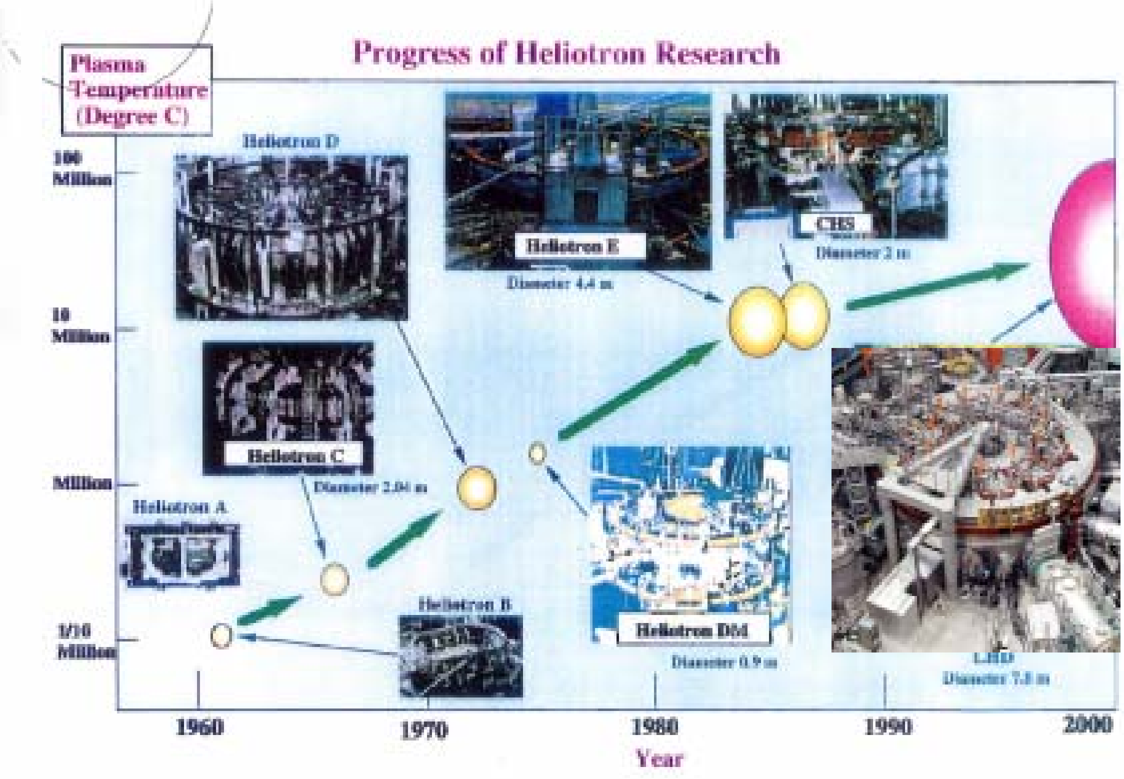
Heliotron E (Kyoto Univ.)
ATF (ORNL)
W7-AS (IPP Garching)
CHS (NIFS)
R/a<2.2m/0.28m

LHD 1999 ⇒

in plan

W7-X 2006-
(IPP Greifswald)
R/a=5.5m/0.53m
B=3T

NCSX 2007-
(PPPL)
R/a=1.42m/0.33m
B>2T



Accumulation of Database for Stellarators (2)

International stellarator database

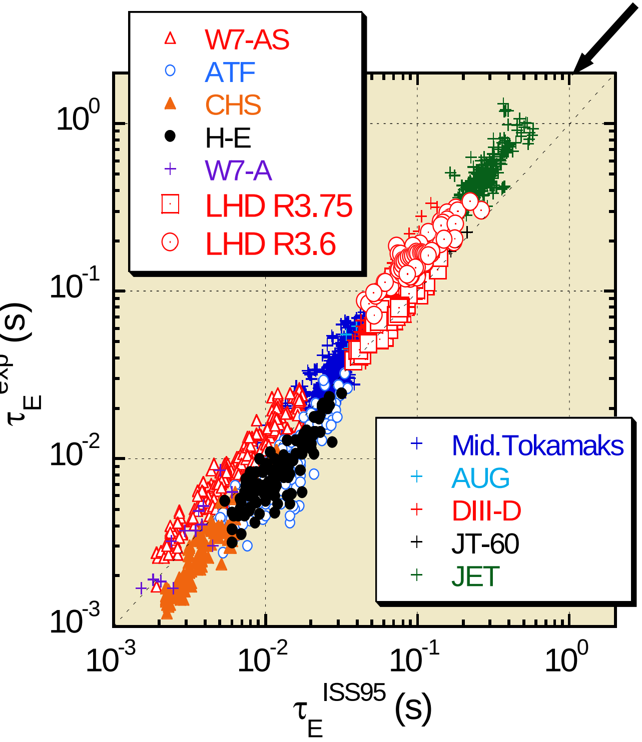
Nucl. Fusion 36 (1996) 1063

- Description and format in conformity of ITER DB.
- Scalar data only

International Stellarator Scaling 95 (ISS95)

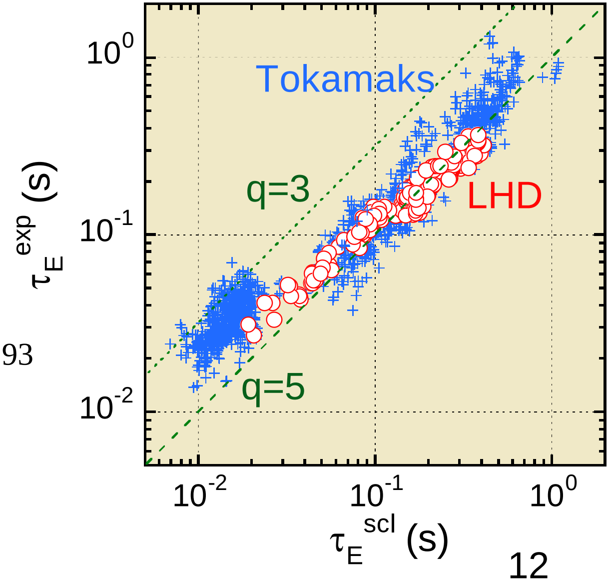
$$\tau_E^{ISS95} = 0.26 B^{0.80} P^{-0.59} \bar{n}_e^{0.51} R^{0.65} a^{2.21} q_{2/3}^{-0.40}$$

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



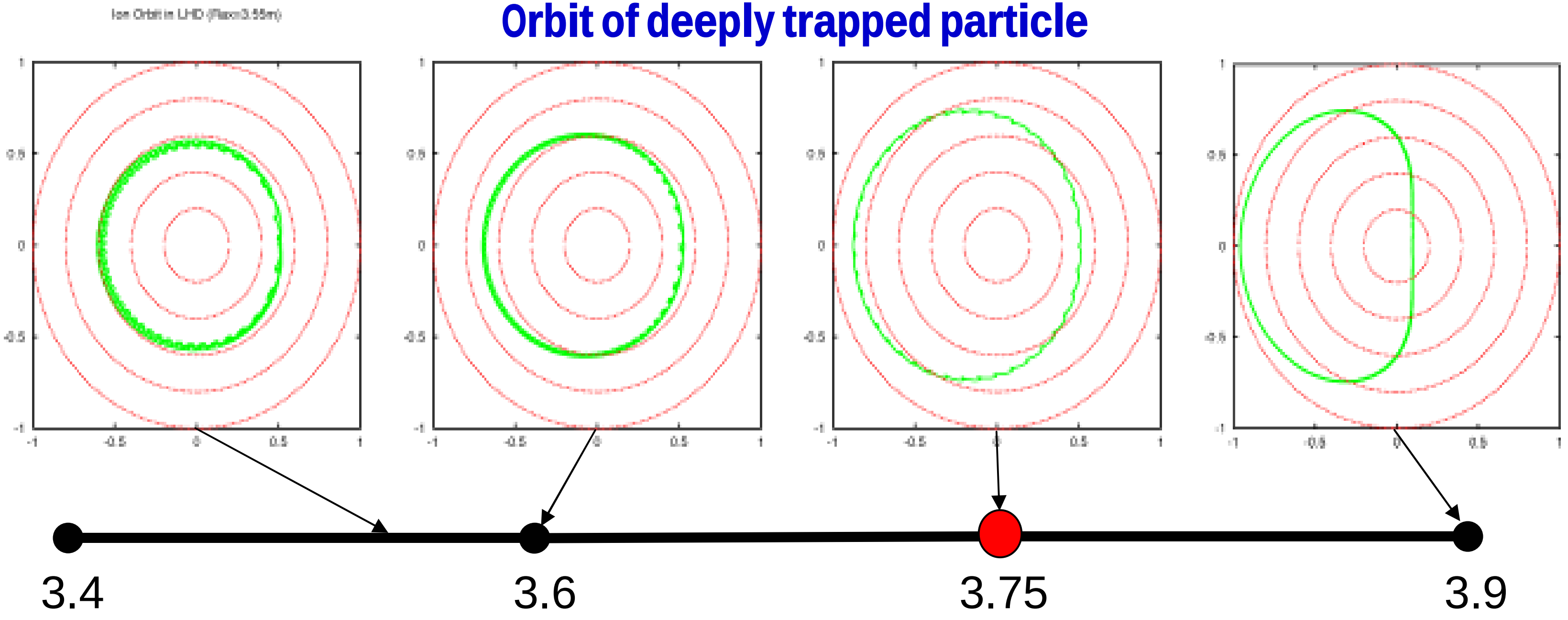
Extract *q* dependence
➔Comparison with
ELMy H-mode

$$\tau_E^{scl} = \tau_E^{IPB98(y,2)} (q/5)^{0.93}$$

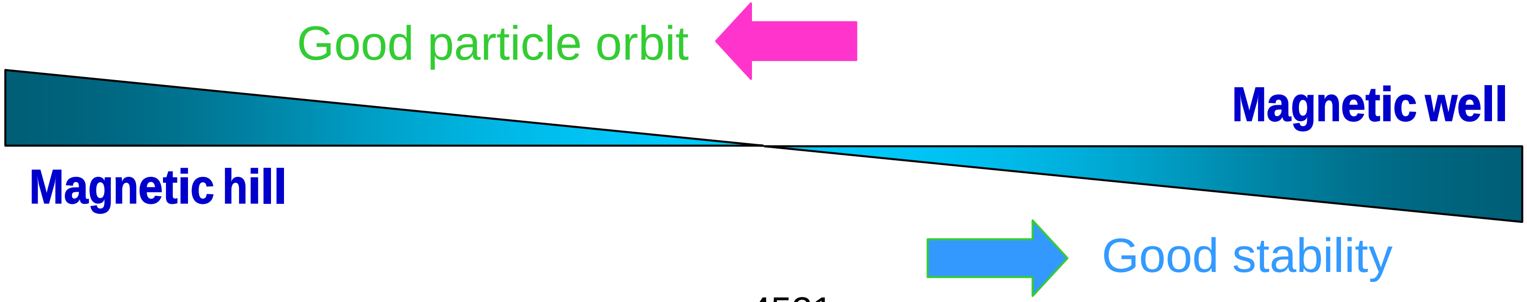


Performance of LHD plasma depends on the position of magnetic axis

Orbit of deeply trapped particle



Magnetic Axis Position (m)



Good particle orbit

Magnetic well

Magnetic hill

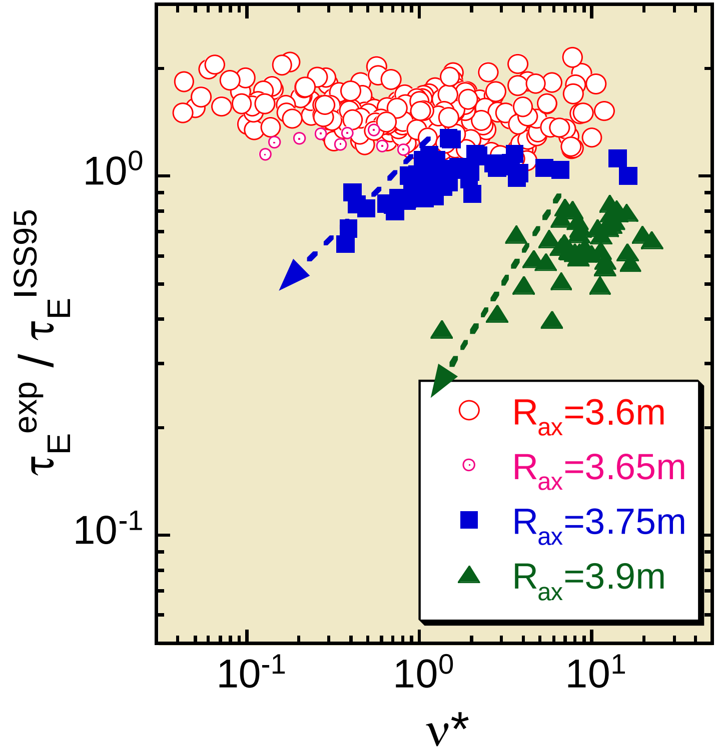
Good stability

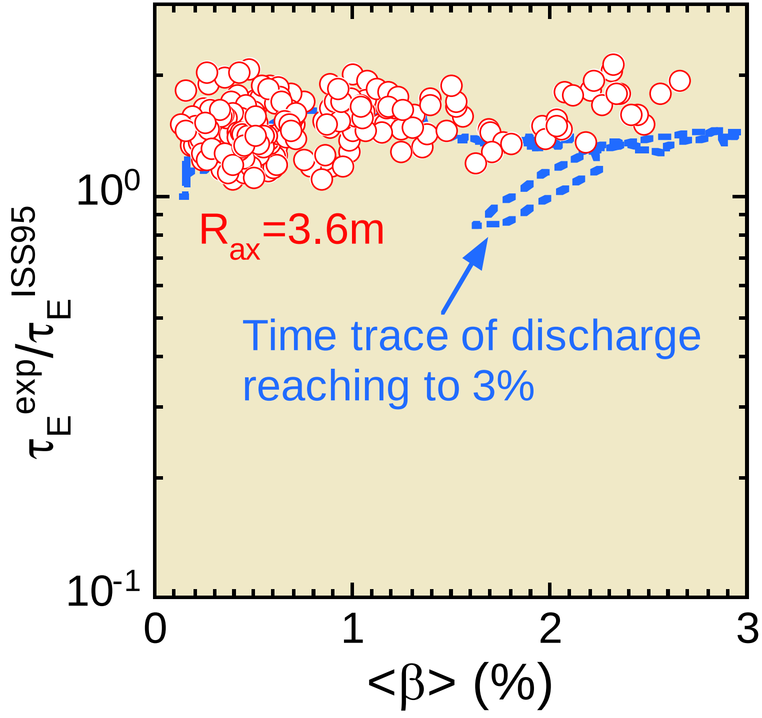
New finding of breakthroughs on confinement

Successful suppression of neo-classical helical ripple transport by geometrical optimization

ISS95 $\tau_E^{exp}/\tau_E^{ISS95}$ ~1.5 is robust towards β of 3% in R_{ax}=3.6m

🡐 Keep good confinement down to ν_b* of 0.05 by inward shift of magnetic axis





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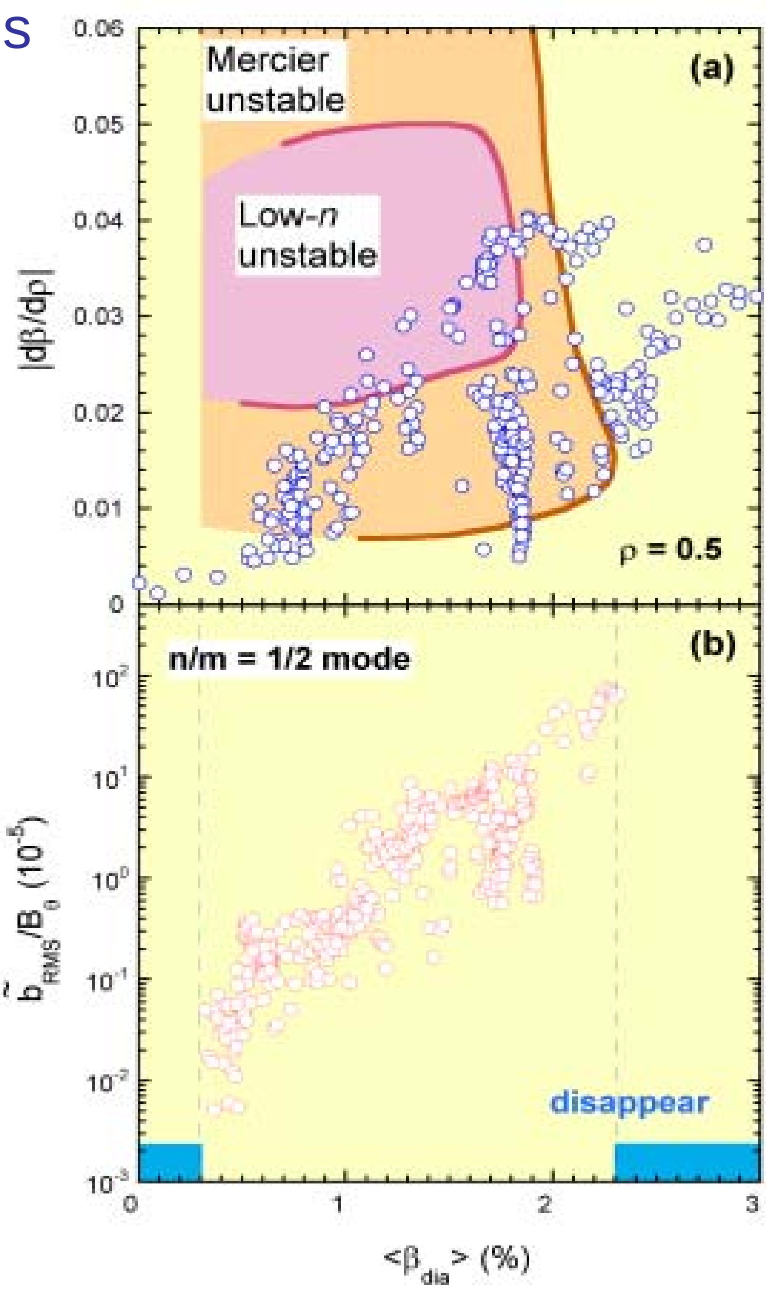
Good confining property observed i
Unfavorable configuration from
linear theory on MHD instabilities

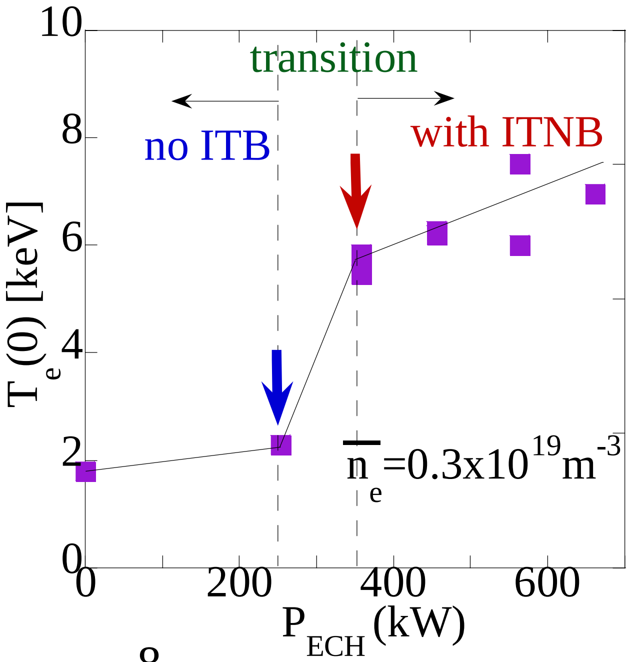
Information from Pressure gradient and MHD activities in high β discharge

(around $\iota \neq 0.5$)

- Observed pressure gradient at $\rho=0.5$ is predicted to be Mercier unstable even from low beta value of 0.5%. However, the pressure gradient increases as beta.
- It is suggested that the plasma enters the second stability region over $<\beta_{dia}>\sim 2.3\%$ by beta effect (forming magnetic well).
- n/m=1/2 mode appears from 0.3% to 2.3% where the region is Mercier unstable, and it disappears when the plasma enters the second stability.



Observation of Internal Transport Barrier in LHD



Electron root plasma

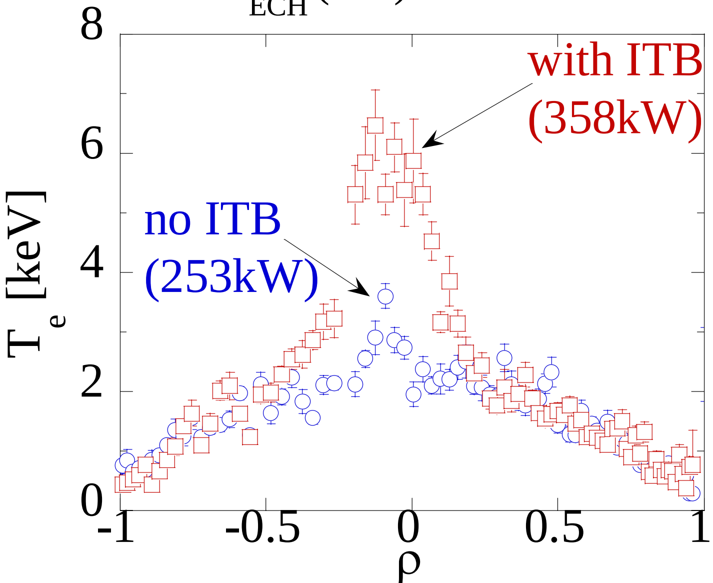
Central ECH is applied to NBI plasma with low collisionality in the electron root

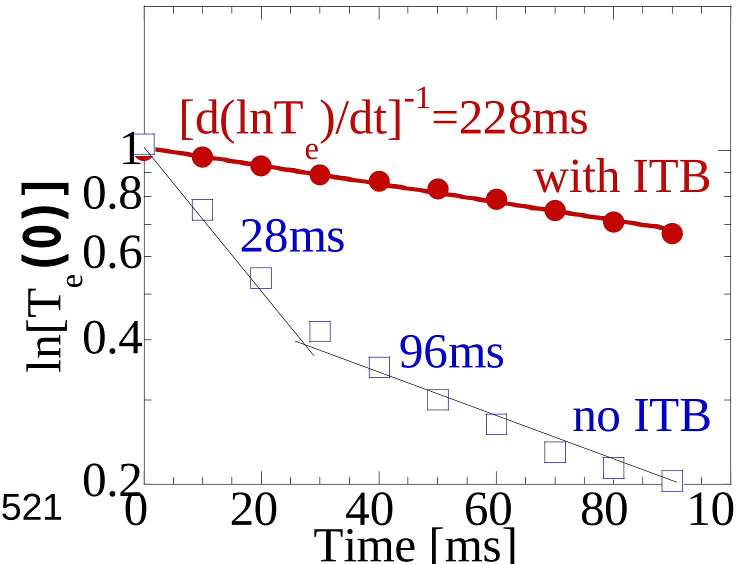
Bifurcation phenomena

Internal Transport Barrier (ITB) appears when the ECH power exceeds the threshold

Confinement improvement

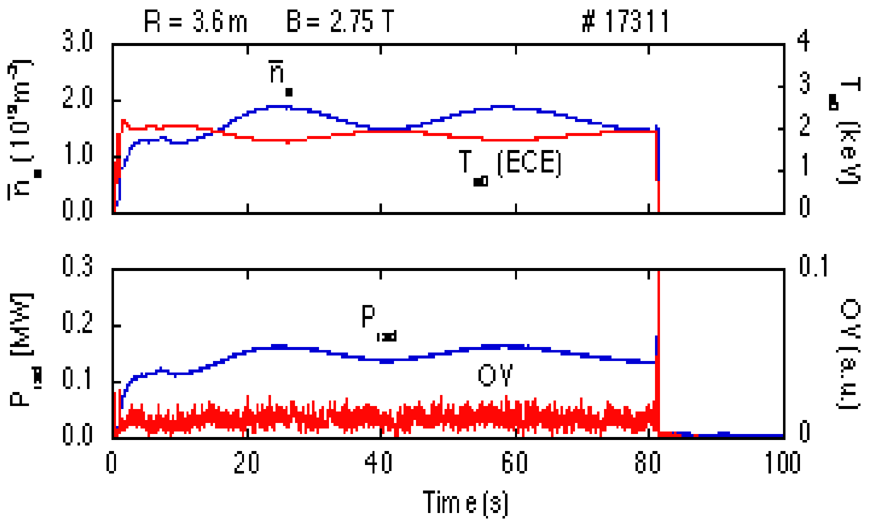
Slow decay of T_e after ECH turned-off shows the lower χ_e inside the ITB



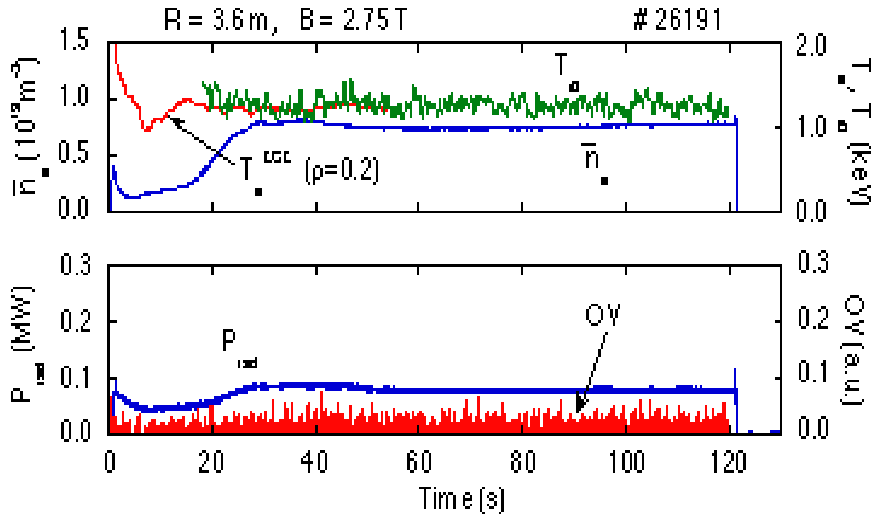


Long pulse discharge is quite stable.

Plasma heated by NBI



Plasma heated by ICRF



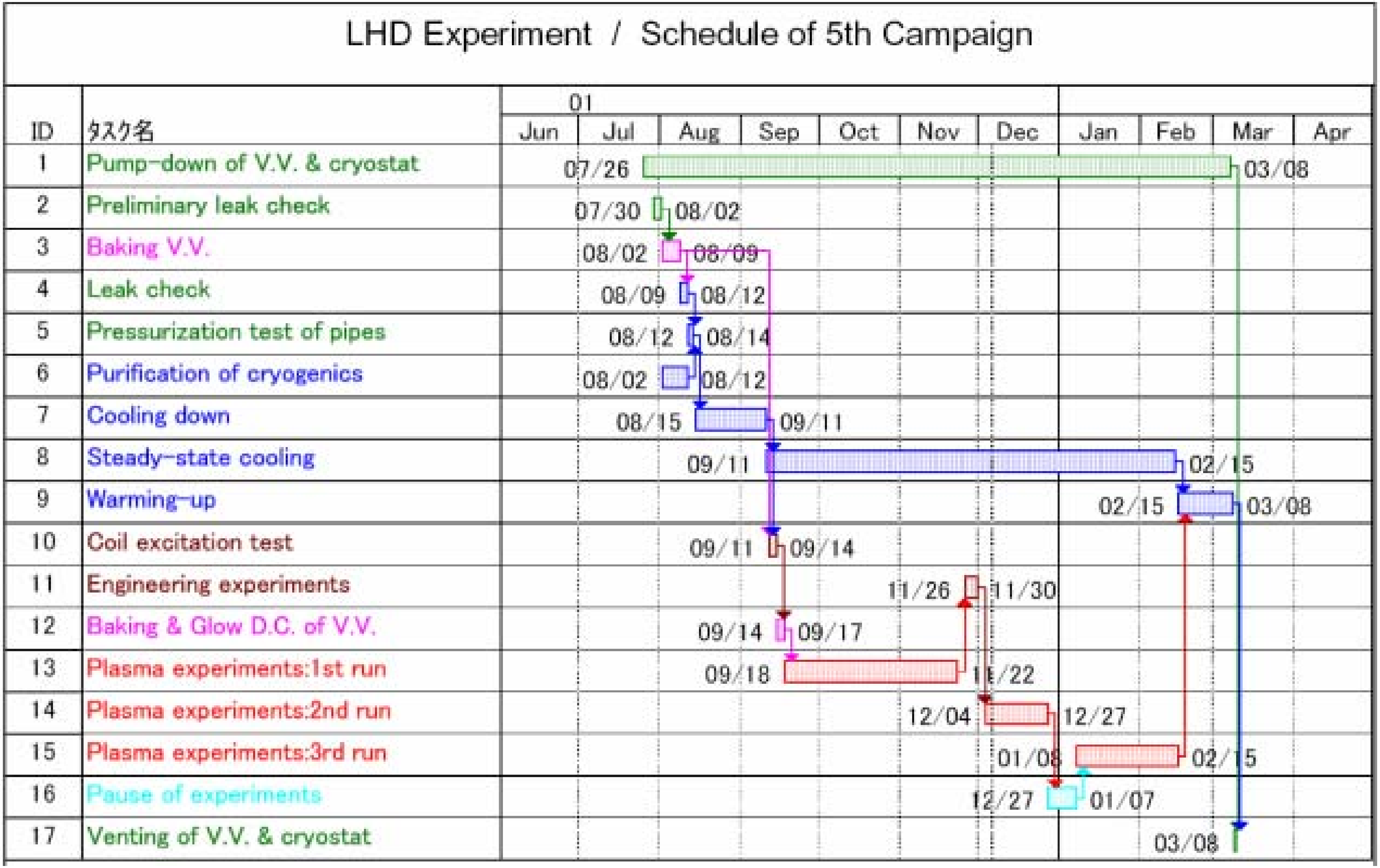
◎ Plasma discharges have been prolonged to 80 s by NBI(0.5 MW) and 120 s by ICRF(0.8 MW) .

◎ Temperature, density, radiation, and emission from impurities are almost constant during a discharge.

◎ Carbon divertor plates have enabled us high density operation.

◎ Next goal
10^4 sec Steady state operation by ICRH

LHD 5th Campaign



LHD Experiment / Schedule of 5th Campaign

ID	タスク名		
1	Pump-down of V.V. & cryostat	07/26	03/08
2	Preliminary leak check	07/30	08/02
3	Baking V.V.	08/02	08/09
4	Leak check	08/09	08/12
5	Pressurization test of pipes	08/12	08/14
6	Purification of cryogenics	08/02	08/12
7	Cooling down	08/15	09/11
8	Steady-state cooling	09/11	02/15
9	Warming-up	02/15	03/08
10	Coil excitation test	09/11	09/14
11	Engineering experiments	11/26	11/30
12	Baking & Glow D.C. of V.V.	09/14	09/17
13	Plasma experiments:1st run	09/18	11/22
14	Plasma experiments:2nd run	12/04	12/27
15	Plasma experiments:3rd run	01/08	02/15
16	Pause of experiments	12/27	01/07
17	Venting of V.V. & cryostat	03/08	

Plan in 5th Experimental Campaign (Sep.2001-Feb.2002)

Major objectives

Production of high-temperature & high-β plasmas

Clarification of confinement physics

Targets (Achievements)

Plasma performance

Temperature 100 million ˚C (120 million˚ C)

Stored energy 1.5 MJ (1.03 MJ)

Heating power

NBI	9	MW	(7 MW)
ECH	1.5	MW	(1.7 MW)
ICH	3	MW	(2.7 MW)

Magnetic field

2.976 T @ Rax=3.5 m

Research subjects

Confinement
- Scaling law
- Transport barrier
- Role of electric field
- Magnetic island effect

MHD in high-β regime
- Equilibrium
- Stability

Long pulse discharge
- Particle control
- Real-time control of magnetic field

Density control
- Pellet injection
- Density limit
- Radiation collapse
- Impurity effect

Edge plasmas & Divertor

Summary

1. LHD is opening new perspective towards attractive fusion reactor by net current-free plasmas.
2. Complementary role to tokamaks

   Major physics should be common for toroidal plasmas.

   - No net currents, Reversed shear

     ➔ Intrinsic suppression of neoclassical tearing mode
   - Density limit
   - No disruption
3. New findings as well as performance improvement have extended frontiers.
4. More than one minute long operation with maintaining performance is easy (10000-s demonstration in plan)

   ➔ Unique contribution to steady-state related issues.

Near term plan (2001-2002)

- Increase heating resources
- Active particle control by Local Island Divertor

Long term plan : Second experimental phase (2008-)

- Deuterium operation
- Magnetic field of 4 T by superfluid He cooling
- Closed divertor system

Contributions to ITC-12/APFA'01 from the LHD Team

1. **Invited Talks**

(1) Impact of energetic-ion-driven global modes on toroidal plasma confinements

by K.Toi on Wed.

(2) Role of radial electric field shear at the magnetic island in the transport of plasmas

by K.Ida on Thu.

(3) Study of time evolution of toroidal current in LHD

by K.Y.Watanabe on Fri.

2. **Posters on Tue. & Wed.**

Plasma experiment	**25 papers**
Theory	**6 papers**
Engineering/Technology	**4 papers**

3. **NIFS Tour**

In the afternoon on Thursday (Dec.13)