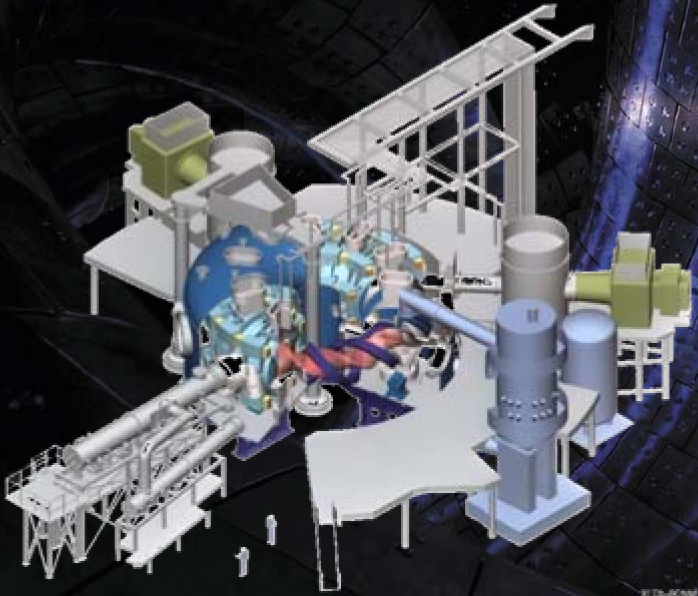
Fusion Power Associates Annual Meeting and Symposium
Livermore, 3-4 December, 2008

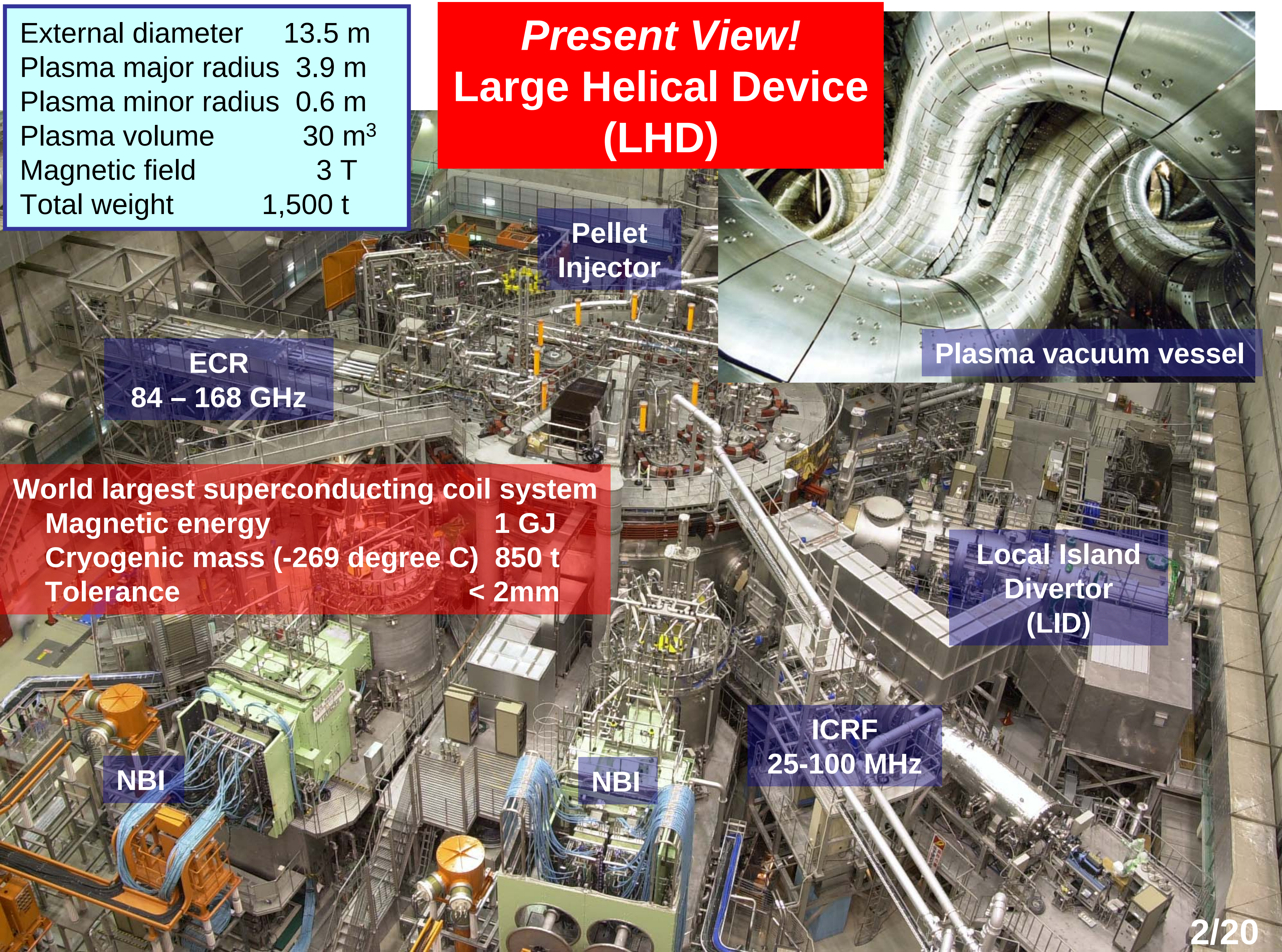
Overview of Fusion Research at NIFS



O.Motojima
National Institute for Fusion Science
Japan

Present View!
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



Plasma vacuum vessel

Pellet Injector

ECR
84 – 168 GHz

World largest superconducting coil system

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

Local Island Divertor (LID)

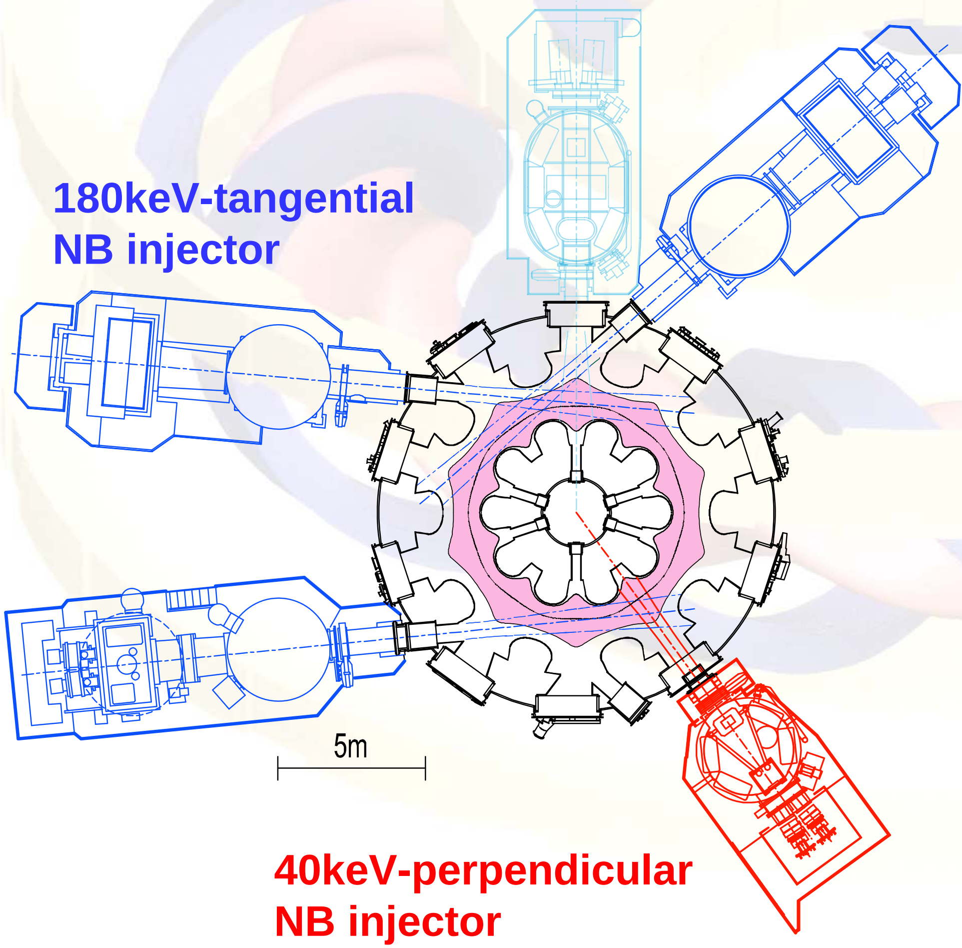
ICRF
25-100 MHz

NBI

NBI

New perpendicular NBI
Improves ion transport study
- High-power NBI of 23 MW in total -

✓ 4 beam lines of NBI
= 3 tangential + 1 perpendicular (+ 1 perpendicular in 2010)



180keV-tangential NB injector

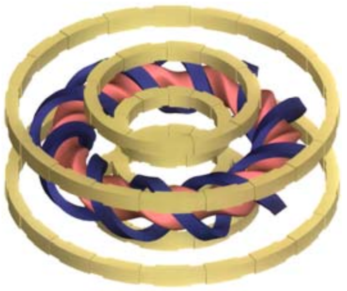
40keV-perpendicular NB injector

Three Tangential beams
- 16 MW in total, E_{NBI} = 180 kV with negative-ion sources
- Primarily electron heating
- Less fraction of trapped particles

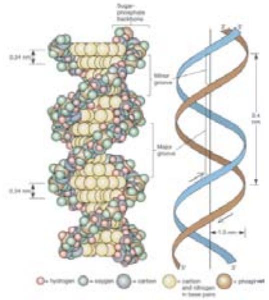
New Perpendicular beam
- 7 MW, E_{NBI} = 40kV with positive-ion sources
- **Ion heating (** $T_i(0)$ **= 5.2 keV)**
- works as a diagnostic beam for **CXRS (** T_i **,** V_ϕ **,** V_θ **,** E_r **)**
- Confinement of trapped particles secured by geometrical optimization

National Institute for Fusion Science and LHD

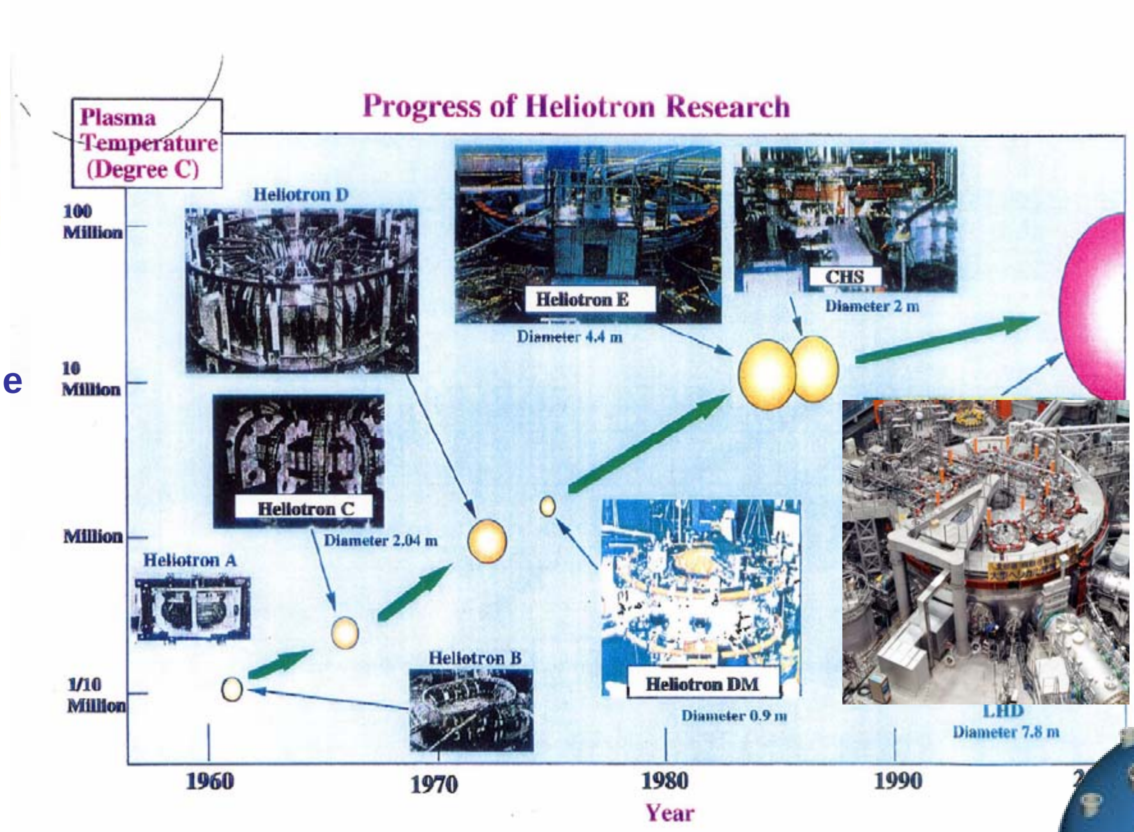
History of Heliotrons



Proof of Principle



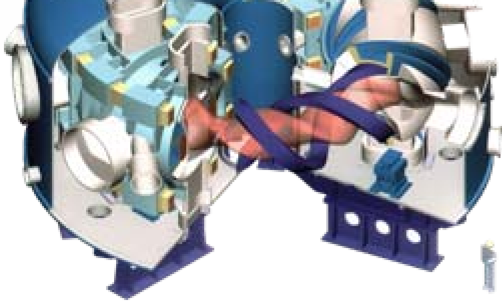
l=2 is a magic number



Break Even

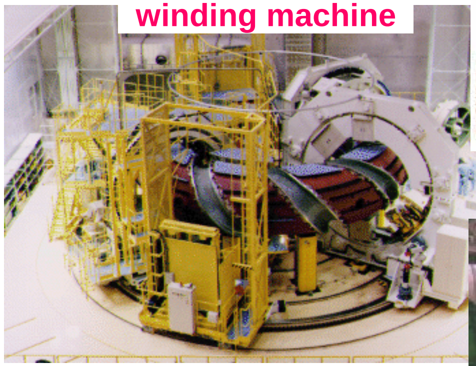
$Q=P_{fusion}/P_{heat}=1$

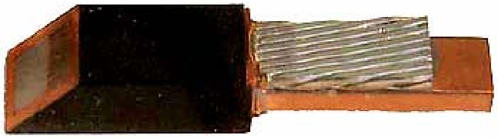
This is a Heliotron Path from a Table-top Device to the Reactor.



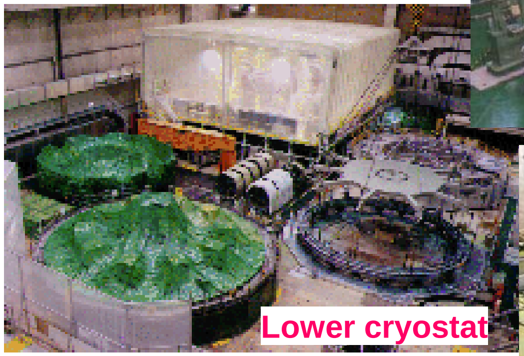
Results of LHD Construction

Helical coil winding machine





Superconductor for helical coils



Lower cryostat

Plasma vacuum vessel

Upper cryostat

Completed assembly

Needs Pull
System Integration

Milestones

1989 Establishment of NIFS
Started R&D for superconducting technology
1990 Started R&D for vacuum vessel
1991 Fabrication of Helical coil winding machine, IV coil
Construction of LHD building
Fabrication of conductors for helical coil
Fabrication of IS coil, lower cryostat
1994 Start of helical coil winding
1995 Fabrication of OV coil, vacuum vessel
Construction of control building
1996 Fabrication of upper cryostat, central control system
1998 Completion of LHD

FUSION SCIENCE

Japan Readies Helical Device To Probe Steady-State Plasmas

TOKI, JAPAN—Japan's effort to understand and harness the power that drives the stars will take a big step forward on 31 March when plasma physicist Atsuo Iiyoshi steps up to a panel in a cavernous control room here and pushes a button. Barring last-minute glitches, he will initiate production of the first plasma in a fusion reactor that is the largest of its kind. For Iiyoshi, director-general of Japan's National Institute for Fusion Science (NIFS), the $650 million Large Helical Device (LHD) is the next step in making this type of reactor a contending design for a commercial fusion power plant.

For Japan, the machine marks the newest component in what is arguably the world's most ambitious fusion research program. The LHD is just one element in the country's $250-million-a-year fusion research budget—some $18 million more than the United States is spending. Japan also operates one of the world's most advanced tokamaks, the JT-60, and it's the odds-on favorite to host the planned $10 billion International Thermonuclear Experimental Reactor (ITER). "They're certainly going to give other countries a run for their money [in fusion research]," says Robert Goldston, director of the Princeton Plasma Physics Laboratory in New Jersey.

The design for the LHD was pioneered at Princeton in the 1950s with a device called a stellarator. However, Princeton and most other labs around the world later turned their attention to a competing fusion device, the tokamak. Both approaches rely on heating a plasma of ionized light atoms so that they fuse into heavier atoms, releasing energy in a process that mimics the sun's power plant. To maintain the required temperature of 100 million degrees Celsius, the plasma is confined by a magnetic field that spirals through a doughnut-shaped vessel.

The difference between the two machines lies in how that field is created. In a tokamak, the field is the sum of what is generated by a current sent through the plasma itself and coils that fit like rings around the doughnut. In a helical device, the coils themselves are wound in a helix around the doughnut.

Neither approach is trouble-free. The current running through the plasma in a tokamak can only be applied in short pulses, limiting the duration of the magnetic confinement and, thus, the fusion reaction. Large currents also can cause a phenomenon called disruption, a sudden rapid loss of energy that can damage reactor components. The magnetic field in a helical device is independent of the plasma and can run in a steady state, allowing a continuous fusion reaction. But the plasmas in the early stellarators lost energy at rates an order of magnitude greater than that of the best tokamaks. In addition, their helical coils were hard to build and their magnetic fields were difficult to analyze.

D. NORMILE

NIFS

Inside story. Iiyoshi with a model of the Large Helical Device, in which helical coils create a powerful magnetic field to confine burning plasma.

While much of the rest of the world abandoned helical devices in the 1960s, a few groups, notably at Kyoto University in Japan and the Max Planck Institute for Plasma Physics in Garching, Germany, continued working on the energy-loss problem. Proponents see the LHD and a German device being built of comparable size but different configuration as opportunities to show that a helical device could be an alternative to the tokamak for commercial power reactors. "There is no unique solution for fusion power yet," Iiyoshi says.

Japan's fervent interest in fusion starts from one simple fact: The nation imports all of its oil. The economic devastation wrought by the oil shocks of the 1970s is still a vivid memory here, fueling the search for alternative energy sources. Policy-makers also believe that fusion research will be a boon to the country's heavy industry. Osamu Motojima, NIFS's director of research operations, points proudly to the LHD's superconducting coils, which required advances in everything from the material of the wires to a new machine to wind them. "Very few countries could build something like this," Motojima says.

The project has also gotten a boost from ongoing competition between rival agencies. "Happily, Japan has two [science] ministries," says Iiyoshi. With JT-60 and Japan's ITER efforts supported by the Science and Technology Agency, NIFS benefited from a willingness of its funding agency, the Ministry of Education, Science, Sports, and Culture (Monbusho), to fund an alternative.

Despite the LHD's domestic importance, Iiyoshi stresses that it will be an international facility and that any scientist can apply for time on the machine. "They are more than just open, they're very eager for people to come here," says John Rice, a research scientist at Massachusetts Institute of Technology now working on diagnostic devices at NIFS.

Iiyoshi says that the parallel efforts on helical devices and tokamaks are complementary and necessary. Tokamaks are far ahead of helical devices in terms of the plasma densities and temperatures achieved. In the last few years, tokamaks have crept closer to break even, where the energy generated by the fusion reaction equals the energy put into heating the plasma (*Science*, 3 October 1997, p. 29). Günter Grieger, director of the new Greifswald branch of the Garching institute, where the new Wendelstein 7X stellarator is being built, adds that their track record makes tokamaks the obvious choice for the next step—investigating the self-sustaining fusion reaction using the deuterium and tritium that would be used in future reactors. "For ITER, it is the right way to go," Grieger says.

But ITER is not the last word in fusion reactors. While ITER plans to operate only in pulses of up to about 1000 seconds, the Japanese and German machines will confine the plasma for hours or even days. "We will be able to investigate parameters of steady-state plasma physics in ways that tokamaks can't," Iiyoshi says. That contribution, says Princeton's Goldston, "makes the LHD an important part of the world fusion research effort."

Helical device proponents hope to make more than just a contribution. Iiyoshi predicts that the performance of the LHD and the Wendelstein 7X will put helical devices back in the running by 2015, when it's time to design a demonstration reactor. "It could be the choice if we have great success with the LHD experiments," he says, a process that starts after he pushes the button.

–Dennis Normile

1846 SCIENCE • VOL. 279 • 20 MARCH 1998 • www.sciencemag.org

Science: 20 March 1998
Just before Commissioning
Reported:
First Plasma Production:
31 March 1998

Motojima said, " Very few countries could build something like this"

"Original Scientific Projects with High Potential and Identity" are always necessary in any country trying to contribute to the nation' s benefit and to make a global impact.

Next day was April Fool's Day. If one day delayed, no body would believe this great achievement

Summary: IAEA FEC Geneva, Oct. 2008

General Topics

1. ITER oriented
- (1) ELM mitigation (S)
- (2) Divertor armor strategy (D)
  PMI, Tungsten
- (3) Current drive and heating (W)
- (4) Disruption mitigation (S)

2. ITER/DEMO oriented
- (1) Steady state (W,S)
- (2) High β (S), NTM, RWM
- (3) PMI & SOL/DIV physics (D)
- (4) TAE (W, S)
- (5) Heating (W), EBW etc.

High Lights of LHD Experiments

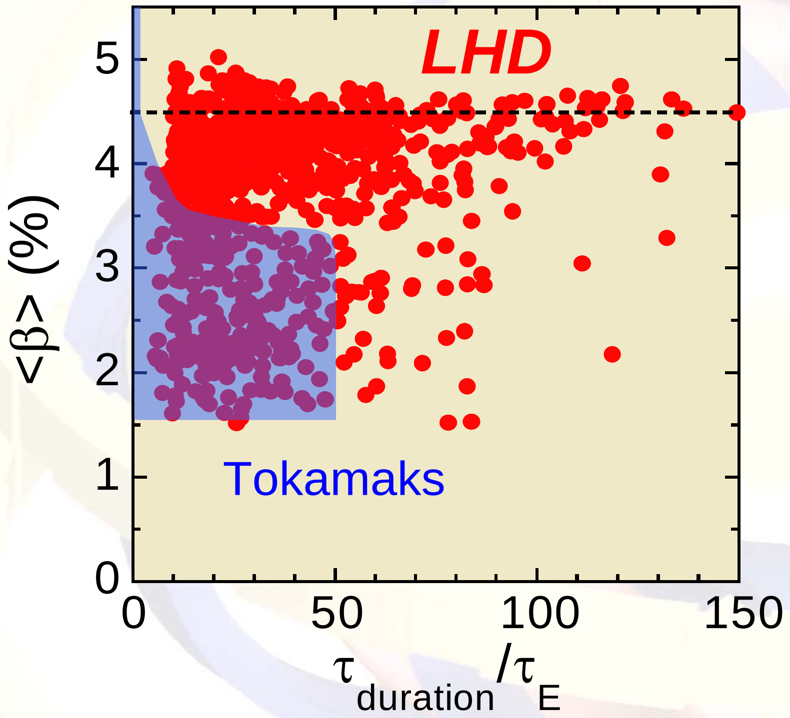
(1) High β
(2) High Density (IDB)
(3) High Ti (ITB)
(4) Steady State

Primarily ITER oriented
High Priority Technical Issues Identified at STAC-2

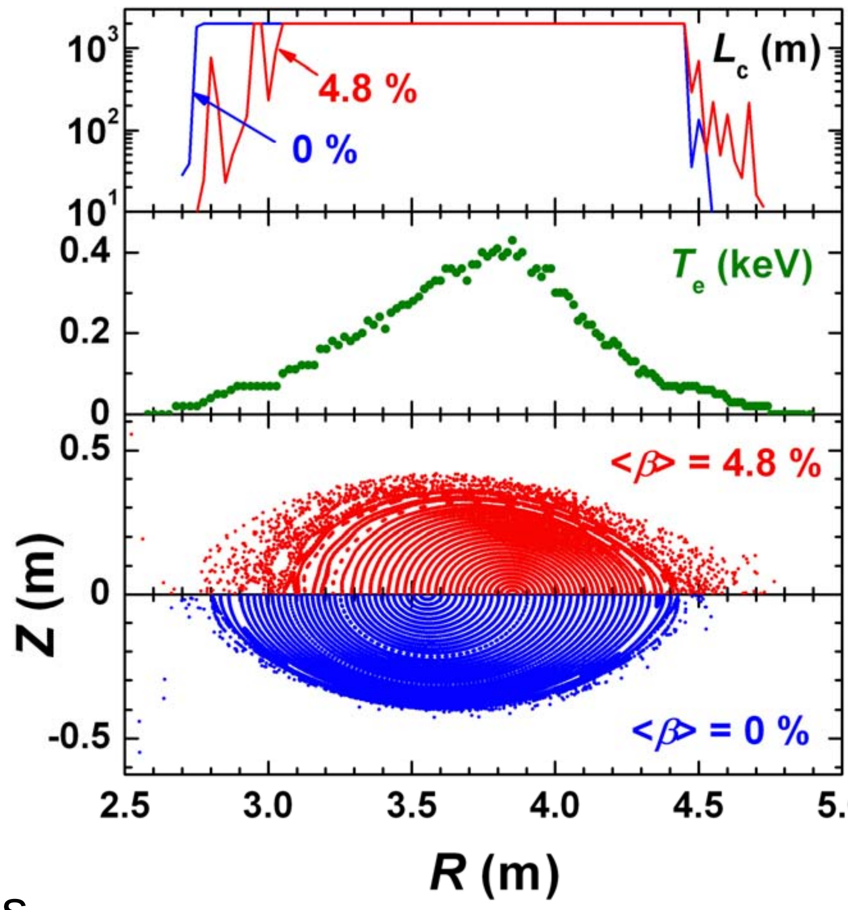
1. **Vertical Stability**
2. **Shape Control / Poloidal Field Coils**
3. **Flux Swing in Ohmic Operation and CS**
4. **ELM Control**
5. **Remote Handling**
6. **Blanket Manifold Remote Handling**
7. **Divertor Armour Strategy**
8. **Capacity of 17 MA Discharge**
9. **Cold Coil Test**
10. **Vacuum Vessel / Blanket Loading Condition Test**
11. **Blanket Modules Strategy**
12. **Hot Cell Design**
13. **Heating Current Drive Strategy, Diagnostics and Research Plan**

High β Experiment

β of 5 % has been achieved and β of 4.5 % has been maintained in steady state



3-D equilibrium calculated by HINT

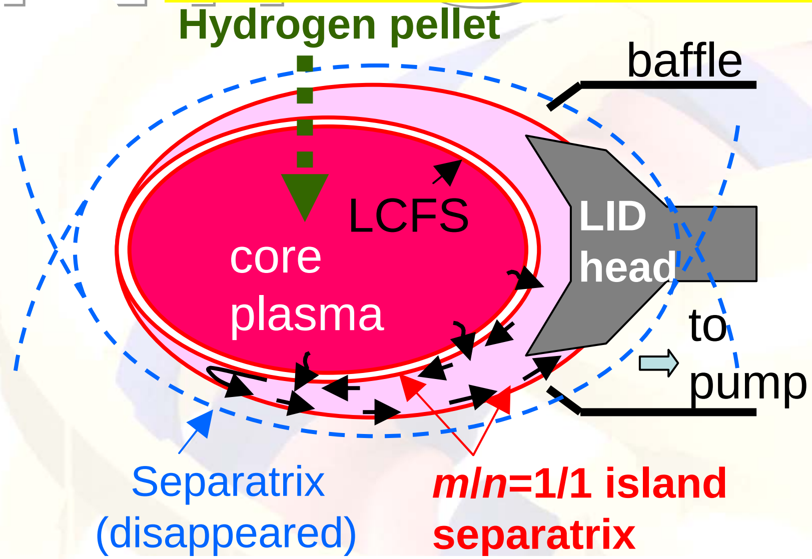


- ✓ Beta limit
- ✓ Transport in the ergodic layer
- ✓ Change of magnetic topology,
  e.g., magnetic island dynamics

Effect of stochasticity has been investigated in detail

Realization of IDB

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



Hydrogen pellet

baffle

LCFS

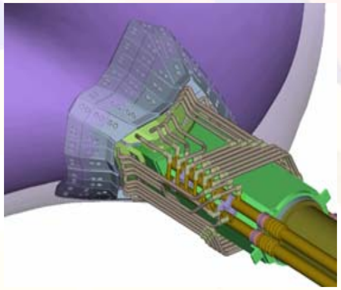
core plasma

LID head

to pump

Separatrix (disappeared)

***m*/*n*=1/1 island separatrix**



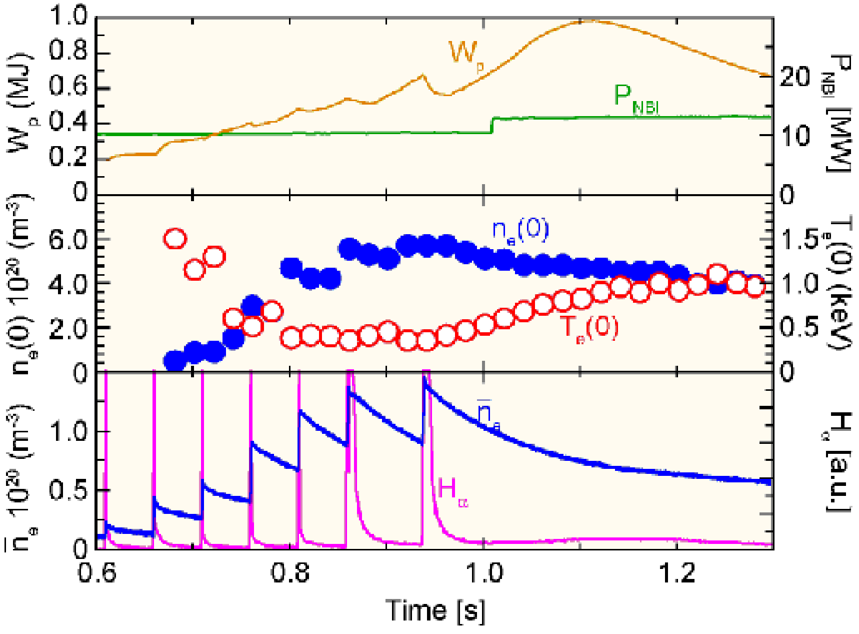
W_p =1.1MJ, P_{abs}=10MW

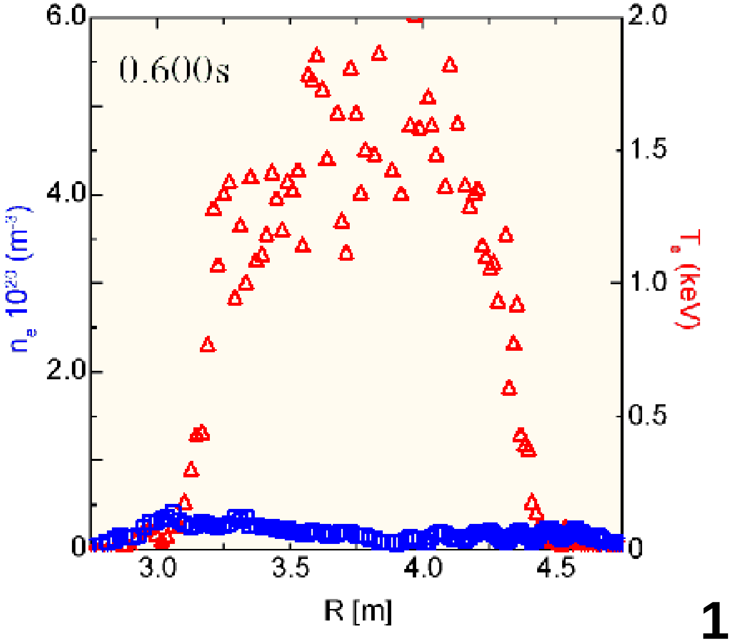
$n\tau_E T$ =4.4×$10^{19}$$m^{-3}$ s keV

$\beta(0)$ =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 m^2/s, a very low value

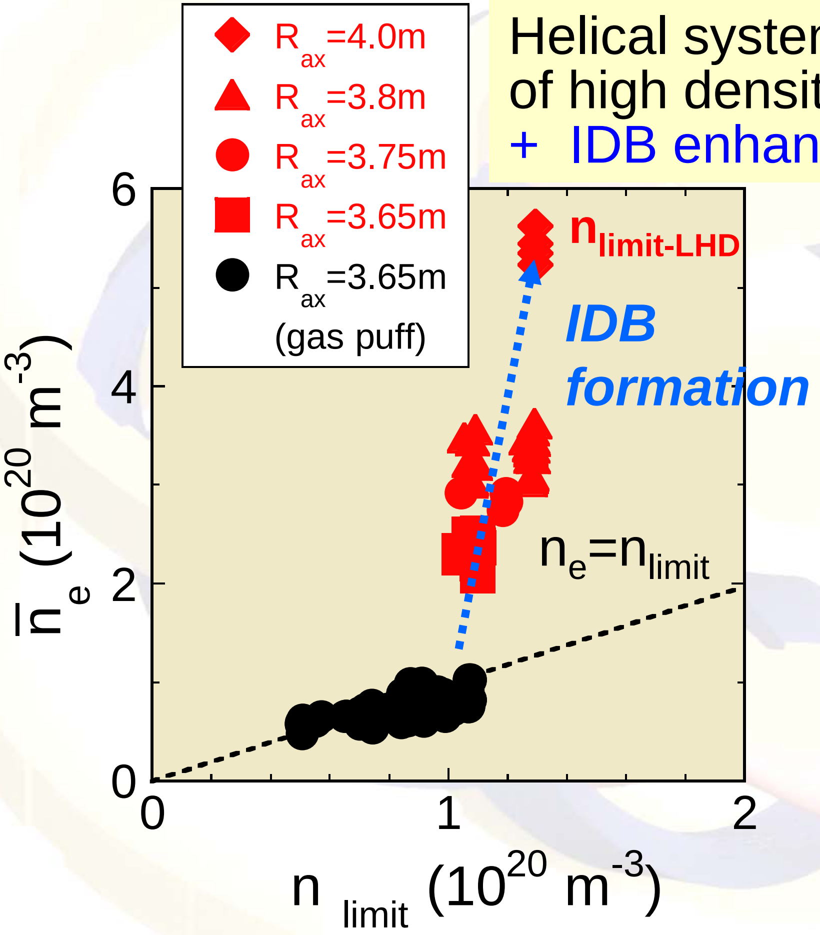


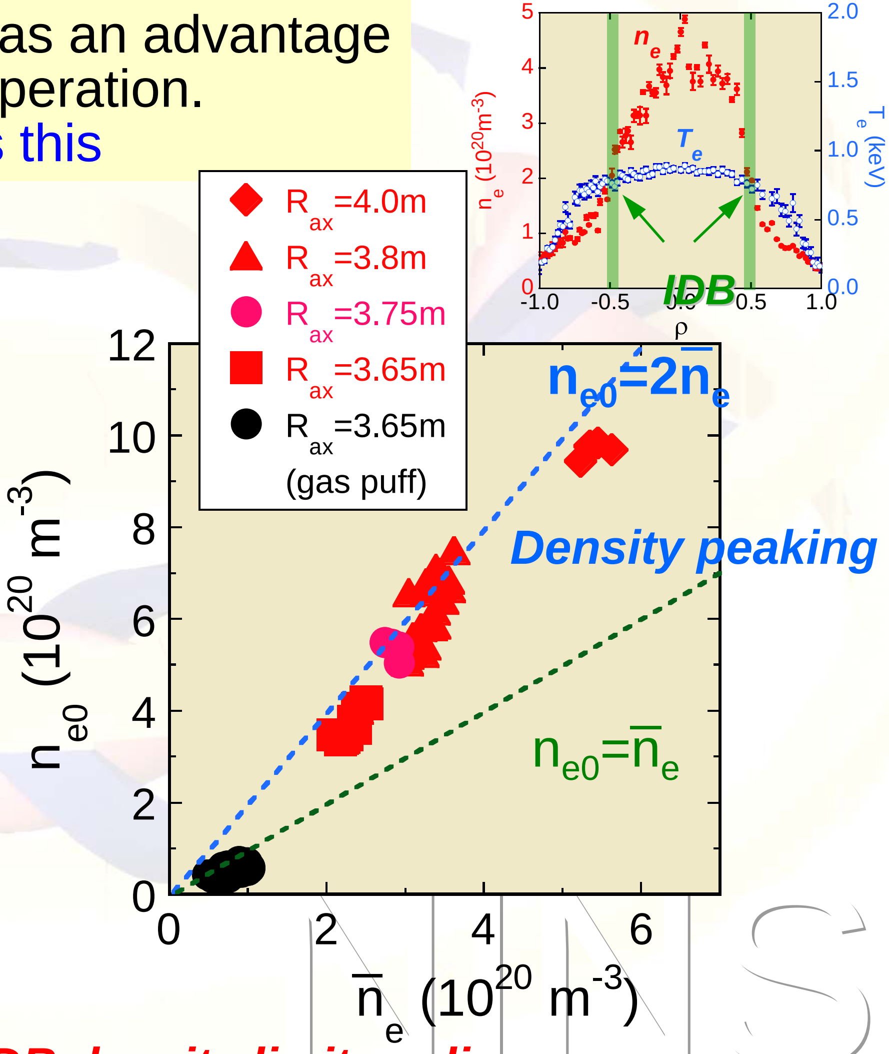


High Density Experiment

LHD plasma with IDB has been extended to the density regime of $10^{21} m^{-3}$

Helical system has an advantage of high density operation.
+ IDB enhances this





Density limit in helical systems

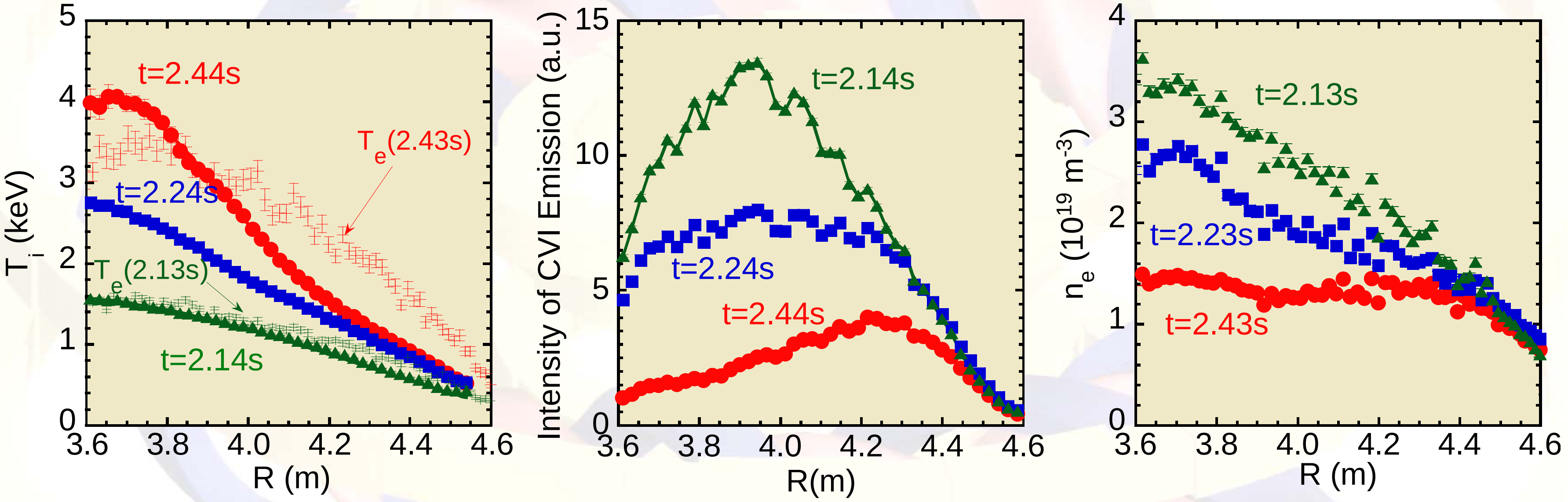
$$n_e^{limit} = 0.25(PB/(a^2R))^{0.5}$$

→ *New IDB density limit scaling*

LHD demonstrated the high capability of high density operation

Finding of Impurity Hole

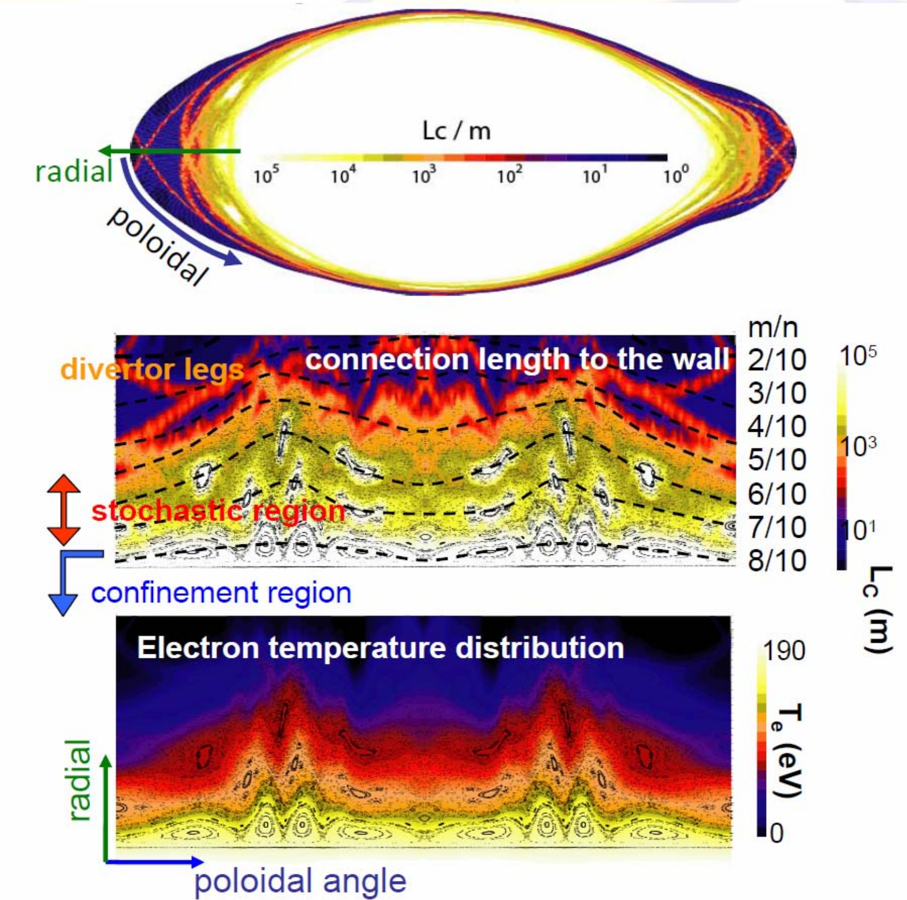
Carbon impurity is expelled due to Outward convection in ITB phase



- ✓ More hollow as the ion temperature gradient is increased
- ✓ Steep Ti gradient ➔ Extremely hollow carbon profile "**impurity hole**", which is quite different from electron density profile.
- ✓ Contradicting NC prediction ➔ suggests anomalous impurity convection

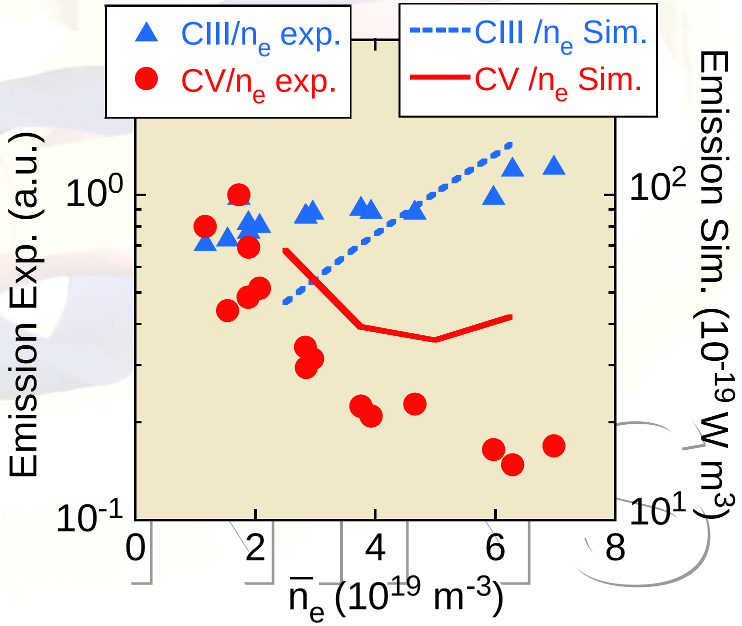
Transport Study

Ergodic layer plays a key role to realize high density plasmas with high performance



3-D edge transport code : EMC3-EIRENE

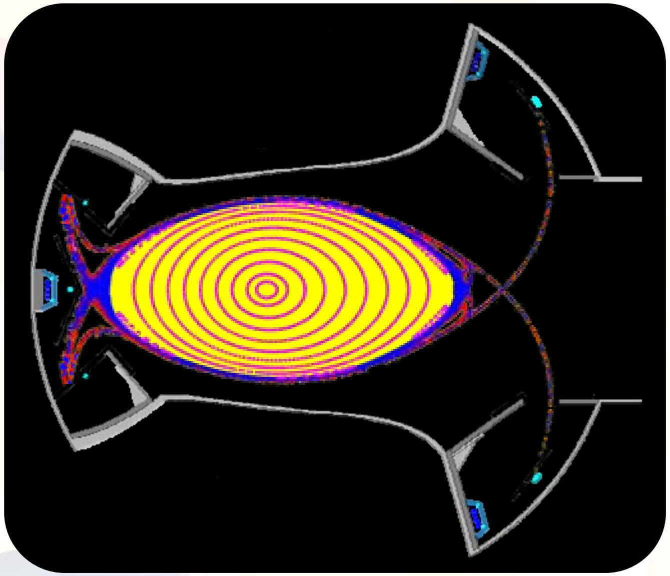
Core plasma is surrounded by ergodic layer with magnetic islands



✓ **Impurity screening** effect in stochastic region by friction with bulk plasma flow

➔ **Effective reduction of impurity contamination in high density operation**

Nearest Future Plan



1. **Upgrade of heating capability**

NBI	5th beam line 7 MW, 60 keV
ICH	3 MW steady state
ECH	1 MW steady state

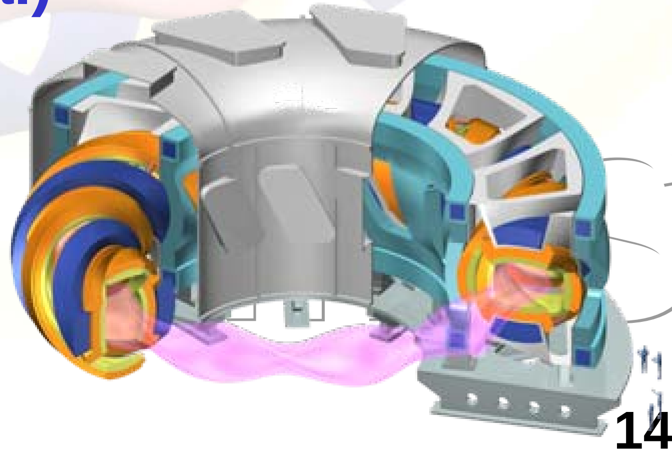
2. **Closed helical divertor**

3. **Deuterium**
    - Identification and documentation of isotope effect
    - Upgrade of NBI (32 MW in total)

4. **Reactor design study**

FFHR :

Force-Free Helical Reactor



Summary

1. High beta $\langle\beta\rangle = 5.1$ %, $\langle\beta\rangle > 4.5$ % for $> 100\tau_E$

2. High density $n_e(0) = 1.2\times10^{21}\mathrm{m}^{-3}$ at $B = 2.5$ T
   with *Internal Diffusion Barrier (IDB)*

3. High ion temperature 5.2 keV at $\bar{n}_e = 1.5\times10^{19}\mathrm{m}^{-3}$
   with confinement improvement similar to *ITB*

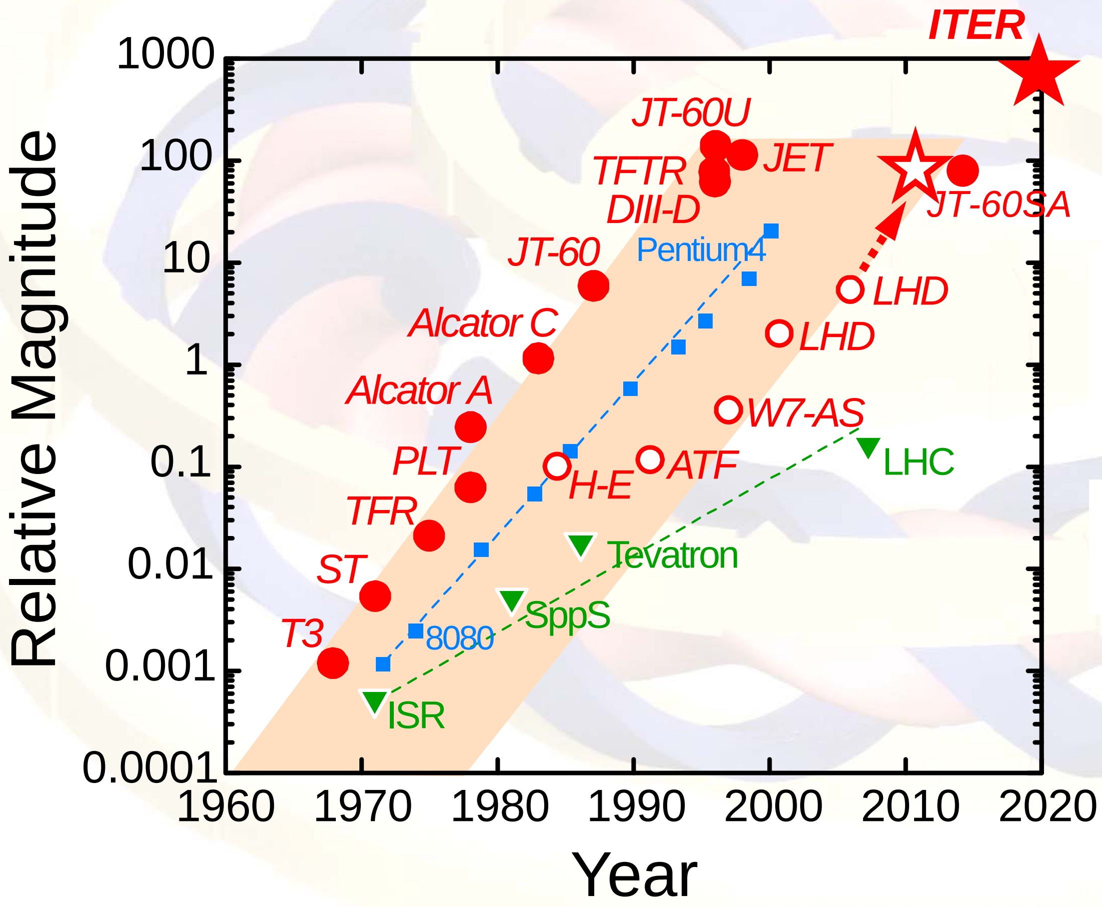
4. Steady state 0.5MW for 3268s, 1MW for 800 s

5. Near-term upgrade package
   closed helical divertor, heating capability, deuterium

6. 3-D effect inspiring new advanced physics model and theory which are to be validated in LHD experiment

Summary: IAEA FEC Geneva, Oct. 2008

Up to now, fusion research has progressed as rapidly as other areas of big science and high-technology, i.e. computers and high energy physics



Fusion:
Triple product $nT\tau_E$ doubled every 2 years

Moore's law :
Transistor number doubles every 2 years

Accelerators :
Energy doubles every 3 years

This is the development by 1 Million times in 50 years from a table top device to big science

IDB Scenario and Super Dense Core (SDC)

- **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 (SDC Reactor)**

  High Density and Lower Temperature Core

  Parameters (n, T, beta) obtained are encouraging

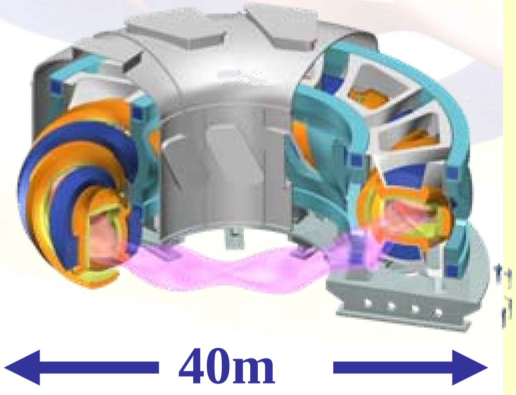
SDC Reactor reduces engineering demand and neoclassical ripple transport

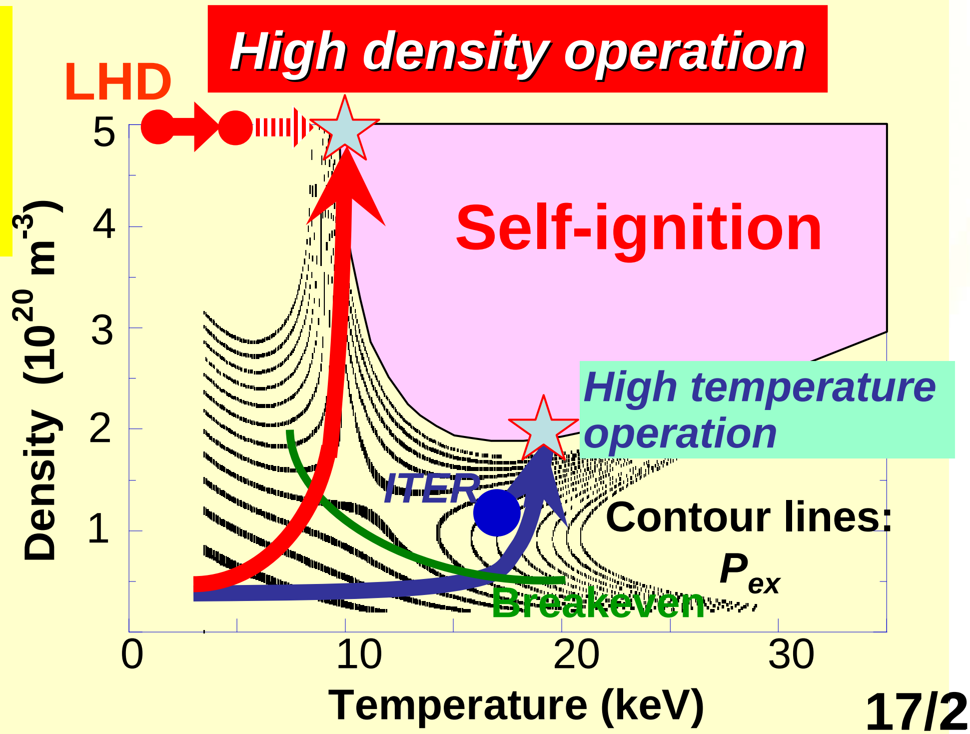
FFHR

1,000 MW

6Tesla

25,000 ton

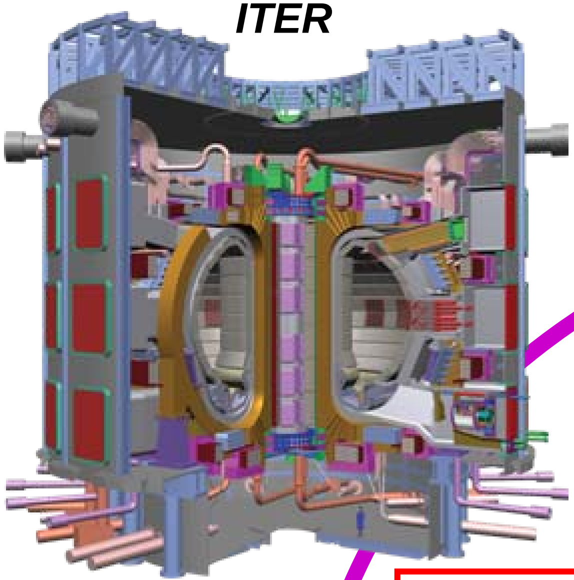




Role of Design Study to Helical Demo-Reactor based on LHD Project

Tokamak Experimental Rector

ITER



LHD-type Helical Reactor FFHR
Electric Power 1GW
Weight 25,000ton
Magnetic Field 6T

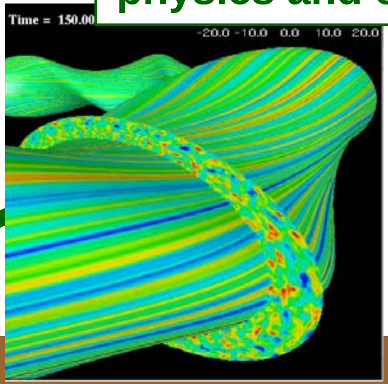
Helical Demo Rector
(28 years to go)

Physics of burning plasmas

Demonstration of steady-state, high-density, high beta by net-current free plasma

Multi-layer models covering physics and engineering

LHD



LHD-NT
LHD Numerical Test Reactor

Basic Science

Conclusion: Roles and Functions of Fusion Research

This 22nd IAEA FEC will be recorded as a landmark conference addressing the environment problem of the Earth

- Achieving long-term integration of physics and engineering necessary for energy development
- Promoting the development of research that follows the critical path
- Securing the basic sciences and supporting technologies necessary for fusion research
- Continually disseminating scientific results and leading the development of advanced science and technology in the field of nuclear fusion
- Steadily training necessary human resources

The Dream is Alive
Now Fusion Energy is an Achievable Goal!

Thank you very much!

It is my greatest pleasure to be awarded such an honorable prize. I would like to thank President Dr. Stephen O. Dean and all of the members of Fusion Power Associate for their strong encouragement.

I believe that this reward was the result of my engaging in the construction and experiments of the Large Helical Device (LHD) ever since our research institute was established in 1989.

I have been able to produce so many world-leading results only because every one of my colleagues, researchers and staff in the National Institute for Fusion Science as well as collaborative researchers in various universities And research institutions all over the world gave me such warm support.

I would like to show my sincerest appreciation to all of the related persons.

And above all, I would like to thank my wife for supporting me for all these years.

With this prize, I will be further dedicating myself to the development of fusion energy research.