Overview of Fusion Research at NIFS

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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 m³
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
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)

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

New Perpendicular beam
• 7 MW, $E_{\text{NBI}} = 40$ kV
  with positive-ion sources
• Ion heating ($T_i(0) = 5.2$ keV)
• works as a diagnostic beam for
  CXRS ($T_i$, $V_{\phi}$, $V_\theta$, $E_r$)
• Confinement of trapped particles
  secured by geometrical optimization
National Institute for Fusion Science and LHD
History of Heliotrons

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

I=2 is a magic number

Break Even
Q=\frac{P_{\text{fusion}}}{P_{\text{heat}}} = 1
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
Japan Readies Helical Device To Probe Steady-State Plasmas

FUSION SCIENCE

TOKYO, 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 Asao Iyohsi steps up to a panel in a cavernous control room here and pushes a button. Baring last-minute glitches, he will initiate production of the first plasma in a fusion reactor that is the largest of its kind. For Iyohsi, director-general of Japan's National Institute for Fusion Science (NIFS), the $600 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 $350-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 cold-weather host for 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 Childs, 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 tokamak. 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 contained 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 that flows 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, or "poloidal" field. 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 can also 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 plasma 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.

"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.

Inside story, Iyohsi with a model of the Large Helical Device, in which tokamaks create a powerful magnetic field to confine and burn 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," Iyohsi says.

Japan's fervent interest in fusion stems 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), director of research operations, points proudly to the LHD's supporting field coils, which required advanced 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 Iyohsi. 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 (Mombusho), to be innovative.

Despite the LHD's domestic importance, Iyohsi insists that it will be an international facility and that any scientific breakthroughs will pay time on the machine. "They are more than just open, they're eager for people to come here," says John Ruiz, a research scientist at Massachusetts Institute of Technology now working on diagnostic devices at NIFS. Iyohsi says that the parallel effort 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. 25). Gunter Orisager, director of the newly created branch of the CERN fusion 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," Orisager says.

But ITER is the last word in fusion reactors. While ITER plans to operate 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," Iyohsi says. That contribution, says Princeton's Golovin, "is making the LHD an important part of the world fusion research effort.

Helical device proponents hope to make more than just a contribution. Iyohsi 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.

"Very few countries could build something like this."
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 $\beta$ (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 $\beta$
   (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 $\beta$ Experiment

$\beta$ of 5% has been achieved and $\beta$ of 4.5% has been maintained in steady state

- 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

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 m$^2$/s, a very low value

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

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

$\beta(0) = 4.4\%$, $<\beta> = 1.5\%$

$R_{ax} = 3.75m$, $B = 2.64T$

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

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

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

New IDB density limit scaling

Density limit in helical systems

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

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 \( \Rightarrow \) Extremely hollow carbon profile “impurity hole”, which is quite different from electron density profile.
- Contradicting NC prediction \( \Rightarrow \) suggests anomalous impurity convection
Transport Study
Ergodic layer plays a key role to realize high density plasmas with high performance

Core plasma is surrounded by ergodic layer with magnetic islands

3-D edge transport code: EMC3-EIRENE

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 $n_e(0) = 1.2 \times 10^{21} \text{m}^{-3}$ at $B = 2.5 \text{T}$ with *Internal Diffusion Barrier (IDB)*

3. High ion temperature 5.2 keV at $\bar{n}_e = 1.5 \times 10^{19} \text{m}^{-3}$ with confinement improvement similar to *ITB*

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

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
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
- 6 Tesla
- 25,000 ton

**Contour lines:**
- $P_{ex}$
- Self-ignition
- Breakover

**High density operation**

**High temperature operation**

**Temperature (keV)**

**Density ($10^{20}$ m$^{-3}$)**

$40 \text{ m}$
Role of Design Study to Helical Demo-Reactor based on LHD Project

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

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-NT
LHD Numerical Test Reactor

Tokamak Experimental Reactor

ITER

LHD

Helical Demo Reactor
(28 years to go)
Conclusion: Roles and Functions of Fusion Research

This 22\textsuperscript{nd} 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.