Strategy of Development of SC Magnet for Helical Reactors

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1. Present magnet technology
2. Specifications of Helical Demo
3. Necessary R&Ds for a helical winding
4. A roadmap to heliotron DEMO
History of Development of Fusion Magnets

(1) Since the construction of big three tokamaks in 1980’s, fusion devices with SC magnets were constructed and operated successfully.
(2) LHD, constructed in 1998, is the world largest superconducting magnet until the construction of ITER.
Requirements

- Hysteresis losses ($Q_h$)
  $1,000 \text{mJ/cm}^3$ (±3T, 4.2K)
- Critical current density ($J_c$)
  $291 \text{A/mm}^2$ at 11.3T, 5.7K, strain of -0.77%

Achievement

- Trial of mass production
- Required values were attained by large amount production of 0.1 tons.

<table>
<thead>
<tr>
<th></th>
<th>$J_c$ (A/mm$^2$)</th>
<th>$Q_h$ (mJ/cm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal Sn</td>
<td>1,000</td>
<td>700</td>
</tr>
<tr>
<td>Bronze</td>
<td>750</td>
<td>700</td>
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</tbody>
</table>

**Development of High Performance Nb$_3$Sn Strands**

Internal Sn: $800 \text{A/mm}^2$ 以上
Bronze: $700 \text{A/mm}^2$ 以上

**Hysteresis loss (mJ/cm$^3$) for ±3T**
Improvement of Critical Current Density

Higher current density is needed to reduce the amount of superconductor. $J_c$ of Nb$_3$Sn will be improved through the production of the ITER conductors. Nb$_3$Al needs an original R&D program.
Structural Material for ITER-TF

<table>
<thead>
<tr>
<th>Class</th>
<th>$\sigma_y$ at 4 K</th>
<th>Material</th>
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<tbody>
<tr>
<td>1</td>
<td>&gt;1000MPa</td>
<td>JJ1</td>
</tr>
<tr>
<td>3</td>
<td>&gt;850MPa</td>
<td>316LN (C+N ≥ 0.18%)</td>
</tr>
<tr>
<td>5</td>
<td>&gt;650MPa</td>
<td>316LN (C+N ≥ 0.13%)</td>
</tr>
<tr>
<td>5A</td>
<td>&gt;290MPa and at RT</td>
<td></td>
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<tr>
<td>6</td>
<td>&gt;550MPa</td>
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Shape and weight
- Thickness: 60 – 500 mm
- Final weight: 200 tons/coil
- 19 coils: 3800 tons

JJ1: 0.03C-12Cr-12Ni-10Mn-5Mo-0.24N
316LN: 0.03C-18Cr-11Ni-1.5Mn-2Mo-(0.12-0.22)N

Courtesy of JAEA
Present Technology of SC Magnets

(1) SC material: NbTi, Nb₃Sn
   Nb₃Al (few companies)

(2) Magnetic field:
   13.5 T @ 6 GJ (ITER-CS)
   11.8 T @ 41 GJ (ITER-TF)

(3) Conductor current:
   68 kA @ 11.8 T (ITER-TF)
   41.8 kA @ 13.5 T (ITER-CS)

(4) Conductor length: 1,000 m

(5) Structural materials (SS316LN, JJ1)
   Yield stress at 4 K: ~1 GPa (JJ1)
   Thickness: 0.5 m
Helical Coil with CICC (ITER technology)

<Design criteria of CIC (Cable-in-conduit) conductor [ITER-TF coil]>
- Max. length of cooling path < 550 m [390 m]
- Current < 100 kA [68 kA]
- Max. field < 13 T [11.8 T]
- Coil current density < 30 A/mm² [20.3 A/mm²]

<Concept to adopt CIC conductor for HC (five times longer than ITER-TF)>
(1) To reduce a turn number with a large current conductor
(2) To shorten the cooling length with five parallel winding

<TF conductor>
SC strands(Ø39.5mm)
Nb₃Sn:1,152 or Nb₃Sn:720 + Cu:360
Channel Ø8mm
Conduit
Tape (stainless)
Tape (Inconel)
Coil case
Radial plate
Conductor
TF winding
800
Concept of Helical Coil with CICC

(1) Layer winding by 5 in hand
(2) Winding guides are grooved in the internal plates whose sectors are welded on site.
(3) CIC conductors are wound into the groove with insulation.
CIC conductors for a large helical coil can be produced with the same technology for ITER. Improvement of current density is preferred.

<table>
<thead>
<tr>
<th></th>
<th>H-power plant</th>
<th>ITER-TF</th>
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</thead>
<tbody>
<tr>
<td>Bmax</td>
<td>11.6</td>
<td>11.8</td>
</tr>
<tr>
<td>Magnetic energy</td>
<td>136.5</td>
<td>41</td>
</tr>
<tr>
<td>Length of a cooling path</td>
<td>493</td>
<td>390</td>
</tr>
<tr>
<td>Conductor current</td>
<td>90.2</td>
<td>68.0</td>
</tr>
<tr>
<td>Number of parallel winding</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>Current density (winding) A/mm²</td>
<td>25</td>
<td>20.33</td>
</tr>
<tr>
<td>SC material</td>
<td>Nb₃Al</td>
<td>Nb₃Sn</td>
</tr>
<tr>
<td>Cu ratio of strand</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Non-Cu current density A/mm²</td>
<td>400.0</td>
<td>273.4</td>
</tr>
<tr>
<td>Ratio of Cu strands (area)</td>
<td>0.452</td>
<td>0.360</td>
</tr>
<tr>
<td>Central tube diameter mm</td>
<td>12.0</td>
<td>8.0</td>
</tr>
<tr>
<td>Void fraction</td>
<td>0.34</td>
<td>0.34</td>
</tr>
<tr>
<td>Conduit outer diameter mm</td>
<td>45.6</td>
<td>43.4</td>
</tr>
<tr>
<td>Number of coils</td>
<td>2</td>
<td>18</td>
</tr>
<tr>
<td>Total length of conductor km</td>
<td>138.0</td>
<td>82.2</td>
</tr>
<tr>
<td>Total weight of SC strands ton</td>
<td>498</td>
<td>351</td>
</tr>
<tr>
<td>Total weight of Cu strands ton</td>
<td>458</td>
<td>206</td>
</tr>
</tbody>
</table>
Increase of $J_c$ by Grading

- Maximum field in each layer of HC is lower at the outer layers. Therefore, average current density $J_c$ of SC strands can be increased by grading the conductors.
- $J_c=400$ A/mm$^3$ at $B_{\text{max}}=11.5$ T can be attained by an ITER relevant conductor.

<table>
<thead>
<tr>
<th>$B_{\text{max}}$ (T)</th>
<th>$J_c$ at $B_{\text{max}}$ (A/mm$^2$)</th>
<th>3 grades</th>
<th>4 grades</th>
<th>5 grades</th>
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</thead>
<tbody>
<tr>
<td>11.0</td>
<td>361</td>
<td>514</td>
<td>534</td>
<td>543</td>
</tr>
<tr>
<td>11.5</td>
<td>304</td>
<td>449</td>
<td>468</td>
<td>477</td>
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<tr>
<td>12.0</td>
<td>254</td>
<td>391</td>
<td>409</td>
<td>417</td>
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<tr>
<td>12.5</td>
<td>209</td>
<td>338</td>
<td>355</td>
<td>363</td>
</tr>
<tr>
<td>13.0</td>
<td>170</td>
<td>290</td>
<td>305</td>
<td>314</td>
</tr>
</tbody>
</table>

$J_c \sim J_{c1} \propto B^{-0.5}(1-B/20.64)^2 = 7866B^{-0.5}(1-B/18.03)^2$ (for strain -0.5%, 7 K)
### Spec. of Heliotron DEMO

<table>
<thead>
<tr>
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<th>H-Power plant</th>
<th>H-Demo</th>
<th>ITER</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>H-factor of</strong> τ&lt;sub&gt;E&lt;/sub&gt;, H&lt;sub&gt;H&lt;/sub&gt;</td>
<td>1.2 to LHD</td>
<td></td>
<td>←</td>
</tr>
<tr>
<td><strong>Energy gain, Q</strong></td>
<td>∞ (self ignition)</td>
<td>&gt; 20</td>
<td>10 (∞ by H&lt;sub&gt;H&lt;/sub&gt;=1.5 x LHD)</td>
</tr>
<tr>
<td><strong>TBR</strong></td>
<td>&gt; 1.0</td>
<td>&gt; 1.0</td>
<td>←</td>
</tr>
<tr>
<td><strong>Operation</strong></td>
<td>Steady state</td>
<td></td>
<td>←</td>
</tr>
<tr>
<td><strong>Min. blanket space [m]</strong></td>
<td>&gt; 1.1</td>
<td>&gt; 0.9</td>
<td></td>
</tr>
<tr>
<td><strong>Fusion power [GW&lt;sub&gt;th&lt;/sub&gt;]</strong></td>
<td>4 - 5</td>
<td>~ 2</td>
<td>0.5</td>
</tr>
<tr>
<td><strong>Major radius of plasma [m]</strong></td>
<td>15-16</td>
<td>13.2</td>
<td></td>
</tr>
<tr>
<td><strong>Minor radius of plasma [m]</strong></td>
<td>~ 2</td>
<td>1.9</td>
<td></td>
</tr>
<tr>
<td><strong>Central field [T]</strong></td>
<td>~ 5</td>
<td>4.8</td>
<td></td>
</tr>
<tr>
<td><strong>Max. field [T]</strong></td>
<td>11-12</td>
<td>10.6</td>
<td>13.5</td>
</tr>
<tr>
<td><strong>Stored magnetic energy [GJ]</strong></td>
<td>120-140</td>
<td>70-80</td>
<td>41 (TF)</td>
</tr>
<tr>
<td><strong>Weight of magnets [tons]</strong></td>
<td>~16,000</td>
<td>~10,000</td>
<td>~10,000</td>
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<tr>
<td><strong>Construction costs</strong></td>
<td>&lt; 2 x ITER</td>
<td>&lt; 1.5 x ITER</td>
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<td>74.8</td>
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Concept of Helical Winding by R&W

(1) Conductors are heated for reaction of Nb₃Al on a bobbin the circumference of which is same as the length of one pitch of the helical coil.
(2) The conductors are transferred to the reel of the winding machine.
(3) The conductors are pulled aside by the winding guide and wound in grooves of the inner plate with being wrapped with glass tapes.
(4) After winding the whole turns in a layer, the next inner plate are assembled.

\[ r\theta = \frac{r \cdot \tan^{-1} \beta}{\frac{2\pi a_c}{4}} \approx 0.3\% \text{ (average)} \]
Torsion strain for \( r = 0.021 \text{ m} \) (%)

- Torsion induces shear strain in a homogenous material. In the case of CIC conductor, tension and compression will be applied on the strands in the outer and inner area, respectively.
- A feasibility study is needed to know the effect of the torsion.

(1) The bending strain after the reaction on the bobbin is less than 0.05%.

(2) The torsion strain is the largest at the inside of the torus. It is less than 0.6%.
Strain Effect on Superconductor

If the torsion strain of 0.6% induce +0.6% of tensile strain, it is preferable for Nb$_3$Al strands. Even if it induces + and - 0.3% of axial strain, it will be allowable for Nb$_3$Al strands.

Nb$_3$Al is a good candidate for helical coil conductor wound with React & Wind method.

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Necessary R&Ds for Helical Winding

(1) Demonstrate helical winding with large CIC conductors
(2) Estimate the effect of torsion on critical current density if react & wind method is applied
(3) Establish facility for mass production of Nb$_3$Al strands
(4) Establish machining and welding technique for large and thick supporting structure
R&D Plan for Helical Winding (tentative)

(1) Subsize Nb$_3$Al CIC cable (3x3x6 strands, ~6 kA, ~100 m)
   1-1) $J_c$ measurement with torsion strain
   1-2 Helical winding of the CIC cable with React&Wind method
      $m=10$, 1 turn helical coil (Major radius: 2.7 m =16 m x 7 mm/42 mm)

(2) Real Nb$_3$Al CIC cable
   2-1) Mass production trial and conductor tests
   2-2) Model coil test

<table>
<thead>
<tr>
<th>Year</th>
<th>1</th>
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<td>$J_c$ vs torsion</td>
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<td>Real CIC cable</td>
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<td>Model coil</td>
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Roadmap to Heliotron DEMO

**Basic Science**

- **ITER**
- **LHD**
- **LHD-NT**

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

**Physics of burning plasmas**

**R&Ds on SC magnets, blankets, and divertor.**

**Multi-layer models covering physics and engineering**

**Heliotron Demo**

**Tokamak Experimental Reactor**

**Roadmap to Heliotron DEMO**

**R&Ds on SC magnets, blankets, and divertor.**
Aiming at Helical Fusion Reactor (Original)

- LHD (Heliotron)  
  - Q=0.075
  - LHD Numerical Test Reactor
  - High performance
  - High fusion gain

- LHD Exp.  
  - Hydrogen ➔ Deuterium
  - Reactor design, Power generation
  - Fuel breeding, System development
  - Reactor material development

- Fusion Reactor  
  - Construction
  - Operation

- Neutron Source Project (IFMIF)  
  - Demonstration of scientific feasibility

- ITER (tokamak)  
  - Exp. Reactor (France)  
  - Construction
  - Operation  
    - H ➔ D ➔ DT

- Generation of electric power by fusion in 27 years  
  - Steady state Net current free
  - High density

- Conversion to Basic Science  
  - Demonstration of steady state operation
  - Multi-layer physics/engineering model

- Understanding of burning plasmas
Aiming at Helical Fusion Reactor (Proposal)

- **LHD (Heliotron)**
  - *Q = 0.075*
  - High performance
  - High fusion gain
  - LHD Neutral Test Reactor

- **LHD Exp.**
  - Hydrogen → Deuterium
  - Fusion Reactor
  - Reactor design, Power generation
  - Fuel breeding, System development
  - Fusion Reactor material development

- **Conversion to Basic Science**
  - Multi-layer physics/ engineering model
  - Understanding of burning plasmas

- **Operation**
  - Net current free
  - High density
  - Fusion Reactor

- **Generation of electric power by fusion in 27 years**

- **ITER (tokamak)**
  - Demonstration of scientific feasibility

- **Exp. Reactor**
  - Construction (France)
  - Operation
  - H → D → DT

- **Neutron Source Project (IFMIF)**
  - Reactor design, Power generation
  - Fuel breeding, System development

- **1st Construction**
  - H (D) plasma

- **2nd Construction**
  - DT plasma
Continuous Development of Fusion Technology

SC magnet technology is continued from ITER to DEMOs.

- ITER Construction
- Operation
- EPP
- 1st Construction
- 2nd Construction
- 3rd Construction
- IFMIF
- 10-20 dpa
- 40-150 dpa
- Tokamak DEMO
- Basic science
- LHD experiments
- Numerical test reactor
- H-DEMO
- Design
- 1st Construction for D-D plasma
- H and D plasma
- 2nd D-T plasma
- SC magnet R&Ds
Summary

(1) The necessary size of a LHD-type power plant will be the coil major radius of 16-17 m and the magnetic energy of 120-140 GJ. Based on the ITER technology, further R&Ds are necessary. React & Wind with Nb$_3$Al CIC conductors is key technology for the helical coil. Nine year R&D program is proposed.

(2) In order to prove the capability of reliable operation of heliotron power plants, H-DEMO with the magnetic energy of 70-80 GJ is proposed. The amount of its magnets is comparable to ITER.

(3) Two step construction can shorten the start of H-DEMO and reduce the project risk. Also, early construction of H-DEMO contributes to successive development of the fusion engineering.
Two Step Construction of H-DEMO

<Objectives at 1st step>
(1) Confirm the plasma confinement at the reactor regime.
(2) Establish the plasma control method and diverter design.
Two Step Construction of H-DEMO

<Objectives at 1st step>
(1) Confirm the plasma confinement at the reactor regime.
(2) Establish the plasma control method and diverter design.

Replace divertor & diagnostics. Install the blanket, T system, and generation system.

<Objectives at 2nd step>
(1) Demonstrate Q>20, TBR>1, steady state operation, and production of electricity.

Two step construction can reduce the project risk.
The design of magnets should be optimized from the results of LHD and the numerical reactor.