Superconducting Magnet Design and R&D with HTS Option for the Helical DEMO Reactor

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Alternative Ideas:
1. Helical
2. HTS (High-Temperature Superconductor)
3. Simple stacking of HTS tapes
4. Segment-fabricated windings

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Heliotron Magnetic Configuration

- **Steady-state** → no need for current drive and no disruption
- **Large machine size** → low neutron wall load (~1.5 MW/m²)
- **Built-in helical divertors**
  - Heat flux <10 MW/m² (on toroidal average)
  - Protected from direct neutron irradiation

![Diagram of Heliotron Magnetic Configuration](image-url)
The LHD-Type Helical DEMO Reactor FFHR-d1

- **Major / minor radius of helical coils**: 15.6 / 3.9 m
- **Helical pitch parameter, \( \gamma \)**: 1.25
- **Toroidal magnetic field**: 5.1 T
- **Stored magnetic energy**: 160 GJ
- **Major / minor radius of plasma**: 14.4 / 2.54 m
- **Plasma volume**: 1880 m³
- **Fusion power**: 3 GW
- **Neutron wall load**: 1.5 MW/m²
- **Average beta**: 5 %

**What kind of superconductor should we use?**
LHD Superconducting Magnet System

Helical Coils
- Conductor current: 13 kA
- Magnetic field: 6.9 T
- NbTi/Cu Rutherford, Al-stabilized
- Pool-cooled by liquid helium
- Temp. 4.4 K \( \Rightarrow \) 3.8 K (subcooled)

Poloidal Coils
- Conductor current: 31.3 kA
- Magnetic field: 5 T
- NbTi/Cu Cable-in-Conduit
- Force-cooled by supercritical helium
- Temp. 4.5 K

Dimensions:
- Helical Coils: 18 mm
- Poloidal Coils: 27.5 mm
Cable-in-Conduit (CIC) Conductors for ITER

- **Well established and current standard for fusion magnet**
- **High cryogenic stability by internal cooling with supercritical helium**
- **High mechanical and electrical rigidity**
- **Complicated plumbing (worry of leakage) and limited conductor length**
- **Degradation by repetitive excitation**

**TF Conductor**

- **Nb$_3$Sn**
- **68 kA, 11.8 T**

**CS Conductor**

- **Nb$_3$Sn**
- **40 kA, 13 T**
Helical Coil Winding with Nb₃Al CIC Conductor

S. Imagawa

(1) CIC conductors are heat treated in a “reel” and transferred to a “spool” with a same diameter
(2) Conductor is extracted and formed into a helical shape and imbedded into grooves of the internal plate
(3) Conductors are wound in 5 parallel paths (the cooling path <500 m)
(4) Complicated layout for plumbing of supercritical helium and joints
(5) Huge winding machine is required
Strain due to helical winding with LTS

Strain due to the difference of thermal contraction between strands and jacket: ~0.7%

Torsional strain during the helical winding:
ave. ~0.3%, max. ~0.6%

100 kA
Conductor

Reel of winding machine (R=5.71 m)
Bobbin for heating (R=5.71 m)

S. Imagawa et al., Nucl. Fusion 49 (2009) 075017

Copper Oxide High-Temperature Superconductors (HTS)

Bismuth-based 1st generation HTS (Bi-2212, Bi-2223)

Rare Earth-based 2nd generation HTS (REBCO) (Coated Conductor)

Critical Temperature (K)

Year

Critical Current Density (A/mm²)

Magnetic Field (T)

77 K: Liquid Nitrogen
Characteristics of HTS Conductors

(1) High critical current density up to high magnetic field

(2) High cryogenic stability by thermal capacity of metals at 20-30 K

(3) Low cryogenic power

(4) Mechanically strong with REBCO tapes 
   Hastelloy substrate (>1 GPa rigidity) + stainless-steel (or Al-alloy) jacket w/o. void

(5) Industrial production of HTS tapes (Bi-2223 and REBCO) for electrical power applications (transformers, power cables, SMES, motors, etc.)

(6) Beneficial for the preservation of helium resources

(7) Robust against neutron irradiation

Stability Margin
(Allowable Disturbance)

\[ \Delta Q < C_p \rho \Delta T \]

\[ C_p \rho \Delta T \approx 2 \times 10^5 \text{ (J/m}^3\text{K)} \times 10 \text{ (K)} \]

\approx 2 \text{ (J/cc)}

Larger stability margin than CICC

\(\Rightarrow\) Lower probability of coil quench!
Tokamak Reactor Design by HTS (~2000)

ARIES-AT (USA)

VECTOR (JAEA)

Bi-2212

T. Ando, S. Nishio, T. Isono 10/23
Application of HTS for Fusion

RT Project at Univ. of Tokyo

Mini-RT (2003)
HTS floating coil with Bi-2223
\[ \tau \sim 40 \text{ hrs} \]

Mini-RT/Y (2012)
HTS floating coil with GdBCO
\[ \tau \sim 230 \text{ hrs} \]

RT-1 (2006)
HTS floating coil with Bi-2223
Discussion for Large-Current HTS Conductor (1)

Basics for LTS conductors

- Multi-filamentary strands
- Transposition of strands
- Twisting of strands

Conductor design with HTS tapes (Present trend in EU and US)

- Subdivision of HTS tape
- Transposition by “Roebel”
- Twisting by “Twist-stack” or “Conductor On Round Core (CORC)”

Images: Val Fishman, MIT
**Is simple-stacking of HTS tapes available?**

- Non-uniform current distribution among tapes can be allowed due to high cryogenic stability (especially for DC magnets)
- AC losses are accepted (especially for DC magnets)
- Adjustment of tape orientation ($B$ parallel to ab-axis) gives high critical current and low AC losses
- Mechanically strong
- Low cost
- Low joint resistance
- Roebel structure could be included at joints on demand by “Roebel-MITO”

**Discussion for Large-Current HTS Conductor (2)**

- Subdivision
- Roebel
- Twist-stack and CORC

- Complicated production method
- Critical current degradation by anisotropy ($B$ parallel to c-axis)
- Mechanically weak
- High cost

10 kA class HTS conductor w. Bi-2223 tapes & Cu jacket
NIFS (2005)
100 kA-Class HTS Conductor Design for FFHR

- Superconductor: YBCO
- Conductor size: φ55 mm
- Operation current: 100 kA
- Maximum field: ~13 T
- Operation temperature: > 20 K
- Current density: ~40 A/mm²
- Number of HTS tapes: 39
- Cabling method: Simple-stacking
- Outer jacket: Stainless-steel or Al-alloy
- Cooling method: Indirect-cooling
Segmented Fabrication of Helical Coils with HTS

- **Concept of Demountable Helical Coils**
  
  K. Uo, 14th SOFT (1986)
  
  Huge helical coils can be fabricated  
  *Too large joule heating at 4 K with LTS…*

- **Renewal of the Concept with HTS**
  
  
  Joule heating accepted for HTS @ >20 K (~3 MW @ R.T.)  
  *Difficulty of connection of whole coil segments…*

- **Segmented Winding of HTS Conductors**
  
  N. Yanagi, Fusion Technology (2011)
  
  Engineering feasibility of connection of segmented HTS conductors with low joint resistance
Segmented Fabrication of Helical Coils with HTS

**Bridge-type joint**
- Joint resistivity: $1 \times 10^{-11} \, \Omega \, m^2$
- Resistance for one joint: $1 \, n\Omega$
- Number of joints: 8000
- Joule heating with 100 kA: 80 kW
- Electrical power: 5 MW

**Finger-type joint**
- Joint resistivity: $1 \times 10^{-11} \, \Omega \, m^2$
- Resistance for one joint: $0.1 \, n\Omega$
- Number of joints: 8000
- Joule heating with 100 kA: 8 kW
- Electrical power: $\sim 0.5$ MW
30 kA-Class HTS Conductor Test
Collaboration between NIFS and Tohoku Univ.

- **GdBCO tapes**
  - Fujikura, FYSC-SC10
  - Width: 10 mm, Thickness: 0.22 mm
  - Critical current: ~650 A @77 K, self-field
  - IBAD + PLD

- Simple stacking of 20 GdBCO tapes in a copper jacket
- Stainless-steel jacket for mechanical support
- FRP jacket for thermal insulation
HTS Conductor Sample (Short-Circuit Type)

Excitation by the change of bias field
Large current (> 100 kA)
Low heat load without current leads
Transient excitation by joint resistance

Self-inductance of the sample coil : 2.21 μH
Mutual inductance with split coils : 411 μH

\[
\phi = L_S I_S = MI_C
\]

\[
I_S = \frac{M}{L_S} I_C
\]
Conductor Joint

- Mechanical “bridge-type” joint developed by S. Ito at Tohoku Univ.
- Indium foils between HTS
- Titanium bolts for tight connection (6 Nm for 30 MPa)

Expected joint resistivity: 110 nΩ/cm²
Contact area:
~ 2.8 cm × 1 cm × 10 layers × 2 rows = 56 cm²
Joint resistance for two joint parts ~ 4 nΩ

Expected decay time constant of current:

\[
\frac{L_S}{R} = \frac{2.2 \times 10^{-6}}{4 \times 10^{-9}} = 550 \text{ (s)}
\]
Excitation Test Result #1
(Measurement of Critical Current @20 K)

Quenched at ~40 kA @20 K and 6 T

20 K, ~6 T

Critical current reached…
(Analysis being conducted including self-field effect and redistribution of current)
Excitation Test Result #2
(Trial of Large Current Excitation @4 K)

Quench occurred at the joint part...

Improvement of joint and 2nd test
(March 2013)
⇒ 100 kA @ 4 K, 2 T ...

Joule Heating
Joint #1 : ~ 5 W
Joint #2 : ~ 40 W
Problem with the Joint and Improvement

Improvement of joint

- Joint length: 620 mm → 860 mm
- Step length: 30 mm → 40 mm (to avoid overlapping)
- SS jacket: 10 mm thick, flat → 20 mm thick, 𓏧 shape
- Bolts: Ti-alloy, φ4 mm, 25 mm pitch → SS, φ6 mm, 15 mm pitch
- Cu jacket: one piece, side walls disconnected → two pieces, side walls connected
- Work: done by NIFS → by Tohoku Univ.
Summary

• Helical DEMO reactor is being designed

• HTS option seems feasible owing to the rapid progress of YBCO production technology

• Simple stacking of YBCO tapes: mechanically strong, low cost, low joint resistance, suitable for DC magnets

• Segmented conductors with joints can be a promising method to construct huge & continuous helical coils

• 40 kA @20 K, 6 T has been successfully attained by GdBCO HTS conductor (collaboration of NIFS & Tohoku Univ.)

• 100 kA @4 K, 2 T will be tried in March 2013

• 100 kA @20 K, 6 T will be tested in January 2014
  100 kA @20 K, 13 T is being planned to be tested in 3 years
  100 kA @20 K, 13 T R&D coil is being planned to be tested in 5 years