Innovative fabrication method of superconducting magnets using high $T_c$ superconductors with joints (for huge and/or complicated coils)

Nagato YANAGI
LHD & FFHR Group
National Institute for Fusion Science, Toki, Japan

HTS$^4$Fusion Conductor Workshop
May 26, 2011
The Large Helical Device (LHD)

- Outer 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 tons

World largest superconducting fusion system

- Magnetic energy: ~0.9 GJ
- Cryogenic mass: 850 tons
- Tolerance: < 2 mm
**Heliotron Magnetic Configuration**

- Belongs to the stellarator family
- Proposed by Koji Uo at Kyoto University in 1958
- Continuous helical coils generate rotational transform
  = no net toroidal plasma current
    - Intrinsically steady-state (no need for current drive)
    - No disruption
- Other favorable features
  - Large surface area ➔ low neutron wall load and heat flux
  - Built-in helical divertors ➔ robust and protected
Vacuum Magnetic Surfaces of FFHR-2m2

- Neutron wall load $<1.5 \text{ MW/m}^2$
- Divertor tiles are protected by blankets from direct irradiation of neutrons
- Strike point sweeping reduces the divertor heat flux $<1 \text{ MW/m}^2$
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)
- Diameter: 18 mm

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
- Diameter: 27.5 mm
Heliotron-Type Fusion Reactor FFHR

Main Parameters of FFHR-2m2 (Commercial Reactor)

- Major radius of HC: 17.0 m
- Minor radius of HC: 4.08 m
- Helical pitch parameter: 1.20
- Toroidal field: 5.1 T
- Maximum field: ~12 T
- Stored magnetic energy: 160 GJ
- Conductor current: ~100 kA
- Plasma volume: 1970 m$^3$
- Fusion power: 3 GW
- Neutron wall load: 1.5 MW/m$^2$
- Average beta: 5.6%

Options for Conductor Type and Cooling Method

- CICC (force-cooled) ➔ LTS = Ext. of ITER Technology
- Solid (indirectly cooled) ➔ LTS

Options for SC Materials

- LTS ➔ Nb$_3$Al, Nb$_3$Sn
- HTS ➔ YBCO

HTS
HTS Conductor Design for FFHR

Major Specifications of HTS Conductor

- **Superconductor**: YBCO or GdBCO
- **Conductor size**: 60 mm × 40 mm or φ50 mm
- **Operation current**: ~100 kA
- **Maximum field**: ~13 T
- **Operation temperature**: ~20 K
- **Current density**: ~40 A/mm²
- **Number of HTS tapes**: ~40
- **Bending strain**: ~0%
- **Cabling method**: Simple-stacking or Transposed-type
- **Outer jacket**: Stainless-steel or Aluminum-alloy
- **Cooling method**: Indirect-cooling
Application of HTS to Fusion Machines
RT Devices at Univ. of Tokyo

Mini-RT

HTS floating coils wound with Bi-2223
HTS wires

RT-1
Advantages of HTS Option

- High stability at elevated temperature (e.g. 20 K)
- Higher current density
- Stronger winding pack with YBCO substrate
- No need to use liquid helium (good for helium resources)
- Lower refrigeration power
- Segmented fabrication of huge and/or complicated magnets
- Cold test of conductor pieces

Issues for HTS Option

- Lower mechanical strength of structures ➔ ~5% at 20 K
- Cost for wires ➔ Competitive with Nb₃Al by mass production
- Difficult to make transpositions with tapes ➔ Roebel-type
- Quench detection and protection ➔ Should be studied carefully
- Cooling techniques ➔ Innovative method (LNe, heat pipes)
Superconductor YBCO & GdBCO
Conductor size 13.0 mm × 7.5 mm
Critical current of a tape (@77 K, s.f., 10 mm wide) ~200 A ➞ 1000 A
Width / thickness of a tape 10 mm / 0.1 mm
Thickness of REBCO layers ~1 μm
Number of HTS tapes 16

Critical current at 20 K, 8T 15 kA ➞ > 75 kA
Stability margin ~40 J/cc
Segmented Fabrication of Helical Coils (1)

- Winding of LHD helical coils (w. continuous conductors & big winding machine)

Concept of demountable helical coils

K. Uo et al., Proc. 14th SOFT (1986) 1727

“Renewal of the idea with HTS conductors”

“Easiness of winding (demountability is not necessary…”
Mechanical Butt Joint of BSCCO Conductor
(S. Itoh and H. Hashizume, Tohoku Univ.)

Mechanical butt joint
(Demountable electrical butt joint)

10-layer stacked BSCCO conductor
(without jacket)

10-layer stacked BSCCO conductor with copper jacket

Joint resistance in mechanical butt joint of BSCCO conductors

Demountable solenoid coil
(5-layer stacked BSCCO conductor, 2 turns, 4 joints)
Mechanical Butt Joint of ReBCO Conductors
(S. Itoh and H. Hashizume, Tohoku Univ.)

Polishing process of joint surface
#400 → #600 → #800 → #1200 → #1500 (Using grinding wheel)

Joint condition
Dry joint: The cables are jointed directly.

To reduce joint resistance for ReBCO conductors...
- Using ReBCO tapes having copper layer to make current path at joint region

4 layered GdBCO conductor
(GdBCO tapes have no copper layer)
Segmented Fabrication of Helical Coils (2)

- Segmented fabrication with entire half-pitch segments of helical coils having ~400 turns and joints (in simultaneous work) may not be possible.
- However, segmented fabrication of conductors may be feasible.
- Thus, ~8000 pieces of half-pitch conductors preformed into helical shapes will be fabricated, installed into helical coil cans and jointed.
- The jointing work will be done by soldering and welding.
Joint resistance evaluated for a 50 mm tape: ~6 nΩ (~31 nΩ cm²)
Joint resistance for a 100 kA conductor: ~0.3 nΩ
Number of joints: ~8000
Required power for 20 K cooling: ~1.5 MW (@ R.T.)
Low-Resistance Joint for the NbTi/Cu Conductors in the LHD Helical Coils

36 joints in the LHD helical coils ➔ ~8000 joints for FFHR
(Re) Evaluation of Joint Resistance of Single YBCO Tapes w. Cu Lamination

4.3 mm wide w. copper lamination (both sides)
Measurement of Joint Resistance of Single YBCO Tapes with Cu Lamination

Joint Sample (single cable, Cu to Cu)

- 96.7 nΩ
- (41.6 nΩ cm²)

Cu side to Cu side

Joint Sample (single cable, substrate to substrate)

- 4.44 μΩ
- (1.91 μΩ cm²)

Substrate side to substrate side
Measurement of Joint Resistance of 10-kA Class YBCO Conductors
Measurement of Joint Resistance of 10-kA Class YBCO Conductors (in LN2 first)

- 3 times higher than expected from single tape measurement
- ≈4.5 MW
- Accepted but could be further reduced
Segmented fabrication of “complicated” coils using joints

Central solenoids of Spherical Tokamaks interlinked with TF coils

Poloidal coils could be installed after the completion of helical coils or in parallel
Demountable TF Coils for In-Vessel Maintenance

VULCAN (D. Whyte, MIT)

HTS cables
Structure/Cooling surface

Pressure (either pneumatically or mechanical)

Courtesy of L. Bromberg, MIT
Instead of punching YBCO tapes, meandering structure is formed by jointing tapes

- installed on demand for uniform current dist.
- could be a quasi-superconductor (locally)
  (joule heating < nuclear heating, AC losses)

“Roebel-MITO” Conductor
(Meandering with Inter-Transposition Optimization)
Resistance of internal joints: \( \sim 22 \text{ n}\Omega / 1.2 \text{ m} \)

Good agreement with prediction (\( \sim 24 \text{ n}\Omega / 1.2 \text{ m} \)) by single tape measurements
Summary

- Conceptual design studies on the heliotron-type fusion reactor FFHR are being carried out at NIFS
- HTS could be a counter option to LTS
- Innovative fabrication method using HTS conductors with joints may be applied to huge and complicated coils
- Joint resistance is measured with single-tape samples and 10 kA-class conductor samples
- 100 kA-class conductor and joint will be fabricated and tested (next year...)

25/25