Design, construction and test of reduced insulation Nb_3Sn coils for fusion applications

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Background

Neutron radiation damage to organic insulation in the coil winding pack is a critical issue for the next step fusion reactors where orders of magnitude higher neutron fluence than that in ITER are expected. On the other hand, slow current charging time is an issue in a fully non-insulation coils for fusion. We present design, construction and cryogenic testing of mid-level field PPPL in-house built Nb_3Sn solenoid coils with a new design of significantly reduced organic insulation in the coil winding pack. Coil performance and behavior during current charging and discharging is investigated for magnetic flux swing needed from the FNSF CS magnet design.

Objectives

- New simplified construction of radiation tolerant superconducting solenoid coils with ITER wire, and reduced insulation but better structural reinforcement.
- Investigate coils of simplified fabrication (without VPI) to improve ***winding pack current density*** while subsequent lower cost and enhance radiation resistance.

Conclusion

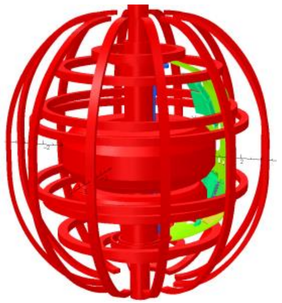
- A new design of irradiation tolerant Nb_3Sn coils of reduced insulation and simplified fabrication process has been realized.
- The reduced insulation Nb_3Sn coil fabricated at PPPL was successfully test at University of Geneva high field magnet facility.
- Nb_3Sn coils of simplified fabrication process (without expensive vacuum pressurized impregnation) reached up to 85% wire critical current limit, and subsequently reduced cost while maintaining coil structural integrity when energized.
- The overall current density in the coil winding pack is over 1000 A/mm^2 under coil self field of ~3 T.
- Simplifying fabrication process is critical to significantly reduce cost of non-fusion applications such as NMR and MRI magnets. Test results showed that PPPL in-house built Nb_3Sn coils with reduced insulation while improving performance with increased coil winding pack current density and structural integrity.

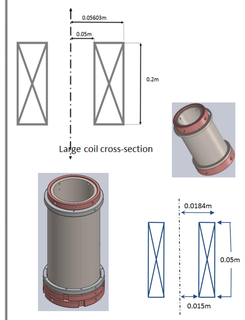
Methods

Integrating magnet design with physics

PPPL is currently leading the design studies for the next-step fusion devices based on the most promising magnetic configurations. Superconducting fusion magnets with high current density are particularly beneficial for low aspect ratio "spherical" tokamaks and the compact stellarators.

To integrate magnet design with burning plasma physics for fusion energy beyond ITER, a clear strategy with focused effort on targeted R&D activities is needed.





Coil Design

	Inductance (mH)	Current (A)	Energy (J)	B Field (T)	Quench Temp. (K)
Mini-coil	0.4	500	45	1.6	54
Large coil	65	500	7932	6.5	125

Coil insulation scheme variants:

- Large coil – 120 mm diameter and 250 mm height (5 layers) – no turn to turn insulation for high WP density
- Mini coil – 35 mm diameter and 50-60 mm height (3 layers , ~130 turns)

Large coils without turn to turn insulation but small coils with various insulation schemes were fabricated and tested.

Samples

Coil Winding

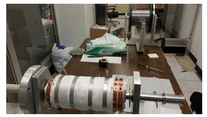
- **Winding approach:**
Coils are wound by a hand winder on a steel coil form under 5 pounds winding tension using bare Nb_3Sn wire (US ITER TF conductor wire from Luvata) no glass sleeve on wire as in convention process

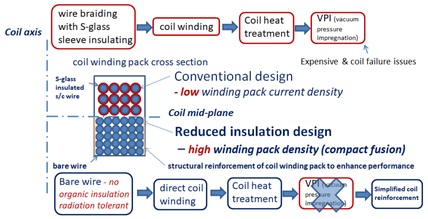
- **Coil insulation:**
No turn to turn insulation but one layer of S-glass cloth was applied between layers

- **Tension control:**
Uniform tension during winding applied by weight

Simplified Coil Fabrication Process

Simplified coil construction process significantly reduced fabrication cost while improving radiation resistance. However, novel structural reinforcement is needed in the design to ensure structural integrity at higher magnetic field.

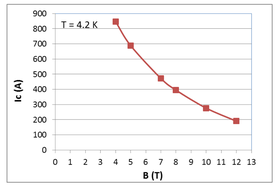


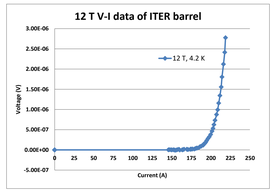


Large coils of over 1100 number of turns with no turn insulation were fabrication in addition to the small coils. Large coils will be tested this fall to validate scalability of the coil design. Additional external reinforcement may be needed for the large coils to reach over 5-6 T magnetic field.

Results

Wire Characterization and Coil Heat Treatment





Field (T)	Ic (A)	n-value
12	190	23
10	276	23
8	395	24
7	472	24
5	688	26
4	846	29

Use 0.1 μV/cm criteria for I_c. N values are obtained from linear fit of log-log plot of data between 0.1 μV/cm and 1 μV/cm.

Two pair of voltage taps 50 cm and 25 cm respectively, data from 50 cm V tap is reported.

Courtesy of J. Lu from NHMFL

US ITER supplied the Luvata Nb_3Sn wires (over thousand pounds leftover wires) for PPPL in-house coil fabrication. Wire critical current characterization was confirmed by testing performed at NHMFL. (J. Lu)

Critical current achieved ~200 A at (4.2 K, 12 T). 500 A needed for a large coil to reach >5 T (<0.1% axial strain)

1) Heater power on, vacuum @ 5.0E-5 torr
2) Back-fill furnace with high purity argon to 350 militorr
3) Ramp @ 3oC/min to 210oC
4) Soak @ 210oC for 50hrs
5) Ramp @ 3oC/min to 340oC
6) Soak @ 340oC for 25hrs
7) Ramp @ 3oC/min to 450oC
8) Soak @ 450oC for 25hrs
9) Ramp @ 3oC/min to 575oC
10) Soak @ 575oC for 100hrs
11) Ramp @3oC/min to 650oC
12) Soak @650oC for 100hrs
13) Ramp @ 3oC/min to 500oC
14) Heater power off, argon purge off
15) Evacuate to high vacuum
16) Furnace cool to ambient.

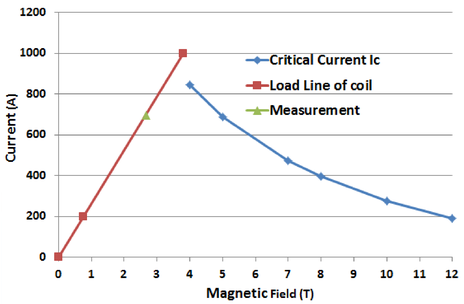
Coils went through standard heat treatment from ITER specification in the PPPL vacuum brazing furnace. Tin leak was found in one of the small coils.

Structural reinforcement (clamping rings) is applied on exterior of coil winding pack (remove the VPI process) to ensure compactness and structural integrity of winding pack while improving overall winding pack current density.

Coil Performance in Current Ramp Test

Current ramp up to ~300 A; Field reached ~ 1 T (0.9 T)

Coil cryogenic test performed at PPPL indicated better control of current ramp and monitor of quench voltage is needed for the reduced insulation coils.



Further tests of the no-insulation coils at University of Geneva with better control of current ramp rate (<1 A/s) showed excellent coil performance.

No-insulation coil reached ~700 A in current ramp and generated ~3 T field at coil central bore.

Presented at the 25th International Conference on Magnet Technology, 2017 Aug. 28 – 31, Amsterdam, The Netherlands; Session: Superconducting Magnets for Fusion; Program I.D. number: Thu-Af-Po4-1170