Progress on 25 T Design and Subscale Coil Tests with Bi-2212 Inserts

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OVERVIEW

- Cryomagnetics received a 2018 DOE STTR Phase I and a 2019 DOE STTR Phase II award to design a viable 25 T all superconducting magnet using an 8 T Bi-2212 insert inside of a 17 T LTS background coil, suitable for commercial use.

- The 17 T background coil is based on a magnet already built by Cryomagnetics, currently in the field at a customer site.

- Cryomagnetics is collaborating with the team at ASC to design the 25 T.

- Two subscale coils have been built for preliminary testing, another is currently under construction, and more are planned for the near future.
25 T All Superconducting Magnet

- 25 T design consists of
  - 8-Tesla Bi-2212 insert
  - Three Nb3Sn coils generating 2-3 Tesla each
  - NbTi coil generating 9 Tesla

- Cold bore of 40 mm

- Quench protected and strain mitigated
Bi-2212 Wire

- 0.8 mm wire appears to be the smallest diameter wire that can be presently trusted to perform reliably.
- Even so, 0.8 mm wire has mostly been used in Rutherford cables, where single-strand defects are not as critical as they are in a solenoid configuration.
- Solenoids made by ASC typically consist of >1.0 mm wire.
- While the initial 25 T design will use separate power supplies for the HTS and LTS portions, one goal of Cryomagnetics is to have a series-connected system, so small diameter wire is desirable.
Bi-2212 Wire

- Y. Huang at Bruker-OST provided data that shows that the Bi-2212 filament diameter stays at a consistent 15 μm over a wide range of wire diameters, including down to 0.8 mm.
- However, as mentioned, a single serious wire defect will render an entire solenoid unusable.
- 0.8- and 0.9-mm subscale coils were made and tested, and a 1.0 mm coil is currently under construction, all produce ~5 T.
- The subscale coils are small (~20 mm bore, ~4 cm length) and are used to characterize the performance of the Bi-2212 wire to aid us in the design of the 25 T magnet.
Subscale Coil Design

- Two subscale Bi-2212 coils, one with 0.8 mm wire, and one with 0.9 mm wire, were created in collaboration between Cryomagnetics and ASC.

- The 0.8- and 0.9-mm coils are complete, and were tested in a 13 T background coil at Cryomagnetics, and a 14 T background coil at ASC.

- A 1.0-mm subscale coil is underway, testing expected later this year.
0.9 mm Subscale Coil Design

- The design has both $J_E$ and strain within safe margins
  - $< 800 \text{ A/mm}^2$ @ 18 T
  - $< 0.4 \%$ peak strain
Test results for 0.8 mm coil

Test summary, 0.8 mm coil

- Coil tests
- Short sample tests
- Lead in/lead out tests
- Witness sample test (1.0 mm wire)
- Best result to date of NHMFL tests (0.8 mm wire)
Test results for 0.9 mm coil
Full subscale coil results

0.8 mm and 0.9 mm coil test results

- 0.8 mm coil test
- 0.9 mm coil test at Cryomagnetics
- 0.9 mm coil test at NHMFL
The background magnet was charged to a range of field levels (5-12 Tesla) and the Bi-2212 coil was charged until a voltage was detected, when a dump resistor was switched in.

The power supply we used on the Bi-2212 runs (not a Cryomagnetics supply) did not allow precise control over the ramping rate, so consistency was challenging.

One of the Bi-2212 quenches (at 8 T background) caused the LTS magnet to quench, and the Bi-2212 coil survived with no degradation despite significant inductive coupling (i.e. successful passive quench protection).
Why was 0.8 mm coil not tested at Cryomagnetics?

Shipping damage occurred in transit from ASC to Cryomagnetics

Unforeseen surprises are the rule in science, not the exception. –Leonard Susskind
25 T Magnet Design: Strain Considerations

- While there’s a desire to use Bi-2212 wire with the smallest diameter possible, achieving high $J_E$ with moderate currents, and helping to ultimately lead to a series-connected HTS/LTS design, strain mitigation is crucial, and grading will be necessary.
25 T Magnet Design: Strain considerations
Unmitigated strain of existing subscale coils

Strain levels, 0.8 mm and 0.9 mm coils

- 0.8 mm coil
- 0.9 mm coil
- Acceptable level
- Safe level
25 T Magnet Design: $J_E$ considerations

- 0.8 mm wire carries about 930 A/mm² in the 25 T design (short sample limit predicted to be about 1260 A/mm² from P. Lee's 2017 plot)
- Operating at 73% of $J_E$, 96% load line
25 T Magnet Design: $J_E$ considerations

- 1.0 mm wire
  - $J_E = 485 \text{ A/mm}^2$
  - 47% of P. Lee’s 2017 plot, 42% of ASC record sample
  - 61% load line (w.r.t Lee 2017)

- 0.9 mm wire
  - $J_E = 600 \text{ A/mm}^2$ (lower than barrel test results)
  - 52% of Lee 2017 plot, 50% of ASC record sample
  - 67% load line

- 0.8 mm wire
  - $J_E = 760 \text{ A/mm}^2$ (on par with barrel test results)
  - 61% of Lee 2017 plot, 40% of ASC record sample
  - 73% load line
OPHT at ASC
Full Heat Treat
OPHT at ASC
Melting Phase Detail

Zoomed-in Through the Melt

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0.9 mm Subscale Coil—Finished Product
Conclusions

- The $J_E$ values achieved in the 0.8- and 0.9-mm subscale coil tests were low (~1/3 of ideal $J_E$), but we believe we have found and isolated an issue and it will not arise in future coils, including the 1.0 mm subscale coil currently under construction.

- The full-scale 25 T magnet design takes all expertise from ASC, as well as all results from Cryomagnetics’ and ASC’s full battery of tests on the subscale coils, into account.

- Construction of the 25 T magnet will be performed in Year 2 of the STTR period, paving the way for commercial very high field magnets.
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