Challenges and opportunities for HTS accelerator magnets

Some additional considerations and thoughts

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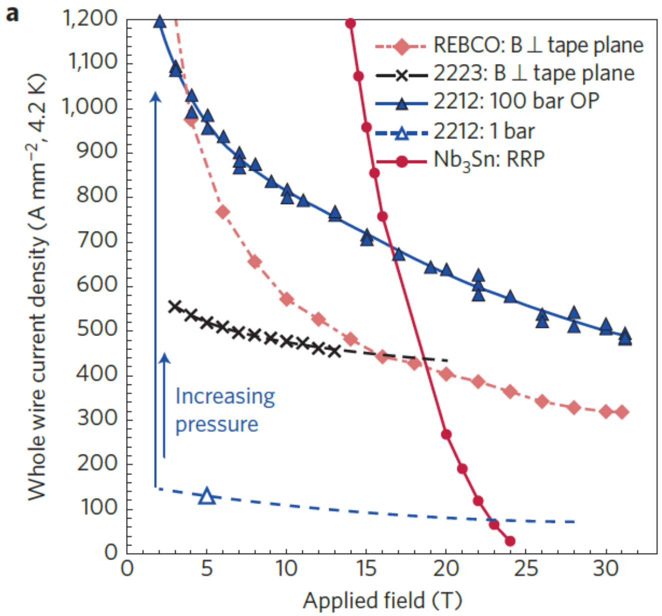
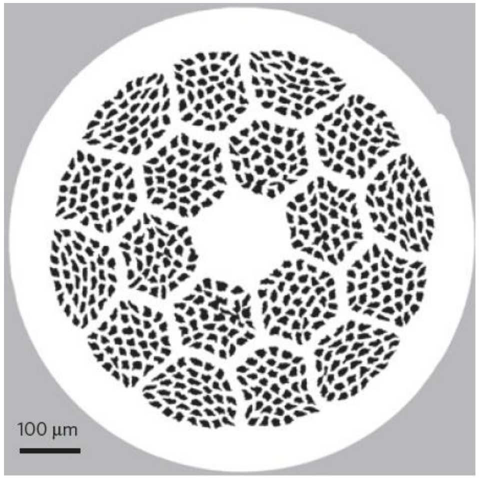
WAMHTS-2

Introduction

- Bi-2212 becomes a practical magnet conductor thanks to the VHFSCM collaboration





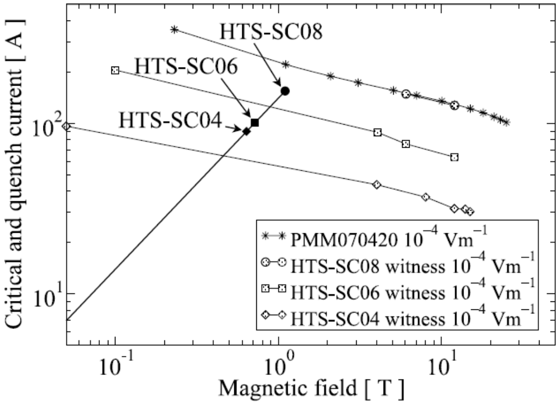
Larbalestier *et al.*, Nature Materials, 2014

- Pressing need to assess the feasibility of a Bi-2212 accelerator insert
- Among many unknowns and challenges, two issues from the magnet standpoint
  - Heat treatment of Bi-2212 accelerator coils
  - Coupling between HTS/LTS components

Develop Bi-2212 accelerator coil technology

- A focus of LBL's magnet program towards high-field accelerator magnets

- A. Godeke and collaborators demonstrated the W&R technology for 2212 accelerator coils [Godeke *et al.*, SUST 2010, Physics Procedia 2012]
  - Quench current reproduced within 10% by two coils of same design and heat treatment schedule (85% of witness sample limit)
  - Most recently, pioneering the Bi-2212 CCT technology [Godeke *et al.*, IEEE TAS 2015] (see also Shlomo's talk)



Overpressure heat treatment of accelerator coils

- Issues observed [Godeke *et al.*, SUST 2010, Physics Procedia 2012]
  - Variation in the I_c data of helical witness samples and short straight samples
  - Limiting segments inconsistent between similar coils
  - Minor leakage

- Issues observed in Bi-2212 solenoid coils [Dalban-Canassy *et al.*, SUST 2012]
  - Leakage
  - Coil performance lower than witness samples

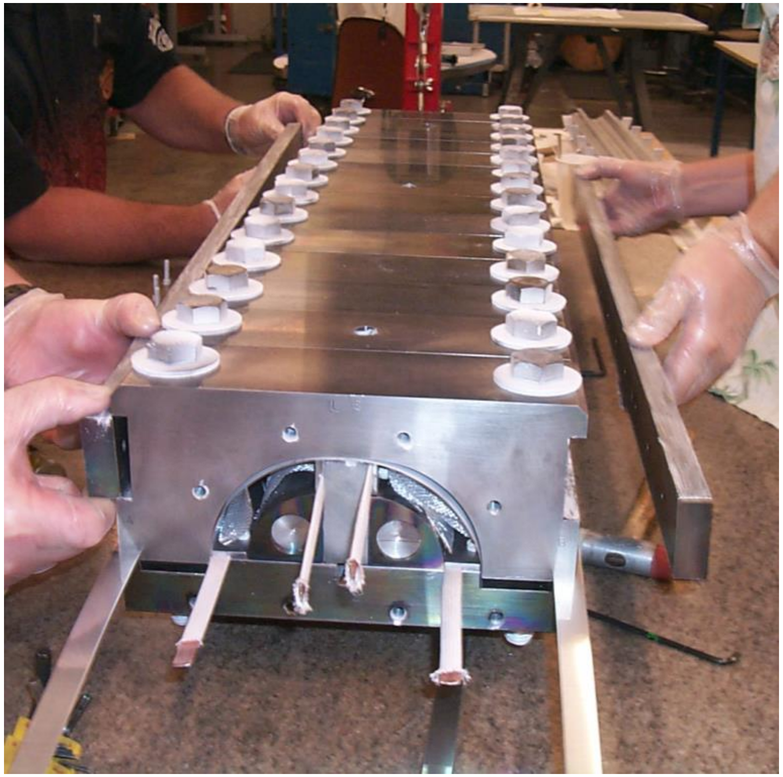
- Gas bubbles contribute to these issues
- Overpressure heat treatment should be applied to accelerator coils
  - Reproducibility is important

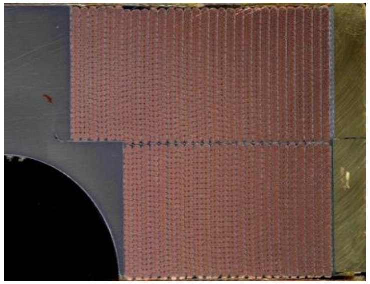
- What can be different from short sample/small coil to larger coils?
- What do we need to know?

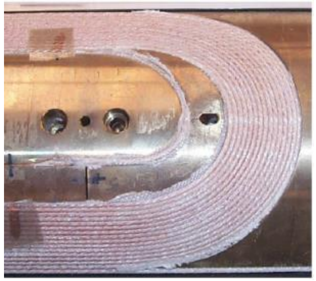
Slower and non-uniform thermal diffusion in large coils

- Longer duration at peak temperature for coil reaction [Dalban-Canassy *et al.*, SUST 2012, Tollestrup FERMILAB-TM-2505-APC, 2011]
- Typical order of magnitude: 1 – 10 m in length, 10 – 100 layers of cables
- Metal structural components and fixtures

Nb_3Sn coils and a Bi-2212 CCT coil

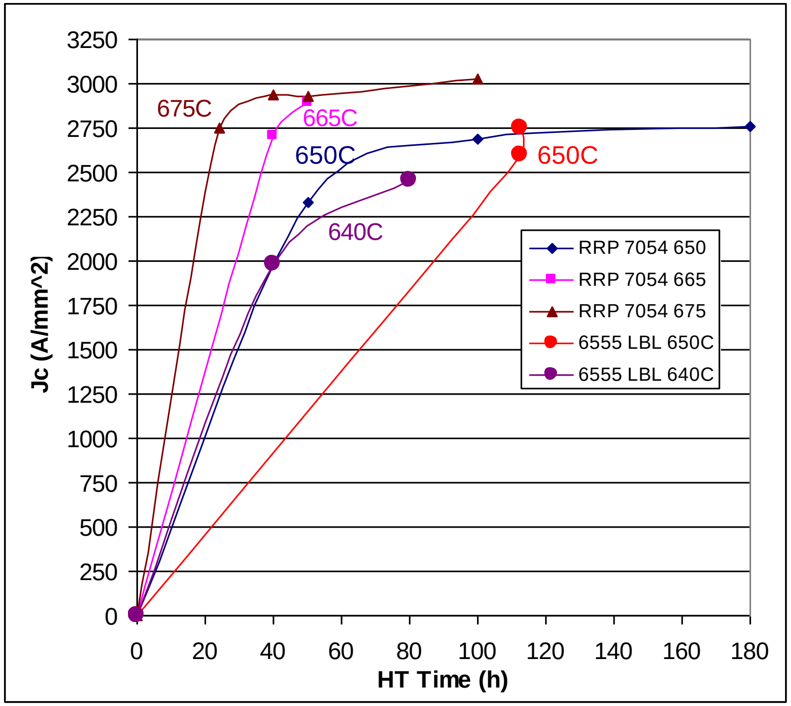






Nb_3Sn accelerator coil case

- Study on RRP strands for LBL HD2 magnet [data courtesy of D. R. Dietderich]
- J_c saturates with increasing duration at reaction temperature

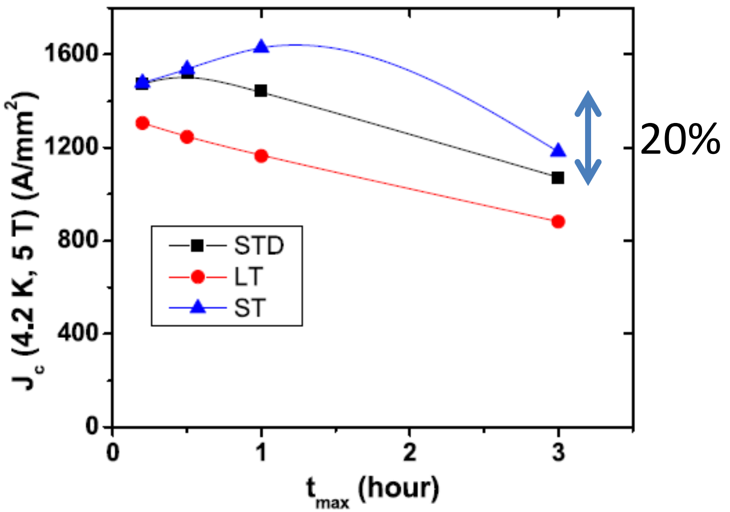


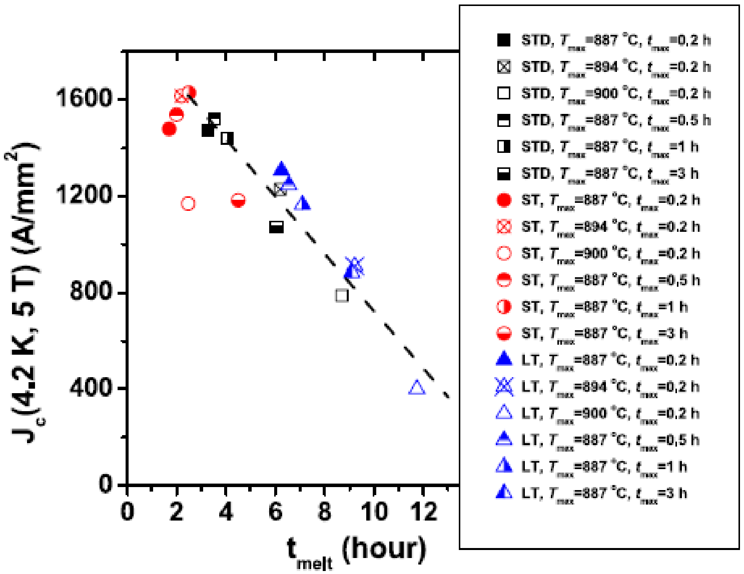
Implications for Nb_3Sn coils:

- Longer heat treatment time allows magnet coils to reach uniform J_c
- We can use the J_c of witness samples to evaluate magnet performance

- How does Bi-2212 conductor behave?

Bi-2212 with bubbles is sensitive to heat treatment schedule





Shen *et al.*, SUST 2011, 115009

- Samples were heat treated at 1 bar. Bubbles play a significant role
- It is critical to know the behavior of a bubble-free Bi-2212 conductor
  - Impact on optimization of coil heat treatment
  - Evaluation and understanding of coil performance

Options to get rid of bubbles

- Are there alternatives to high pressure?
  - High pressure may not be trivial in industrial scale

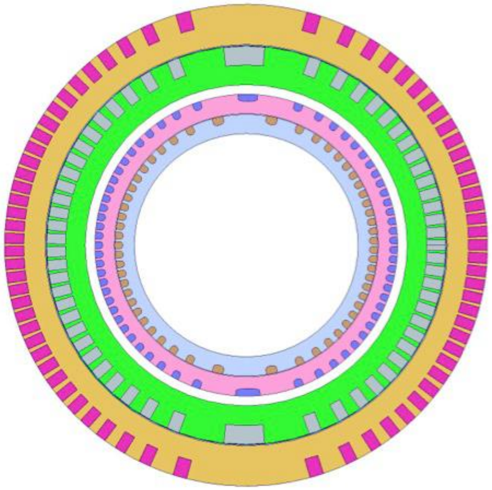
- Cold iso-static process, conductor swaging [Jiang *et al.*, SUST 2011, IEEE TAS 2013]
- Groove-rolling [Malagoli *et al.*, SUST 2014]
- A combination of these alternatives + moderate pressure?
- Gas-X for Bi-2212?

- The over-pressure technique is the first choice
  - Demonstration of Bi-2212 accelerator insert with high field strength is the top priority

- Collaborations with well-defined goals between labs/industries with various expertise/resources to ensure continuous breakthrough (e.g., VHFSCM, BSCCo)

Coupling between HTS/LTS

Impacts of HTS/LTS coupling



- A few examples of coupling
  - J_c and stress margin
  - Quench behavior
    - Coupling simulation [Härö *et al.*, IEEE TAS 2013]
    - Bi-2212: Ag/SC ~ 3
    - Degradation limits
  - Field quality
  - Structure and assembly
- Powering scheme adds one more dimension on complexity (opportunities)
- The coupling/interaction between HTS/LTS impacts the hybrid
  - Performance
  - Design
  - Operation
- Understand HTS insert from a system standpoint from the beginning
  - Measurements can be started with simplified configuration

Sensitivity to transverse stress

- Well defined measurements on strands and cables define the guidelines [A. Godeke and collaborators]

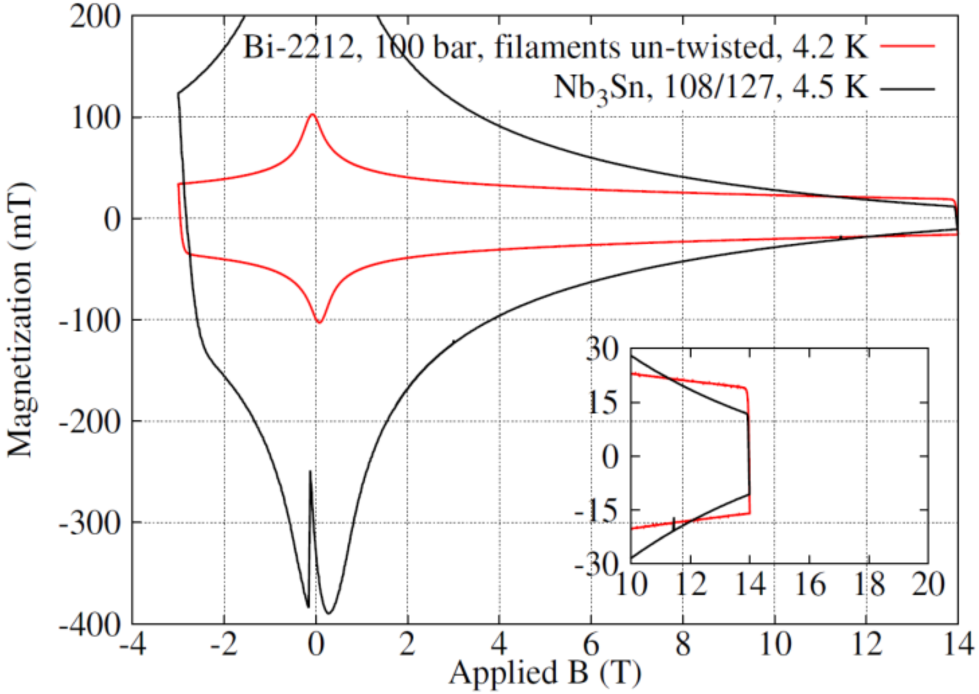
- Magnet test is necessary too
  - LARP Nb_3Sn TQS03, 5% degradation with up to 260 MPa transverse pressure on the cable [Felice *et al*., Performance of a Nb_3Sn Quadrupole Under High Stress, IEEE TAS 2011]

- For Bi-2212, CCT concept is the baseline concept to mitigate the stress accumulation [see Shlomo's talk]
  - Other design concepts should be explored

Field quality

- The HTS insert will likely dominate the field quality as it is next to the magnet aperture
- Geometric effect
  - The alignment between the axes of two dipoles
  - Effect of conductor displacement at high fields
- Magnetization effect (next slide)
- Dynamic effect with small time constant (order of magnitude: 1 ms – 10 s)
  - Necessary to control of inter-strand and inter-filament coupling in the insert
  - No flux jump at 4.2 K
- Dynamic effect with large time constant (decay, and snapback?)
  - Recent results from HTS NMR showed the long term decay [Maeda and Yanagisawa, IEEE TAS, 2014]
- What are the requirements from the beam dynamics?

Magnetization: Bi-2212 vs Nb_3Sn



- Bi-2212 data courtesy of J. Jiang, ASC/NHMFL
- QXF 108/127 Nb_3Sn data courtesy of M. Sumption and X. Xu, OSU

- Applied field perpendicular to the wire axis (no transport current), ramp rate 6 mT/s
- Additional AC contribution in Bi-2212 as filaments are not twisted

- Non-negligible persistent-current effect is expected at high field (collision level)
- Reducing subelement diameter is likely most effective to correct this effect
  - d_{sub} of the sample shown here is about 90 μm (37x18 design), about twice of the Nb_3Sn sample (57 μm)
- No flux jump in Bi-2212 at 4.2 K

Coupling with hybrid solenoid programs

- An excellent knowledge base established on the hybrid solenoid/NMR magnet technology/system
  - Started with resistive insert 50 years ago [Iwasa, Case Studies in Superconducting Magnets, Springer, 2009]
  - Bi-2212 and Bi-2223 tape insert was demonstrated a decade ago; recent focus on YBCO and Bi-2212 round wires [Schwartz *et al.*, IEEE TAS 2008; Weijers *et al.*, 2010; Maeda and Yanagisawa, 2014]

- Hybrid accelerator and NMR magnets are very different but some issues share the same physics
  - Insert technology, coupling/interaction between components, system integration
  - Quench detection and protection
  - Screening current, field stability
  - Measurement/simulation techniques and tools…
  - There are things that we can learn

Summary

- Challenges (opportunities)
  - Bi-2212 accelerator coil technology needs to catch up the significant conductor progress
  - Heat treatment of coils with over pressure
  - Measurements and analysis on the coils

- Plans
  - Heat treat coils with simplified structure
    - Racetrack and CCT coils
  - Understand the sensitivity of bubble-free J_c to the heat treatment parameters
    - Duration at peak temperature
  - Make coils, take measurements and learn

- Outcome
  - An accelerator insert responding to the capability of Bi-2212

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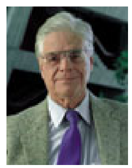
Mar 7, 2000

The magician: Robert Rathbun Wilson 1914-2000



Robert Rathbun Wilson

Bob Wilson was a magician. Take, for example, his creation of Fermilab. This laboratory started as a proposal from the Lawrence

seven years for $300 m
Accelerator Laborator
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it should be built in Ba
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There was one small problem - no such magnet had ever been built. A few superconducting magnets had been used in experiments, but none reaching the stringent requirements of accelerator magnets. Also, one needed not a few but a thousand, very accurately made and highly reliable. Undeterred, he set to work building them. He set up an experimental facility at Fermilab, where he could build a magnet in a few weeks, test it, discover any problems and build an improved version, until he knew how to make them with sufficient accuracy and reliability. He did this himself, with his sleeves rolled up and his hands dirty. Of course, he had talented people working with him, particularly Alvin Tollestrup. It was a