NATIONAL HIGH MAGNETIC FIELD LABORATORY

LTS and HTS super conductor status and future – session 9 comments

David Larbalestier*

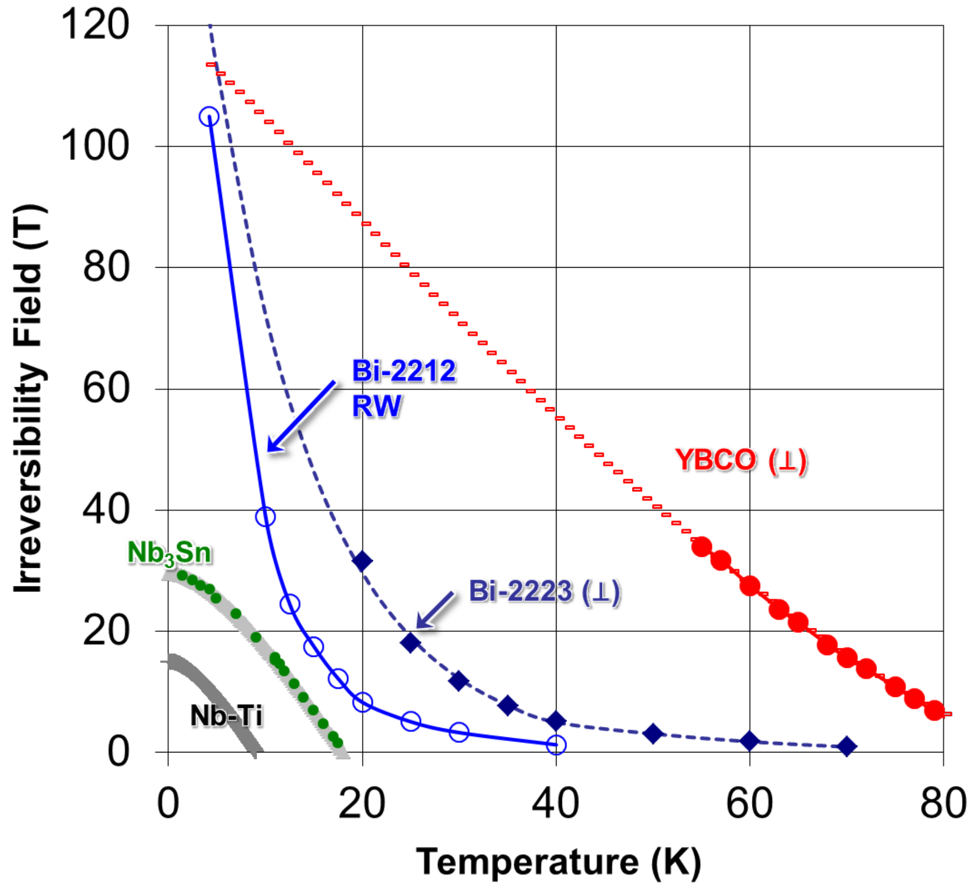
Ultrahigh Field NMR and MRI Workshop

Session 9: Development of LTS and HTS Magnet Technologies in MRI and NMR

November 12-13, 2015

Addendum to my talk in session 1 on November 12, 2015

HTS supplies 3-4x higher H_{c2} or H_{irr}



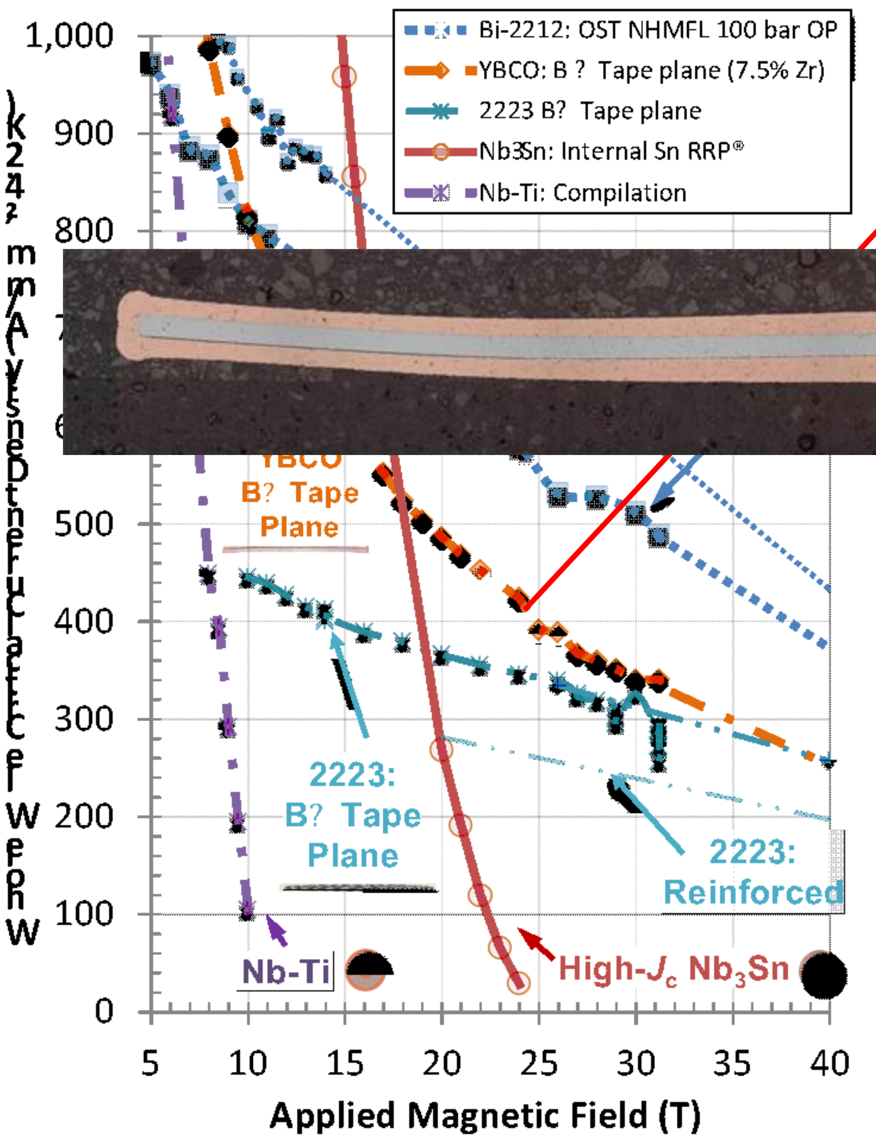
Bruker ready to deliver the 1.2 GHz version with HTS extender, persistent and recondenser cryogen-free starting in 2018.

The H_{c2} limit of Nb_3Sn is swept away!

3-4 GHz now conceivable!

State of the art 1 GHz Nb_3Sn NMR magnet in Lyon. France in persistent state at 23T

Excellent engineering current densities: what further prospects? REBCO



Master plot kept up by Peter Lee

SOME OPPORTUNITIES FOR REBCO

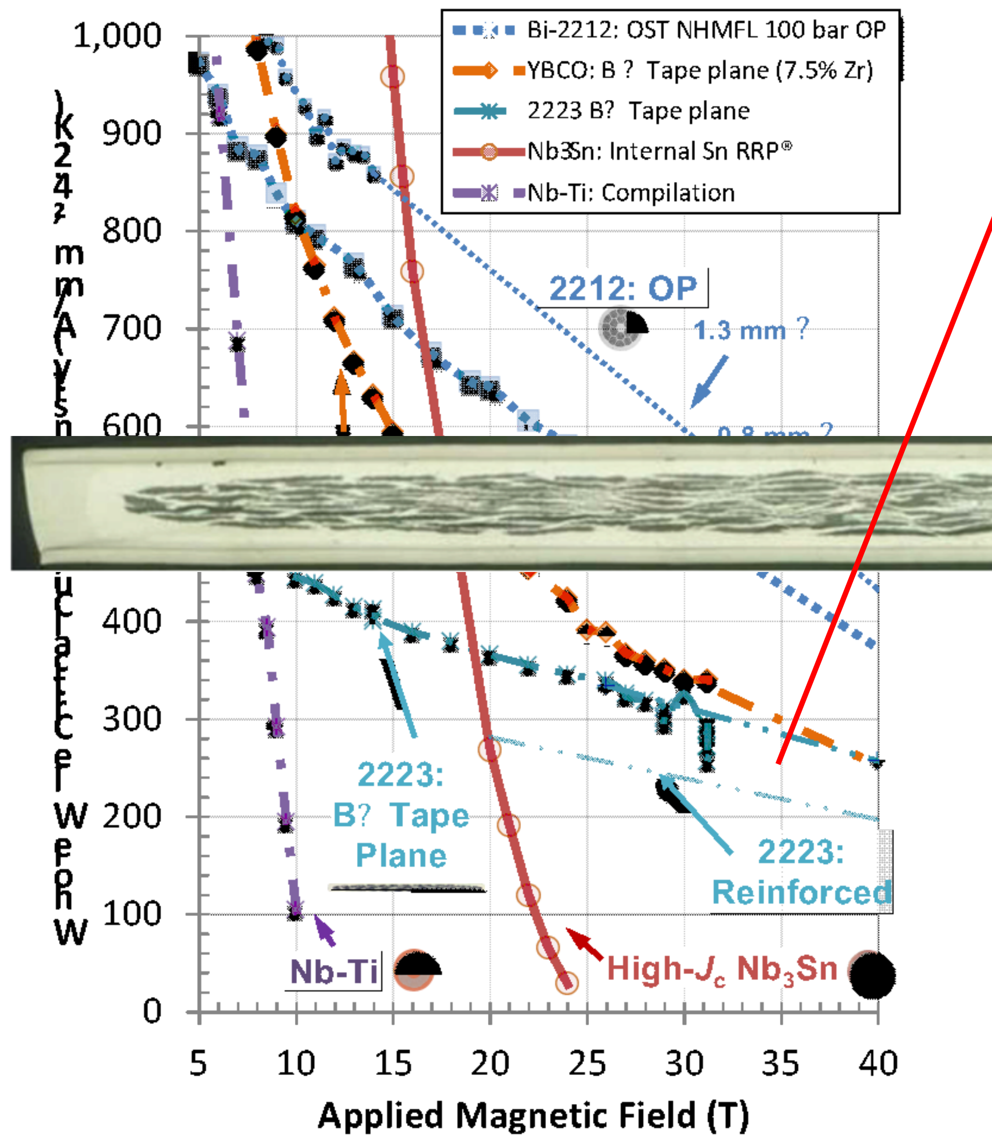
- Huge upside for increase in Je for REBCO if thicker films can be grown – now 1-2 … 0
  … driven by promise of electric utility applications – increasingly uncertain – can magnets support REBCO?
- Wind off the delivery spool – very strong

SOME THREATS FOR REBCO

- Loss of electric utility applications drives companies from the field
- Large magnetizations seriously compromise field quality
- Need for perfection over km lengths cannot be achieved

1 excellent US manufacturer (3-4 others world wide)

Excellent engineering current densities: what further prospects? Bi-2223



Master plot kept up by Peter Lee

SOME OPPORTUNITIES FOR 2223

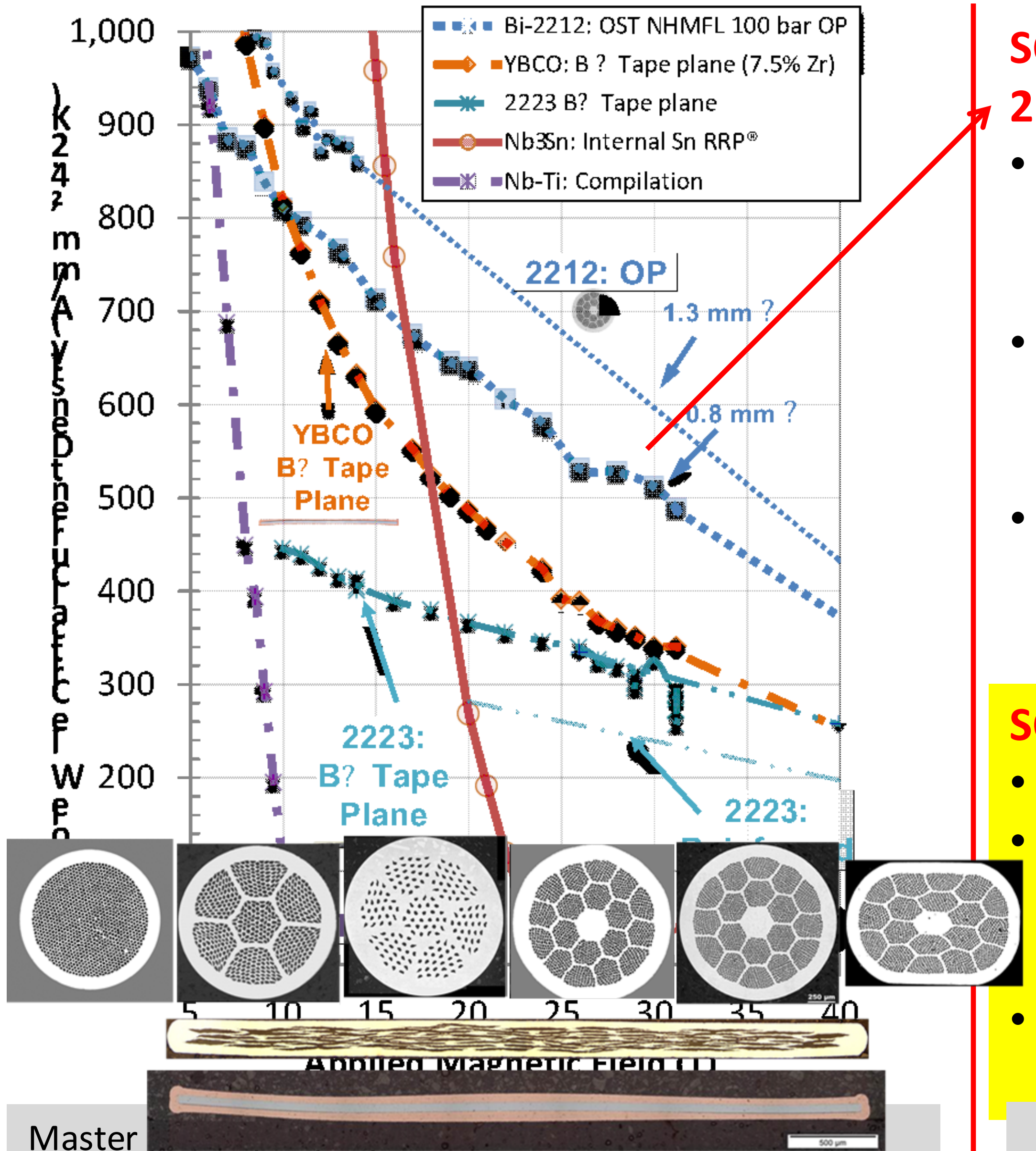
- Strong 2223 (NX) opens up the UHF magnet market – wind direct off the spool
- A new market for UHF magnets prompts fabrication of more versatile

SOME THREATS FOR 2223

- Loss of electric utility applications drives their core business away (2223 often beats out REBCO for utility demonstrations) – why stay in the field for magnets?
- Superconducting performance is mature and needs a refresh
- One size, one Ic(H) does not allow grading

1 excellent Japanese manufacturer only

Excellent engineering current densities: what further prospects? Bi-2212



Master

SOME OPPORTUNITIES FOR ROUND WIRE 2212

- The first round HTS conductor – twisted, filamentary, with excellent stabilizer conductivity
- Made on standard production lines used for Nb-Ti and Nb_3Sn – production flexibility
- Multiple architectures suitable allow graded coils – already at single piece lengths of 2 km at 0.8 mm dia.

SOME THREATS FOR 2212

- Production is easy, utilization is hard
- 50-100 bar overpressure at almost 900 C needed, insulation process too (NHMFL has both capabilities)
- Strengthening expected but may not be practically or economically feasible

1 excellent US manufacturer (easy to replicate)

Key points: conductors

- We have 3 good HTS conductors today – we should use all 3 ASAP to understand their tradeoffs - merits and drawbacks
- No magnet is ever better than its conductor!
- No HTS conductor is yet at Nb-Ti or Nb_3Sn maturity (length, uniformity, cost)
- We have blasted through the H_{c2} limit of Nb_3Sn – more subtle but real limits of stress, quench and cost are present and still challenge us!
- UHF NMR cannot support a major HTS conductor market by itself! (Risk of losing REBCO and 2223)

Conclusions:

We have all-superconducting magnets that have broken the LTS magnet record and a commercial supplier ready to deliver 2018

Let's go hard, go big now (Bruker 1.2 GHz – let's go for 1.4-1.6 GHz as precursor for 2 GHz)

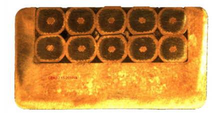
High Field Magnet Technology in the US

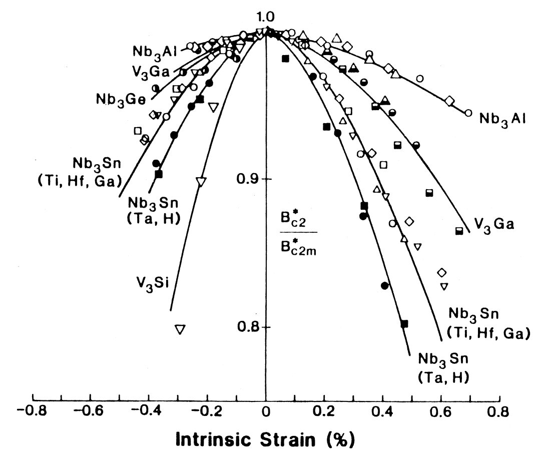
Large Scale, High Field

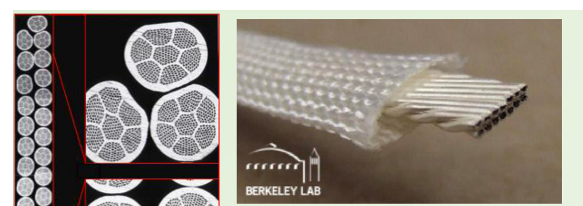
- NHMFL
  - Hybrid magnets
  - SC outsert, 500 mm, 13-14 T
- HEP
  - NbTi dipoles to 9 T
  - Nb3Sn dipoles and quads to ~14 T
  - Bi2212 Rutherford Cable Development
- Fusion
  - 12-13 T, Nb3Sn, bore size of meters
  - REBCO Tape Conductors

Large Bore High Field Technology

- High currents
  - Multistrand (or tape)
  - Resistive joints/terminations?
  - Cryogenic losses in current leads
  - Power supply driven
    - Stability and ripple
- Very High Forces and Stresses
  - Strain limits on superconductor
  - Structure integration with windings
- High Stored Energy
  - Quench detection
  - Quench Protection
- Many unknowns remain in using large scale HTS conductors in large magnets
- R&D should begin now of MRI







Bi-2212 Rutherford cables (Arno Godeke LBNL) with mullite insulation sleeve

Round Table Discussion Session 9:

Development of LTS and HTS Magnet Technologies in MRI and NMR: Roadmap

Science Drivers for Ultrahigh Field NMR

Discussion leader: *T Budinger*
Scribe: *T Polenova*

Discussion of Science Drivers for Ultrahigh Field NMR:

A McDermott

1:30 – 3:15 pm Friday Nov 13

Structural, Molecular, Cell and Chemical Biology:

Understanding and manipulating key players in disease, neuroscience, development, and aging: IMP, amyloids, cytoskel. assemblies, viruses and infectious agents, IDP, immunology and cancer, metabolomics, drug metabolism…..

Materials Science, Energy, and Catalysis, Bioengineering and the Environment:

In situ studies of structure and mechanism : Optimizing new materials, developing strategies for environmental stewardship

Key enabling techniques have a profound effect on the scope of knowledge:

NMR and MRI, New Optical Methods, Xray Diffraction, Cryo EM.

Optimal integration of the techniques leverages each one.

NMR is unique in its integration of dynamical and structural information at a detailed molecular level: "it puts the molecular in molecular sciences." For this a broad range of field strengths is essential.

NMR is powerful because of the scope of conditions that are suitable, including the possibility of in situ and in vivo studies. Many players are expected to have emergent properties in the appropriate environment.

Representative Proteins Relevant Conditions

Image Redacted

TIG March 2000, volume 16, No. 3

Sakakibara, D. *Nature* **458,** 102–105 (2009).

In Situ Materials Science

A Sea Change in NMR at 1.5 GHz:

Most elements/isotopes that are very important for life, for materials, happen to be quadrupolar. The range from ca. 800 to 1.5 GHz will literally transform these components form being invisible to being high value reporters.

Resolution of ^{13}C and ^{15}N in solution and solid state NMR spectra improve significantly from 600 to 800 to 1 GHz. The promise of 1.5 GHz is to bring us to "typical complexity and full- length" Eukaryotic membrane signaling proteins, IDP, amyloids, and high order assemblies can be characterized in terms of structure, binding, allostery, dynamics, and function.

^{1}H spectroscopy of solids is capable of rendering studies of materials and biopolymers much more insightful, with lower limit of detection, faster recording times and more direct probe of chemistry. The quality of ^{1}H SSNMR spectra are dramatically field dependent and are likely to become routinely useful at 1.5 GHz. We can expect that the throughput of the instruments improves considerably when proton recording becomes standard.

Ongoing development suggests that experiments to improve sensitivity through large polarization effects (DNP) are likely to work well at these high magnetic fields.

Quadrupolar Nuclei and UHF

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^{27}Al MAS spectra of aluminoborate
$9Al_2O_3+2B_2O_3$

Transformational role of ultrahigh field: at 40 T, second order quadrupolar broadening and shift are diminished; the line width is mainly due to field drift

Z. Gan et al., *JACS*, 124, 5634 (2002)

^{15}N- detected 2D TROSY of a 70 kDa protein at 800 MHz

Image Redacted

Benefit of UHF in ^{13}C MAS NMR

Image Redacted

11.7, 17.6 and 21.1 Tesla 500, 750, 900 MHz: Resolution in the C-C region increases by 42% for DsbA

High Resolution NMR Spectroscopy of Nanocrystalline Proteins at Ultra-High Magnetic Field
Lindsay J. Sperling, Andrew J. Nieuwkoop, Andrew S. Lipton, Deborah A. Berthold, and Chad M. Rienstra

Benefit of UHF in ^{1}H MAS NMR

Image Redacted

Pintacuda, Emsley et al Angew. Chem. 2012

UHF ¹H MAS NMR: High Throughput

Image Redacted

J Am Chem Soc. 2014 Sep 3; 136(35): 12489–12497.
Published online 2014 Aug 7. doi: 10.1021/ja507382j
PMCID: PMC4156866

Rapid Proton-Detected NMR Assignment for Proteins with Fast Magic Angle Spinning

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Development of a Roadmap, Some Considerations

- The many driving scientific problems : concise, legible, and compelling to nonscientists that have a vetted funding base, indeed we should show/argue the funding base should be highly leveraged by the instrumentation. The importance of thee problems as well as the role of NMR should have endorsement from outside our community.

- The dramatic (superlinear) benefit of UHF for resolution and detection sensitivity : quantitation, data , predictions, and clearly explain the transformative impacts on scope of science and emergent phenomena.

- A “short list” of specific instruments with specific scientific rationale.

- Governance and Practical Implementation issues that need to be agreed on:, business model , funding model, criteria for siting selection, management of access and time allocation, cooperation with other facilities and outreach, travel facilitation, training and remote access.