U.S. MAGNET DEVELOPMENT PROGRAM

Opportunities and Threats for Next Generation Accelerator Magnets

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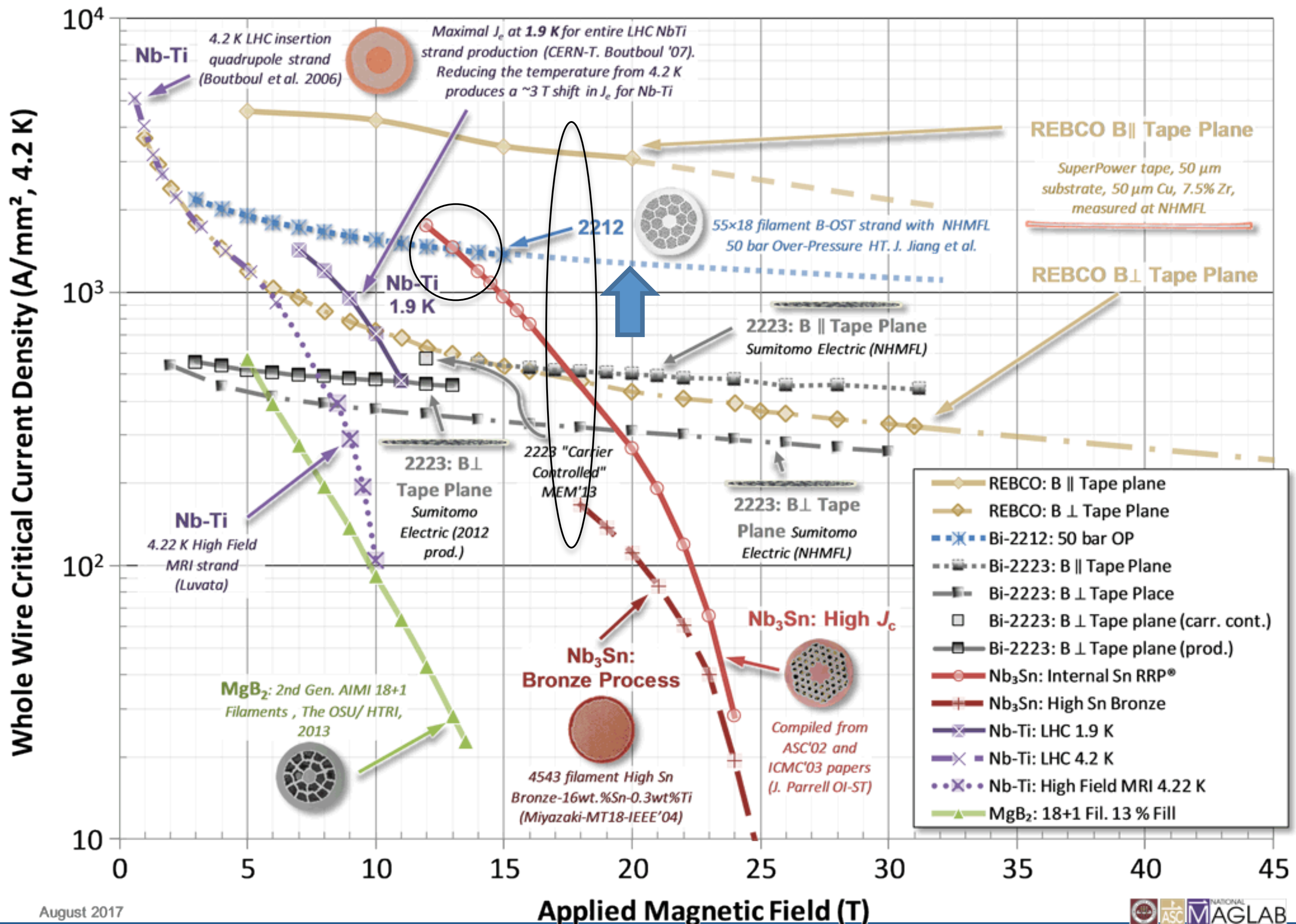
US Magnet Development Program
LBNL

Outline

- Overview – Where are we now?
- Conductors and magnet technology
- Advantages and Potential of HTS
- Threats and Opportunities/Opportunities and Threats
- Reducing Threats and Increasing Opportunities
- Moving Forward – Next Steps

Status of conductors



Snapshot of Conductor and Magnet Technology

- LTS
  - 27 km of Nb-Ti accelerator magnets at near operational potential
  - First Nb_3Sn accelerator magnets to be installed in LHC
  - LHC Quads on the way
  - High field solenoids
  - Fusion magnets
- HTS
  - MgB_2 links for LHC upgrade
  - Power cable demos
  - Power leads
  - EuCard-2 dipole
  - Beam deflecting magnet
  - > 1 GHz NMR magnets
  - And – 32T solenoid!
  - Several active R&D programs

Much work on materials (Bi-2212, REBCO, and some on IBS) but very few examples of accelerator magnets so far

LTS is not perfect

- **Let's say that Nb-Ti technology is maxed out.**

- **What are the challenges with Nb_3Sn?**
  - **Max operating field 16T or less for accelerator magnets**
  - **Lots of training**
  - **Strain sensitivity**
  - **Does not consistently reach short sample (see "training")**

This is what we are facing right now. What are the possibilities for the **Next Generation**?

Early Activities in HTS

- At time of discovery of HTS, SSC was in full R&D mode
  - Excitement generated by HTS almost derailed the project but was short-lived – it died anyway . . .
- Emphasis shifted to power transmission
  - $20M/yr for several years in US
- Work continues on motors, generators, FCL, NMR, . . . But only recently has there been any serious work on accelerator magnets

HTS Potential for Accelerator and other Magnets

- General Advantages . . .
  - High Field
  - High J_c
  - High stability
  - Large thermal margin at low temp – no training?!
  - Can operate in forced-flow helium gas at 20 – 30K, greatly reducing the complexity and cost for operation

These are some of the elements of the new paradigm

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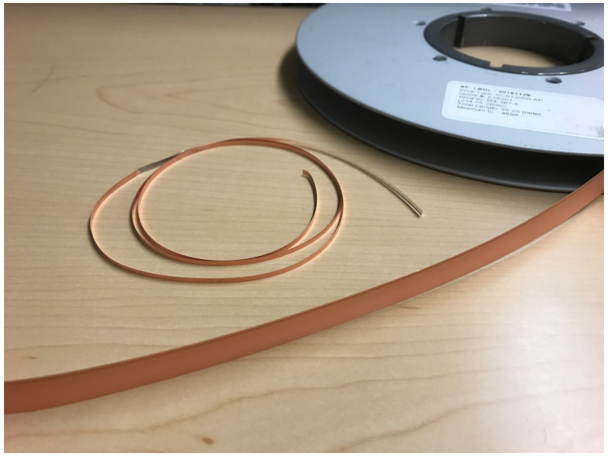
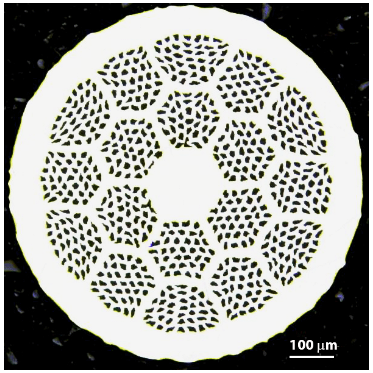
High critical-temperature superconductors - background

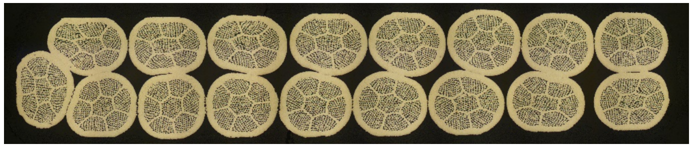
Two primary HTS materials with sufficient maturity

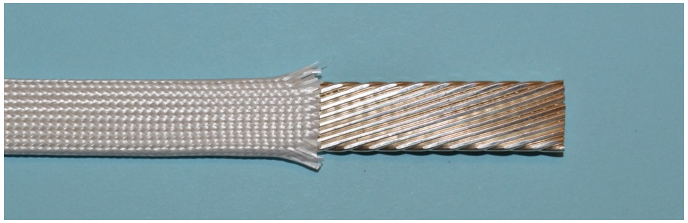
- **REBCO tapes (main focus for Fusion)**
  - Current densities an order of magnitude higher than LTS
  - Has achieved fields over 40 T in solenoids (X2 over target for high field designs)
  - No heat treatment required
  - Good strain properties





- **Bi-2212 round strands**
  - High current density
  - High current cable
  - Complex heat treatment
  - Strain sensitive
  - Possible use in pulsed systems





- *Operating temps at 20 – 30K*

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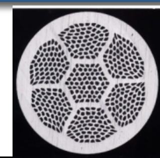
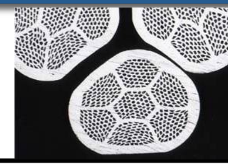
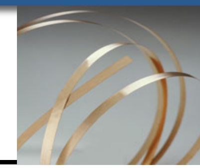
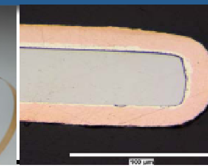
HTS Properties Comparison

	Bi-2212	ReBCO
Process	**High temperature, high pressure reaction**	**Pre-reacted Tape**
Scalability	**Rutherford cables**	**Roebel, CORC®, Twisted Stack (Still in development stages)**
Winding	**Existing methods**	**Tape**
Field Orientation	**Isotropic**	**Anisotropic***
Mechanical Properties	**Poor**	**Relatively good compared to Nb_3Sn**

*Progress in reducing anisotropy and development of round wires mitigate the problem

The Conductor Competition

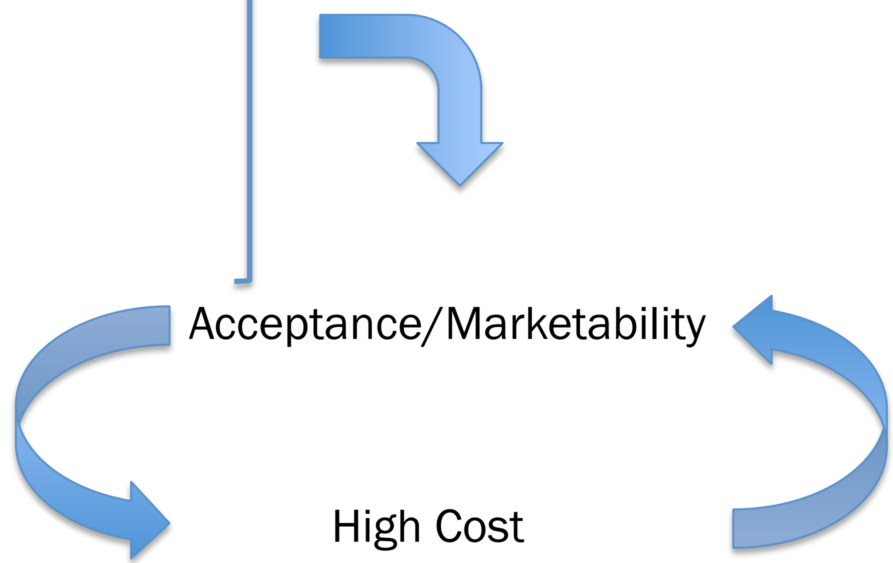
- With few exceptions all accelerator magnets use Rutherford-style cables
  - **Multi-strand – reduce strand length, fewer turns (lower inductance)**
  - **High current density (J_{coil} ~ 600 – 1,000 A/mm^2)**
  - **Precise dimensions – controlled conductor placement (field quality)**
  - **Current redistribution – stability**
  - **Fine filaments (5 – 40 microns)**
  - **Twisting to reduce interstrand coupling currents (field quality)**

Threats to Applications for HTS

Potential comes with some disadvantages

- Technical
  - Quench Detection and Magnet Protection
  - Manufacturability
  - Magnetization
  - Subject to Degradation (REBCO)
  - Strain Sensitivity
  - *Cryogenics*

"Circle of Death"



There are Challenges but Still Reasons and Ways to Move Forward

- HEP is still the major driver of accelerator magnet development*
- HTS is the only option for accelerator magnets with fields above 16T
- Opportunity to be non-conventional. For example, Quench Detection and Magnet Protection
- Despite the current high cost, I believe there is huge potential for significant cost reduction. Especially REBCO and some in Bi-2212.

*See also Threats

High Field Arc Magnets are Challenging

Consider the FCC

- 16 – 20T Dipoles (more than twice operating field of LHC)
- Synchrotron radiation (high field magnets and smaller ring)
  - Current LHC is 0.2 W/m/beam
  - For 16T/100 km - 28.4 W/m/beam for a total heat load of 4.8 MW
  - For 20T/80 km - 44.3 W/m/beam for a total heat load of 5.8 MW

If this load is falling directly on the magnet cold masses working at 1.9 K/4.5 K, the corresponding total electrical power to refrigerators is

–> 4.3/1.1 GW for FCC-hh 100 km
–> 5.2 /1.3 GW for FCC-hh 80 km

L. Tavian, CERN

- CERN baseline is currently 100km/16T/1.9K

Interaction Region Quads/Dipoles have their own challenges

- Debris from interaction region at detectors generates enormous radiation induced heat loads and high radiation dose of magnet components

- Mitigation includes larger bore (higher field on the conductor)
  - Intercept less energy or add shielding inside magnet bore

Some Threats/Opportunities

- From a HEP perspective
  - Is there any new physics to warrant another big machine? Still possible for LHC Energy upgrade (LHC-HE) . In fact, this could be the best case

  But . . .

  - Still no sign of new physics at LHC
  - Near-term focus is on Higgs (e+e-) and neutrinos.
    - Not much demand for next-gen magnets except specialty magnets
  - Not much help so far from outside HEP
    - The usual suspicion and reluctance to use superconductivity. Hard to crack the market. See the last 100 years for LTS and last 30 for HTS
  - Another reason to look at applications outside HEP in addition to development drivers

Opportunities to Break the Circle (The Timing is Good!)

- Taking advantage of accelerating development rate and new applications on the horizon. -> non-linear progress
- Performance improvements
  - Higher current density with APC at low temperatures
  - Reduced anisotropy
- Active magnet R&D programs on the verge of demos that will stimulate the environment
- Fusion Energy Sciences moving back to some technology development

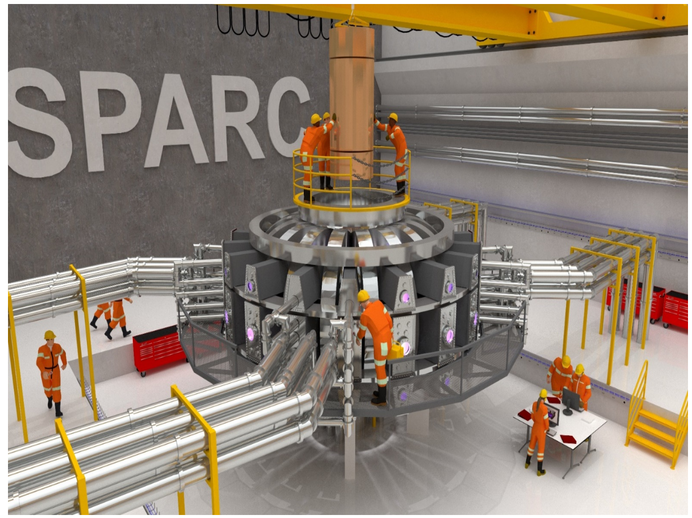
Biggest obstacle to progress is access to conductor in quantity

Opportunities in Fusion

- Fusion Energy Sciences Technology Advisory Committee (FESAC) subpanel on Transformative Enabling Capabilities (TEC)
  - A large number of topics examined including HTS for high field, high operating temp magnets for magnetic confinement fusion
  - Report just completed and is now available on the FESAC webpage: https://science.energy.gov/fes/fesac/reports/
  - HTS was chosen as one of four "Tier 1" TECs. "Most Promising"
- Performance goals common with HEP will increase opportunities
  - High current cables under high stress conditions

MIT and Commonwealth Fusion Systems (CFS) announced a new approach to fusion energy based on REBCO superconducting magnets

ARC – affordable, robust, compact
SPARC – smallest possible ARC

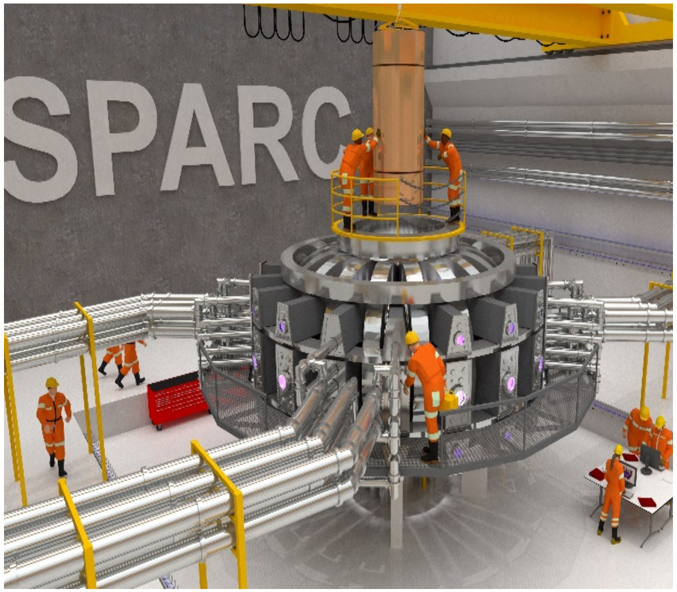


SPARC

Courtesy
J. Minervini, MIT

- CFS is a private company spun out of MIT; it has announced $50M in private financing and raising more
- MIT and CFS will collaborate closely to demonstrate large-bore, high-field REBCO magnets in ~3 years
- If successful, they will then build SPARC, a ~100MW net energy device, in following ~4 years

SPARC is a net-energy tokamak using REBCO magnets



- *Compact:* R_0 < 2m
- *High-field:* B_0~12T, B_{max}~21T
- *Fusion power:* 100 MW
- *Net-energy:* Q>2
- *Pulsed:* 10+ seconds

SPARC

Courtesy J. Minervini, MIT

SPARC technical mission:

- Demonstrate break-even fusion energy production
- Demonstrate fusion-relevant REBCO magnets at scale
- Demonstrate high-field fusion plasma scenarios for ARC

SPARC strategic mission:

- Rapidly bootstrap to fusion energy as fast as possible
- Reinvigorate fusion energy efforts and provide urgency
- Enable parallel efforts in complementary fusion R&D

SPARC is small enough to be built:

- By the MIT, CFS, and partnering teams in <5 years
- Within precedent of several other tokamaks
- With existing or near-term technology
- Leveraging existing MIT infrastructure for speed

Potentially Big Boost for REBCO

- The focus is solely on REBCO.

SPARC

- They will need about 60,000 kA*m over the next few years to build one full TF coil. If the machine is built, they will need 18 TF coils (note: specs for kA*m for 700 A/mm^2 @ 20T, 20 K).

- An ARC size device will require many times that amount.

Increasing the Opportunities and Eliminating the Threats

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Quench Detection and Magnet Protection

- Still a tough nut to crack
  - Have to deal with success
  - Higher current density increases energy that may exceed the coil's heat capacity – add more copper?

- Several solutions close to demo that could provide early detection – key to magnet protection.

- But . . . Totally different environment ← Primary element of the new paradigm
  - The only reasons for an HTS magnet to quench is because it exceeded its critical current or temperature increase due to cryo failure or beam induced heat load.

- However, cryo failure gives sufficient warning and transient beam induced heat loads are probably not enough to initiate quench – unless it's catastrophic (then you're screwed)

- Another mitigation might be to have rather poor cooling, allowing more time to detect the quench

Creating a New Paradigm

- Look to near term demos of technology feasibility to help create/drive a sustainable market.
  - Development of high current cables is critical
  - Explore magnet geometries
  - Provide platforms for Quench Detection concept development
- Other applications outside HEP/Fusion (ion sources, undulators, gantries, solenoids, NMR, 25T solenoids for x-ray and neutron facilities . . . and wind turbines
- Upshot
  - Development of a new enabling capability is key to adoption of any new technology (regardless of cost)
  - Stop worrying about cost and make more magnets!

What's Next?

- Hybrids
  - Difficult to separate forces (insert from outsert)
  - Combined – lose higher temperature option
  - Compact geometries like CCT are a natural fit for Bi-2212
- Start to think about all HTS accelerator magnets
  - Active program to develop magnet technology
- Continue to improve cost/performance

Moving forward with REBCO in HEP

- Special applications could benefit
  - High temperature operation
  - High field
- Rethink quench protection philosophy
- High current cables a necessity
  - Apply some of the No-Insulation coil techniques to cables?
- Cost is a continuing concern
  - Need a market
  - Indirectly we can demonstrate viability of REBCO for magnets
  - Disruptive processing technology?

Improving Cost/Performance

- High current cables with current sharing
  - Allows use of tapes with defects
  - Increases thermal stability
  - Increases effective piece length
  - Strengthened Bi-2212
- Ultimate goal is to have highest current density in coil pack
  - J_c
  - J_e of tape (Mostly regarding REBCO)
  - J_e of cable
  - Reduce anisotropy
  - Increase coil packing fraction

Moving Forward – concentrate on positives and mitigation of negatives

- The number of activities developing REBCO accelerator magnets is growing

- We absolutely need to build magnets!

  - Emphasis on development of high current cables
  - Handle the magnetization effects
  - Geometries that can effectively utilize tapes/cables from tapes

LARP* Racetrack Quad Reduces Energy Deposition

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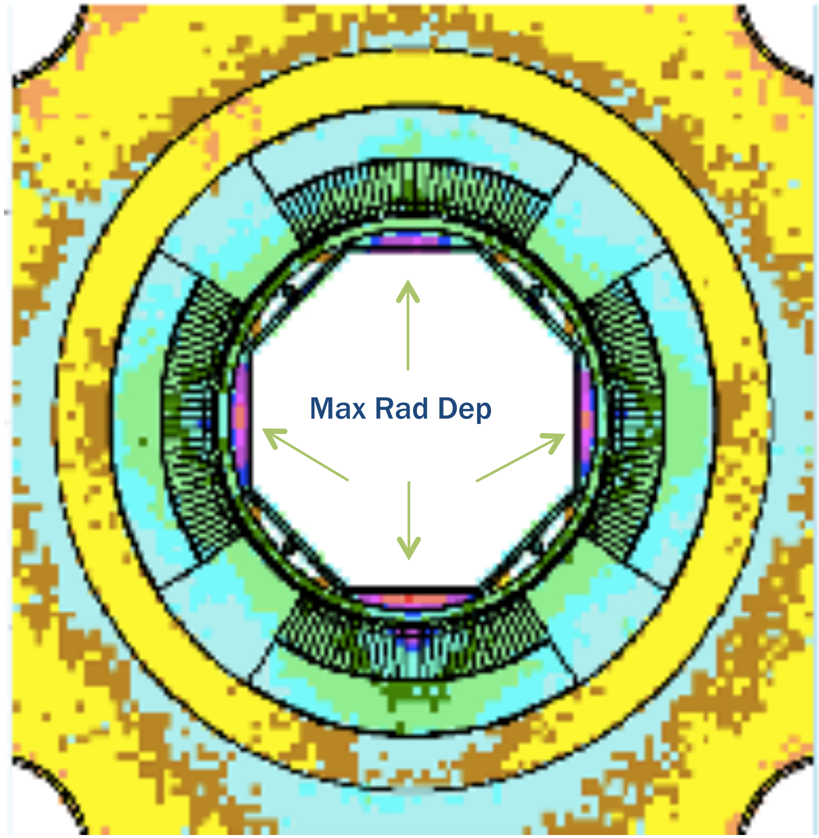
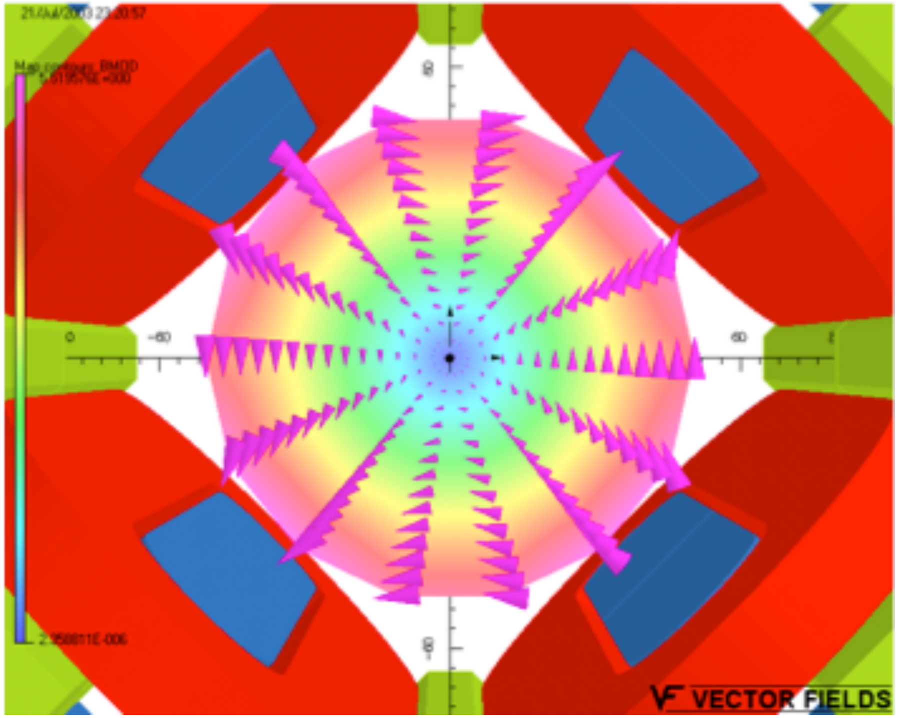
Nb_3Sn LHC IR Quad

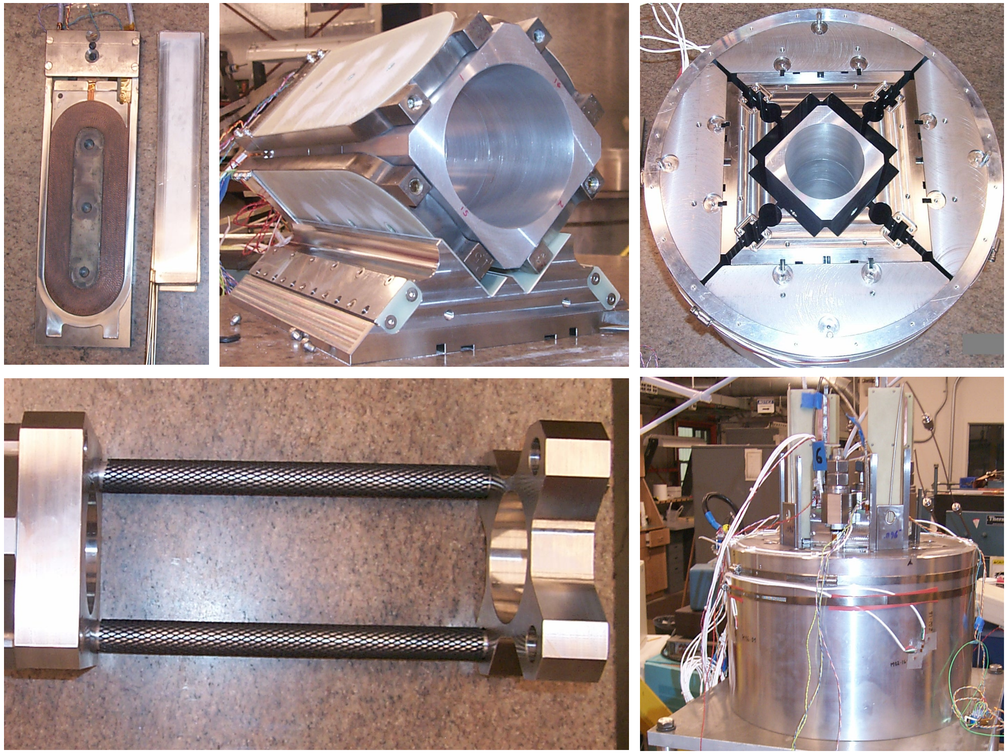


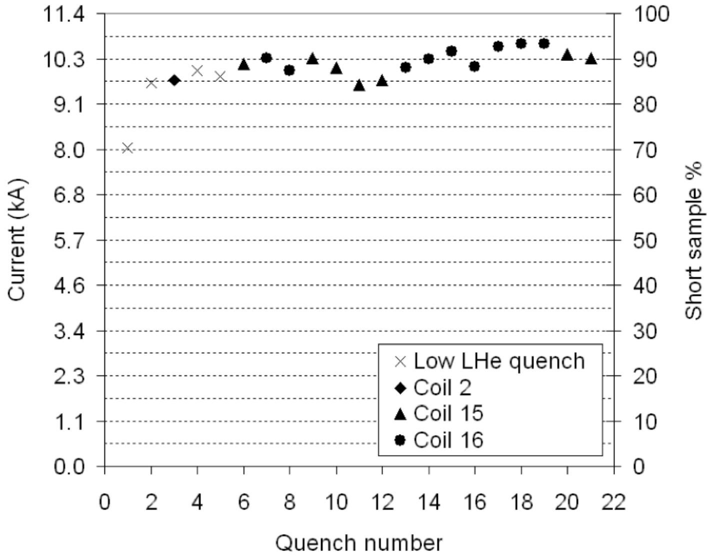


N.V. Mokhov, et al. Phys. Rev. ST Accel. Beams **18**, 051001 (2015)

*LHC Accelerator Research Program

Nb_3Sn Prototype Performed Well

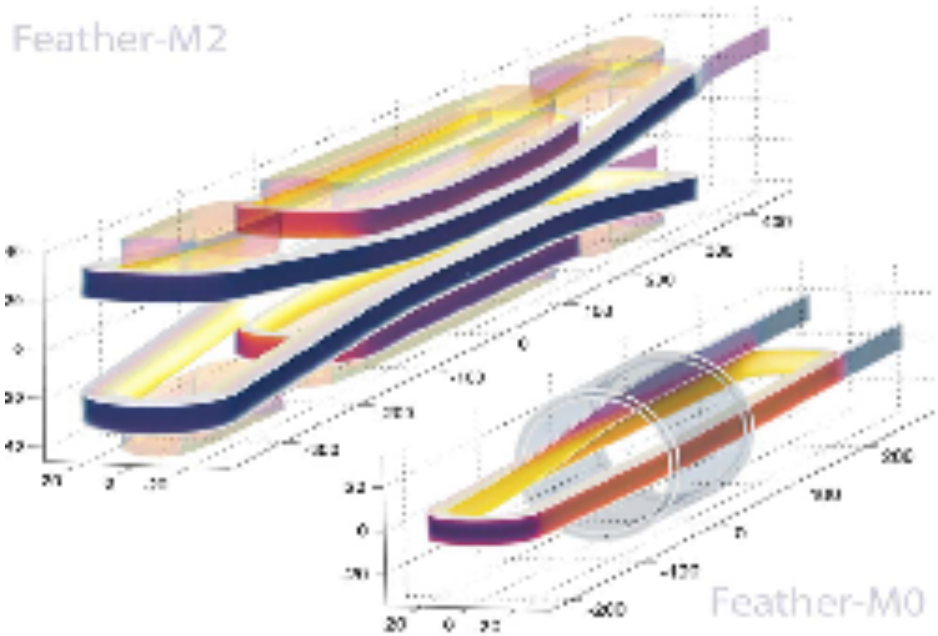




Favorable geometry for tape

EuCARD-2 "Feather" Insert

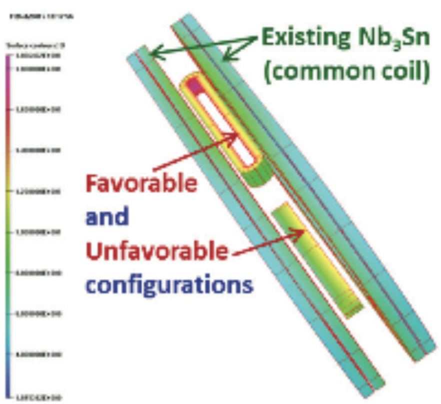
5T, 40mm aperture
accelerator quality demonstrator
to produce 17 – 20 Tesla when inserted into FRESCA-2 (100 m bore)

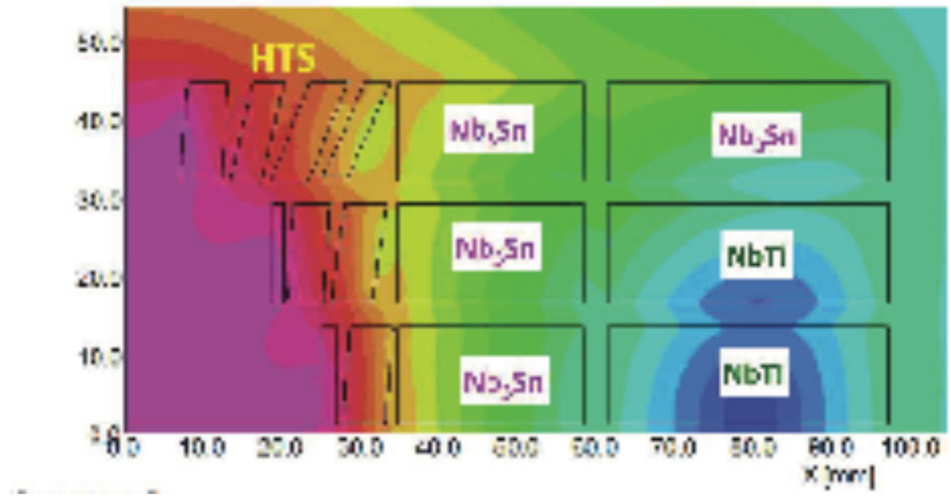


G. Kirby, et al., IEEE Transactions on Applied Superconductivity, Vol. 25, No. 3, June 2015

BNL 20T Hybrid Design and Insert Tests

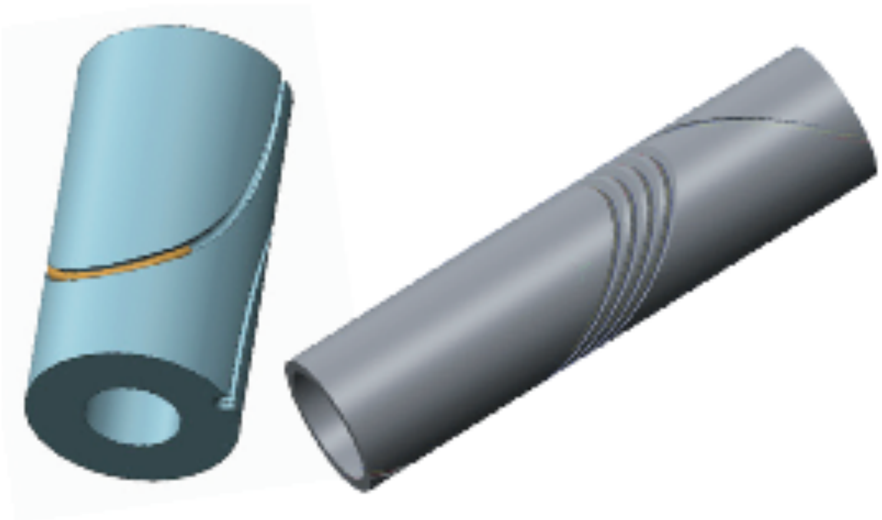
10T Nb_3Sn Common Coil for inset tests

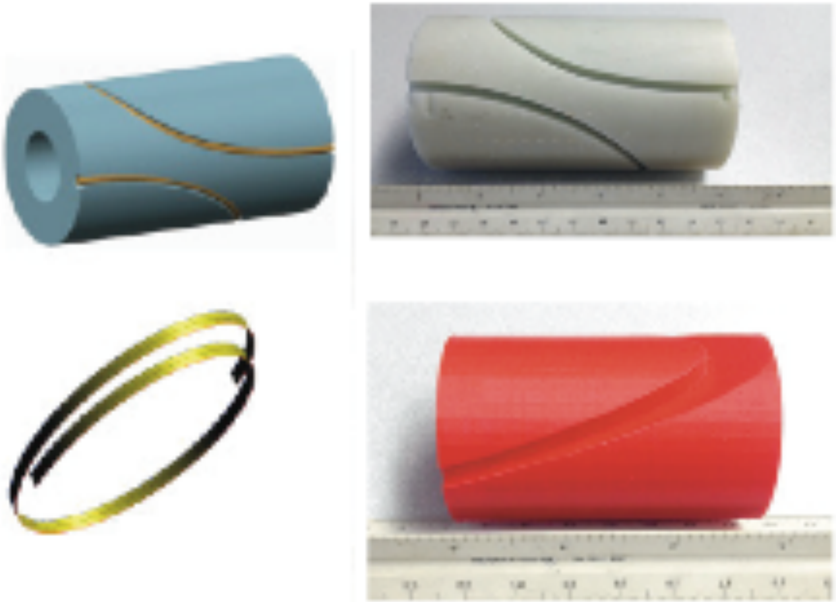




Gupta, et al., Proceedings of IPAC15

Stacked Tapes and CORC® Canted-Cosine Theta (CCT)





Develop insert testing infrastructure using 10T CCT

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X.Wang, LBNL

What is Driving the Field Forward?

- Some talk of 7.5 TeV with 11T (Nb_3Sn) lattice inserts
- HE-LHC still buzzing – 20T (Hybrids or all-HTS?)
- FCC - ee, hh
- CepC, SppS
- Nuclear Physics in the US – Electron Ion Collider
  - IR's, high heat loads in some areas
- High Intensity Neutrino Sources?
- Special applications, e.g. high heat loads, high operating temperature, cryogen-free

Our new role?

- We are neither the chicken nor the egg.
- In the process of fulfilling program needs we demonstrate feasibility with the hope of creating a market we can leverage.
  - We need to pay more attention to the latter by working closely with industry and university partners.
- Fusion program could help with cost and development. On parallel paths in some areas.

Collaboration is Key

- In the context of a future high energy pp collider collaboration is essential.
- We should not fear competition, we should embrace it.
- The best way to win?

Run faster!