US Magnet Program

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Renewed US Interest in pp Colliders

Particle Physics Project Prioritization Panel (P5)

pp colliders are one of P5’s long term priorities

“The future of particle physics depends critically on transformational accelerator R&D to enable new capabilities and to advance existing technologies at lower cost. “

“The program is driven by the physics goals, but future physics opportunities will be determined by what is made possible.”

“Going much further, however, requires changing the capability-cost curve of accelerators , which can only happen with an aggressive, sustained, and imaginative R&D program.”

“Primary goal, ... build the future-generation accelerators at dramatically lower cost. For, example, the primary enabling technology for pp colliders is high-field accelerator magnets, . . .”

“Strengthen national laboratory-university R&D partnerships, leveraging their diverse expertise and facilities.”

US National High Field Magnet Program

DOE created an accelerator R&D Subpanel to align accelerator R&D with P5

Report will be presented at the April 6 HEPAP Meeting

US magnet programs (BNL, FNAL, LBNL, and NHMFL) submitted a joint "white paper" outlining a coordinated US magnet R&D program to

Goal 1: Develop accelerator magnets at the limit of Nb_3Sn capabilities. This is presently believed to be approximately 16 T.

Goal 2: Explore LTS accelerator magnets with HTS inserts for fields beyond the Nb_3Sn capabilities. The present target is 20 T or above.

Goal 3: Drive high-field conductor development, both Nb_3Sn and HTS materials, for accelerator magnets.

Goal 4: Address fundamental aspects of magnet design, technology and performance that could lead to substantial reduction of magnet cost.

Perspective: The State of State-of-the-Art

About 27 km of NbTi magnets running at 1.9K and 7 - 8T

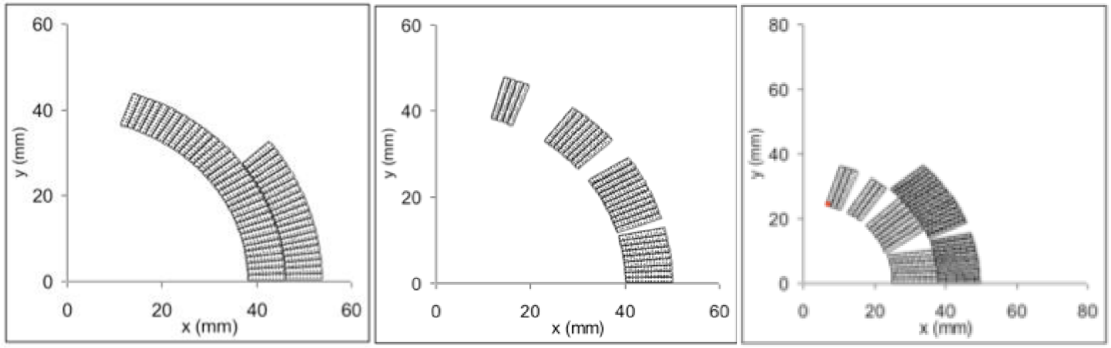
More than half a century after discovery, Nb_3Sn is ready for major implementation in an operating accelerator. HL-LHC

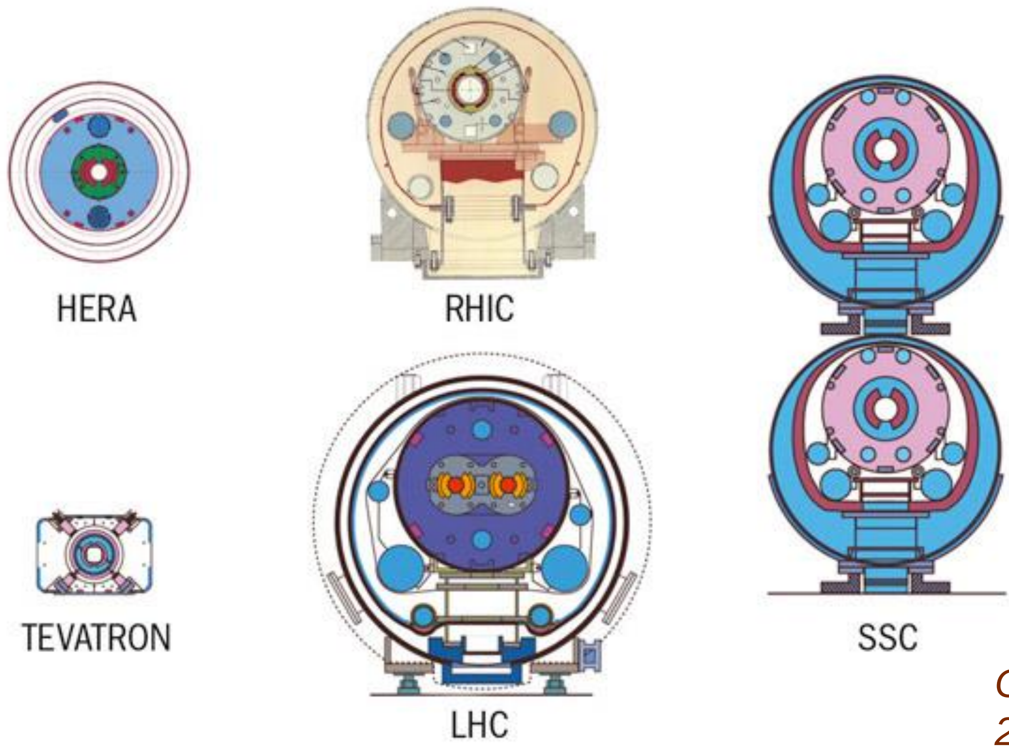
Some significant improvements in HTS conductors, but much left to do.

High field accelerator magnet development has reached 14 – 15T. Getting close to the Nb_3Sn limit.

Training is still a problem

~ 4 Decades of Magnet Technology Evolution





CERN Courier, Oct. 2011

We Have a Very Big Challenge Ahead of Us

- FCC calls for superconducting accelerator magnets that operate (very) reliably at twice the operating field of LHC
- Cost will be a dominant issue along with performance
- Quench detection and protection – simple and reliable
- The magnets must operate and survive in a much more hostile environment:
  - Synchrotron Radiation, large stored energy

In the end, it is the cost of the machine, not just the magnets. In order to be able to reduce the overall cost we need flexibility in magnet design choices – bore size, field, geometry.

A simple extension of what we have done in the past will not be sufficient

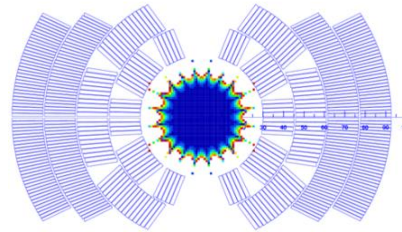
We need a technological mutation

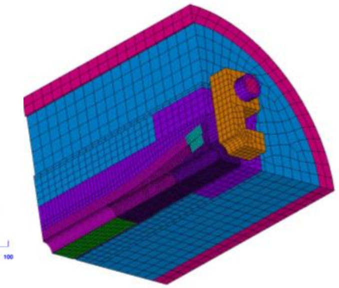
The Program will Focus on These Grand Challenges

- Achieve a field of 16T in a bore of at least 50mm
  - Focus on simple, manufacturable designs
- Understand training of Nb_3Sn magnets and develop ways to reduce or eliminate it
- Produce an HTS (Bi-2212/YBCO) insert with a self-field of > 5T and measure the field quality
- Reduce cost and improve performance of Nb_3Sn
  - Increase the current density by 30% with a scalable sub-element structure
  - Aim for a cost per kg the same as NbTi
- HTS development
  - Focus on magnets as technology drivers
  - Other aspects under discussion

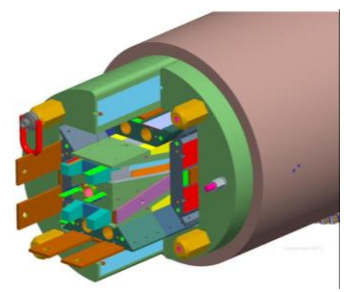
We have Built a Strong R&D Platform and are Ready to Launch an Aggressive New Program that will Meet the P5 Challenge

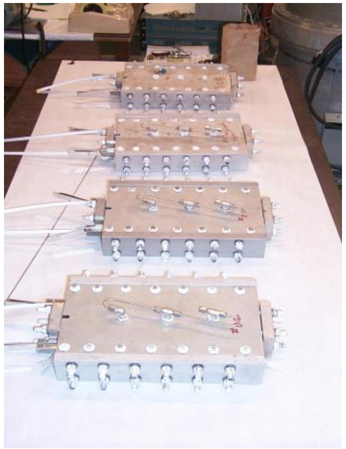
- Experience with a variety of geometries
  - Cos-Theta – D20 and more recently, LARP and 11T
  - Common Coil
  - Block
  - Sub-scale racetracks
  - Some Canted-Cos-Theta
- Analysis tools
- Instrumentation and Diagnostics
- Infrastructure
  - Fabrication
  - Testing





We have the tools and experience required for success

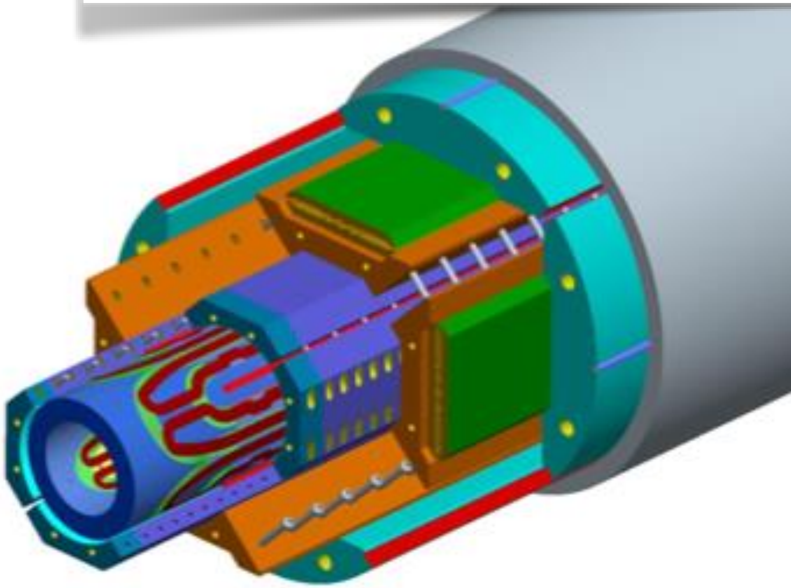


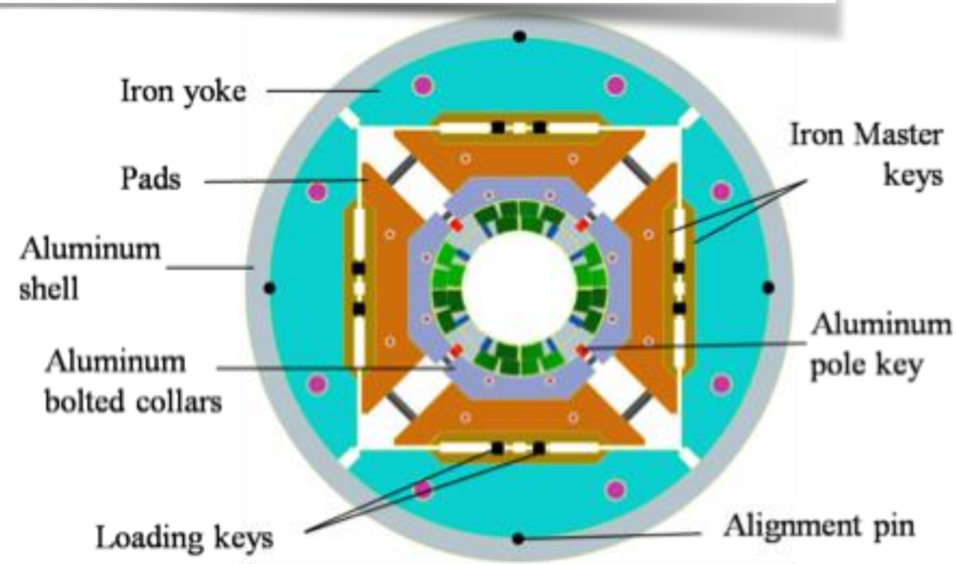


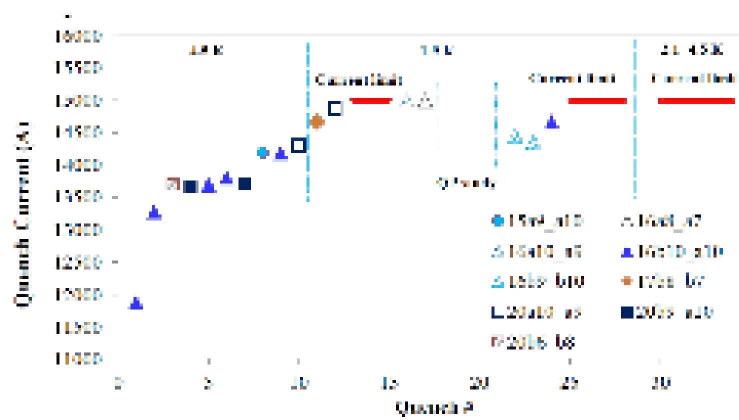
We have time but not that much time. And we need to substantially raise the level of expectation for magnet performance.

Nb_3Sn technology is being readied by LARP: HQ ➠QXF ➠ Hi-Lumi upgrade

Design, fabrication, and test results from LARP: FNAL, LBNL, BNL







Conductor Development Program: Expanding the List of Challenges

Prioritize and distinguish between “wants” and “needs”

- Significantly reduce cost
  - Scale up of – 100-200 kg billets
  - Work with scalable sub-element designs
- Reproducible, uniform Properties
- J_c
  - Significant J_c improvement
- Magnetization
  - Can we get around this via magnet design, AP mitigation?
  - Share the burden, don’t toss it over the fence to conductor manufacturers

Philosophy: Raise the Bar on Expectations and Implement an Aggressive Approach

- Leverage through collaboration
- Shoot for the moon – high risk, high payoff
  - Aim for the highest dipole fields
  - New ideas for simplicity
  - Explore the limitations of materials and structures
- Implement a technically driven program that strives for one test at least every 3 months. i.e. make our mistakes quickly and learn from them

Outcomes are . . .

- New record dipole fields
- A discontinuity in superconducting magnet technology
- A platform that can be used to design and build magnets for a variety of applications with optimal field, coil configuration and bore size
- Significant increase in performance/cost ratio

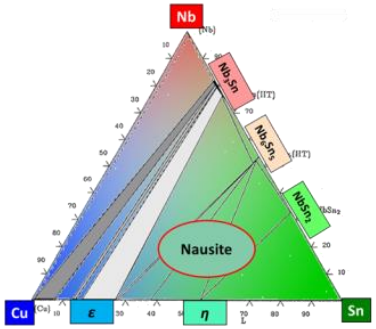
Contributions to a US Magnet R&D Program

To achieve the program goals we need a portfolio that combines baseline technology development with a strong component of higher risk, potentially high payoff disruptive technology development that can leapfrog the status quo.

Conductor is the Foundation

ASC is foundation of a strong US conductor R&D program
Other contributors as well from labs and universities

- **Nb_3Sn - Still much to do on cost reduction and improved performance**
  - Near-term focus on reaction path, grain size and manufacturing variables
  - Both RRP and PIT suffer from formation of unstable phase that negatively affects transport J_c, also pinning for high J_c
  - Deformation of filaments also affects reaction path



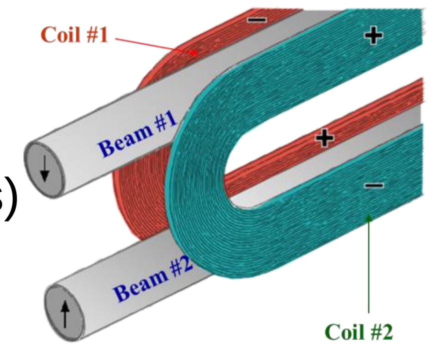
HTS Materials R&D

- Bi-2212
  - Key issues
  - Overpressure processing, scale-up and cost reduction
  - Making stronger, less Ag-intensive versions
  - Ensuring power supply
- CORC (Cable on Round Core) REBCO
  - Very effective partnership between ACT, SuperPower and some end-users multi-kiloamp cables to play by end of 2015 at ~400 A/mm^2 J_E at 20 T
  - ARPA-E support for wind turbine technology enhancement has enabled strong enhancement of J_c at TcSUH
- New Materials?
  - Round wire, multifilament, lower raw material cost conductors based on MgB_2 or $(K,Ba)Fe_2As_2$ both show potential

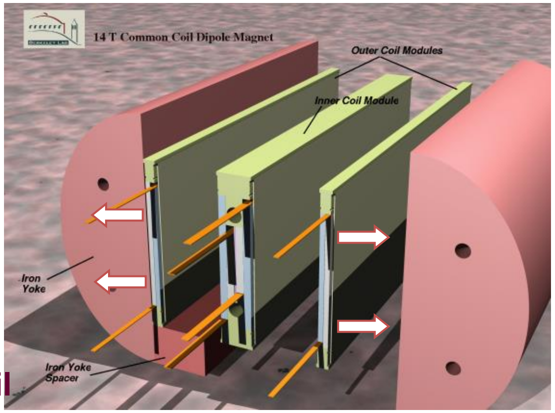
16 T Nb_3Sn 2-in-1 Common Coil

<u>Motivation for Common Coil Design:</u>

- •Simpler coils (mostly flat racetrack)
- •Fewer coils (½, shared between 2 bores)
- •Lower cost magnets expected
- •Attractive in dealing with large forces
- •Larger bend radius allows both approaches - "React & Wind" and "Wind & React"
- •Several R&D Magnets built
- •Next phase – field quality 16 T magnet



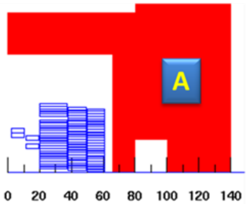
Main coils of common coil

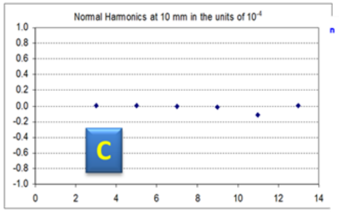


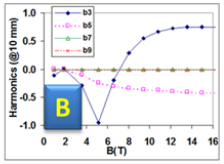
In common coil design, unlike in conventional designs, coils move as a block, without straining the conductor in the ends. This could be important in high field/stress magnets in minimizing the quenching.

Good field quality magnetic design

- ➢ Geometric
- ➢ Saturation
- ➢ Ends







(from 1/4 model)

MAIN FIELD: -1.86463 (IRON AND AIR):

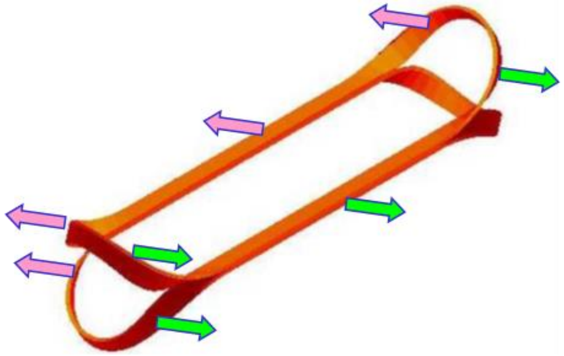
b 1:	10000.000	b 2:	0.00000	b 3:	0.00308
b 4:	0.00000	b 5:	0.00075	b 6:	0.00000
b 7:	-0.00099	b 8:	0.00000	b 9:	-0.01684
b10:	0.00000	b11:	-0.11428	b12:	[illegible]
b13:	0.00932	b14:	0.00000	b15:	[illegible]
b16:	0.00000	b17:	-0.00049	b18:	[illegible]

D

End harmonics in Unit-m

n	Bn	An
2	0.00	0.00
3	0.01	0.00
4	0.00	-0.03
5	0.13	0.00
6	0.00	-0.10
7	0.17	0.00
8	0.00	-0.05
9	0.00	0.00
10	0.00	-0.01
11	-0.01	0.00
12	0.00	0.00
13	0.00	0.00
14	[illegible]	0.00
15	[illegible]	0.00
16	[illegible]	0.00
17	0.00	0.00
18	0.00	0.00

F



BNL HTS/LTS High Field (~20 T) Hybrid Dipole

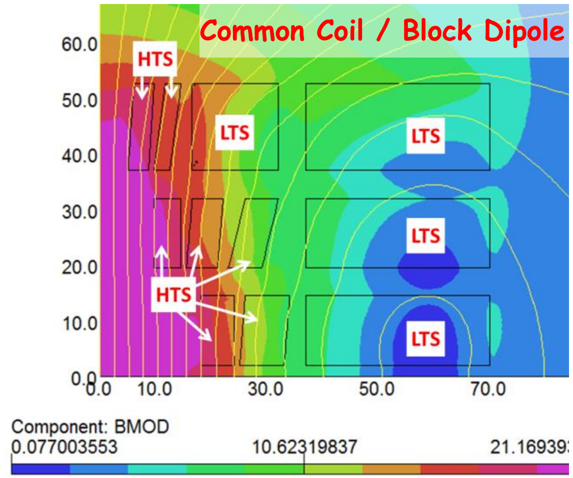
Hybrid design to minimize cost
- **HTS in high field region for ~4 T**
- **LTS in low field region for ~16 T**

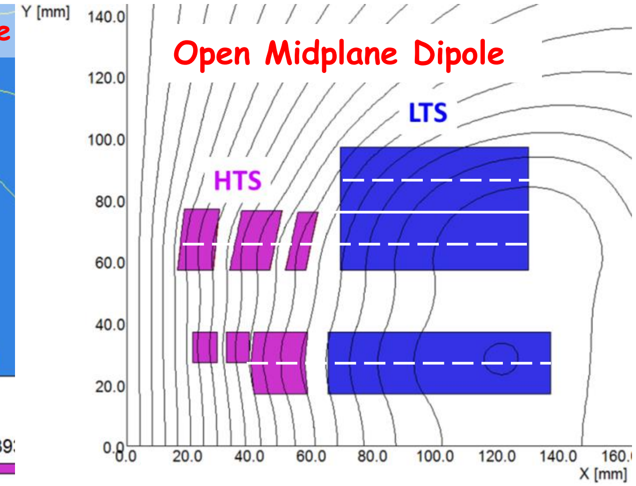
HTS Options
- **Bi2212 – round wire**
- **ReBCO tape – high strength**

HTS Challenges
- **High Cost**
- **High Magnetization**

Aligned ReBCO Tape Design
- **Reduce Magnetization**
  - **Depends on the tape side that is perpendicular to the field**
- **Reduce Requirement (cost)**
  - **Depends on the direction of field**

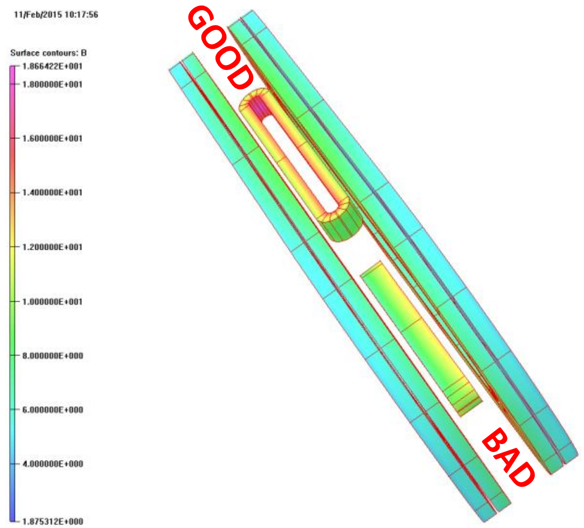
Proof of Principle Test at BNL
- **Part of PBL/BNL/E2P STTR**
- **Unique dipole with large opening**





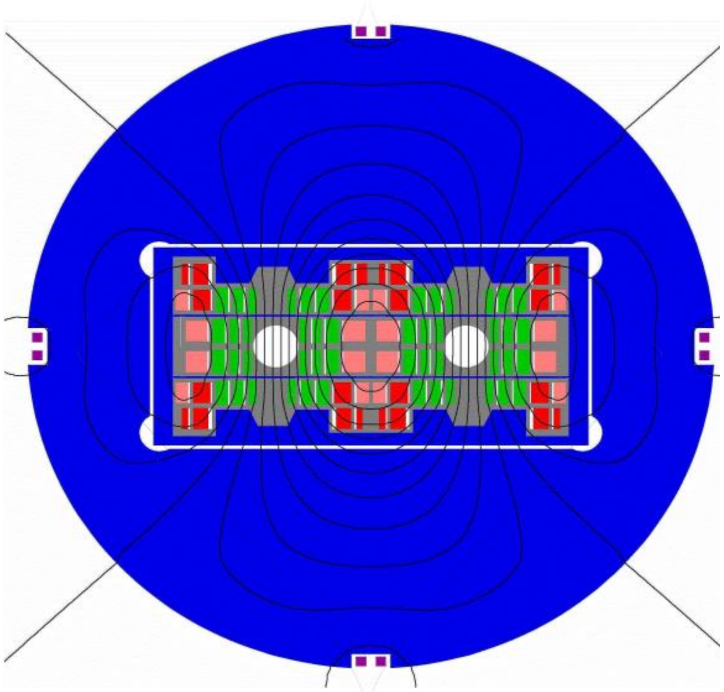
Proof of Principle Test - PBL/BNL/E2P Phase II STTR

(compare magnetization in two configurations)



Texas A&M

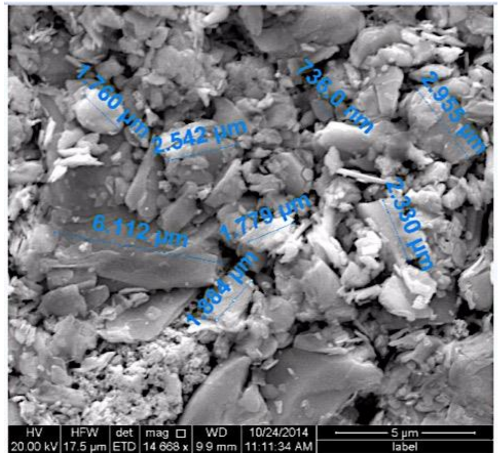
High Field, Low Circumference

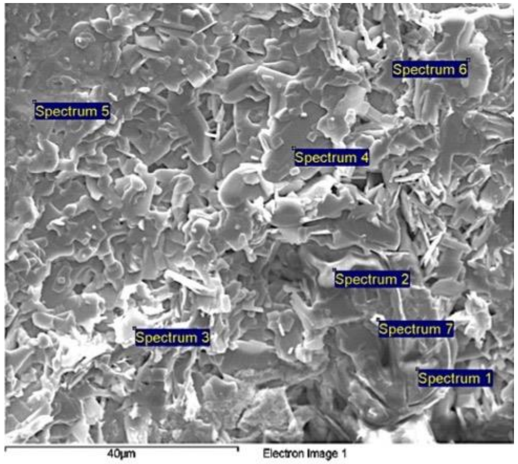


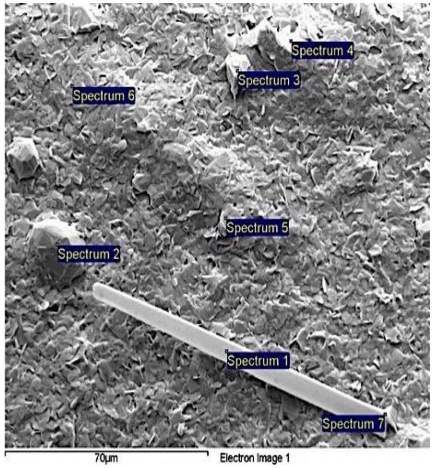
- Need ~16 T dipoles for the double ring = Nb_3Sn and Bi-2212.
- Very expensive superconductor (wire would be >$15 B today)
- Conductors are fragile, require stress management in windings.

Texas can help two ways...

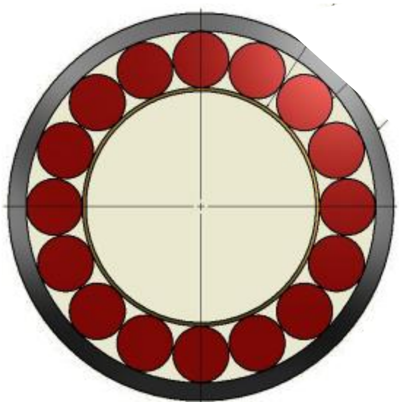
Enhanced Textured-Powder processing of Bi-2212/Ag to enhance j_c, improve mechanical properties.

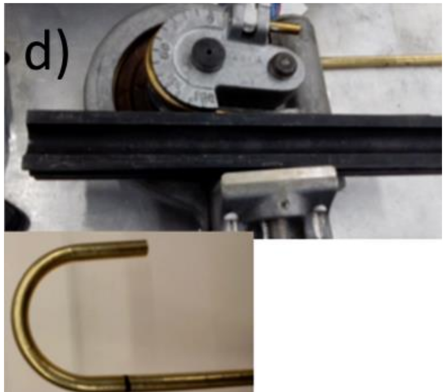






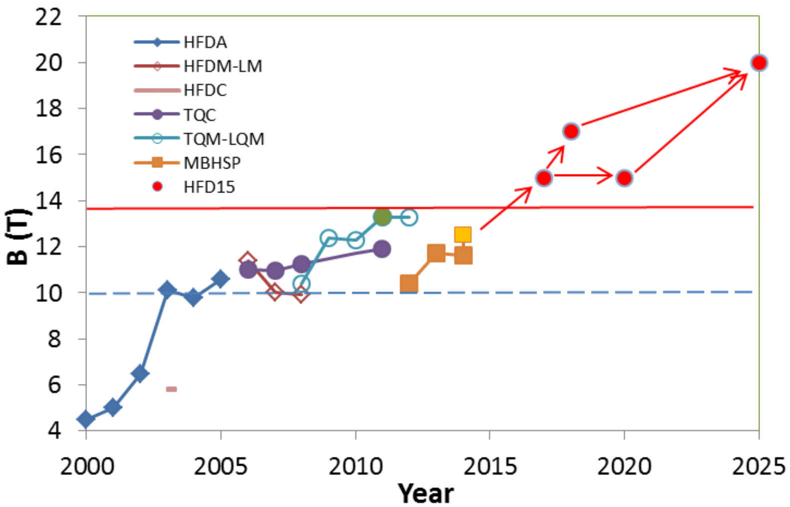
Stuctured cable-in-conduit provides intrinsic stress management, compatibility for heat treatments.





FNAL HFM Program

- FNAL HFM plan was coordinated with P5 recommendations and updated DOE-HEP GARD program.
- In collaboration with U.S. National labs, universities and industry, develop accelerator magnets with world record parameters
  - 60-mm aperture 15 T Nb_3Sn dipole suitable for FCC, 2 T HTS insert
  - 120-150-mm aperture 15 T Nb_3Sn dipole and 5+ T HTS insert with stress management
  - Small-aperture 20 T accelerator dipole based on LTS (Nb_3Sn) and HTS (Bi-2212 or YBCO) coils
- Magnet cost optimization studies.
- Continue structural material R&D for 15-20 T accelerator magnets.



15 T Dipole Demonstrator (FNAL)

Approach:

- use the 11 T dipole components, tooling, and FNAL fabrication and test infrastructure
  - R&D cost and time reduction

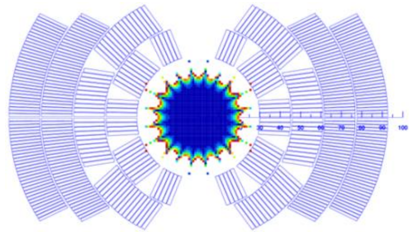
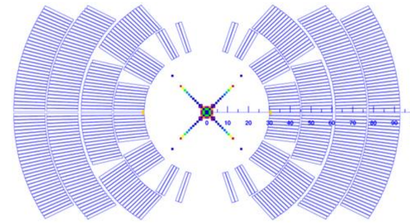
Design concept:

- 4-layer 60-mm bore graded coil
- Interim design with 11 T coil
- Minimal coil size
- Stress and quench protection requirements are respected
- B_{des}= 15.2/16.3 T at 4.3 K

Mechanical design:

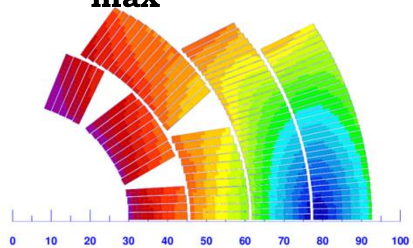
- Thin coil-yoke spacer
- Vertically split yoke, SS clamps
- Bolted skin from 11 T dipole
- Cold mass OD<610 mm (VMTF limitation)

First test in Jan-March 2016.

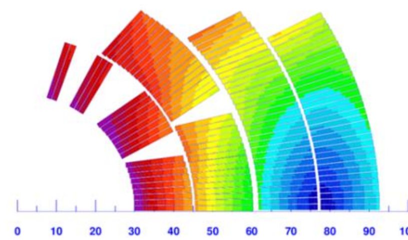



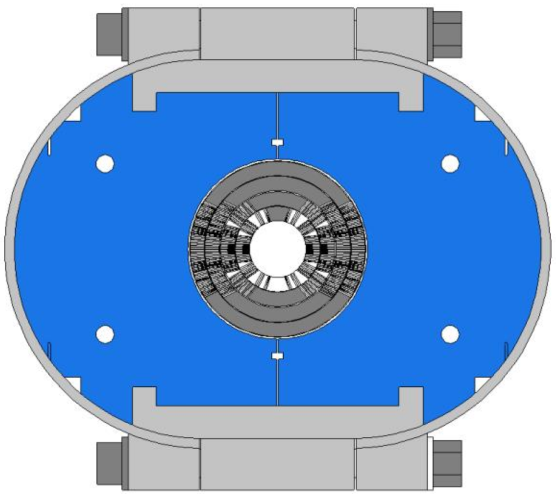
Optimized graded co **Interim coil desig**

B_{max}=16.3 T



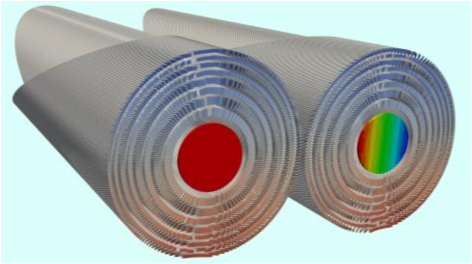
B_{max}=15.2 T





LBNL

The CCT has the Potential to Meet the Goals of the New Paradigm but Needs to be Demonstrated



Simplicity – better performance?
- Robust, reproducible, manufacturable
- Minimal external structure (little or no prestress?)
- Mandrel (ribs + spar) replaces pole, collars, end parts, spacers
- No body-end transition
- Modest tooling requirements

CCT is BCMT's highest priority

Intrinsic Stress Reduction
- No accumulation of stress on the midplane
- Allows grading (near optimal conductor efficiency)
- Allows larger bores (conductor scales with bore radius only)

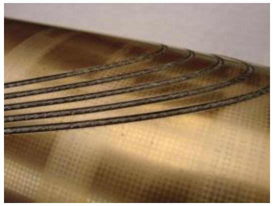
Excellent geometric field quality

Combines the best of our former program
- Subscale characteristics – simple and relatively inexpensive
- High field – scalable to highest fields and use of inserts
- A natural platform to apply the tools we have developed over the last 2 decades

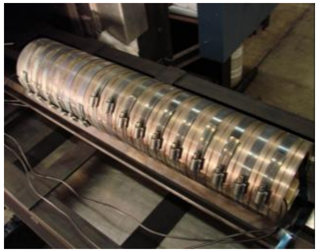
LBNL A Step by Step Approach to High Field

FY14

2.5T NbTi



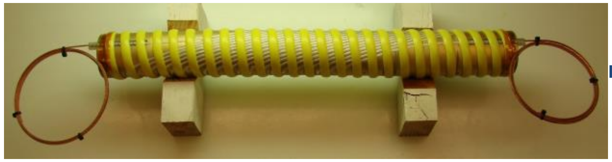
Nb_3Sn CCT Reaction test



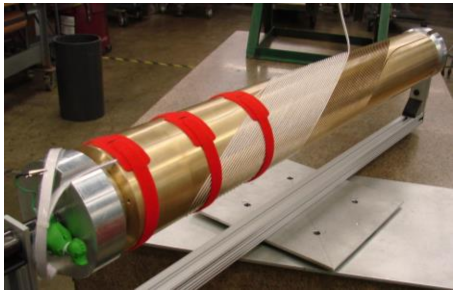
Tooling/Fab Development

FY15

5T NbTi



Bi-2212 6/1



10 T Nb_3Sn

FY16

- **Progress in 2-layer steps to 8-layer, 16 Tesla**
  - **Might take a more aggressive approach depending on results (and resources)**
- **Continued program on HTS CCT**

18 T Nb_3Sn/HTS hybrid

Dual bore all-Nb_3Sn, 18T

Need the materials for this (CDP)

Sociological Concerns

- Everyone agrees that we need a world-wide effort
  - How do we actually make this work effectively and efficiently?
  - The definition of "collaboration" today is, "you do something and we do something else"
- Conductor performance improvement and cost reduction needs a driver outside High Energy Physics
  - How can we help create new markets for superconductors?

Conclusions

- Accelerator quality dipoles with an operating field of 16T are feasible
- Making them at a reasonable cost is a challenge and will take time and require much greater effort than we have now.
- Significant cost reduction can only be achieved by raising expectations and aggressively pushing the technology beyond the accepted limits.
  - Evolutionary improvements will not be adequate.
- Program has to be integrated (AP, cryo, etc) and take into account ancillary problems, e.g. SR heat load
- HTS has many issues to understand and overcome
  - Can we achieve what it promises? Now is the time to push.