Transformational R&D for a 100 TeV scale pp colliders

National high-field magnet program (including material development)

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Lawrence Berkeley National Laboratory

With input from Magnet Experts from
BNL, FNAL, LBNL, NHMFL, TAMU
via the
White Paper for a National Program on
High Field Magnet R&D

The charge provided by the sub panel

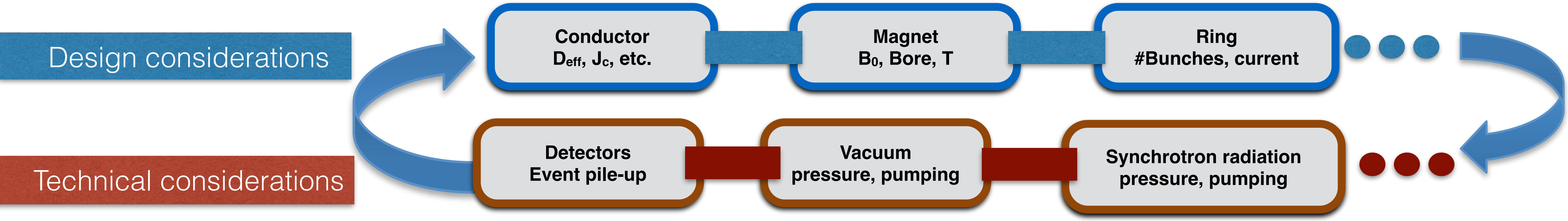
1. What are the appropriate goals for medium- and long-term U.S. accelerator R&D required for a world-leading program in accelerator-based particle physics consistent with the scientific priorities outlined in the HEPAP-P5 report?
2. The scope of the current medium- and long-term R&D efforts and how well these address the goals for this program.
3. What is needed to achieve these goals including resources, management of research efforts, and existing and expected expertise and infrastructure?
4. How the training of future accelerator scientists and technologists through accelerator R&D efforts is going?
5. With a sufficiently exciting program, it is possible to increase the funding in accelerator R&D. What would be the elements of such a program especially in long-term R&D both at the intensity and energy frontiers?

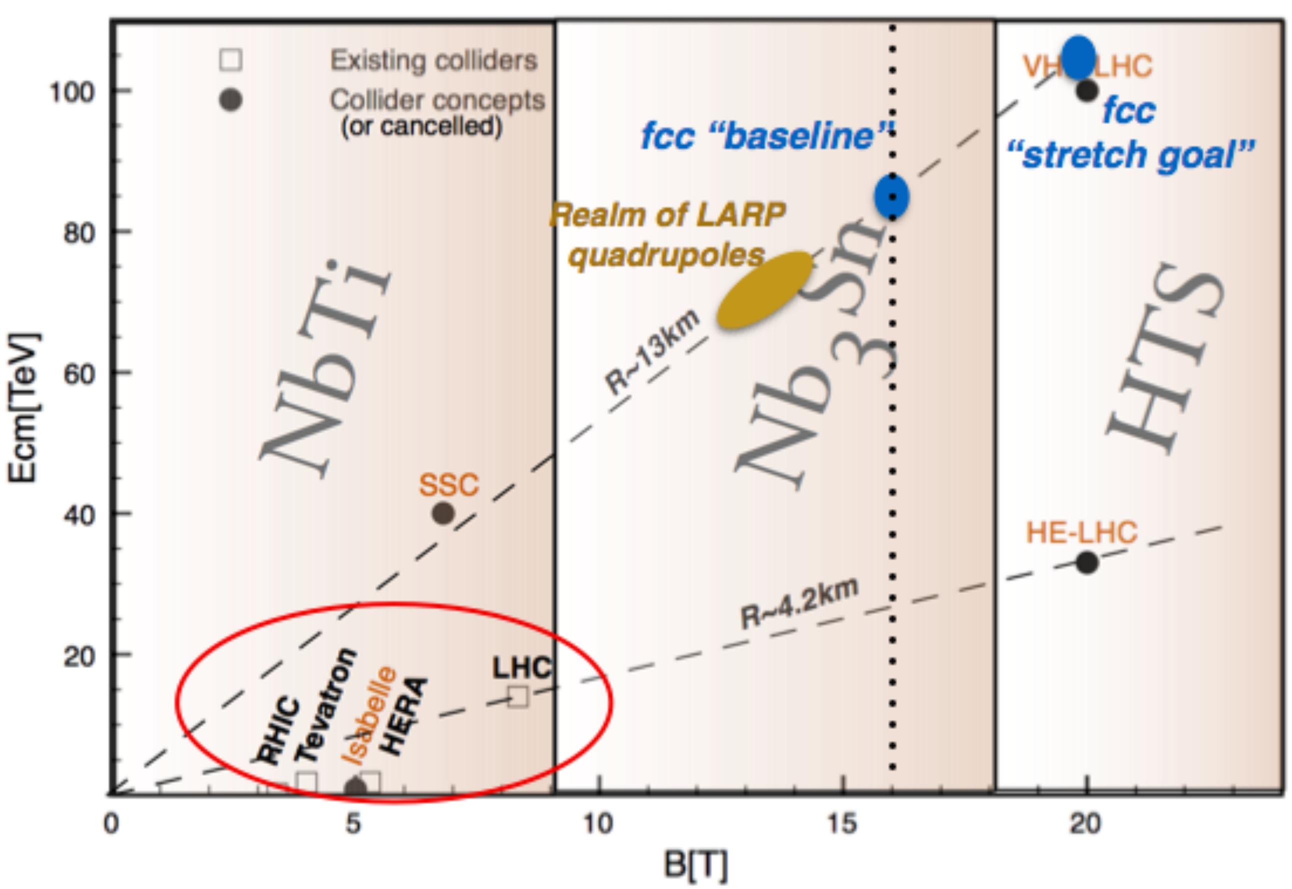
Setting the context:
Superconductors and high field magnets play lead role

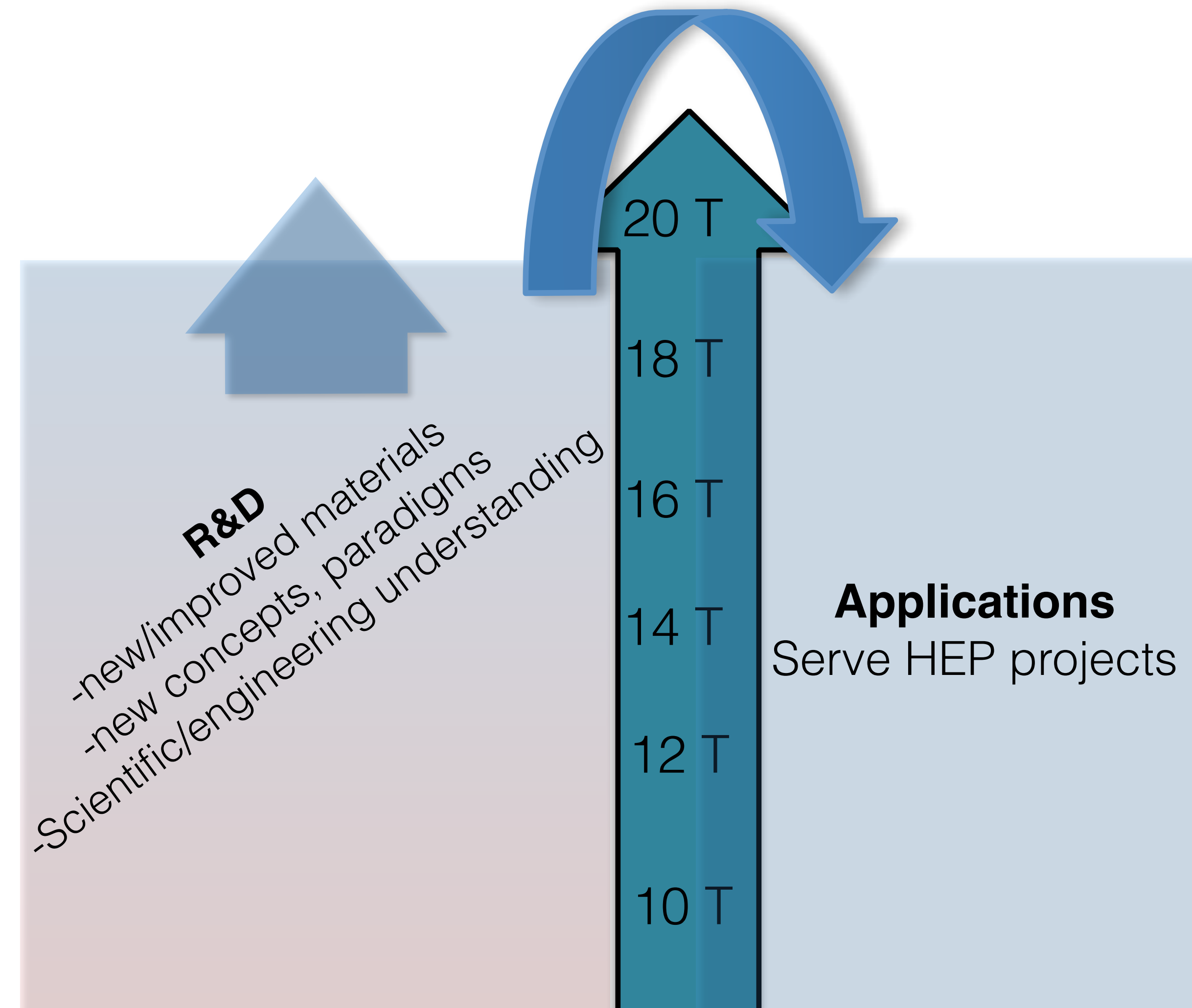
- A 100 TeV scale pp collider will be…
  - ➡ the largest experiment ever undertaken by the HEP community
  - ➡ the largest single experiment consumer of modern superconductors
- The cost of the collider will be driven by…
  - ➡ Tunneling ⇒ cost reduction driven by others
  - ➡ Magnets ⇒ cost reduction driven by HEP (frankly no one else cares)

The US is ***the recognized world leader*** in high-field magnet technology, the primary technology pillar of a 100TeV collider

R&D to maximize science:
Start with broad parameter space, identify drivers



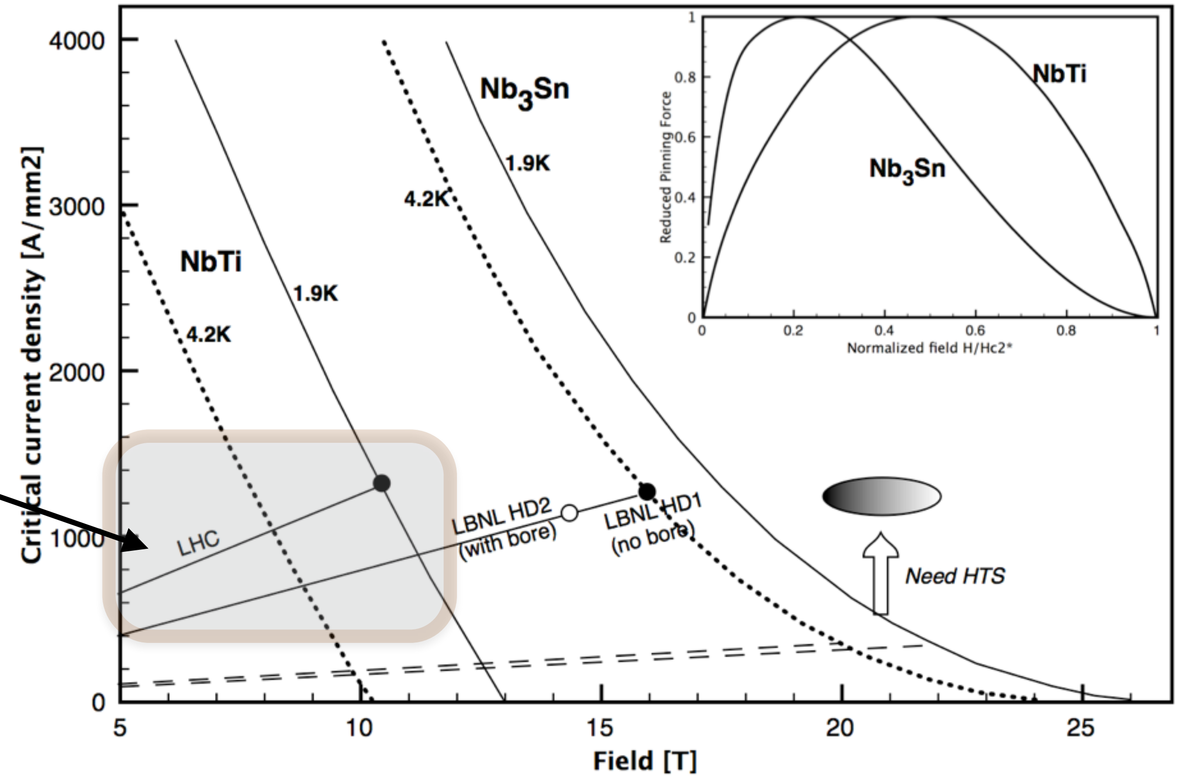


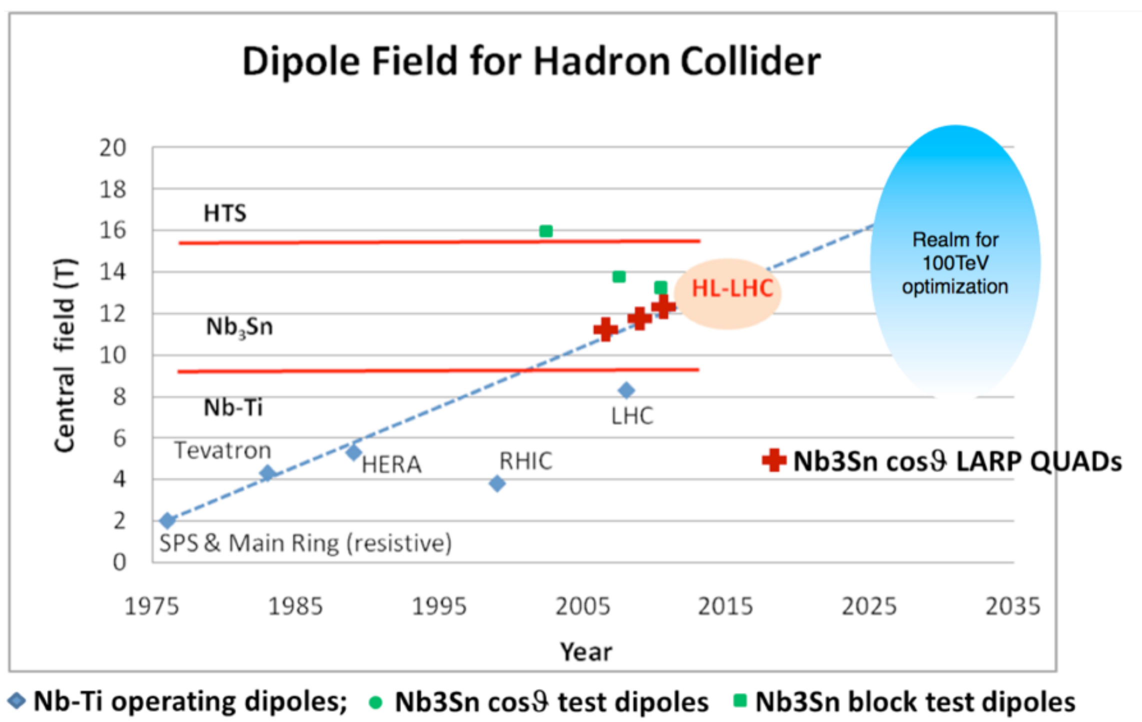


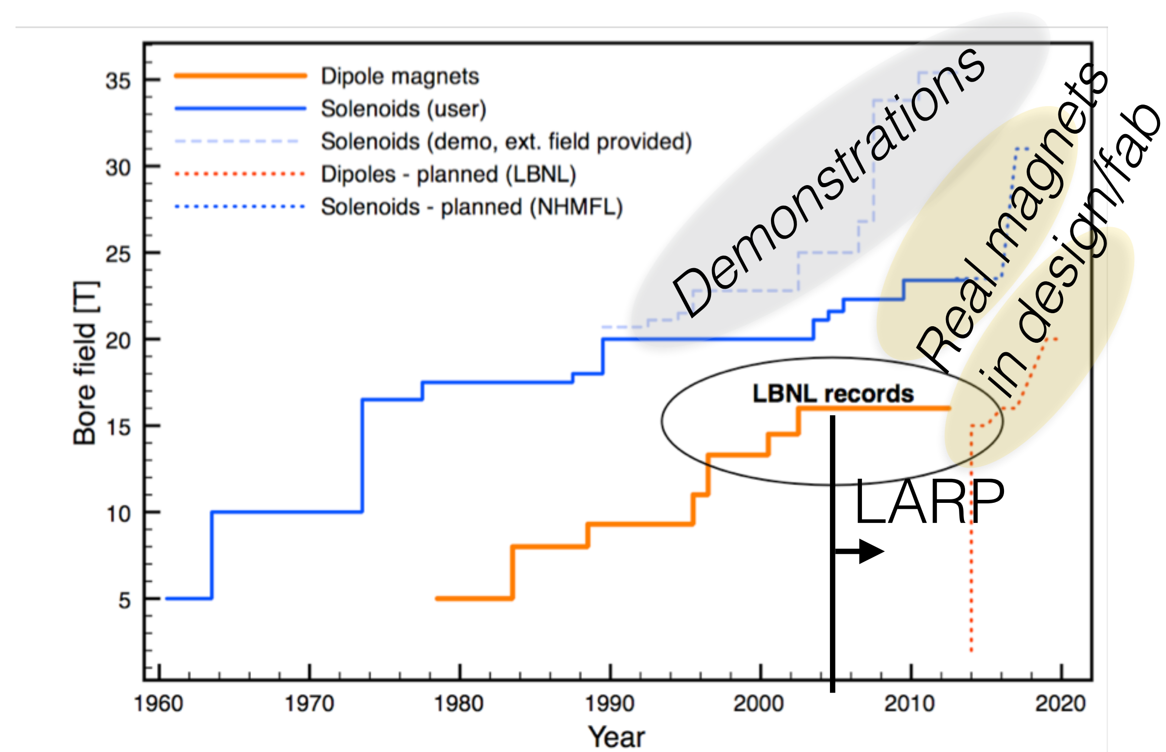
Transformational R&D comes from pushing the limits and introducing new paradigms

Setting the context:
There has been significant progress ⇒ US Leadership

Benefitted significantly from US-lead NbTi improvements, US magnet program developments for SSC







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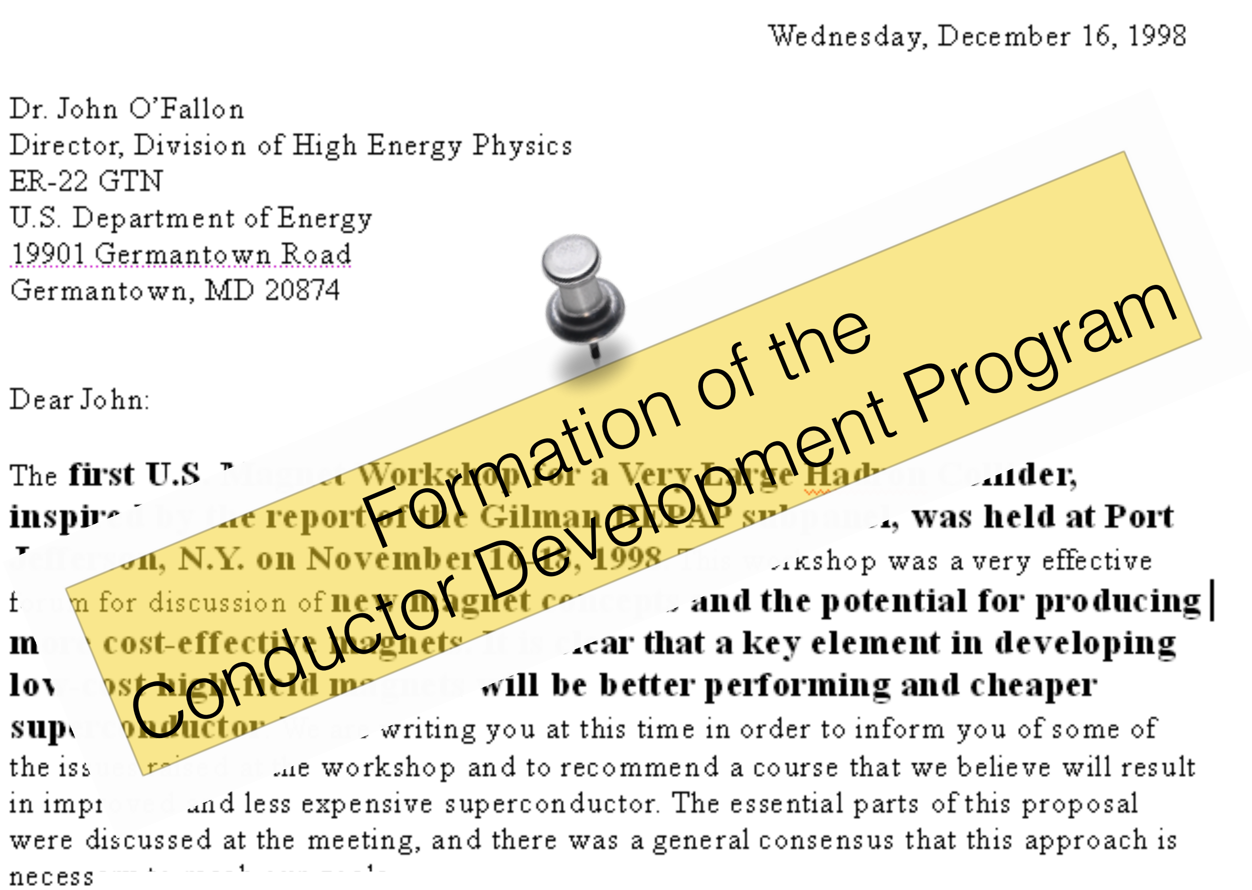
Goals based on *performance*, *realizability,* and *cost*

- Goals should
  - ➡ take into account performance:
    - ✓ *deliver significant materials improvements*
    - ✓ *deliver magnet technology advancements*
  - ➡ consider realizability:
    - ✓ *stress/probe the limits of technology (without breaking them!)*
    - ✓ *focus on simplicity, ability to industrialize*
  - ➡ ultimately focus on cost:
    - ✓ *approaching cost from multiple angles can result in significant subsystem/system/facility cost reductions*

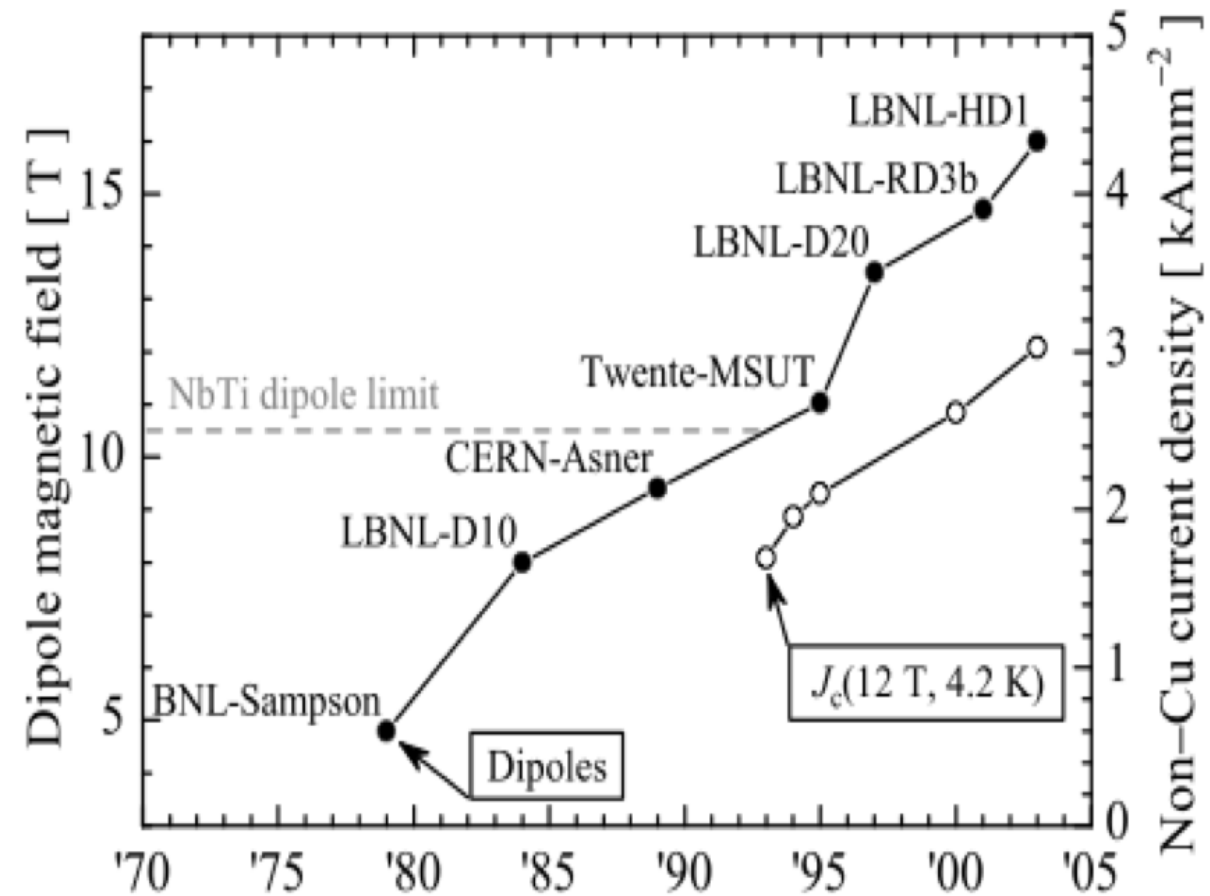
Conductor improvements⇒magnet performance


Wednesday, December 16, 1998

Dr. John O'Fallon
Director, Division of High Energy Physics
ER-22 GTN
U.S. Department of Energy
19901 Germantown Road
Germantown, MD 20874

Dear John:

The **first U.S** ... **Workshop for a Very Large Hadron Collider, inspir... the report of the Gilman HEPAP subpanel, was held at Port ... N.Y. on November 16-18, 1998** ... workshop was a very effective f... for discussion of **new magnet c... and the potential for producing m... cost-effective magnets ... clear that a key element in developing low cost high field magnets will be better performing and cheaper sup... conductor** ... writing you at this time in order to inform you of some of the iss... the workshop and to recommend a course that we believe will result in impr... and less expensive superconductor. The essential parts of this proposal were discussed at the meeting, and there was a general consensus that this approach is necess...



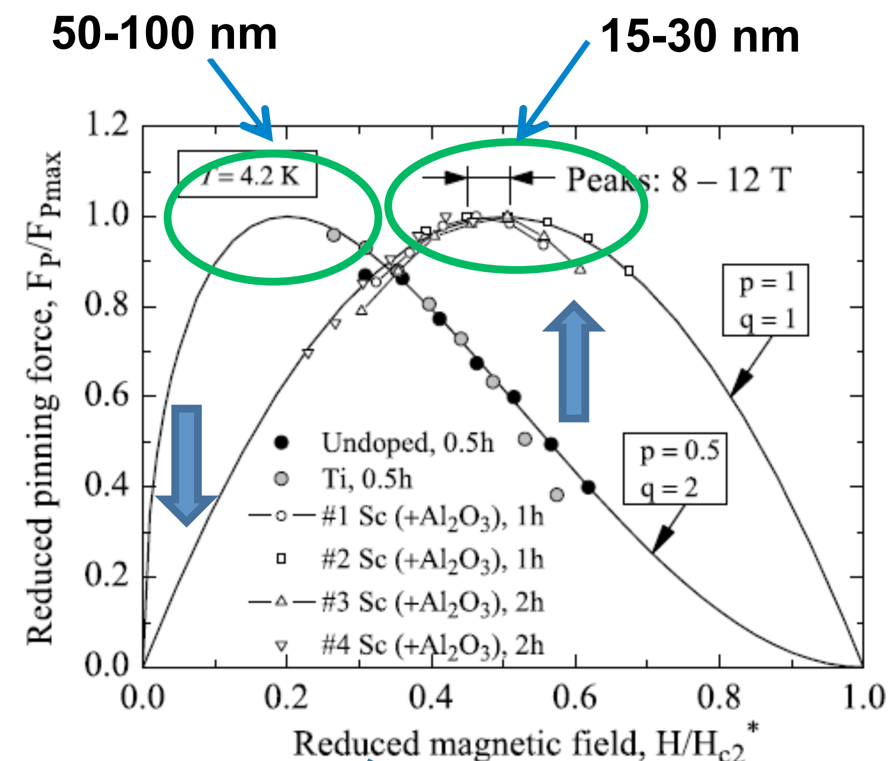
HEP-supported materials science at DOE&Universities+
Conductor Development Program+
Small-business Innovative Research+
Yearly Low-temperature Superconductor Workshop=
Consistent, significant conductor improvements

Nb_3Sn continues to impress: still has performance growth!

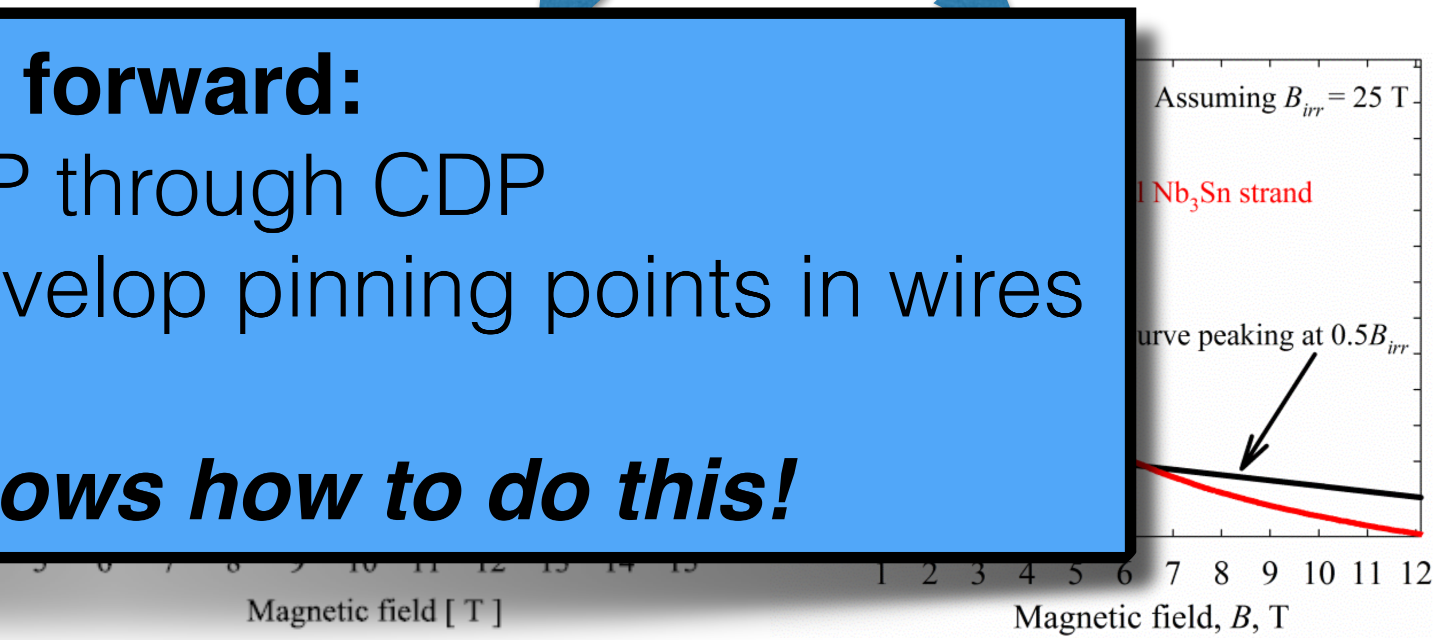
- Improve Jc(15T) ⇒2200-2500A/mm^2
- Maintain RRR>100-150
- Reduce D_{eff}
- Improve strain dependence

Not yet possible to get all of these; work with acc. phy. and magnet designers to ***optimize tradeoffs***

Significant D_{eff} reduction; Already sufficient?



D_w	Sub
Wire Diameter, mm	54/61 Stack
# of Sub-elements, N	54
1	93
0.85	79
0.8	74
0.778	72
0.7	65



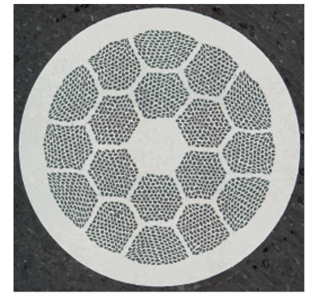
Path forward:

- Innovate with OST RRP through CDP
- Support industry to develop pinning points in wires

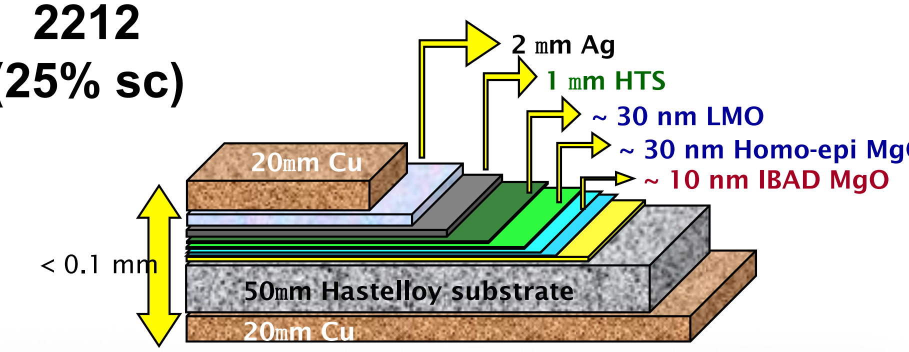
Only the US knows how to do this!

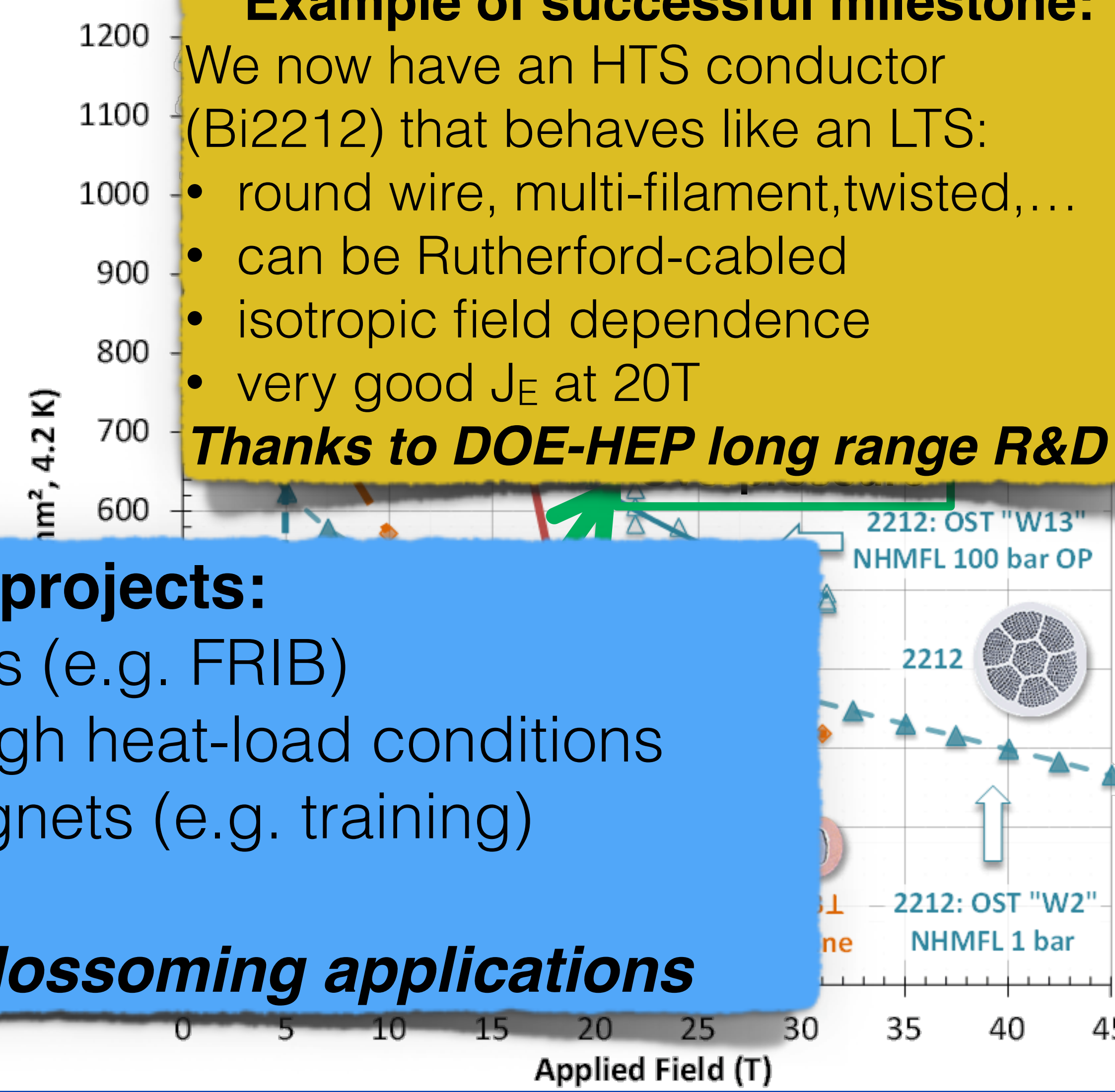
HTS: long-range critical technology for HEP, and DOE SC more broadly

- Long-term R&D is essential to:
  - ➡ *Develop critical conductor characteristics*
  - ➡ *Identify material compatibility for magnets*
  - ➡ *Develop associated magnet technologies*
    - ✓ Joints, insulation,…
    - ✓ Magnet protection
- Technology will feed broader HEP and other SC areas
  - ➡ *Fast ramping magnets, conduction cooled systems, etc.*



2212 (25% sc)





Example of successful milestone:

We now have an HTS conductor (Bi2212) that behaves like an LTS:

- round wire, multi-filament,twisted,…
- can be Rutherford-cabled
- isotropic field dependence
- very good J_E at 20T

Thanks to DOE-HEP long range R&D

Broad potential for projects:

- Being applied to specific HEP projects (e.g. FRIB)
- Candidate for high-radiation and/or high heat-load conditions
- May alleviate issues for high-field magnets (e.g. training)

Further development will result in blossoming applications

Goals for conductor development

- Define aggressive goals, focussed on real need. Examples for Nb_3Sn are:
  - ➡ *J_c(15T, 4.2K)>2200A/mm2*
  - ➡ *D_{eff}<40 microns (30?; 20?); requires tradeoff with acc. physics*
  - ➡ *Cost reduction of factor 2 (3?; more?) in $/kA-m(15T)*

The existing HEP-driven CDP, SBIR programs, and LTSW structure are well-suited to identify goals for LTS and HTS materials, aligned with HEP needs

Summary

- Maintain (possibly grow) very successful CDP and SBIR programs, and LTSW
  - ***Collaboration between HEP Univ. programs, DOE labs, and industry is exemplary***
- ***Balanced program*** focusing on cost/performance improvements:
  - *Improving Nb_3Sn at higher field: ~x2 improvement in Jc(15T) within ~5 years*
  - *Improving Nb_3Sn cost reduction potential through conductor design, scalability*
  - *Developing HTS for accelerator applications:*
    - reliable J_E>600A/mm^2 at ~20T in magnet-relevant lengths
    - cost-effective, magnet-suitable cables for high-current operation

Goals for magnets

- The magnet community needs
  - ➡ To make breakthroughs in ***understanding*** magnet performance
    - ✓ The ***science*** and ***advanced engineering*** of magnets and associated systems
  - ➡ To leverage knowledge to develop ***improved concepts***
    - ✓ Address stresses, fabrication simplicity and reproducibility, system cost

Focus on significant cost reduction

Address key areas that are costly:

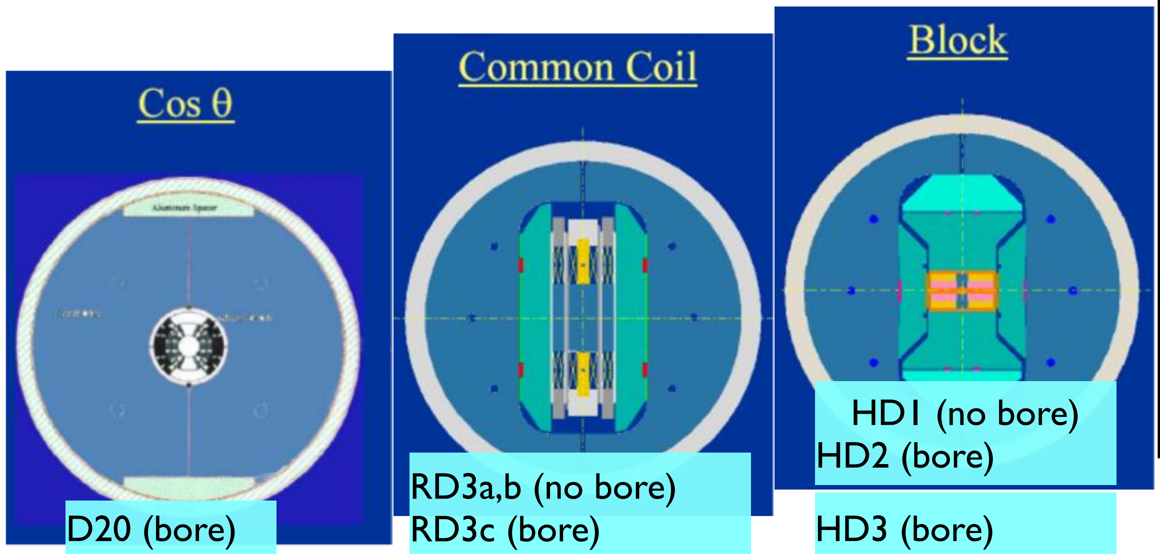
- *Fully leverage conductor potential*
- *Reduce training and required operational margin*
- *Reduce dramatically the touch-labor required in fab*

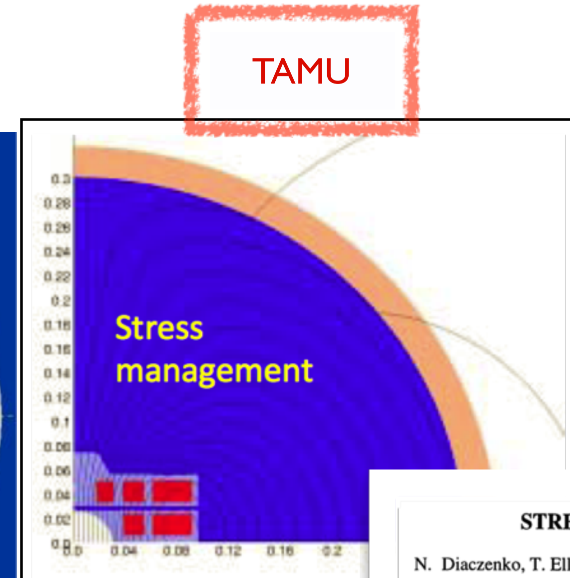
Current US Leadership in the field is testament to a historically robust program

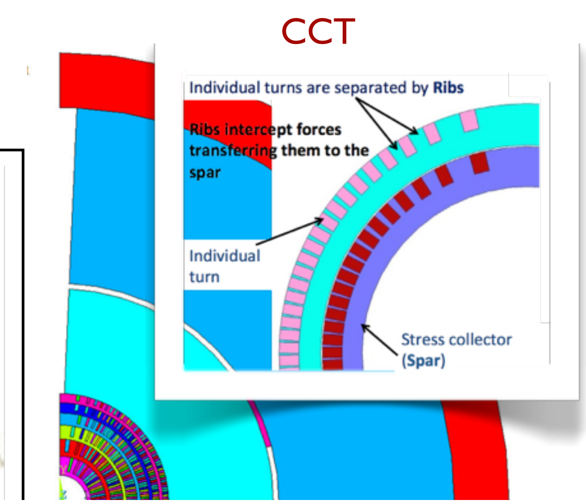
Moving forward, a goal-oriented, coordinated National Program will serve to:

- focus research groups
- provide objective measures of progress/success
- provide quantitative measures for DOE Program Managers

Many design concepts: room for new paradigms: Block and CCT challenge traditional Cos(θ)

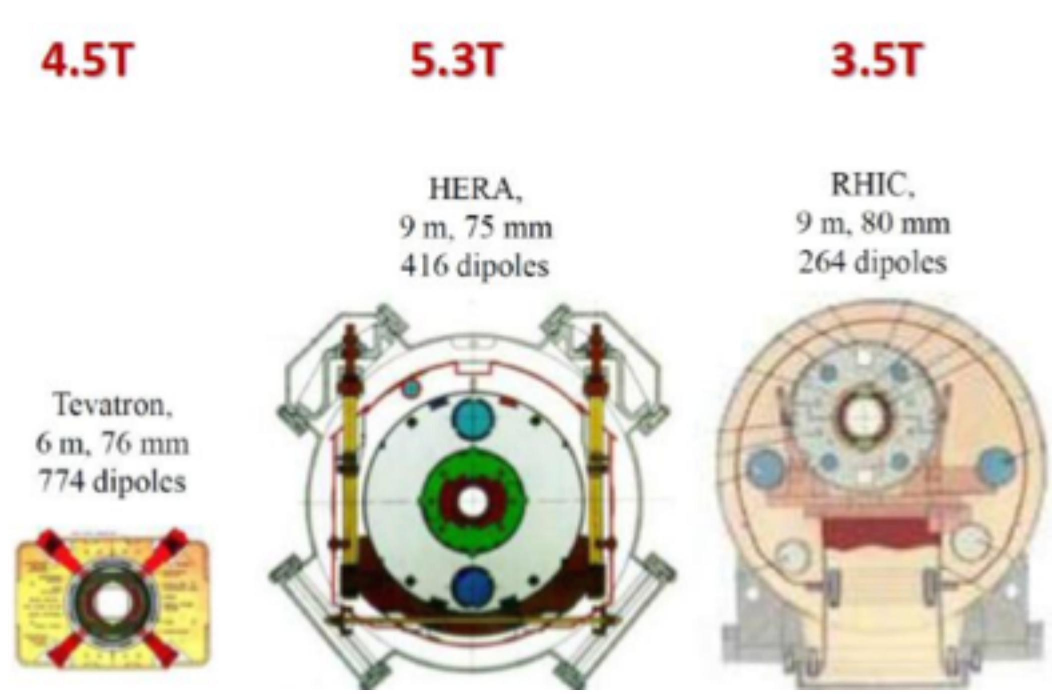




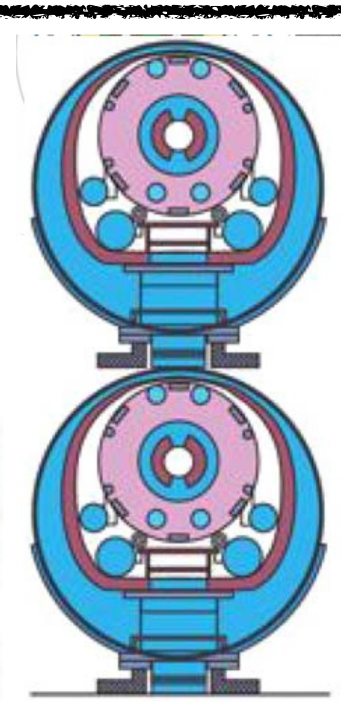


STRESS MANAGEMENT IN HIGH-FIELD DIPOLES

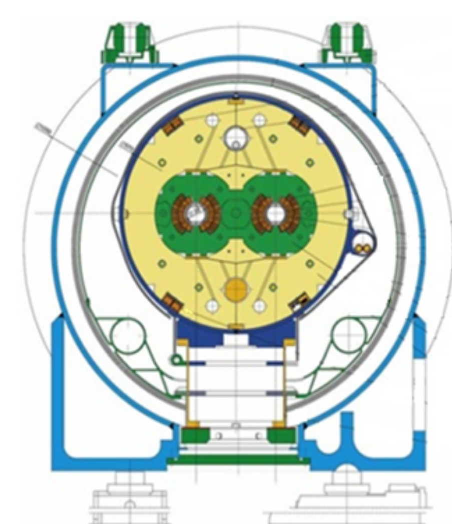
N. Diaczenko, T. Elliott, A. Jaisle, D. Latypov, P. McIntyre, P. McJunkins, L. Richards, W. Shen, R. Soika, D. Wendt, Dept. of Physics, Texas A&M University, College Station, TX 77843
R. Gaedke, Dept. of Physics, Trinity University, San Antonio, TX 78212



Shiltsev/Zlobin

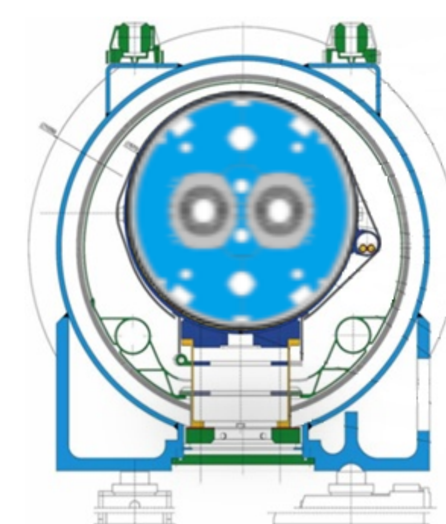


SSC, 50 mm
6.6 T, 4.3 K

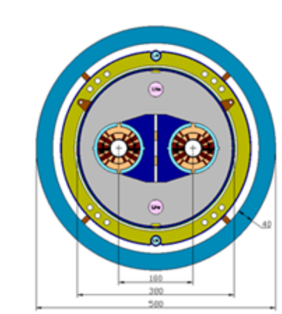


LHC, 56 mm
8.3 T, 1.9 K

Being developed: FNAL⇒CERN



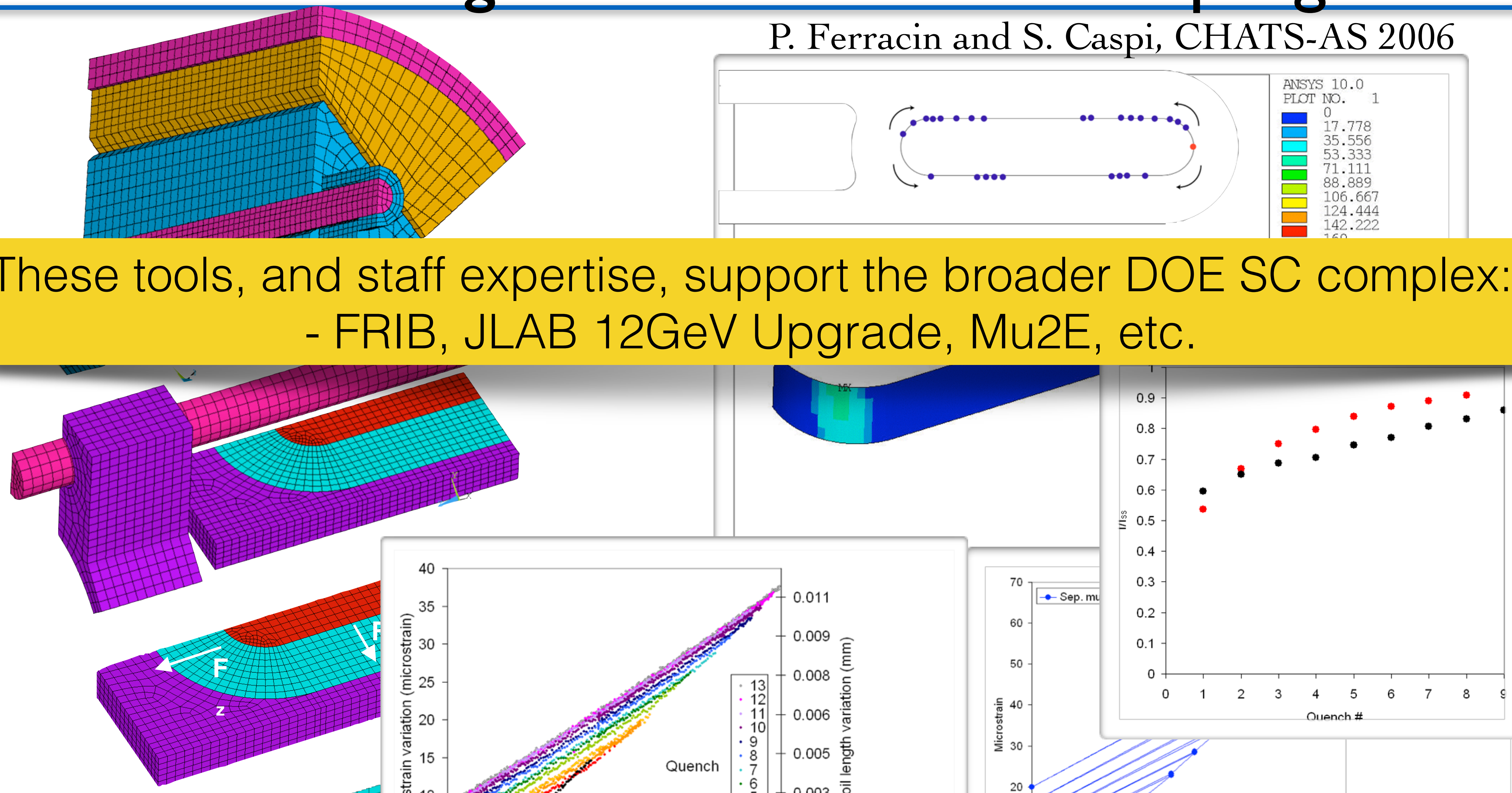
LHC, 60 mm
11 T, 1.9 K



VLHC, 43 mm
10 T, 4.5 K

Example of magnet science:
Understanding is critical to sustained progress

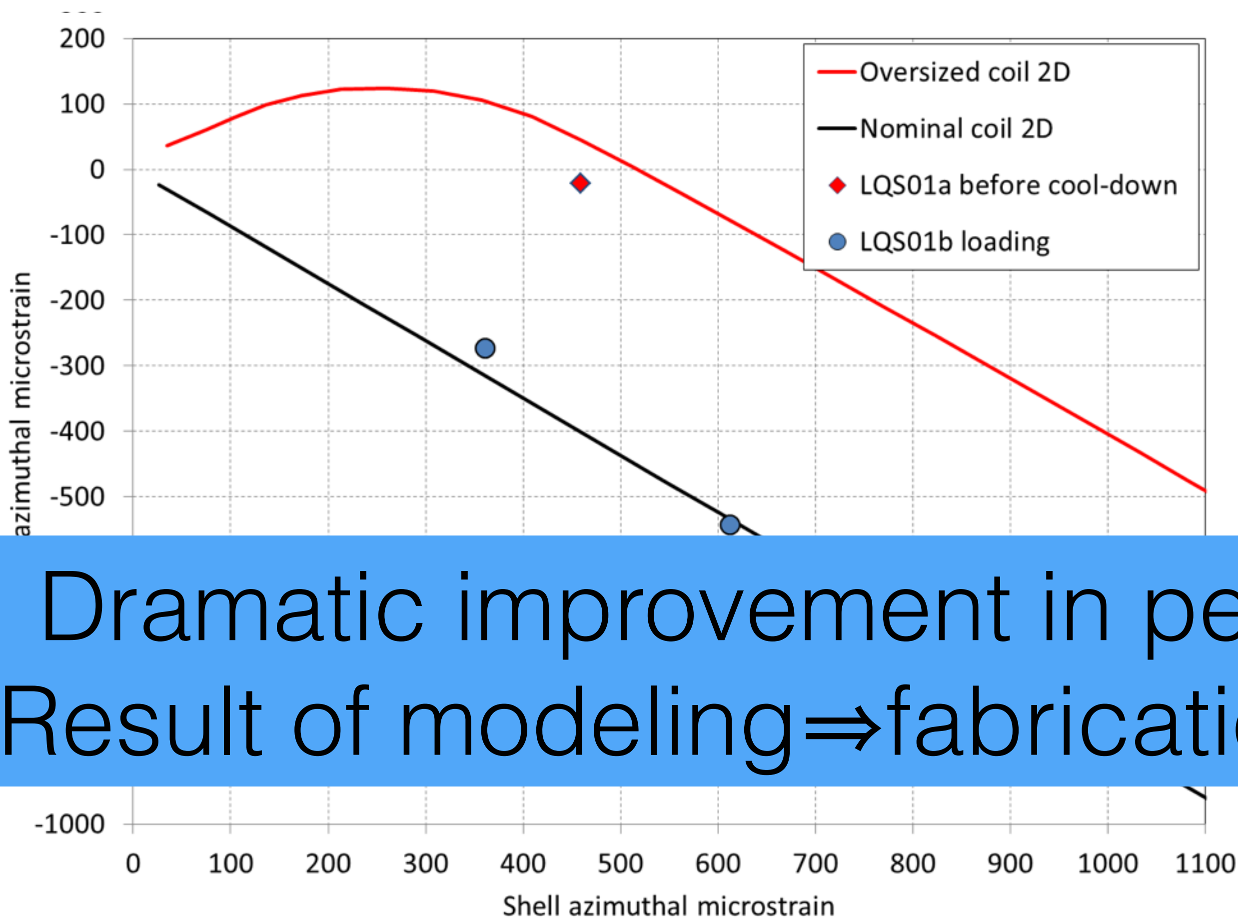
P. Ferracin and S. Caspi, CHATS-AS 2006

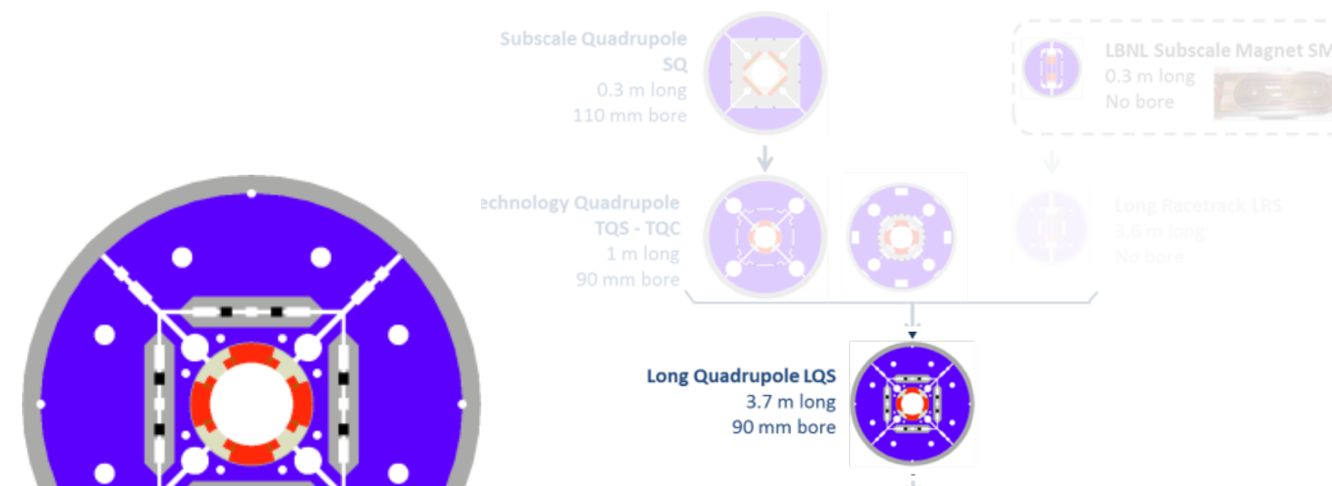


These tools, and staff expertise, support the broader DOE SC complex:
- FRIB, JLAB 12GeV Upgrade, Mu2E, etc.

Understanding ***mechanisms*** of magnet ***training***
Result of modeling⇒diagnostics⇒testing⇒feedback

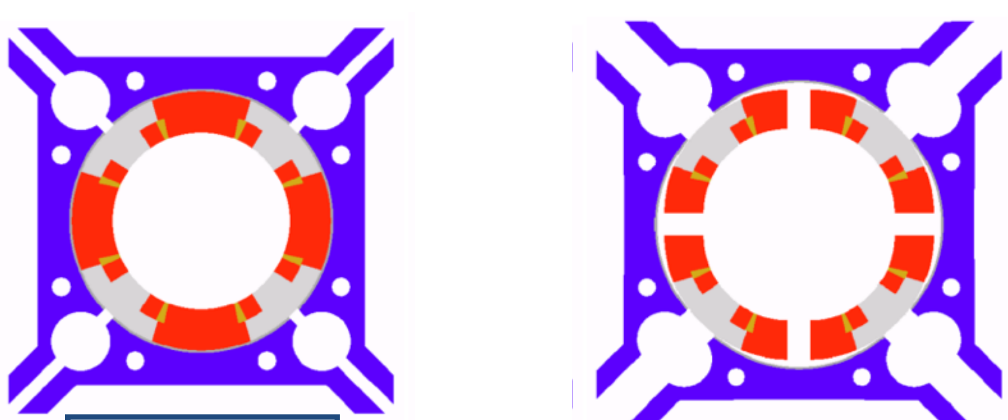
Example of integrated approach between magnet modeling, assembly and performance





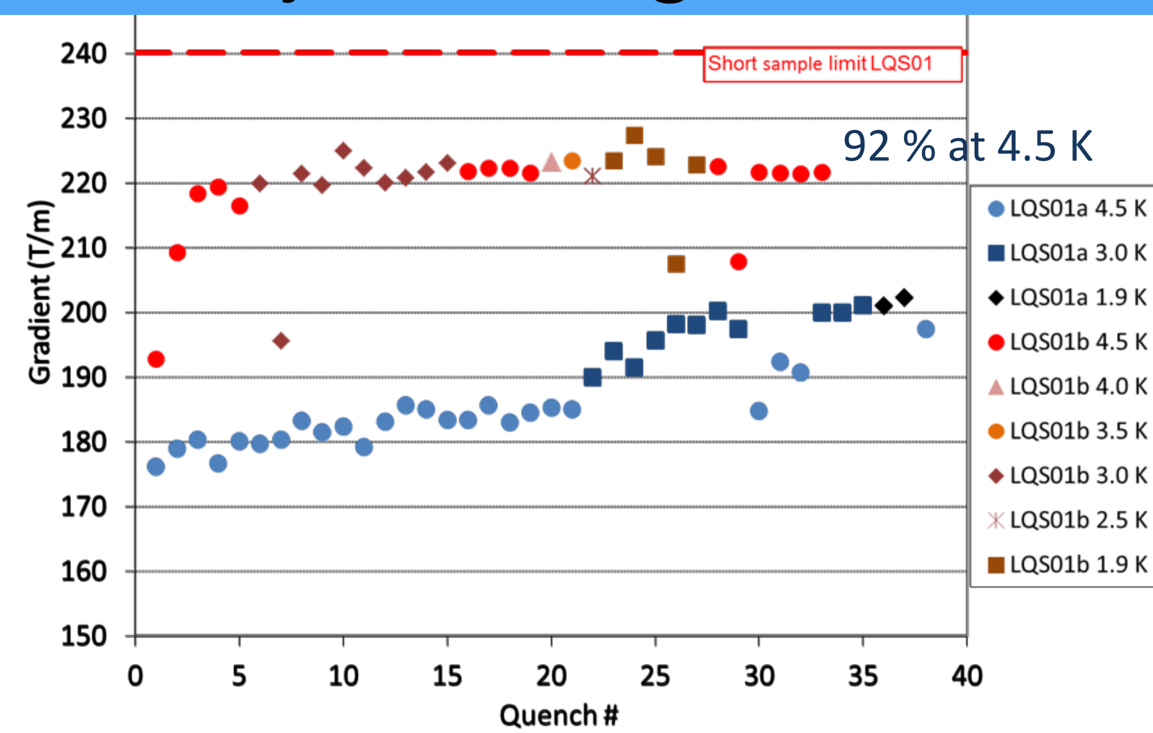
Dramatic improvement in performance: *training and margin*

Result of modeling⇒fabrication&assembly⇒testing⇒feedback



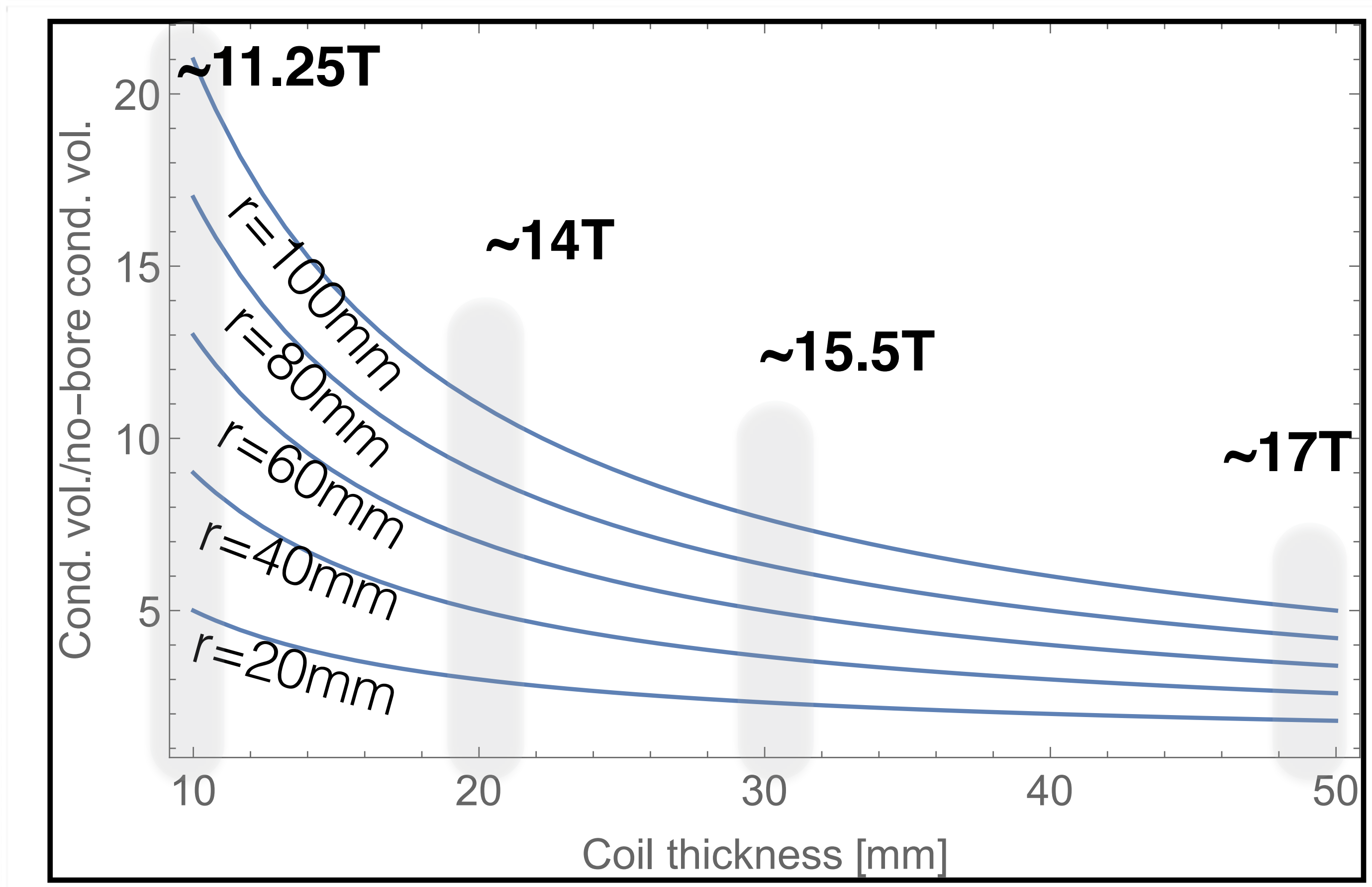
Nominal

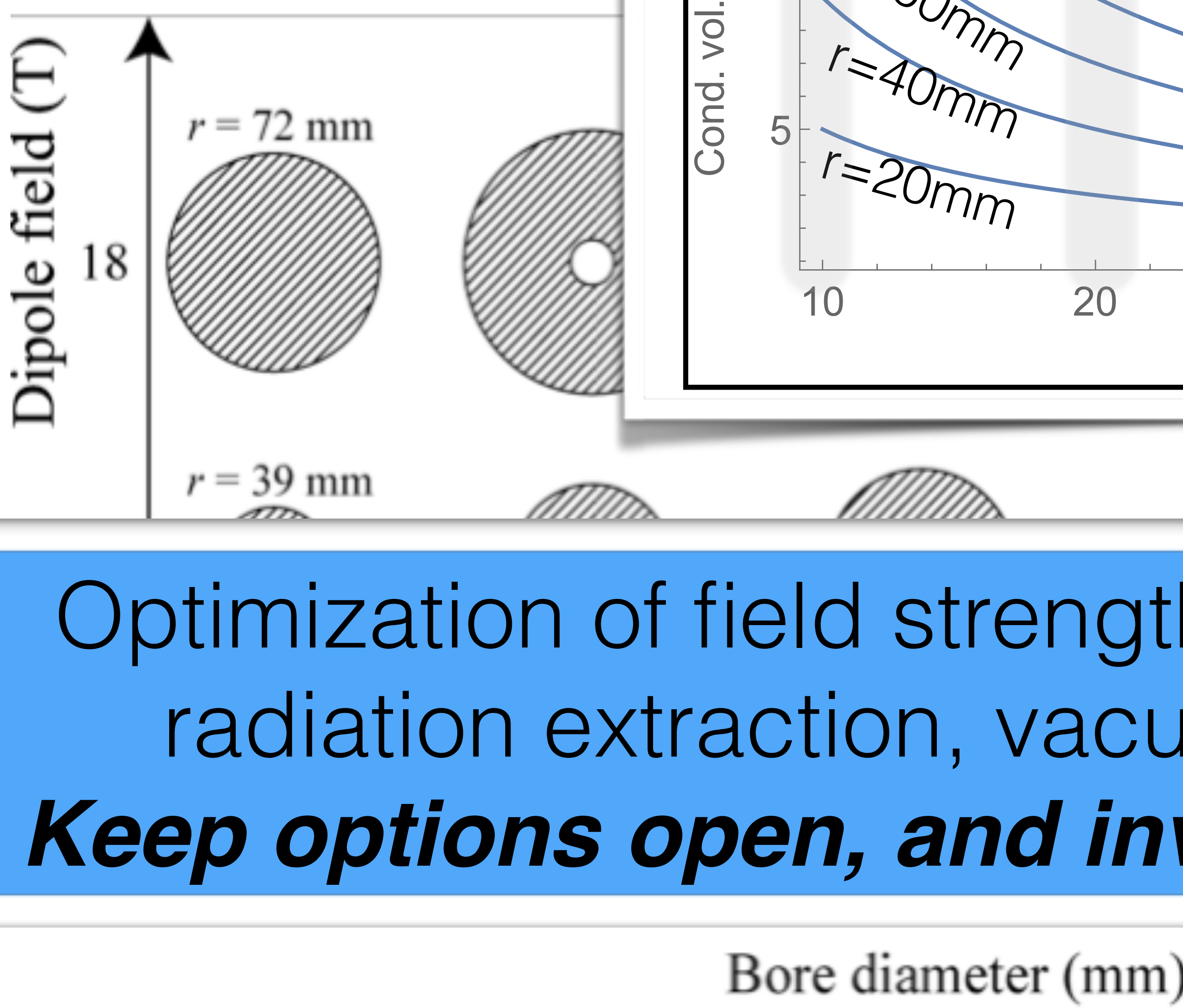
Oversized

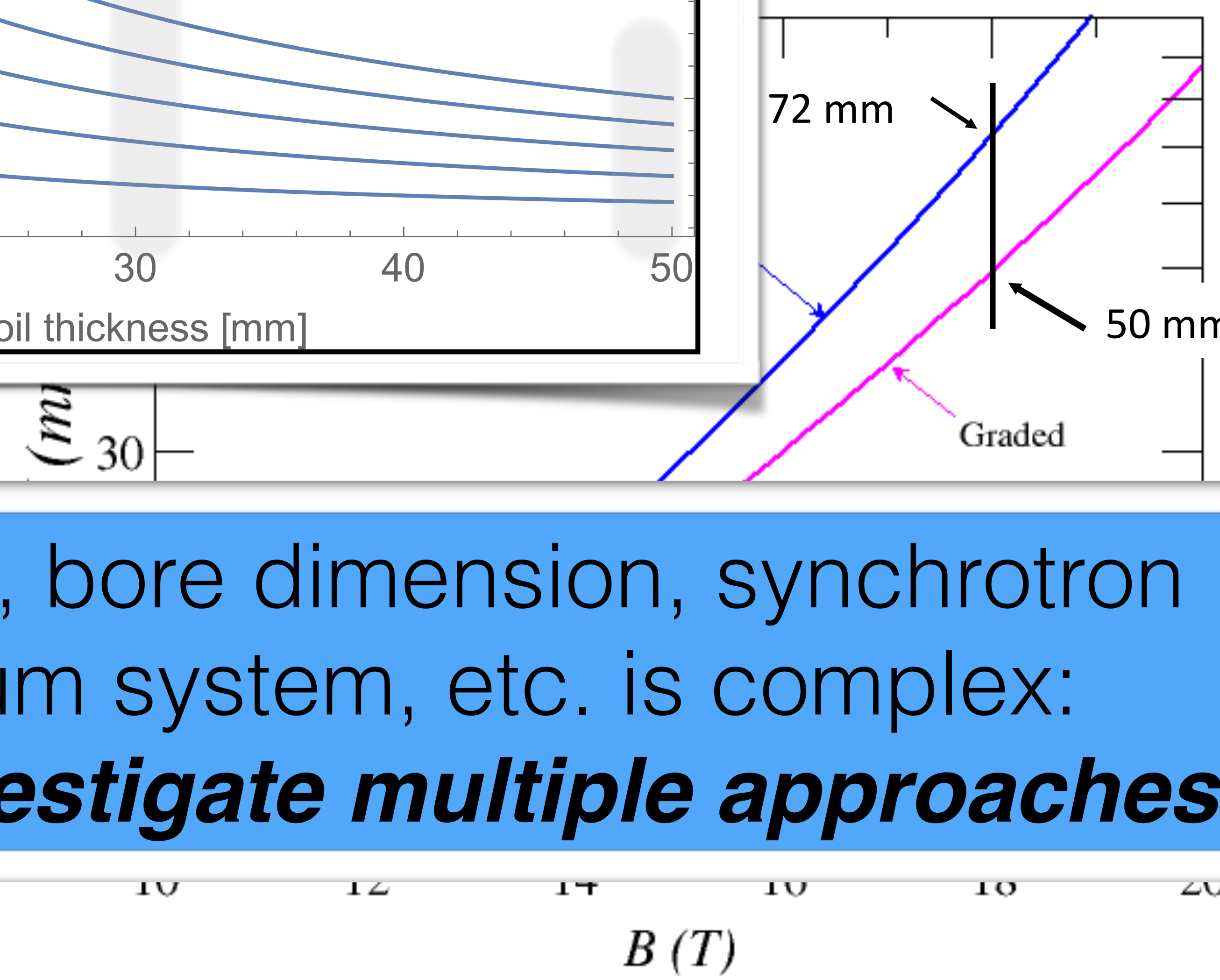


Accounting for coil size variations: from R&D to production

Focus on cost model assumptions:
Relative impact of bore size decreases at high field





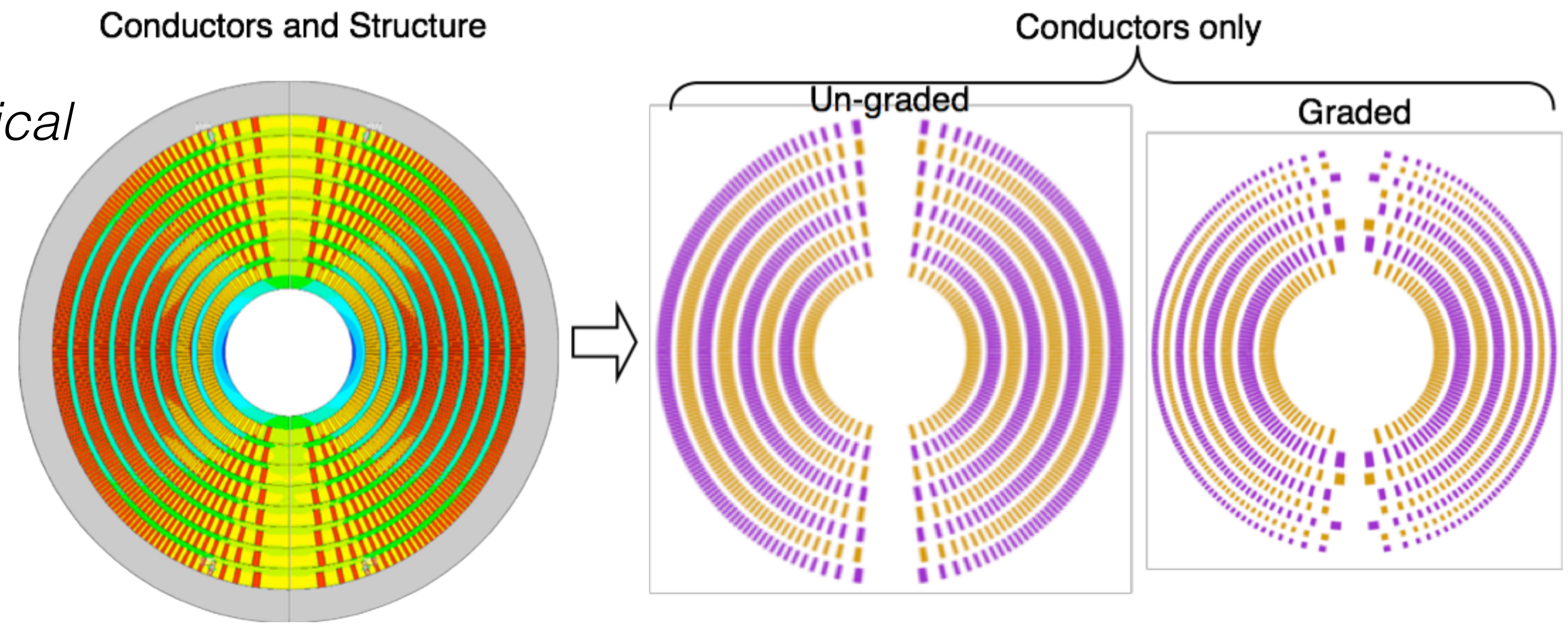


Optimization of field strength, bore dimension, synchrotron radiation extraction, vacuum system, etc. is complex:

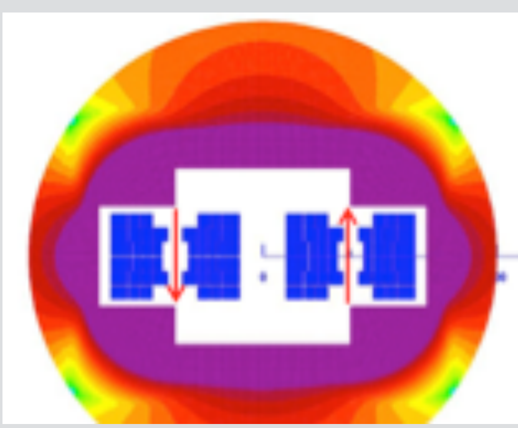
Keep options open, and investigate multiple approaches

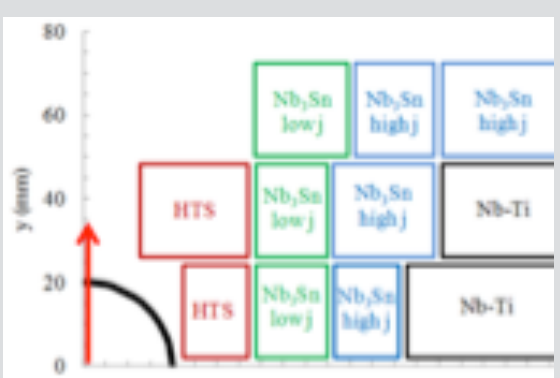
Focus on cost model assumptions: Grading the conductor ⇒ ~40% less conductor at 16T

- Example of CCT
  - ✓ *intercepting azimuthal stress is critical*
- LHC dipoles (Cos(θ)) had 2 grades of conductor
- *Requires stress interception*

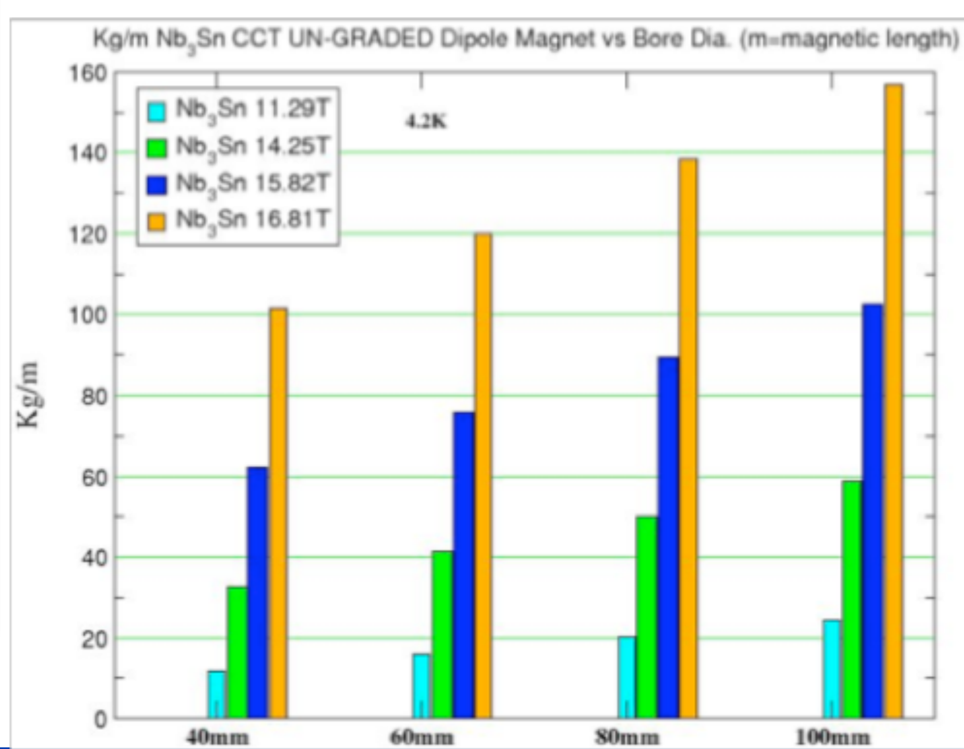


CERN concept for block:

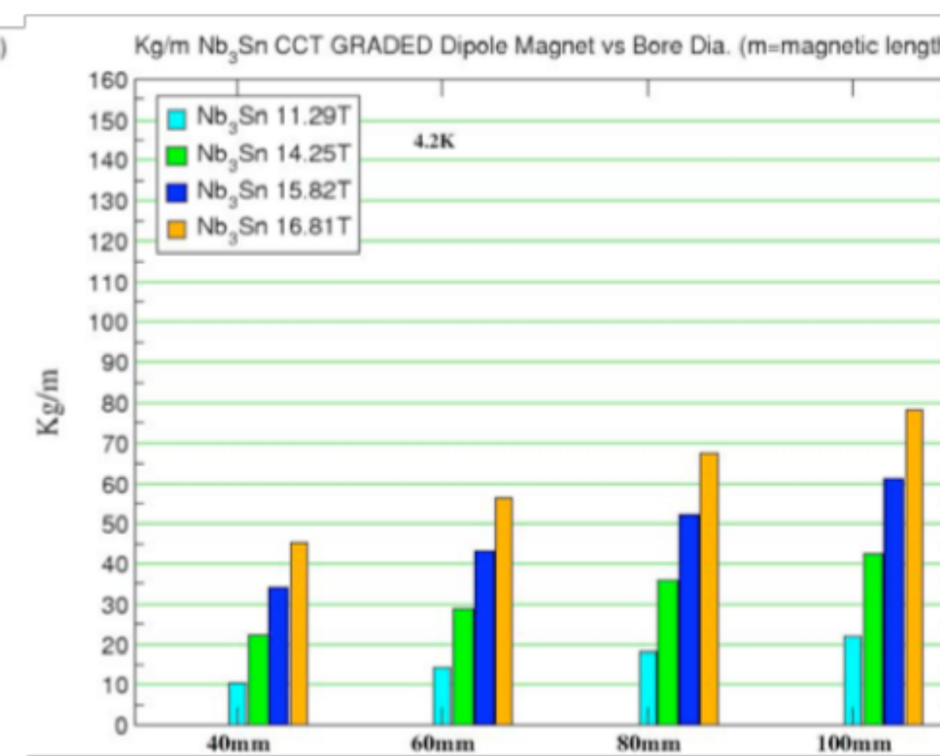




Un-graded CCT



Graded CCT



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Achieving the goals requires ***resources*** and ***accountability***

- Progress in magnets requires consistent application of the research loop:
  - ➡ *Design&analysis - fabrication - test&diagnostics - feedback*
  - ➡ *Need to push for results, e.g. multiple tests/year*
  - ➡ *Need freedom to make mistakes, but expectation of real breakthroughs*
- Magnet research results in tools/capabilities that feed the community
  - ➡ *Design and analysis yields tools that support HEP projects*
  - ➡ *Materials developments (superconducting, dielectrics, etc.) that feed projects*
  - ➡ *Magnet testing provides novel diagnostics, feedback on design tools*

US leadership in the field stems from a strong, large US superconductor industry, closely linked to DOE-HEP, and from innovative magnet programs that enable new accelerator capabilities

Achieving the goals requires ***resources*** and ***accountability***

- Staff need to be dedicated to (or sizable fraction of time on) R&D
  - ➡ *need to foster culture of innovation & intensity/urgency of research*
  - ➡ *Interfacing/consulting with HEP projects is valuable*
  - ➡ *Need key expertise to make rapid progress*
- Need dedicated (or good availability of) fabrication and testing capabilities
- Funding must provide good balance of M&S and Staff
  - ➡ *need to avoid pitfall of "resources without hardware"*

Programs need…

- ***to be sufficiently funded to accomplish their mission***
- ***to be accountable for progress on achieving goals***

Research management

- Consider mechanisms for national coordination of magnet community efforts, and develop a process to define and focus program goals
  - ➡ Characteristics sought:
    - ✓ coordination of efforts for efficiency
    - ✓ goal-oriented efforts, ***but not project-ized!***
    - ✓ focus research on key areas (avoid dilution of funds)
    - ✓ research should have ***science*** at core: advances must ***last***

Goals, milestones, and performance should guide funding in a budget-limited environment

- Magnet efforts should be communicated, and possibly coordinated, among the international research groups
- Design tradeoffs between accelerator physics and magnets must be understood for design optimization:
  - ➡ recommend strong communication between these areas, e.g. routine workshops

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Training and staff development

- The DOE labs, the NSF-funded NHMFL, and the HEP-funded university programs are the primary source of accelerator magnet expertise
  - ➡ *USPAS provides excellent opportunities for staff development*
- The US laboratories have successfully recruited top talent from international (primarily European) laboratories
  - ➡ *Recently this tide is changing due to HEP uncertainties*
- Reestablishment of a healthy HEP magnet program is necessary to rekindle interest from early-career talent, critical to maintain long-term leadership in the field
  - ➡ *Also critical to provide scientific support of LARP⇒HiLumi*

We are the go-to laboratories for superconducting accelerator magnet scientists, but maintaining this role requires sustained commitment in funding and programs

The Magnet Programs have fostered critical expertise

- Examples of magnet/materials staff that came up through the DOE / University programs:
  - ➡ In labs now: Cooley, Prestemon, Wang, Godeke, Shen, Holick…
  - ➡ In industry: Parrel, Field, …
- Examples from Europe:
  - ➡ Sabbi, Ambrosio, Felice, Pong, …
- But also the other way:
  - ➡ Ferracin [CERN], Bordini [CERN], Borgnolutti [SACLAY], Rochepault[CERN],…

> Maintaining, and strengthening, the pool of expertise in superconducting materials and magnets is critical to DOE-SC's mission

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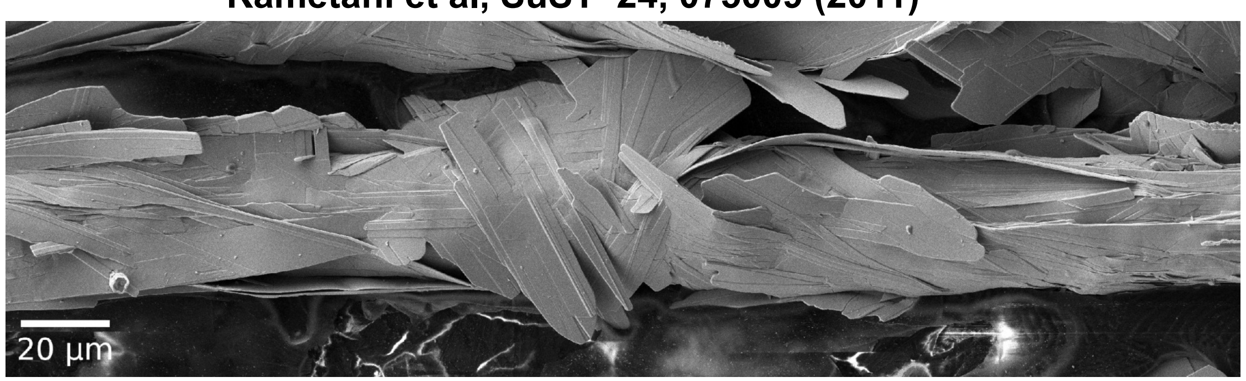
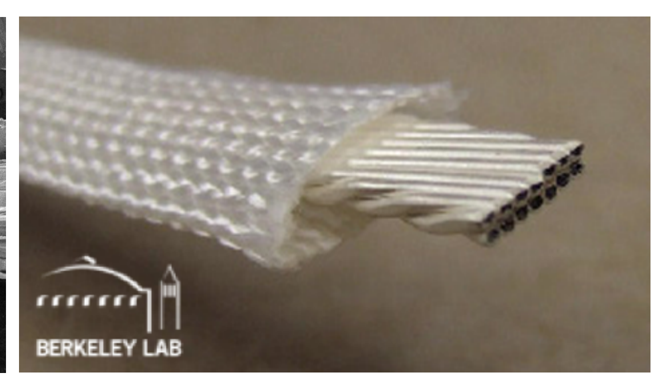
A well-funded R&D effort starts with conductors

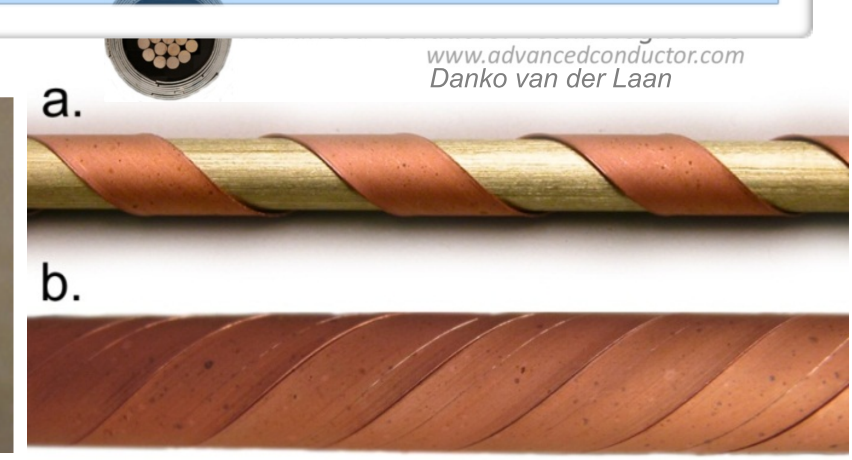
- Enhanced superconducting materials research:
  - ➡ *Fund parallel efforts to increase Jc(15T) of Nb_3Sn*
    - ✓ impacts HEP, but also NMR, condensed matter physics
  - ➡ *Significant investment in both Bi2212 and YBCO efforts*
    - ✓ DOE labs and Universities can provide critical expertise in these efforts, and provide an application pull
    - ✓ Industry needs to see application pull to justify investing in development

Would impact other HEP and SC programs, e.g. fast-ramping synchrotrons, magnets in high-radiation environments

Kametani et al, SuST 24, 075009 (2011)







A well-funded magnet R&D effort would have broad impact

- Parallel investigation of new magnet concepts:
  - ➡ fast-paced, energetic, friendly but competitive concept development
    - ✓ most effective approach for fast R&D payback
  - ➡ investigate broader spectrum of magnet configurations for pp colliders to improve cost and performance models & system optimization ⟹*significant US role in facility optimization*
  - ➡ would result in significant new diagnostics for the community, and insight into magnet performance ⟹*understanding the science is key to long-term leadership*
  - ➡ would provide important magnet advances relevant to broader HEP and other SC arenas: fast-ramping magnets, magnets for high-radiation environments
- Strong staff development
  - ➡ provide effective *risk mitigation for LARP/HiLumi*
  - ➡ cement *US leadership* in this arena

A goal-oriented National Magnet Program is a core element of transformational R&D for a collider

- Focus programs on innovation towards cost reduction on 3 fronts:
  - ➡ Improved scientific/engineering understanding⇒reduce training, margin
  - ➡ Simplified magnet construction
    - ✓ Coil fabrication ⇒ *reduce hardware and touch-labor cost*
    - ✓ Structures
  - ➡ Improved use of conductor⇒leverage Jc improvements, incorporate grading

Area	Comment on todays technology	Improvement potential	Cost reduction potential
Training	Must be very low for dipoles		
Margin	Typically 20-25%, driven by "unknowns";	bring to <10%	factor 1.5 (?)
Coil & Structure	Lots of touch labor, special components	Significant; simplify parts, focus on scalability	factor 2-3 (more?)
Conductor	Nb_3 expensive; HTS is early in development, very expensive	Nb_3Sn: significant increase in Jc(15T) possible, and cost reduction also; HTS: significant increase inJ	factor 2-3

Summary

- Focus on changing current paradigms ⇒ transformational R&D
  - ➡ Identify and address limitations of current state of the art
  - ➡ Identify and focus on cost drivers in current models

> Historical Edisonial approach is being replaced with ***science-based research & development***

Magnet model (based on earlier studies[8, 9])

- Current densities vs. B by fits to NHMFL data[10]
- Assume degradations, packing factors, & margins from LHC[6]
- Determine a cos theta coils thickness
- Add Fe to return all flux^2 assuming $B_{sat} = 2$ T
- Leaving spaces for cryogenic insulation taken from LHC
- Cost super-conductor per kgm using HE-LHC[1] costs
- Cost structures $\propto$ weight escalated from SSC[11]
- Cost cryogenics $\propto$ cold surface area$/T(K)$, scaled from SSC[11]
- Add linear costs based on escalated SSC[11]
- Iron & stainless steel, including manufacture, proportional to weights as determined from SSC[11] study

Three R&D pillars

Conductors

Science&Engineering

Magnet Construction