Proposed US Activities for Future Circular Colliders

W. Barletta, G. Sabbi

Exploring the Physics Frontier with Circular Colliders

January 26 - February 1st, 2015

Outline

- P5 Recommendations relevant to Future Circular Colliders
- Accelerator R&D priorities and proposals under consideration
  - Accelerator studies for a 100 TeV proton collider
    - Vacuum and synchrotron radiation
    - Machine protection, radiation, beam physics
  - Magnet development for a 100 TeV pp collider
    - Main drivers and opportunities for cost reduction
    - Results from ongoing US programs (GARD and LARP)
    - Proposals for future activities
  - Potential contributions to FCC-ee, CEPC and SppC
- Summary

P5 Guidance on Future Circular Colliders

From the Particle Physics Project Prioritization Panel (P5) May 2014 Report *"Strategic Plan for U.S. Particle Physics in the Global Context"*

- Recommendation #24: Participate in global conceptual design studies and critical path R&D for future very high-energy proton-proton colliders. Continue to play a leadership role in superconducting magnet technology focused on the dual goals of increasing performance and decreasing costs.
- Recommendation 26: Pursue accelerator R&D with high priority at levels consistent with budget constraints. Align the present R&D program with the P5 priorities and long-term vision, with an appropriate balance among general R&D, directed R&D, and accelerator test facilities and among short-, medium-, and long-term efforts. Focus on outcomes and capabilities that will dramatically improve cost effectiveness for mid-term and far-term accelerators.
- A HEPAP subcommittee on accelerator R&D will provide detailed guidance on the implementation of accelerator R&D aligned with P5 priorities.

Accelerator R&D Sub-Panel

Charge (June): provide input on

- Appropriate goals for medium- and long-term R&D
- Scope of the current effort and its alignment with goals
- Requirements/impediments related to resources, management, expertise and infrastructure
- Assess if training of accelerator scientists and engineers is adequately addressed
- How to maintain an appropriate balance for the program in different budget scenarios

Community input (August-September):

- Meetings at BNL (energy frontier), FNAL, SLAC/LBNL
- Public submissions through the website: http://www.usparticlephysics.org/p5/ards

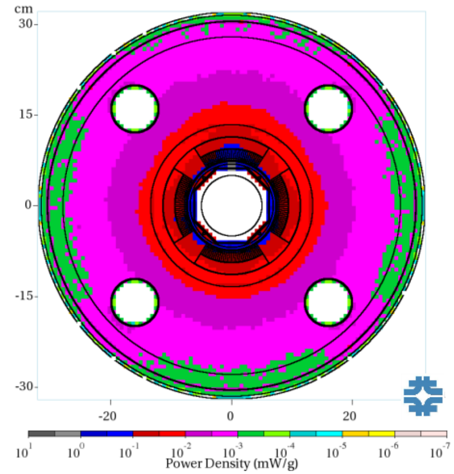
Next phase: discussions and deliberations:

- Sub-panel meetings and teleconferences
- Reporting

Members:

- Bill Barletta (MIT)
- Ilan Ben-Zvi (BNL, Stonybrook)
- Marty Breidenbach (SLAC)
- Oliver Bruning (CERN)
- Bruce Carlsten (Los Alamos)
- Roger Dixon (Fermilab)
- Steve Gourlay (LBNL)
- Don Hartill, Chair (Cornell)
- Georg Hoffstaetter (Cornell)
- Zhirong Huang (SLAC)
- Tadashi Koseki (KEK/J-PARC)
- Geoff Krafft (JLAB)
- Andy Lankford (UC Irvine)
- Lia Merminga (Triumf)
- Jamie Rosenzweig (UCLA)
- Mike Syphers (MSU)
- Bob Tschirhart (Fermilab)
- Rik Yoshida (Argonne)
- Young-Kee Kim (Univ. Chicago)

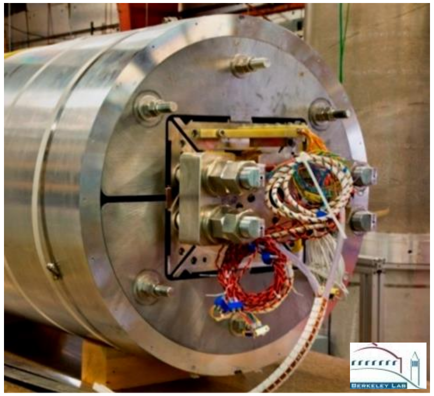
Program elements under discussion



Energy deposition studies for HL-LHC (MARS)

Accelerator design and performance optimization

- Strong US expertise in critical areas
- Building on previous US studies (e.g. VLHC)
- Guidance/support to magnet R&D (LARP example)
- Presentations on specific studies on Saturday:
    - FCC-pp: Mike Syphers
    - FCC-ee: Uli Wienands
    - CEPC/SppC: Weiren Chou



HD2: highest bore field in accelerator dipole (13.8 T)

Accelerator technology

- Superconducting magnets: most critical component for the high energy pp colliders
- High priority to cost reduction, consistent with P5
- Exploit synergies with other accelerator R&D thrusts (e.g. SCRF)

Considerations on High Energy pp Colliders

Community input - using excerpts from V. Shiltsev's presentation at the BNL meeting, but similar considerations were made in other ARD sub-panel presentations and submissions

- Overarching R&D goals: address feasibility of acceptable cost, better understand the performance reach, explore cost/performance trade-offs
- R&D goal #1: **Superconducting Magnets**
  - Most suitable for the US: world-leading expertise in SC magnets R&D and construction, synergy with LARP & HL-LHC
  - Program should be *focused on the substantial reduction of the magnet cost* and performance optimization:
  - In close coordination with the accelerator design teams (to understand the specs) as well as with magnet design and development partners (to avoid duplications)
- R&D Goal #2: **Performance and Design**
  - Launch limited scope long-term research on selected topics of importance for optimization of the most cost-effective machine design
  - *In coordination with (much bigger) global design studies in Europe and Asia*
  - Assure the best benefits from synergies with LARP, activities in Accelerator Science and Modeling thrust and R&D Toward Multi-MW Beams

FCC-pp Collider Design Activities

- Criteria: address key technical challenges; synergy with past/ongoing projects (VLHC, LARP), and with other ARD thrust areas; relevance to magnet R&D

Potential areas for US contributions	Motivation
Coping with SR power: 28 W/m/aperture (x100 LHC) & 4.8 MW total (330 x LHC) Collider design optimization, vacuum system technology.	Key challenge; US Lab expertise (FNAL, SLAC) and facilities for SR tests (Cornell). VLHC studies and absorber R&D; coupled to magnet aperture, layout.
Coping with ~100kW of radiation load at each IP (~45 x LHC, 8 x HL-LHC)	Extension of LARP IR optics studies; IR Quad R&D; heat deposition calculations
Instabilities at injection energy, impedance and feedback systems	Extension of LARP AP & feedback system; coupled to magnet aperture, field quality
Beam stored energy and machine protection	Critical issue potentially limiting beam current and luminosity; collimator design
Electron cloud effects	Critical issue; US expertise and synergy with other ARD thrusts and projects

- FCC-pp machine physics topics discussed in M. Syphers's presentation, Saturday PM

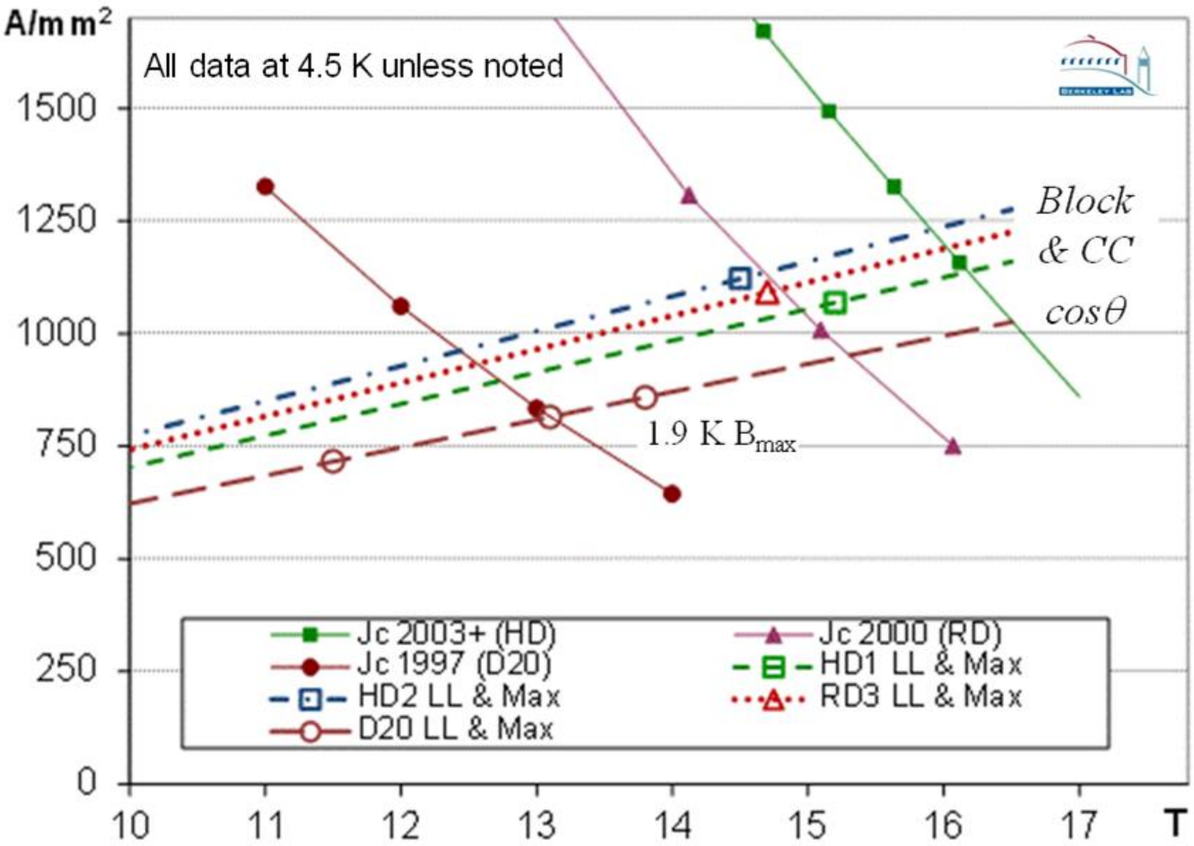
Improving Magnet Performance vs. Cost

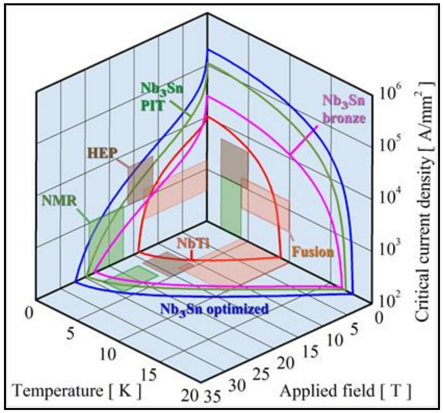
1. **Superconductor development**
   - Improvements in fundamental properties (current density, stress limits)
   - Fabrication and processing (production scale-up, cabling, insulation, reaction)
2. **Magnet design specifications**
   - Aperture: coil volume approximately scales linearly in the range of interest
   - Field: rapid increase of coil volume as we approach the conductor limit

     \- Still *appropriate to push field in R&D in order to shift the cost optimum*
3. **Magnet design optimization**
   - Coil layout, compactness, grading, protection (minimum copper fraction)
4. **Magnet performance optimization**
   - Design/operating margin: nominal field vs. conductor limit
   - Minimum quenches to nominal field and robust operation (cycling, radiation)
5. **Magnet fabrication**
   - Cost of structural materials and components; streamlined/automated processes
6. **Cryogenic system**:
   - Operating temperature vs. design field
   - Handling of synchrotron radiation: coil layout, beam screen/absorber design

Cost *reduction* target: need to establish an appropriate reference as a first step

Past improvement of Nb_3Sn J_c





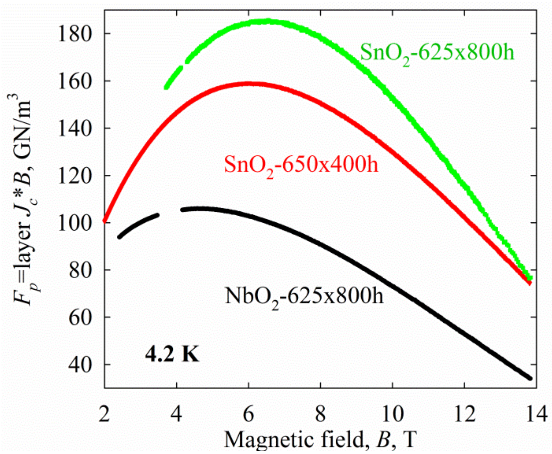
Bore field to peak field ratios:

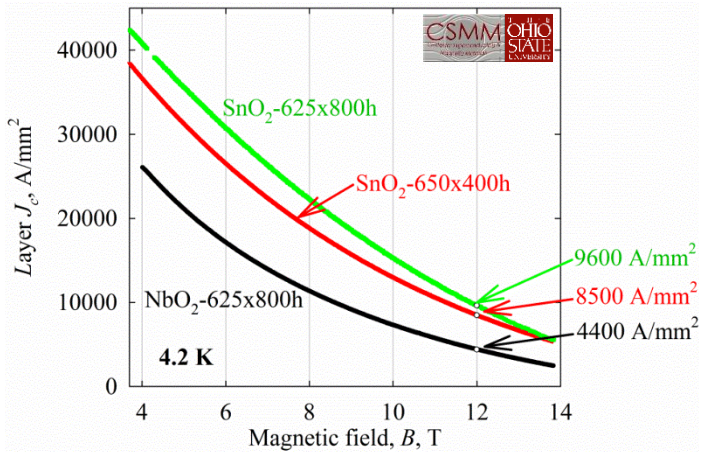
D20 : 0.98
HD2: 0.95
HD1: 1.06
RD3: 0.99

- HEP conductor development program resulted in +3T field potential (4.5K)
- Achieved performance consistent with improvements in conductor properties
- Optimal design choices driven by accelerator requirements and production cost

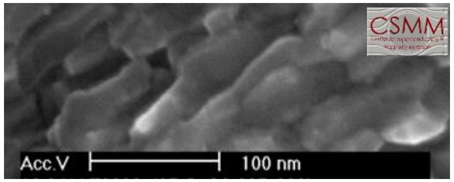
Potential for further improvements

- Principle: increase of Nb_3Sn pinning force at high field through grain refinement
- Exciting recent results in wires *(X. Xu et al, Appl. Phys. Lett. 104 082602 & ASC14):*

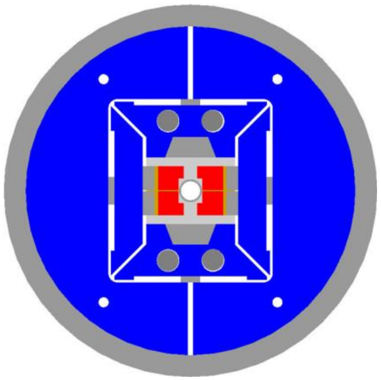




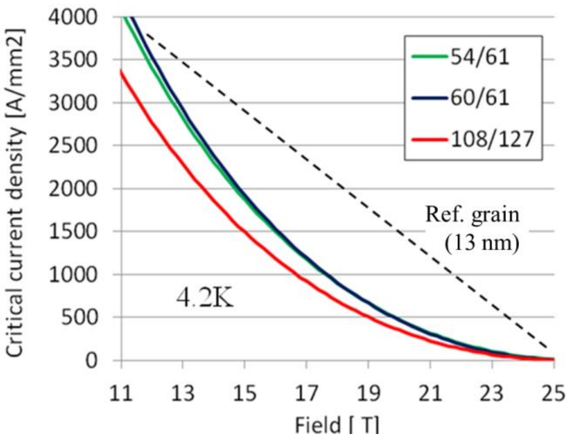
J_c(12 T, 4.2K): from **3.5 kA/mm²** @ **100+ nm** (e.g. best HD2 wire) to **9.6 kA/mm²** @ **~35 nm**

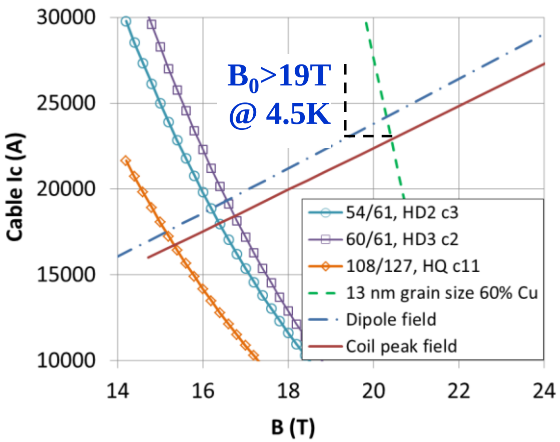


- Extrapolation to HD2 & **13 nm** grain size *(G. Sabbi et al., IEEE-TAS 25 (3) 4001407):*



HD2 cross-section

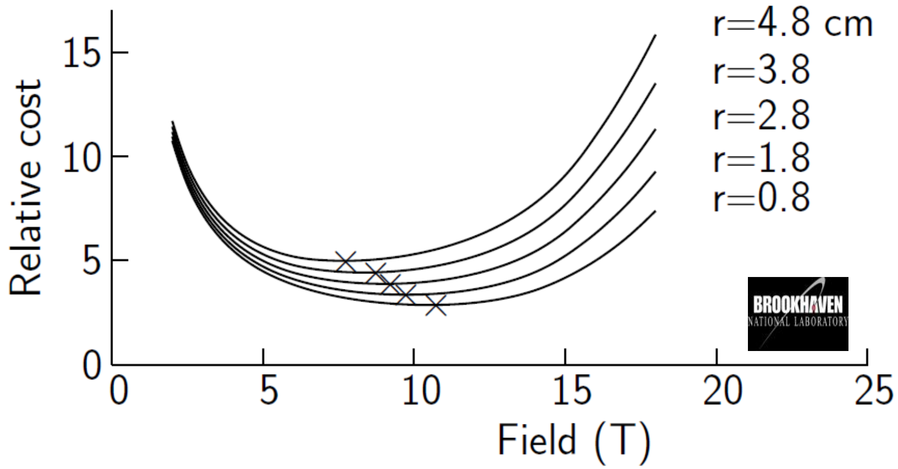




Aperture Considerations

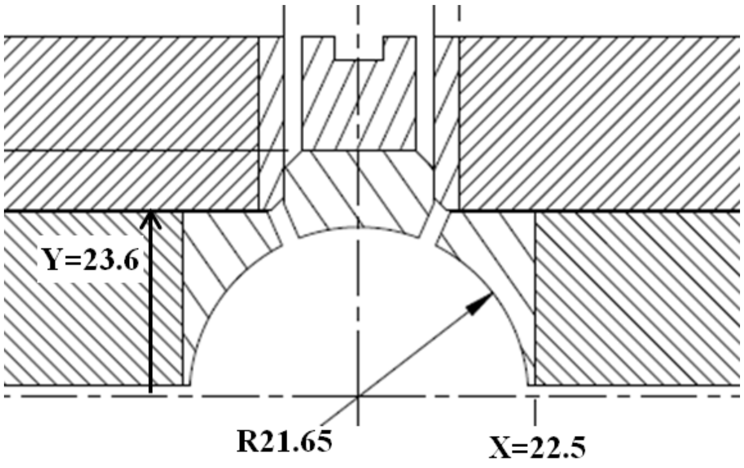
- Conductor and structure requirements depend on the magnet aperture
- Scaling is approximately linear in the parameter range of interest
  - Consistent findings by parametric models and realistic magnet designs
  - +25% aperture (40 to 50 mm) would have a significant impact on cost
- For same reason, optimization of internal bore components is essential
  - Integrate magnet design with vacuum, cooling etc.

Parametric model (B. Palmer)



Ref: B. Palmer, presentation to ARD panel, BNL

HD2 bore design

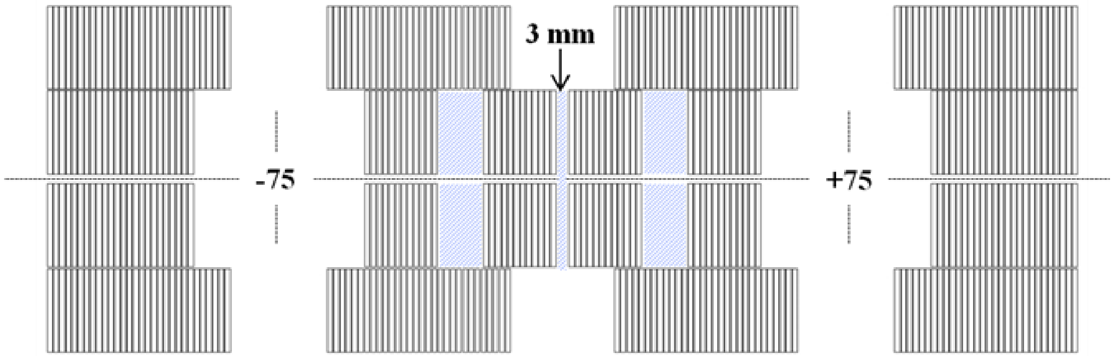


Ref: G. Sabbi et al., IEEE-TAS 25 (3) 4001407

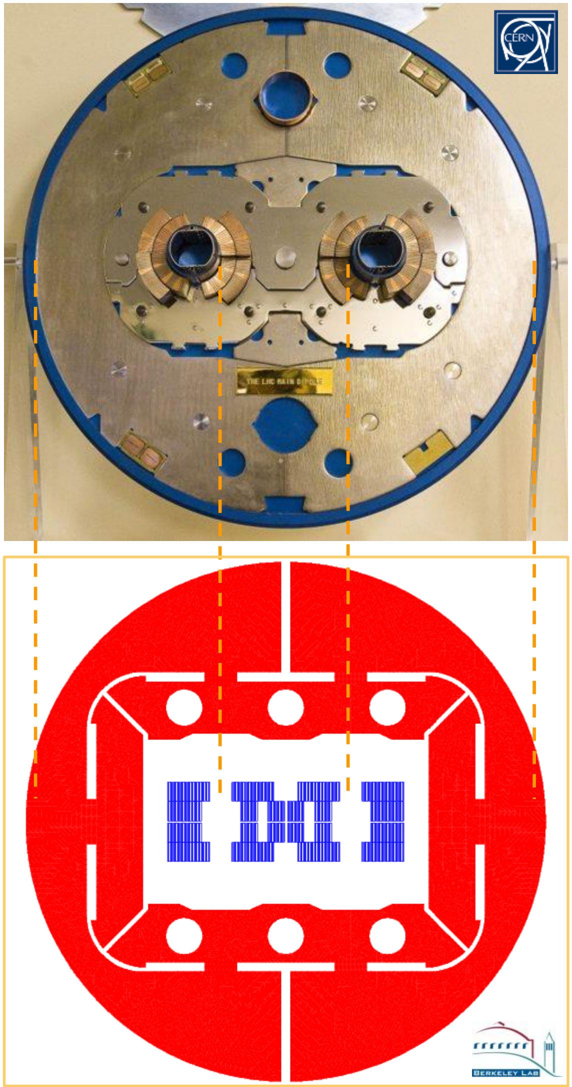
Minimizing the cold mass size

- Compact arrangement has significant cost benefits
- Beam separation may be lowered to 150 mm
- Smaller beam separation allows smaller yoke OD
- 60 cm yoke OD to be compared with 55 cm LHC

Short sample performance	I_{ss}		B_1^{ss}	
Temperature	4.5K	1.9K	4.5K	1.9K
Single aperture (HD2)	18.0	20.1	15.52	17.15
Double aperture (2HD)	17.8	19.7	15.49	17.12

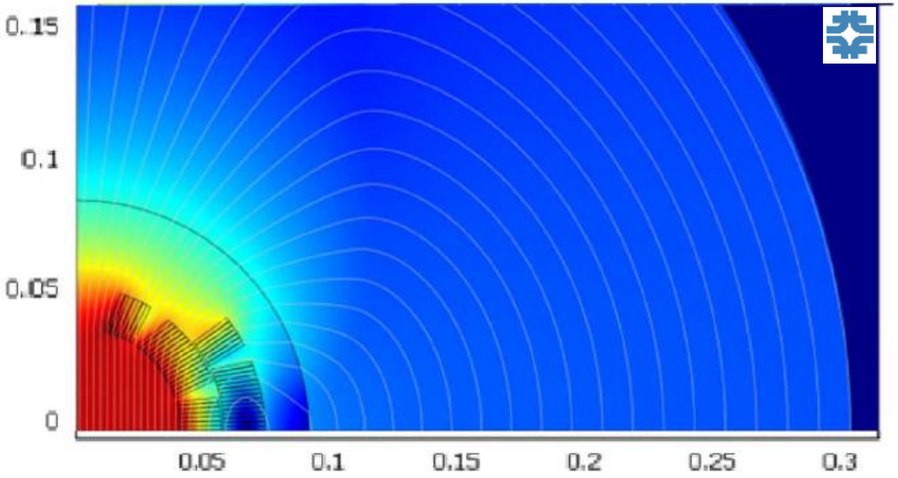


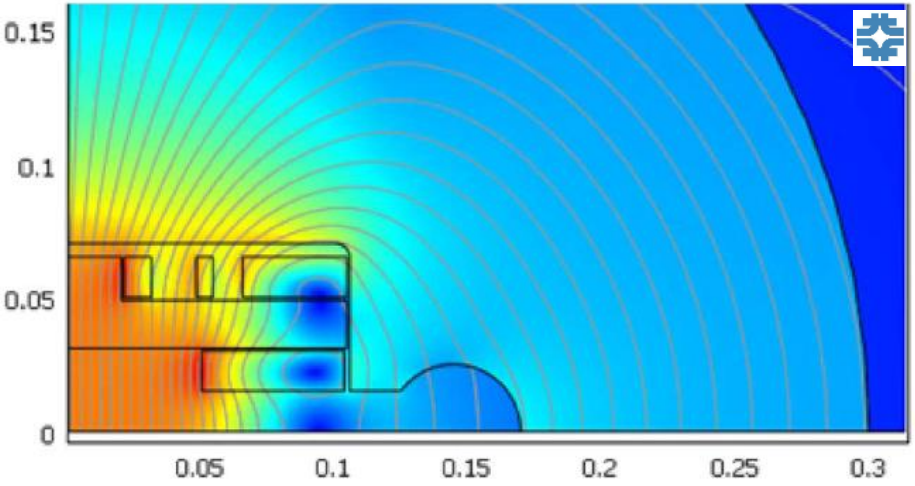
Asymmetric coil design for minimal spacing between apertures
G. Sabbi et al., IEEE-TAS 25 (3) 4001407 (2015)

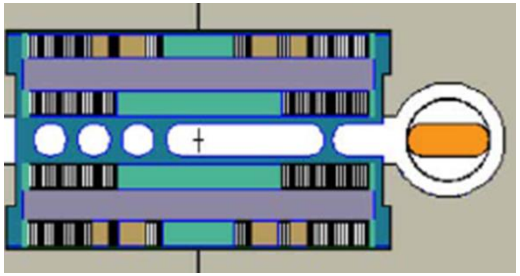


Open Mid-plane Dipole Design Studies

- Goal: provide a channel for synchrotron radiation to be absorbed away from the bore
- *Ref: I. Novitski, et al, Conceptual design of Dipole Magnet for **Muon Collider** Storage Ring, IEEE-TAS 21 (3) June 2011 (several other studies performed at BNL, LBNL etc)*
- Mechanical support assumptions have critical impact: need experimental verification







Parameter	Open mid-plane design	Shell-type design
B_{max} in coil at 4.5K (T)	13.5	13.7
B_{max} in bore at 4.5 K (T)	11.2	12.5
B_{op} (T)	10.0	10.0

2-in-1: Horizontal vs. Vertical Layout

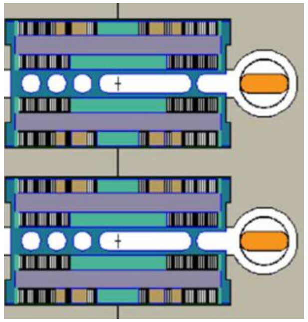
Horizontal layout is favored by magnetic and mechanical efficiency:

- Magnetic flux from one aperture is returned through the other
- Horizontal forces between apertures may be reacted against each other

Open mid-plane design favors a vertical layout:

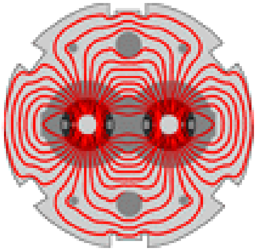
- Loss of magnetic efficiency is not large if peak fields are balanced
- Mechanical structure needs to contain 2x force from single apertire
- Potential issue for common coil design: *coil ends cross the mid-plane*

Open mid-plane w/SR channel

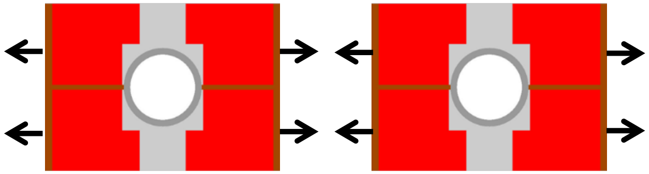


Horizontal 2-in-1 layout

Flux return:

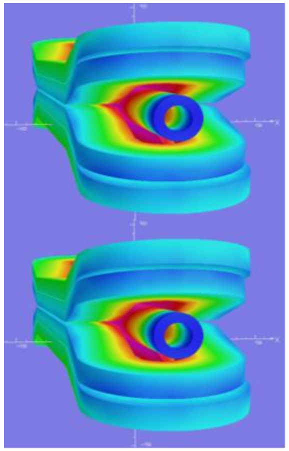


Horizontal forces

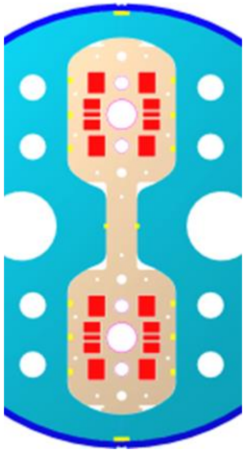


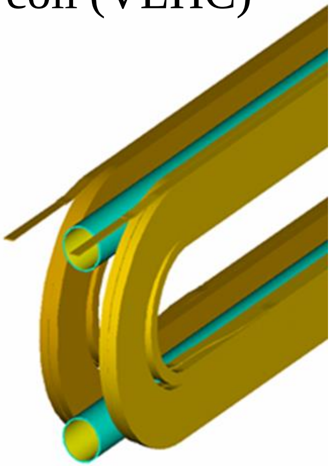
Vertical 2-in-1 layout

Block (or cosθ)



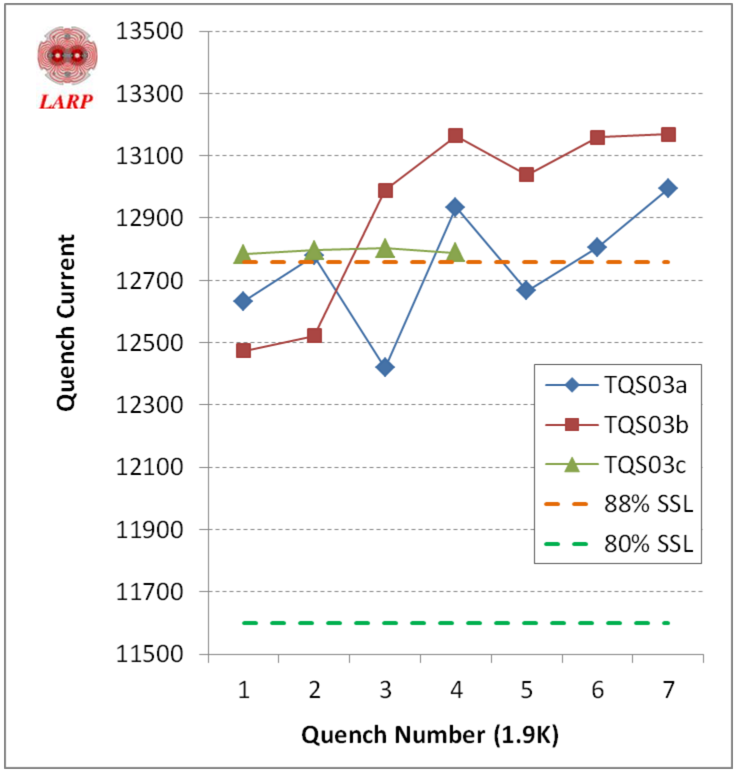
Common coil (VLHC)

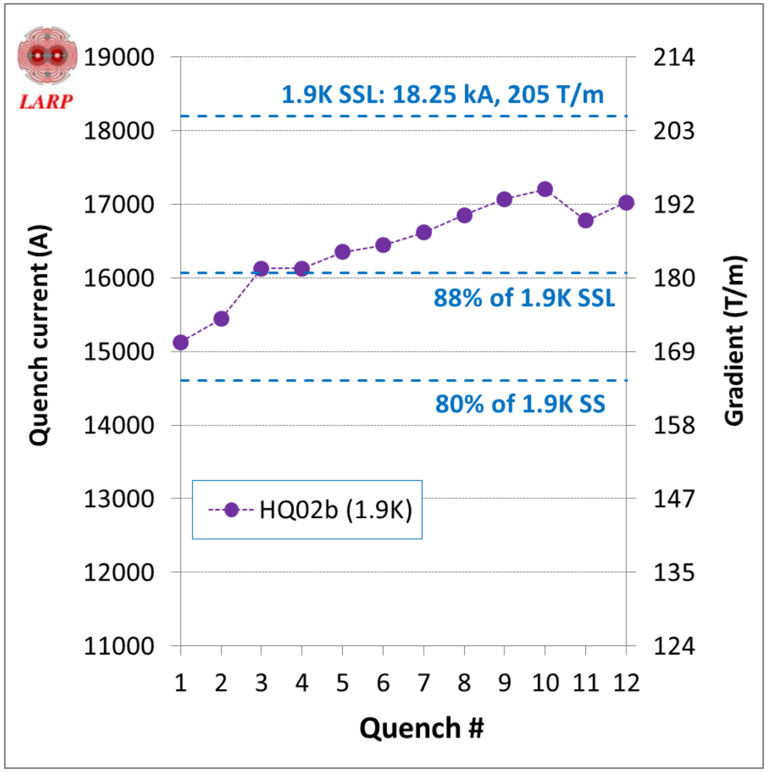




Target Operating Field vs. SSL

- Critical cost driver, in particular for high field designs and large production
- Optimized Nb_3Sn models reach ~95% of the conductor limit with fast training
- Support target operating field level at 85% of the conductor limit, or even higher





Ref: G. Sabbi, "IR Quadrupole R&D Program as a basis for MQXF", MQXF Design Review, December 2014 (http://indico.cern.ch/event/355818/contribution/3/material/slides/5.pdf)

Field Reach vs. Technology Readiness

Bi-2212
YBCO

Technology foundation:

- *Conductor properties*
- *Fabrication methods*
- *Design concepts, tools*

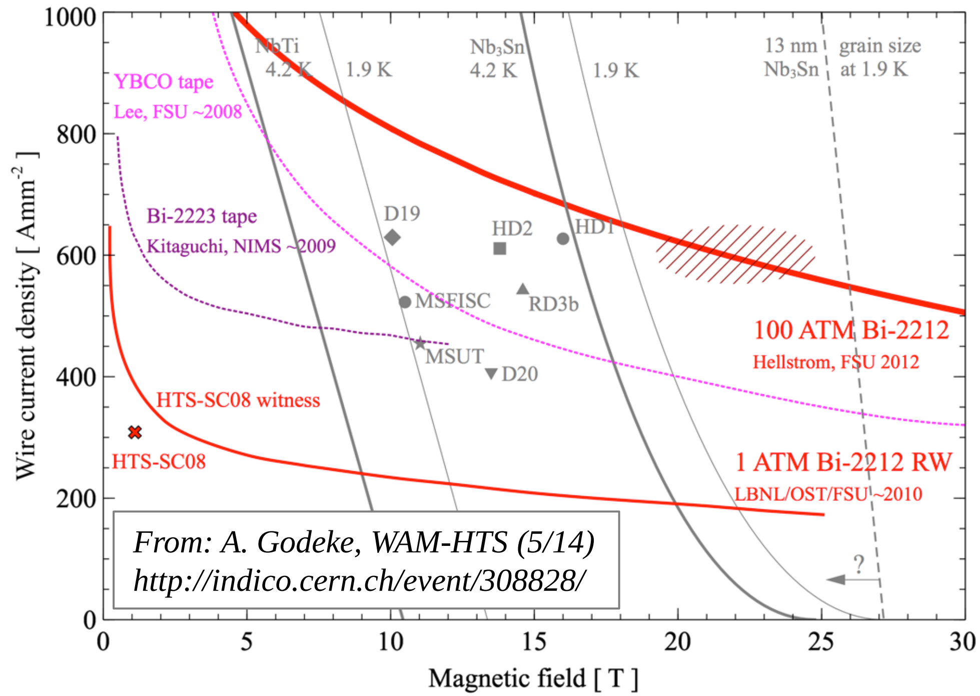
Performance demonstration in simple configurations

Nb_3Sn

Full qualification in accelerator configurations

NbTi

System integration



In-depth analysis & optimization

- *Conductor properties*
- *Fabrication technology*
- *Material characterization*
- *Modeling and diagnostics*

High Field Magnet R&D Proposal

White paper submitted to HEPAP ARD subpanel: G. Apollinari et al., *"National Program on High Field Accelerator Magnet R&D"* Fermilab-FN-0993-TD

- Calls for creation of a US Lab Program (BNL, FNAL, NHMFL, LBNL) coordinated with international efforts to support P5 priorities

Main objectives:

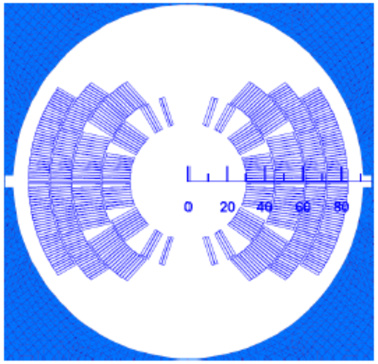
1. Develop accelerator magnets at the limit of Nb_3Sn capabilities.
2. Explore LTS accelerator magnets with HTS inserts for fields beyond Nb_3Sn capabilities.
3. Drive high-field conductor development, both Nb_3Sn and HTS materials, for accelerator magnets.
4. Address fundamental aspects of magnet design, technology and performance that could lead to substantial reduction of magnet cost.

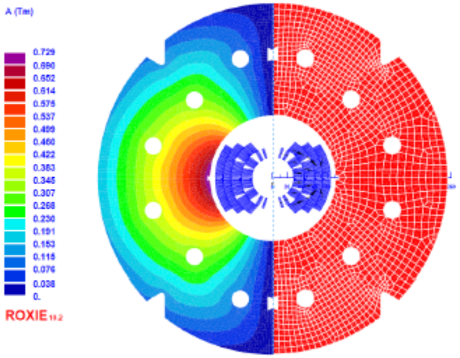
These common goals are implemented focusing on different coil geometries

FNAL: Cosθ 16 T Nb_3Sn Dipole

Approach:

- utilize the available components (cable, coils, yoke, skin, etc.) of the 11 T dipole models, tooling, and fabrication and test infrastructure developed in support of the HFM and LARP
  - substantial reduction of R&D cost and time

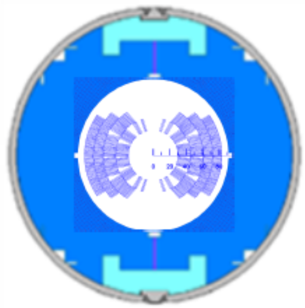




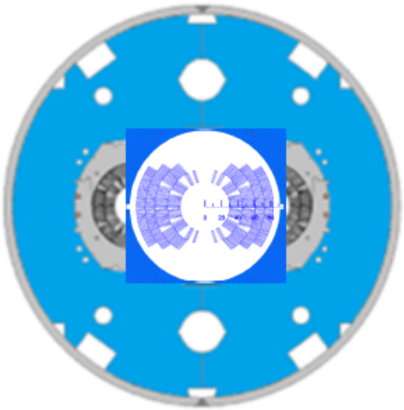
4-layer graded coil

Design concept:

- 60 mm aperture
- 4-layer coil, coil grading
- 40 cm or 55 cm iron yoke
- B_{des}= 15.5 T at 4.3 K (17 T at 1.9 K)
- Minimal coil size



400 mm yoke



550 mm yoke

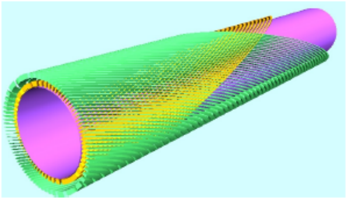
A. Zlobin, ASC-FCC Meeting Presentation, August 2014

LBNL: Canted Cosine Theta Concept

The CCT has the potential to meet the goals of the new paradigm but needs to be demonstrated

Simplicity – better performance?

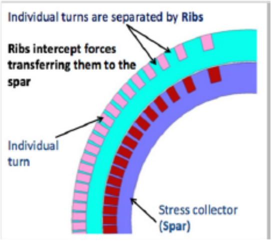
- Robust, reproducible, manufacturable
- Minimal external structure (little or no prestress?)
- Mandrel (ribs + spar) replaces pole, collars, end parts, spacers
- No body-end transition
- Modest tooling requirements



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)

CCT is our highest priority



Excellent geometric field quality

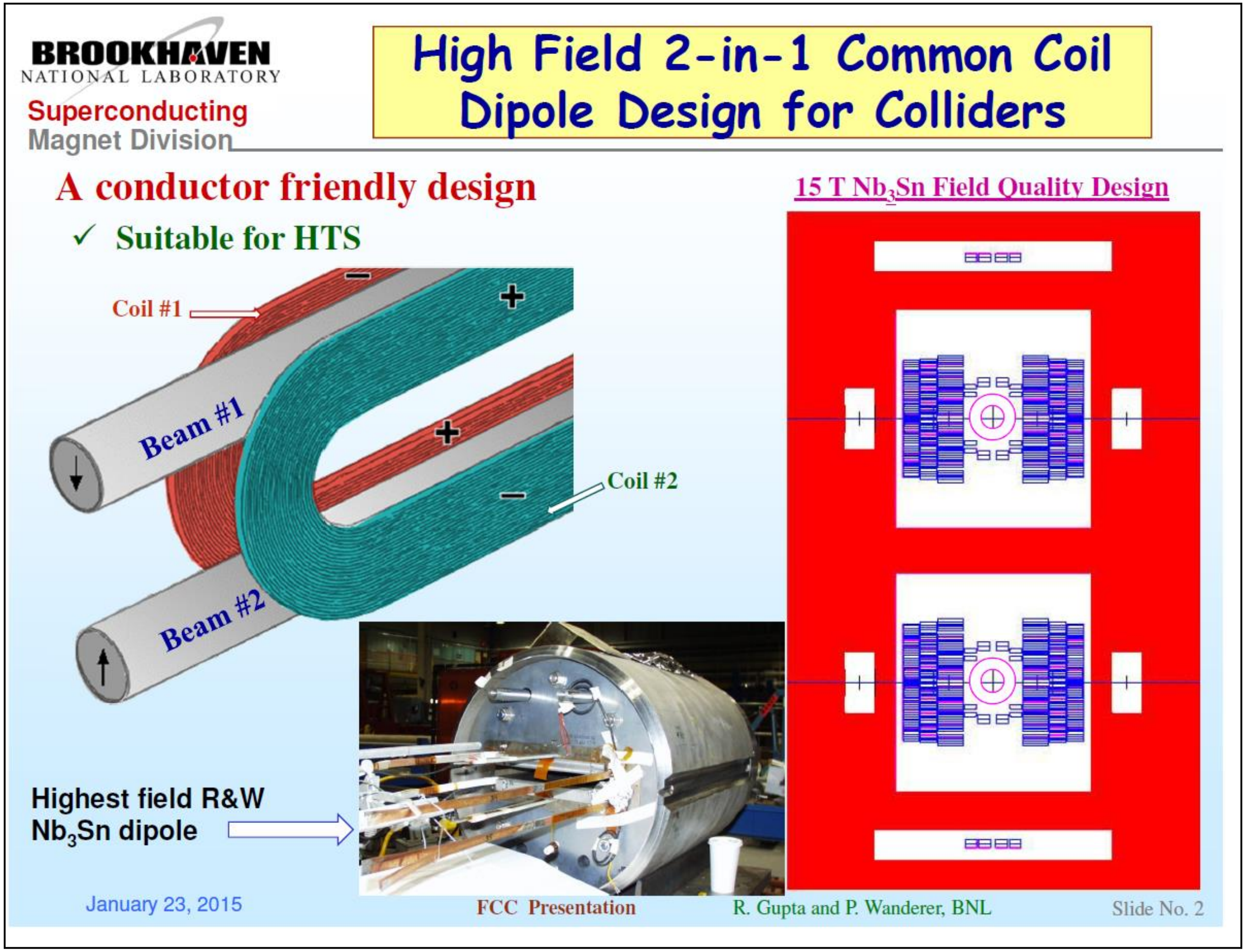
Combines the best of our former program

- 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

U.S. DEPARTMENT OF ENERGY | Office of Science — High Energy Physics — 14

S. Gourlay, ASC-FCC Meeting Presentation, August 2014

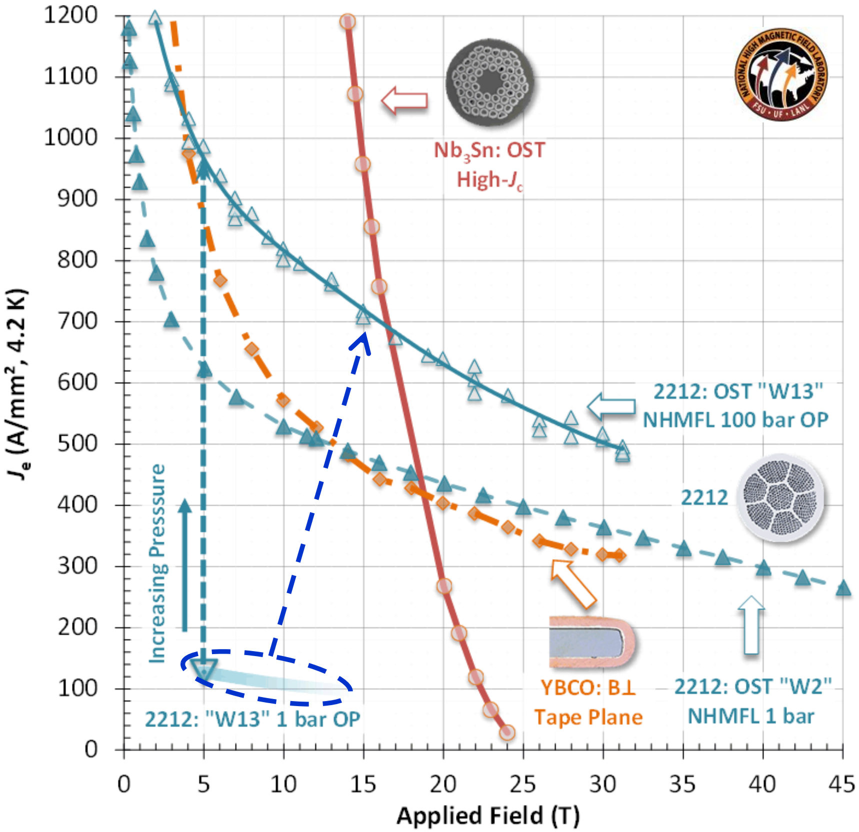
BNL: Common Coil Dipoles



R. Gupta, P. Wanderer, ASC-FCC Meeting presentation (updated)

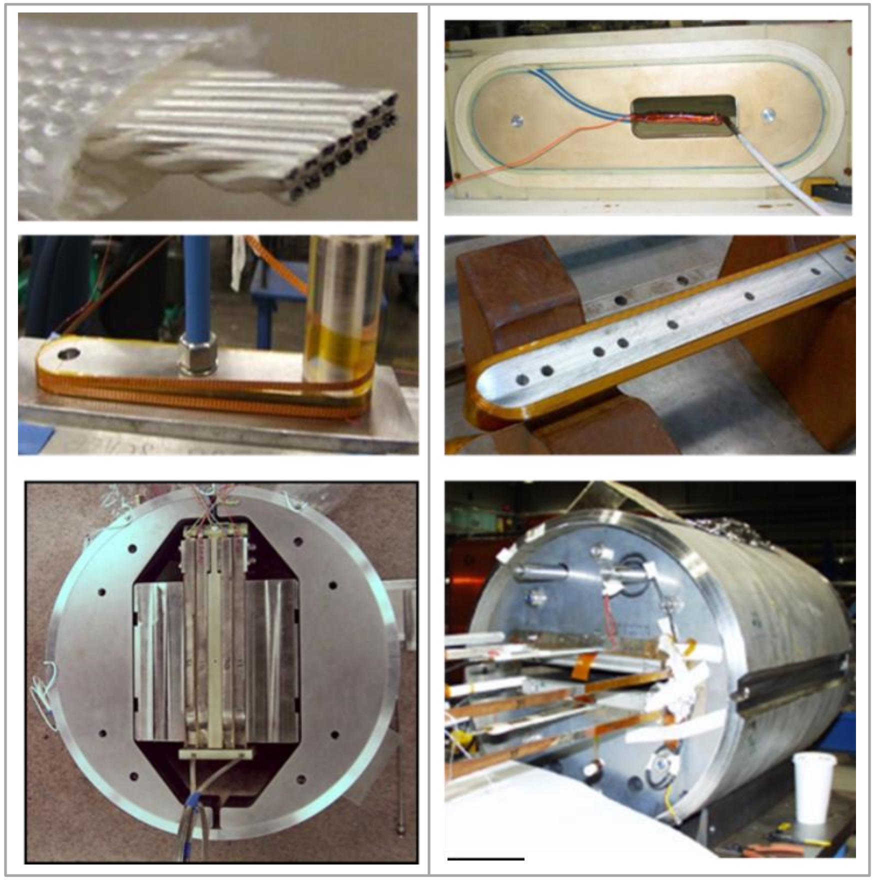
HTS Conductor & Technology Development

- Bi-2212: significant Jc improvement by reaction under high pressure (~100 bar)
- Challenge: application to large systems



D. Larbalestier, ASC-FCC Meeting, August 2014

- Development of HTS cable and coils for eventual use as inserts in Nb_3Sn dipoles (BNL, FNAL, NHMFL, LBNL)



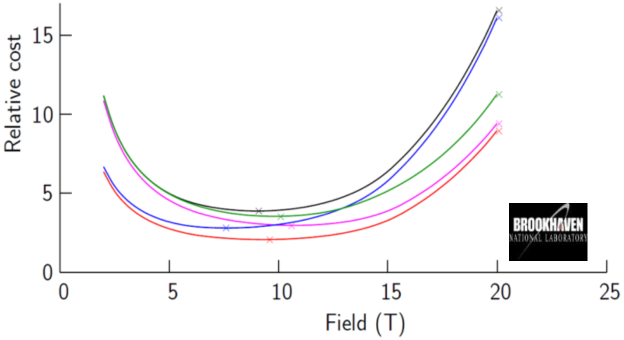
Studies of pp Colliders at Lower Field

- Motivated by cost models (from VLHC study) and open mid-plane design
- *Longer circumference (or lower energy) not consistent with FCC/SppC goals*
- Can provide valuable insights and new design concepts for global optimization

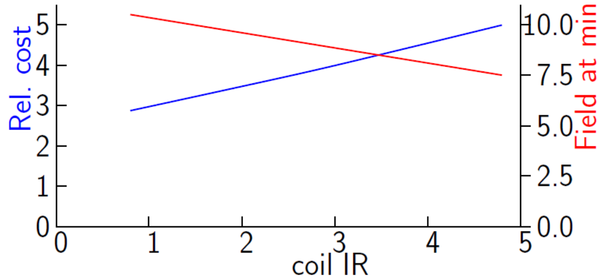
B. Palmer et al., "Accelerator Optimization issues of a 100 TeV collider", ARD panel meeting, BNL

Updating/refining VLHC models

Sensitivity to different assumptions



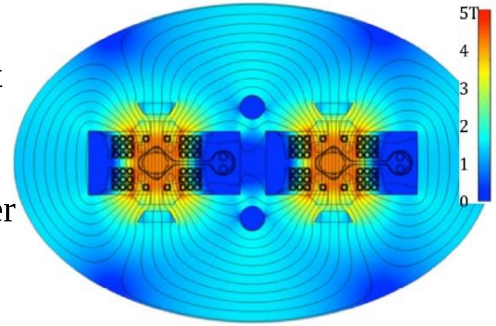
Dependence on aperture



P. McIntyre et al., "4.5T, cable-in-conduit SC dipole for future hadron colliders", ASC 2014

Dipole design:

- cable in conduit
- warm iron
- open mid-plane
- SR anti-chamber



Automation techniques from electrical industry

FCC-ee Collider Design Activities

- Criteria: address key technical challenges; areas of special US expertise; synergies with past/ongoing projects, with other ARD thrust areas and between pp/ee studies

Potential areas for US contributions	Motivation
Vacuum system design and technology	US Lab expertise (FNAL, SLAC) and facilities for SR tests (Cornell). Relevant to both hadron and electron positron machines.
Machine design and optics, beam dynamics, impedance and stability thresholds; IR design and machine-detector interface	US expertise with electron-positron colliders (e.g. PEP-II at SLAC); synergy with FCC-hh studies.
Diagnostics and feedback systems counteracting beam instabilities	US-Lab expertise and collaboration on fast feedback (e.g. LBNL-SLAC on Hi-Lumi LHC, PEP-II); luminosity monitoring etc.
RF cavity and system design	US Lab expertise in SCRF (FNAL, Jlab, Cornell); synergy with other R&D thrusts

- FCC-ee design machine physics topics discussed in U. Wienands talk, Saturday AM

CEPC/Sppc Activities

Collaboration activities were discussed at US-China HEP annual meeting in October 2014 in Beijing:

- Strong interest in joint studies on the science of future colliders
- Six US laboratories (Fermilab, BNL, LBNL, ANL, Jlab and SLAC) plan to work together with IHEP and other Chinese institutions to identify specific R&D topics and to arrange mutual exchange and workshops:
  - *Extended visits* by US scientists (theory, experiment and accelerator) to IHEP
  - *Contributions to the CEPC-SPPC Preliminary Conceptual Design Report* (10 US co-authors)
  - Joint organization and participation of an ICFA mini-workshop on SC magnets in June 2015 in Shanghai, China.

- Details on CEPC/SppC machine design in Weiren Chou's presentation, Saturday AM

Summary

- HEPAP P5 report strongly supports studies and R&D toward future very high energy colliders:
  - Exploration of the energy frontier is one of the key science drivers
  - US expertise in critical aspects of machine design and technologies
  - Synergies with other previous/ongoing programs and P5 R&D thrusts
  - R&D focus: improving performance and reducing cost
- Discussions on details of US involvement are underway as part of the ARD sub-panel activities
  - Community input: strong interest from all HEP Labs, and proposals consistent with P5 recommendations
  - Key areas of machine studies and technology R&D have been identified
  - High field superconducting magnets viewed as a primary US contribution

Acknowledgement: *input from discussions, presentations and papers by:*

W. Chou, A. Godeke, S. Gourlay, R. Gupta, D. Larbalestier, P. McIntyre, B. Palmer, V. Shiltsev, M. Syphers, P. Wanderer, U. Wienands, X. Xu, A. Zlobin

BACKUP SLIDES

FNAL Magnet R&D Proposal

Phase 1 (FY15-17)

1. Development and test of a small-aperture 15-16 T Nb_3Sn dipole.
   – This magnet could be used to test first small HTS inserts in the framework of the proposed National HFM program
2. Design study and cost optimization.
   – Design concepts of twin-aperture 15-16 T dipoles with the goal of reducing the Nb_3Sn magnet cost by a factor of ~3-4 wrt the LHC main dipole
   – Results will be available for FCC CDR planned to be released by 2018
3. Development and study of Nb_3Sn and Bi-2212 strands and cables.
   – Nb_3Sn strands and cables: focus on the increase of the conductor J_c at high fields and the cable transport current (with CDP and OST).
   – Bi-2212 strands and cable: development and demonstration of 10-20 kA class Bi-2212 cables

FCC@ASC meeting, 8/13/2014 A.V. Zlobin, FNAL HFM program 7

FNAL Magnet R&D Proposal

Phase 2 (FY18-20)

1. Design, fabrication and test of a large-aperture 16 T Nb_3Sn dipole.
   - 15 T background field for the 5-10 T HTS insert providing a substantial reduction of magnet total cost
   - large-aperture high-field magnets for FCC interaction regions
2. Development and test of a small-aperture Bi-2212 5 T dipole insert.
   - design and fabrication technologies of Bi-2212 dipole inserts
3. Nb_3Sn and HTS strand and cable R&D.
   - Studies and optimization of Nb_3Sn and Bi-2212 strands and cables will continue in collaboration with CDP, universities and industry in support of the HFM Program

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FNAL Magnet R&D Proposal

Phase 3 (FY21-25)

1. Development and test of a small-aperture 20-25 T accelerator-quality dipole based on HTS/LTS coils.
   – Based on the results of Phase 2 a series of 5-10 T HTS dipole inserts and 15 T Nb_3Sn dipole outserts with stress management to reduce conductor degradation and magnet training will be designed, fabricated and tested
   – Magnet operation margin, field quality and quench protection issues will be experimentally studied and demonstrated
2. Nb_3Sn and HTS strand and cable R&D.
   – Studies and optimization of Nb_3Sn and HTS strands and cables will continue in collaboration with CDP, universities and industry in support of the HFM Program

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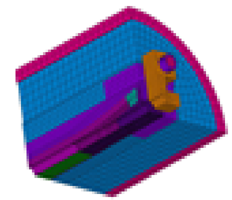
LBNL Magnet R&D Proposal

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
- Common Coil
- Block
- Sub-scale racetracks
- Some Canted-Cos-Theta

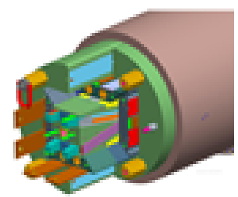


Analysis tools

Unique Instrumentation and Diagnostics

- Infrastructure
  - Fabrication
  - Testing (still need for facility improvements)

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.

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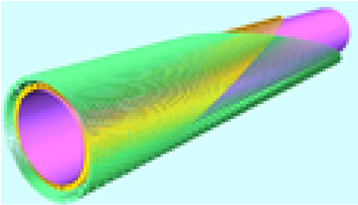
LBNL Magnet R&D Proposal

The CCT has the potential to meet the goals of the new paradigm but needs to be demonstrated



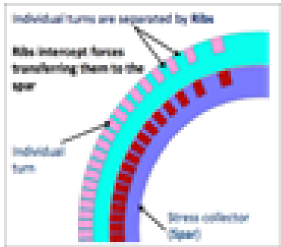
Simplicity – better performance?

- 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 our 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

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LBNL Magnet R&D Proposal

R&D Plan Summary

- **An aggressive 2-year plan to demonstrate the CCT concept**
  - 16 T Nb_3Sn, 90 mm clear bore
  - HTS insert to take it to 18 – 19 T
- **Next iteration of HD**
  - Utilize LARP experience
  - We have a clear idea of what we want to do
  - A significant step to understanding and conquering training in a design that could be used for FCC
- **A modest sub-scale program to support technology development**
- **Highly leveraged materials R&D to support the program**
- **Strong collaborative partnerships**

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BNL Magnet R&D Proposal

BROOKHAVEN NATIONAL LABORATORY
Superconducting Magnet Division

HTS Magnet Program at BNL

- HTS magnet R&D over a wide range:
  - High field, Medium field and low field (high temperature)
  - Many geometries – racetrack, cosine theta, solenoid
- Number of HTS coils/magnets designed built & tested:
  - Well over 100 HTS coils and well over 10 HTS magnets
- Type of HTS used:
  - Bi2223, Bi2212, ReBCO, MgB_2 – wire, cable, tape
- Amount of HTS acquired:
  - ~50 km (4 mm tape equivalent)
- Recent activities have been largely on magnets with ReBCO
  - (yet one Bi2223 and one MgB_2 magnet are being tested this year)

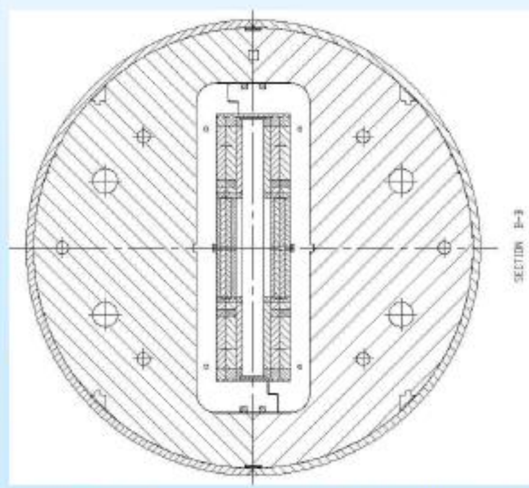
January 23, 2015 FCC Presentation R. Gupta and P. Wanderer, BNL Slide No. 1

BNL Magnet R&D Proposal

BROOKHAVEN
NATIONAL LABORATORY
Superconducting
Magnet Division

Common Coil Dipole at BNL for Testing HTS Insert Coils as in a Hybrid Magnet

- BNL has a unique 10^{+} T Nb_3Sn common coil dipole with large open space to test HTS coils in background field.
- Provides fast turn around and economic R&D as no disassembly/assembly of the magnet is required
- HTS coil become a part of the hybrid magnet test (~15 T)



High current 2212 coil

January 23, 2015 FCC Presentation R. Gupta and P. Wanderer, BNL Slide No. 3

BNL Magnet R&D Proposal

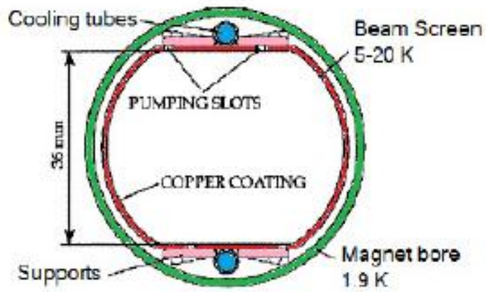
BROOKHAVEN NATIONAL LABORATORY
Superconducting Magnet Division

Open Midplane Dipole for FCC

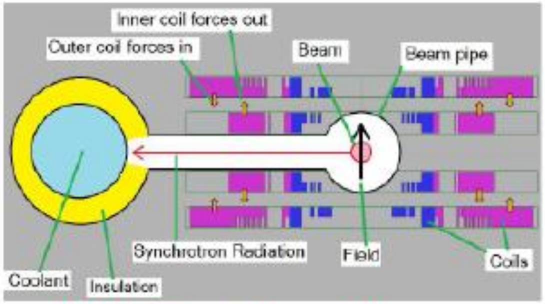
SYNCHROTRON RADIATION

In 100TeV p-p collider (CERN FCC-hh) 0.5 amp 16 T:

- Total SR power = 4.8 MW
- If on magnet bore: wall power to cool is crazy
- Requires beam screen at 50 K
- If screen inside beam pipe: uses valuable space
- If screen in beam tube: Emits electrons ⟶ electron cloud
- If deposited away from beam tube, as in e+e- ring colliders, BOTH PROBLEMS SOLVED



CERN Beam Screen



With Open-Plane Magnet

Courtesy: Bob Palmer

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