U.S. MAGNET DEVELOPMENT PROGRAM

The US Magnet Development Program (MDP) Roadmap for Future Particle Physics Colliders.

S. Gourlay

Lepton-Photon 2025

U.S. DEPARTMENT OF ENERGY | Office of Science

Brookhaven National Laboratory | BERKELEY LAB | FLORIDA STATE UNIVERSITY 1851 ASC | Fermilab

US MDP is a collaboration among 4 US laboratories (BNL, FNAL, LBNL, NHMFL) established in 2016 as a result of the 2014 HEPAP Accelerator R&D Subpanel that followed the 2013 P5 Report

- BNL: M. Anerella, J. Cozzolino, R. Gupta, F. Kurian, M. Palmer, V. Teotia, B. Yahia
- FNAL: G. Ambrosio, K. Badgley, M. Baldini, S. Gourlay, Va. Kashikhin, Vl. Kashikhin, S. Krave, V. Marinozzi, I. Novitski, S. Stoynev, D. Turrioni, G. Velev, F. Wan, X. Xu
- LBNL: D. Arbelaez, L. Brouwer, M. D'Addazio, L. Garcia Fajardo, M. Marchevsky, N. Menon, C. Messe, M. Mosat, A. Hafalia, M. Juchno, S. Prestemon, J.L. Rudeiros Fernandez, A. Saravanan, T. Shen, R. Teyber, G. Vallone, X. Wang, Y. Yan, Y. Yang
- NHMFL: L. Cooley, D. Davis, D. Larbalestier

Guidance from the international community on Future Colliders

- Second European Strategy for Particle Physics (ESPP) Update
  - Initiated in 2018 with Open Symposium in 2019
    - ILC still on the table
- Snowmass 2021
- Particle Physics Project Prioritization Panel (P5) – Report in 2023
- National Academies: Elementary Particle Physics, *The Higgs and Beyond - 2025*
- Third ESPP Update
  - Initiated in 2024 with Open Symposium in 2025 – Report in 2026

P5 Recommendations on Colliders

- **Finish what you started!**

  . . . complete construction projects and support operations of ongoing experiments and research to enable maximum science.

  - **HL-LHC**
  - **The first phase of LBNF/DUNE and PIP-II**

- **Higgs**

  . . . US should actively engage in feasibility and design studies for an off-shore Higgs Factory

- **Support vigorous R&D toward a cost-effective 10 TeV pCM collider**

- **Convene a targeted panel**

  - **. . . that makes decisions on the US accelerator-based program at the time when major decisions concerning an off-shore Higgs factory are expected, and/or significant adjustments within the accelerator-based R&D portfolio are likely to be needed. A plan for the Fermilab accelerator complex consistent with the long-term vision in this report should also be reviewed.**

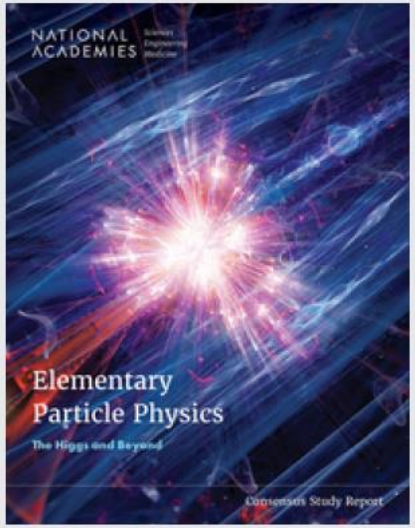
Snowmass21 and P5

- **Snowmass 2021** strongly positions the **Muon Collider** as a promising future collider for the U.S. — one that capitalizes on its compact size, energy reach, and dual precision–discovery potential. With an aligned roadmap, clear R&D milestones, and international partnerships in place, the community is poised for the next step: a Reference Design Report and cost–benefit case over the coming 5–7 years.
- **P5**
  - Strong endorsement of R&D toward a 10 TeV pCM collider
    - Aligns with long-term vision of hosting a major international collider facility in the US
  - "**Muon shot**"—US engagement and leadership encouraged
  - R&D-focused, phased approach emphasized
    - General accelerator science R&D, e.g., superconducting magnets, RF, beam dynamics.
    - Targeted collider R&D, including technology demonstrators, feasibility studies, site planning, and international coordination.
  - International collaboration prioritized
- **USMCC Charter Adopted May 8, 2025**

And recently

NATIONAL ACADEMIES Sciences Engineering Medicine

Elementary Particle Physics: The Higgs and Beyond (2025)



Recommendation 1: The United States should host the world's highest-energy elementary particle collider around the middle of the century. This requires the immediate creation of a national muon collider research and development program to enable the construction of a demonstrator of the key new technologies and their integration.

Even more recently

- Options for the next CERN collider
  - Preferred – Integrated FCC
    - FCCee (~2046) followed by FCChh (~2070)
  - Plan "B" – TBD, but <u>not</u> a muon collider

. . . . . The door is open for a US-based energy frontier machine

Summarizing magnet needs for potential future colliders

- Large fraction of the community would like to pursue a higher energy hadron collider, however we do not know how to do so within "reasonable" budgets
  - Simply using LHC Nb-Ti technology to get to 40 TeV would be ~20B$ (CERN) and HL-LHC technology (Nb_3Sn) for 80 TeV is more expensive at this time
  - R&D aspires to reduce magnet cost by factor of 2 ~ 4

- High field dipoles – 14T for FCC-hh
- Large aperture dipoles with fields up to 13T (or more)
- (Very) fast ramping magnets
- High field solenoids (2T - > 30T, large and small bore)
- Large aperture interaction region quadrupoles

} Muon Collider

High radiation environment
- Damage
- Heat deposition

Manage stress

High Temperature Superconductors required in many cases

Goals of the US Magnet Development Program

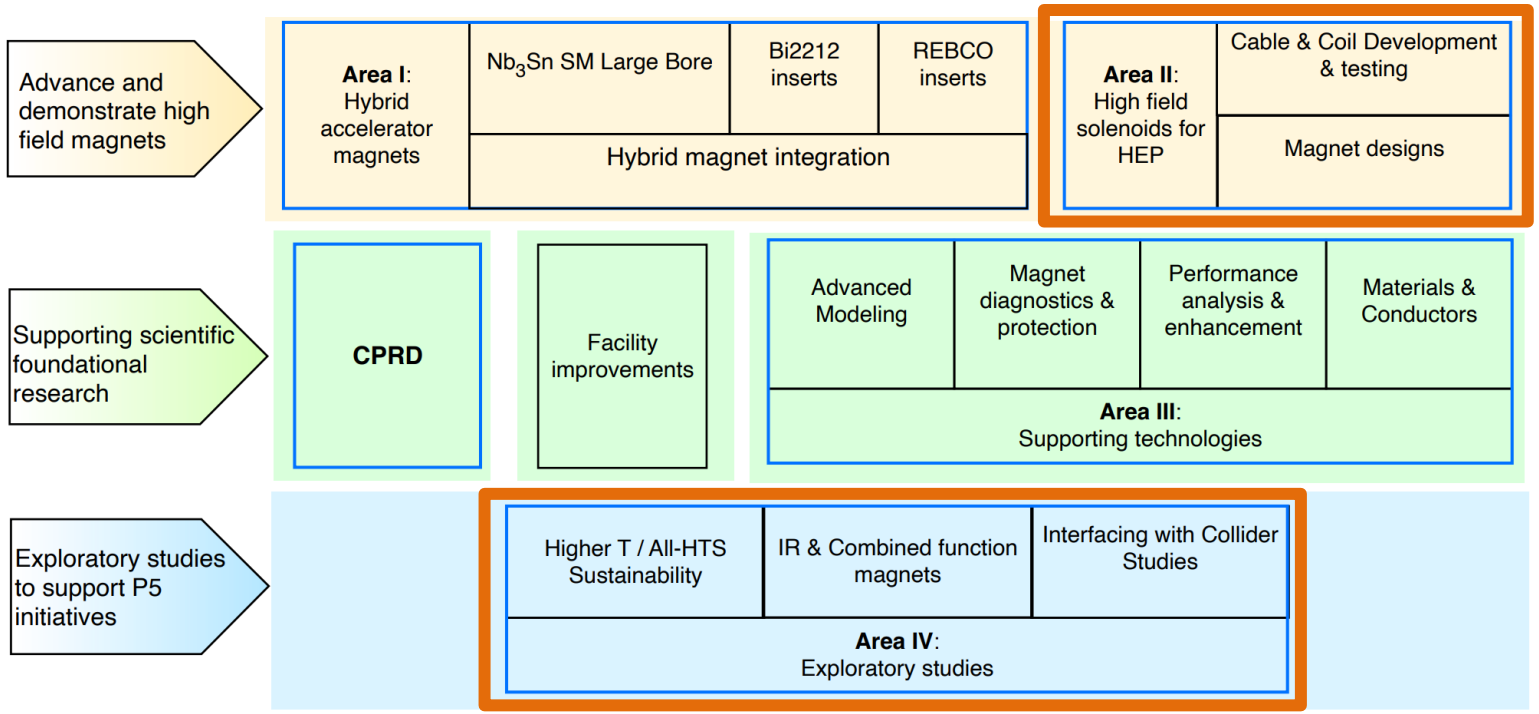
- The general goal is to perform generic R&D to develop next generation high-field accelerator magnets
  - R&D not specifically directed towards one of the possible next accelerators, but elements of the program chosen for relevance

- More specifically the strategic priorities are
  - Explore and define the performance limits of superconducting accelerator magnets
  - Develop, understand and demonstrate high field HTS magnet technology
  - Investigate and understand the fundamental science of magnet design and performance
  - Pursue conductor R&D to achieve properties that align with accelerator magnet goals
  - Support the development of advanced workforce for superconducting magnet technology

Workforce development is an intrinsic element of the program

US Magnet Development Program

- Road map updated in 2025, as a result of 2023 P5 report
  - Priority for 10 TeV pCM colliders like FCC-hh and Muon colliders
- Activities organized in four Areas (two new areas defined)



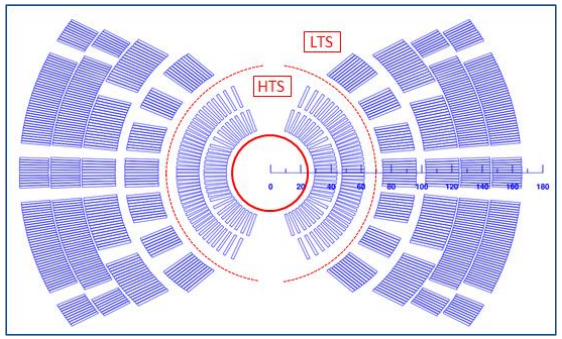
NHMFL (MagLab) will provide expertise in high field solenoid R&D

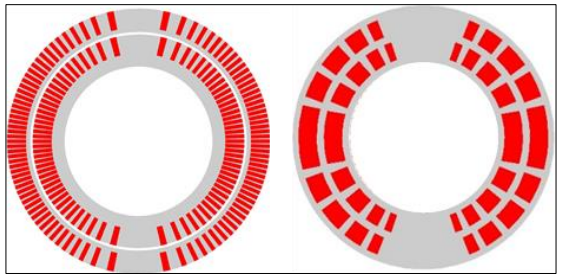
Nb_3Sn Magnet Activities

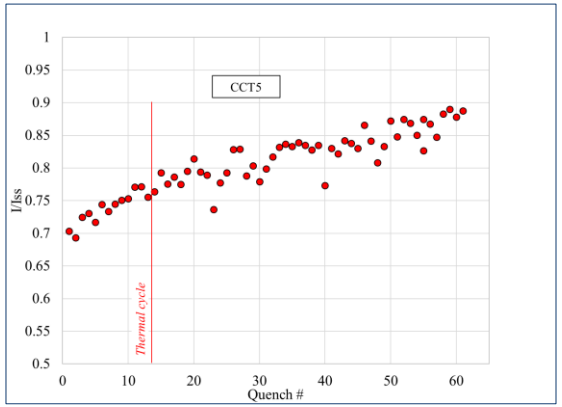
- Main goals
  - High field (for every application)
    - Lare bore – muon collider, IR magnets
    - Small bore – FCC-hh

The obstacles

- Training – reduce or eliminate
  - Reduce test time and decrease required operating margin
- Stress – Develop structures to manage
  - All conductor options for higher fields are stress sensitive

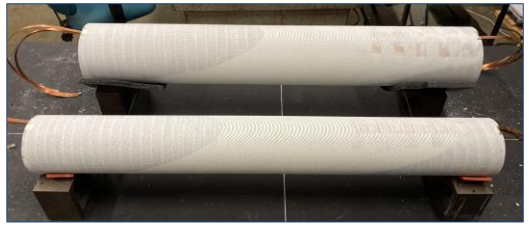


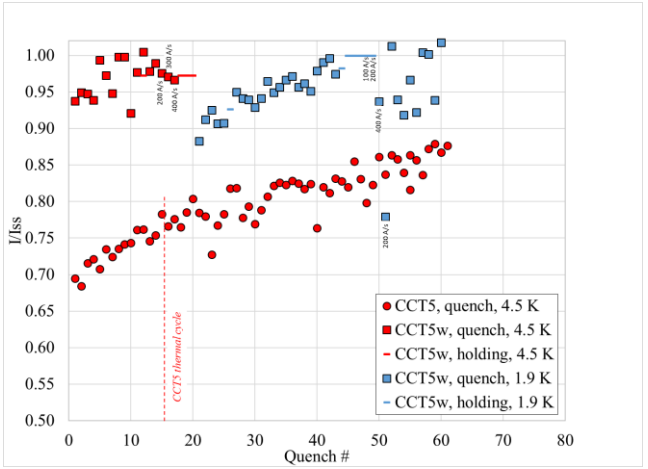




"New" Impregnation Materials to Reduce Training

- CCT5 with filled wax (CCT5w)
  - Goal: ~10-11 T in 90 mm aperture with minimum/no training
    - Exploring filled wax in higher field and stresses



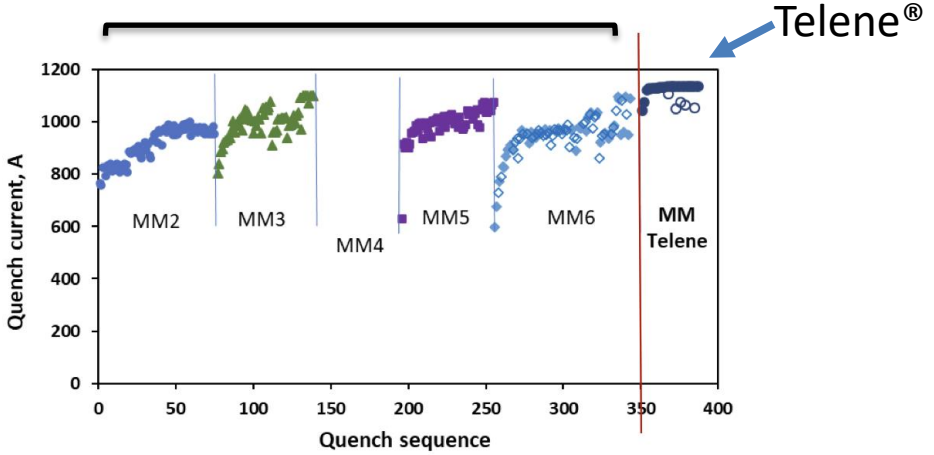


- US-Japan funded project/WFO ANL

Novel organic olefin-based thermosetting dicyclopentadiene (DCP) resin, commercially available as **TELENE®** at RIMTEC.

CTD-101K

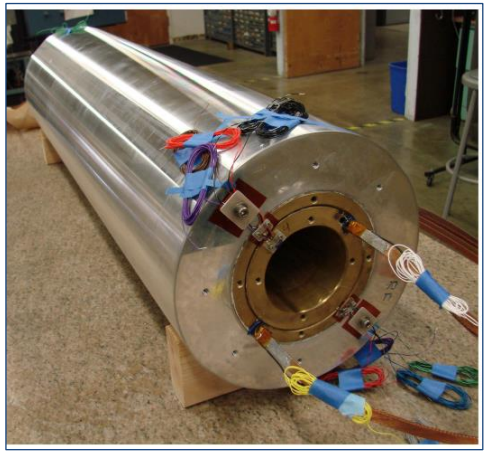
Telene®

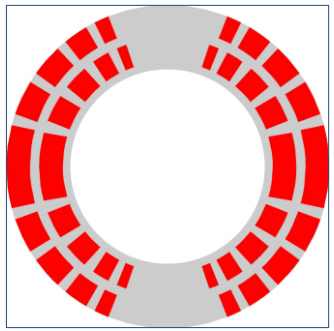


E. Barzi, D. Turrioni, I. Kesgin, M. Takeuchi, Wang X., T. Nakamoto, and A. Kikuchi, E. Barzi et al, "A New Ductile, Tougher Resin for Impregnation of Superconducting Magnets", 2024 Supercond. Sci. Technol. 37 045008 (2024)

A few Options to Minimize Stress

- Canted-Cosine Theta (CCT)
  - Cable protected in groove
  - Tilted solenoid geometry
- Stress-Managed Cosine-Theta (SMCT)
  - Large channels
  - Cos-theta geometry

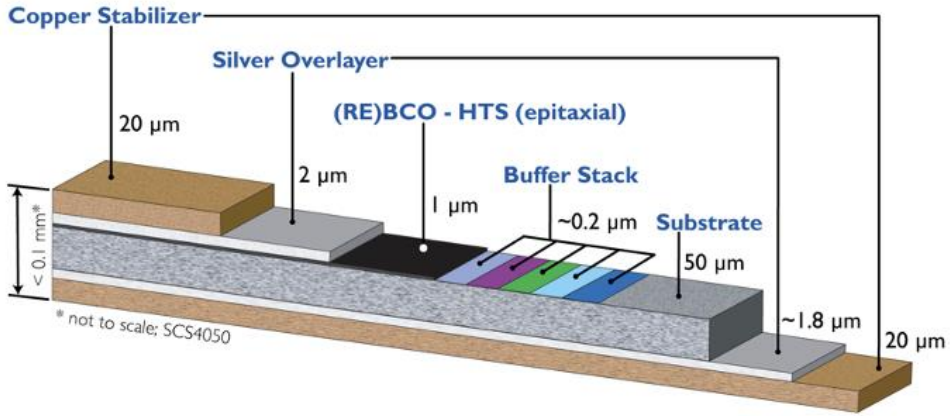


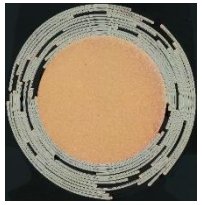


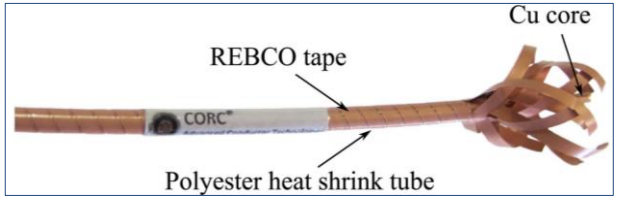
High Temperature Superconductors (HTS)

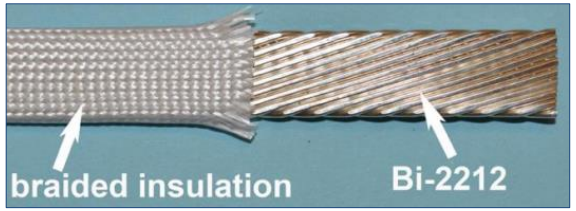
- Coated conductor
  - Excellent $J_c(B)$ performance at elevated temperatures
  - Available as flexible tapes
  - Not good for field quality
  - A dozen+ manufacturers world-wide (and growing)
    - Driven by private investment in Fusion Power Plants
  - Currently very expensive
  - Not a magnet conductor (yet)
- Bi2212
  - Rutherford cable, heat treatment 50 bar in O_2 at 885-900 °C
  - Challenges: leaks/degradation and furnace

Degradation due to stress a challenge for both





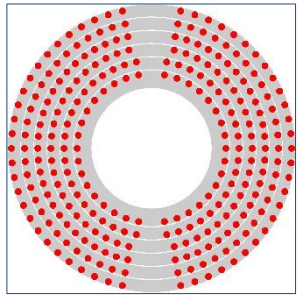


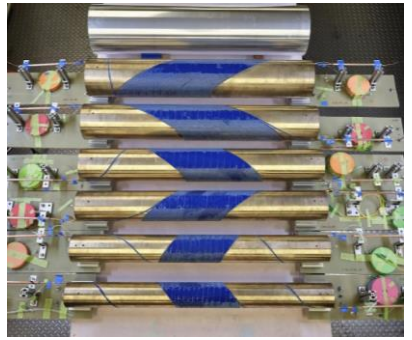


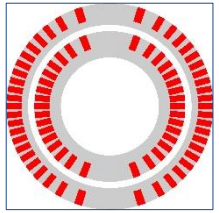
Multi-Pronged Approach to HTS Magnet Development

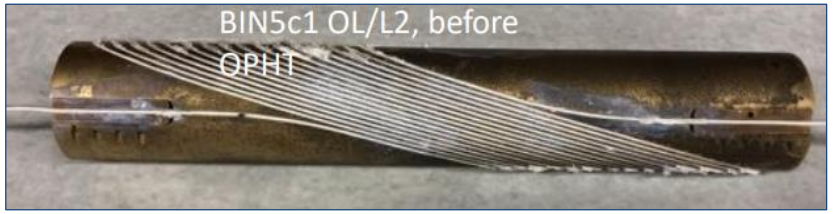
- CCT ReBCO accelerator magnet achieved record field of 6T
- Bi-2212 CCT
  - 1.6 T in 31 mm aperture
  - Ready for first hybrid test
- COMB (Conductor on Molded Barrel)
  - SMCT with single conductor in groove
  - Double-layer coils with layer jump
- COMB-STAR-1 (2024)
  - 1.5 T field in 60 mm bore

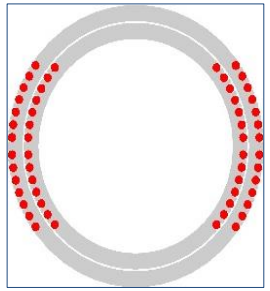
Higher fields coming soon!

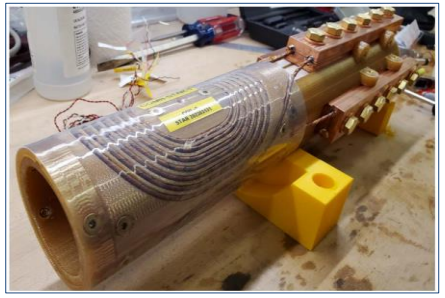


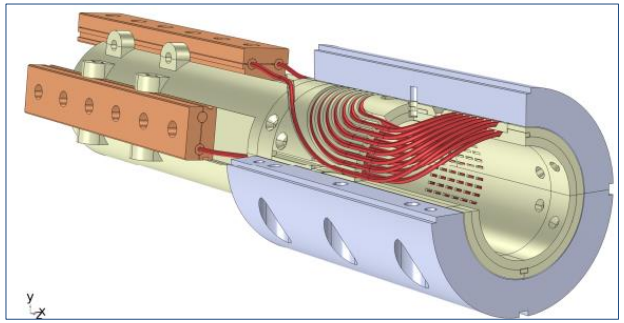






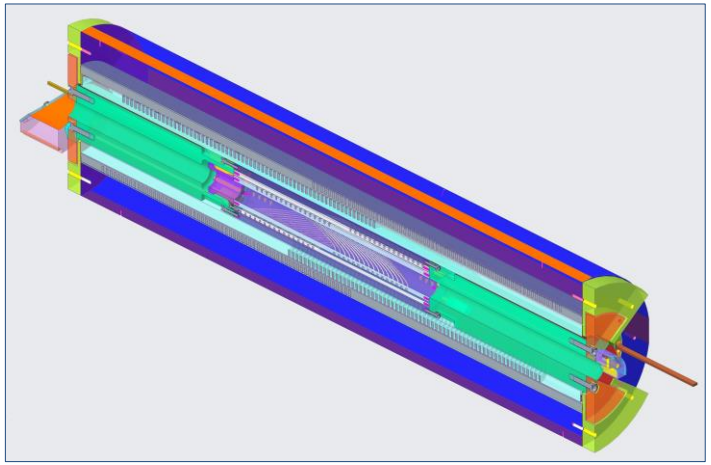






Supporting Activities

- LTS/HTS Hybrid Magnets
  - Most effective way to reach high field (and explore stress mitigation)
  - Key goal for MDP in the near-term



- Modeling
  - Support training studies
  - Current sharing of ReBCO cables
  - Minimize degradation

- Diagnostics
  - Provide benchmarks for simulation
  - Explore techniques to detect temperature rise in HTS

Summary

- The US Magnet Development Program has been modified to align with the priorities of the particle physics community and, in collaboration with our international partners, is ready to take on the technological challenges posed by potential future colliders.

Thanks to . . .

- Paolo Ferracin, LBNL – especially Paolo!
- Soren Prestemon, LBNL
- David Larbalestier, FSU/NHMFL
- Lance Cooley, FSU/NHMFL
- Mark Palmer, BNL
- George Velev, FNAL