U.S. MAGNET
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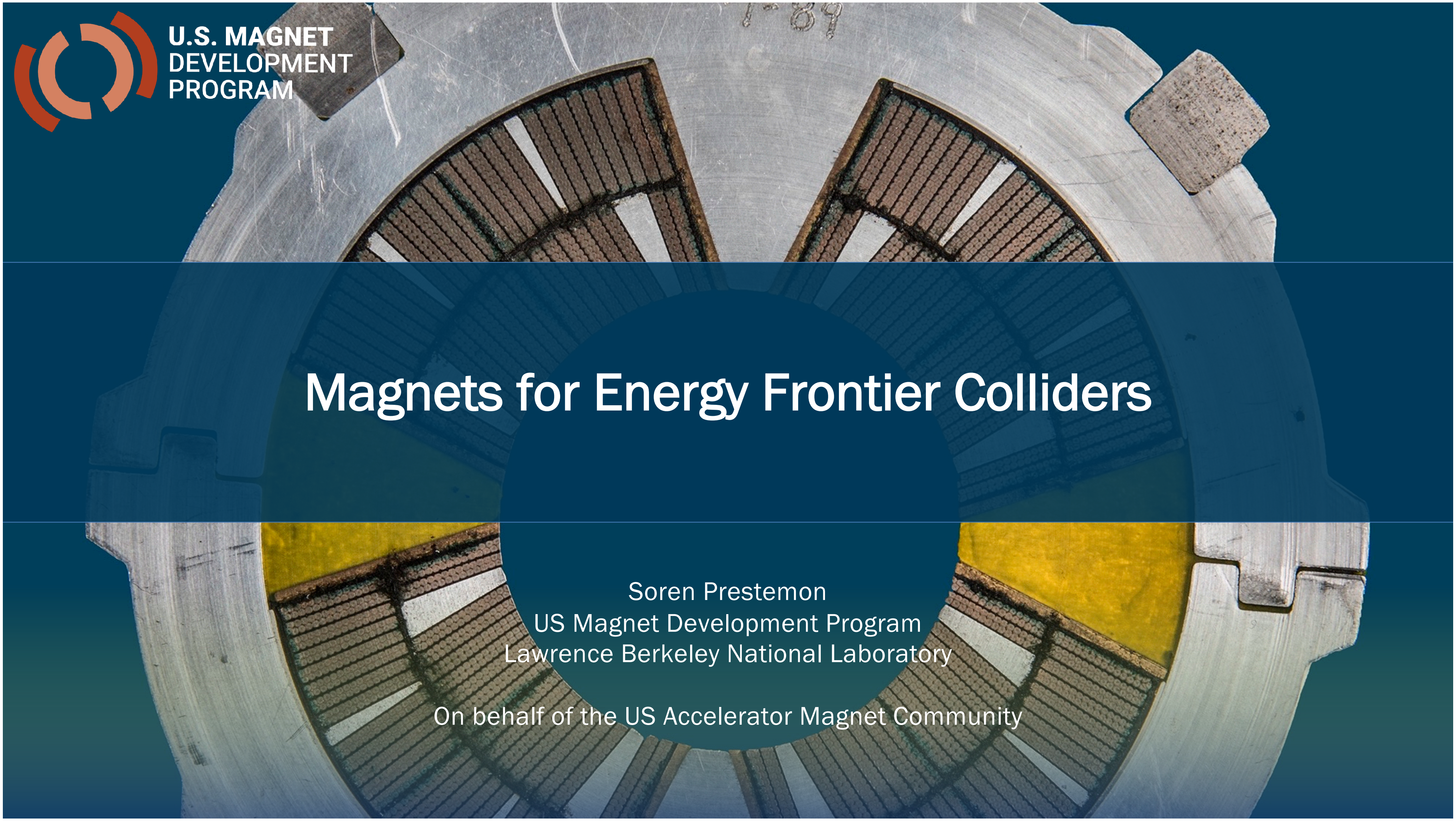


Magnets for Energy Frontier Colliders

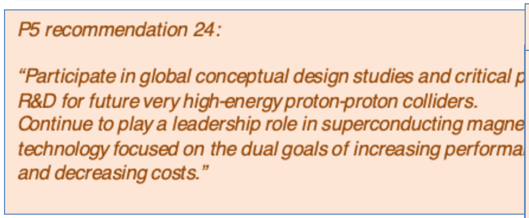
Soren Prestemon
US Magnet Development Program
Lawrence Berkeley National Laboratory

On behalf of the US Accelerator Magnet Community

Physics motivation and strategic planning

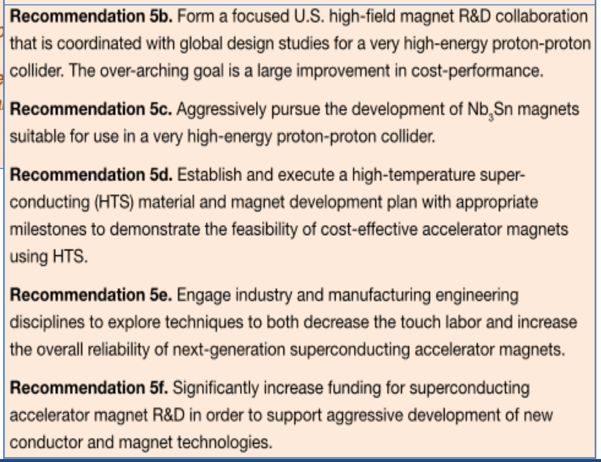
- **The physics drivers for a future hadron collider have been discussed and documented by community planning, e.g.**
  - o **2014 P5 & 2022 US "Snowmass" processes**
  - o **2020 Update of the European Strategy for Particle Physics**

Last US "P5" report ~2014


P5 recommendation 24:

"Participate in global conceptual design studies and critical p
R&D for future very high-energy proton-proton colliders.
Continue to play a leadership role in superconducting magne
technology focused on the dual goals of increasing performa
and decreasing costs."

HEPAP Accelerator R&D Subpanel recommendations

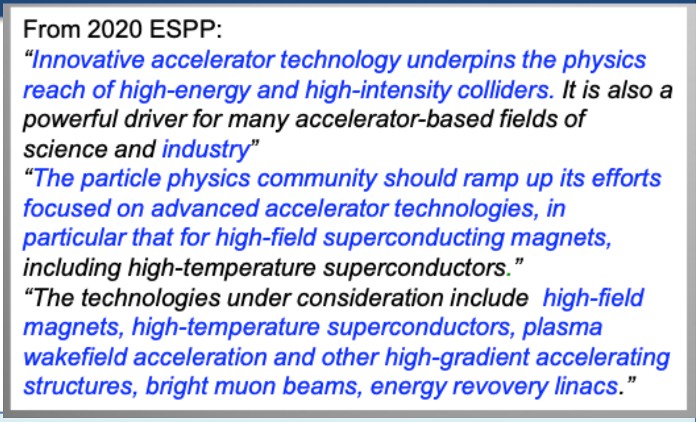

Recommendation 5b. Form a focused U.S. high-field magnet R&D collaboration that is coordinated with global design studies for a very high-energy proton-proton collider. The over-arching goal is a large improvement in cost-performance.

Recommendation 5c. Aggressively pursue the development of Nb_3Sn magnets suitable for use in a very high-energy proton-proton collider.

Recommendation 5d. Establish and execute a high-temperature superconducting (HTS) material and magnet development plan with appropriate milestones to demonstrate the feasibility of cost-effective accelerator magnets using HTS.

Recommendation 5e. Engage industry and manufacturing engineering disciplines to explore techniques to both decrease the touch labor and increase the overall reliability of next-generation superconducting accelerator magnets.

Recommendation 5f. Significantly increase funding for superconducting accelerator magnet R&D in order to support aggressive development of new conductor and magnet technologies.

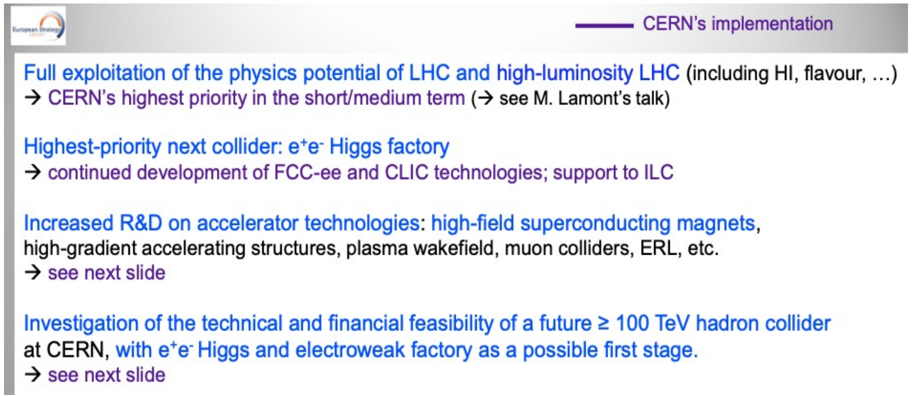

From 2020 ESPP:

"Innovative accelerator technology underpins the physics reach of high-energy and high-intensity colliders. It is also a powerful driver for many accelerator-based fields of science and industry"

"The particle physics community should ramp up its efforts focused on advanced accelerator technologies, in particular that for high-field superconducting magnets, including high-temperature superconductors."

"The technologies under consideration include high-field magnets, high-temperature superconductors, plasma wakefield acceleration and other high-gradient accelerating structures, bright muon beams, energy revovery linacs."

Fabiola Gianotti (CERN), LHCP, 7 June 2021


CERN's implementation

Full exploitation of the physics potential of LHC and high-luminosity LHC (including HI, flavour, …)
→ CERN's highest priority in the short/medium term (→ see M. Lamont's talk)

Highest-priority next collider: e^+e^- Higgs factory
→ continued development of FCC-ee and CLIC technologies; support to ILC

Increased R&D on accelerator technologies: high-field superconducting magnets, high-gradient accelerating structures, plasma wakefield, muon colliders, ERL, etc.
→ see next slide

Investigation of the technical and financial feasibility of a future ≥ 100 TeV hadron collider at CERN, with e^+e^- Higgs and electroweak factory as a possible first stage.
→ see next slide

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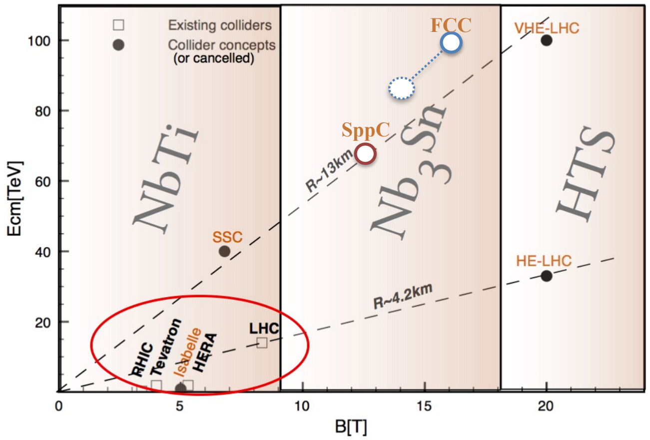
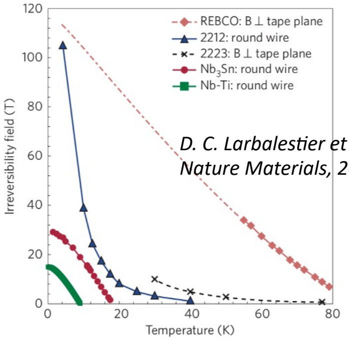
Magnet technology drives the cost and reach of a future collider





D. C. Larbalestier et al., Nature Materials, 2014

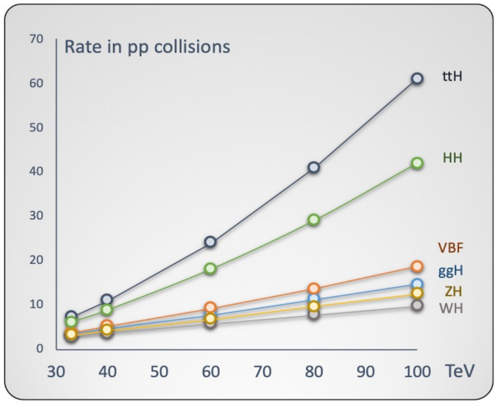


Figure 2: Higgs production cross sections versus collision energies normalized to the 14 TeV rates.

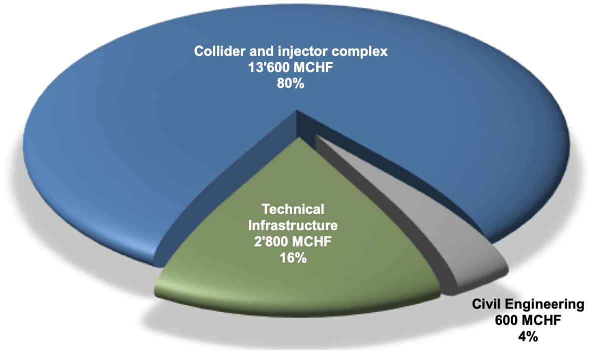


Figure 7: FCC-hh capital cost per project domain as a combined project, if FCC-hh is built after FCC-ee.

Note: The magnets are estimated to be ~70% of the Collider & Injector complex cost

Physics reach is driven by magnet technology

Source: Future Circular Collider - European Strategy Update Documents, 2019, CERN-ACC-2019-0005

“Low temperature” superconductors: NbTi, Nb_3Sn
“High temperature” superconductors: REBCO (e.g. $YBa_2Cu_3O_{7-x}$), Bi2212 (e.g. $Bi_2Sr_2Ca_{n-1}Cu_nO_{2n+4+x}$)

Dominant cost drivers for energy frontier colliders: Magnets and tunnel

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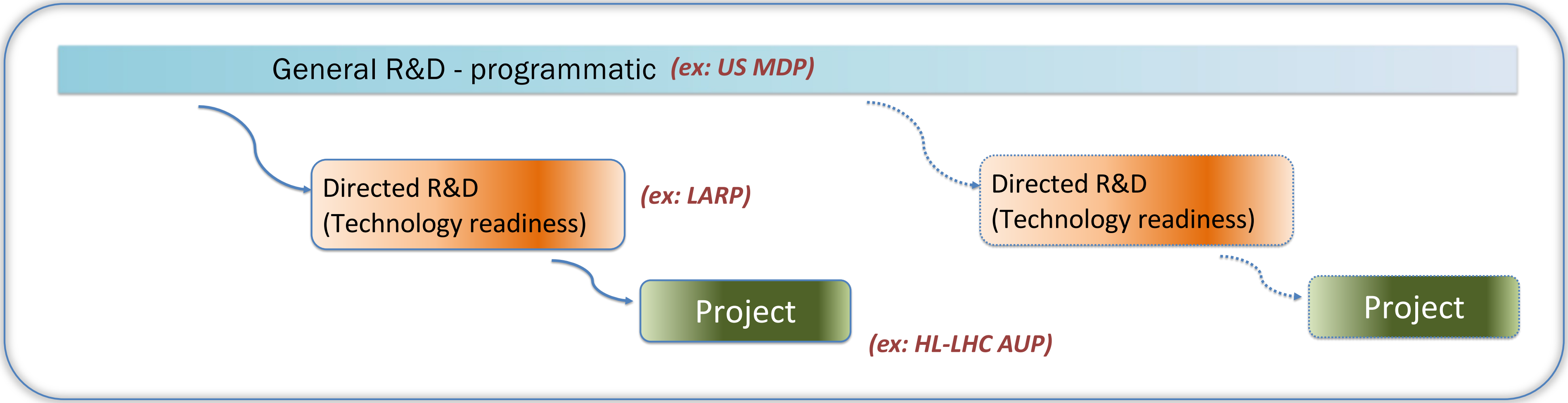
DOE-OHEP has an excellent record of developing advanced technology

- **Long term investments in general accelerator R&D set the stage for dedicated readiness programs, which in turn enable successful delivery of advanced technology for colliders**

The programs strive to coordinate efforts to more rapidly advance technology development



General R&D - programmatic *(ex: US MDP)*

Directed R&D
(Technology readiness)

(ex: LARP)

Project

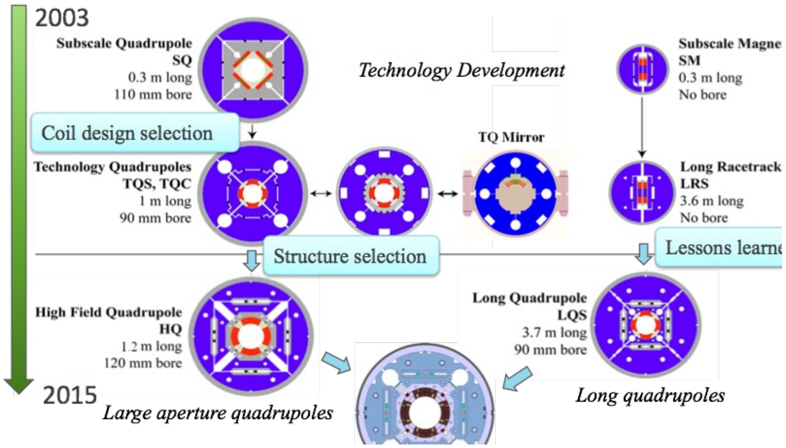
(ex: HL-LHC AUP)

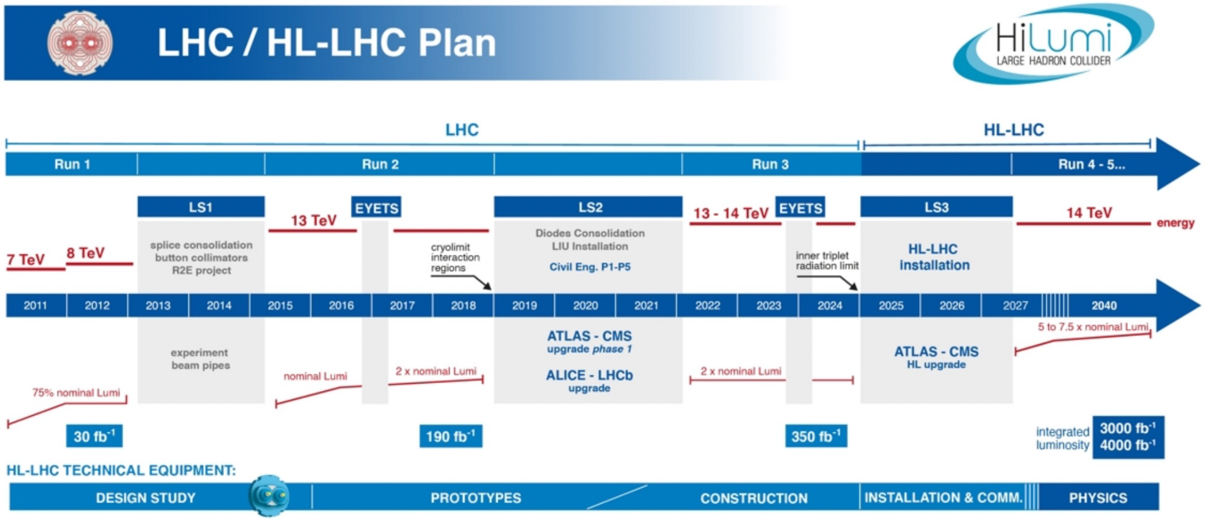
Directed R&D
(Technology readiness)

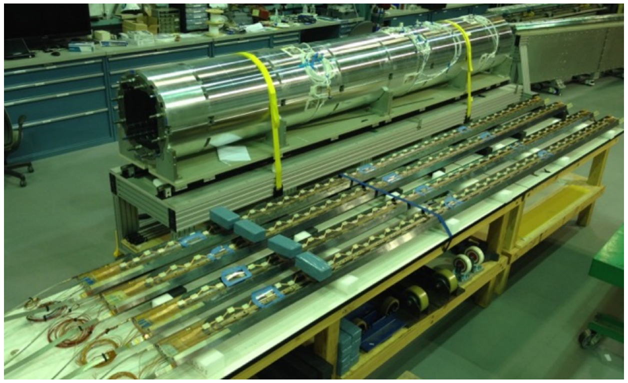
Project

The US DOE approach balances long-range R&D and project preparation

Nb_3Sn accelerator magnet technology is - *for the 1st time* - being installed in a collider







HiLumi magnet production is arguably “boutique production”

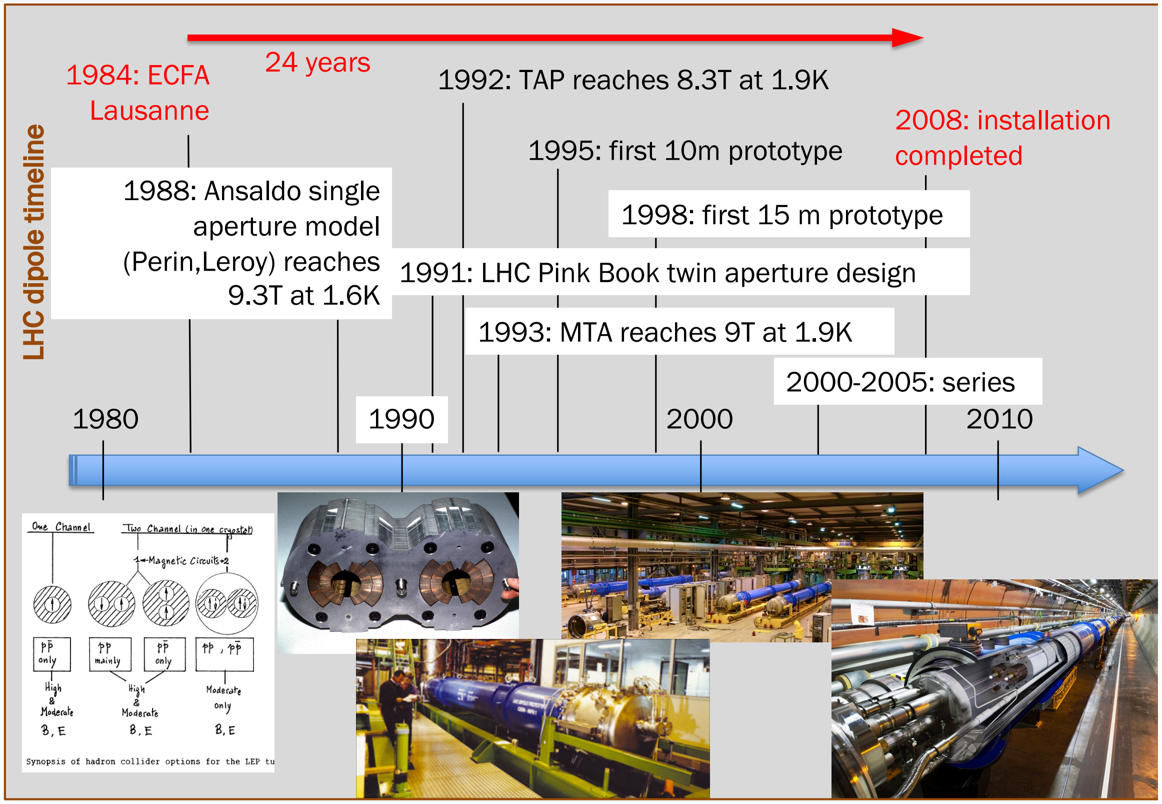
- First implementation of Nb_3Sn superconductor in a collider
- What are the risks and benefits of full-scale industrial production of Nb_3Sn magnets?
- What elements of the design are “robust”, and what elements generate risk/performance limitations?

⇒ ***There is significant value-engineering that can be performed***

A look at the timeline from the LHC itself

- **The path to next generation magnet technology for a collider is complex:**
  - Need R&D to probe concepts, develop and understand potential
  - Need robust industrial suppliers of conductor
  - Need to ready a given technology for a project
  - Need to develop industrial partners for magnet production
  - And finally need to produce reliable, cost-effective magnets for the next collider

Requires a strong ecosystem of laboratory, University, and industrial partners



LHC dipole timeline

24 years

1984: ECFA Lausanne

1988: Ansaldo single aperture model (Perin,Leroy) reaches 9.3T at 1.6K

1991: LHC Pink Book twin aperture design

1992: TAP reaches 8.3T at 1.9K

1993: MTA reaches 9T at 1.9K

1995: first 10m prototype

1998: first 15 m prototype

2000-2005: series

2008: installation completed

1980

1990

2000

2010

Courtesy Luca Bottura

R&D efforts for accelerator magnet technology are becoming more structured

- **DOE created the US Magnet Development Program (MDP) in ~2016**
- **Europe has initiated the High Field Magnet Program (HFM)**

https://arxiv.org/abs/2011.09539

http://arxiv.org/abs/2201.07895

These are significant programs, derived from ~decadal community planning processes

=> Strive to coordinate efforts to more rapidly advance technology development

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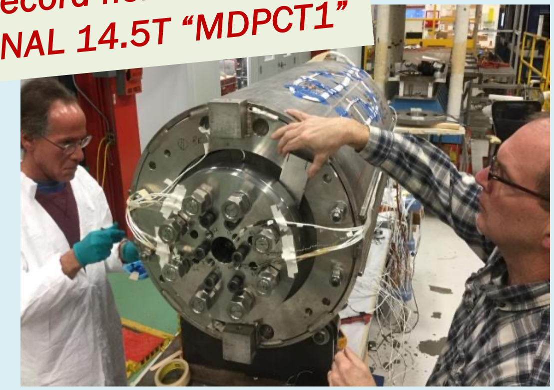
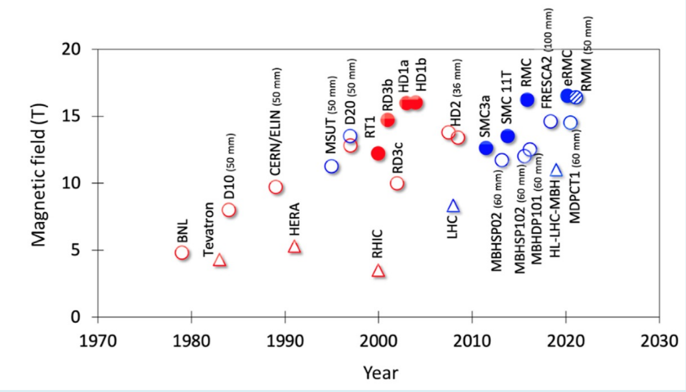
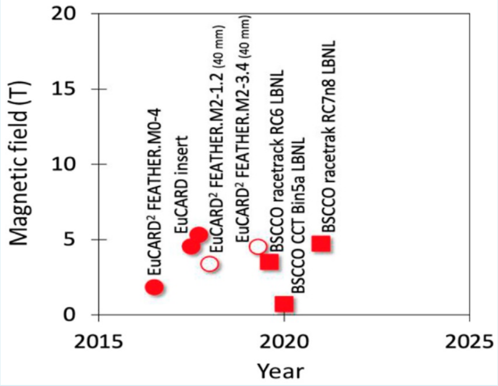
We are poised to break new ground with hybrid LTS/HTS magnets in the coming years

Record field!
FNAL 14.5T "MDPCT1"



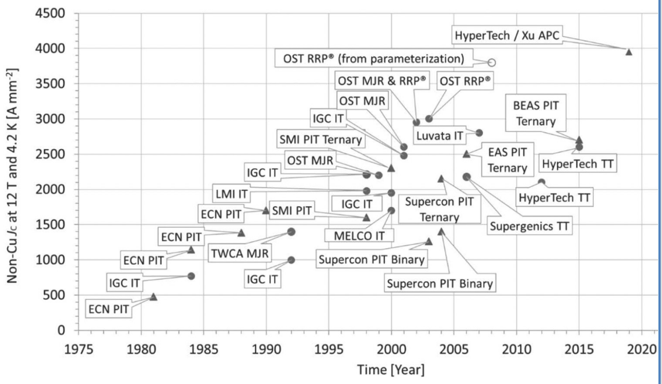
Bottura, Prestemon, Rossi, & Zlobin, Front. Phys., 12 October 2022



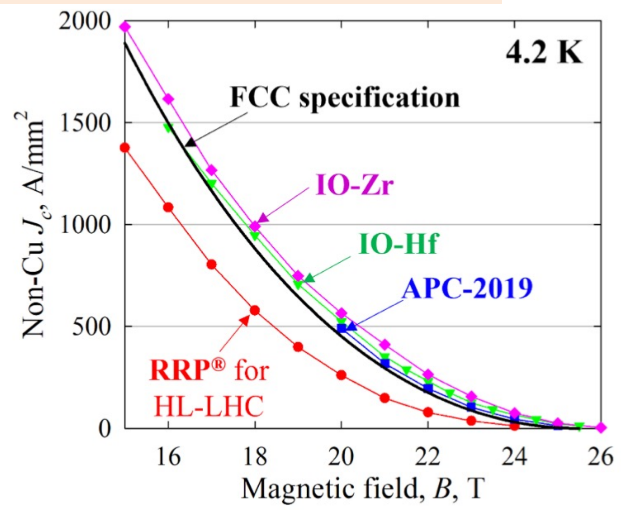


Superconductor advances are heavily driven by OHEP magnet developments, needs, and focused and consistent investments

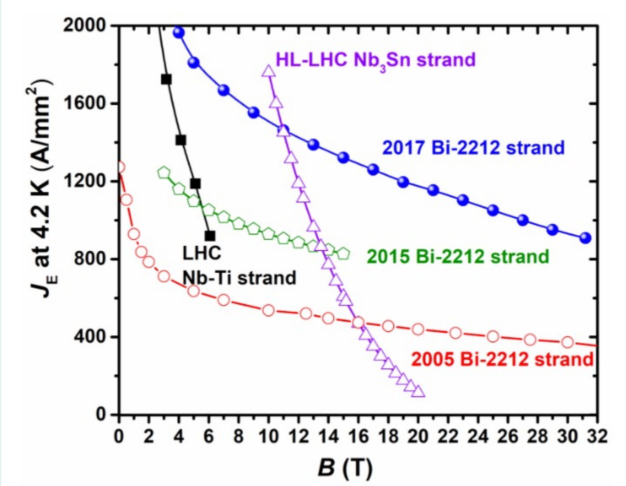
Xingchen Xu received the IPAC23 Sacherer Prize



I. Pong, Handbook of Superconductivity, Chapter E3.8



X Xu *et al* 2023 *Supercond. Sci. Technol.* **36** 035012



Shen & Fajardo, Instruments, 2020

A longstanding history of public/private partnership driving performance of superconductors

Driving the development of the next generation Nb_3Sn superconductor

Advancing Bi2212 as a magnet-ready high temperature superconductor

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The US Magnet Development Program (MDP) Vision and Goals

- ***Maintain and strengthen US Leadership*** in high-field accelerator magnet technology for future colliders

- Focus on the ***four primary goals*** identified in the the original MDP Plan
  - Explore the performance limits of Nb_3Sn accelerator magnets, with a focus on minimizing the required operating margin and significantly reducing or eliminating training
  - Develop and demonstrate an HTS accelerator magnet with a self-field of 5T or greater, compatible with operation in a hybrid HTS/LTS magnet for fields beyond 16T
  - Investigate fundamental aspects of magnet design and technology that can lead to substantial performance improvements and magnet cost reduction
  - Pursue Nb_3Sn and HTS conductor R&D with clear targets to increase performance and reduce the cost of accelerator magnets

- Further ***develop and integrate the teams*** across the partner laboratories and Universities for maximum value and effectiveness to the program

- Identify and ***nurture cross-cutting / synergistic activities*** with other programs to more rapidly advance progress towards our goals

BERKELEY LAB

Brookhaven National Laboratory

Fermilab

ASC

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European High Field Magnet (HFM) program: plans are in place – teams active and engaged

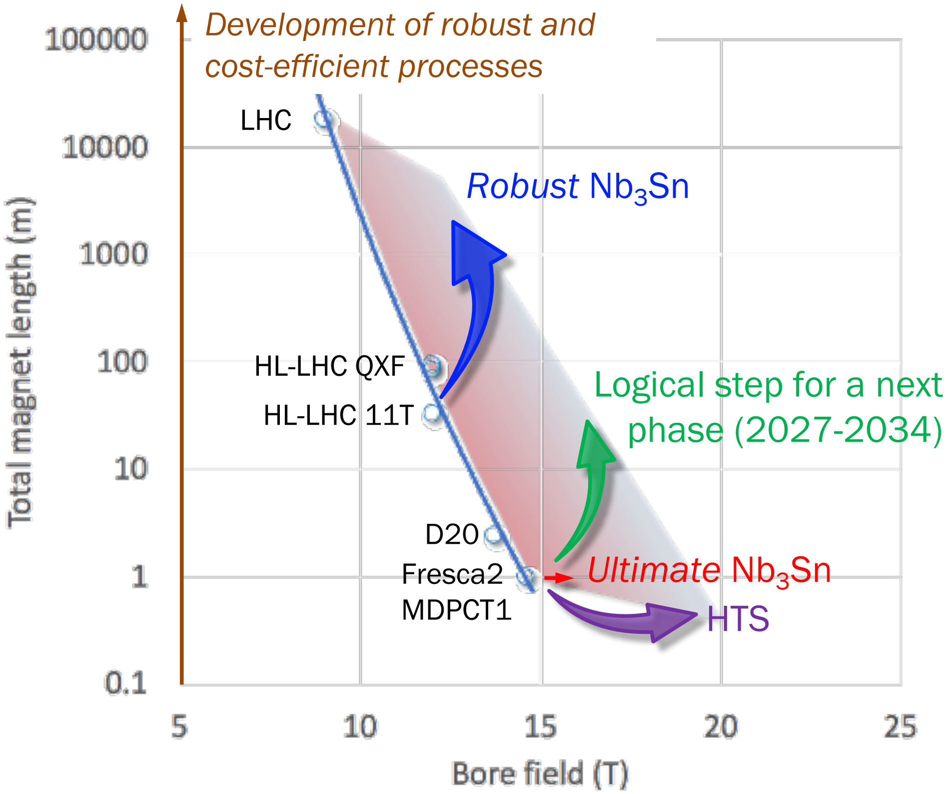
- **The EU Accelerator R&D Roadmap identifies main objectives for the High Field Magnet Programme:**
  - **OBJECTIVE 1:**

    Design and demonstrate a full-size Nb3Sn accelerator magnet to proof the maturity of the most advanced technologies today, based on the HL-LHC design, i.e., 12 T magnets, and applying all the lessons learned from the US LHC Accelerator Research programme (LARP), the US High-Luminosity LHC Accelerator Upgrade project (AUP) and the HL-LHC project
  - **OBJECTIVE 2:**

    Explore the limitations of the LTS state-of-the-art technology and push Nb3Sn magnet technology to its practical limits in terms of ultimate performance, towards the 16 T target targeted by the FCC-hh
  - **OBJECTIVE 3:**

    Explore the capabilities and limitations of state-of-the-art HTS and magnet technology based on these superconductors. Demonstrate the suitability of HTS

Create a European Research Network involving CERN and National Labs



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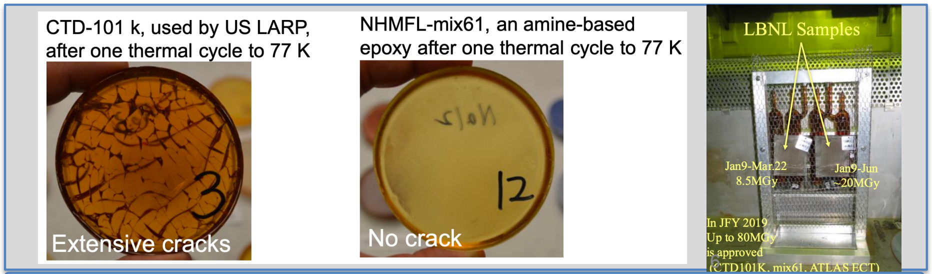
KEK plans and progress – magnet technology examples

- **Task1: HTS magnet technologies for high-radiation environment**
- **Task 2: Stability, quench protection, and magnet safety**
- **Task 3: Measuring and modeling AC loss and field quality of HTS accelerator magnets**
- **Task 4: HTS/LTS high field hybrid accelerator dipole technology**

Strong links with DOE-OHEP strategy

U.S. DEPARTMENT OF ENERGY | Office of Science

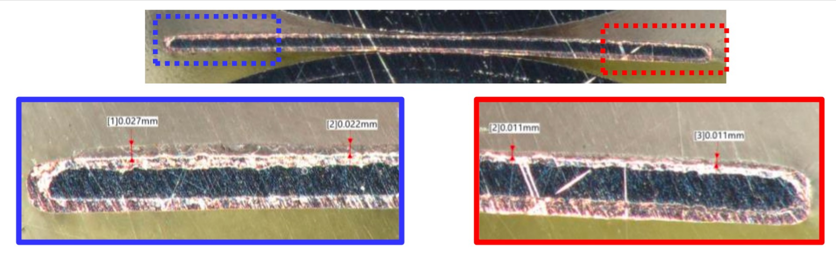
The US-Japan High Energy Physics Program


CTD-101 k, used by US LARP, after one thermal cycle to 77 K

NHMFL-mix61, an amine-based epoxy after one thermal cycle to 77 K

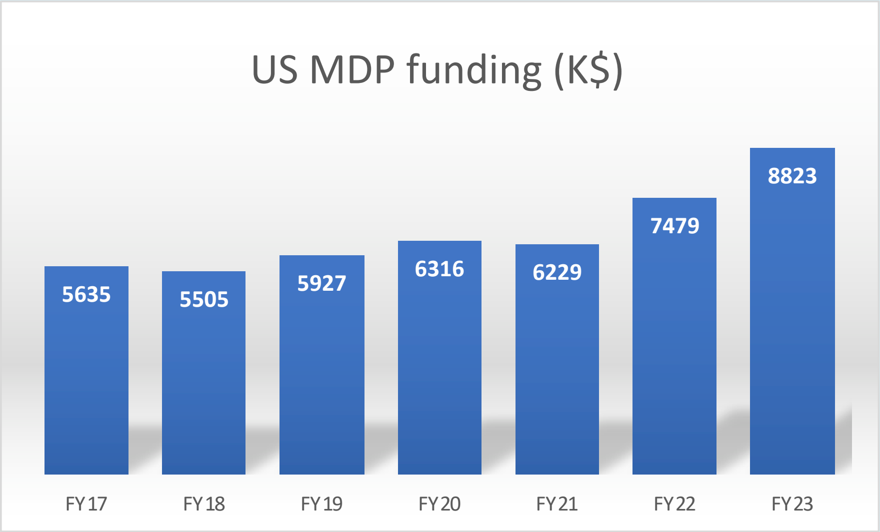
Radiation impacts on magnet materials

Development of inorganic insulation technology



Scale of MDP and HFM investments – focused on developing high field magnet technology for HEP colliders

- **The US MDP is funded by HEP GARD**



An additional ~$6M-$8M is invested annually in University programs and in test facilities at FNAL

- **The HFM is a European program, led by CERN**

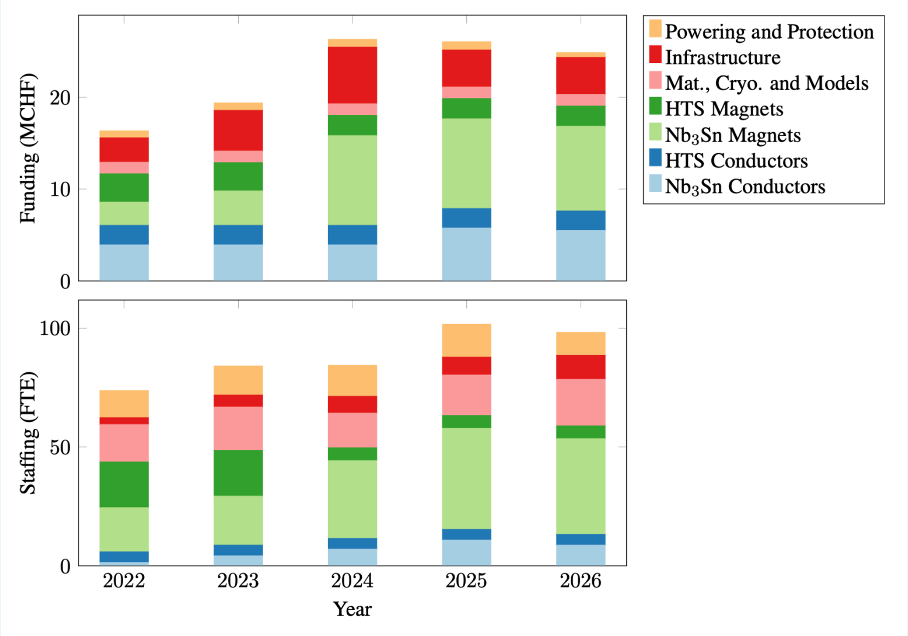


Fig. 2.14: Time profile of estimated nominal HFM material and personnel requirement for the nominal scenario.

In US accounting: ~$15M HEP GARD; ~$37M-$55M European HFM

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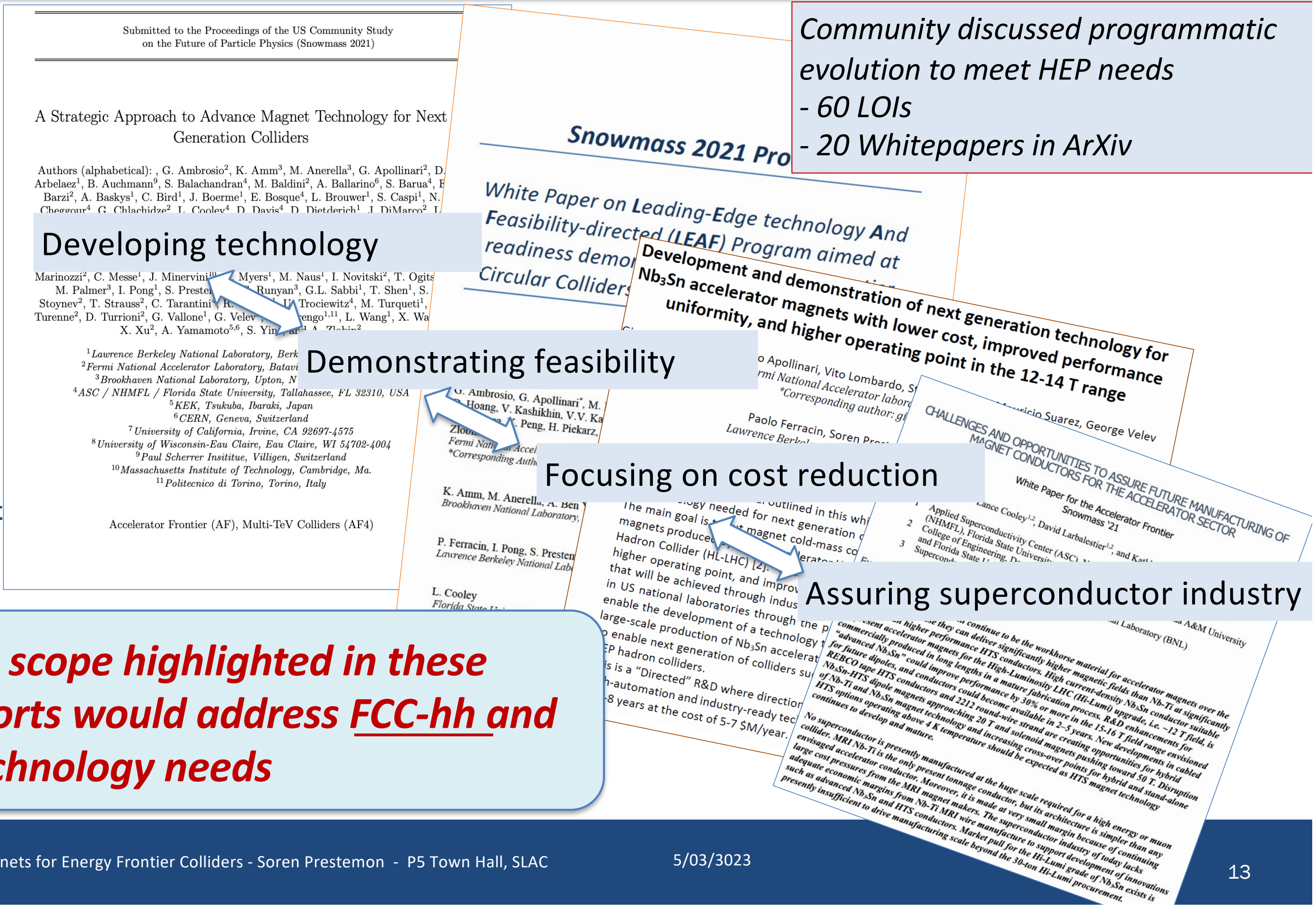
The magnet community was strongly engaged in the Snowmass process, and is highly organized

- The MDP has been very effective in organizing and focusing a multi-lab team on accelerator magnet R&D
  - International leadership, record dipole magnet, advances in HTS magnet technology,…
  - Reviewed positively by OHEP
- The AUP team is delivering state of the art magnets for HiLumi
  - As the project culminates, deep expertise will become available that can significantly accelerate magnet development for the next collider



Community discussed programmatic evolution to meet HEP needs
- 60 LOIs
- 20 Whitepapers in ArXiv

Developing technology

Demonstrating feasibility

Focusing on cost reduction

Assuring superconductor industry

Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

A Strategic Approach to Advance Magnet Technology for Next Generation Colliders

Authors (alphabetical): , G. Ambrosio[2], K. Amm[3], M. Anerella[3], G. Apollinari[2], D. Arbelaez[1], B. Auchmann[9], S. Balachandran[4], M. Baldini[2], A. Ballarino[6], S. Barua[4], Barzi[2], A. Baskys[1], C. Bird[1], J. Boerme[1], E. Bosque[4], L. Brouwer[1], S. Caspi[1], N. Cheggour[4], G. Chlachidze[2], L. Cooley[4], D. Davis[4], D. Dietderich[1], J. DiMarco[2], …

Marinozzi[2], C. Messe[1], J. Minervini[10], … Myers[1], M. Naus[1], I. Novitski[2], T. Ogits… M. Palmer[3], I. Pong[1], S. Presten… Runyan[3], G.L. Sabbi[1], T. Shen[1], S. Stoynev[2], T. Strauss[2], C. Tarantini[4], … U. Trociewitz[4], M. Turqueti[1], Turenne[2], D. Turrioni[2], G. Vallone[1], G. Velev… …rengo[1,11], L. Wang[1], X. Wa… X. Xu[2], A. Yamamoto[5,6], S. Yin… and A. Zlobin[2]

[1] Lawrence Berkeley National Laboratory, Berk…
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[7] University of California, Irvine, CA 92697-4575
[8] University of Wisconsin-Eau Claire, Eau Claire, WI 54702-4004
[9] Paul Scherrer Insititue, Villigen, Switzerland
[10] Massachusetts Institute of Technology, Cambridge, Ma.
[11] Politecnico di Torino, Torino, Italy

Accelerator Frontier (AF), Multi-TeV Colliders (AF4)

Snowmass 2021 Pro…

White Paper on Leading-Edge technology And Feasibility-directed (LEAF) Program aimed at readiness demo… Circular Colliders

G. Ambrosio, G. Apollinari*, M. … Hoang, V. Kashikhin, V.V. Ka… Peng, H. Piekarz, Zlob…
Fermi Nati… Accel…
**Corresponding Auth…*

K. Amm, M. Anerella, A. Ben…
Brookhaven National Laboratory,

P. Ferracin, I. Pong, S. Presten…
Lawrence Berkeley National Lab…

L. Cooley
Florida State Uni…

Development and demonstration of next generation technology for Nb₃Sn accelerator magnets with lower cost, improved performance uniformity, and higher operating point in the 12-14 T range

…o Apollinari, Vito Lombardo, St… …Mauricio Suarez, George Velev
…rmi National Accelerator labora…
**Corresponding author: gi…*

Paolo Ferracin, Soren Pres…
Lawrence Berkel…

CHALLENGES AND OPPORTUNITIES TO ASSURE FUTURE MANUFACTURING OF MAGNET CONDUCTORS FOR THE ACCELERATOR SECTOR

White Paper for the Accelerator Frontier
Snowmass '21

Lance Cooley[1,2], David Larbalestier[1,2], and Kath…

[1] Applied Superconductivity Center (ASC), … (NHMFL), Florida State Universit…
[2] College of Engineering, … and Florida State U…
[3] Supercond…

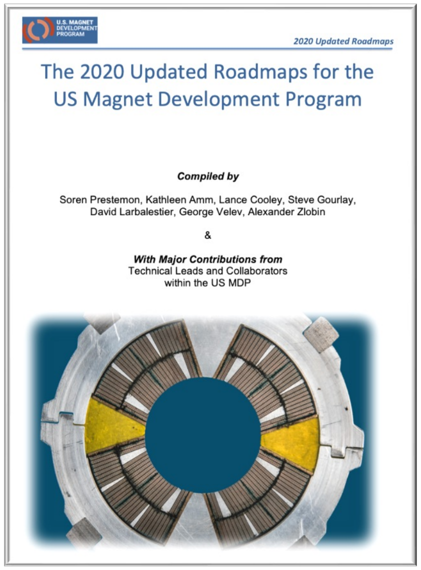
…al Laboratory (BNL) …A&M University

No superconductor is presently manufactured at the huge scale required for a high energy or muon collider. MRI Nb-Ti is the only present tonnage conductor, but its architecture is simpler than any envisaged accelerator conductor. Moreover, it is made at very small margin because of continuing large cost pressures from the MRI magnet makers. The superconductor industry of today lacks adequate economic margins from Nb-Ti MRI wire manufacture to support development of innovations such as advanced Nb₃Sn and HTS conductors. Market pull for the Hi-Lumi grade of Nb₃Sn exists is presently insufficient to drive manufacturing scale beyond the 30-ton Hi-Lumi procurement.

The magnet development scope highlighted in these coordinated proposed efforts would address <u>FCC-hh and Muon Collider</u> magnet technology needs

Magnet and Conductor Plans & Roadmaps are well-advanced globally

- US MDP – ***well established***
- European HFM – ***recently established***
- Japan efforts at KEK - coordinated with CERN and MDP
- China efforts led by IHEP – ***progressing well***



2020 Updated Roadmaps

The 2020 Updated Roadmaps for the US Magnet Development Program

Compiled by

Soren Prestemon, Kathleen Amm, Lance Cooley, Steve Gourlay, David Larbalestier, George Velev, Alexander Zlobin

&

With Major Contributions from
Technical Leads and Collaborators within the US MDP

This is ***not*** a comprehensive list of collaborators… our community is broad and diverse!

中国科学院电工研究所
Institute of Electrical Engineering, CAS

中国科学院高能物理研究所
Institute of High Energy Physics, CAS

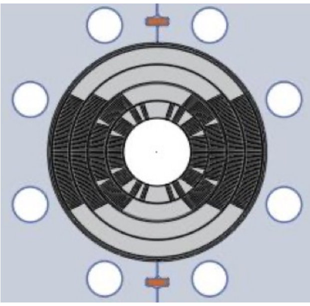
Updated US MDP Roadmaps have been published https://arxiv.org/abs/2011.09539

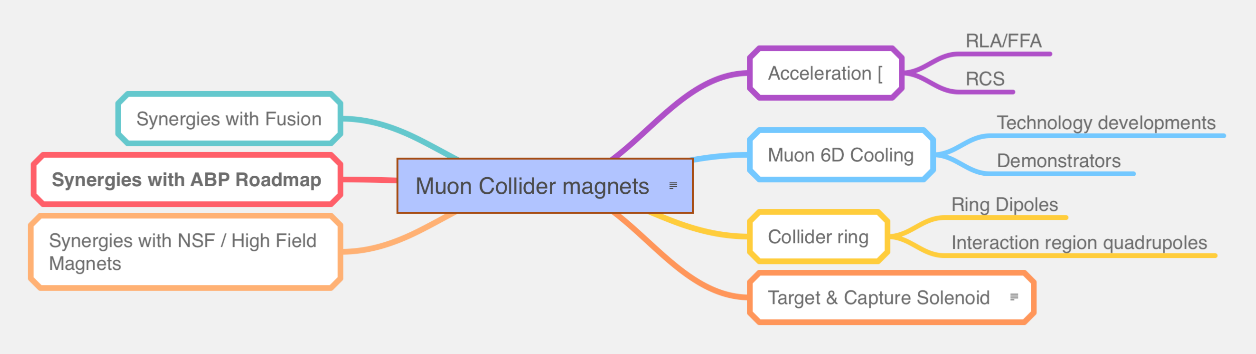
Both the FCC and the muon collider depend on advances in accelerator magnet technology

$$B \propto wJ_0 \implies \sigma_\theta \propto J_O B r$$

“Traditional” Cos-theta

- Midplane stress due to azimuthal force accumulation





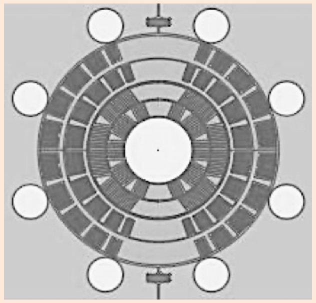
- Muon Collider magnets
  - Synergies with Fusion
  - **Synergies with ABP Roadmap**
  - Synergies with NSF / High Field Magnets
  - Acceleration [
    - RLA/FFA
    - RCS
  - Muon 6D Cooling
    - Technology developments
    - Demonstrators
  - Collider ring
    - Ring Dipoles
    - Interaction region quadrupoles
  - Target & Capture Solenoid

The magnet development scope described in the Snowmass whitepapers addresses FCC-hh and Muon collider needs
=> ***Will require a <u>four-fold increase</u> over the current MDP budget for full implementation***

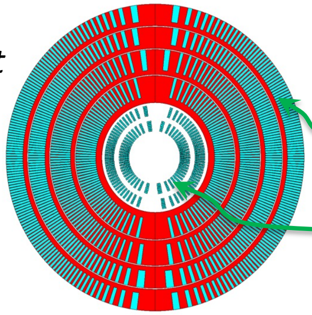
$$\sigma_{\theta,SM} \propto J_0 B \sim F_p$$

“Stress-managed” Cos-theta

- Groups of turns, azimuthal forces intercepted by support



MDP stress-managed hybrid magnets under development
- Critical for strain sensitive Nb_3Sn and HTS conductors



Serves as good candidate for muon collider ring dipole

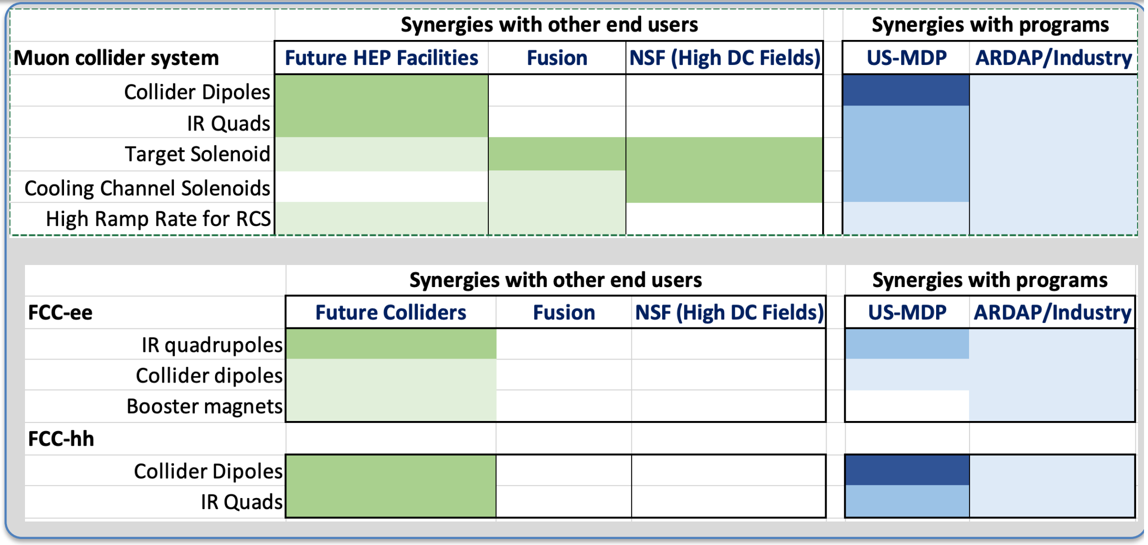
Nb_3Sn outsert

HTS insert

There are synergies in magnet technology that can be exploited across the FCC, muon collider, as well as other offices

Key points:

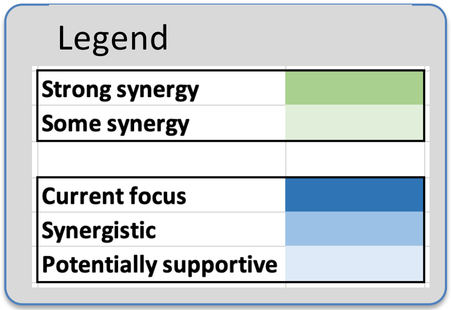
- Muon collider has synergies with Fusion and NSF
- FCC has synergies with muon collider
- MDP works to address a subset of FCC and MC needs
- ARDAP has the potential to support all colliders, for example through support for US conductor industrial development



	Synergies with other end users			Synergies with programs	
Muon collider system	**Future HEP Facilities**	**Fusion**	**NSF (High DC Fields)**	**US-MDP**	**ARDAP/Industry**
Collider Dipoles	🟩			🟦	▢
IR Quads	🟩			▦	▢
Target Solenoid	▨	🟩	🟩	▦	▢
Cooling Channel Solenoids		▨	🟩	▦	▢
High Ramp Rate for RCS	▨	▨		▢	▢

	Synergies with other end users			Synergies with programs	
FCC-ee	**Future Colliders**	**Fusion**	**NSF (High DC Fields)**	**US-MDP**	**ARDAP/Industry**
IR quadrupoles	🟩			▦	▢
Collider dipoles	▨			▢	▢
Booster magnets	▨				▢
FCC-hh					
Collider Dipoles	🟩			🟦	▢
IR Quads	🟩			▦	▢

An ***enhanced magnet research portfolio***, focusing on the most critical magnet development needs for a Hadron collider and a Muon collider, and ***fully leveraging synergies with other DOE and NSF programs***, will be the most effective way to ***aggressively prepare for the next collider***



Legend

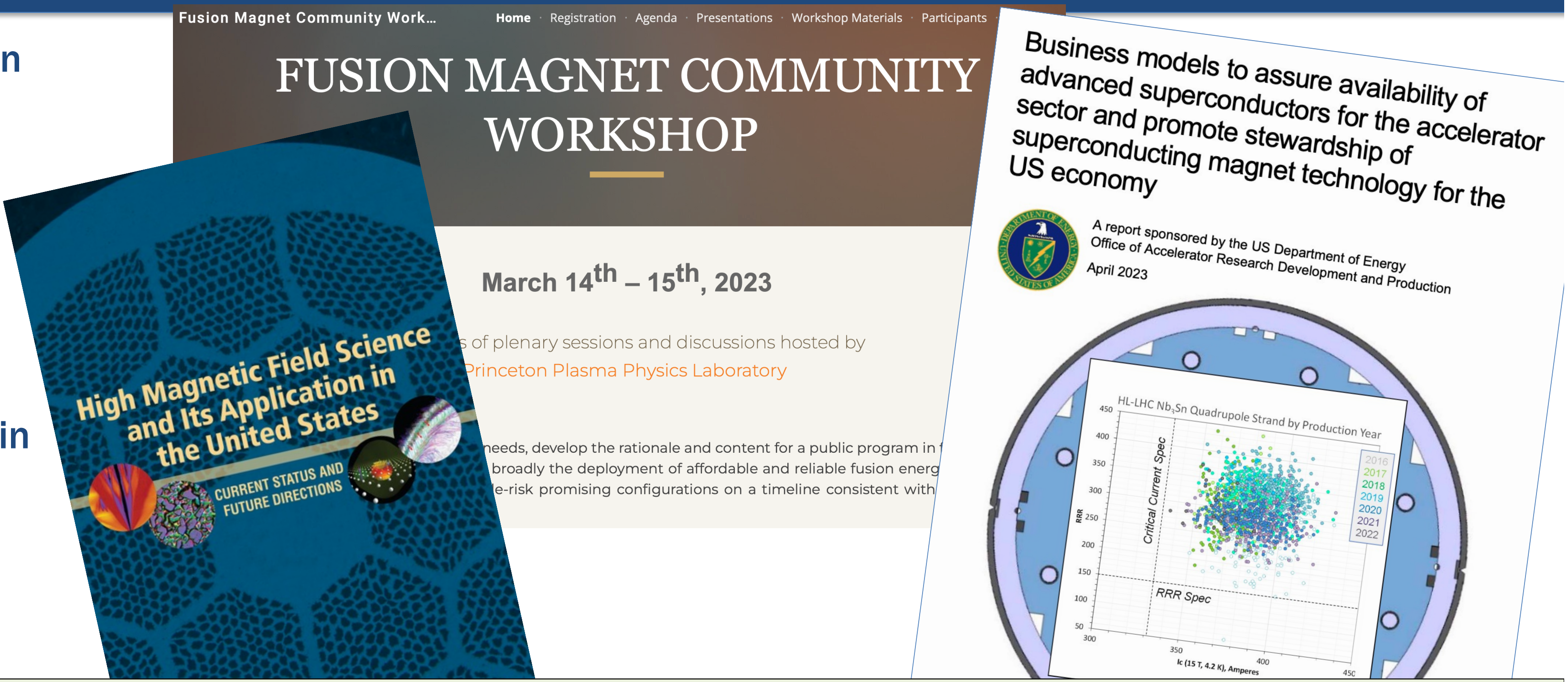
Strong synergy	🟩
Some synergy	▨
Current focus	🟦
Synergistic	▦
Potentially supportive	▢

U.S. MAGNET
DEVELOPMENT
PROGRAM

We are actively engaged in identifying and leveraging synergistic activities to the benefit of HEP

- Active participation in planning efforts
  - for HEP, but also across many synergistic agencies

- Strong participation in public-private partnerships



Fusion Magnet Community Work… Home · Registration · Agenda · Presentations · Workshop Materials · Participants

FUSION MAGNET COMMUNITY WORKSHOP

March 14th – 15th, 2023

s of plenary sessions and discussions hosted by
Princeton Plasma Physics Laboratory

needs, develop the rationale and content for a public program in
broadly the deployment of affordable and reliable fusion energ
e-risk promising configurations on a timeline consistent with

High Magnetic Field Science and Its Application in the United States

CURRENT STATUS AND FUTURE DIRECTIONS

Business models to assure availability of advanced superconductors for the accelerator sector and promote stewardship of superconducting magnet technology for the US economy

A report sponsored by the US Department of Energy
Office of Accelerator Research Development and Production
April 2023

New!

The **National Academies of Sciences, Engineering, and Medicine** is undertaking a forward-looking study to examine

(1) the status of domestic and international high magnetic field science and technology;
(2) current and future science disciplines that have critical needs for new capabilities that could only be enabled by high magnetic fields;
(3) gaps in current high magnetic field science, technology, and infrastructure that could help address critical needs.

Summary

- The High Energy Physics community has clearly indicated the science potential associated with a future colliders that probe significantly higher energies

- There is a concerted effort around the world to integrate teams of specialists and facilities to most efficiently, effectively, and rapidly advance magnet technology

- There is also strong interest in collaborating internationally, where strengths and capabilities are deemed complementary

- To aggressively prepare magnet technology for a hadron or Muon collider, a significant increase in the magnet R&D effort is needed, fully leveraging synergistic activities, e.g. from FES and NSF
  - *To be technically limited, a four-fold increase in R&D investment is needed*

We are at a critical period, where innovation and progress in magnet technology is essential to enable the next generation of colliders – we welcome the challenge while recognizing the responsibility!