U.S. MAGNET DEVELOPMENT PROGRAM

Snowmass Community Summer Study Workshop

Snowmass 2021

The US Magnet Development Program Status and Plans

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The HEP community needs advances in superconducting magnet technology to explore new physics realms via colliders

- A strategic whitepaper detailing progress in magnet R&D was submitted
  - 14 "Statements" are highlighted in the document that summarize key points and future goals for our field
  - Complementary strategic whitepapers were submitted describing the European efforts in the field, as well as complementary US initiatives for directed-R&D – ***see following presentations!***

https://arxiv.org/abs/2203.13985

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

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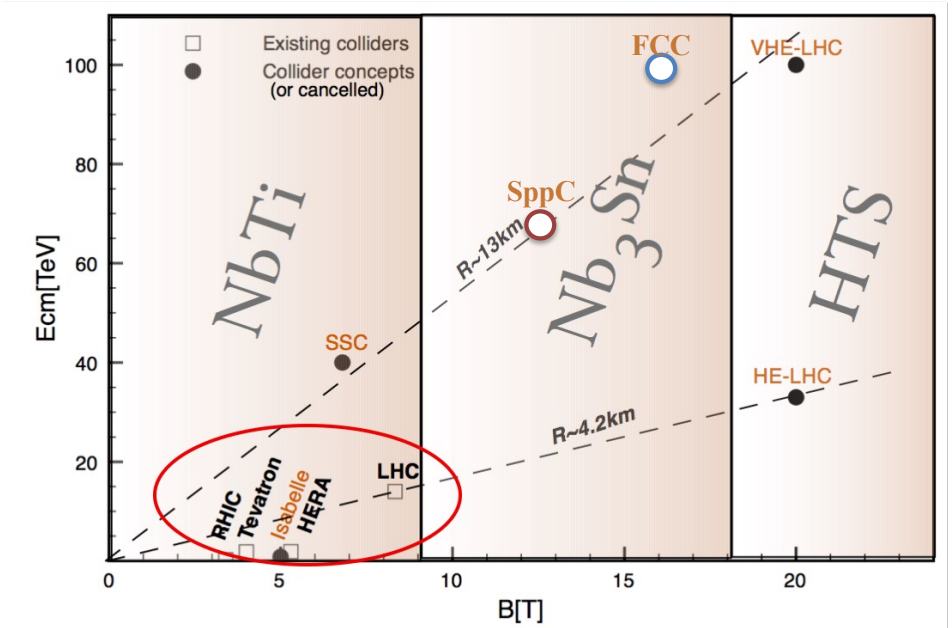
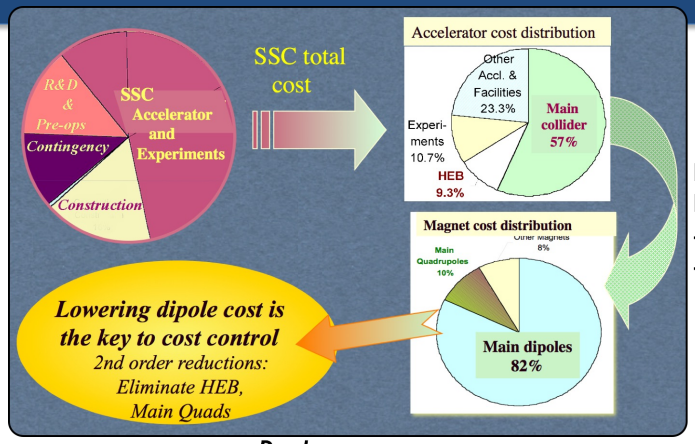
Accelerator Frontier (AF), Multi-TeV Colliders (AF4)

Magnet technology drives the cost and reach of a future collider



Cost/field-strength is the critical metric

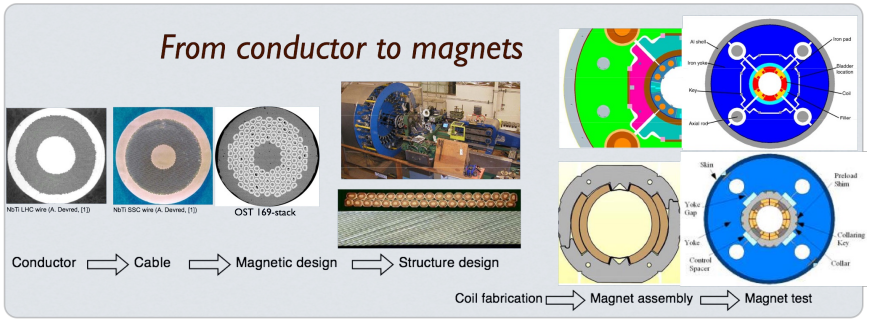


Barletta

CERN cost estimates*:
$\$_{magnets}/\$_{tot}$

LHC: 57%
HE-LHC:
- 70% (26TeV; Nb_3Sn)
- 77% (33TeV; HTS)

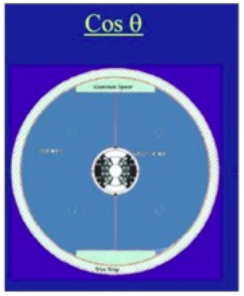
L. Rossi, "TOE" talk

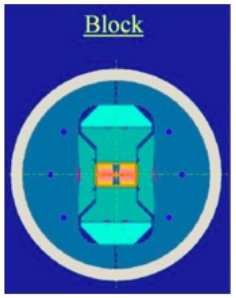


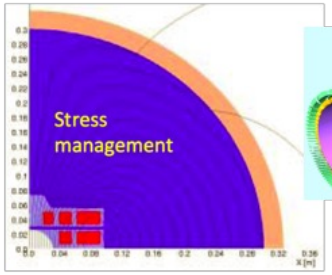
Dominant cost drivers for a pp collider: Magnets and tunnel

The "magnet zoo" of design alternatives

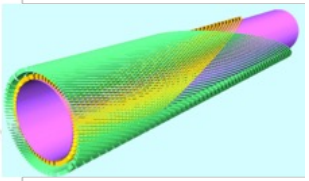
- R&D magnet designs explore layouts that attempt to address issues associated with conductor strain (to avoid degradation) and reduction of conductor/coil motion (to minimize training)
- Colliders (to-date) all based on Cos(t) designs – efficient
- At high field "managing" stress through judicious force interception will be required



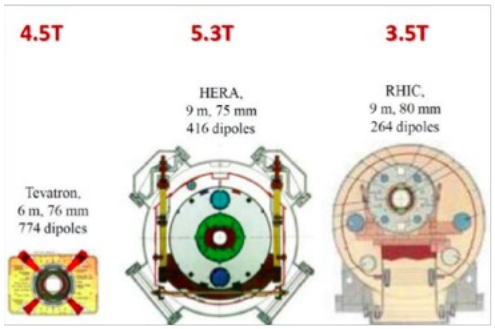




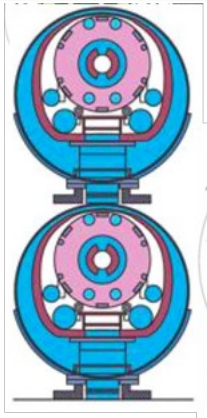
TAMU



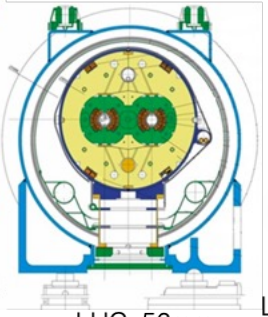
CCT



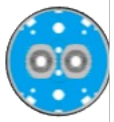
Shiltsev/Zlobin, (FNAL)



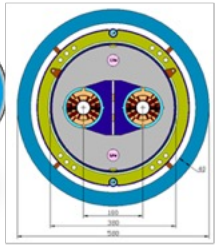
SSC, 50mm
6.6T, 4.3K



LHC, 56mm
8.3T, 1.9K



LHC, 60mm
11T,1.9K
FNAL/CERN



VLHC, 43mm
10T, 4.5K

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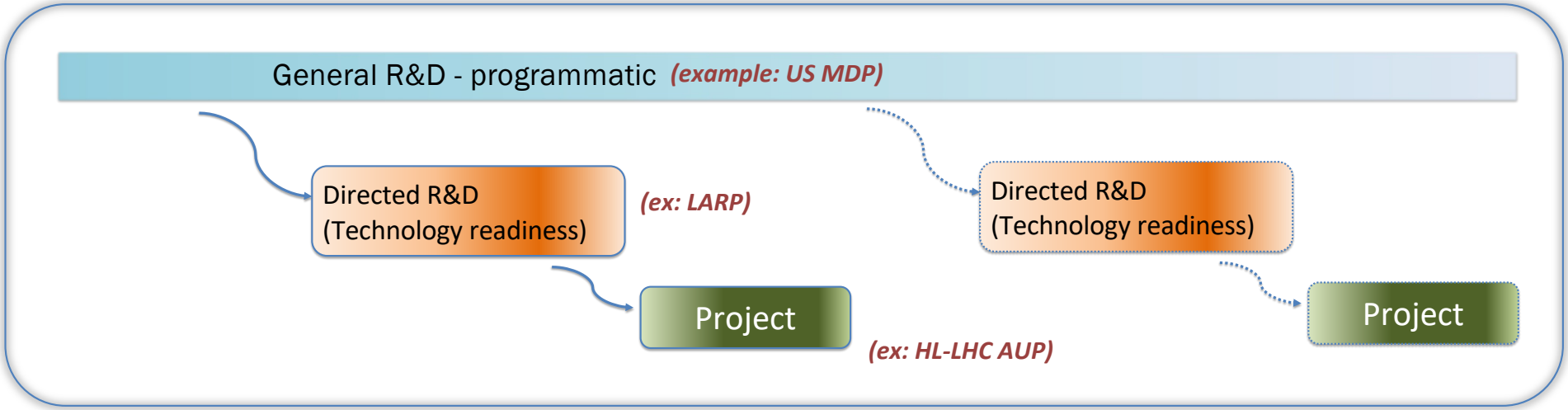
R&D efforts for accelerator magnet technology are becoming more structured

Snowmass 2021

- DOE created the US **Magnet Development Program** (MDP) in ~2016 *https://arxiv.org/abs/2011.09539*
- Europe recently formed the **High Field Magnet program** (HFM) *http://arxiv.org/abs/2201.07895*

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



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

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Program vision and goals

Snowmass 2021

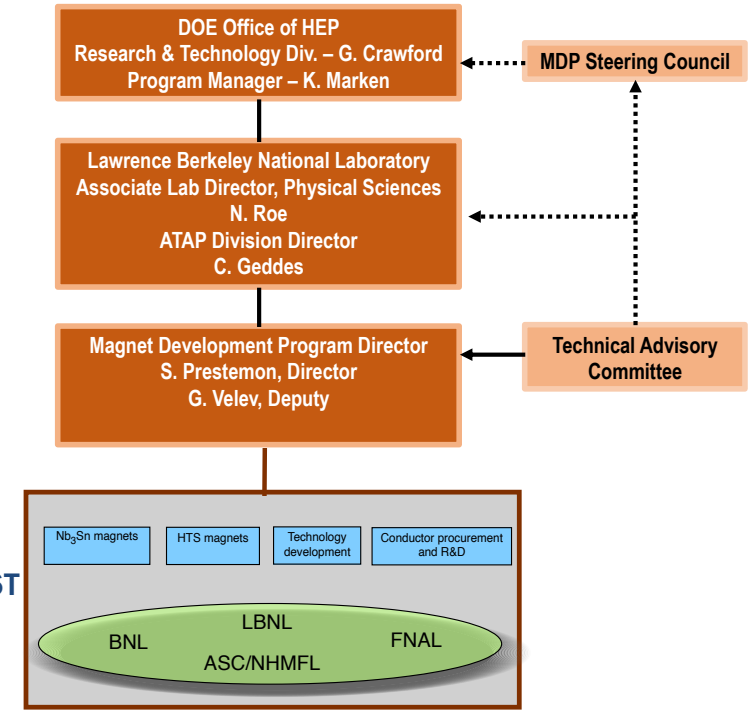
Initiated by DOE-OHEP in response to 2013 Snowmass/P5

•Vision

- Maintain and strengthen US Leadership in high-field accelerator magnet technology for future colliders;
- Further develop and integrate magnet research teams across the partner laboratories and US Universities for maximum value and effectiveness to MDP;
- Identify and nurture cross-cutting / synergistic activities with other programs (e.g. Fusion), to more rapidly advance progress towards our goals.
- Motivate and grow a new generation of magnet experts for future facilities

•Overarching goals:

- ***Explore the performance limits* of Nb3Sn accelerator magnets**, with a sharpened 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, understand present performance limits, and reduce the cost of accelerator magnets



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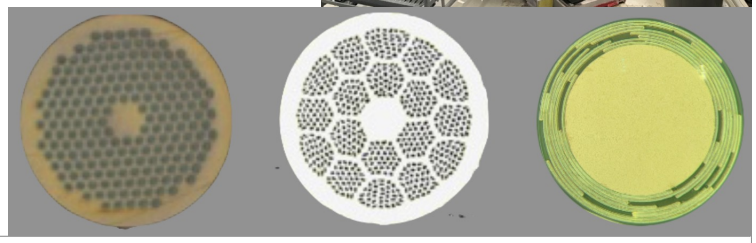
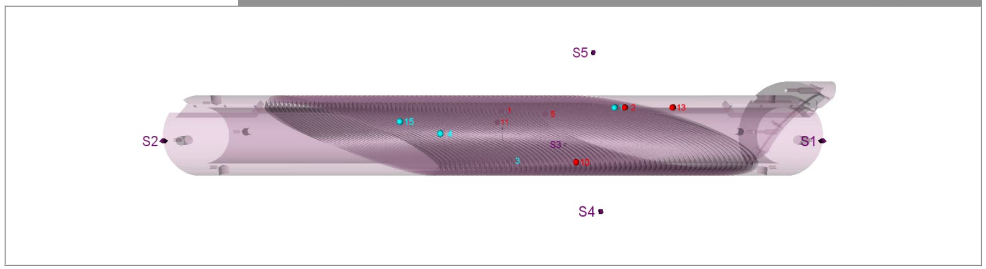
Major results from MDP on multiple fronts

- Progress on multiple fronts
  - Cos-theta magnet MDPCT1 (FNAL) achieved 14.5T (60mm aperture)!
  - First two 2-layer Nb_3Sn Canted-Cos-theta (CCT) magnets (90mm bore) tested
    - Reached 86-88% short-sample; different epoxy => improved training;
  - Steady progress on REBCO CORC™-based magnet technology
  - Significant progress on Bi2212 magnet technology
    - 4.7T common coil => no training!
  - Variety of developments and improvements in diagnostics
  - Important developments in conductor R&D (with industry)
    - Record Nb_3Sn via Zr doping; strong promise from Hf alloying
    - "High-Cp" as a means to improve Nb_3Sn quench performance
    - Record Bi2212 wire performance
      - Significantly exceeds "FCC spec" at 16T
      - New Bi2212 powder producers – seeded by SBIR
  - And many others...





MDP results and developments prepare for high-field prototypes – stress-managed and hybrid magnets

- MDP Magnet R&D results pave path to stress-managed high-field hybrid HTS/LTS magnets

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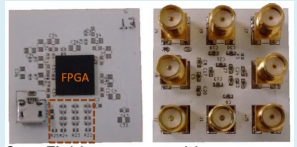
- Conductor/cable samples
- Diagnostics & materials dev.

=> *Fast turn-around, specific experiments*



Cryo-Field-programmable gate array

Plastic optical fiber

Development of advanced epoxies with US industry

CTD 701X After 10 Thermal Cycles

CTD 101K After 10 Thermal Cycles

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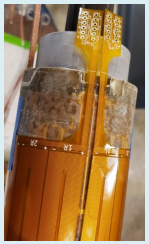
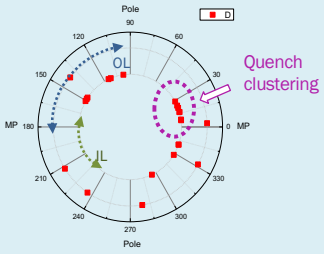
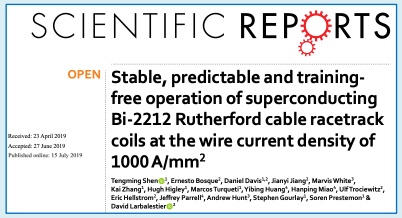
- Subscale / HTS insert magnets

=> *Critical to develop magnet technology*





Subscale CCT with new flexible quench antenna


SCIENTIFIC REPORTS

OPEN

Stable, predictable and training-free operation of superconducting Bi-2212 Rutherford cable racetrack coils at the wire current density of 1000 A/mm²

Received: 23 April 2019
Accepted: 27 June 2019
Published online: 15 July 2019

Tengming Shen[1], Ernesto Bosque[1], Daniel Davis[1,2], Jianyi Jiang[1], Marvis White[1], Kai Zhang[1], Hugh Higley[1], Marcos Turqueti[1], Yibing Huang[1], Hanping Miao[1], Ulf Trociewitz[1], Eric Hellstrom[1], Jeffrey Parrell[1], Andrew Hunt[1], Stephen Gourlay[1], Soren Prestemon[1] & David Larbalestier[1]

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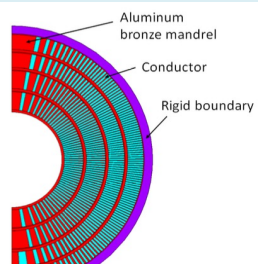
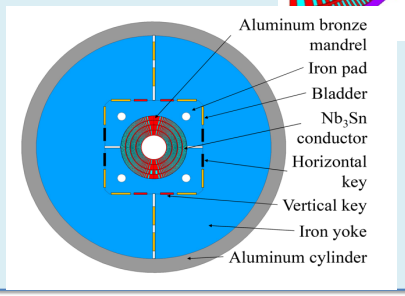
- Full size R&D magnets

=> *Final demonstration of MDP deliverables*





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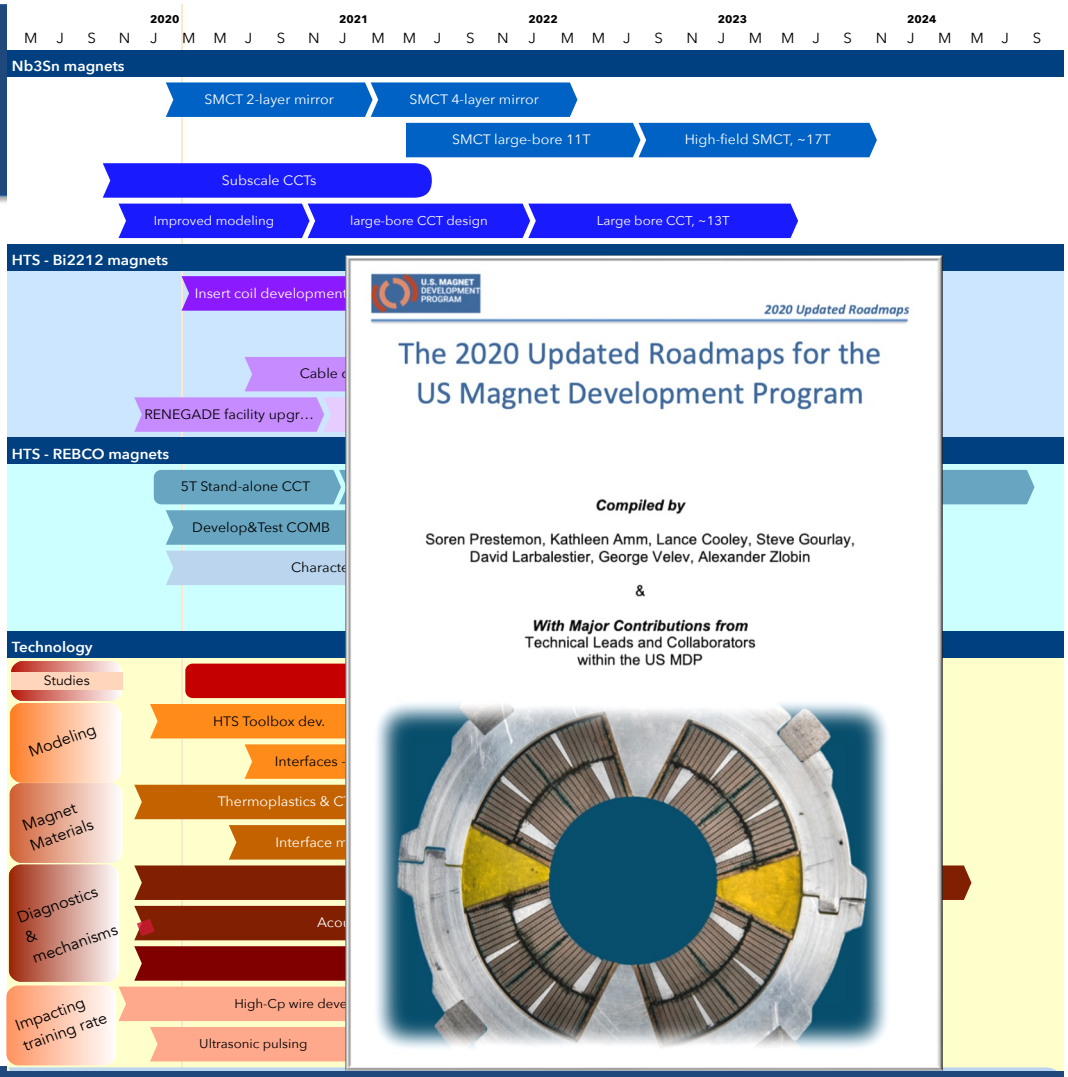
Program roadmap for the 2020-2024 period

- **Strategic directions for the (2020) updated plan:**
  - Probing stress management structures
  - Hybrid HTS/LTS designs
  - Understanding and impacting the disturbance-spectrum
  - Advancing both LTS and HTS conductors, optimized for HEP applications

We also introduced a new technology element

20T Hybrid Magnet Design & Comparative Analysis,

=> designed to prepare for future milestones and directions



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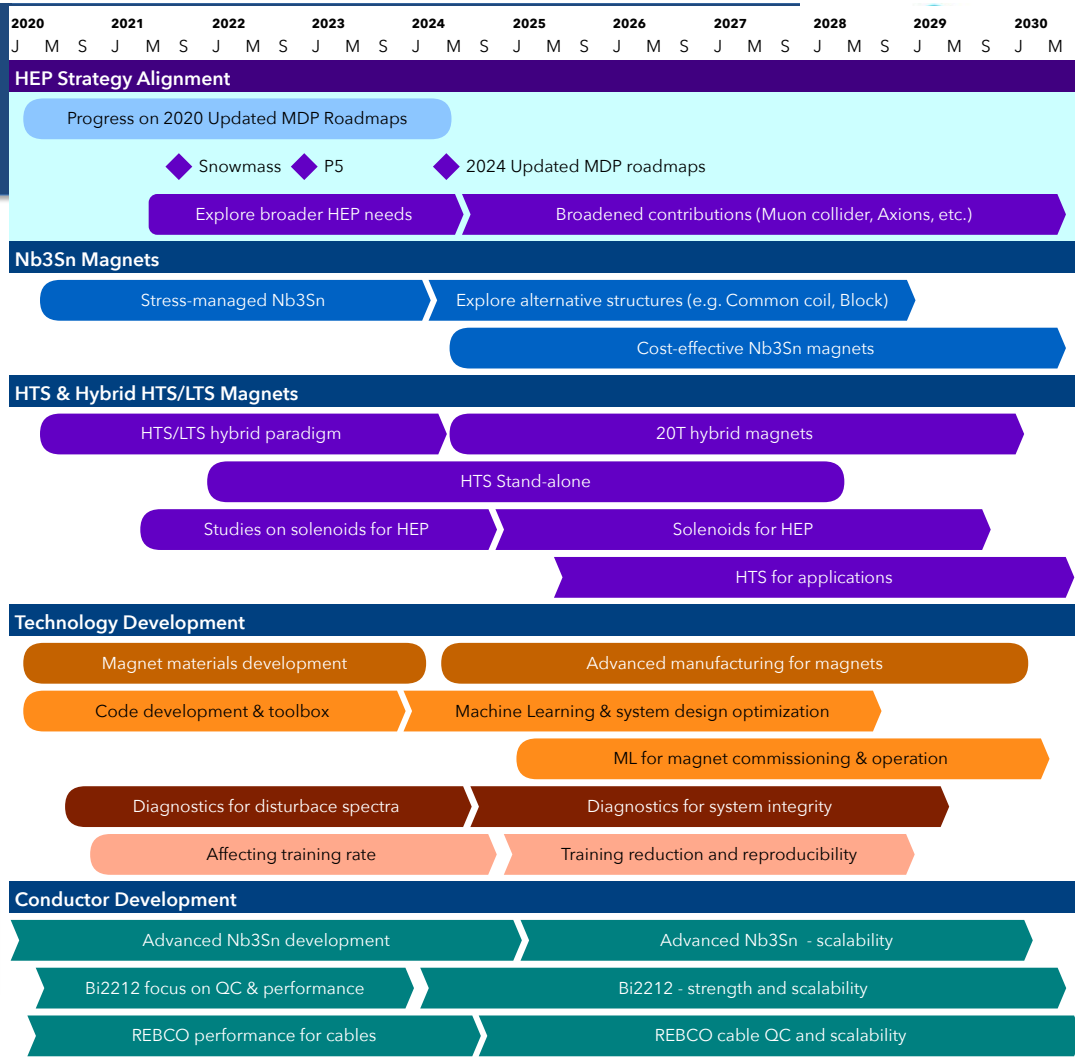
Ten-year roadmap

- A 10-year high-level roadmap recognizes this Snowmass process and possible program adjustments

- Significant synergies with other programs
  - NHMFL development of high field solenoid technologies
  - Fusion development of high-field HTS-based Tokamaks
  - The DOE HEP and FES offices are investing now in a High Field Cable Test Facility
  - We are working with DOE's ARDAP to identify means to strengthen US industrial/laboratory ecosystem in superconductors and magnets

- MDP can provide critical developments for many of the HEP science applications advocated at Snowmass – ***but will require enhanced funding***



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Progress in magnet technology is critical to enable future colliders, and is currently resource-limited

Snowmass 2021

- **MDP is a mature, effective multi-lab program – *Limited by funding resources!***
  - Strong oversight by independent experts
    - Technical Advisory Committee (2-3 times / year):
      – A.J. Lankford (Chair); G. Apollinari, A. Ballarino, J. Minervini, M. Palmer, A. Yamamoto/T. Ogitsu
    - Steering Council (~1 / year):
      – H. Wheerts (Chair); T. Raubenheimer, + Lab Directors (or delegates)

- **Reviewed by DOE-OHEP in December 2019**
  - A.J. Lankford (UCI), Chair; Ruben Fair (Jefferson Lab); Pierre Vedrine (CEA-Saclay)

> *Comments: Effectiveness in implementing a prioritized and optimized program:* MDP management has been effective in establishing a successful R&D program. It has also been effective in implementing its strategic plan, as demonstrated by the important accomplishments in each of its thrust areas.

Summary: A strong magnet R&D program is essential to deliver on HEP science facility needs

MDP focuses on "generic" magnet R&D that builds the foundations for Particle Physics applications

- Strong modeling and analysis developments – leverage HPC, AI/ML
- Strong diagnostics developments – insight into magnet performance, protection, control
- Development of core magnet technologies – materials, processes, testing
- Development of superconductors – performance, scalability and cost
- And most critically => **development of the next generation of magnet experts for the community!**

MDP can be effectively complemented by directed R&D when the time is right - i.e. a potential project is on the horizon

A long-range magnet R&D program, designed to advance magnet technology while fully leveraging the broader community's strengths, is vital to HEP and the future of particle physics.