The US Magnet Development Program

Soren Prestemon, Senior Scientist
Accelerator Technology & Applied Physics Division
Lawrence Berkeley National Laboratory

LDG Open Meeting and Accelerator R&D Workshop
June 6, 2024

U.S. MAGNET DEVELOPMENT PROGRAM

U.S. DEPARTMENT OF ENERGY | Office of Science

Outline

- Program vision and goals
- The message from P5
- MDP roadmap and progress
- Aligning with P5

BERKELEY LAB

Brookhaven National Laboratory

Fermilab

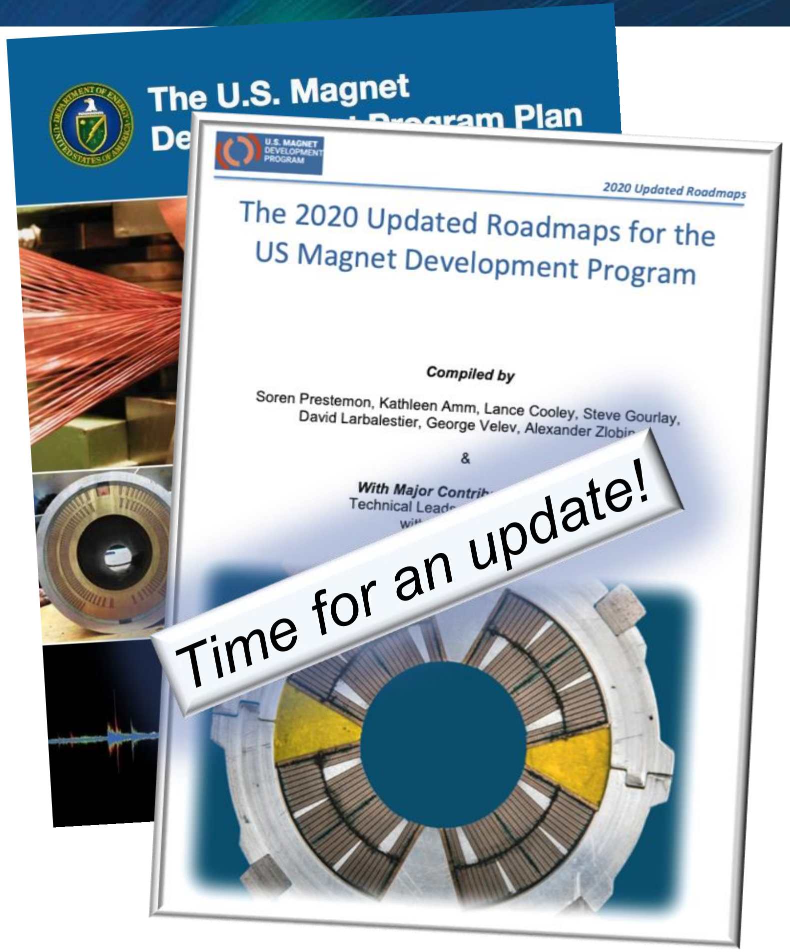
US MDP vision focuses on leadership and team-science

- ***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…
  - Develop and demonstrate an HTS accelerator magnet with a self-field of 5T or greater…
  - Investigate fundamental aspects of magnet design and technology…
  - Pursue Nb_3Sn and HTS conductor R&D …

- 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



We are refreshing the Program Roadmap this year -
the ***vision*** and ***primary goals*** will align with the new P5 report

U.S. MAGNET DEVELOPMENT PROGRAM

Central themes / focus of current MDP magnet R&D

- Understanding the disturbance spectrum and its control
  - Study training, operating margin, and means to mitigate/reduce
- Develop stress-management concepts to enable high-field acc. magnets with strain-sensitive materials (Nb3Sn, HTS)

- *Use fast turn-around platforms (subscale magnets, mirror magnets, etc)*
- *Develop and apply advanced diagnostics, modeling*

- Develop and demonstrate REBCO and Bi2212 magnet technologies

- *Focus on developing conductor / cable / coil / magnet processes, identifying key issues*

- Explore the viability of hybrid HTS/LTS magnets for efficient high-field accelerator magnets

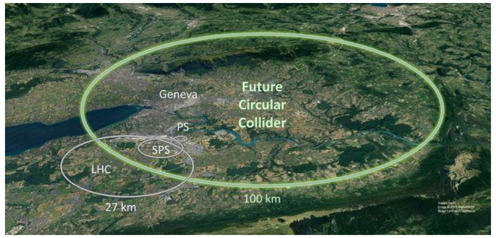
- *Leverage elements above to design optimized high-field configurations*

- Work with industry to advance superconductors tailored to HEP needs

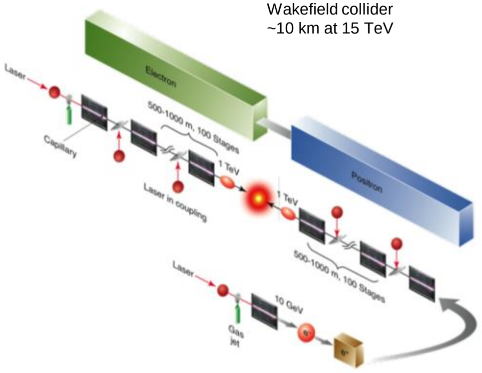
- *Longstanding nexus between Labs, Universities, and industry in the US*

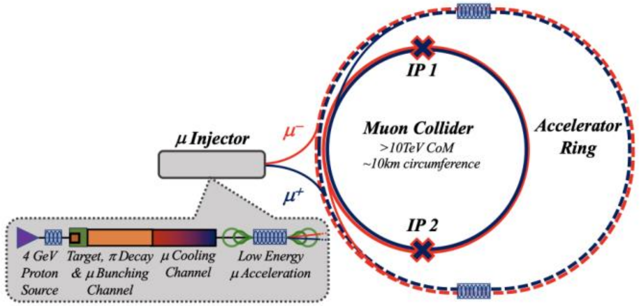
The P5 report had a clear message – 10 TeV pCM colliders!

- Precision studies of the Higgs self-interaction and searches for possible new spin- less particles related to the Higgs require much larger energies per fundamental particle (parton) interaction than previously considered: ***on the order of 10 TeV or more.***
- Theoretical and experimental studies indicate that a comprehensive study of the electroweak scale requires colliders with ***energy of at least 10 TeV pCM***, larger than previously assumed.
- Revealing the secrets of the Higgs boson, characterizing WIMP dark matter, and searching for direct evidence of new particles ultimately requires access to the electroweak scale provided by ***a collider with pCM energy of 10 TeV.***
- ***We do not yet have a technology capable of building a 10 TeV pCM energy machine, but the case for one is clear.*** Extensive R&D is required to develop cost-effective options. Possibilities include **proton beams with high-field magnets, muon beams that require rapid capture and acceleration of muons within their short lifetime**, and conceivably electron and positron beams with wakefield acceleration. All three approaches have the potential to revolutionize the field.



Wakefield collider
~10 km at 15 TeV





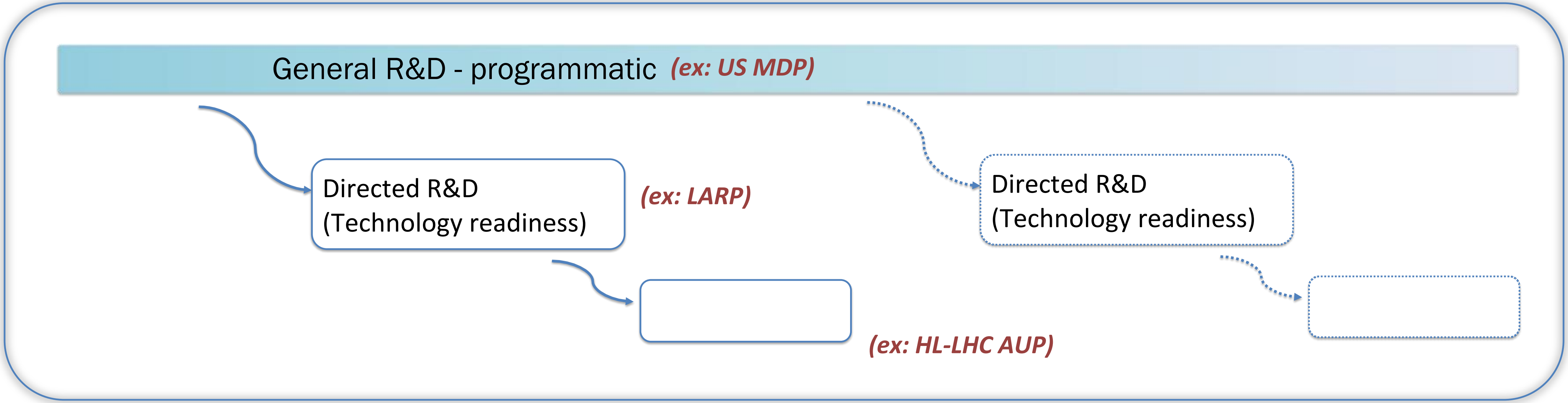
The P5 report provides critical guidance for the US MDP

- All options for a 10 TeV pCM collider are new technologies under development ***and R&D is required before we can embark on building a new collider.***
- Recommendation 4: Support a comprehensive effort to develop the resources—theoretical, computational, and technological—essential to our 20-year vision for the field. ***This includes an aggressive R&D program that, while technologically challenging, could yield revolutionary accelerator designs*** that chart a realistic path to a 10 TeV pCM collider.
- ***Expand the General Accelerator R&D (GARD) program*** within HEP, including stewardship
- ***Conduct R&D efforts to define and enable new projects*** in the next decade
- This is why we recommend pursuing ***revolutionary R&D in areas such as high- field magnets***, a multi-megawatt proton driver, wakefield accelerator technology, and muon cooling (Recommendation 4a).
- We note that there are many ***synergies between muon and proton colliders, especially in the area of development of high-field magnets.*** R&D efforts in the next 5-year timescale will define the scope of test facilities for later in the decade, paving the way for initiating demonstrator facilities within a 10-year timescale (Recommendation 6).

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

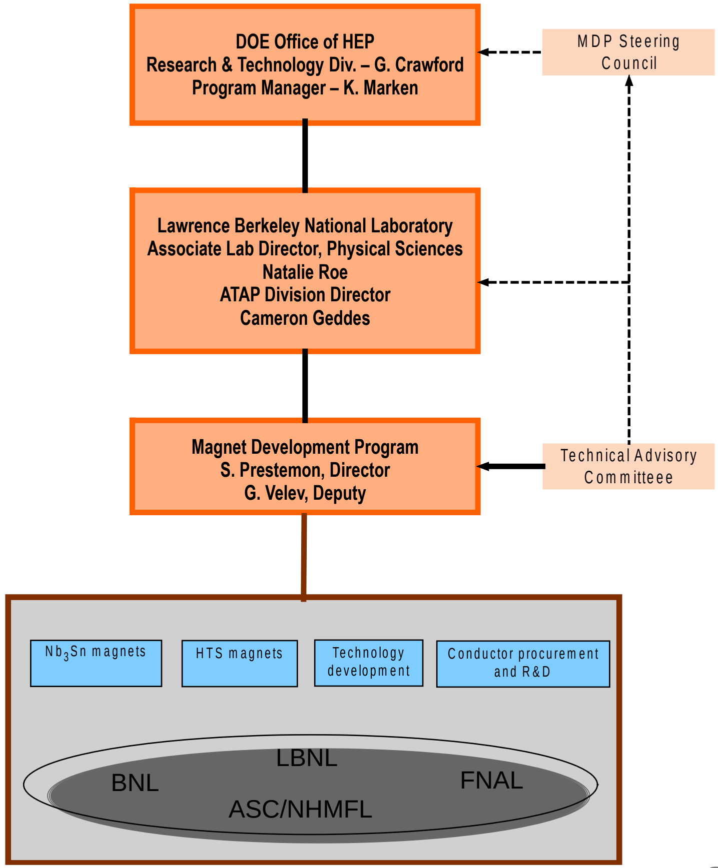


The US DOE approach balances long-range R&D and project preparation

MDP integrates leading US teams from multiple national labs focused on addressing fundamental aspects of accelerator magnet performance

LBNL (lead-lab), FNAL, BNL and the ASC/NHMFL organized under a MOA

- Oversight by a Technical Advisory Committee (chaired by Andy Lankford),
- and a Steering Council (Lab Directors/delegates)



Strategic Priorities:

Probing stress management structures

Hybrid HTS/LTS designs

Understanding and impacting the disturbance-spectrum

Advancing both LTS and HTS conductors, optimized for HEP applications

"G7" Management Team

LBNL:
Soren Prestemon
Steve Gourlay => Paolo Ferracin

FNAL:
Sasha Zlobin => Steve Gourlay
George Velev

BNL:
Kathleen Amm => Mark Palmer

ASC/NHMFL:
David Larbalestier
Lance Cooley

Cond. Proc. and R&D (CPRD)
Chair: Lance Cooley => Ian Pong

Area I: Nb3Sn magnets

Coord.:
Sasha Zlobin & Diego Arbelaez

Area II: HTS magnets

IIa: Bi23212 magnets
Coord.: Tengming Shen

IIb: REBCO magnets
Coord: Xiaorong Wang => Vadim Kashikhin

Area III: Technology

IIIa: Comparative analysis
Coord.: Paolo Ferracin

IIIb: Advanced modeling
Coord: Lucas Brouwer => Giorgio Vallone

IIIc: Magnet materials
Coord: Steve Krave

IIId: Novel diagnostics
Coord: Maxim Marchevsky

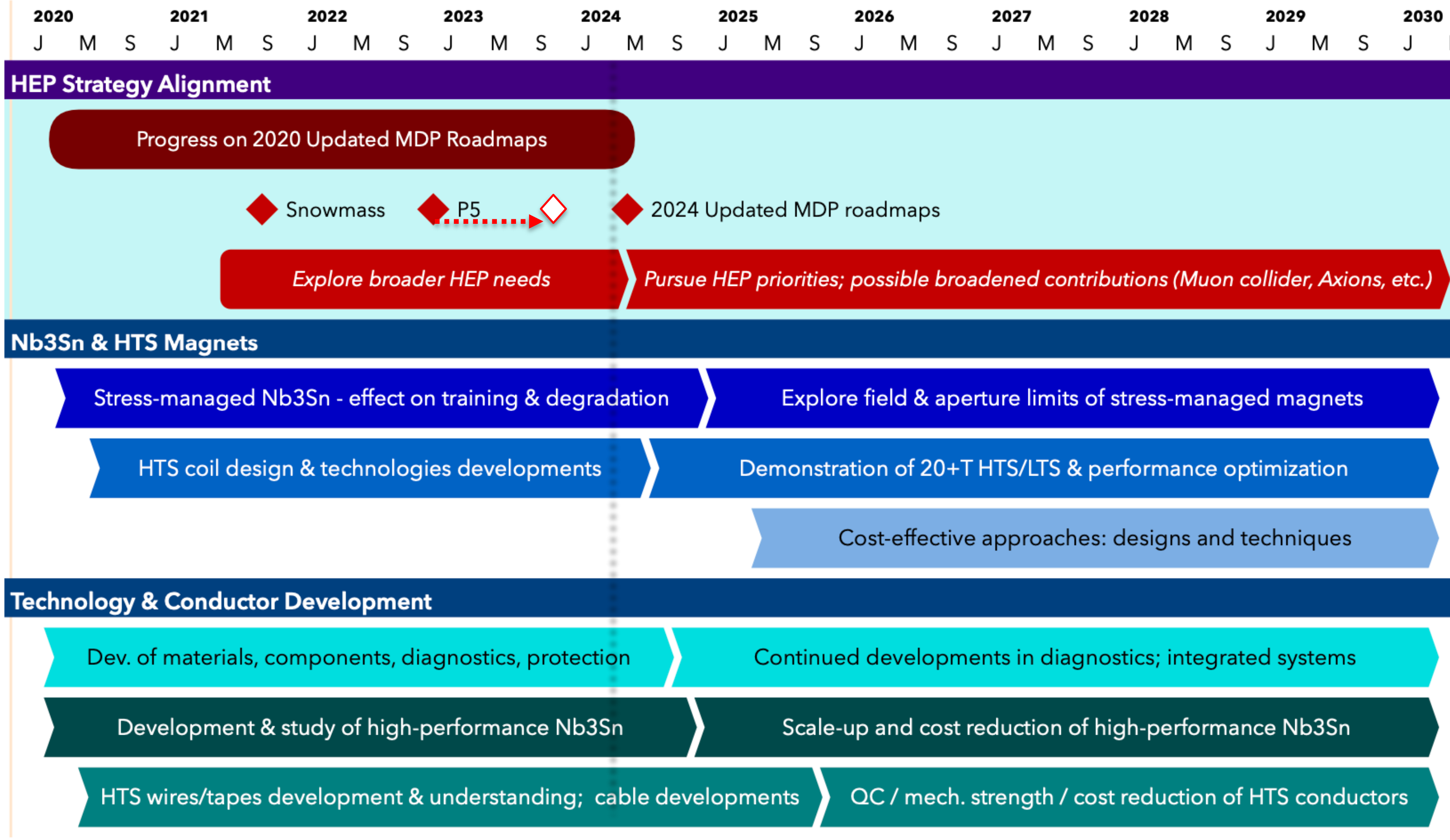
IIIe: Training rate enhancement
Coord. Stoyan Stoynev

U.S. MAGNET DEVELOPMENT PROGRAM

US MDP 2020 roadmaps – long range – time for an update!

P5 guiding light:

- Clear “pull” from 10 pTeV collider science
  - most prominently Muon collider
- High-field remains a driving aspiration
  - Dictates hadron collider energy reach
  - Dicates muon collider luminosity
- Enhanced focus on HTS
  - Muon cooling, collider interaction region magnets
  - Sustainability



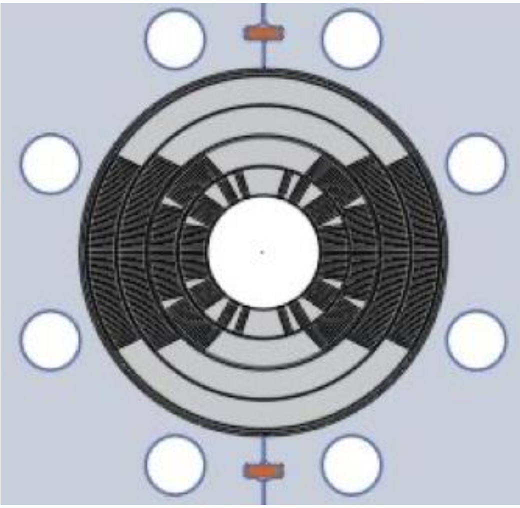
MDP is exploring "stress-management" as an enabling technology to attain high field

- Stress management should enable higher field, larger apertures dipoles
  - Critical development for muon collider ring dipoles that need significant radiation shielding
  - Large aperture dipoles enable HTS "inserts"

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

"Traditional" Cos-theta

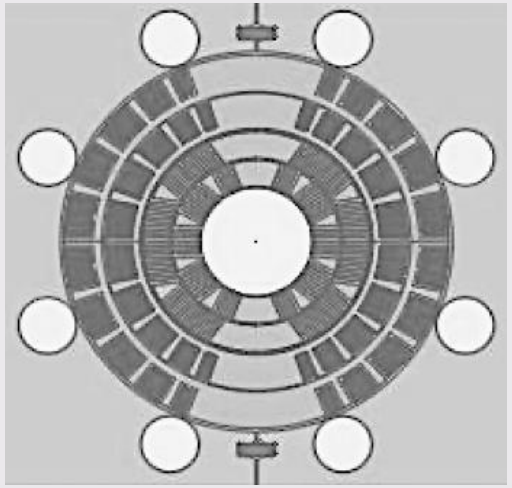
- Midplane stress due to azimuthal force accumulation



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

"Stress-managed" Cos-theta

- Groups of turns, azimuthal forces intercepted by support



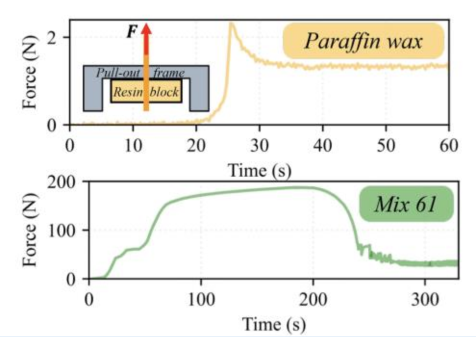
U.S. MAGNET DEVELOPMENT PROGRAM

Eliminating training and the need for significant operating margin is the ultimate challenge for Nb_3Sn magnets – there are indications we may have a breakthrough!

- MDP is addressing training & margin on multiple fronts:
  - Exploring disturbance spectra sources and distributions
  - Detailed analysis/modeling of interfaces
  - Exploring impregnation alternatives
  - Exploring high heat-capacity conductors

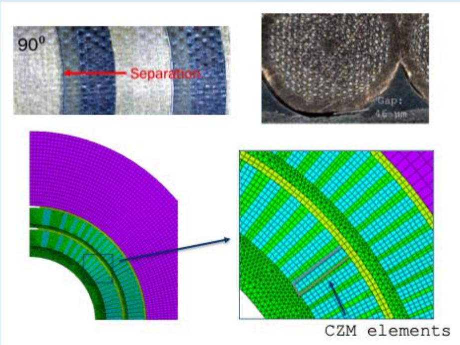
Next steps:
- Test with “filled-wax”
- Then test in high-field stress regime
- Then apply to record Nb3Sn magnet

Characterizing ***interfaces***

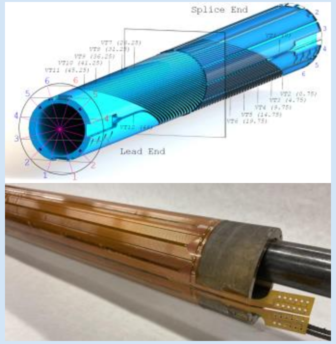


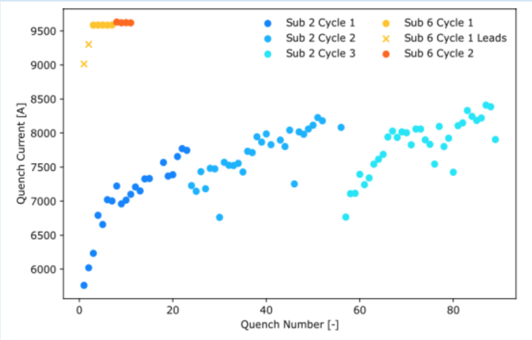
J. L. R. Fernández et al., IEEE Transactions on Applied Superconductivity, vol. 34, no. 5, pp. 1-5, Aug. 2024

Model progressive failure under operation => predict training



Subscale platform demonstrates ***training-free magnets***

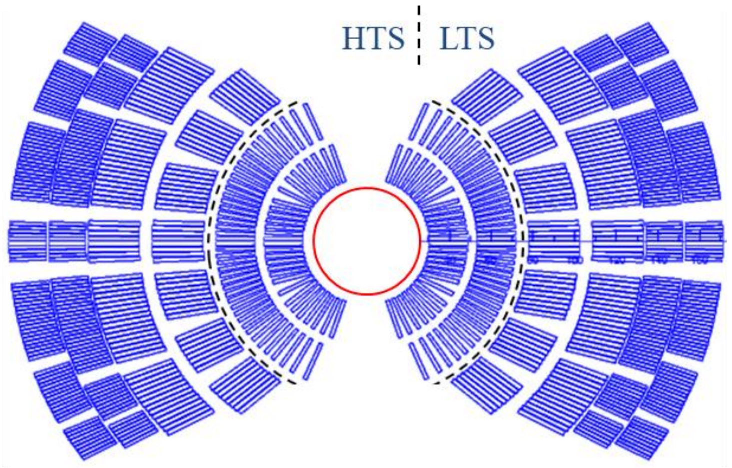


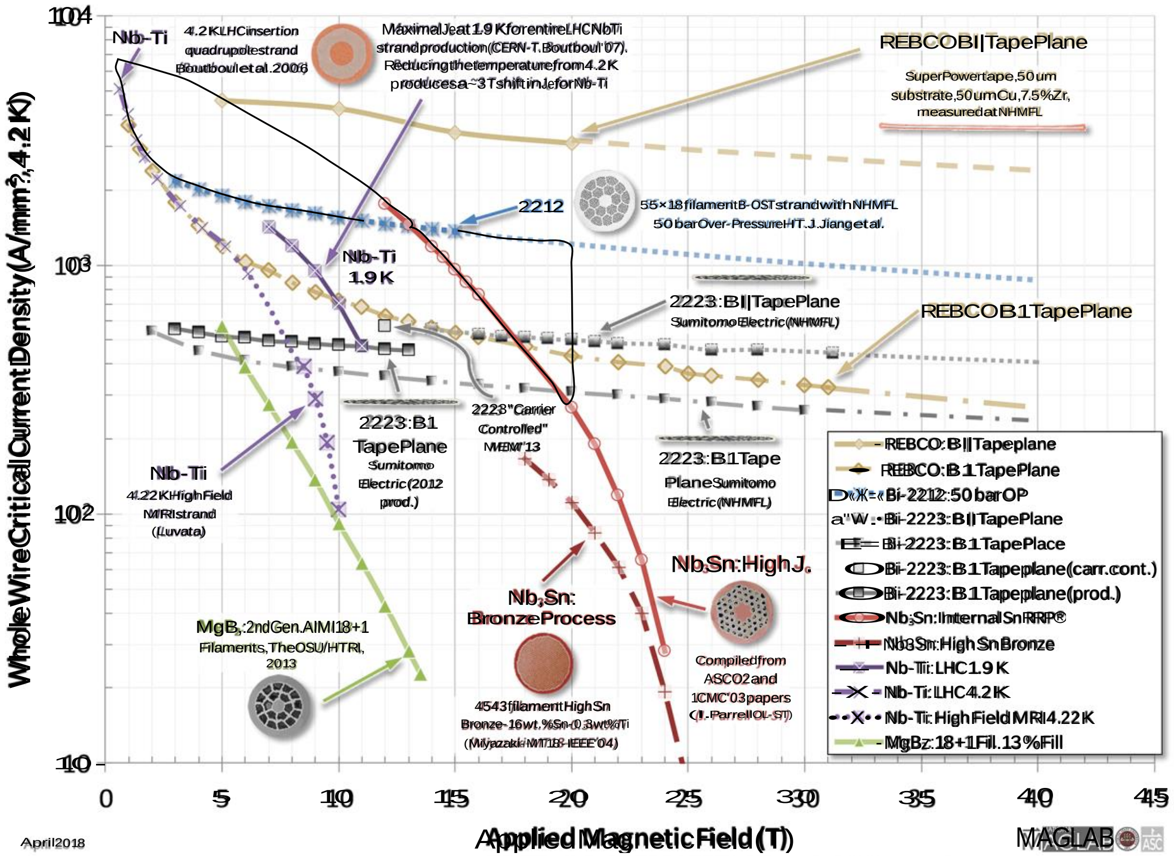


Developing HTS accelerator magnet technology is a key component of MDP – hybrid HTS/LTS provides cost-effective path to high field

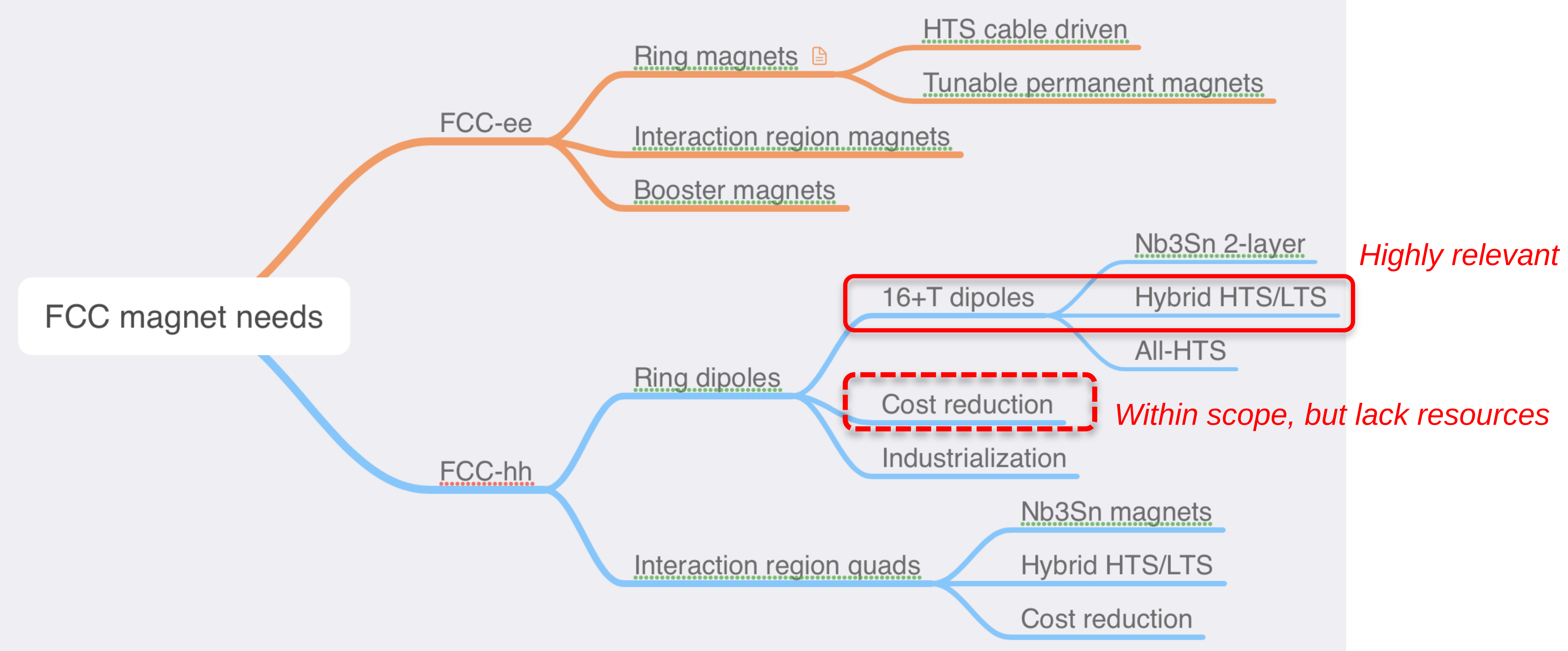
- HTS materials outperform LTS at higher field, but “under-perform” at low field
  - Motivates use of LTS ”outsert”, HTS “insert”

Example layout for a ”stress-managed Cos-theta” hybrid magnet





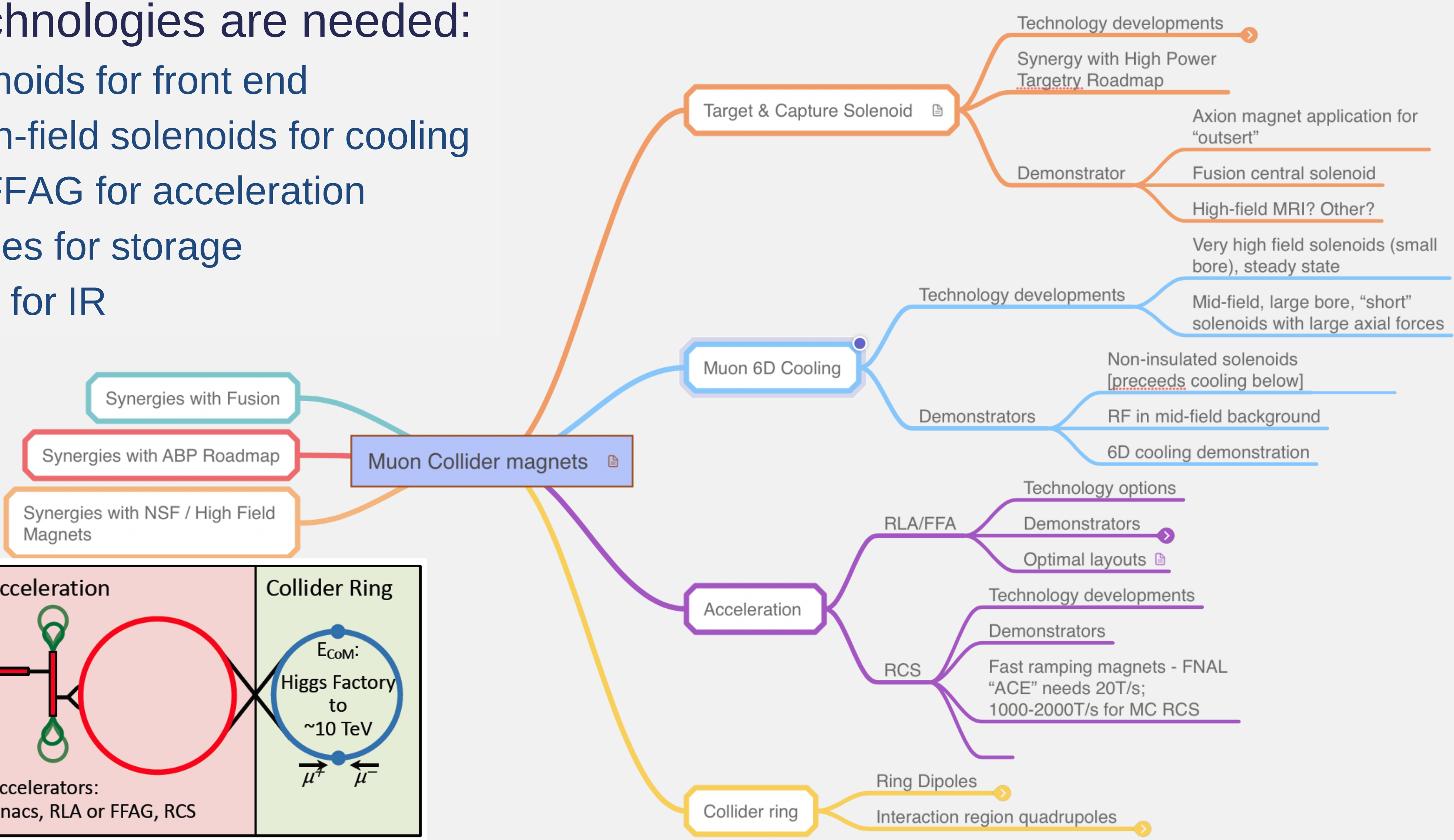
MDP research is highly relevant to the FCC-hh

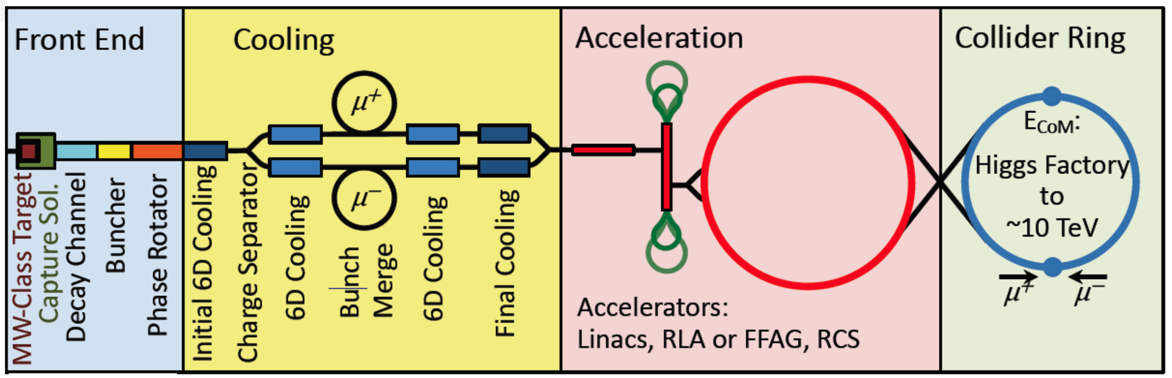


A Muon Collider has serious magnet challenges

- A plethora of technologies are needed:
  - Large bore solenoids for front end
  - RF in field + high-field solenoids for cooling
  - Fast ramping / FFAG for acceleration
  - Large bore dipoles for storage
  - High field quads for IR

"Time is of the essence" in a muon collider

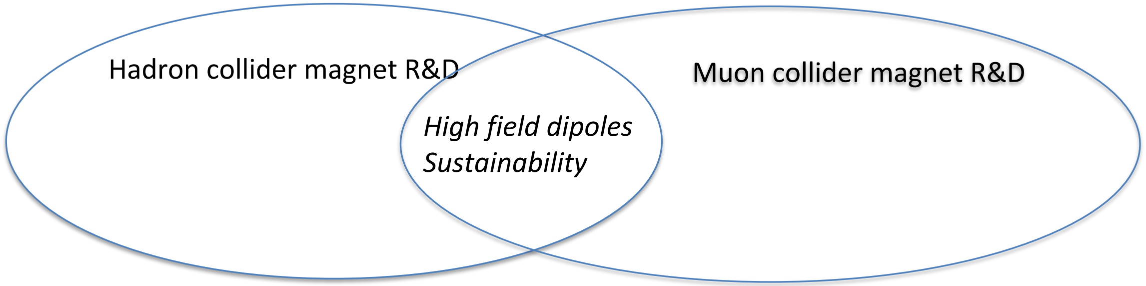




Following the 2023 P5 report, we are developing new aligned roadmaps that build on our progress while addressing the 10 pTeV challenge ahead

U.S. MAGNET DEVELOPMENT PROGRAM

- High-field Magnet R&D remains a “guiding star”
- Stress-managed Nb_3Sn will become “workhorse” outserts to develop and test HTS in high field
- New / enhanced consideration of
  - Muon-collider relevant high field solenoid technology
  - Sustainability – cost of operation



May	June	July	August	September	October	November

Data gathering: ***P5***: - opportunities & priorties ***Structure***: - what works well what can be improved	**Detailing structure** - identify Areas & priorities - identify milestones - timelines, resource needs	**Finalizing document & internal discussions**	**Review with HEP**	**Publish updated MDP Roadmap**

The US MDP strives to be open and collaborative

- We are a mature and vibrant integrated multi-lab research program focused on developing accelerator magnet technology for the next energy frontier collider
- This is an international endeavor, and we are eager to collaborate and join forces to rapidly advance the field
- High field accelerator magnets are essential for the next collider – the onus is on us to deliver!

We strive to…

- **provide a clear vision for magnet development & conductor properties/performance we would like to see**
- **be open with our results and progress so others can benefit from our advances**
- **identify and benefit from the achievements and progress of others**
- **be good collaborators – we recognize the strengths and enthusiasm residing in the broader community!**

Thank You