MDP Plans and Achievements – Relevance to a Muon Collider

Presentation to the 2022 Muon Collider Collaboration Meeting

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For the US MDP Team

Outline

- The US Magnet Development Program: Vision and Goals
- Current MDP focus areas and key challenges
- Muon collider magnet needs and connections to MDP
- Current and future synergistic research

US MDP vision

- ***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
  - o Explore the performance limits of Nb_3Sn accelerator magnets…
  - o Develop and demonstrate an HTS accelerator magnet with a self-field of 5T or greater…
  - o Investigate fundamental aspects of magnet design and technology…
  - o 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

U.S. MAGNET DEVELOPMENT PROGRAM

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

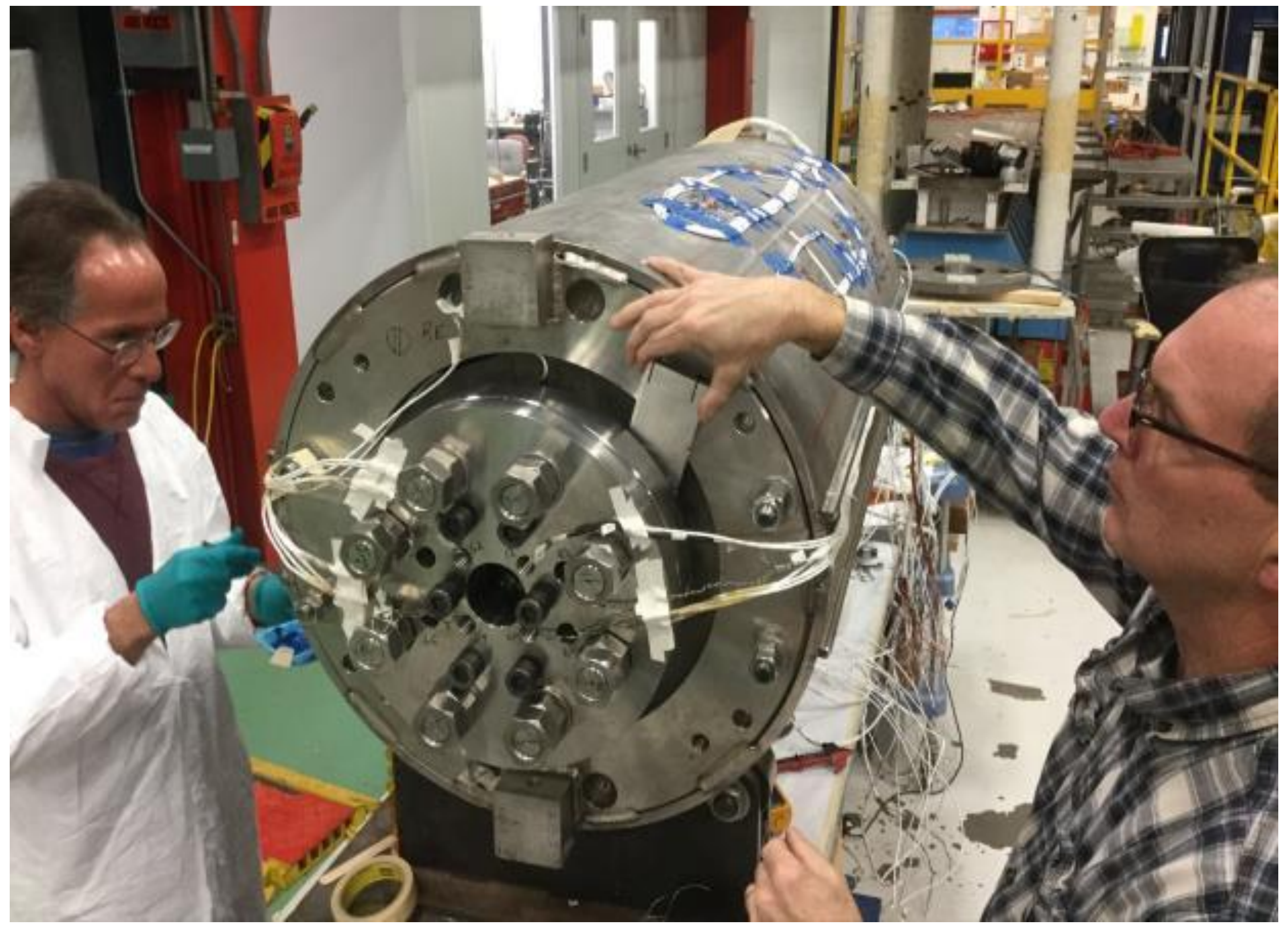
https://arxiv.org/abs/2011.09539

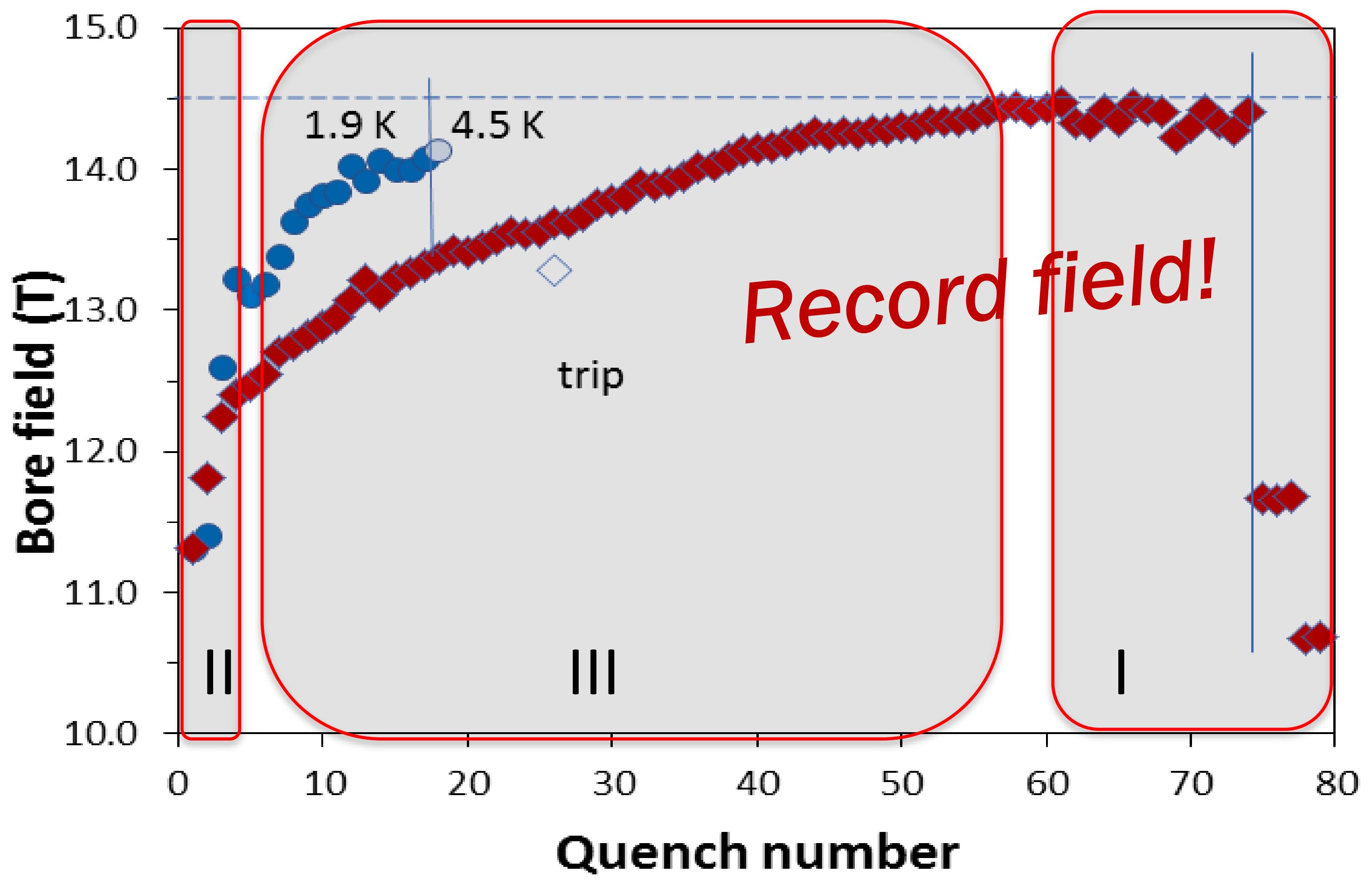
MDP strategy and goals: driving questions related to performance

• Ultimate Performance of Magnets

- What is the nature of accelerator magnet training? Can we reduce or eliminate it?
- How do we best define operating margin for Nb_3Sn and HTS accelerator magnets, and to what degree can/should it be minimized?
- Can we control the disturbance spectrum and reduce operating margin and enhance reliable performance?
- What are the mechanical limits and possible stress-management approaches for Nb_3Sn, HTS, and 20 T hybrid LTS/HTS magnets, and do they have defined mechanical limits?
- Do hybrid designs benefit from the best features of LTS and HTS, or inherit the difficulties of both material technologies?

Example: MDP 4-layer, 60mm bore cosine-theta magnet led by FNAL

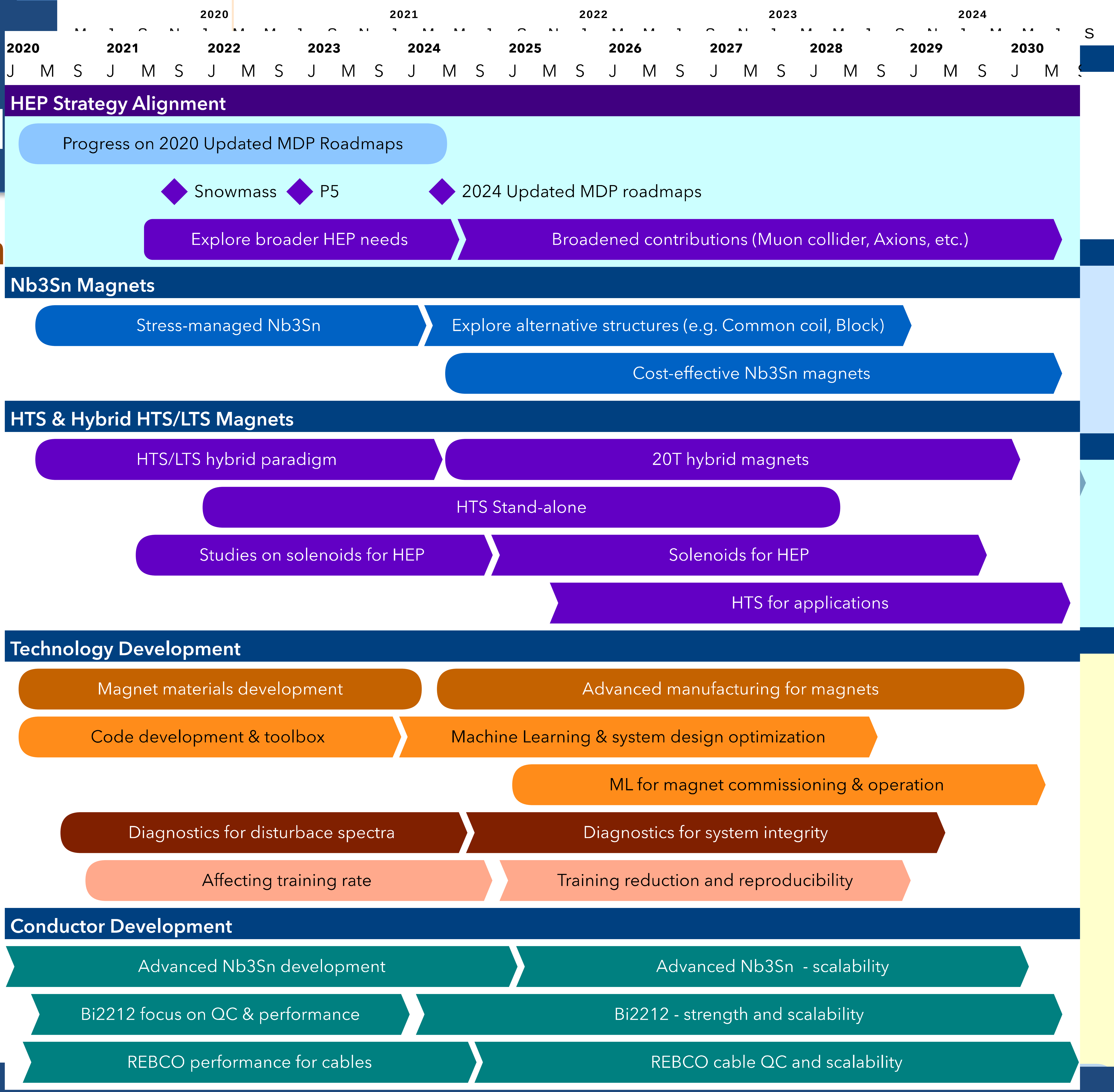




[I]: Highest priority issue: ***degradation***
Mechanisms; design mitigation
[II]: Second priority: Initial quench current
and ***memory after thermal cycle***
[III]: Third priority: ***Training rate***

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

Stress-managed structures avoid force accumulation - at the expense of more interfaces

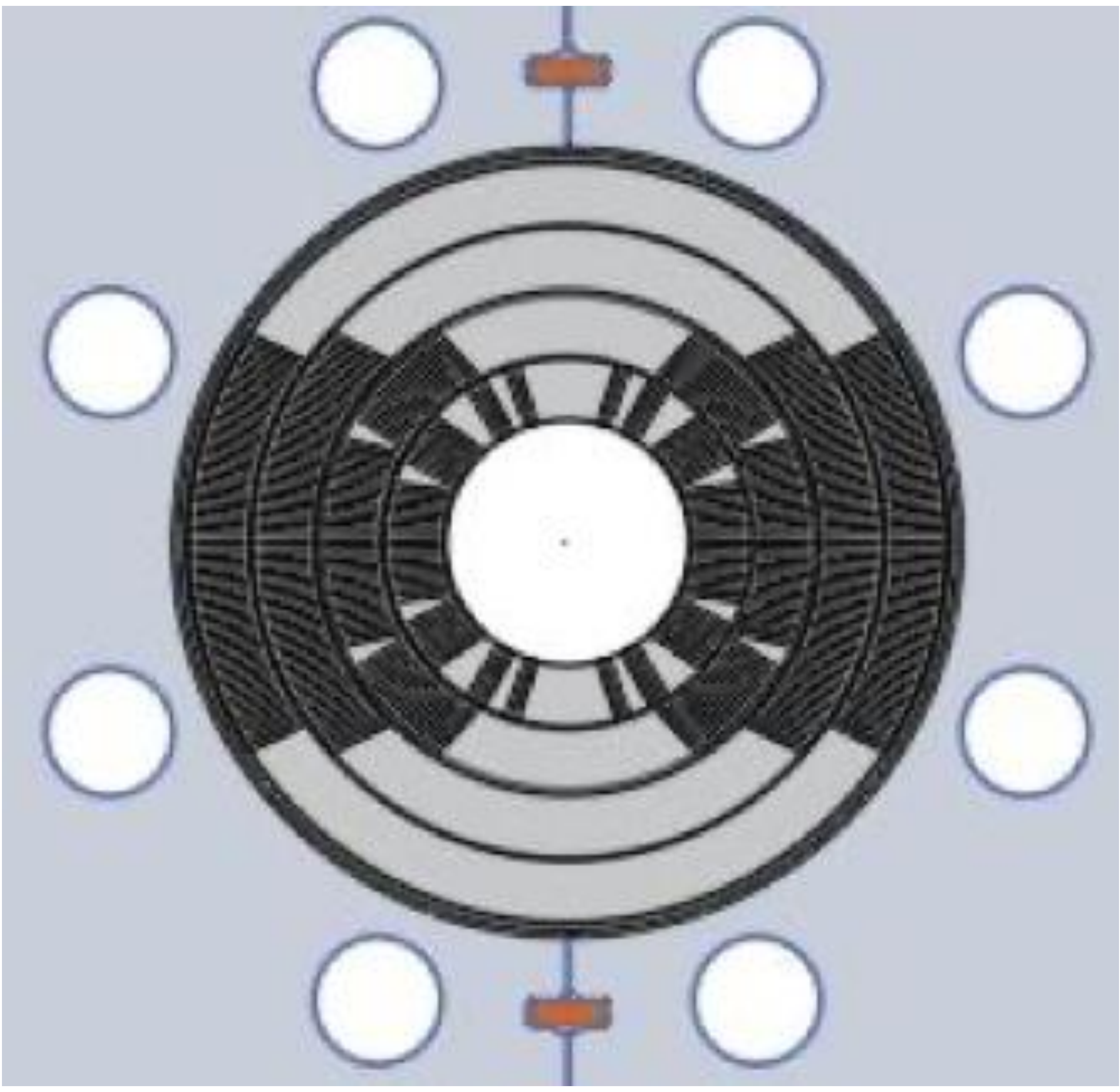
- ***Interception of azimuthal forces*** holds promise to enable high-field and large-bore dipoles – break the traditional scaling of stress with bore and field
- Use new design concepts as opportunity to introduce ***cost-effective fabrication processes***

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

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

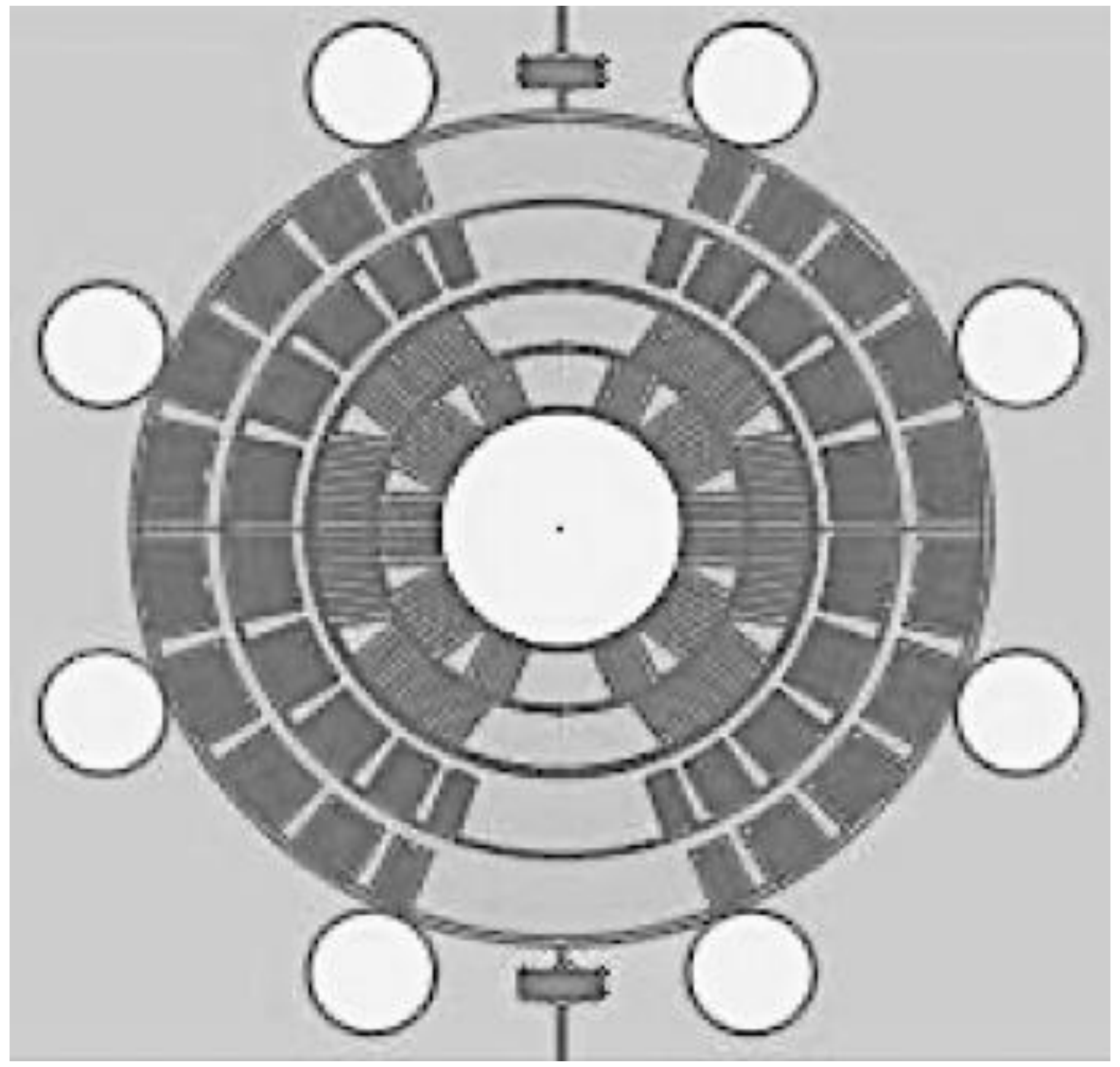
"Traditional" Cos-theta

- Midplane stress due to azimuthal force accumulation



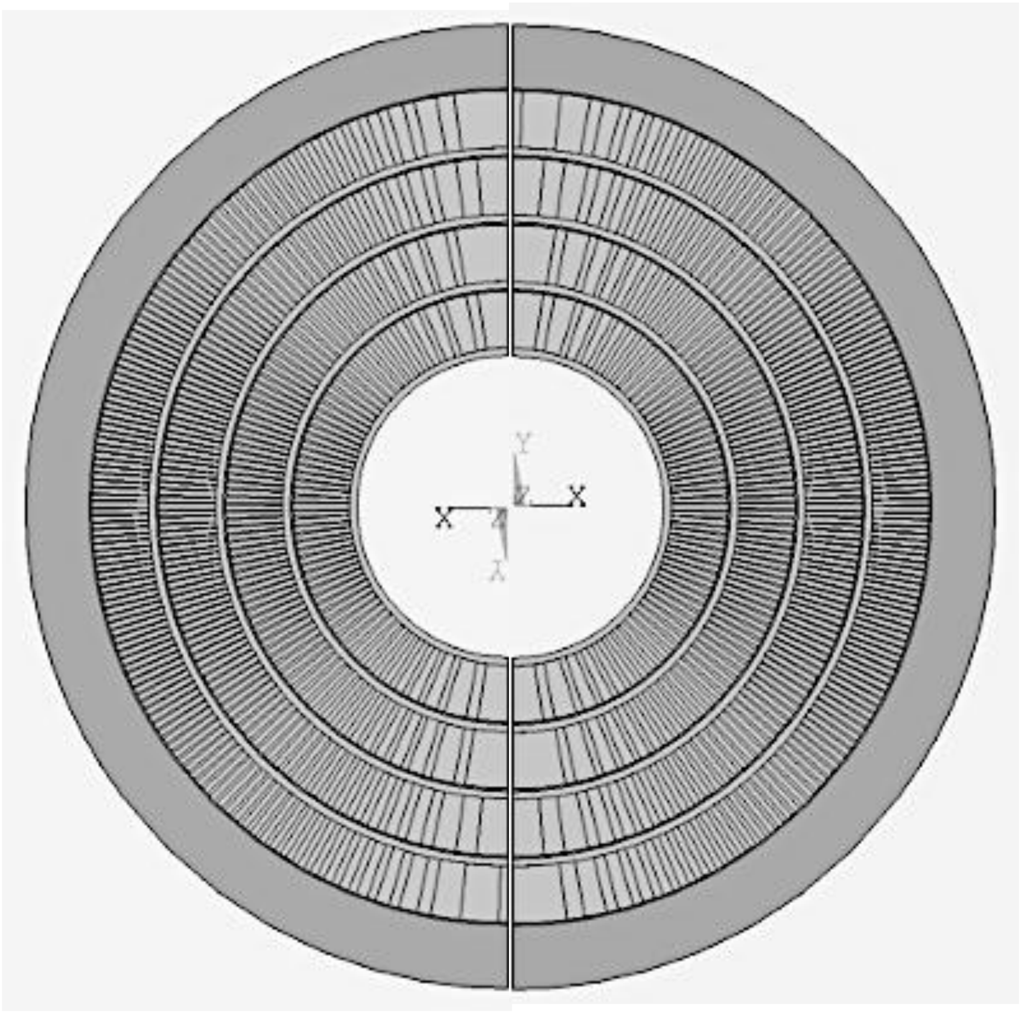
"Stress-managed" Cos-theta

- Groups of turns, azimuthal forces intercepted by support



"Canted" Cos-theta

- Every turn has azimuthal forces intercepted by support

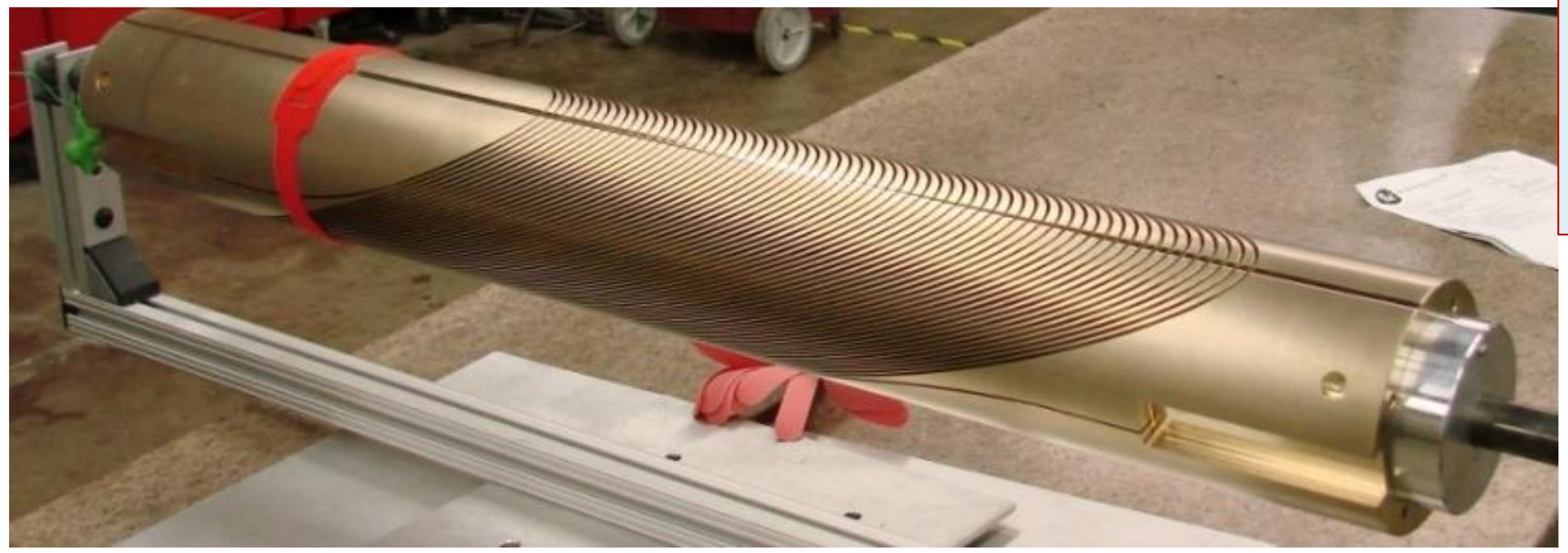


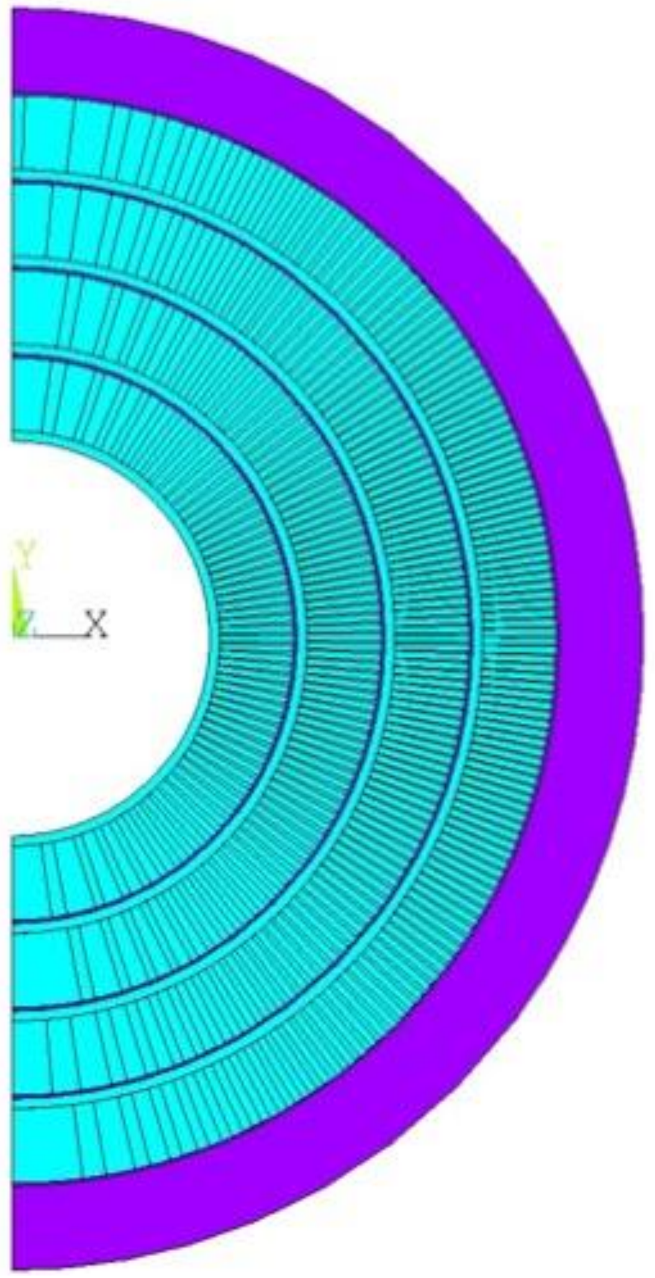
MDP stress management concepts target high fields and large bores for hybrid magnet needs

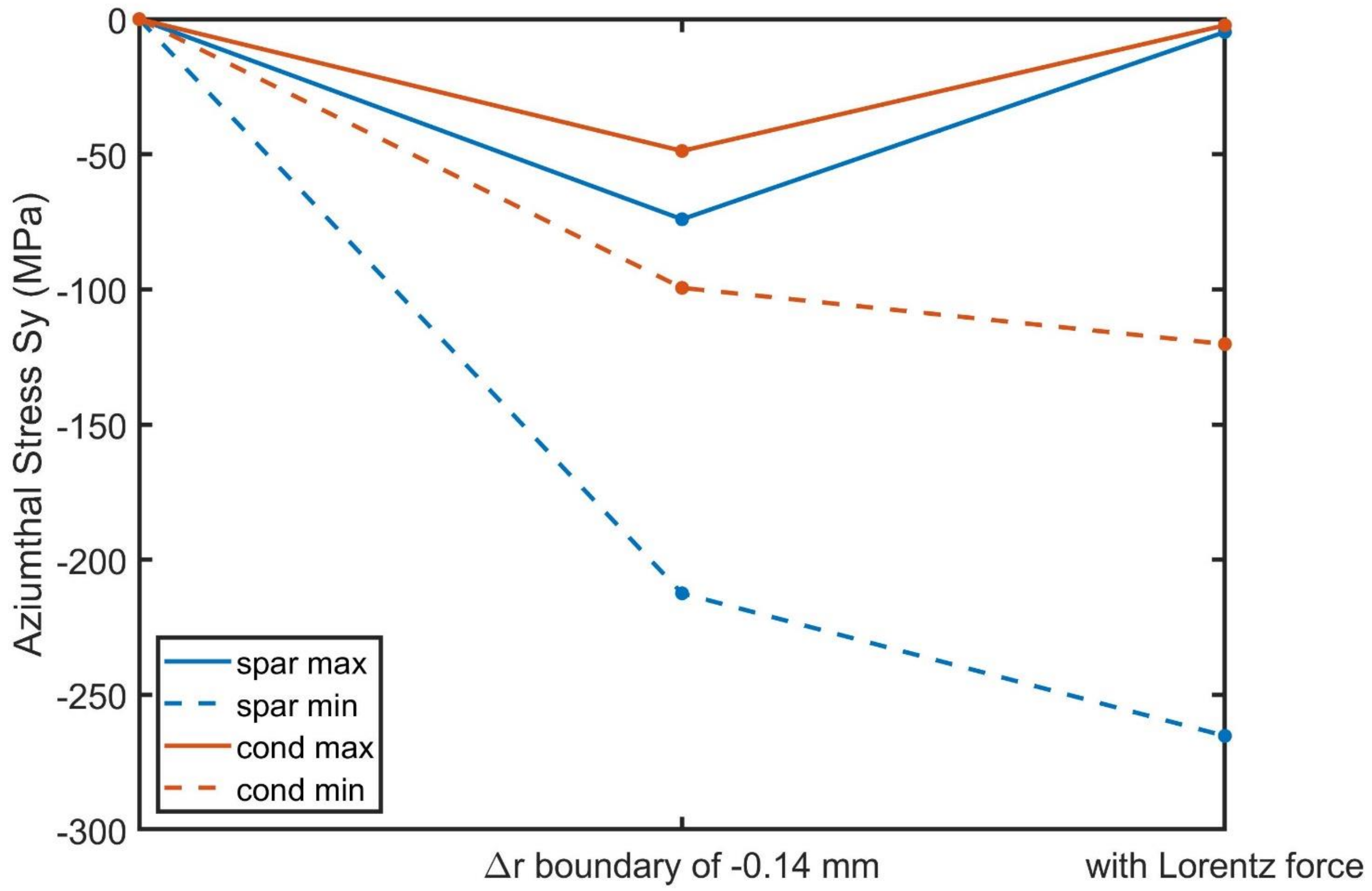
Canted Cosine-theta

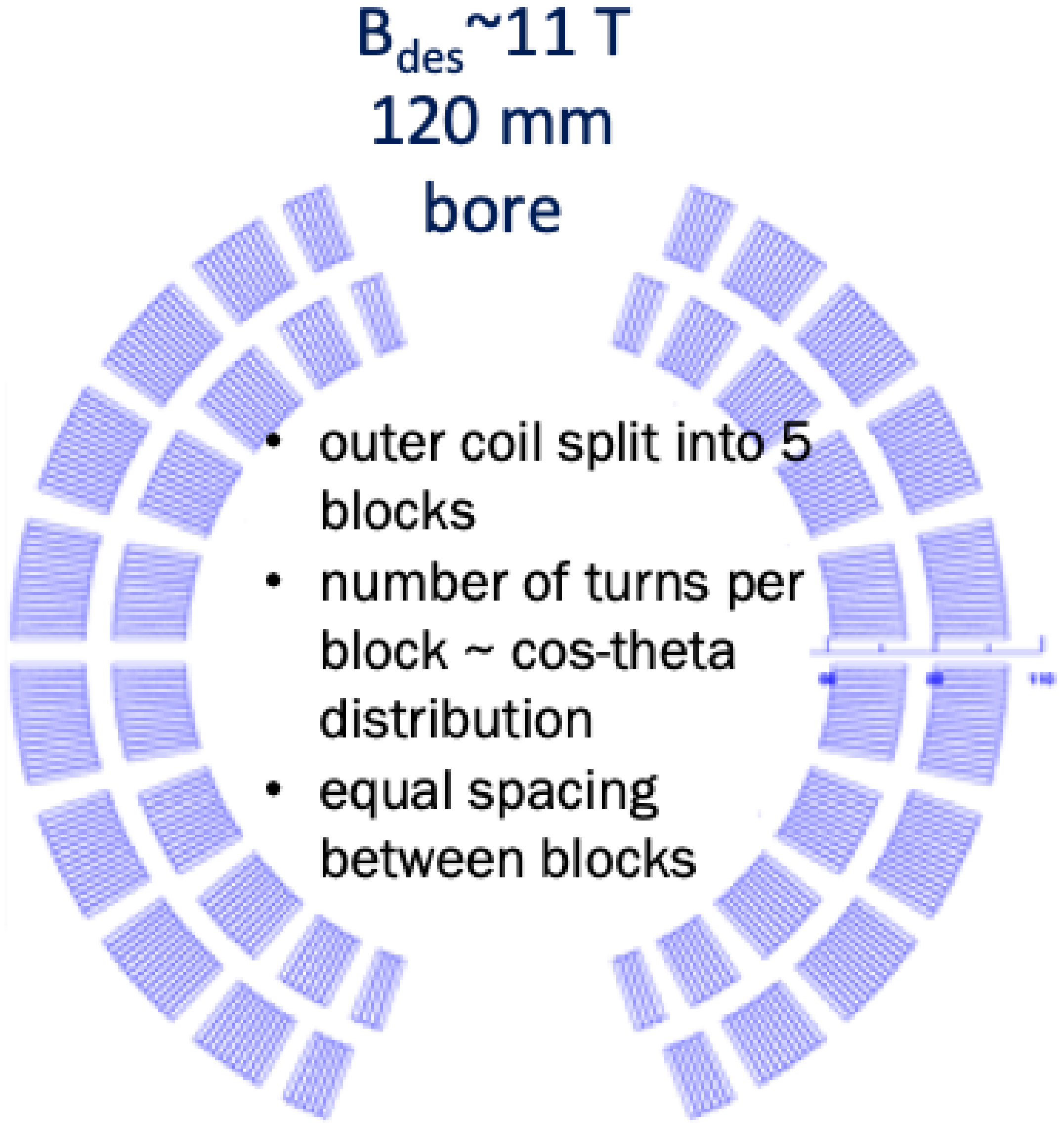
Share utility structure
Shared modeling approaches
Similar instrumentation approaches to be used
Same aperture for HTS inserts

Stress-managed Cosine-theta

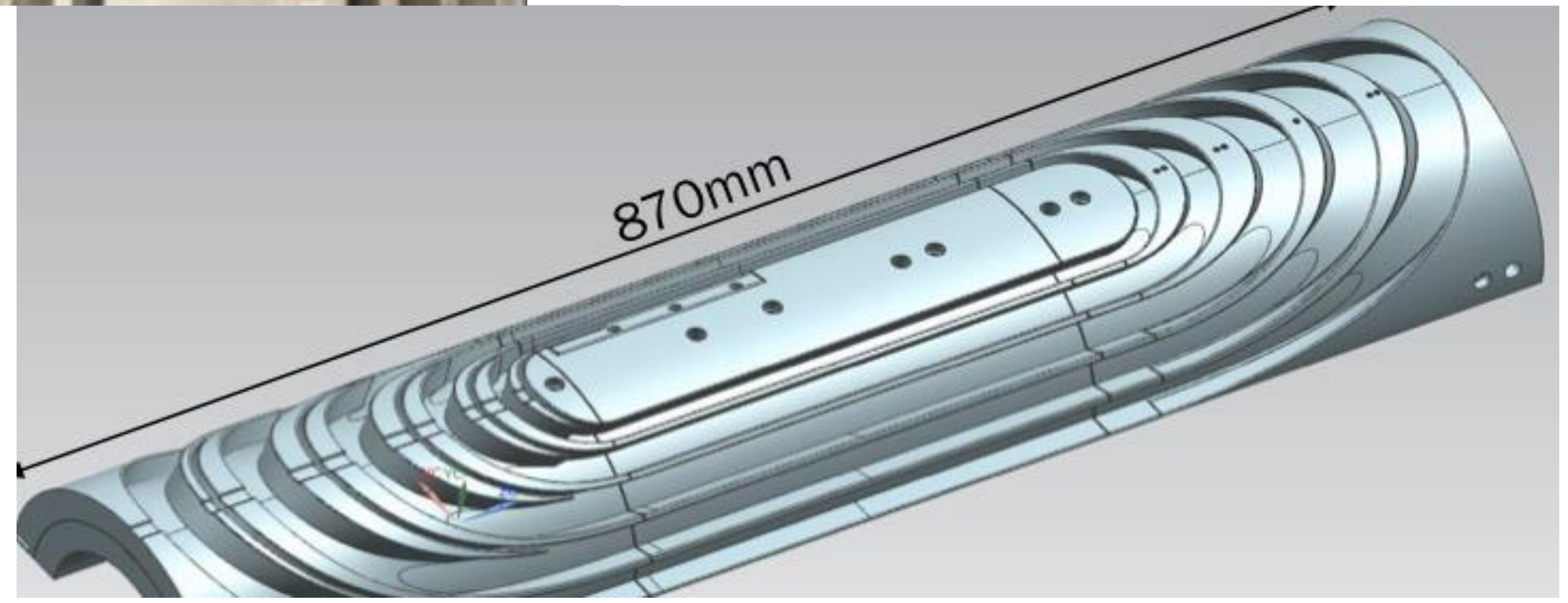






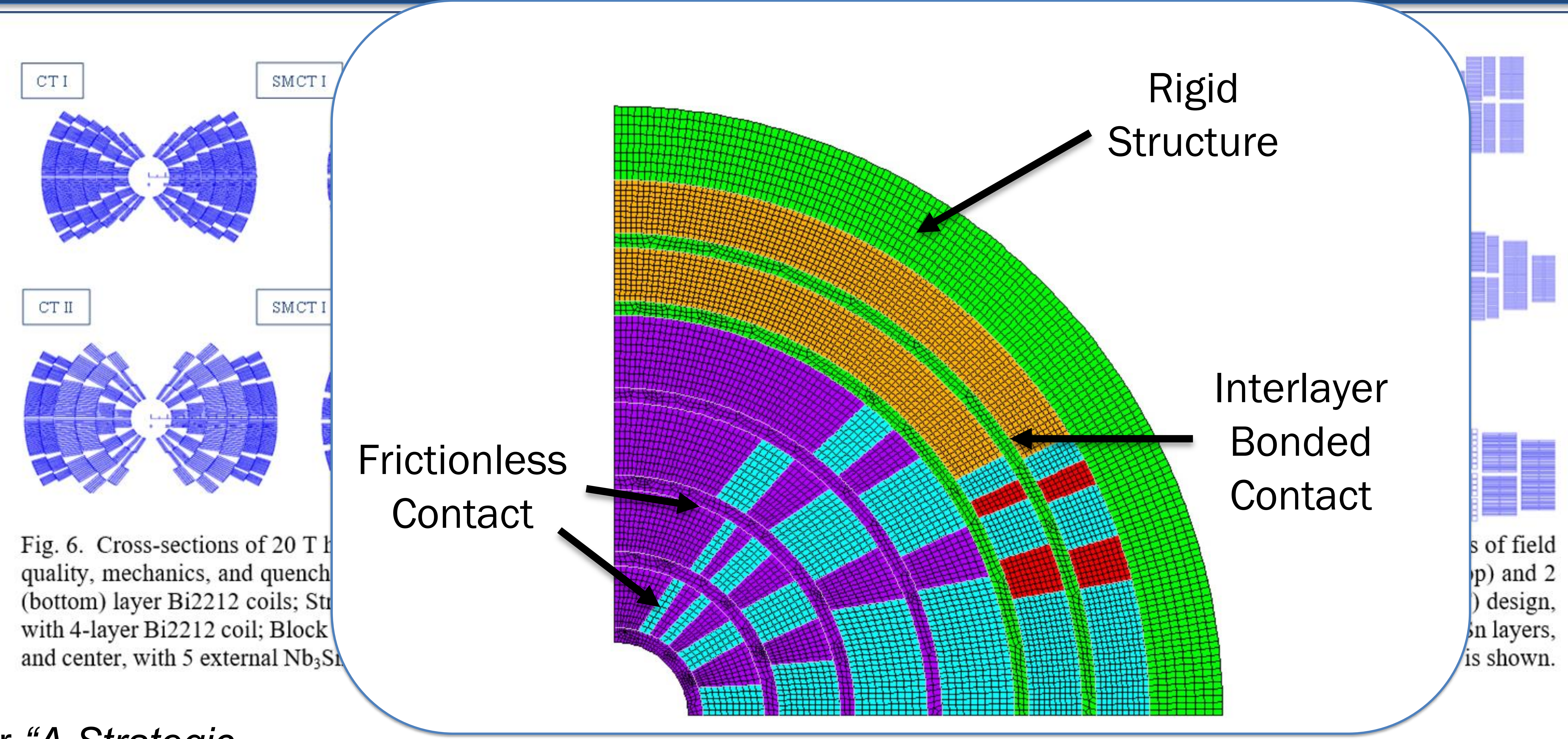


- outer coil split into 5 blocks
- number of turns per block ~ cos-theta distribution
- equal spacing between blocks



For very high field magnets, a “hybrid” HTS/LTS approach is most efficient

- **Design studies underway to explore 20+T dipole concepts**
  - **Optimal use of superconductor**
  - **Comparative study**
  - **Identify research directions**



Example: “stress-managed Cos(t)” concept, inner 2 coils bi2212; analysis underway to find solutions within conductor degradation limits

See Snowmass whitepaper *“A Strategic Approach to Advance Magnet Technology for Next Generation Colliders”* arXiv:2203.13985

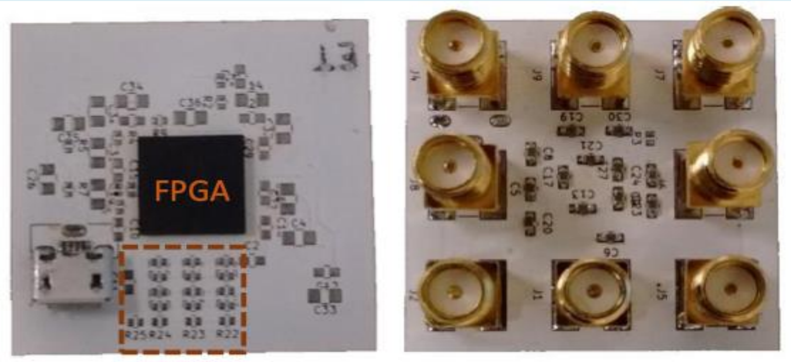
MDP results and developments prepare for high-field prototypes – stress-managed and hybrid magnets

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

BERKELEY LAB · Brookhaven National Laboratory · Fermilab · Florida State University · ASC

- Conductor/cable samples
- Diagnostics & materials dev.

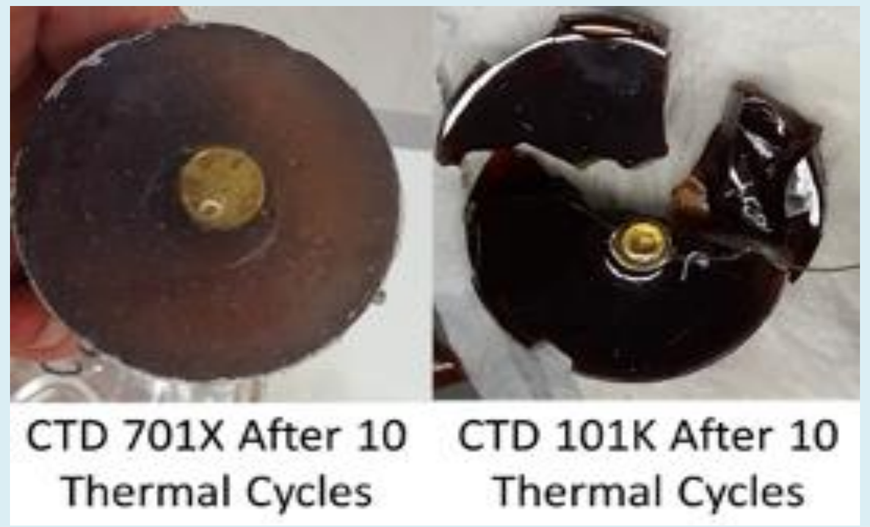
=> *Fast turn-around, specific experiments*



Cryo-Field-programmable gate array

Plastic optical fiber

Development of advanced epoxies with US industry



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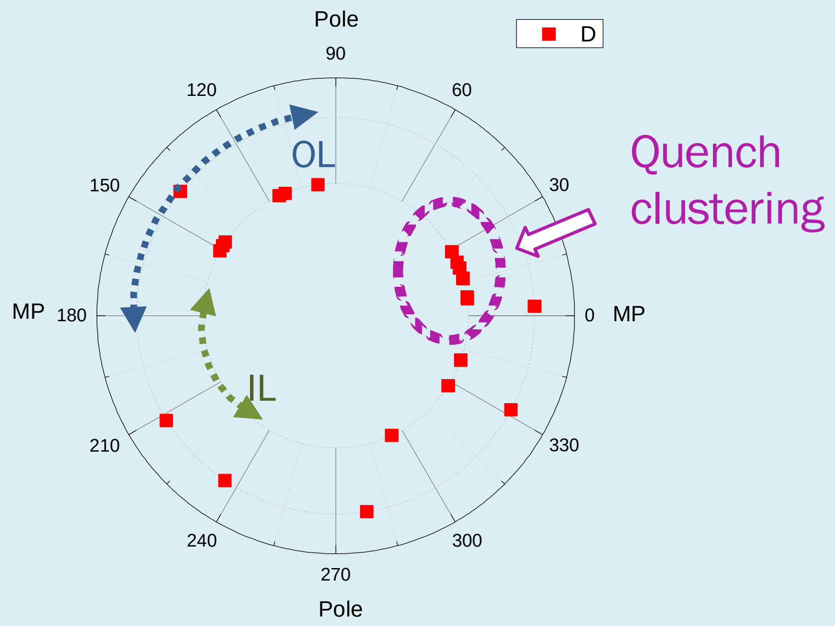
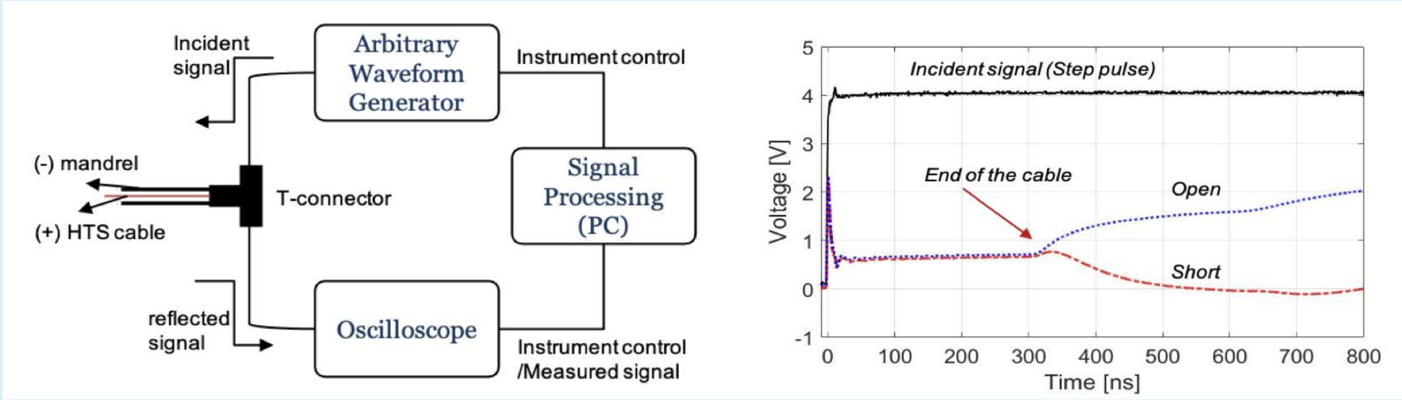
- Subscale / HTS insert magnets

=> *Critical to develop magnet technology*



Subscale CCT with new flexible quench antenna

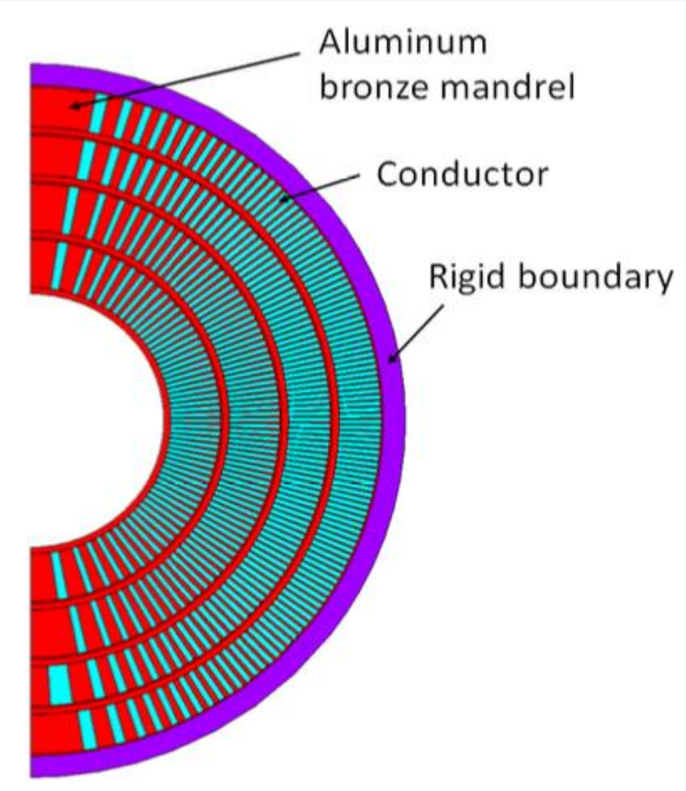


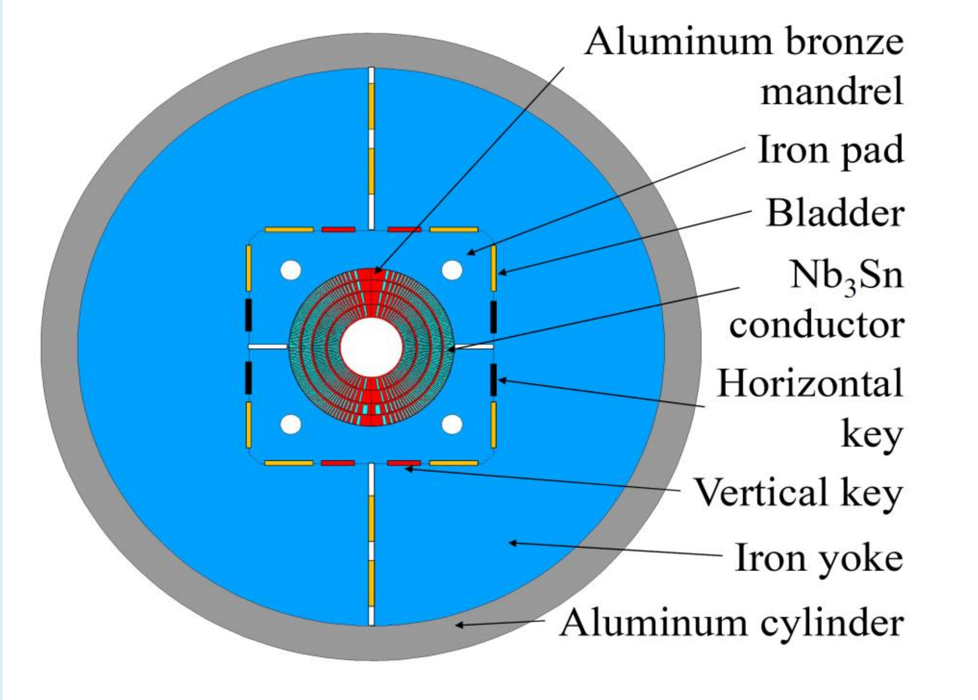
Electrical reflectometry for magnet quality control / monitoring

BERKELEY LAB · Fermilab

- Full size R&D magnets

=> *Final demonstration of MDP deliverables*



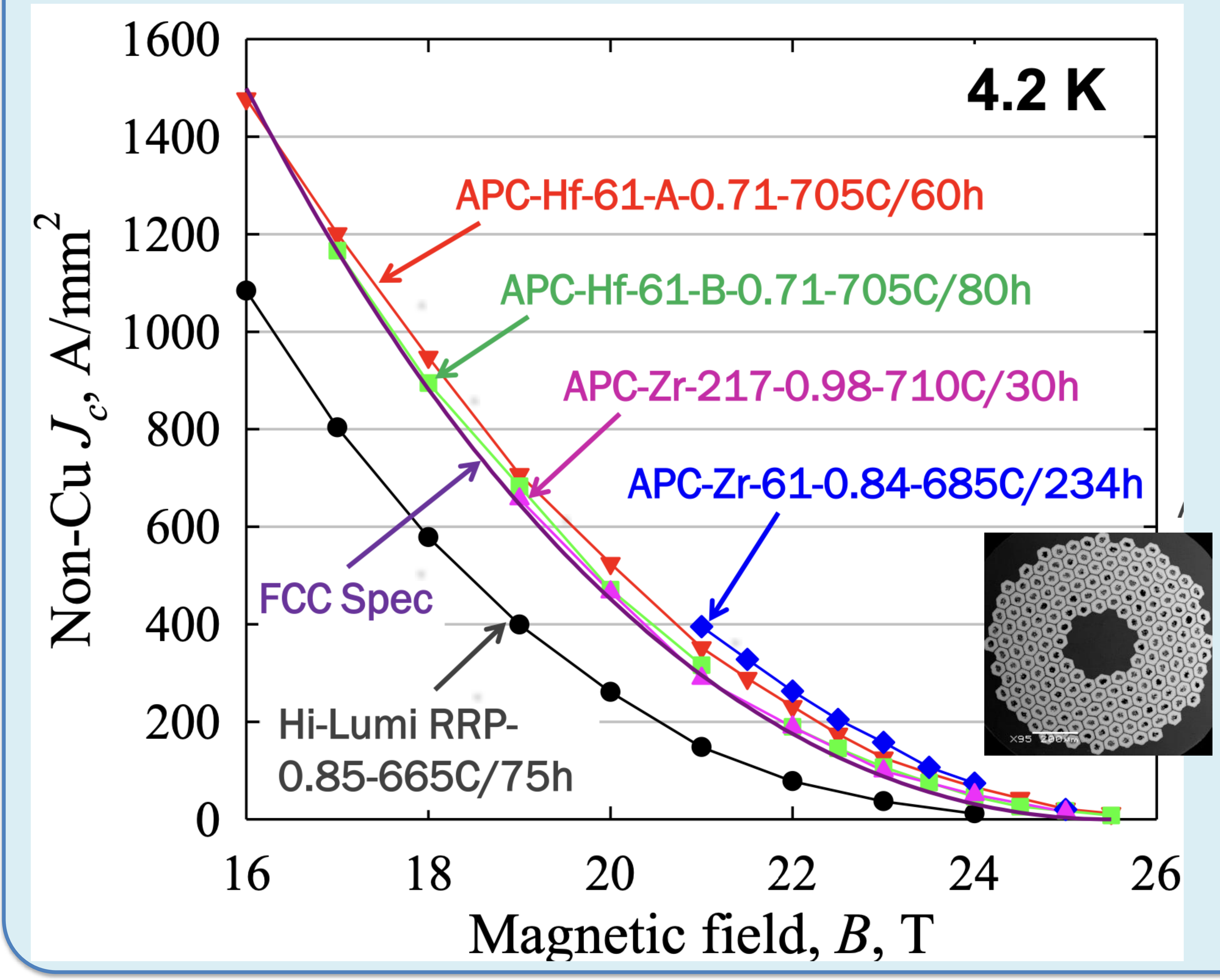


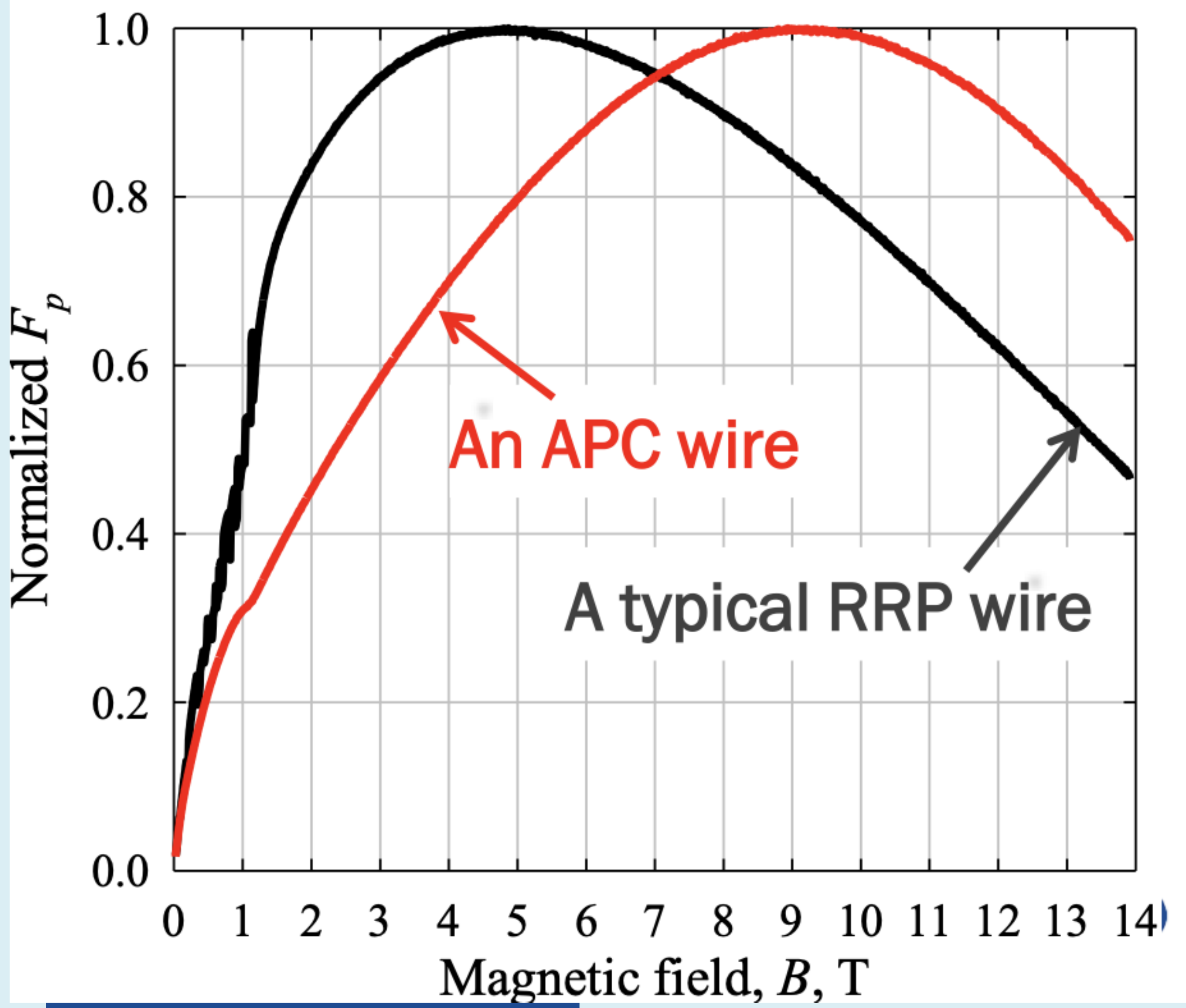
Marchevsky et al, Snowmass whitepaper *"Advancing Superconducting Magnet Diagnostics for Future Colliders"*, *arXiv:2203.08869v1*

Example of Conductor Procurement and R&D: Advances in Nb_3Sn performance by introducing new pinning sites

- Path to "FCC spec" wires exists
  - Powder-in-tube" approach advancing
  - Also exploring Hf doping in "internal Tin" approach

X. Xu, SoftA Workshop, CERN, 2021
See also Xu et al., J. AlloyCompd.857,158270(2021)





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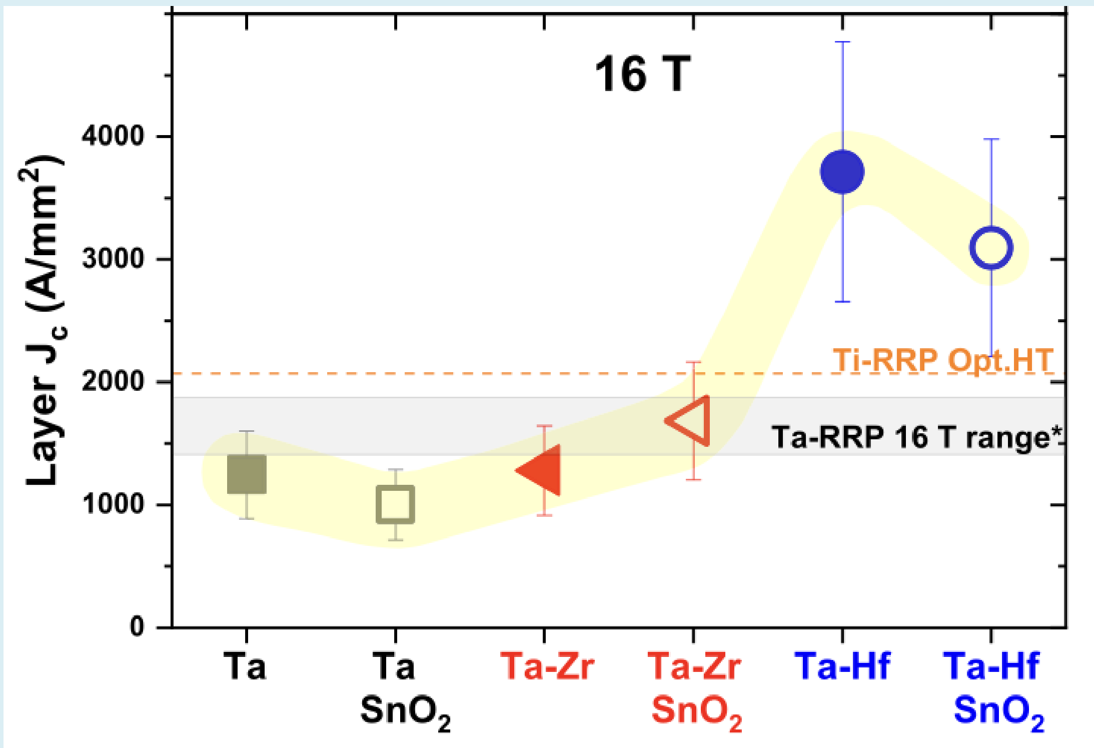
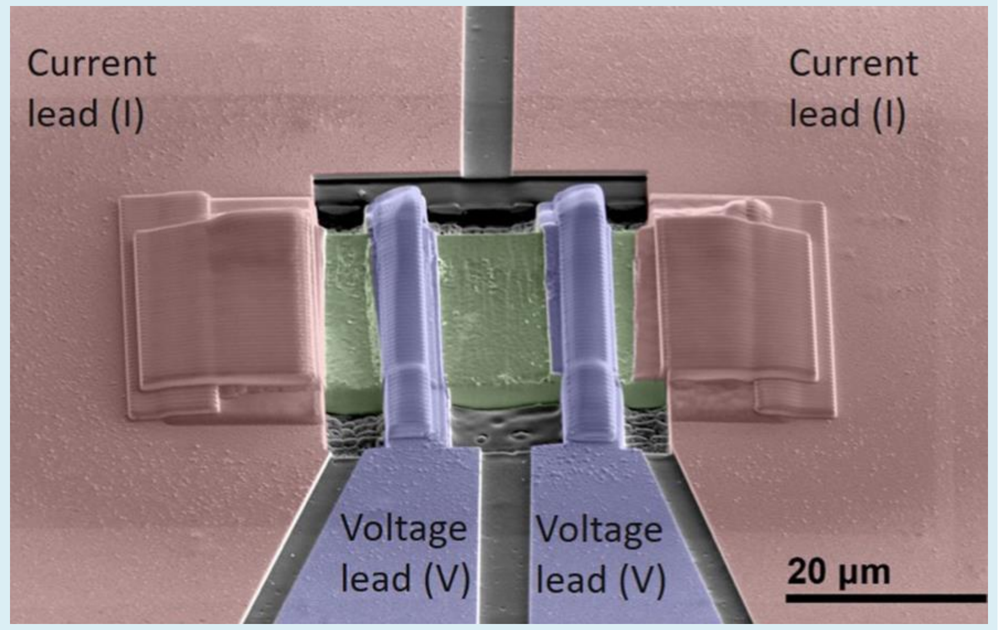
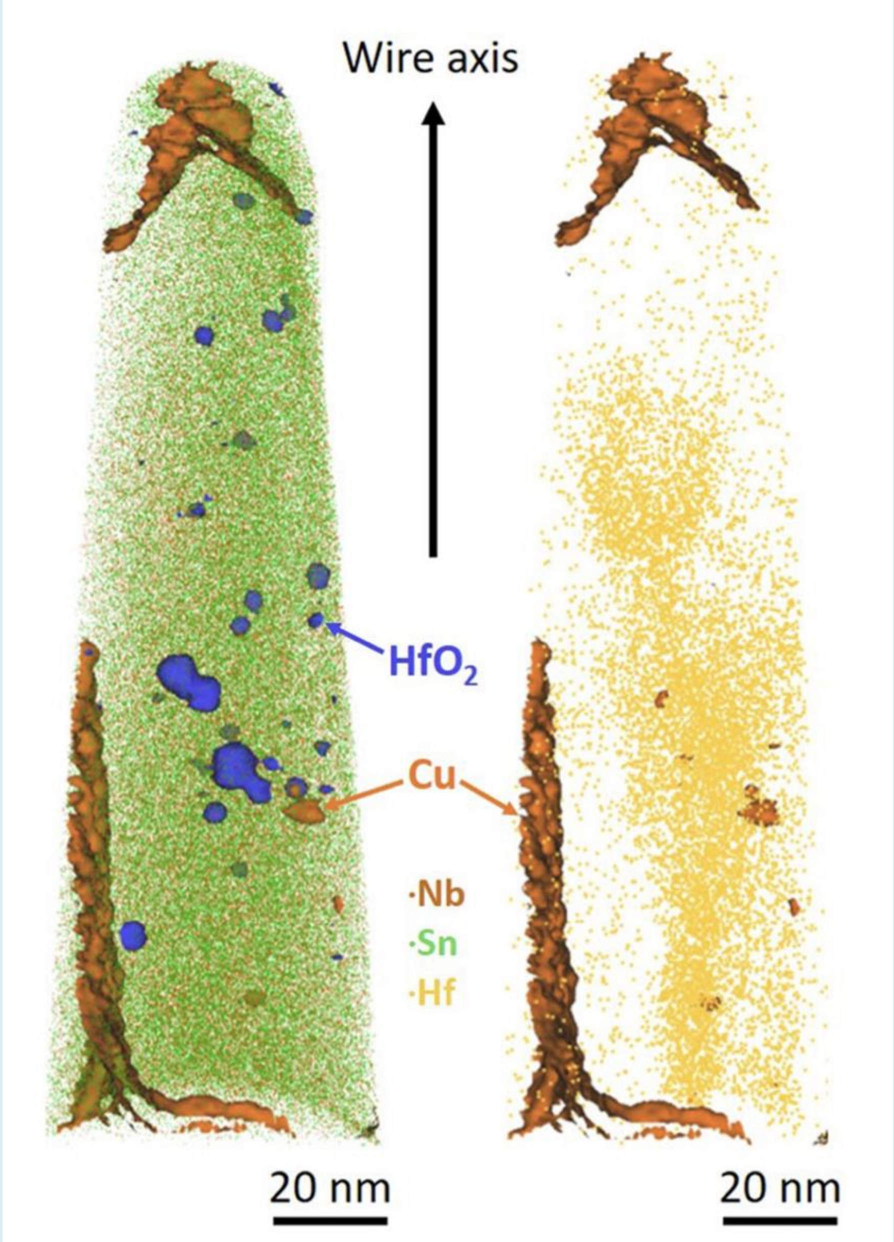
Hyper Tech Research, Inc.



Tarantini et al., Nature Scientific Reports, (2021) 11:17845

S. Balachandran et al 2019 SUST 32





Current MDP focus areas and key challenges

- Can ***stress-management*** provide a viable means of accessing high-field and/or large bore dipole magnets without risk of conductor degradation?

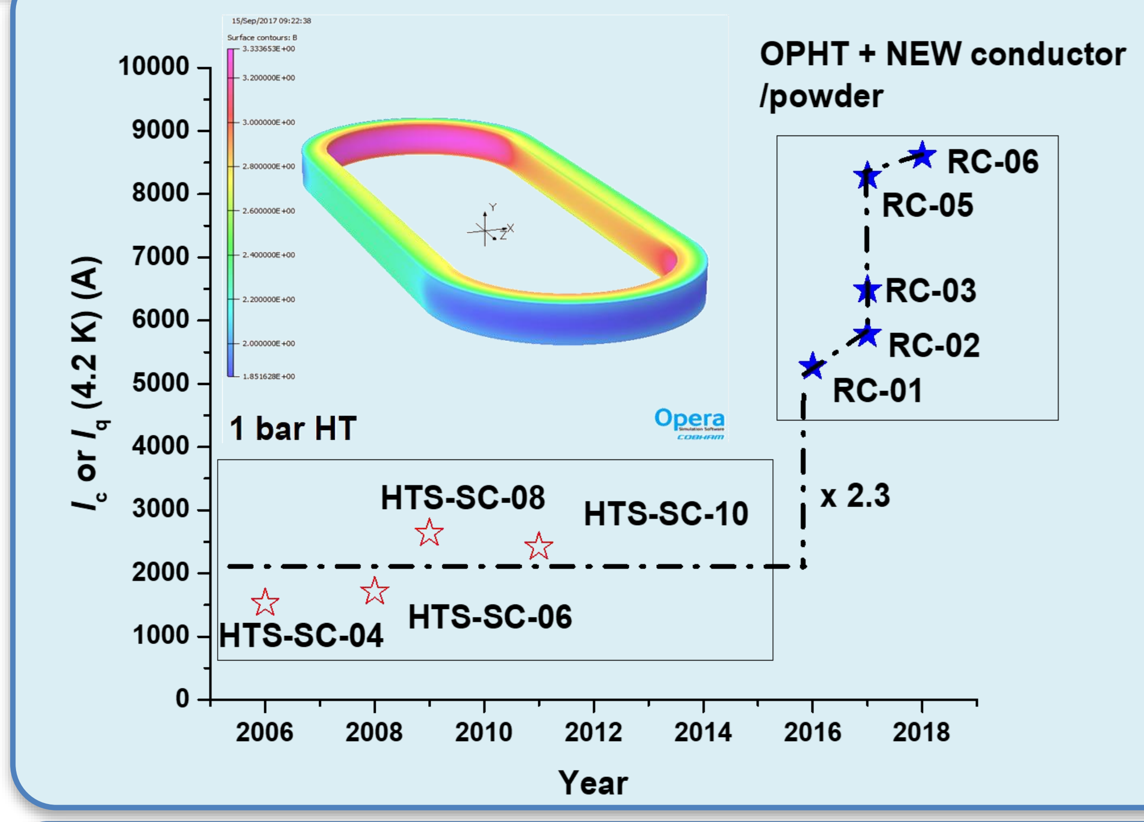
- Can ***hybrid LTS/HTS*** magnets deliver on the promise of efficient high-field dipoles
  - o Will they inherit the "best of both" or the "worst of both"

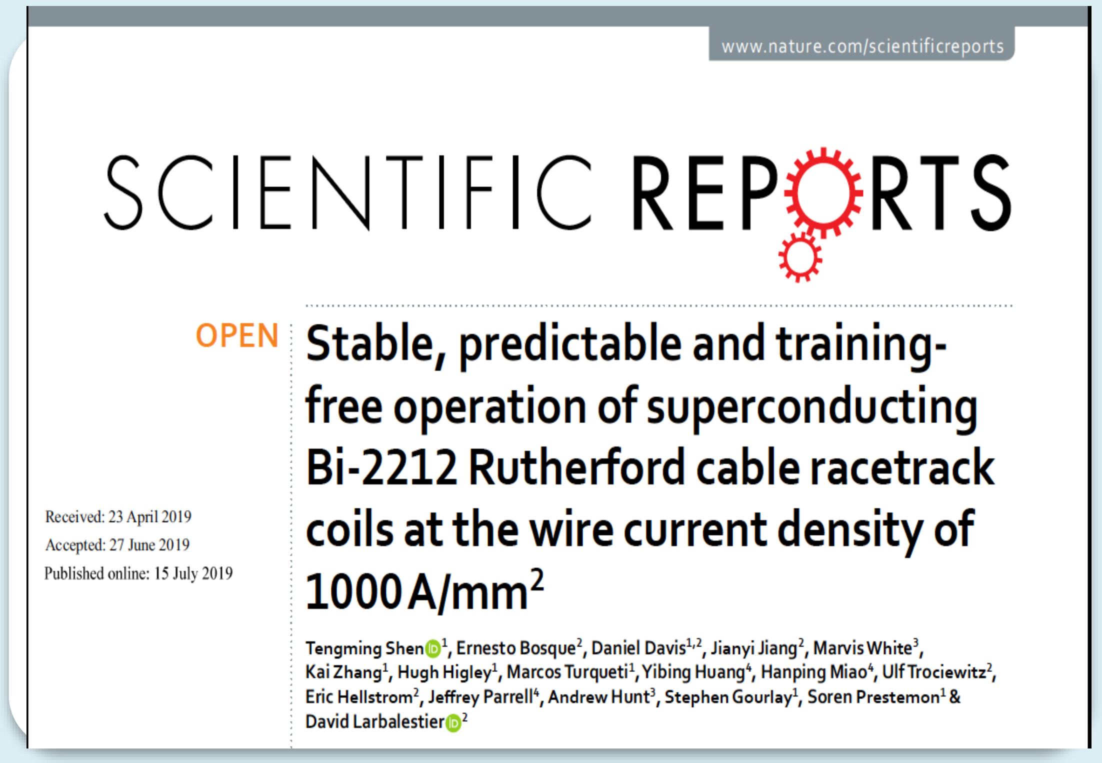
- Advance HTS magnet technology to a respectable level of maturity
  => ***make it "real"***

- Advance diagnostics and modeling to further enhance our insight into magnet performance and issues

- Overcome the advanced Nb_3Sn architecture issues and mature them to industrial levels

- Provide a ***substantial and timely quantity of conductor*** for magnet research and feedback to conductor development

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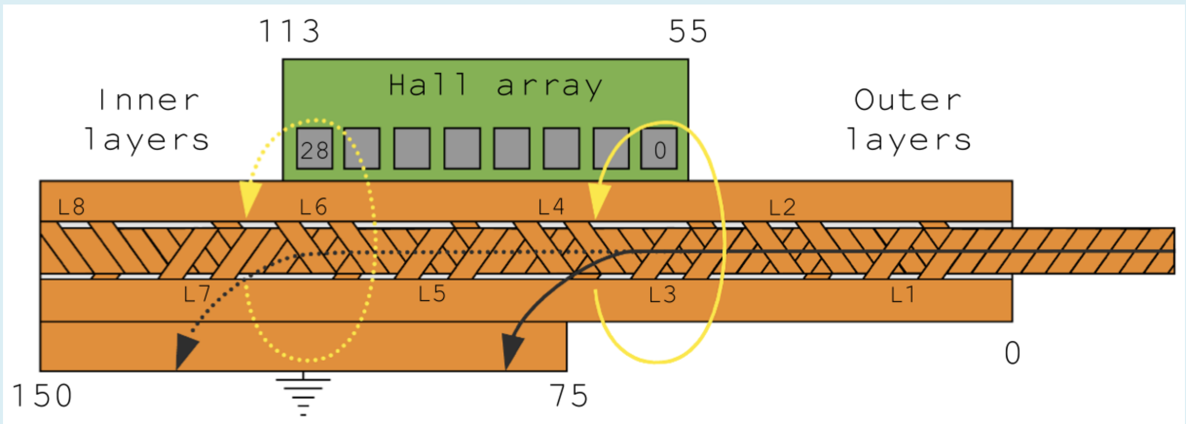
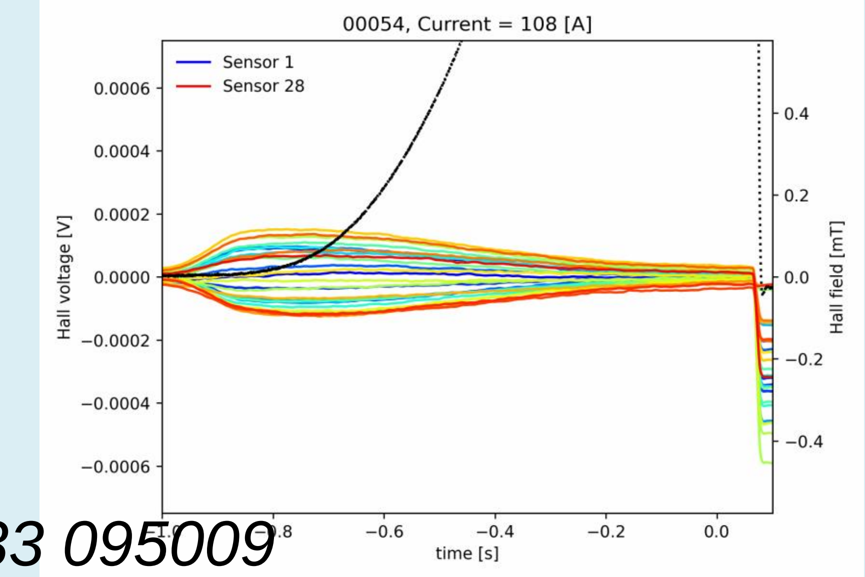
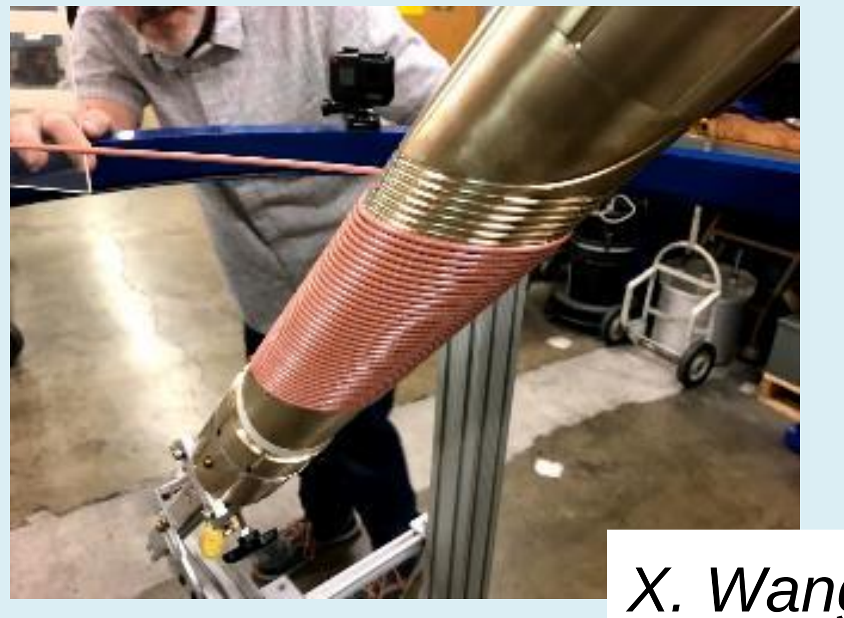
Stable, predictable and training-free operation of superconducting Bi-2212 Rutherford cable racetrack coils at the wire current density of 1000 A/mm²

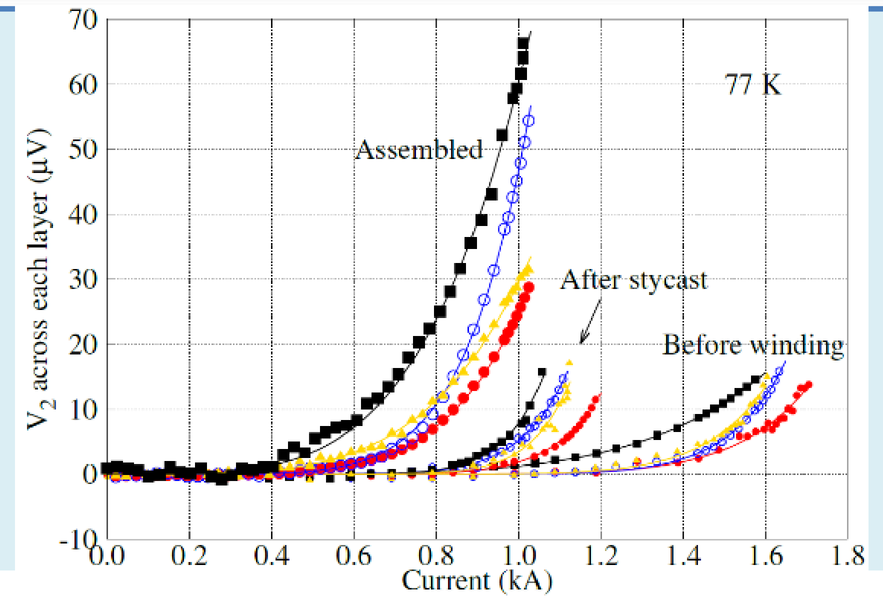
Tengming Shen, Ernesto Bosque, Daniel Davis, Jianyi Jiang, Marvis White, Kai Zhang, Hugh Higley, Marcos Turqueti, Yibing Huang, Hanping Miao, Ulf Trociewitz, Eric Hellstrom, Jeffrey Parrell, Andrew Hunt, Stephen Gourlay, Soren Prestemon & David Larbalestier





Reed Teyber et al 2020 SUST. 33 095009





X. Wang et al SUST 34 (2021) 015012

A Muon collider has unique characteristics that drive magnets

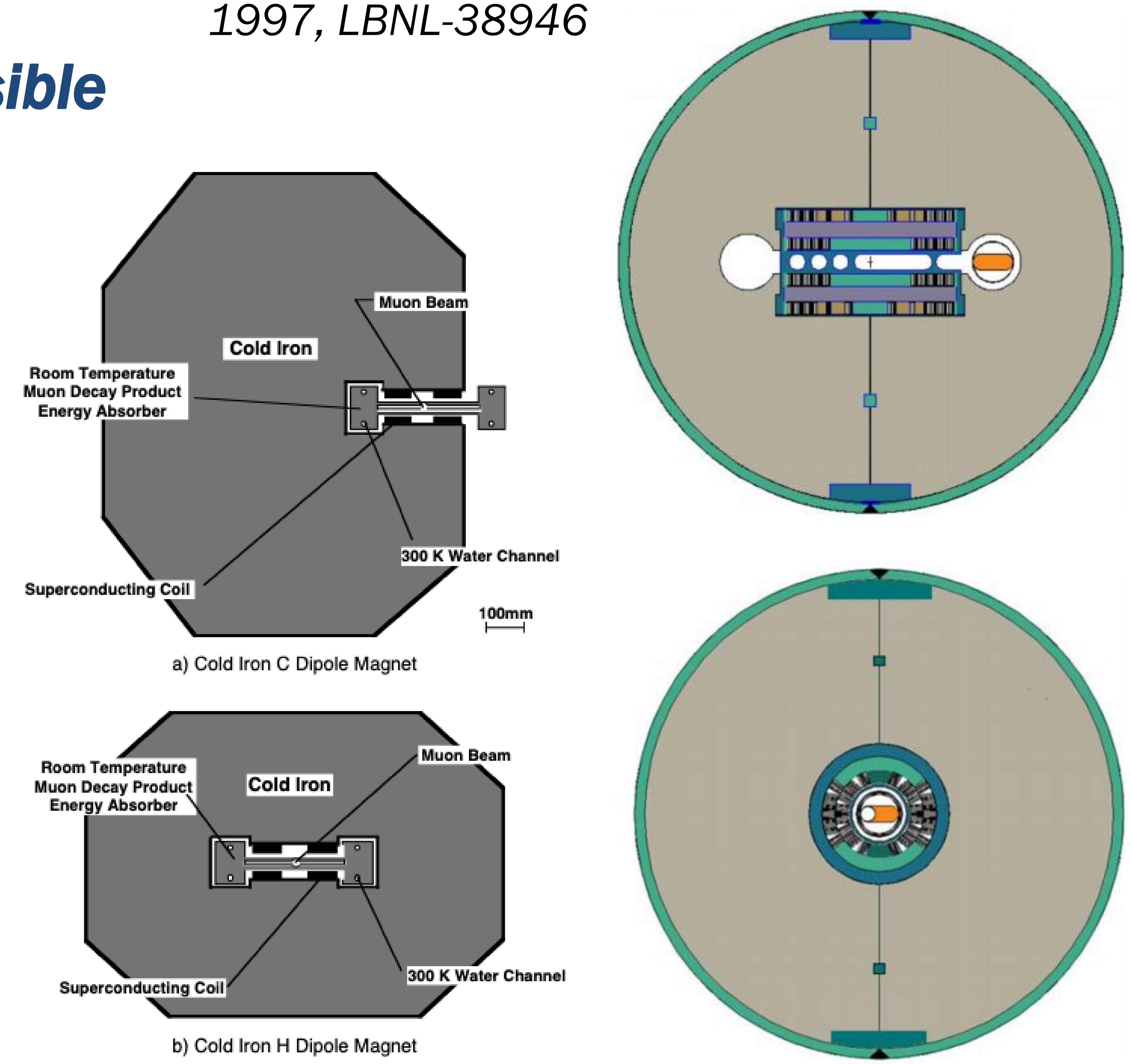
- ***"Time is of the essence"*** in a muon collider – capture and rapidly accelerate precious muons!
- The MAP study identified key R&D challenges:
    - Central elements: high field solenoids, large-bore dipoles,fast ramping, radiation env.

	Issues	Status
Target	• Multi-MW Targets • High Field, Large Bore Capture Solenoid	• Ongoing >1 MW target development • Challenging engineering for capture solenoid
Front End	• Energy Deposition in FE Components • RF in Magnetic Fields (see Cooling)	• Current designs handle energy deposition
Cooling	• RF in Magnetic Field • High and Very High Field SC Magnets • Overall Ionization Cooling Performance	• MAP designs use 20 MV/m → 50 MV/m demo • >30 T solenoid demonstrated for Final Cooling • Cooling design that achieves most goals
Acceleration	• Acceptance • Ramping System • Self-Consistent Design	• Designs in place for accel to 125 GeV CoM • Magnet system development needed for TeV-scale • Self-consistent design needed for TeV-scale
Collider Ring	• Magnet Strengths, Apertures, and Shielding • High Energy Neutrino Radiation	• Self-consistent lattices with magnet conceptual design up to 3 TeV • > ~5 TeV – n radiation solution required
MDI/Detector	• Backgrounds from ∝ Decays • IR Shielding	• Further design work required for multi-TeV • Initial physics studies at 1.5 TeV promising

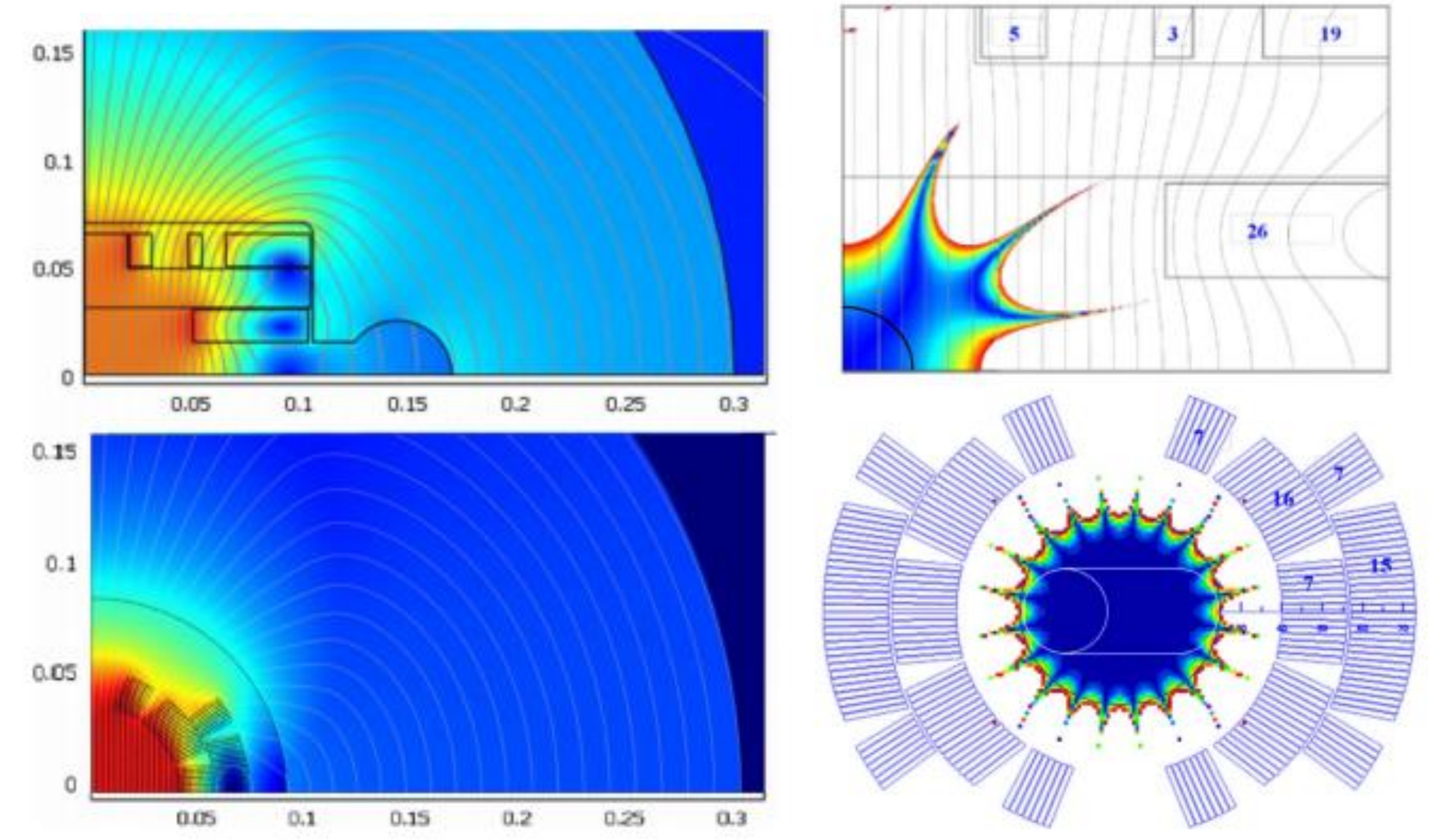
Muon Collider dipole magnets have unique requirements

- Dipoles must address significant heat load as well as radiation load
  - Open midplane or shielding (e.g. Tungsten)
  - Example: 2TeV (4TeV c-m) study suggested 2kW/m deposition
  - ⇒ ***Must extract most heat at higher temperature in order to be feasible***
- Challenge for high field magnets
  - Aperture is “costly” at high field
  - Open midplane complicates field quality

Muon collider feasibility study 1997, LBNL-38946



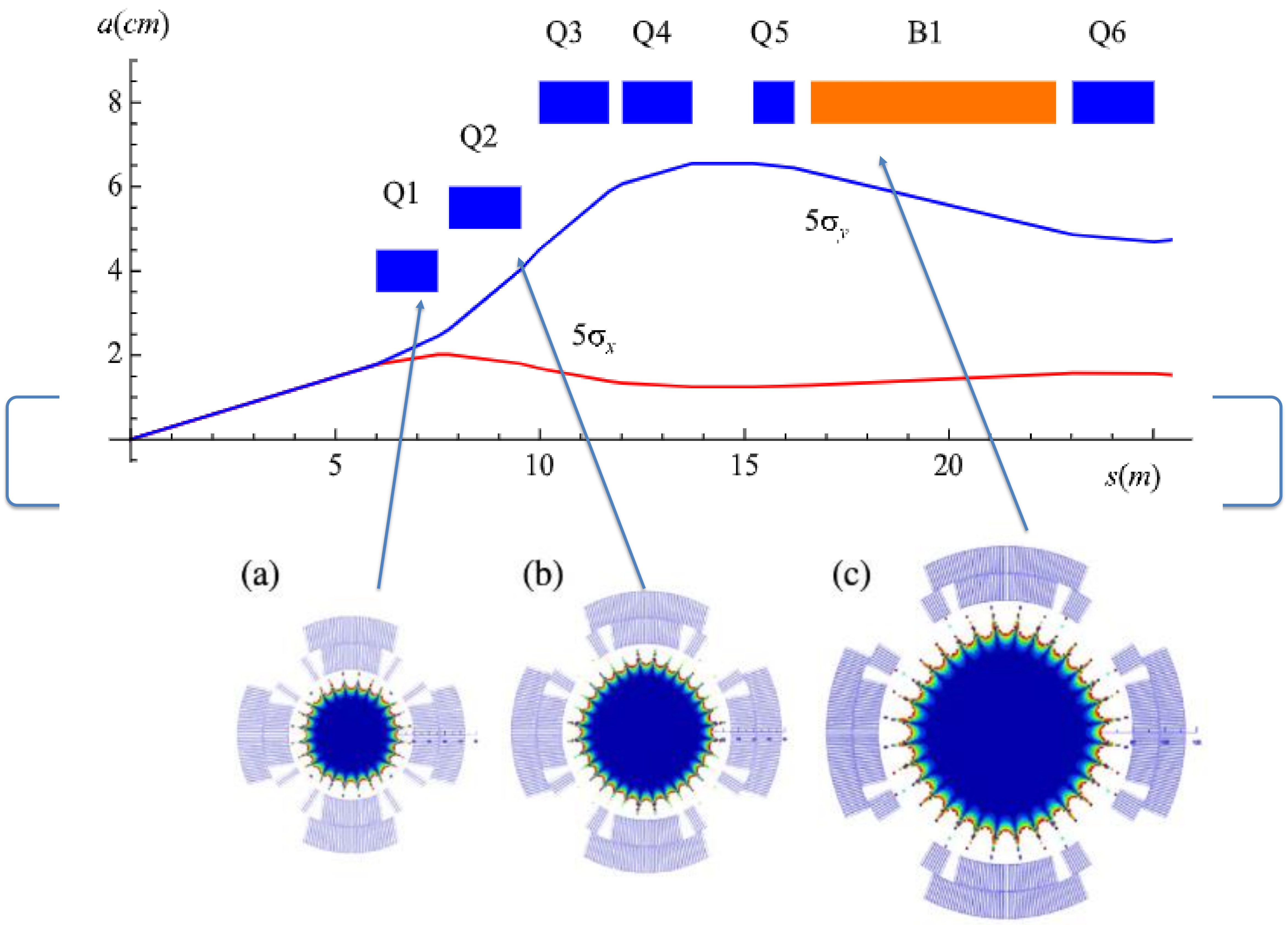
Novitski et al., TAS 2011

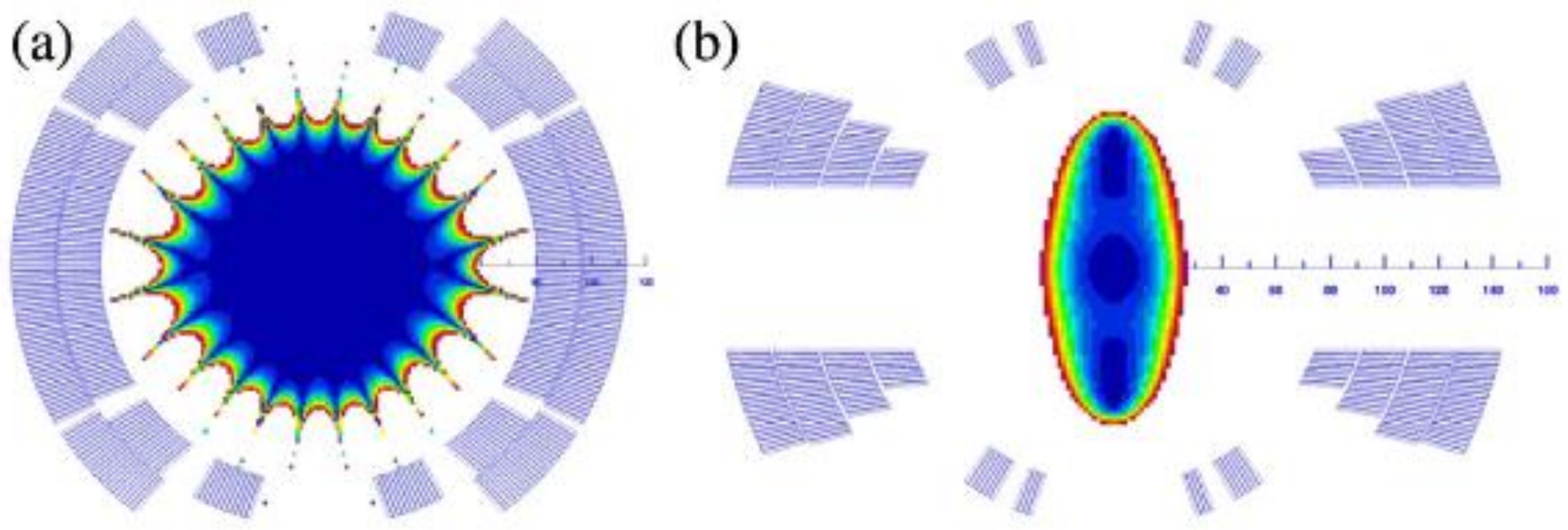


Interaction region magnets have similarities to Hadron colliders

- IR quads operating at ~11-12T
  - Large bore (~150mm)
  - Parameters are similar to HL-LHC quads
- IR Dipoles
  - Need to tolerate high radiation
    - =>Large bore, or open midplane

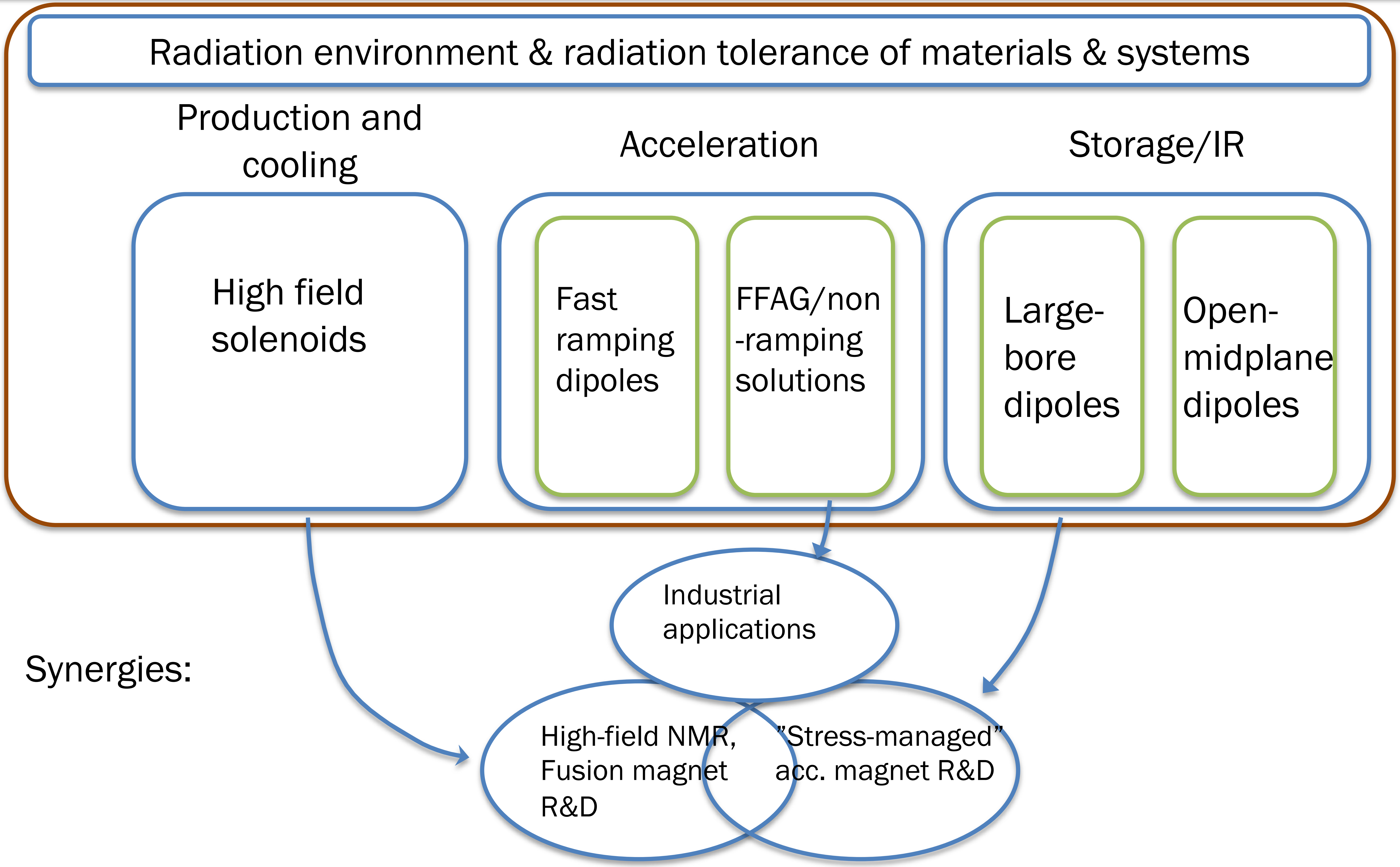
Alexahin et al., PTSTAB 14,2011





Main magnet research areas for a muon collider

- **MDP research is highly relevant to a subset of muon collider magnet R&D:**
  - **the storage ring & IR arena (large-bore)**
  - **HTS development is relevant to the high-field solenoids**
  - **FFAG/non-ramping acc. Solutions**



Some thoughts on areas for enhanced studies for Muon Collider magnets, beyond current MDP focus areas

- **Radiation is a major consideration:**
  - Study tradeoff in aperture/bore+shielding vs magnet radiation hardness
  - Further advance understanding of radiation hardness of superconductors and magnet materials

Example: *“A collaboration framework to advance high- temperature superconducting magnets for accelerator facilities”* **(US-Japan Science and Technology Cooperation Program)**

- **Rapid acceleration is critical:**
  - Study fixed-field booster options where applicable
  - Further investigate high dB/dt magnet concepts
  - Evaluate acceleration (particularly low-energy) schemes in an integrated approach

- **Large thermal loads** suggest higher-temperature operation (i.e. all-HTS)
  - Explore facility and operational cost models

- **Leverage strong synergies with fusion and High-Field magnets** (e.g. condensed matter):
  - Fastest development path for very challenging target and cooling magnets

backup

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!