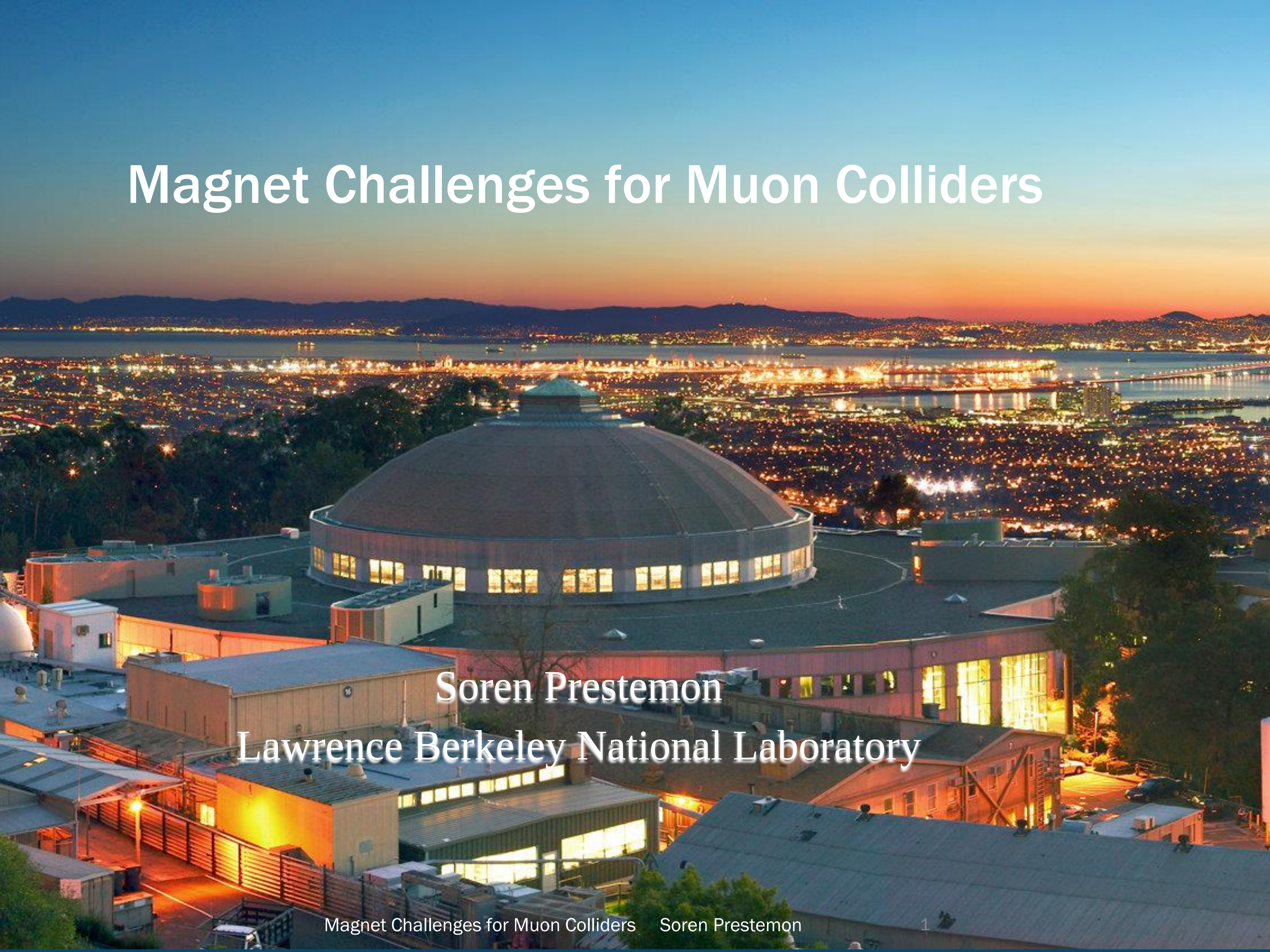
Magnet Challenges for Muon Colliders



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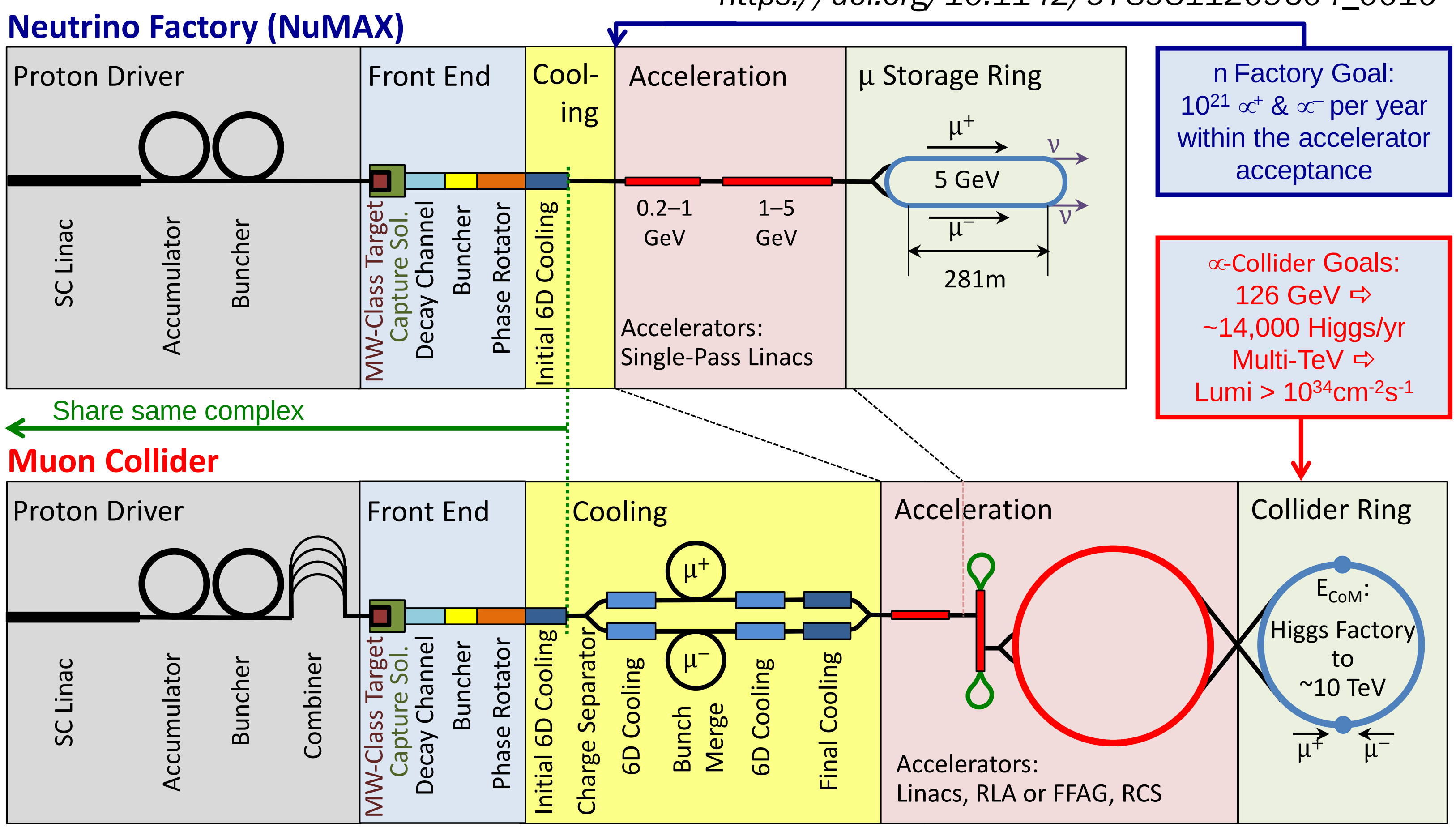
Outline

- Overview – key elements of a muon collider
- Magnet-related issues along the collider path
- Some magnet design paradigms to consider
    - Development & demonstration
    - Magnets for intermediate facilities & for final collider
- A review of key magnet-related challenges

Overview of a Muon Collider

- Magnets are central to target & front end, cooling, acceleration, collider ring

Boscolo, Delahaye, Palmer
https://doi.org/10.1142/9789811209604_0010



- The MAP study identified key R&D challenges
  - o See Palmer's talk yesterday
- Central elements: high field solenoids, 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

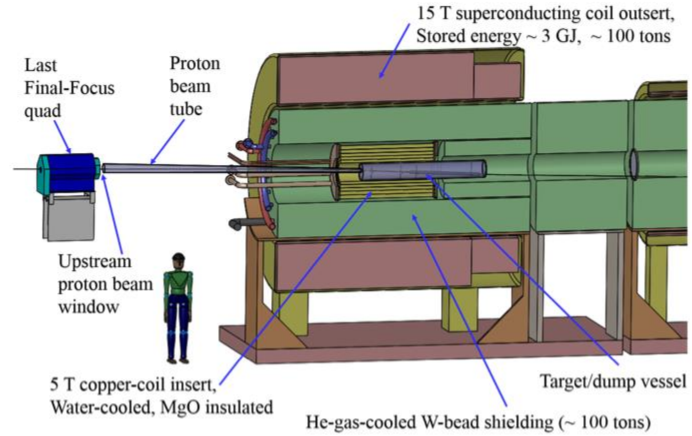
Key issues: Target/front end

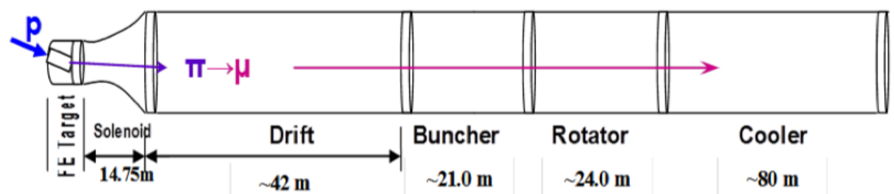
- High field target solenoid
- Tapered field capture solenoid

- Challenges:
  - ~20T solenoid field
  - High radiation environment
  - Likely inaccessible for hands-on maintenance
  - Large stored energy
  - Stray fields

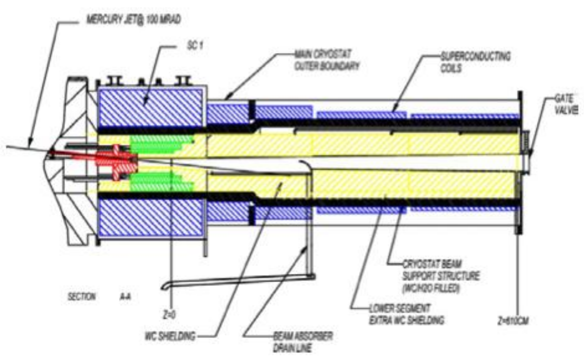
- Mitigations:
  - Optimize bore vs radiation load
    - e.g. Tungsten shielding?
  - CICC technology may be appropriate
  - Active shielding (if necessary)
  - Synergies with
    - NHMFL high field solenoids
    - FES central solenoid developments
      - But leverage DC nature of field

McDonald et al., IPAC2014



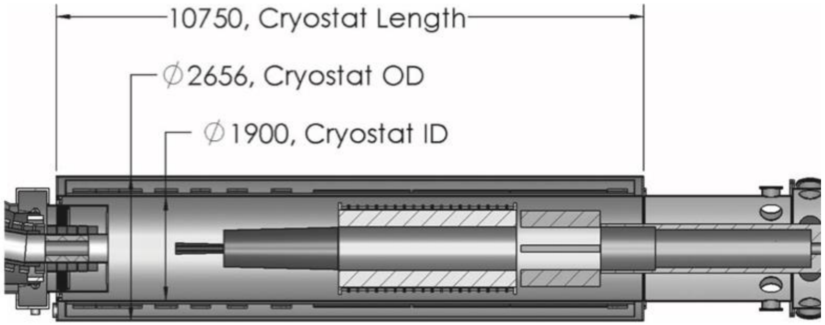


Neuffer et al., https://arxiv.org/pdf/1711.11120.pdf



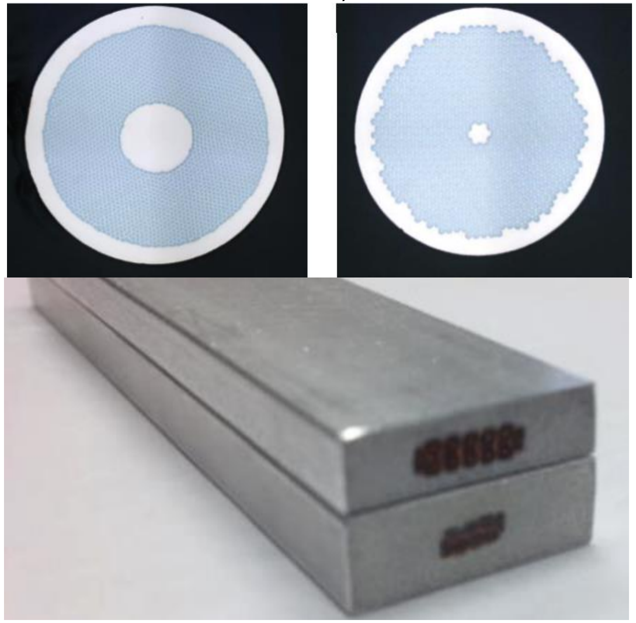
Zisman, TAS VOL. 18, NO. 2, JUNE 2008

Technology options



Ostojic et al., TAS 2013

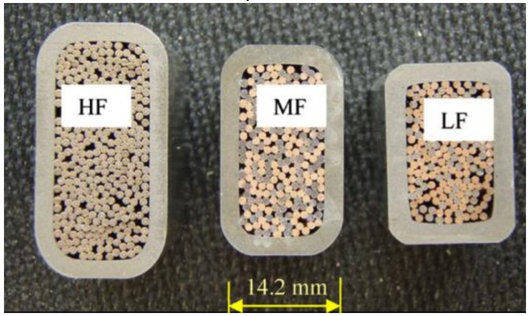
Lombardo et al., TAS 2016



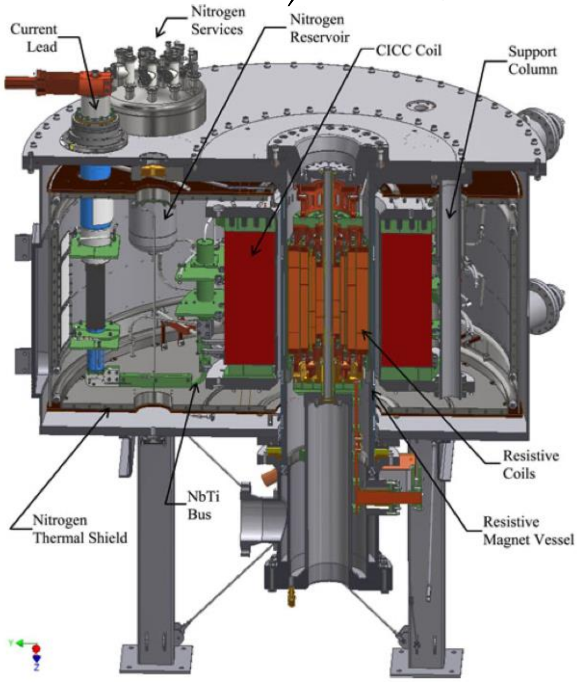
Mu2e detector solenoid (2T, 2m ID)

NHMFL Series connected hybrid Outsert: (~13T, 610mm ID)

Bird et al., TAS 2009



Dixon et al., TAS 2017



Key issues: Cooling

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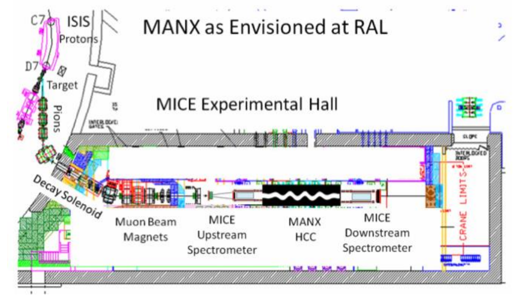
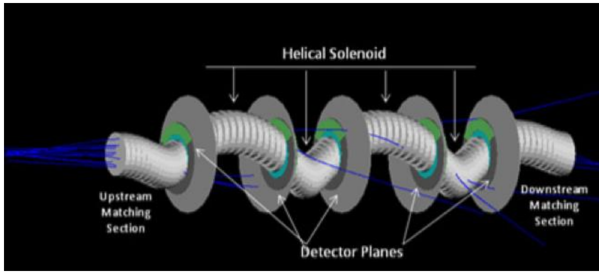
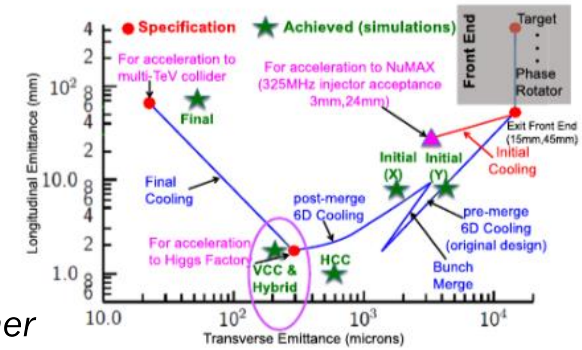
- Multiple cooling sections needed to reduce the beam phase space
  - o Longitudinal =>large momentum-acceptance acceleration and storage
  - o Transverse=>need rapid 4D (some 6D) cooling=>solenoids
  - o For collider, need small energy spread=>6D final cooling
- Ionization cooling:
  - o Requires strong solenoid fields for focusing
  - o Large bore to accommodate (room temp) absorbers and RF
- Challenges:
  - o Requires HTS for fields >~20T
  - o “Bucking” solenoids require croystats/structures to react forces
  - o Helical channel has significant structural complexities

Yonehara et al., PAC09







Boscolo, Delahaye, Palmer
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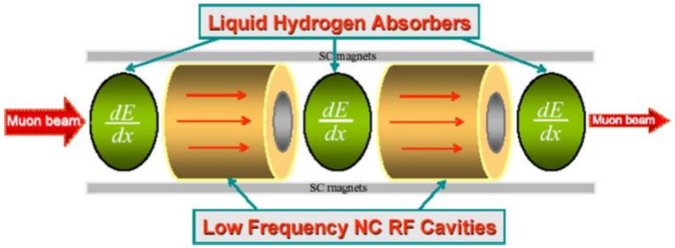
Zisman, TAS, 2008



Key issues: Acceleration

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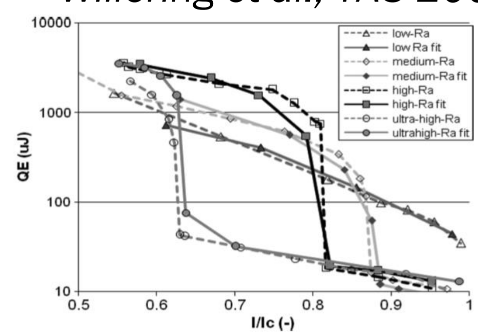
- Classic approach:
  - o synchrotron-based – ramp magnets in concert with RF acceleration
  - o Challenges:
    - dB/dt induces…
      - – heat in conductor (AC losses); =>impacts performance $J \leq J_c(B,T)$
      - – Magnetization in superconductor (=>field errors)
      - – Eddy currents in associated conductive materials (=>field errors)
    - Fatigue considerations drive many design considerations
    - Cycle time drives collider performance
  - o Mitigation approaches:
    - Laminations in all conducting materials (where possible)
    - Small filaments in superconductor
    - Reduce contact resistance between strands
  - o Or different paradigms, e.g.
    - FFAG or similar – the holy grail is to…
      - – Eliminate ramping
      - – Maximize muon momentum acceptance
      - – Store beams of varying energies simultaneously

Volpini et al., TAS 2011

TABLE I
WIRE MAIN CHARACTERISTICS

Diameter after coating	0.825 ± 0.003		mm
Filament twist pitch	5 +0.5 -0		mm
Effective Filament Diameter	1st generation	≤ 3.5	µm
	2nd generation	≤ 2.5	µm
Interfilament matrix material	Cu-0.5 wt% Mn		
Filament twist direction	right handed (clockwise)		
Ic @ 5 T, 4.22 K	> 541		A
n-index @ 5 T, 4.22 K	> 30		
Stabilization matrix	Pure Cu		
ρ_t at 4.22 K	0.4 + 0.09 *B* [T]		nΩ·m
Cu+Cu-Mn : Nb-Ti ratio (α)	>1.5 ± 0.1		
Surface coating material	Staybrite (Sn-5 wt% Ag)		

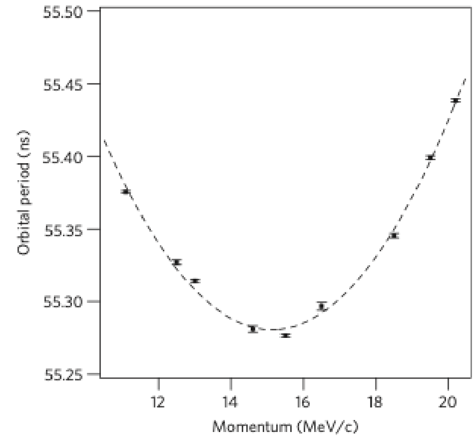
Willering et al., TAS 2008



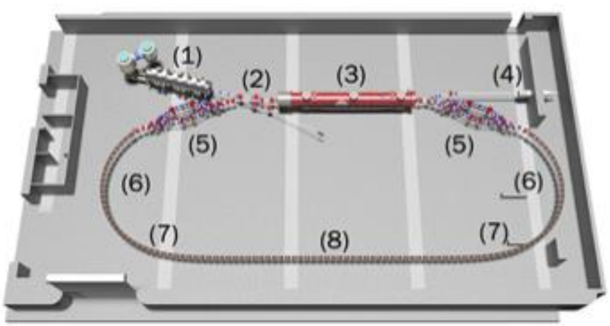
Non-ramping options are intriguing

- Fixed field configurations – can they work?
- Non-scaling FFAG
    - o “built for Muons”

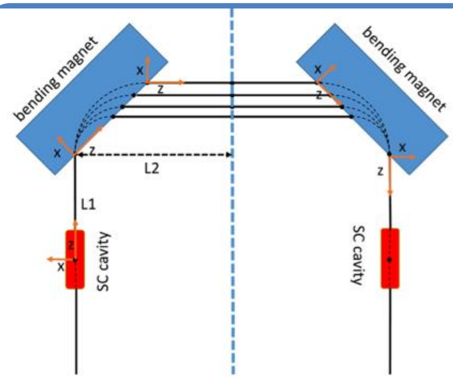
EMMA - Machida et al., Nature Physics, 2012

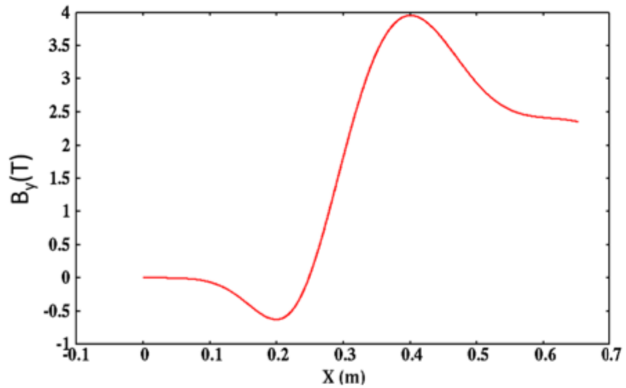


CBETA - Trbojevic et al., IPAC2017



Qiang, Brouwer, Teyber, PRAB 2021





Key issues: Collider ring magnets

- Dipoles, quadrupoles for main ring
- Interaction region magnets

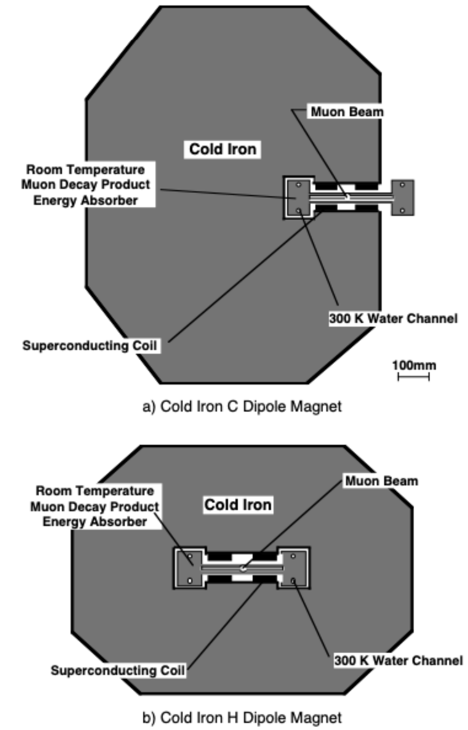
- Significant work has been done on ~1.5TeV muon collider ring concepts
- Major considerations:
  - Compact ring enables increased collision rates and hence physics

  =>Compact implies higher field dipole
  - Apertures of 5-sigma are considered acceptable
  - Significantly heat loads (SR, ***Muon decay***, Muon losses)

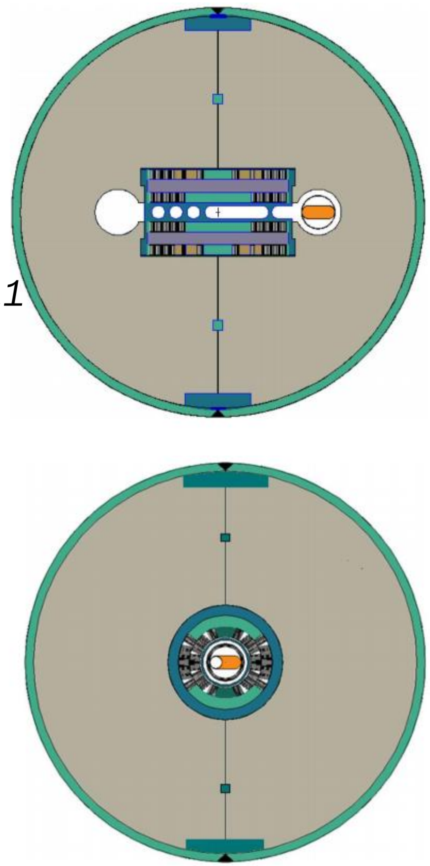
Collider dipole magnets

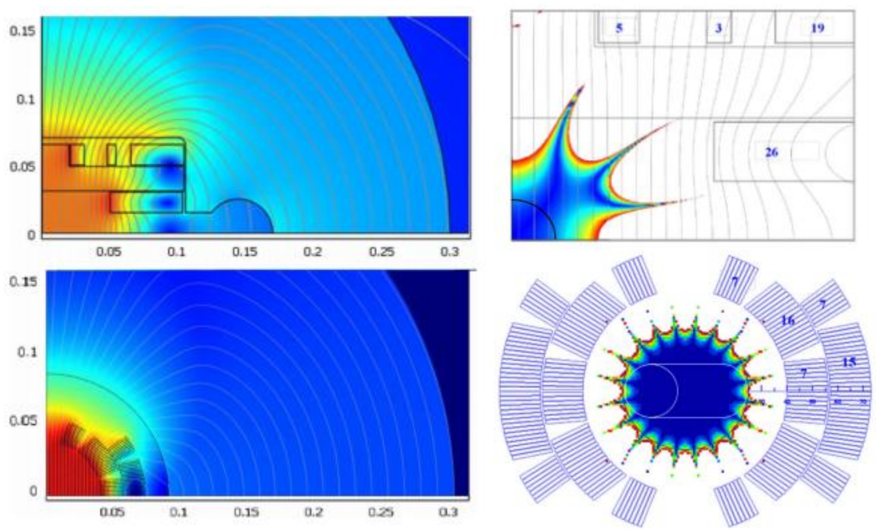
- Dipoles must address significant heat load as well as radiation load
  - o Open midplane or shielding (e.g. Tungsten)
  - o Example: 2TeV (4TeV c-m) study suggested 2kW/m deposition
  - ⇒ Must extract most heat at higher temperature in order to be feasible
- Challenge for high field magnets
  - o Aperture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

Muon collider feasibility study 1997, LBNL-38946



Novitski et al., TAS 2011





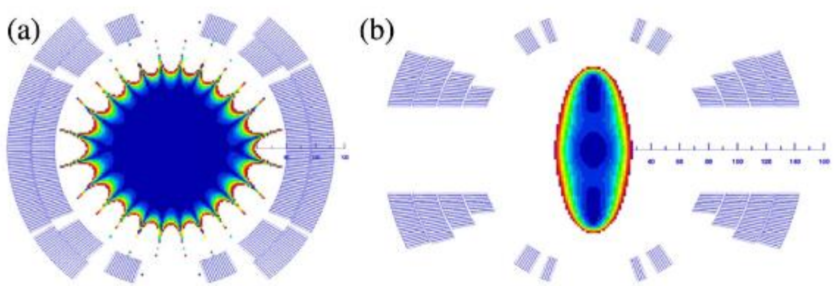
Interaction region magnets

- IR quads operating at ~11-12T
  - o Large bore (~150mm)
  - o Parameters are similar to HL-LHC quads

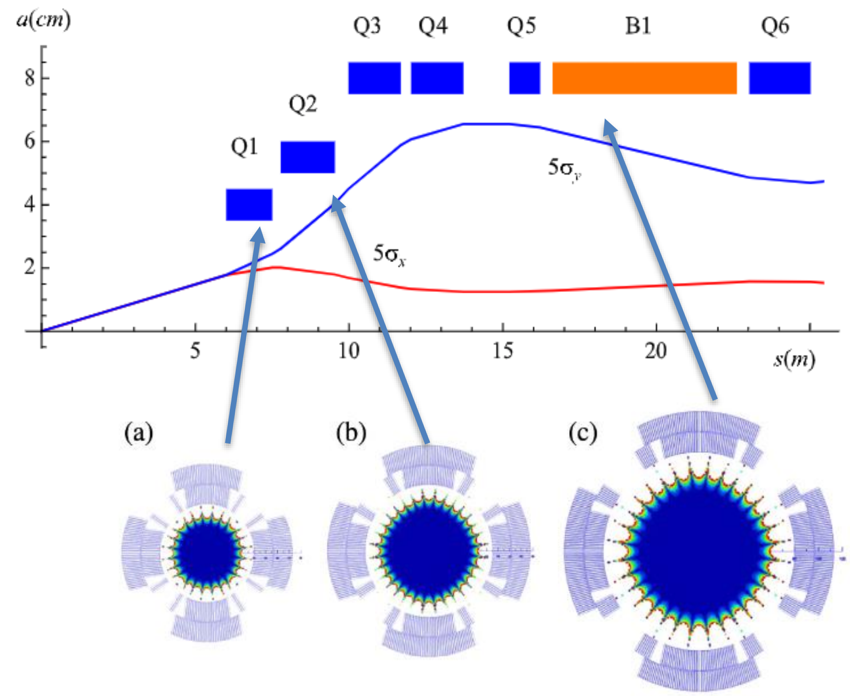
Similar, but HL-LHC quads allow for a Tungsten shield!

- IR Dipoles
  - o Need to tolerate high radiation

  =>Large bore, or open midplane



Alexahin et al., PTSTAB 14,2011



Magnet design paradigms: Dev. & Dem.

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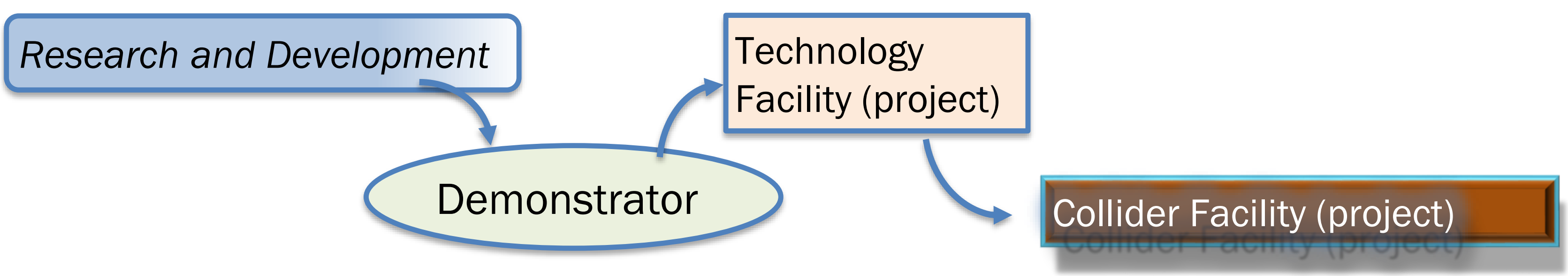
- ***Development***: steady, rigorous R&D that provides the building blocks for a technology
- ***Demonstration***: Application of technology from current R&D status to illustrate (demonstrate) capability

- The two have different aims and are best not fully intertwined!
- A Demonstration often has the benefit of introducing systems engineering aspects that are a critical step towards facilities
    - But it does not allow the critical “try-fail-learn” iterations needed for successful R&D



Magnets for intermediate facilities & for final collider

- There can be a conflict between magnet designs for intermediate facilities and for a final collider – can choose:
  - Use intermediate facility as test bed for ”final” design
    - Negative: Probably “sub-optimal” design
    - Positive: Builds confidence, avoids investing in “one-off” design
  - Or, build magnets tailored to intermediate facility requirements
    - Usually more cost effective in near-term

- Example of MICE:
  - Full facility would use liquifiers, possibly 1.8K
  - “Intermediate facility” used cryocoolers (=>single strand, low current)

Review of magnet-related challenges

- Beam optics & magnet design
  - o should be communicate closely to find best compromise in magnet feasibility and overall performance
- Stresses and stored energy are major challenges in the solenoids

  => need high current conductors (cables)

  $\Rightarrow$ bore size and field strength drive challenges

$$E = \frac{1}{2} L I^2$$

$$V = IR \qquad \tau = L/R$$

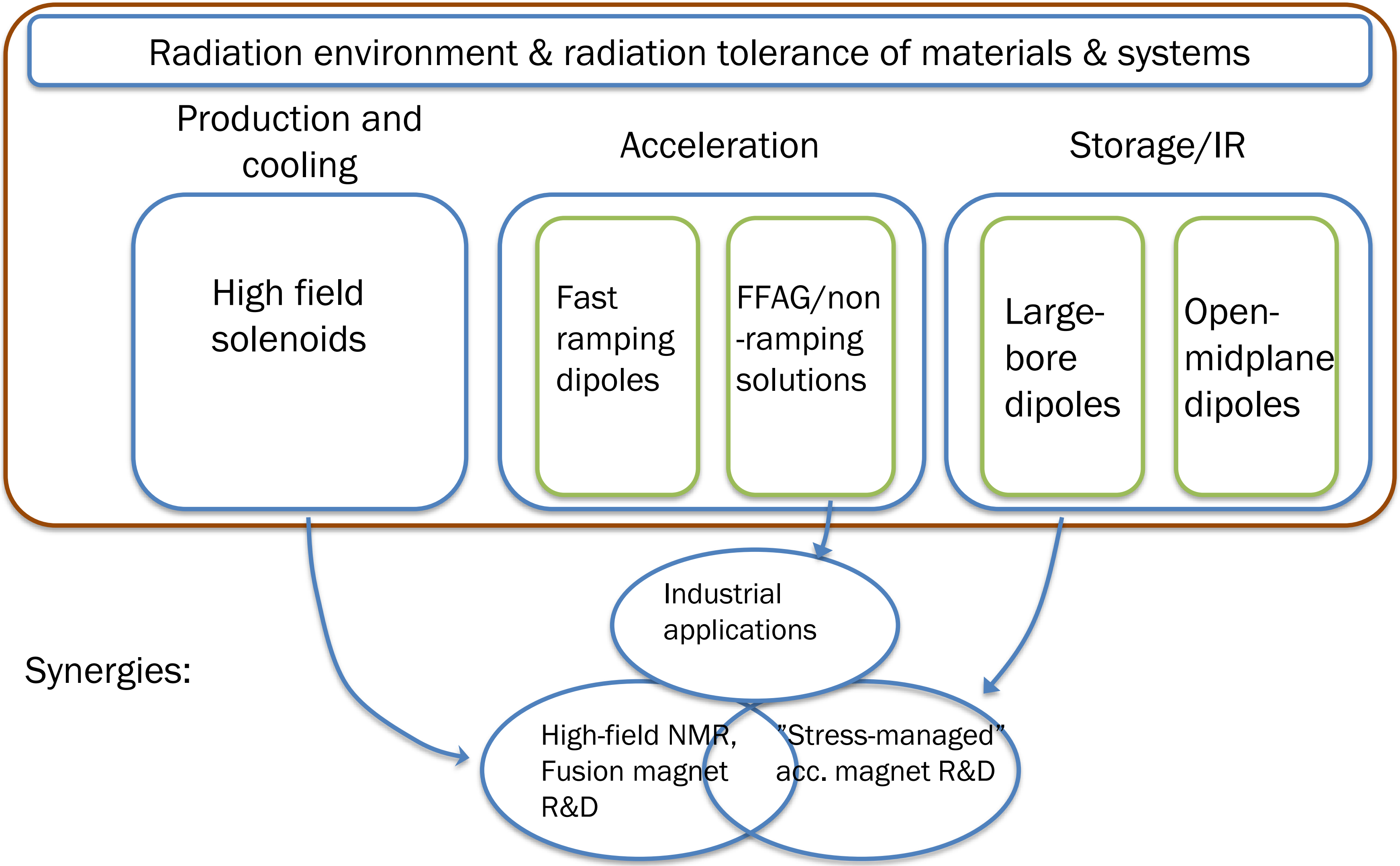
$$\sigma \propto JBr \qquad E \propto B^2 R^2$$

- Fast ramping magnets incur major technical challenges:
  - o AC losses dictate…
    - specialized conductor specifications
    - Specialized support structures
    - Specialized cooling systems

  =>Explore feasibility of non-ramping options in parallel
- Radiation loads are significant – need clear design protocols and relevant testing campaigns

Electrical and mechanical integrity over time is a major concern!

Main research areas



Ideas for a magnet technology roadmap

- Core elements:
    - High-field solenoid development
    - Large bore dipole technologies
    - Fast-ramping dipoles – optimized in pulse duration, frequency, field
    - Understanding radiation environment and appropriate materials

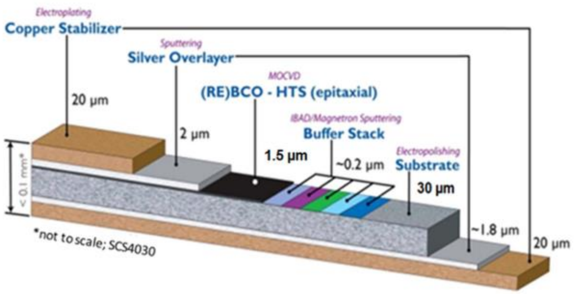
- High-risk / high-reward element:
    - Non-ramping magnet/optics solutions for acceleration

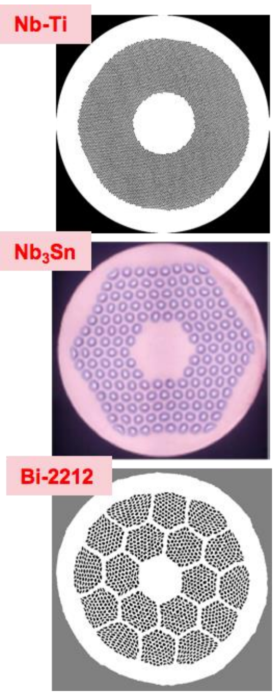
Backup

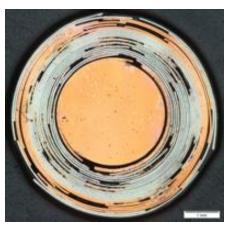
Magnets start with the superconductor

- We are about to put Nb_3Sn into a collider for the first time, and are investigating the potential of HTS

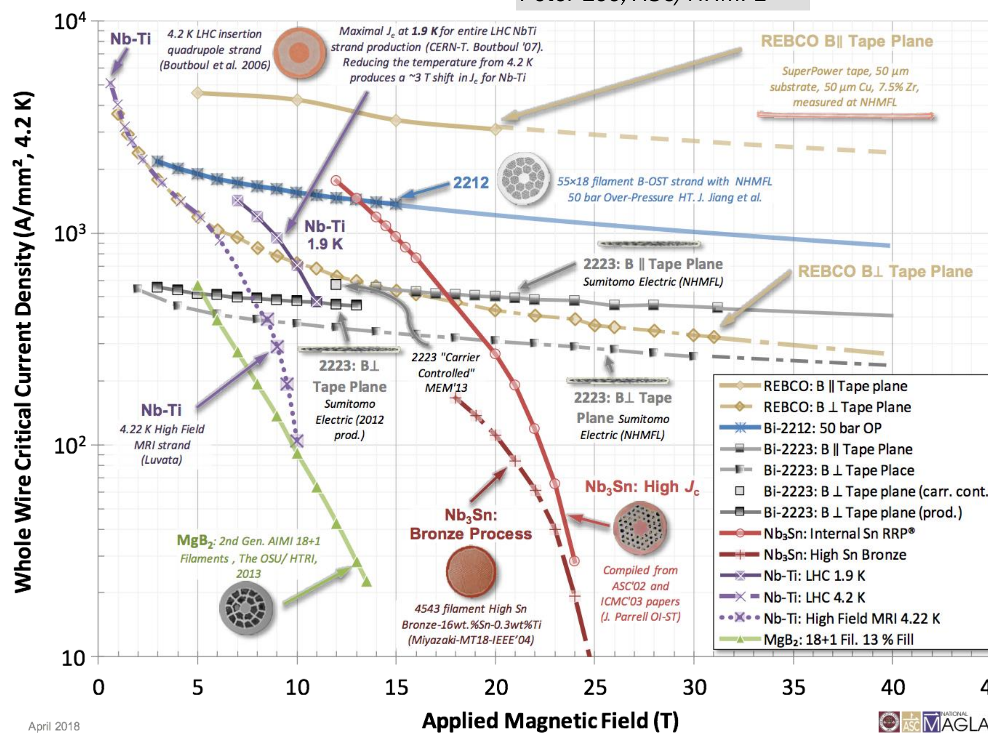
SuperPower Inc







Peter Lee, ASC/NHMFL



In the US, a collaboration is focused on magnet technology for future colliders

U.S. MAGNET DEVELOPMENT PROGRAM

The Updated Roadmap for MDP is publicly available
https://arxiv.org/abs/2011.09539

LBNL, FNAL, BNL, ASC/NHMFL

- **Major themes of the updated Roadmaps:**
  - ***Explore the potential for stress-managed structures*** to enable high-field accelerator magnets, i.e. structures that mitigate degradation to strain-sensitive Nb_3Sn and HTS superconductors in high-field environments;
  - ***Explore the potential for hybrid HTS/LTS magnets*** for cost-effective high field accelerator magnets that exceed the field strengths achievable with LTS materials;
  - ***Advance magnet science*** through the rapid development and deployment of unique diagnostics and modeling tools to inform and accelerate magnet design improvements;
  - ***Perform design studies*** on high field accelerator magnet concepts to inform DOE-OHEP on further promising avenues for magnet development;
  - ***Advance superconductors*** through enhanced performance, improved production quality, and reduction in cost - all critical elements for future collider applications.