Fermilab

July 29, 2026

The Global Effort Towards at 10 TeV Muon Collider

Karie Badgley

On behalf of the US Muon Collider Collaboration

Advanced Accelerator Concepts 2026

U.S. DEPARTMENT of ENERGY

Fermi National Accelerator Laboratory is managed by FermiForward for the U.S. Department of Energy Office of Science

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The 10 TeV pCM Recommendation

- The 2023 Particle Physics Prioritization Panel (P5) and the 2025 National Academy of Sciences recommended immediate and aggressive R&D toward a muon collider

- 2020 update of the European Strategy for Particle Physics Update (ESPPU) recommended an R&D program on technology for bright muon beams

Recommendation 4: Invest in a comprehensive initiative to develop the resources—theoretical, computational, and technological—essential to realizing our 20-year strategic vision. 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.

Fulfilling this vision requires a substantial investment vital to the effective implementation and success of the particle physics program. The initiative requires the following enhancements to current investments:

a. Support vigorous R&D toward a cost-effective 10 TeV pCM collider based on proton, muon, or possible wakefield technologies, including an evaluation of options for US siting of such a machine, with a goal of being ready to build major test facilities and demonstrator facilities within the next 10 years (sections 3.2, 5.1, 6.5, and Recommendation 6).

P5 Report

Recommendation 1: The United States should host the world's highest-energy elementary particle collider around the middle of the century. This requires the immediate creation of a national muon collider research and development program to enable the construction of a demonstrator of the key new technologies and their integration.

NAS

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

ESPPU

IMCC and USMCC

International Muon Collider Collaboration

- 50+ institutions
- US scientist actively engaged and involved in IMCC leadership
- EU funded MuCol design study to develop a collider concept based on realistic collider components
    - Report (~early 2027) to inform next ESPPU
- muoncollider.web.cern.ch

US Muon Collider Collaboration

- ~300 members
- Inaugural annual meeting held Aug 2024
- Upcoming meeting Dec 2026
- www.muoncollider.us

National Lab Accelerator Study Group for a Muon Collider

Purpose and Scope

- Identify the **key accelerator challenges** for a **10 TeV Muon Collider**
- Define the **necessary R&D steps**
- Estimate **timeframes for major R&D areas**
- Evaluate and build on existing **U.S. and IMCC plans**
- Identify **gaps, overlaps, and coordination issues**:
- Strong focus on:
  - **U.S. national lab collaboration**
  - **Alignment with international efforts**
- Goal: ensure **high-impact, complementary U.S. contributions**

The study is about **prioritizing and organizing the critical R&D needed now**—not designing the collider itself—so future planning can be grounded in realistic technical progress.

Membership

Argonne: Philippe Piot

Berkeley: Jean-Luc Vay, Chad Mitchel

Brookhaven: Steve Peggs

Fermi: Steve Gourlay (Chair)

JLab: Robert Rimmer

Los Alamos: Steve Russel

Oak Ridge: Fulvia Pilat

SLAC: Emilio Nanni

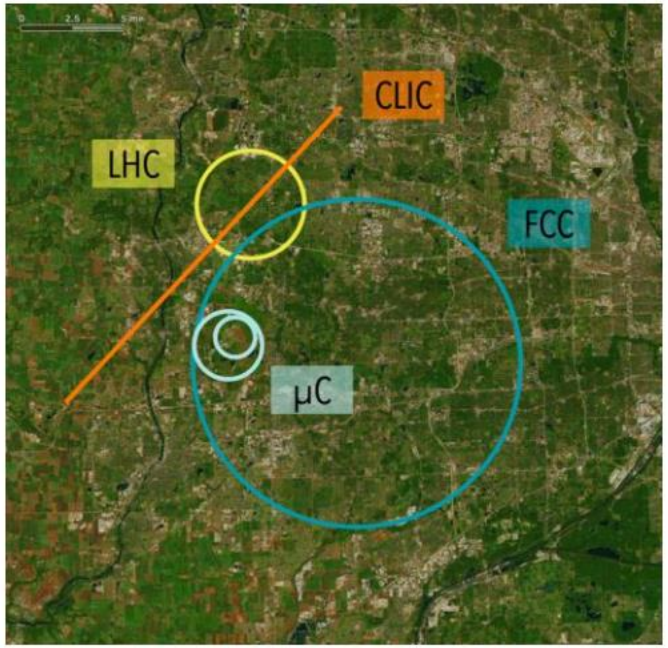
Scientific Secretary, Diktys Stratakis, Fermi

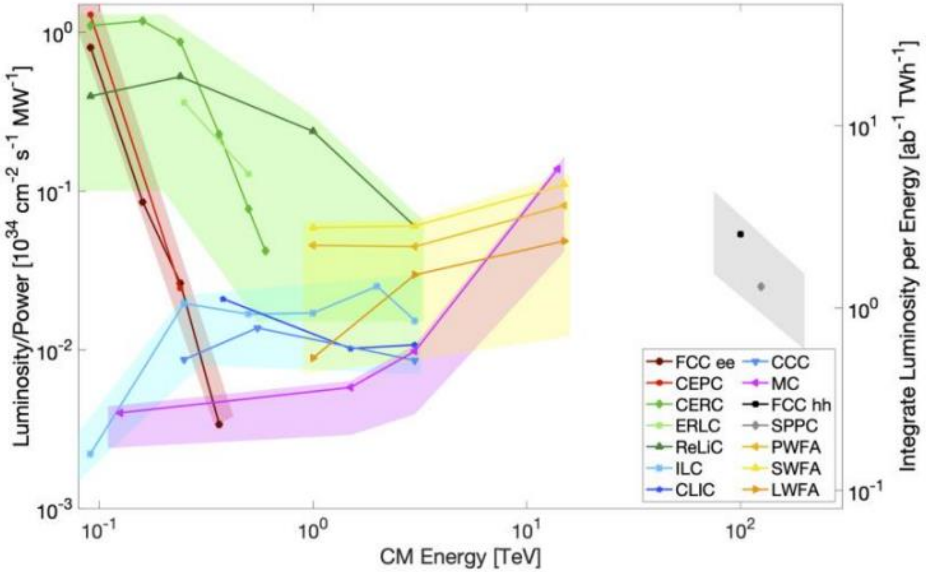
Held 17 Seminars on systems and technologies – report writing in progress – aiming for July 31^th^

Slide credit: D. Stratakis

Why Muons?

- Leptons - all energy goes into collision
- Synchrotron radiation $\propto \frac{E^4}{m^4}$ suppressed, allowing for a more compact and circular machine
- Circular machine allows for multiple bunch collisions
- “beamstrahlung” suppressed – smaller collision energy spread
- S-channel Higgs production is enhanced by $\left(\frac{m_\mu}{m_e}\right)^2 \sim 40{,}000$
- Luminosity to power ration improves with energy





Muon Challenges

Muon production

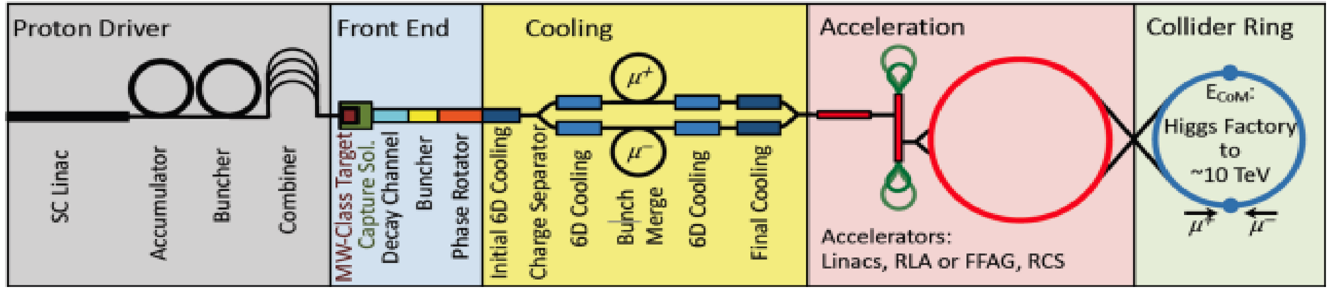
- Produced by proton beam→ target → pion decay → muons
- Very large longitudinal and transverse emittances must be cooled for collider luminosity

Muons decay ~2.2 μs

- Cooling and acceleration must be done quickly
- Electrons from the muon decays deposit significant energy in the accelerator components and physics detector
- Neutrinos from decay can produce ionizing radiation

Muon Collider Overview

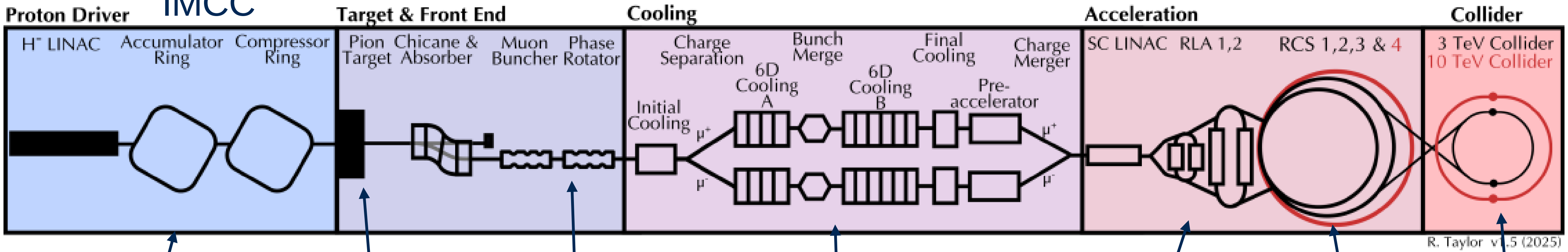
Muon Accelerator Program (MAP) (2011-2016)



Parameter	Symbol	Unit	Baseline
Centre-of-mass energy	E_{cm}	TeV	10
Target integrated luminosity	$\int \mathcal{L}_{target}$	ab^{-1}	10
Estimated luminosity	$\mathcal{L}_{estimated}$	$10^{34} cm^{-2}s^{-1}$	18
Collider circumference	C_{coll}	km	11.4
Collider arc peak field	B_{arc}	T	14
Luminosity lifetime	N_{turn}	turns	1363
Muons/bunch	N	10^{12}	1.8
Repetition rate	f_r	Hz	5
Beam power	P_{coll}	MW	14.4
RMS longitudinal emittance	$\varepsilon_{\parallel}$	eVs	0.025
Norm. RMS transverse emittance	$\varepsilon_{\perp}$	µm	25
IP bunch length	σ_z	mm	1.5*
IP betafunction	β	mm	1.5*
IP beam size	σ	µm	0.9
Protons on target/bunch	N_p	10^{14}	5
Proton energy on target	E_p	GeV	5

MuCol Consolidated Parameters Report

IMCC



MW-scale proton driver to deliver short and intense bunches

High power muon production target

200 MeV bunches

Ionization cooling to reduce 6D emittance

LINAC and 2 RLAs accelerate to 62.5 GeV

Rapid Cycling Synchrotrons accelerate to 5 TeV

Collider Ring for counter propagating muons

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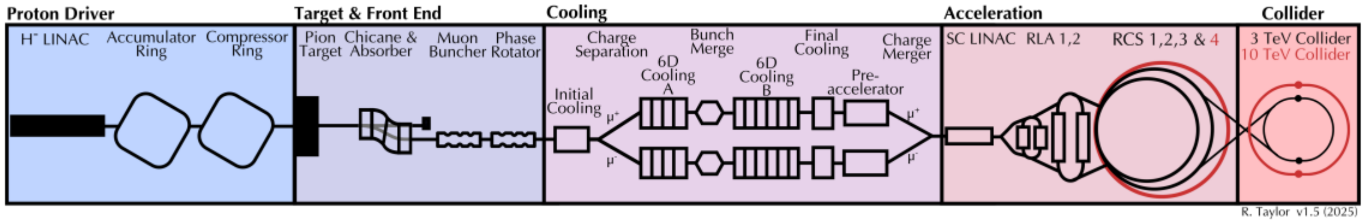
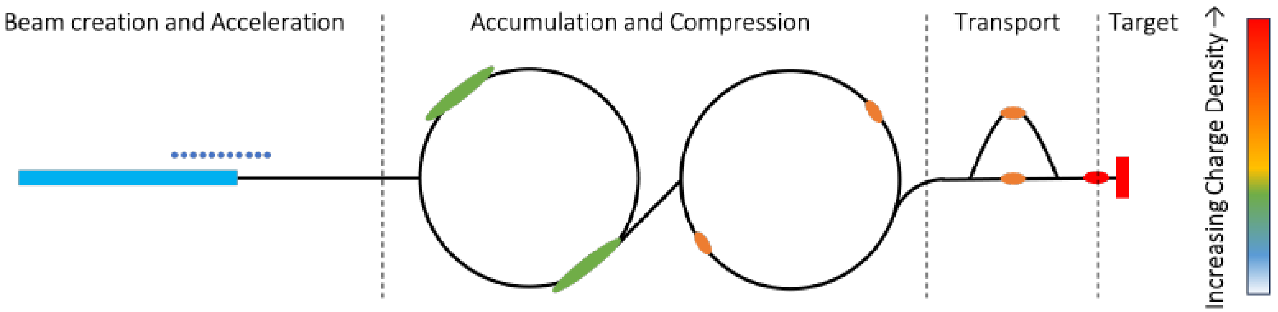
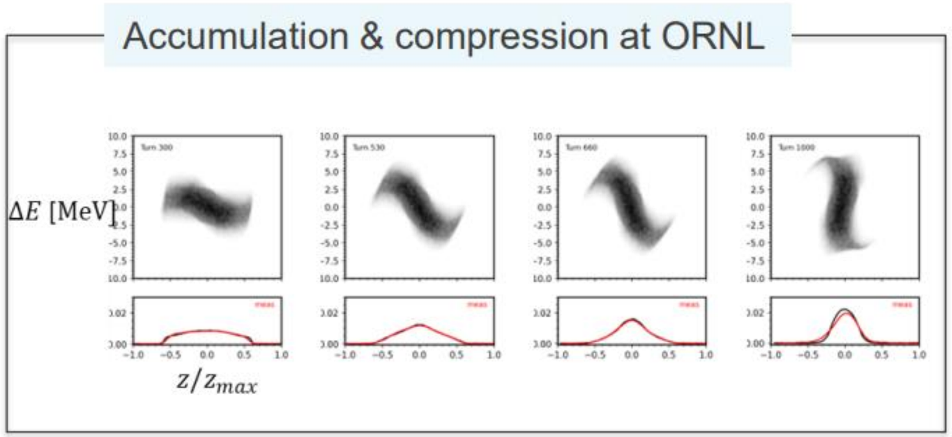
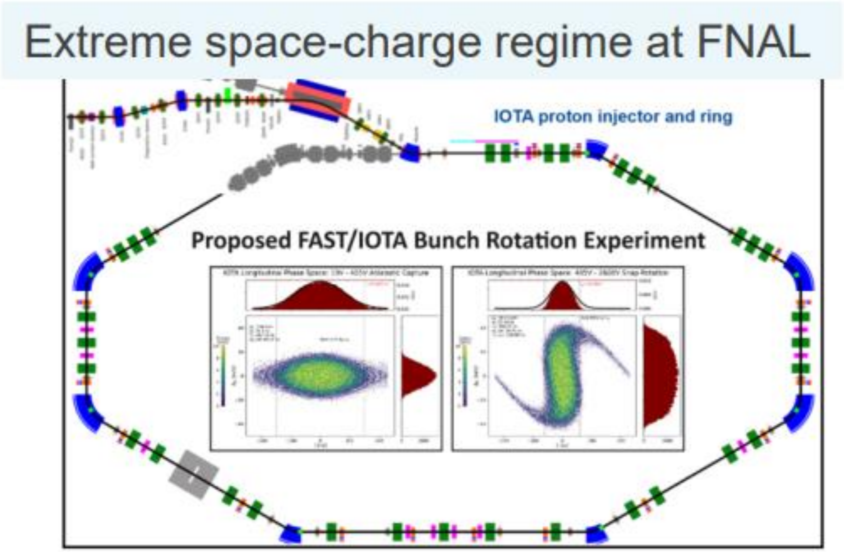
Proton Driver









- >2 MW at 5-10 Hz, pulse length ~2 ns
- 5-20 GeV to maximize pion yield
- Multi MW proton sources exist (PIP-II, SNS, ESS)
  - R&D needed to modify for the MuC
- Requires beam manipulations that need to be experimentally verified
- Relevant R&D ongoing at ORNL and IOTA at Fermilab

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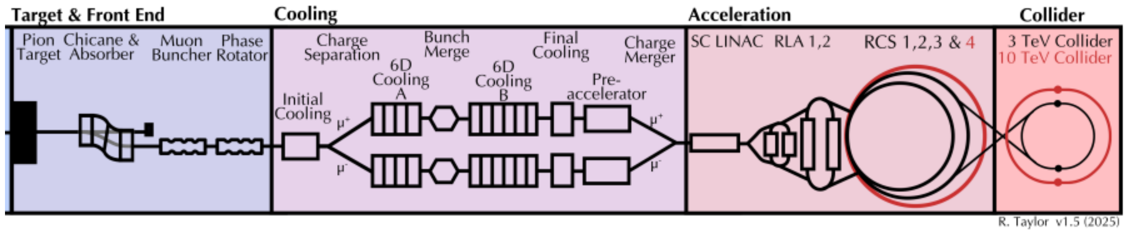
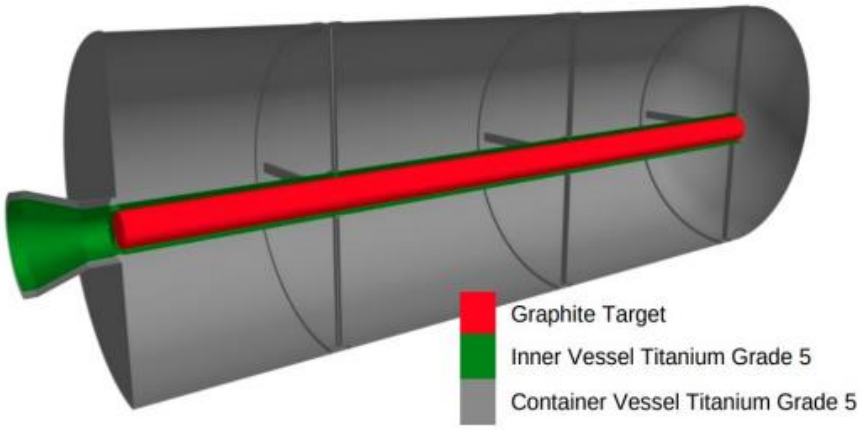
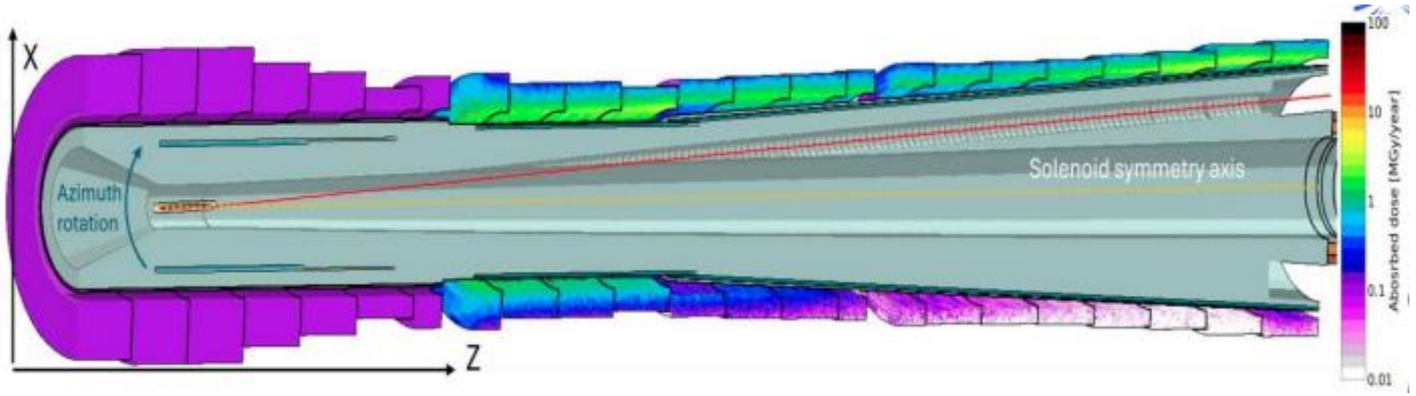
Target

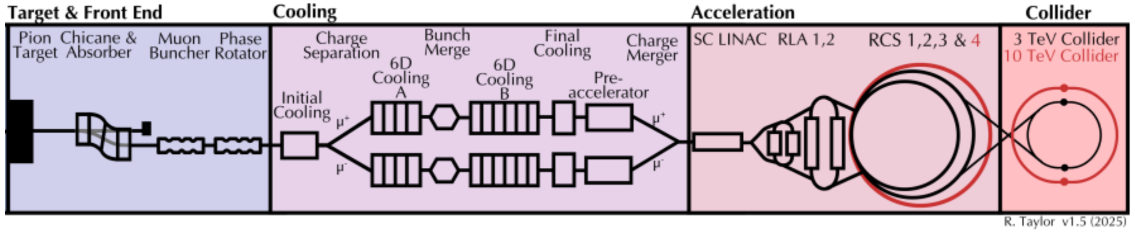


- Energy deposition on target beyond current operating targets
- High pion/ muon yield and high thermal stress tolerance align with high power target goals for future neutrino facilities
- Graphite looks promising but R&D needed
- Considering alternatives
  - Fluidized tungsten
  - Liquid Pb
- Target enclosed in multi-T SC solenoid
- Spent proton beam line maturing
  - Sufficient magnet shielding
  - Need to determine DPA limit on HTS



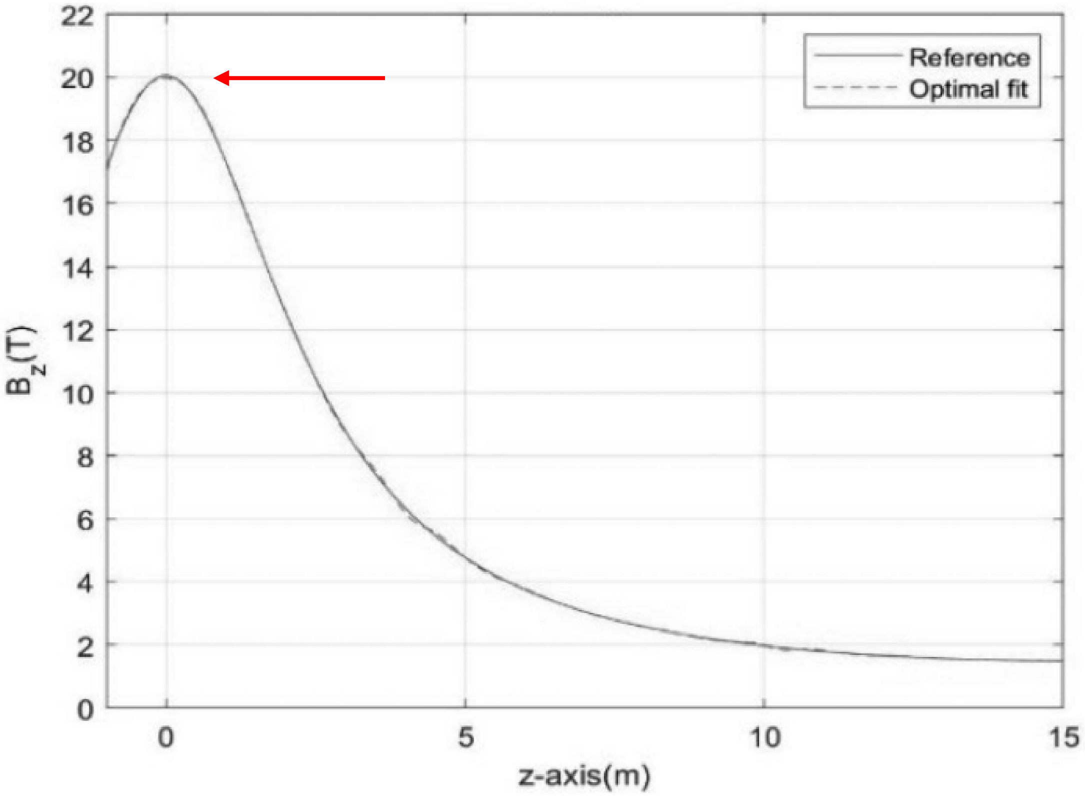


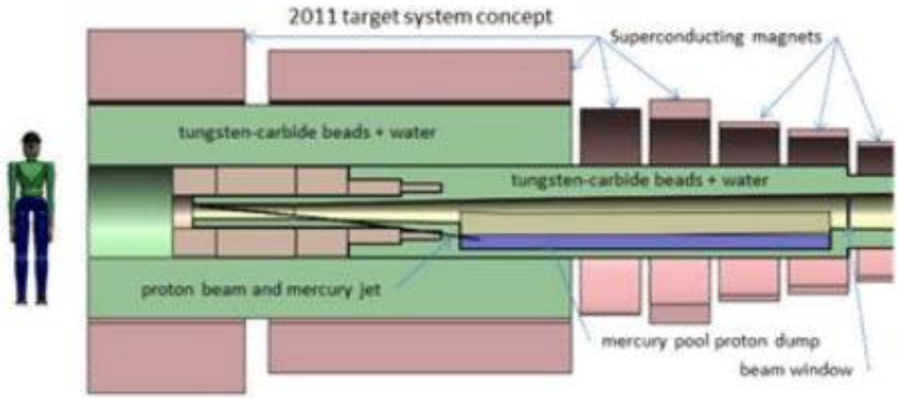
Target & Front End Solenoids

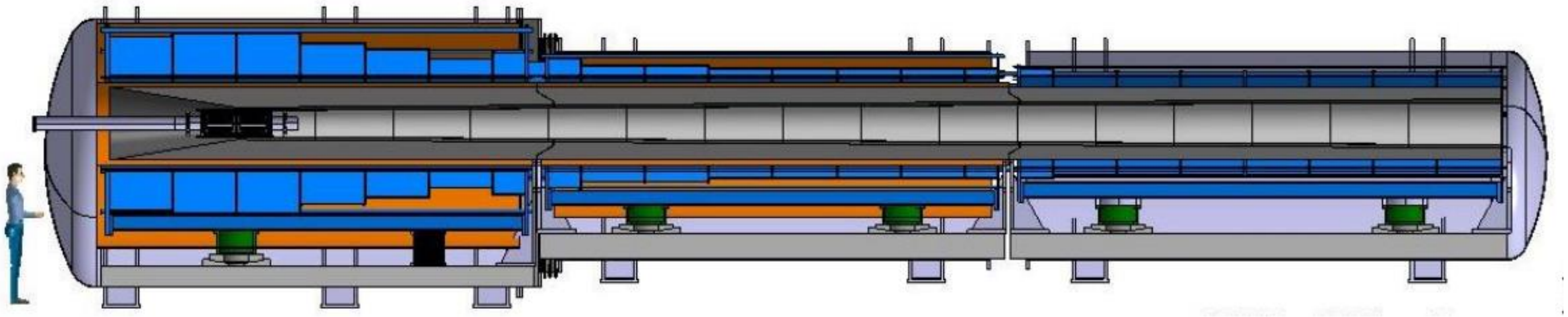


Evolution of MAP design to IMCC design

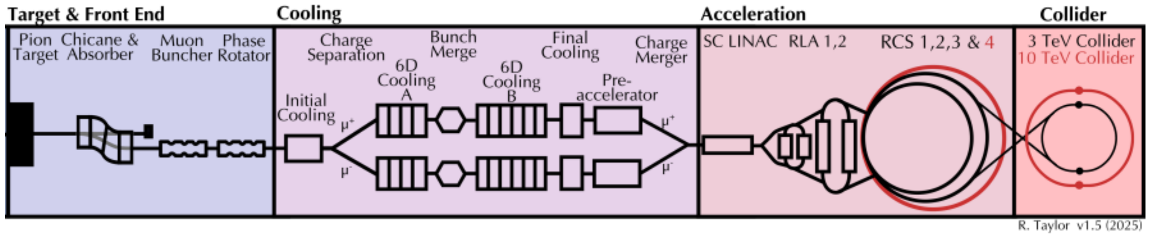
- Resistive hybrid to full HTS
- Increased solenoids spacing for support structure
- Increased bore shielding
- Simplify power supply-all coils at the same current





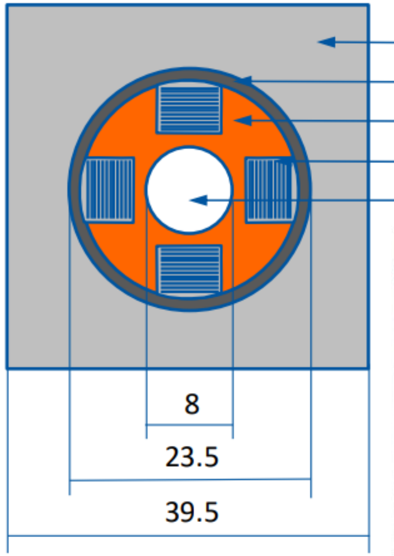


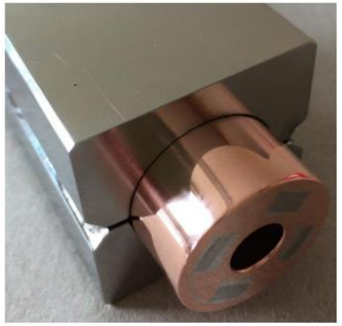
Target & Front End Solenoids

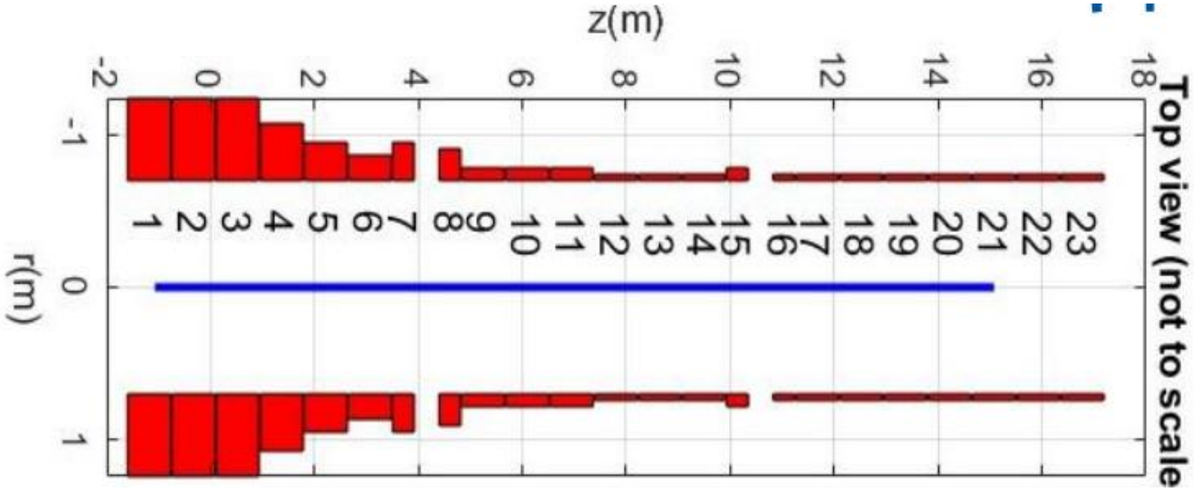


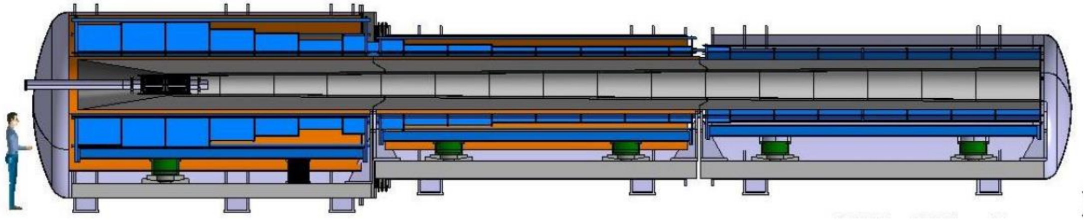
- 23 solenoids tapering from 20 T down to 2 T
- Large 1.38 m bore
- Coil beyond state of the art - R&D needed
- Benefiting from overlap with Fusion

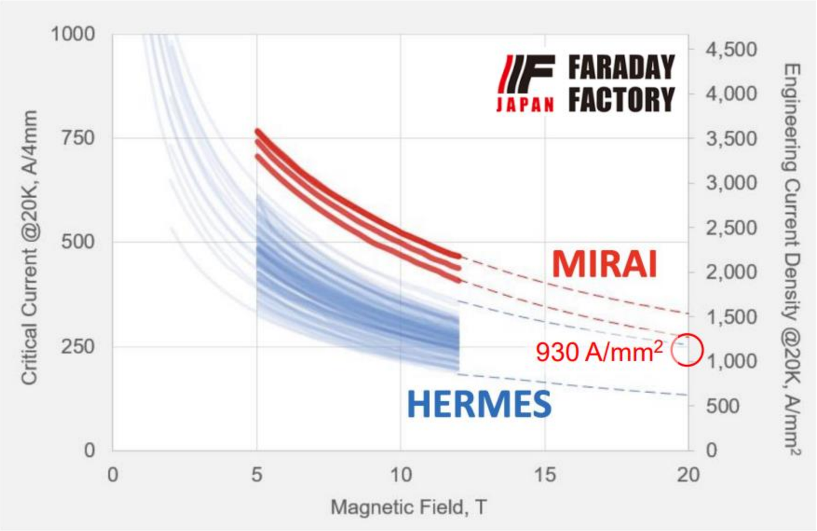
I_{op} = 61 kA
B_{op} = 20 T
T_{op} = 20 K
T_{cs} = 29.7 K
J_e = 930 A/mm^2





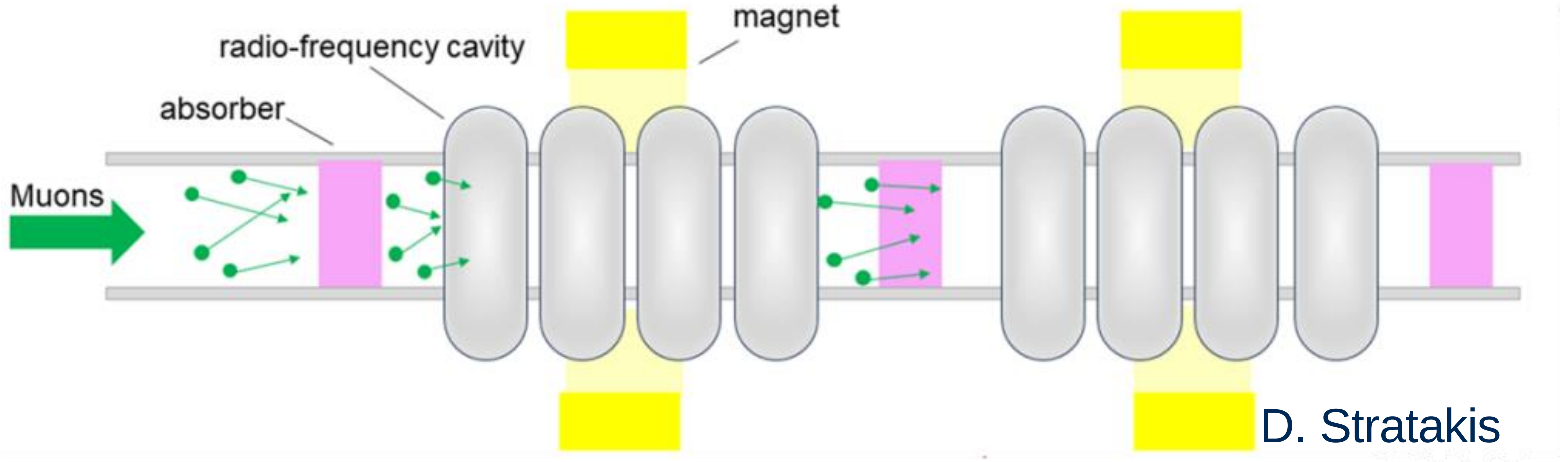


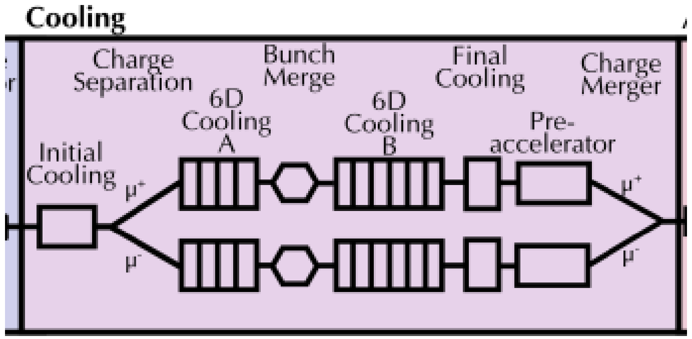


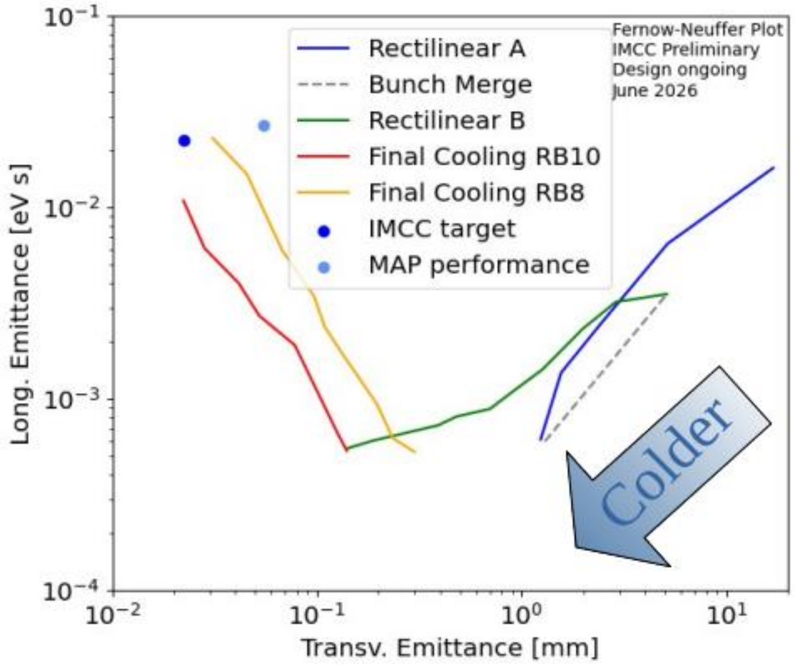


https://indico.cern.ch/event/1431972/contributions/6419983/

Cooling



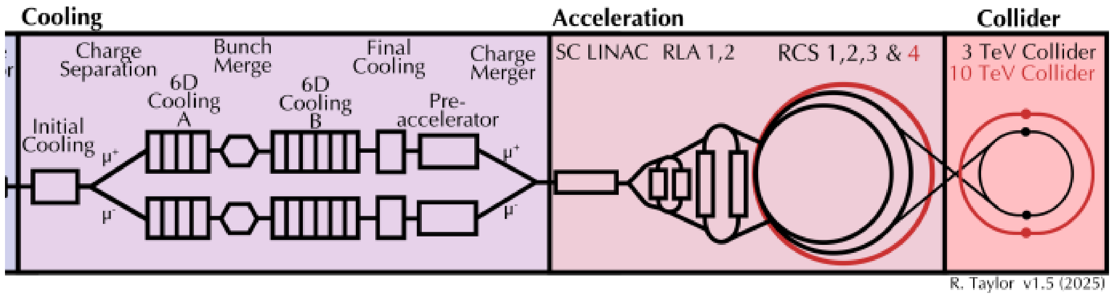


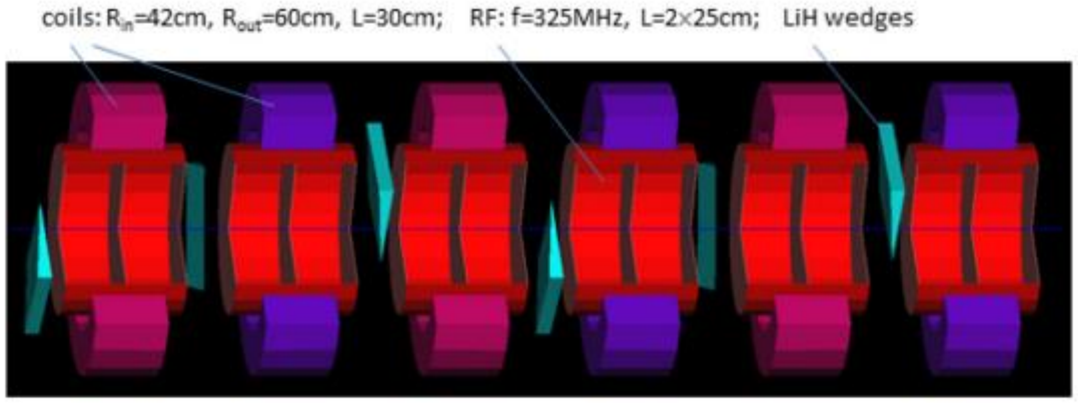


- Magnetic field for focusing and dispersion
- Ionization energy loss in all 3 planes in absorber, larger momentum through thicker material
- Energy restored in longitudinal direction by RF
- 6D emittance needs to be cooled by 6 orders of magnitude!
- Experimentally demonstrated in the MICE experiment and Muon g-2

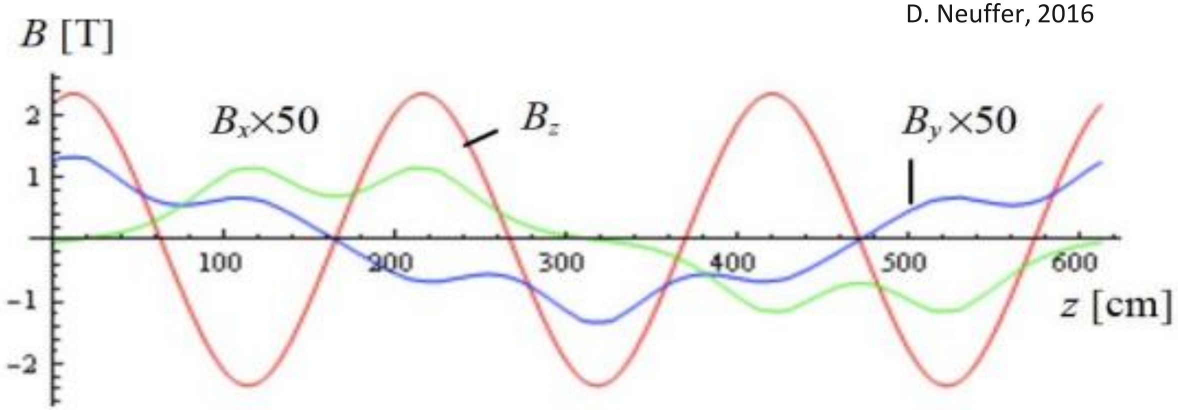
Initial Cooling

- One idea: Helical FOFO (HFOFO)
- Alternating polarity, tilted solenoids (periodic rotations in x and z, pitch and roll) to generate rotating dipole
- ~30 periods with 6 solenoids and RF cavities per period
- Modest magnetic fields, current density <100 A/mm^2 - can be achieved with current technology





D. Neuffer, 2016

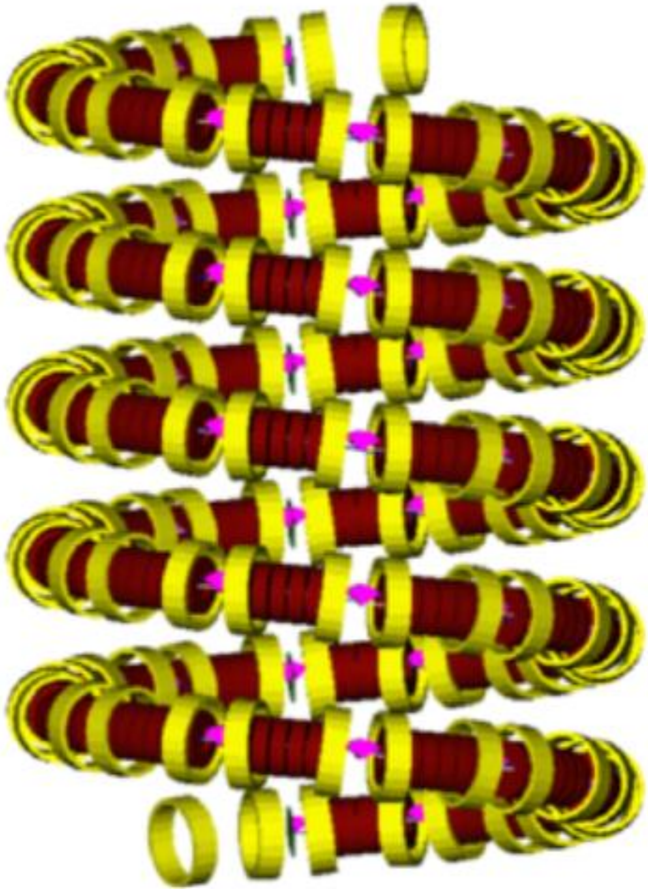


Example of one period

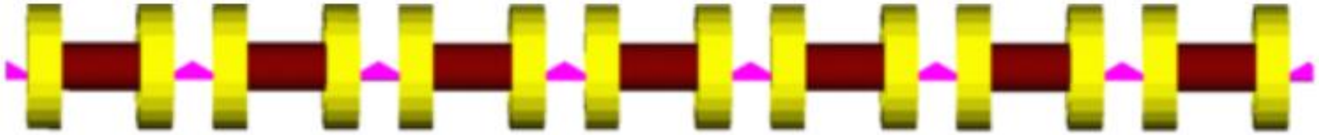
C. Riggall, 2025

6D Cooling Schemes Considered

Ring



Guggenheim helix

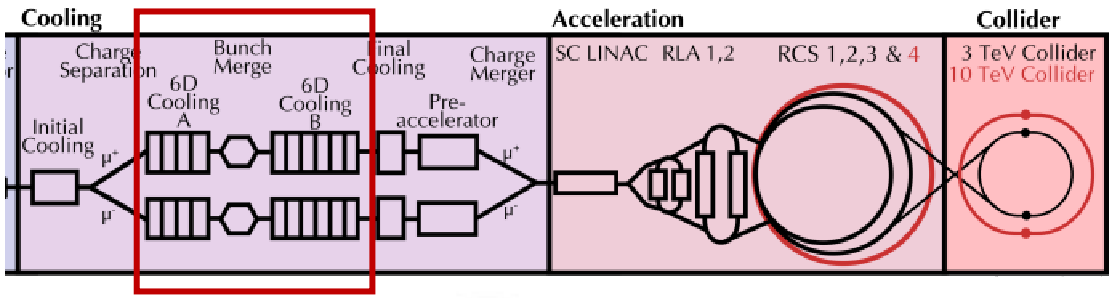


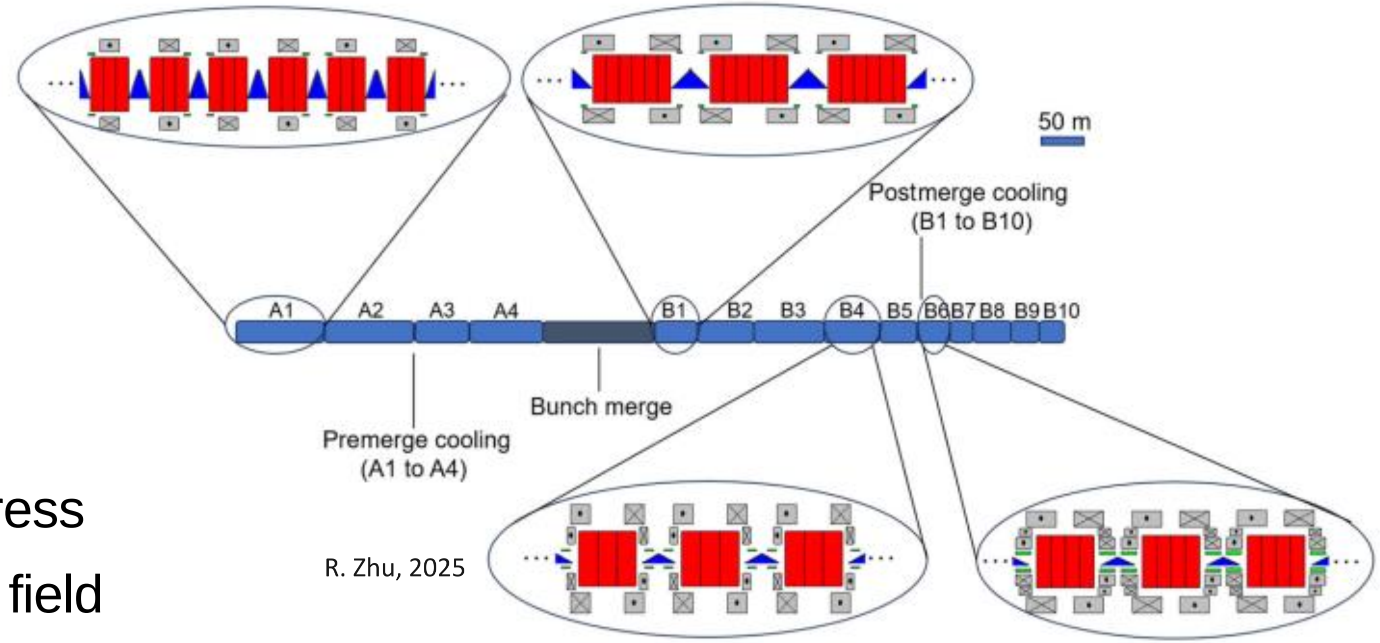
Rectilinear

Helical - Not pictured

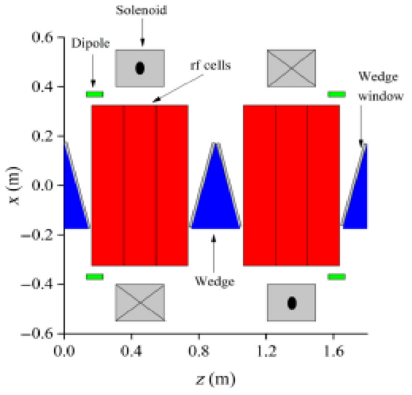
6D Cooling

- Solenoids with superimposed dipole
  - MAP used titled solenoids
  - IMCC solenoids with separate dipoles
- Two lattices: pre-merge (A), post-merge (B)
  - **A** 4 stages
  - **B** 10 stages (IMCC variant with shorter 8 stage)
- Each stage has ~100 cells
- At least three current designs, more in progress
- Large forces (tens of MN) due to alternating field direction and nearby coils

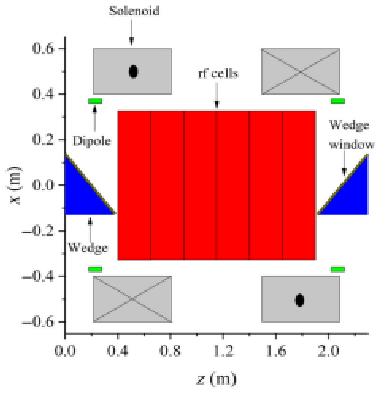




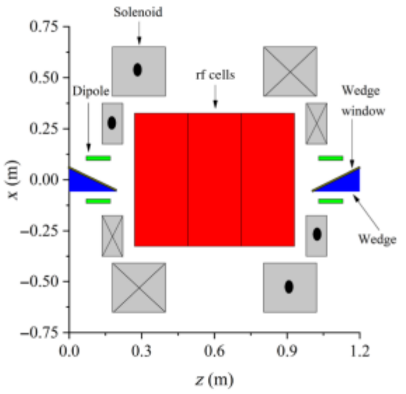
R. Zhu, 2025



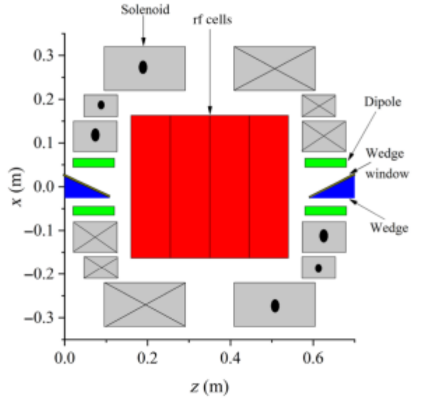
A1 cell



B1 cell



B4 cell



B6 cell

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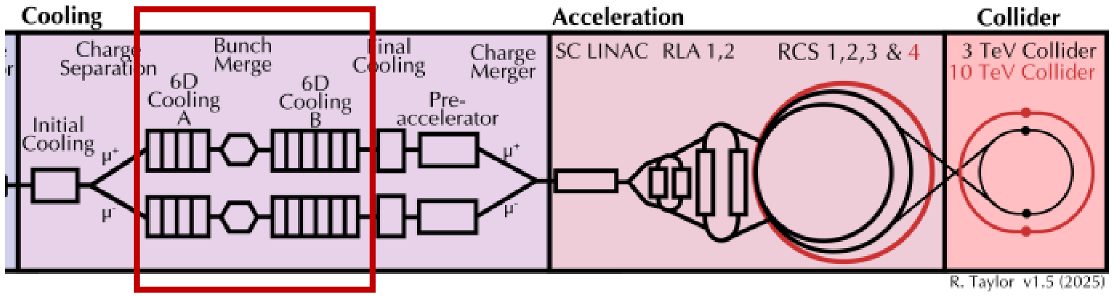
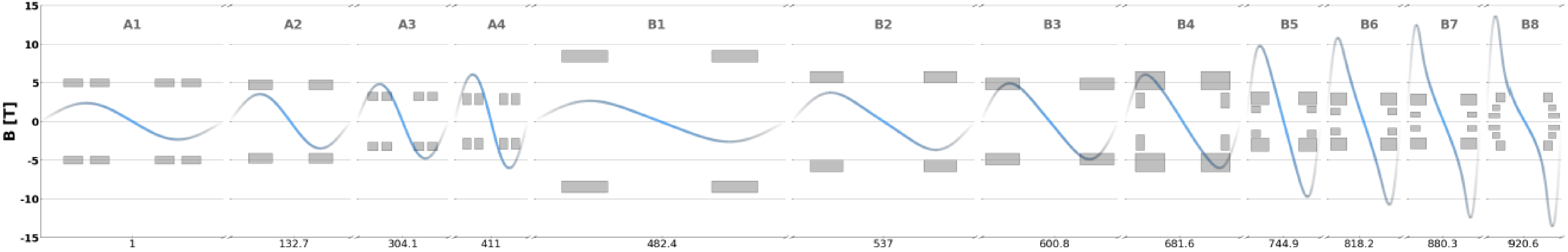
6D Cooling Solenoids

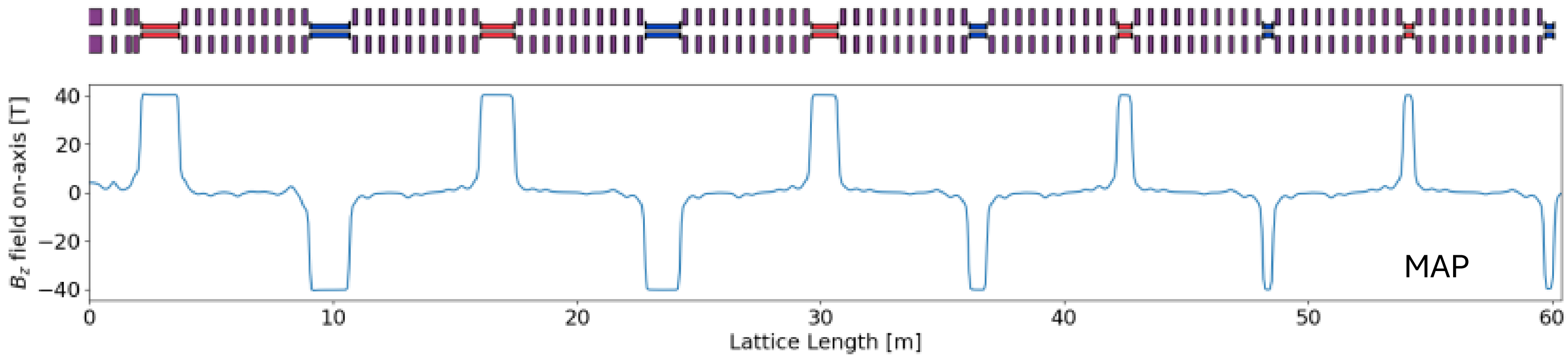


- Fields ~sinusoidal
- Axis field from 2-17 T
- Bore radius 70-600 mm
- Over 25 *unique* solenoids
- Two branches, one for each sign
- One charge branch requires ~3,000 magnets, so a total of ~6,000 solenoids!

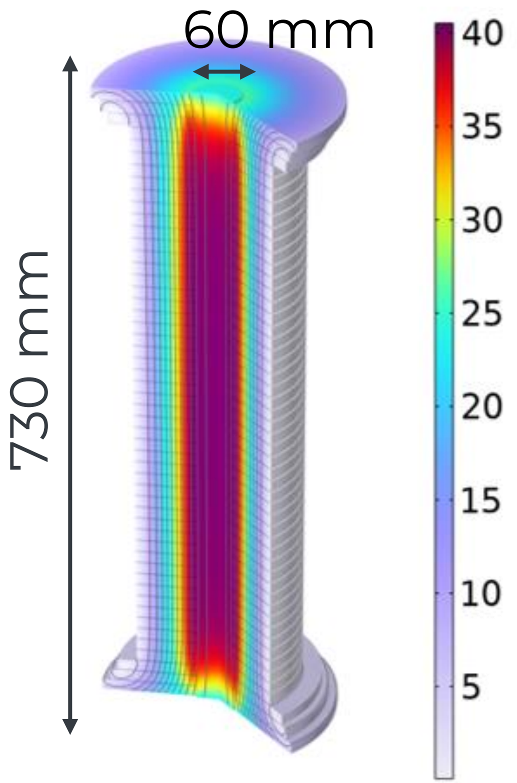


Final Cooling

https://arxiv.org/pdf/2510.27437



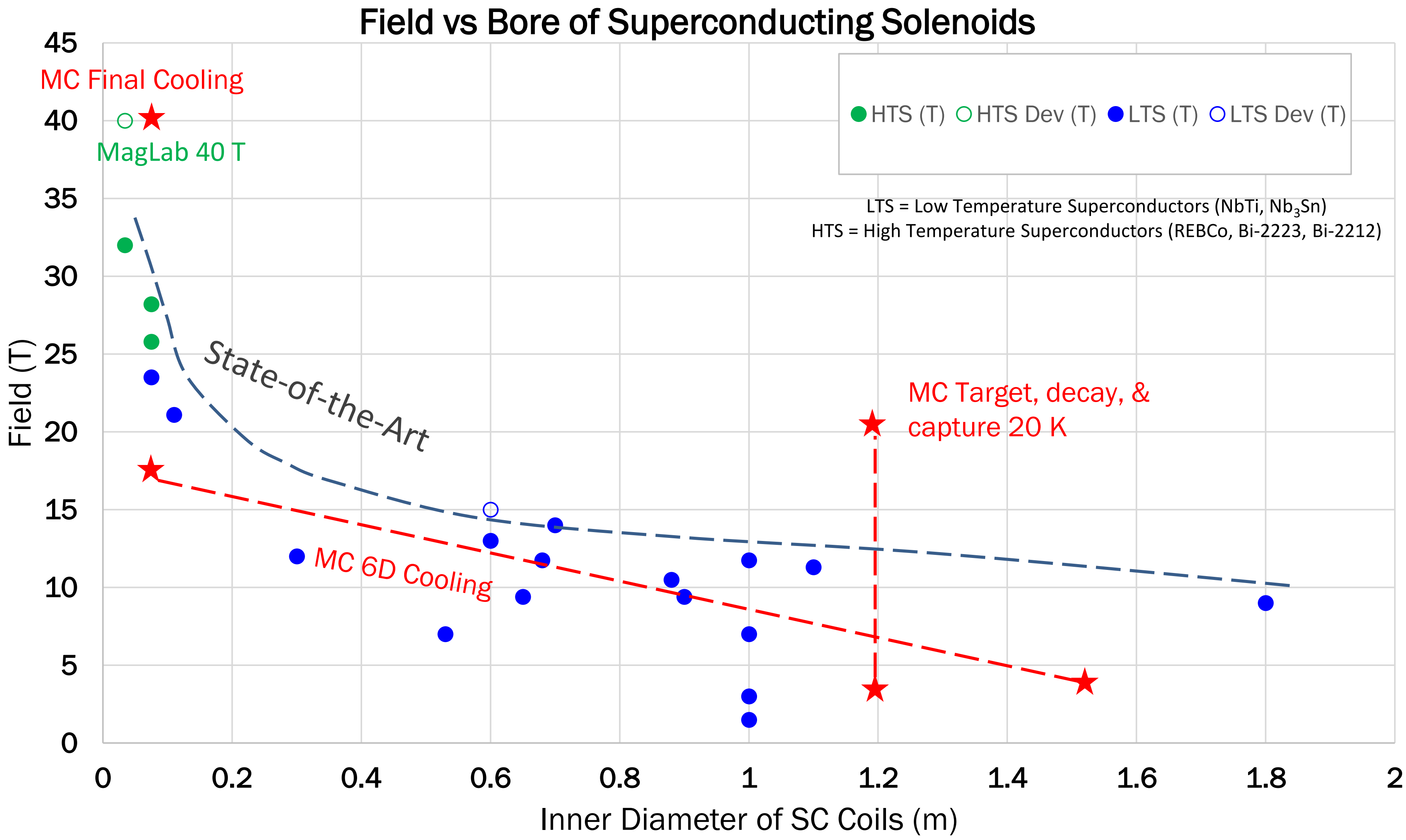
- At least 3 lattice designs at present, depending on 6D cooling choice
  - IMCC- beam after 6D cooling stage 8 and after stage 10
- MAP design 10 alternating high field solenoids separated by 10 lower field solenoids
- Required field up to ~43 T!
- Current density ~632 A/mm^2
- R&D needed on HTS magnets



*B. Bordini *et al.*, "Conceptual Design of a ReBCO Non/Metal-Insulated Ultra-High Field Solenoid for the Muon Collider," in *IEEE Transactions on Applied Superconductivity*, 2024

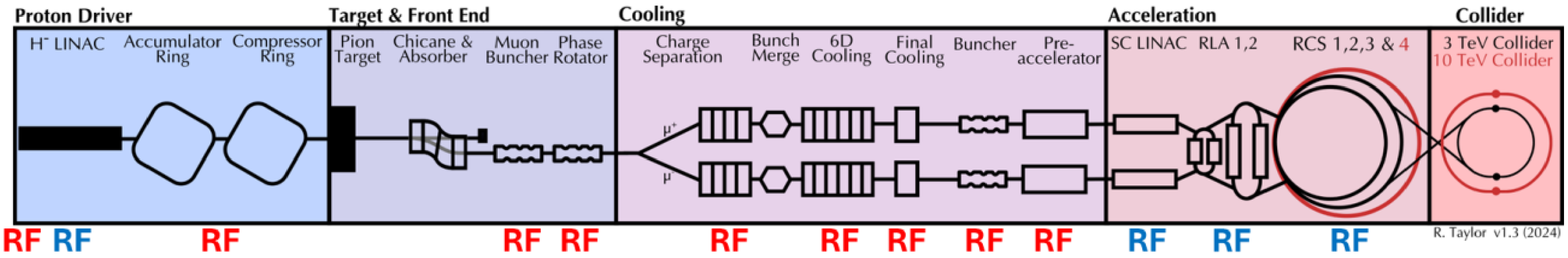
Beyond State-of-the-Art

Complex Unit	Magnet	No.	Aper. [mm]	Length [m]	Field [T]
Target, capture	Solenoid Coils	23	1380	≈ 0.4 – 0.8	2 – 20
6D cooling	Solenoid Coils	≈ 6000	90-1500	0.08 – 0.5	2 – 17
Final cooling	Solenoid Coils	20	50	0.5	>40



Plot from Mark Bird with MuC modifications

RF



NC RF for Proton Driver:

- RFQ and drift tube linac for initial acceleration
- Longitudinal gymnastics in Accumulator and Compressor ring
- Similar to RF in existing high power proton machines – no significant R&D needed

NC RF for Front End and Cooling:

- Large charge and beam size, sub-relativistic
- Tightly packed with SC Solenoid, multi-Tesla B field, large gradient
- ~2,000 cavities per branch
- Major R&D area

SRF for Acceleration

- Large charge, short bunch
- High efficiency at large gradients
- Longitudinal and transverse stability
- Maintain beam quality

Proton driver					
LINAC	RF frequencies	MHz	352	704	
Muon cooling complex					
	RF frequencies	MHz	352	704	1056
6D Cooling Channels	Max accelerating field (conservative)	MV/m	22	30	30
	Max accelerating field (optimistic)	MV/m	35	50	50
Acceleration complex					
	RF frequencies	MHz	352	704	1056
LINAC	Max accelerating field (conservative)	MV/m	20	25	30
	Max accelerating field (optimistic)	MV/m	30	38	45
	RF frequency	MHz		704	1056, 1300
RCS	Max accelerating field (conservative)	MV/m		25	30
	Max accelerating field (optimistic)	MV/m		38	45

MuCol Consolidated Parameters Report

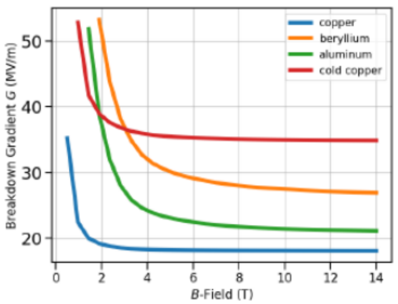
NC RF Challenges and R&D

- In the cooling channel: high peak power (~MW), short pulse length, low rep rate (~Hz), tightly packed with SC solenoids and absorbers
- Frequency 200 MHz to 800 MHz, High gradient 20-30 MV/m
- Good vacuum and surface cleaning, Cu cavities can reach gradients for cooling, 325 MHz (36 MV/m) and
- Ne
- SL
- Inv
  - Cooling Cu
  - Copper alloy
  - Shorter pulse length
- Gas filled cavity?

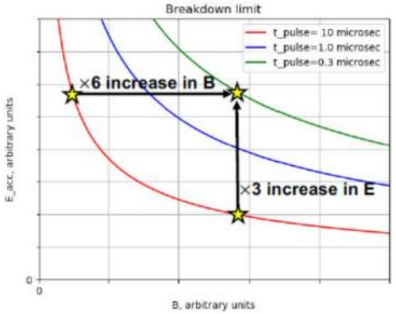
Thursday Plenary:

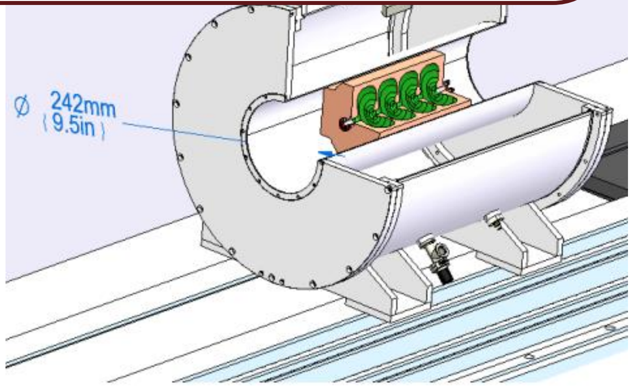
Recent R&D on RF systems for muon collider ionization cooling complex	*Alexej Grudiev*
Ballroom, Luskin Conference Center	09:45 - 10:15

Cold copper



Shorter pulse length





D. Merenich et al, NAPAC2025

S. Arsenyev et al. 2021

69. Analysis of the short-range longitudinal wakefields in accelerating cavities for the muon collider ionization cooling channel

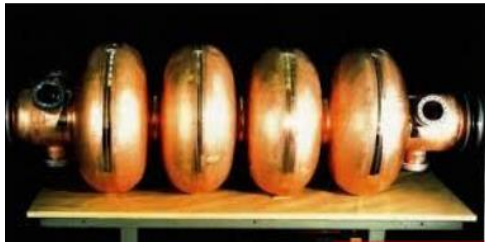
Dillon Merenich (Northern Illinois University)

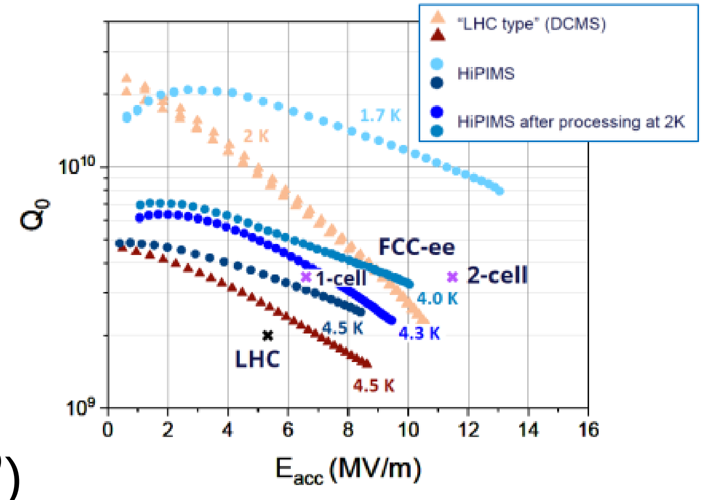
SRF Challenges and R&D

- Large **bunch intensity** (2.7×10^{12} muons in RCS chain) may require larger aperture, lower frequency
- Non-uniform beam loading in RCS chain
- **High-gradient** multi cell lower frequency cavities must be demonstrated
- Need to develop magnetic shielding or alternative materials for **stray fields**
- Use of Nb/Cu for lower frequency cavities requires significant R&D
- Effect of high-intensity muon decay **radiation** needs to be studied
- High peak RF power per cavity (RLA) requires power coupler R&D

SRF Technology

352 MHz LEP2 cavity (Nb/Cu)





400 MHz Nb/Cu results (2023)

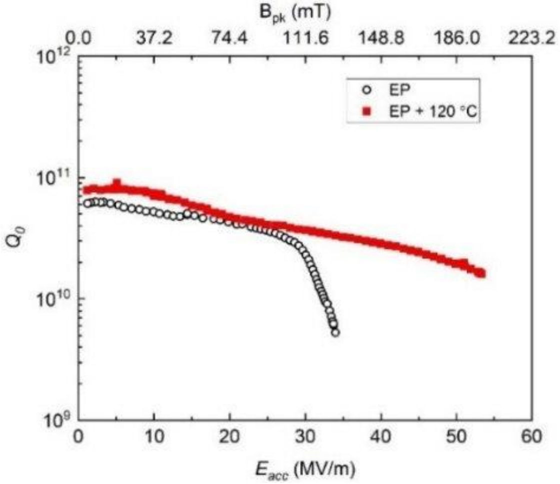
Nb/Cu

- Cu coated with Nb to reduce cost
- Large scale use in LEP2, but still need ~x2 gradient for MuC
- R&D at CERN for FCC-ee (2 cell, 400 MHz,10.6 MV/m, $Q_0 = 2.7 \times 10^9$)

1300 MHz TESLA cavity

Nb

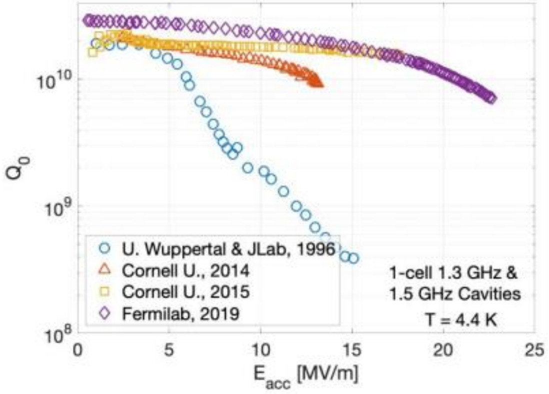
- 1300 MHz developed for future ILC, similar parameters to MuC
- European XFEL using this technology, gradients exceeding 26 MV/m
- Sensitive to magnetic field



53.3 Mv/m 650 MHz at Fermilab

Nb_3Sn/Nb

- Less sensitive to trapped magnetic flux
- Progress, but gradient still low and material is brittle
- More R&D needed



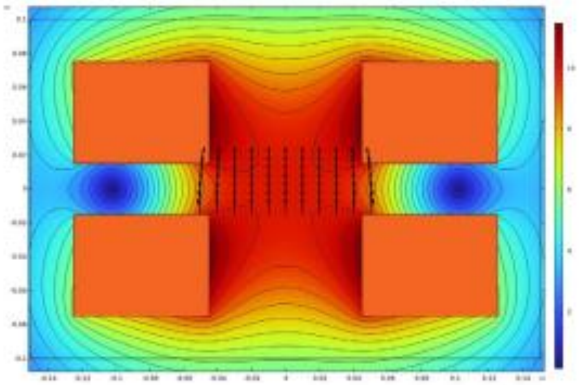
Acceleration

Low Energy (250 MeV to 62.5 GeV)

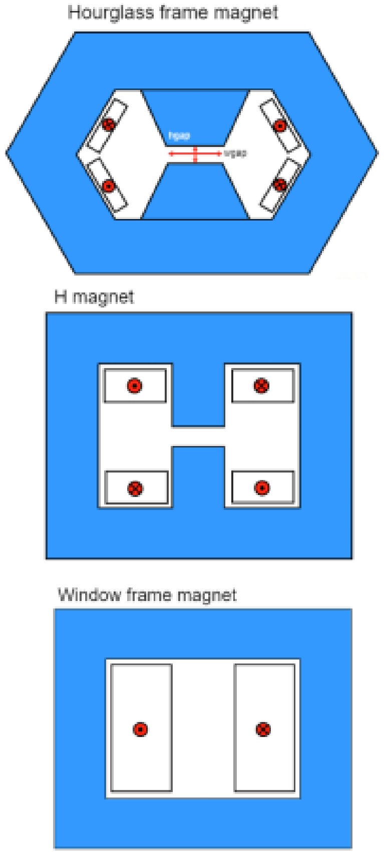
- Superconducting LINAC and two recirculating linear accelerators (RLA)
- Preliminary optics for the RLA2, but no optics design yet for LINAC or RLA1

High Energy (up to 5 TeV)

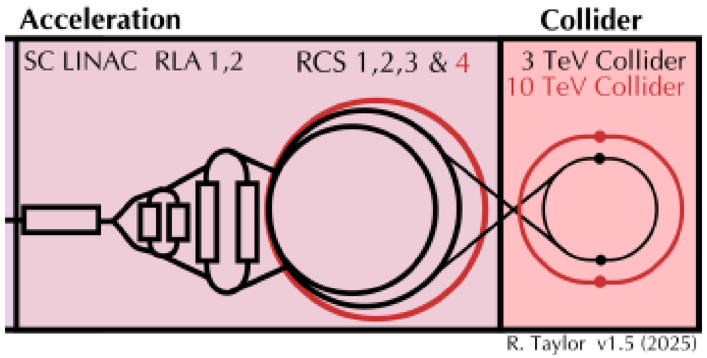
- 4 rapid cycling synchrotrons (RCS)
- Further optimization of lattice needed
- High gradient SRF cavities 650-1300 MHz
- Fast ramping (4000 T/s) NC magnets
  - 10s of GW in resistive dipoles
- 10-16 T DC SC magnet

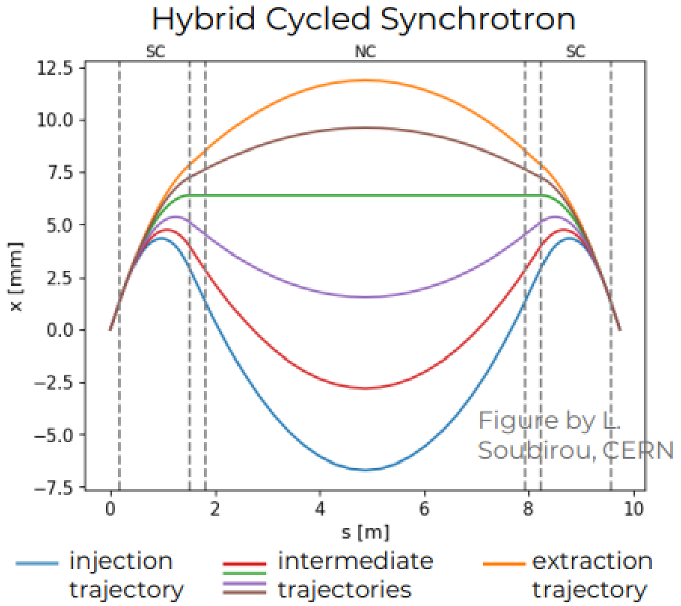


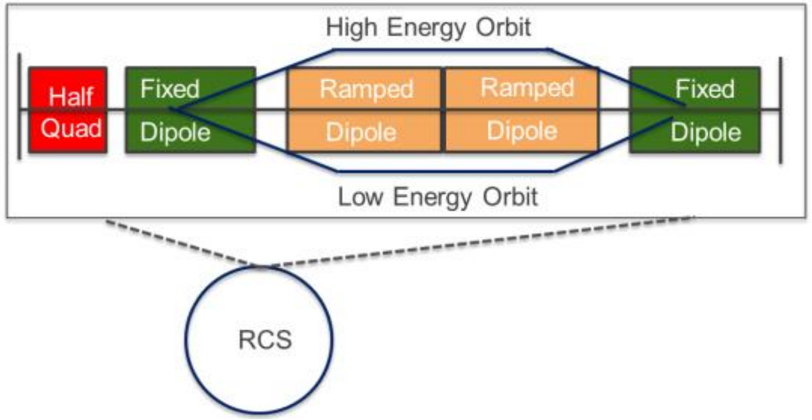
SC Dipole Optimization M. Breschi, F. Boattini



NC Dipole Optimization
M. Breschi, F. Boattini

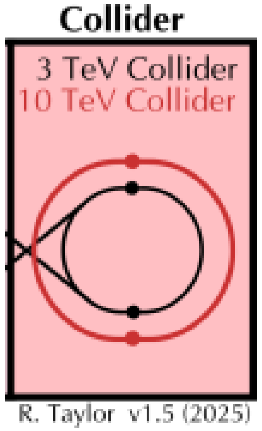


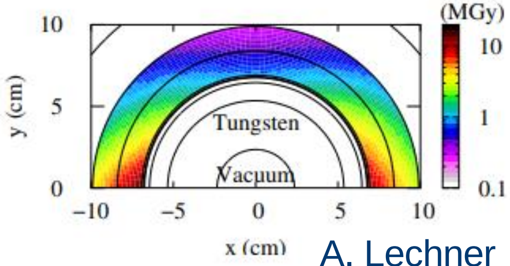




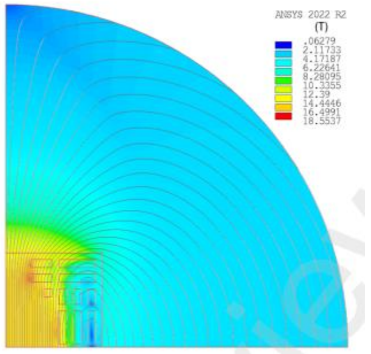
Collider Ring

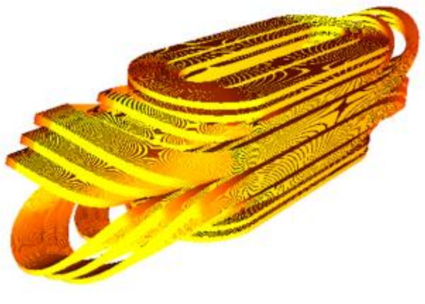
- Would like the smallest possible circumference to maximize collisions in muon lifetime
- Arc magnets and interaction region (IR) dipoles and quads must have high field and large aperture to accommodate shielding
  - heat load of 500 W/m (muon decay and synchrotron radiation) reduced by shielding to below 5 W/m
  - Requires 30-40 mm tungsten
- Minimize straight sections with combined function magnets to reduce collimated neutron beam
- Main dipoles up to 16 T, 140 mm bore
- Arc combined function
  - Dipole/Sext 14T, 7100 T/m^2, 100 mm bore
  - Dipole/quad 8T, 320 T/m, 100 mm bore
- Lattice design and magnet requirements still being updated
  - Design in place for 3 TeV, 10 TeV more challenging β(5→1.5 mm)
  - HTS magnet development needed





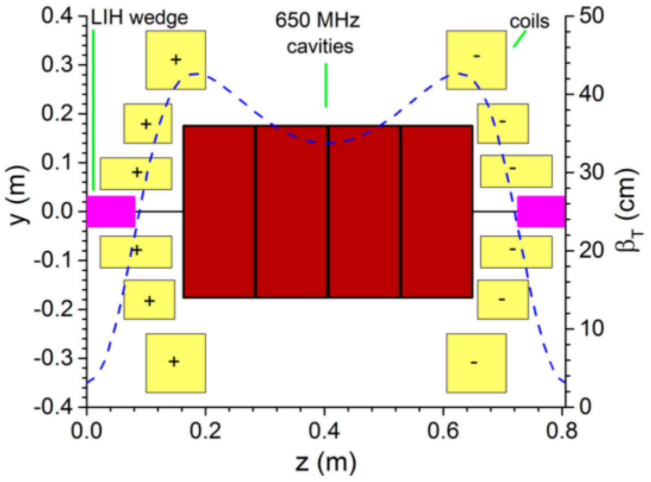
A. Lechner





16 T ReBCO block dipole
L. Alfonso, et al 2026

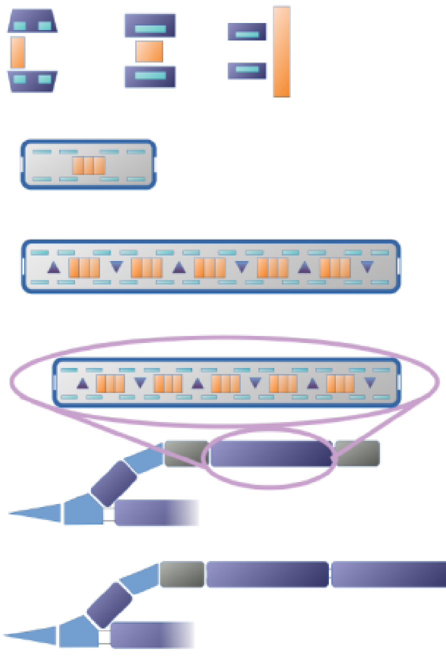
Muon Cooling Demonstrator



- Would like to demonstrate operation of integrated components
  - RF cavities capable of operating in multi-T background fields
  - Solenoids capable of operating in high background field and withstand forces/stresses
  - Realistic cooling cell (Late stage cells in the cooling channel much more challenging)
  - Measurement and characterization tools/simulations
  - Power, cooling,….
- IMCC has laid out a staged approach
  - Potential locations CERN- TT7 facility, CTF3
- IMCC Demonstrator Workshop SLAC Dec 2026
  - Fermilab 2024, INFN Milan 2025
- Studies for having a demonstrator in the US ongoing
  - Poster on Monday:

157. Beam dynamics simulations of a potential muon ionization cooling demonstrator at Fermilab

Tom Harless (Northern Illinois University)



RF Test stands, to develop novel RF and magnet technologies

One-cell module to test RF in operational magnetic environment

Multi-cell module to demonstrate integration of absorber, RF and magnets

Demonstration of cooling module to show operation with beam

Demonstration of cooling to demonstrate beam physics performance

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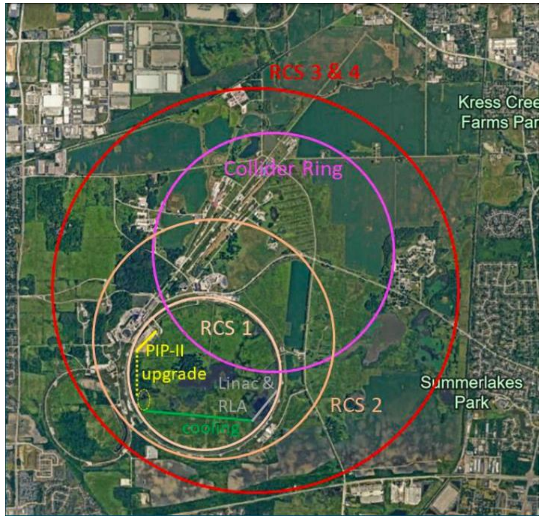
Looking Forward

Recent comments from DOE:

- We will not be able to support vigorous R&D toward a cost-effective 10 TeV pCM
- We plan to reduce funding to the General Accelerator R&D (GARD) program
- Limited R&D funding for the next 5 years to enable new projects
- Unlikely to initiate any new major construction projects for the next 6-7 years

All is not lost

- Large community momentum
- Several significant technology challenges = R&D opportunities
- Look for funding overlap with other areas
  - Fusion, FCC-ee, neutrino facilities …



Fermilab

FermiFORWARD

U.S. DEPARTMENT of ENERGY

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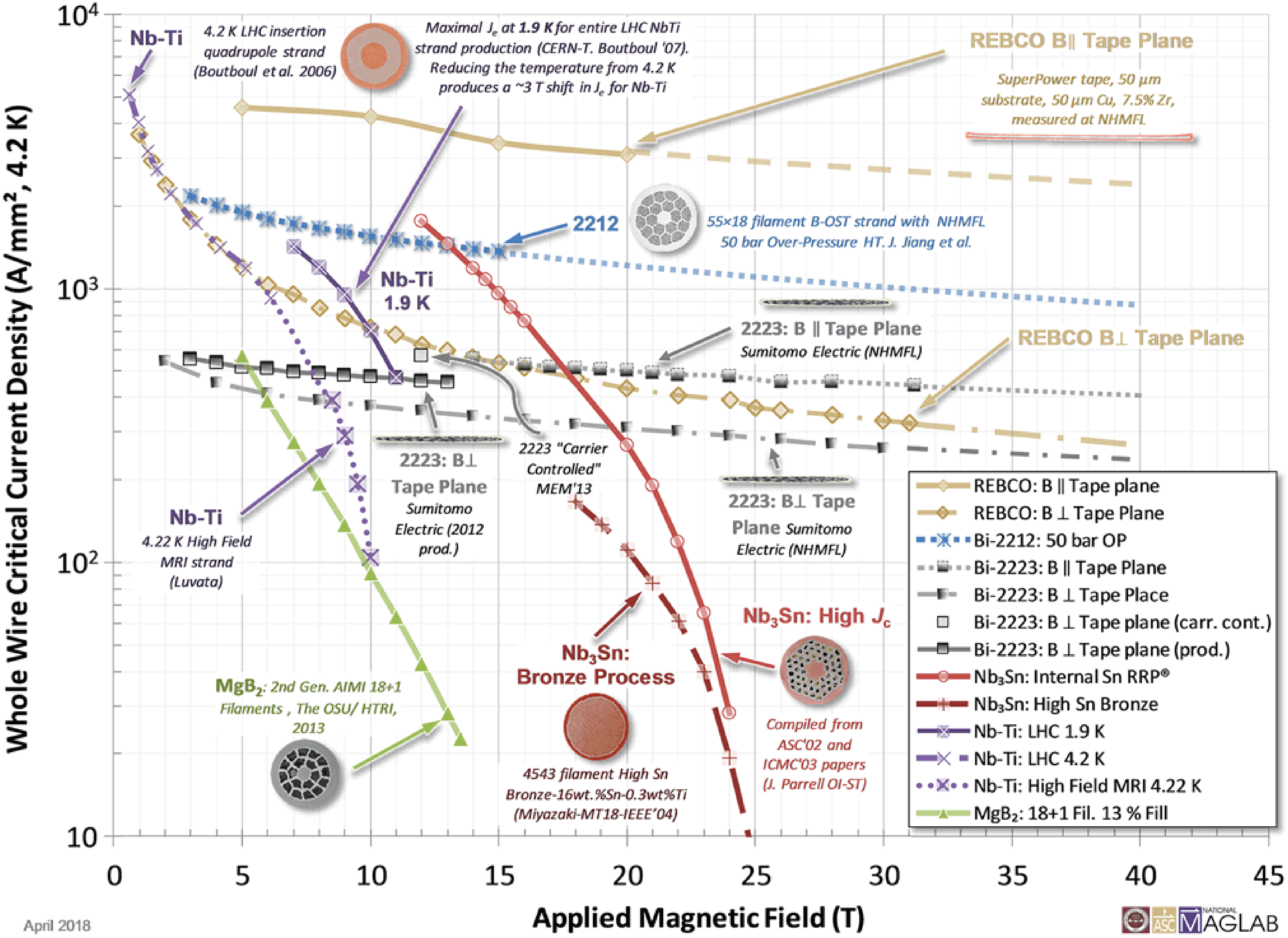
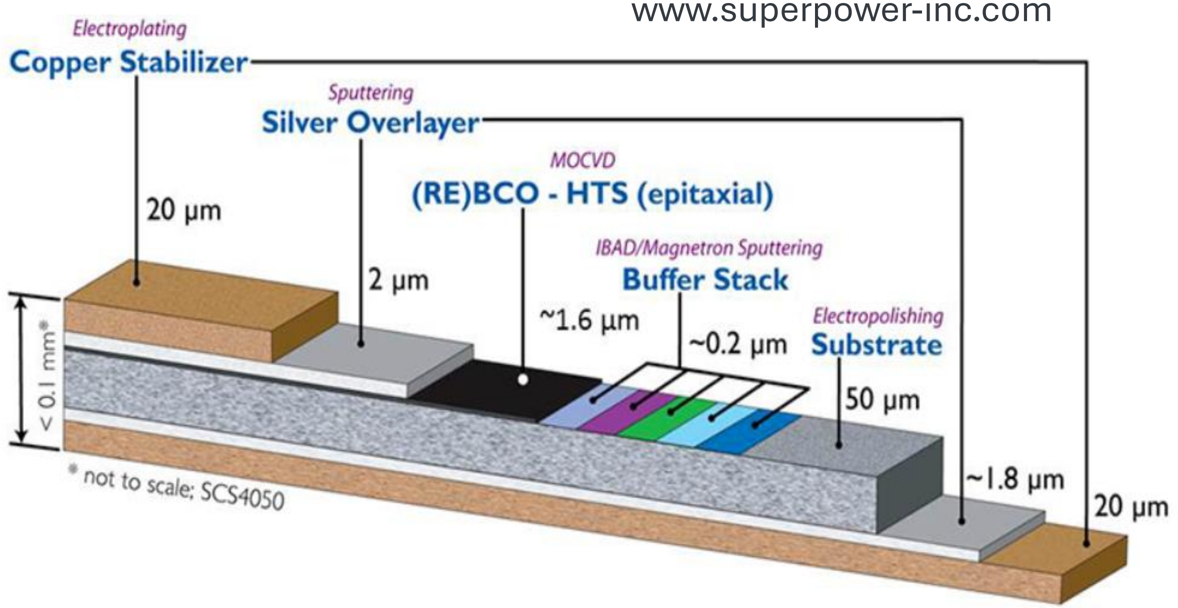


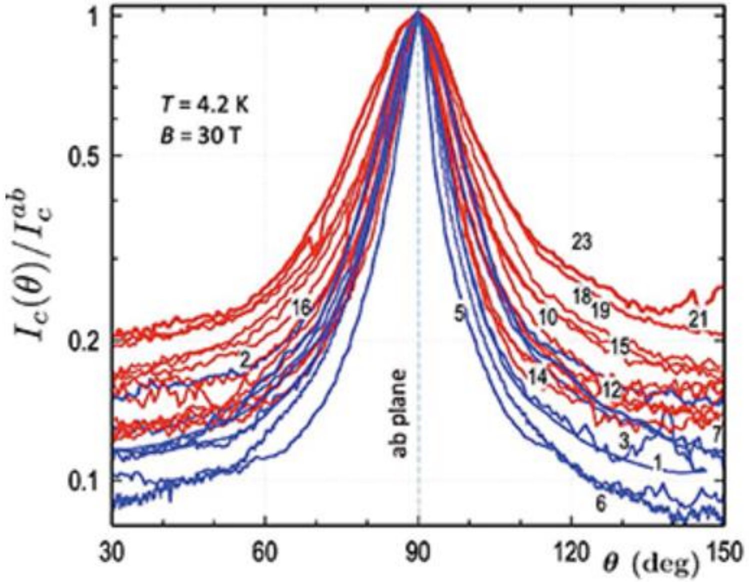
Whole Wire Critical Current Density (A/mm², 4.2 K)
Applied Magnetic Field (T)
Nb-Ti
4.2 K LHC insertion quadrupole strand (Boutboul et al. 2006)
Maximal J_e at 1.9 K for entire LHC NbTi strand production (CERN-T. Boutboul '07). Reducing the temperature from 4.2 K produces a ~3 T shift in J_e for Nb-Ti
REBCO B∥ Tape Plane
SuperPower tape, 50 μm substrate, 50 μm Cu, 7.5% Zr, measured at NHMFL
2212
55×18 filament B-OST strand with NHMFL 50 bar Over-Pressure HT. J. Jiang et al.
Nb-Ti 1.9 K
2223: B ∥ Tape Plane Sumitomo Electric (NHMFL)
REBCO B⊥ Tape Plane
2223: B⊥ Tape Plane Sumitomo Electric (2012 prod.)
2223 "Carrier Controlled" MEM'13
2223: B⊥ Tape Plane Sumitomo Electric (NHMFL)
Nb-Ti 4.22 K High Field MRI strand (Luvata)
Nb_3Sn: High J_c
Nb_3Sn: Bronze Process
MgB_2: 2nd Gen. AIMI 18+1 Filaments , The OSU/ HTRI, 2013
4543 filament High Sn Bronze-16wt.%Sn-0.3wt%Ti (Miyazaki-MT18-IEEE'04)
Compiled from ASC'02 and ICMC'03 papers (J. Parrell OI-ST)
REBCO: B ∥ Tape plane
REBCO: B ⊥ Tape Plane
Bi-2212: 50 bar OP
Bi-2223: B ∥ Tape Plane
Bi-2223: B ⊥ Tape Place
Bi-2223: B ⊥ Tape plane (carr. cont.)
Bi-2223: B ⊥ Tape plane (prod.)
Nb_3Sn: Internal Sn RRP®
Nb_3Sn: High Sn Bronze
Nb-Ti: LHC 1.9 K
Nb-Ti: LHC 4.2 K
Nb-Ti: High Field MRI 4.22 K
MgB_2: 18+1 Fil. 13 % Fill
NATIONAL MAGLAB

REBCO-Structure

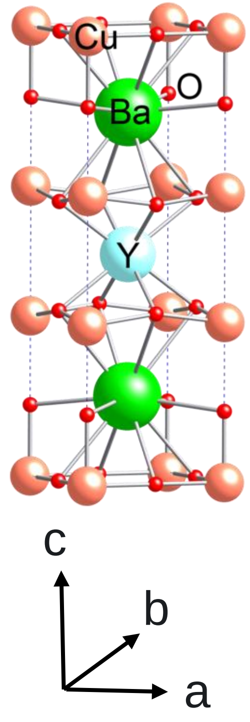
- Rare-earth Barium Copper Oxide
  - yttrium, lanthanum, samarium, neodymium, gadolinium and europium
- Fabrication
  - Physical vapor deposition- pulsed laser, sputtering, molecular beam epitaxy,…
  - Chemical vapor deposition- Metal-organic chemical vapor deposition, plasma enhanced
  - Atomic layer deposition
- a-b plane of crystal structure ~ along plane of tape
- Critical current density is highly anisotropic, depends on B field orientation to crystal structure
  - Design winding to minimize perpendicular field?

www.superpower-inc.com



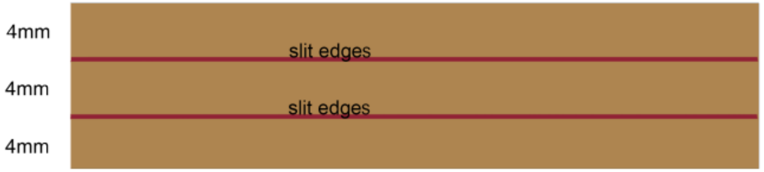


J Jaroszynski *et al* 2022 *Supercond. Sci. Technol.* **35** 095009

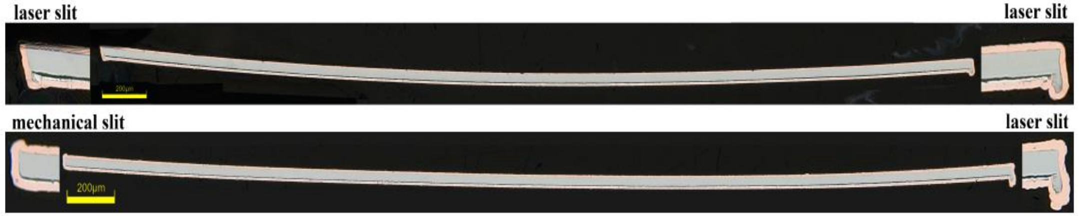


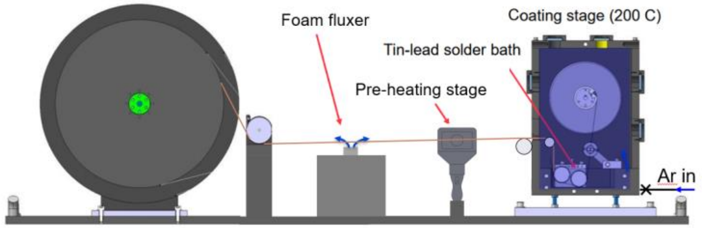
REBCO- Fabrication and Winding

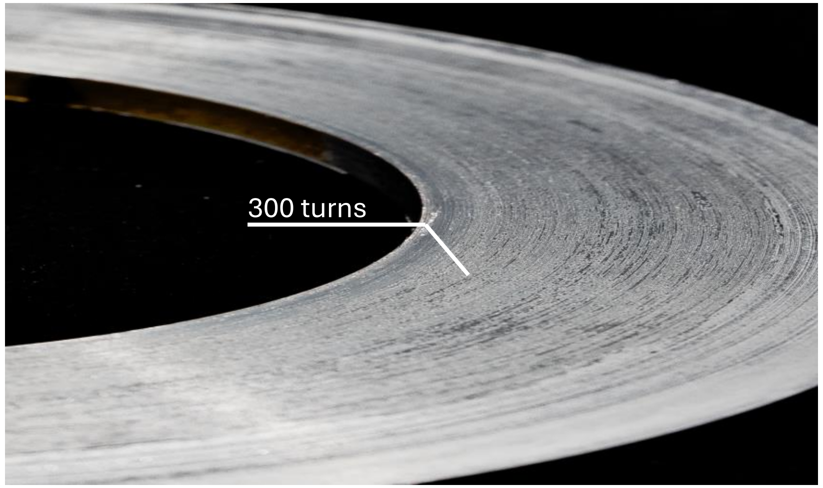
- Formed as wide tape and mechanically or laser slit to desired width, leads to non-uniformity in thickness at the edges
- Non-uniform thickness creates voids in winding, voids lead to kinks and non-uniform turn-to-turn resistance



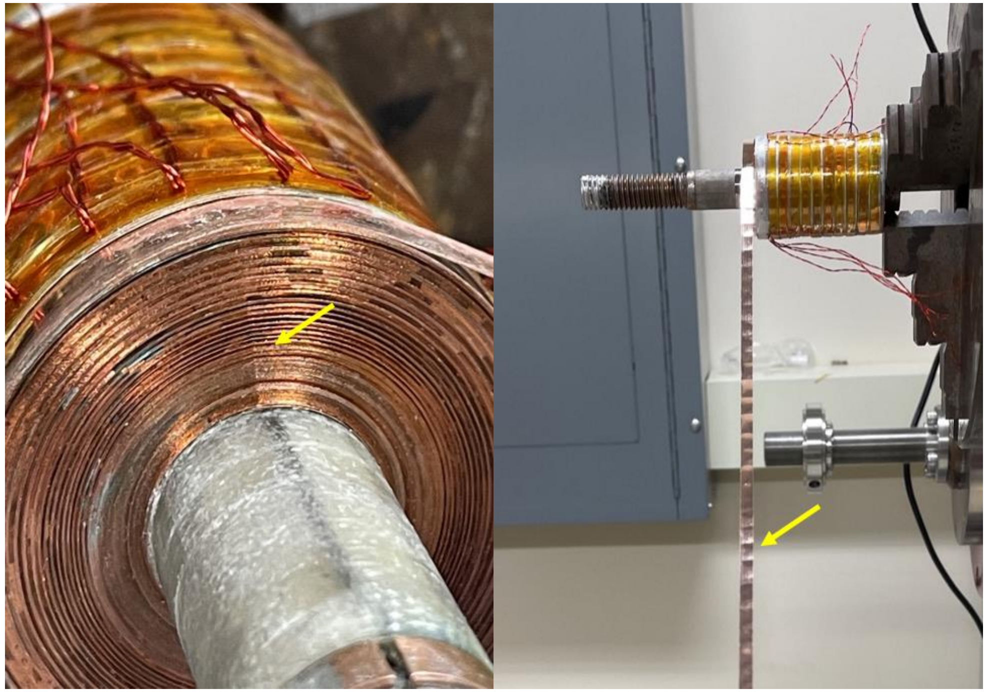
M. Small 2021







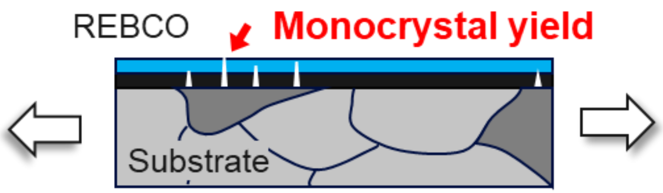
R. Unterrainer 2025

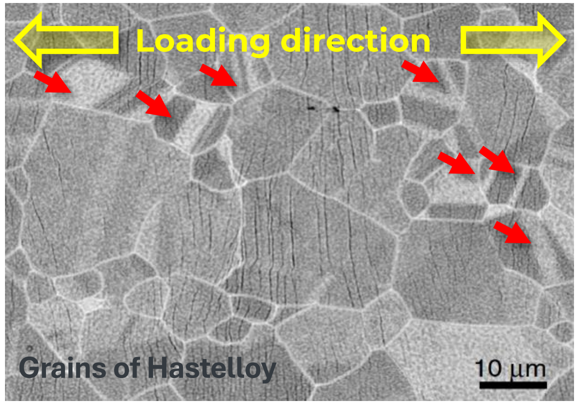


J. Bang 2025 Little Big Coil

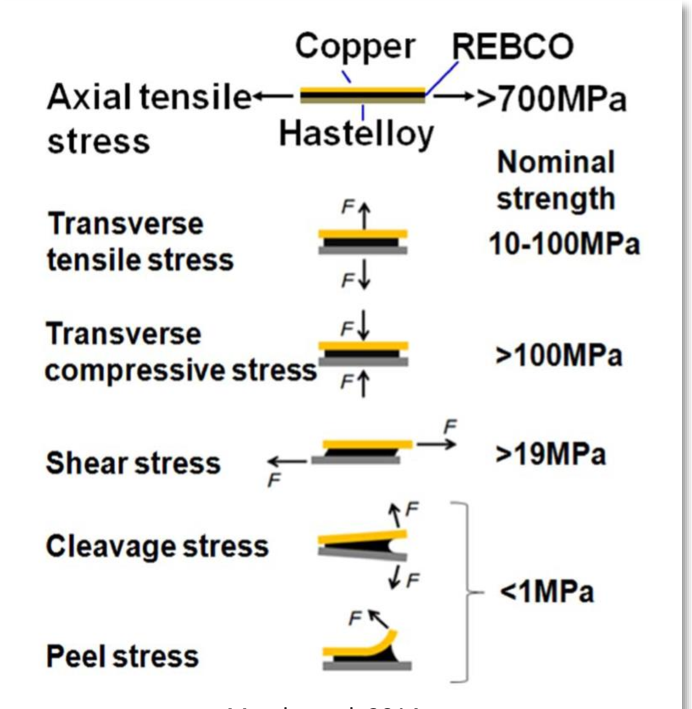
REBCO-Mechanical Limits

- Longitudinal driven by plastic deformation of substrate causing cracking in REBCO





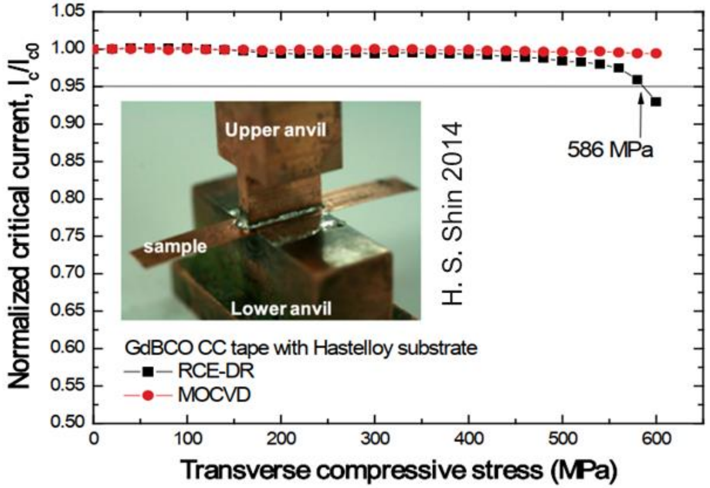
M. Sugano et al 2005 Supercond. Sci. Technol. 18 S344

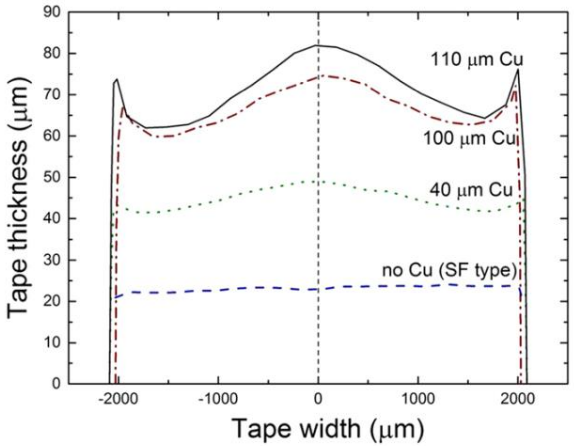


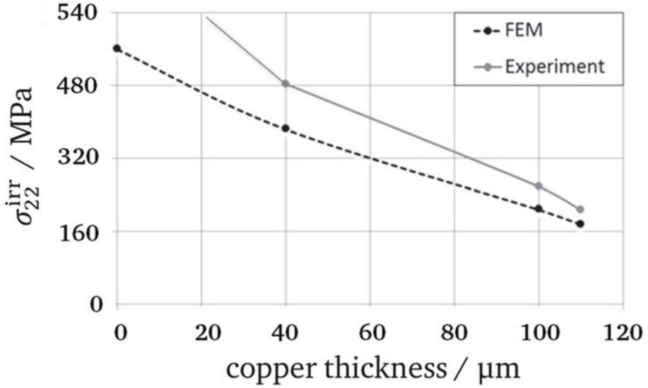
Maeda et al. 2014

Limits bend radius

- Transverse compression driven by stress concentration







Several images taken from G. Vernassa's talk *Performance Limitations of UHF REBCO Solenoids*

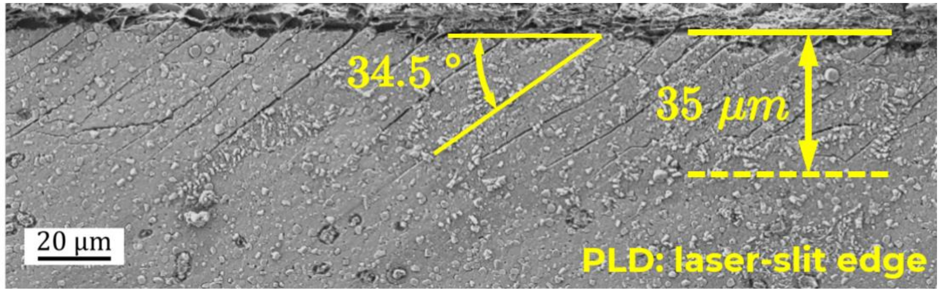
REBCO-Mechanical Limits

- Layered structure vulnerable to delamination
- Delamination driven by local defects
  - Cracks, delamination nucleation sites, inclusions…
- Need non-destructive method of characterizing tapes

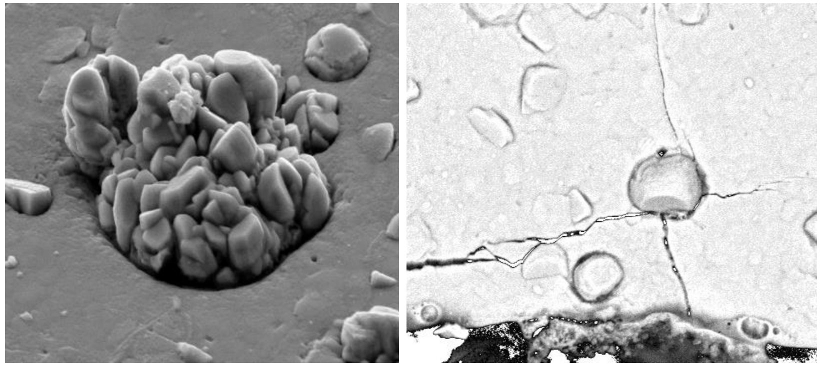
Transverse tension		2 - 170 MPa
Shear stress		10 – 12 MPa
Bending-peel		4 – 30 MPa
Peel		0.5 – 6 N
Cleavage		0.4 MPa

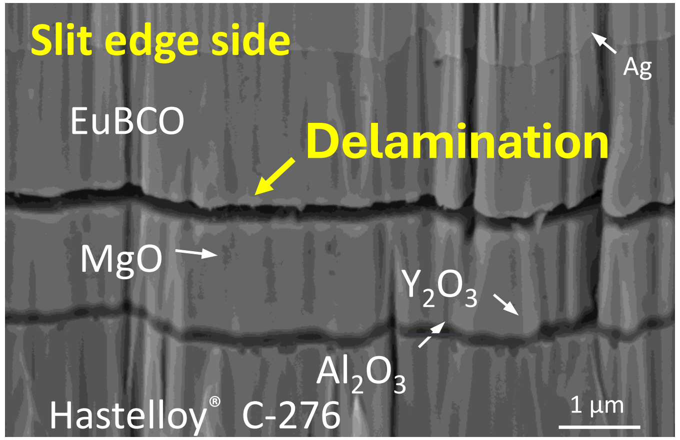
Adapted from P. Gao et al., Supercond. 2023

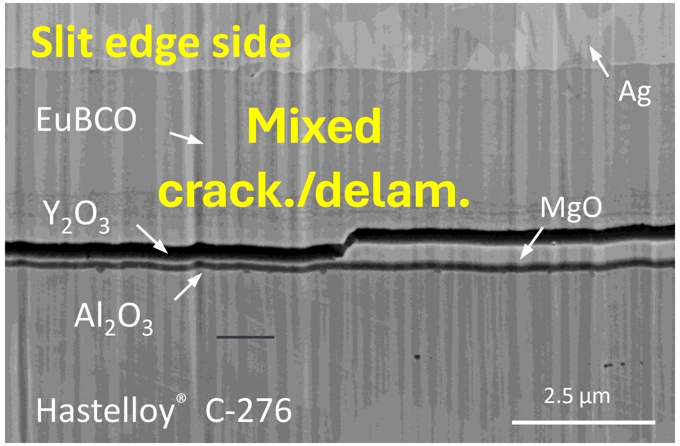
Cracks at slit edges



Stress concentration at crystallites

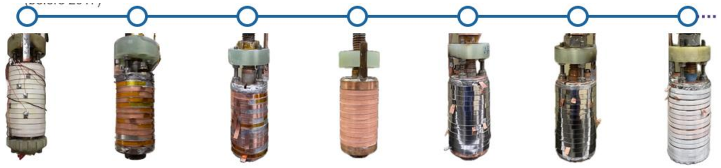




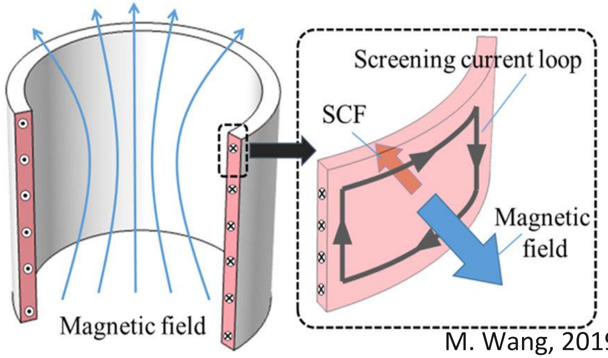


Several images taken from G. Vernassa's talk *Performance Limitations of UHF REBCO Solenoids*

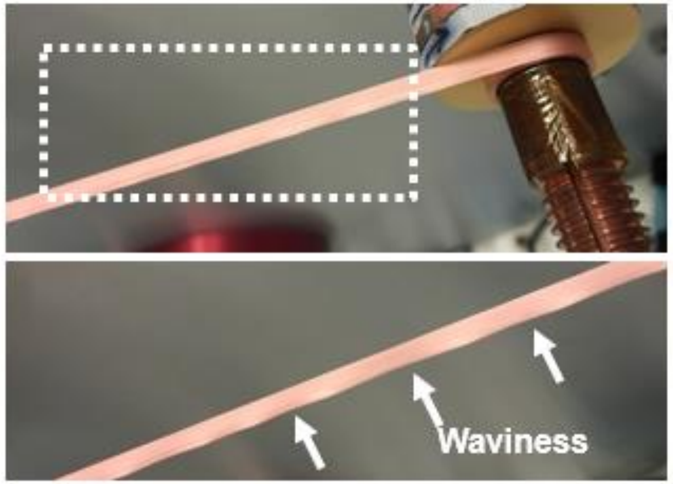
Screening Currents – Little Big Coil Program

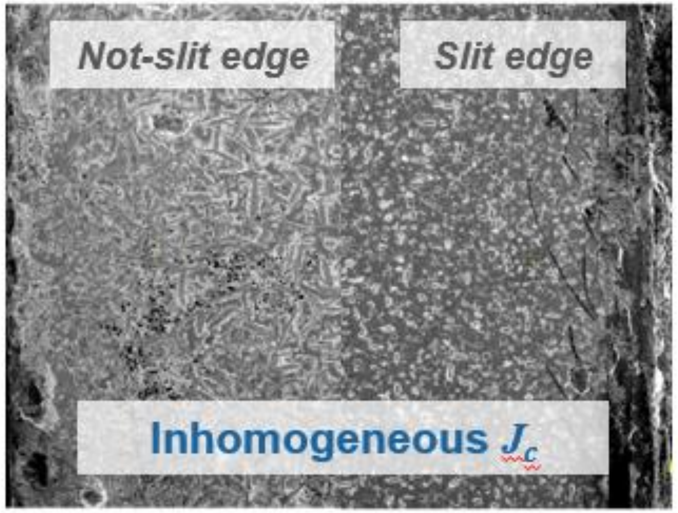


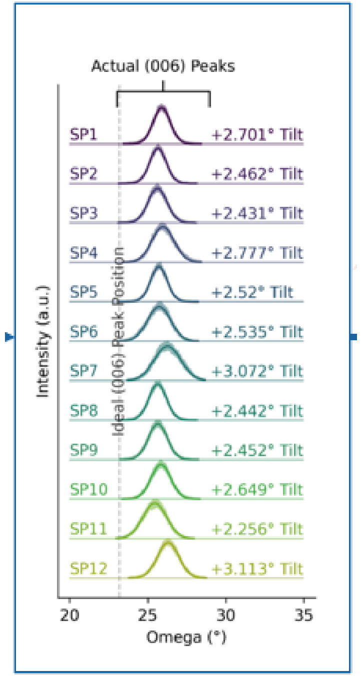
- 12 NI pancakes in 31 T background field
- Stress from screening current caused plastic deformation
- Orientation of slit edge appeared to play a role
  - Result of crystal tilt and non-uniform Jc instead



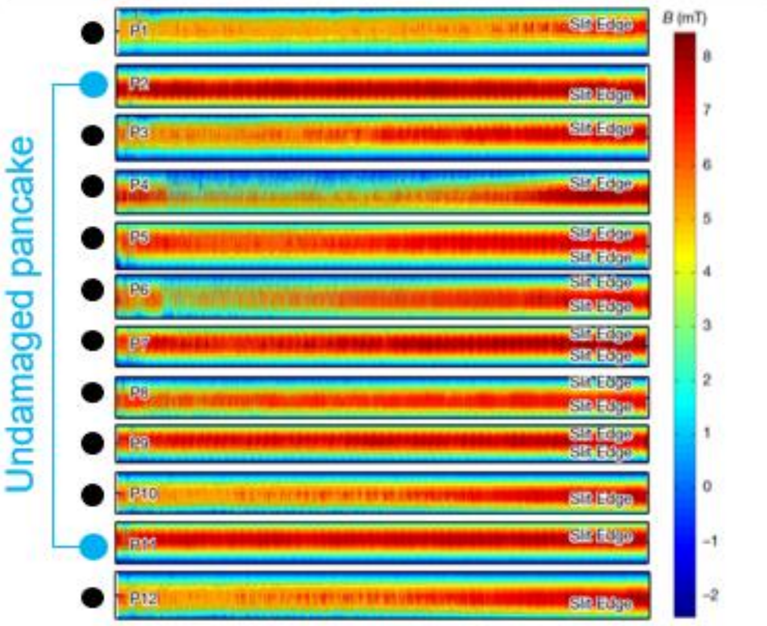
M. Wang, 2019







Crystallographic tilt

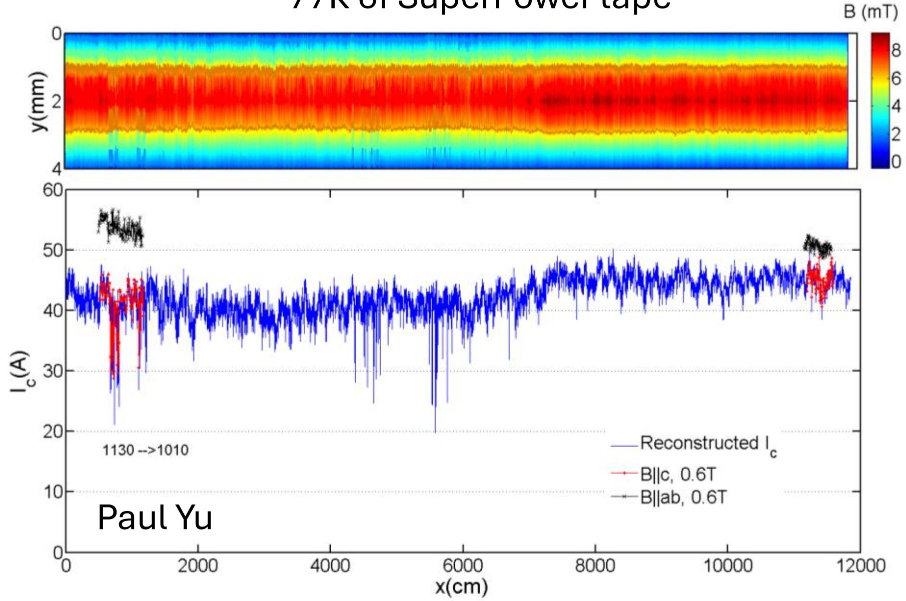


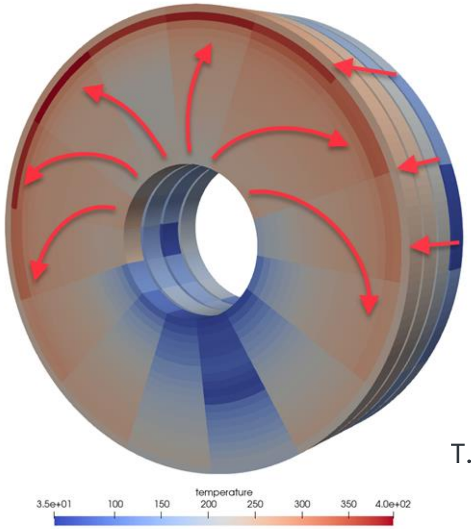
J. Bang, 2025

REBCO – Additional R&D Areas

- Non-uniform critical current across width of tape
  - Use multiple tapes in parallel
- Quench protection
  - Slow normal zone propagation ~cm/s
  - Non-insulated vs insulated
- Low resistance splice method
- Radiation damage
- Need to match simulation to experiments
  - Couple electromagnetic and mechanical simulations
  - Screening currents change inductance
- Test larger coils
  - Cooling, powering, quench protection
- …

YateStar measurement of critical current at 77K of SuperPower tape





T. Mulder

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