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Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

Magnet R&D needs and Priorities for the next 3-5 years

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2/23/2024

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Outline

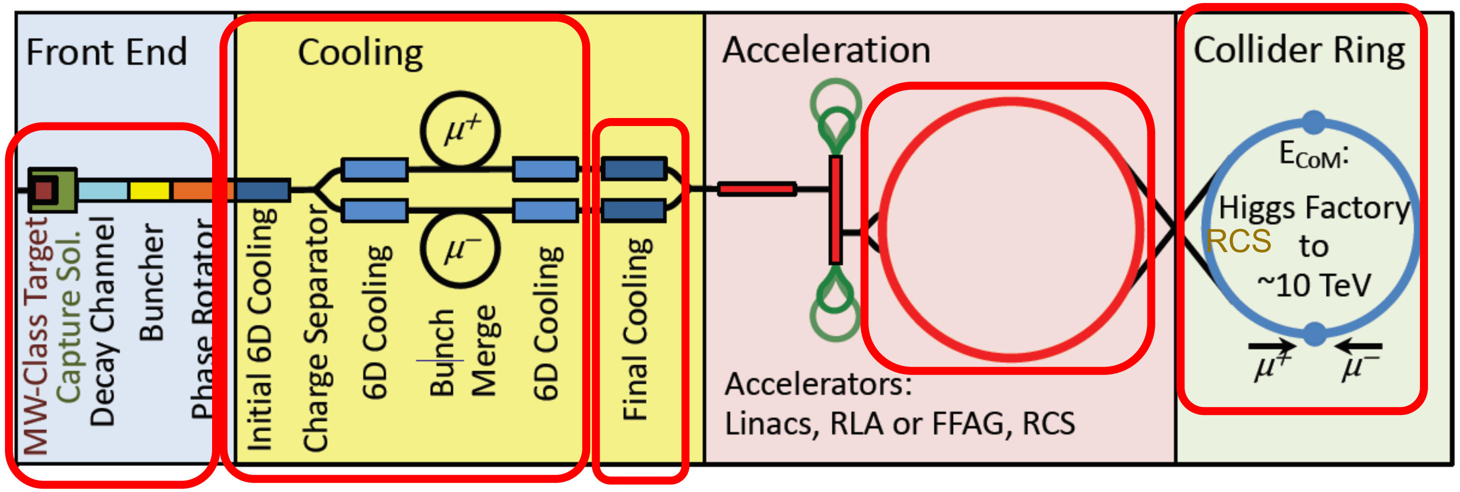
- Magnet needs for Muon colliders – based upon MAP and IMCC progress to date
    - Cover magnet needs for front end, cooling, acceleration and collider ring
    - Potential technologies
    - Challenges
- Synergies
- Summaries

Muon Collider magnet “specs”

Target solenoids
Field: ~20T (15T) … 2T
Bore: 1200 mm
Length: 18 m
Radiation heat: ≈ 4.1 kW
Radiation dose: 80 MGy

6D Cooling solenoids
Field: 4 T … 19 T
Bore: 90 mm … 600 mm
Length: 1 km (x 2)
Radiation heat: TBD
Radiation dose: TBD

Accelerator magnets
Field: ±1.8 T (NC), < 10 T (SC)
Rate: 400 Hz (NC), SS (SC)
Bore: 100 mm(H) x 30 mm(V)
Length: 3 m … 5 m (x 1500)
Radiation heat: ≈ 3 W/m
Radiation dose: TBD



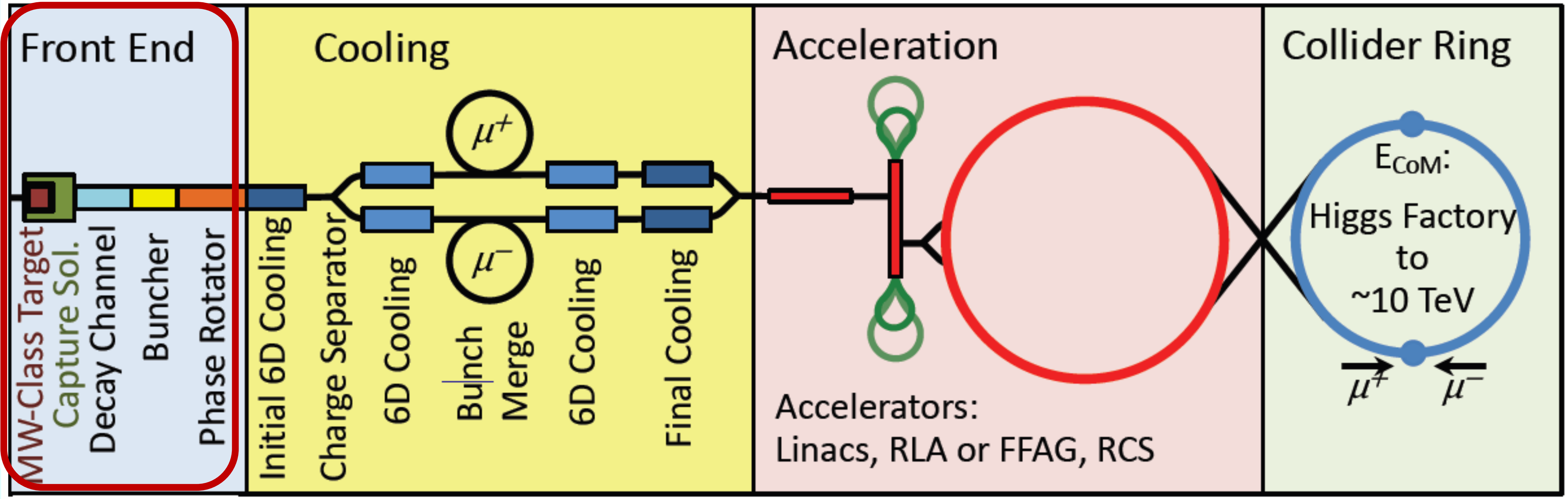
Final Cooling solenoids
Field: ≥30T (MAP), ≥40T (IMCC), ideally ≥50 T
Bore: 50 mm
Length: ≈ 500 mm (x 17)
Radiation heat: TBD
Radiation dose: TBD

Collider ring magnets
Field: 16 T peak (IR 20 T) – NOT a hard requirement! $\mathcal{L} \propto B_{dip}$
Bore: 150 mm
Length: 10 m … 15 m (x 700)
Radiation heat load: ≈ 5 W/m
Radiation dose: ≈ 20…40 MGy

Target and Capture

MAGNET SPECS

Field: 20T (or 15T) … 2T
Bore: 1200 mm
Length: 18 m
Radiation heat load: ≈ 4.1 kW
Radiation dose: 80 MGy



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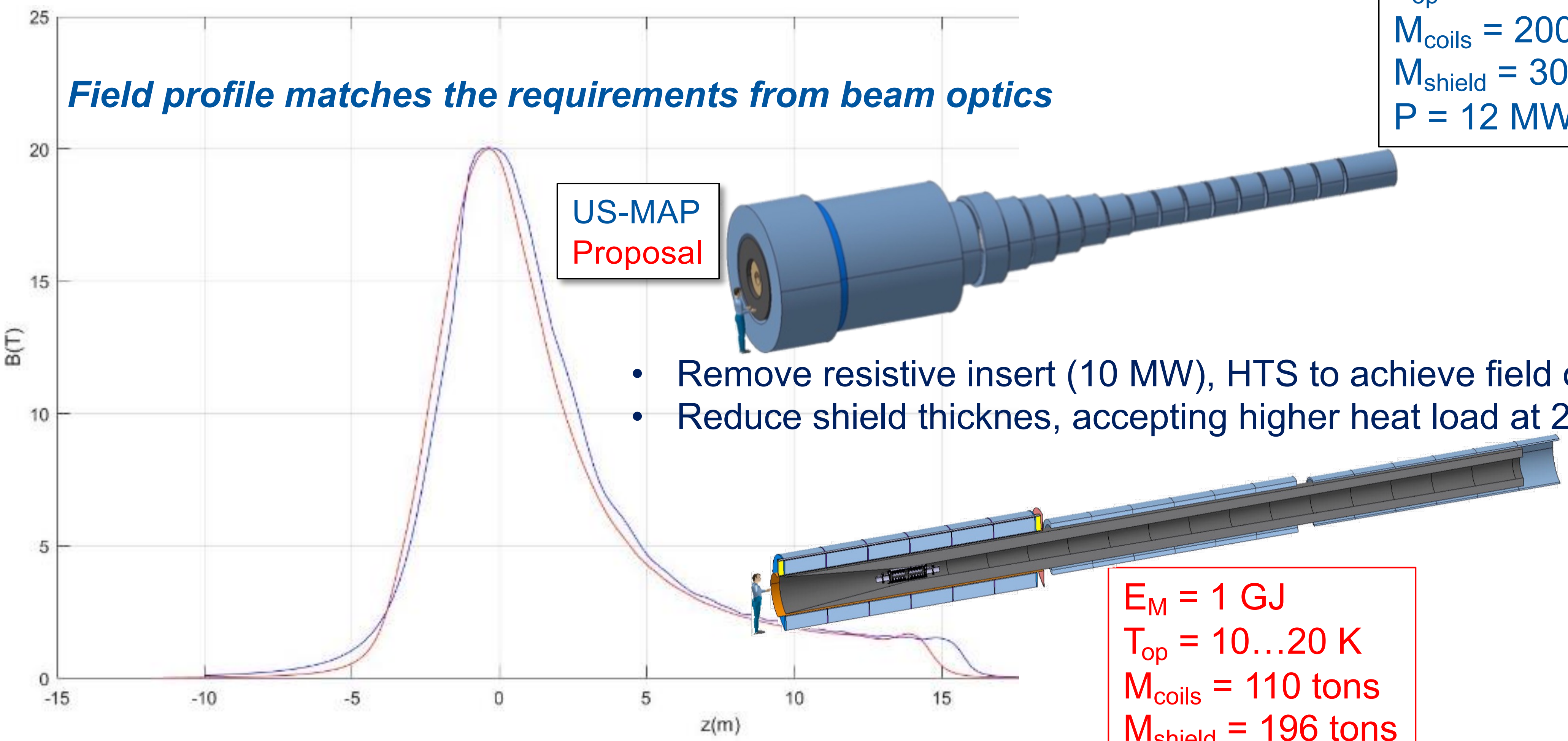
Target and Capture: Magnet Technologies

Technology	Pro's	Con's
ALL Resistive	Known technology (TRL 9)	Large dimension and mass Very large electric power consumption o(100MW)
LTS + Resistive	Known technology (TRL 9)	Large dimension and mass Electric power consumption o(10 MW)
LTS + HTS, Insulated	Known design principles Synergy with other fields of science application Can profit from development by others (e.g. NHMFL)	Large dimension and mass Developmental technology (TRL 6/7)
ALL HTS, Insulated	More compact than LTS/HTS Allows for operation at higher temperature	R&D at low readiness (TRL 4/5)
ALL HTS, Non-insulated	Most compact magnet winding Synergies with other fields of science and societal applications Can profit from development by others (e.g. NHMFL)	R&D at low readiness (TRL 3/4/5) Ramping time and field stability need to be demonstrated

Target and Capture: Magnet specifications

E_M = 2.9 GJ
T_{op} = 4.2 K
M_{coils} = 200 tons
M_{shield} = 300 tons
P = 12 MW



Field profile matches the requirements from beam optics

US-MAP
Proposal

- Remove resistive insert (10 MW), HTS to achieve field of 20 T
- Reduce shield thicknes, accepting higher heat load at 20 K

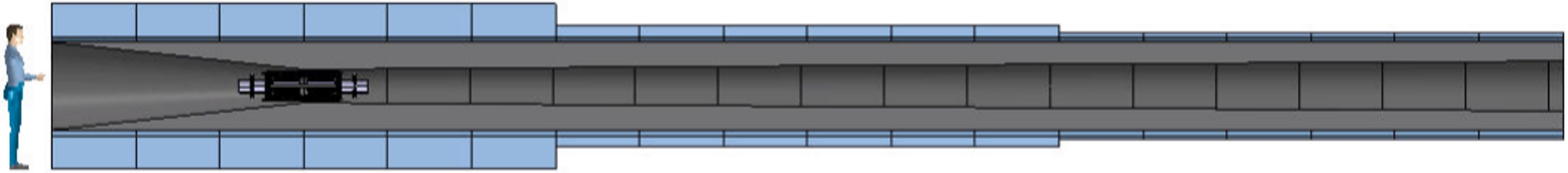
E_M = 1 GJ
T_{op} = 10…20 K
M_{coils} = 110 tons
M_{shield} = 196 tons
P = 1MW

Target and Capture Design Considerations

- Main design drivers are power consumption and heat deposition

- Hybrid US-MAP (5 resistive coils and 19 SC coils, 2.4 m bore ∅) **OR**
- Alternative - All HTS, 1.2 m bore ∅ and operating at 10 – 20K

- Strong synergy with requirements on magnets for tokamak nuclear fusion devices
  - *Central Solenoid Coils:* Higher B_{op} → higher flux → higher reactor availability factor
  - *Toroidal Field Coils*: Higher T_{op} → larger acceptable heat load → compact shielding → cost

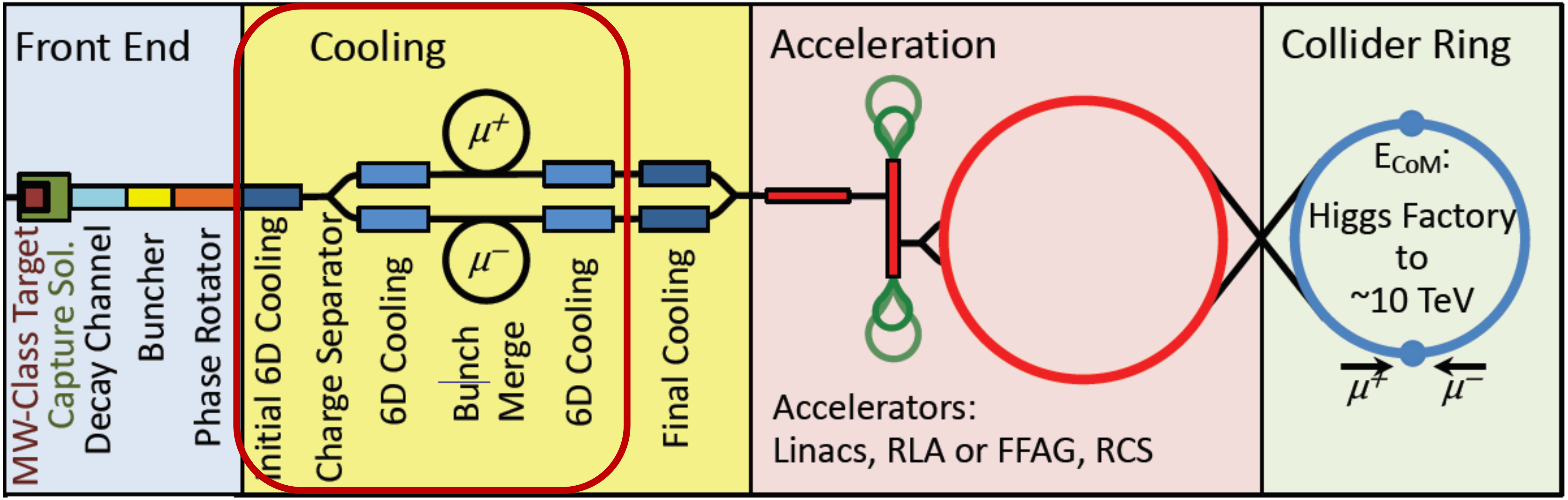


Target and Capture: Magnet Design Highlights

- VIPER-like cable (HTS tapes, central cooling hole, steel jacket) with $I_{max} \approx$ 61 kA
- Set of 23 coils in 3 sections (300 mm gap between sections, 20 mm gap between coils)
- Peak field B=20.9 T, magnetic energy 1.1 GJ, cable length ≈ 8.7 km, winding mass ≈ 115 t
- Field on axis within 4% accuracy of Sayed-Berg formula over 16 m channel length
- Stresses in structural elements within 316 LN limits ($s_Y \approx$ 1000 MPa)
- Stresses in tapes being investigated to be minimized ($t_{xy} \approx$ 30 MPa)
- Coils operating at 20 K, ≈ 20 bar, ≈ 15 W pumping power, ≈ 150 W heat removal
- High conductor stability (DT≥10 K!)
- Detection & dump for quenches in low field/current most challenging (→long detection times) but seems compatible with hot-spot temperature limit ($T_{HS} \approx$ 150-200 K)

6D Cooling

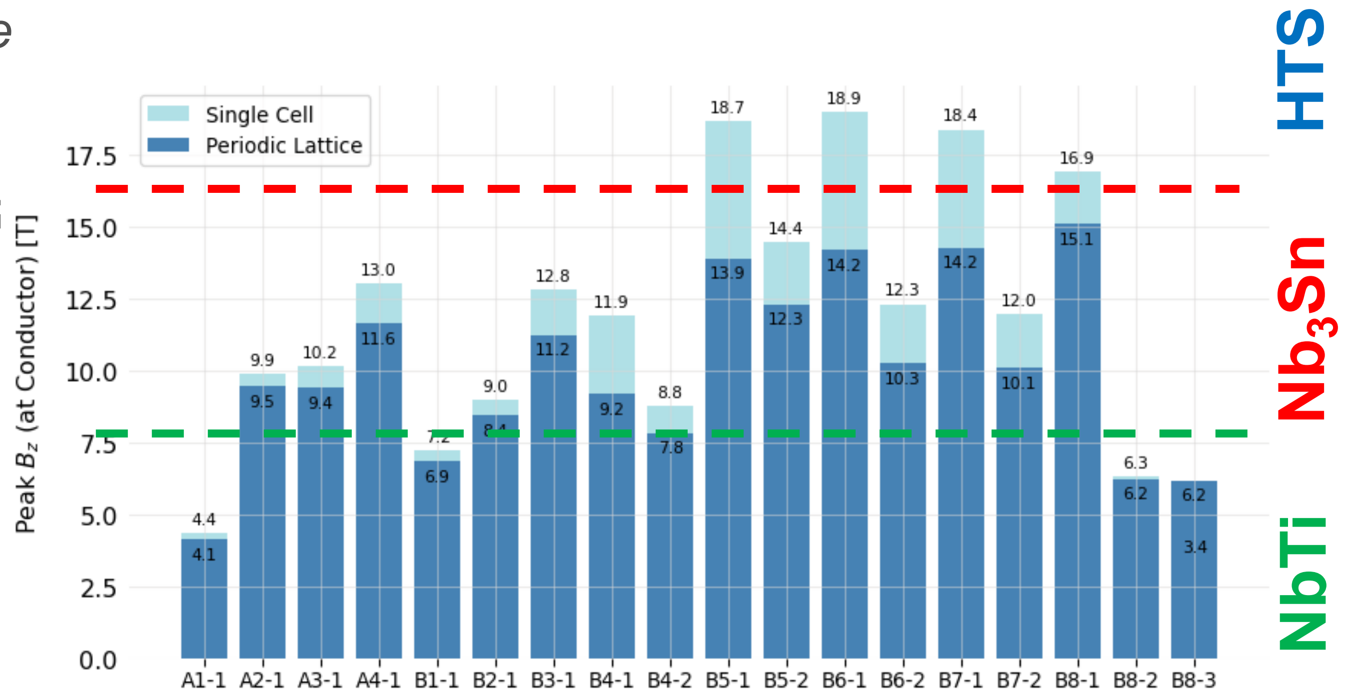
6D Cooling solenoids
Field: 4 T … 19 T
Bore: 90 mm … 600 mm
Length: 1 km (x 2)
Radiation heat: TBD
Radiation dose: TBD



Cooling Channel

Full list based on original US MAP design (field on axis)

- 12 unique stages:
  - 4 cooling stages *before* bunch recombination (A1-A4)
  - 8 cooling stages *after* bunch recombination (B1-B8)
- *Each stage has a repeating series of a cell type*
- High field, very compact solenoids
- Each cell has symmetric solenoids



By S. Fabbri and J. Pavan

Some stats:

- Fields on axis: 2 to 14 T
- Cell Lengths: 0.8 to 2.7 m
- Total length of all Stages: ~ **1 km**
- Total number of solenoids: 2432

To be investigated

We are defining technologies

- Conductor
- Operating conditions, i.e. temperature and cooling method

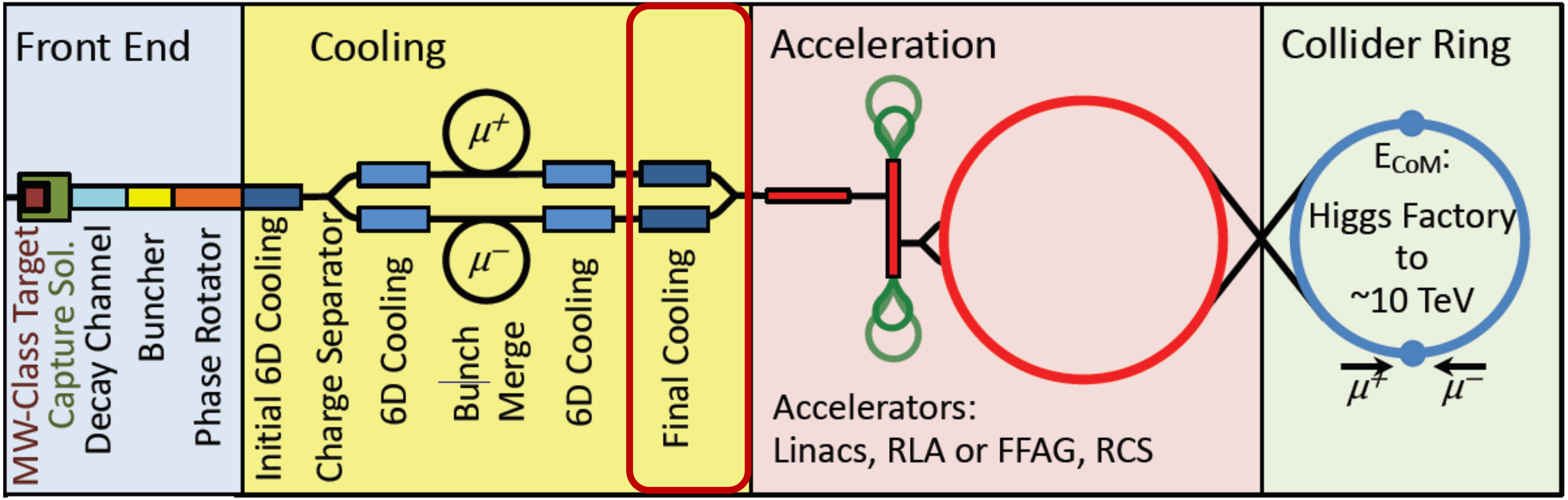
To be investigated

- Conductor performance
- Conductor configuration
- Field quality
- Thermal/mechanical configuration

Technologies 6D cooling solenoids

Technology	Pro's	Con's
LTS	Known technology (TRL 9)	Operating temperature
HTS ReBCCO Insulated	More compact than LTS/HTS Allows for operation at higher temperature Batch above 100 m demonstrated	R&D at low readiness (TRL 4/5) Quench detection protection Production of km batches to be demostrated
HTS ReBCCO Non-insulated	Most compact magnet winding Synergies with other fields of science and societal applications Batch above 100 m demonstrated Can profit from development by others (e.g. NHMFL)	R&D at low readiness (TRL 3/4/5) Ramping time and field stability need to be demonstrated Quench detection and protection Production of km batches to be demostrated
HTS BiSSCO/IBS	Round wire demonstrated for BiSSCO	R&D at low readiness (TRL 3/4) for IBS Production lengths (?)

Final Cooling Channel

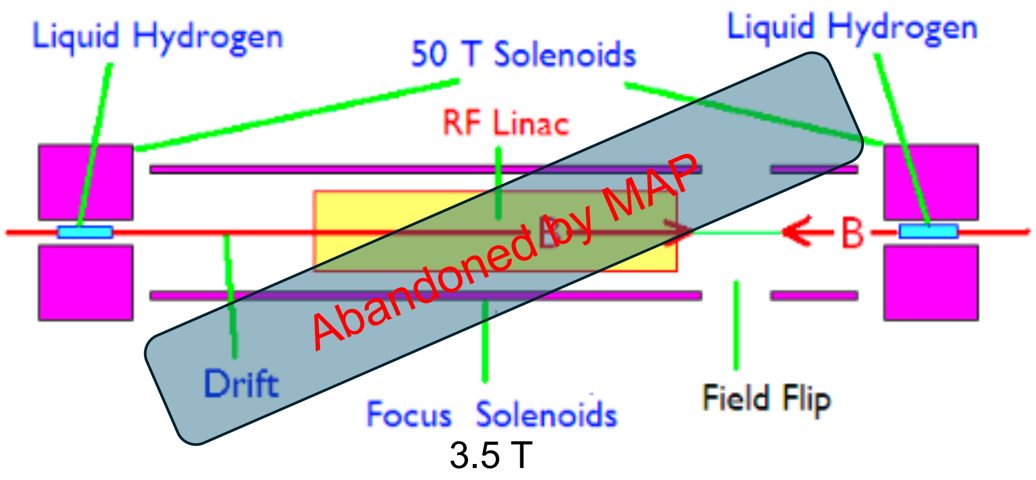


Final Cooling solenoids
Field: ≥30T (MAP), ≥40T (IMCC), ideally ≥50 T
Bore: 50 mm
Length: ≈ 500 mm (x 17)
Radiation heat: TBD
Radiation dose: TBD

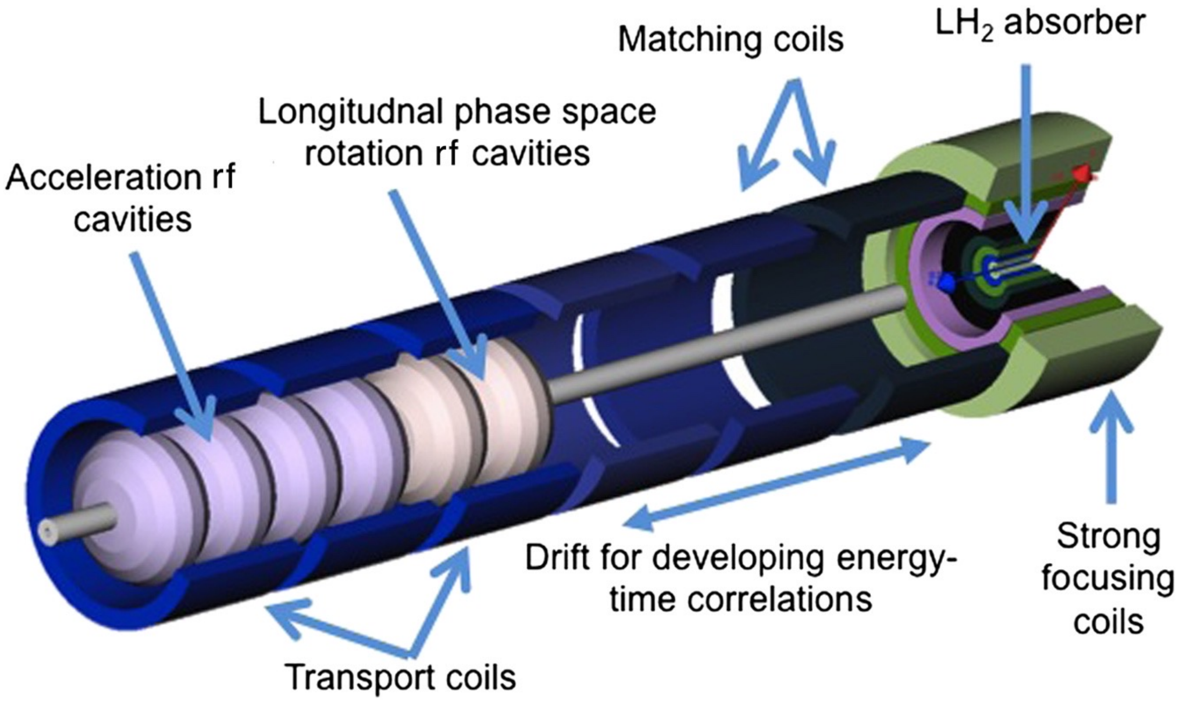
Ionizing Cooling Cell

- 16 Cells (MAP)
  - Set of eight superconducting coaxial coils
  - Peak field of **30T,** 50 mm diameter
  - Sayed et al. Phys. Rev. ST Accel. Beams **18**, 091001

- 14 Cells (CERN-IMCC)
  - B > 40T, 50 mm diameter



R. Palmer, BNL

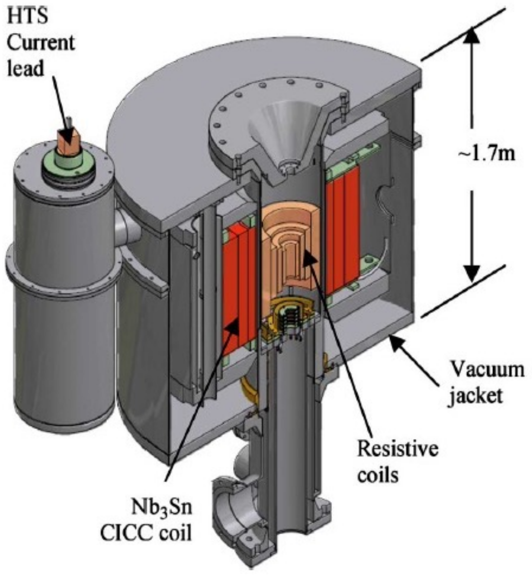


MAP 30T Design

Not exactly starting from scratch on high field solenoids – but . . .

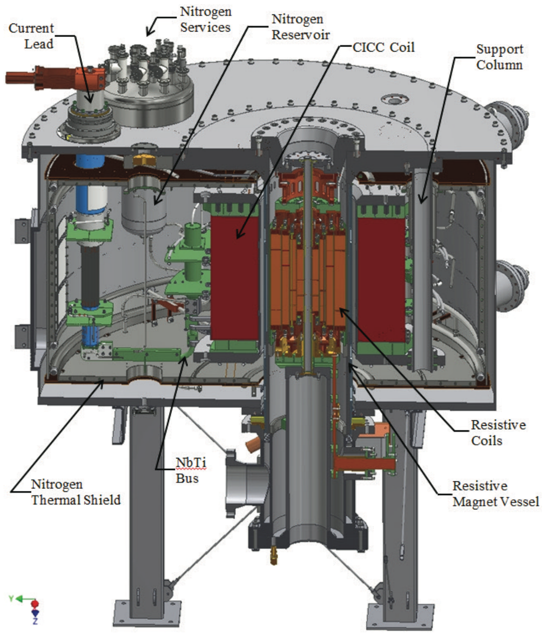
https://nationalmaglab.org/user-facilities/dc-field/magnets-instruments/

http://english.hmfl.cas.cn/uf/ms/202202/t20220224_301451.html

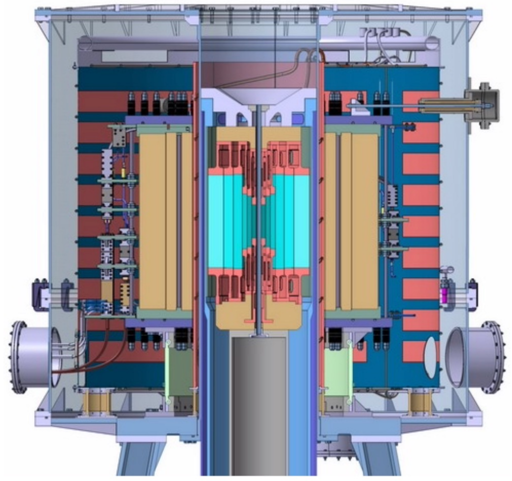


Tallahassee magnet system.

Cross section of 45 T, **32 mm** **NHFML** user facility solenoid
Hybrid Magnet 33.5 T from resistive insert, 11.5 T by superconducting outsert
30 MW power comsumption



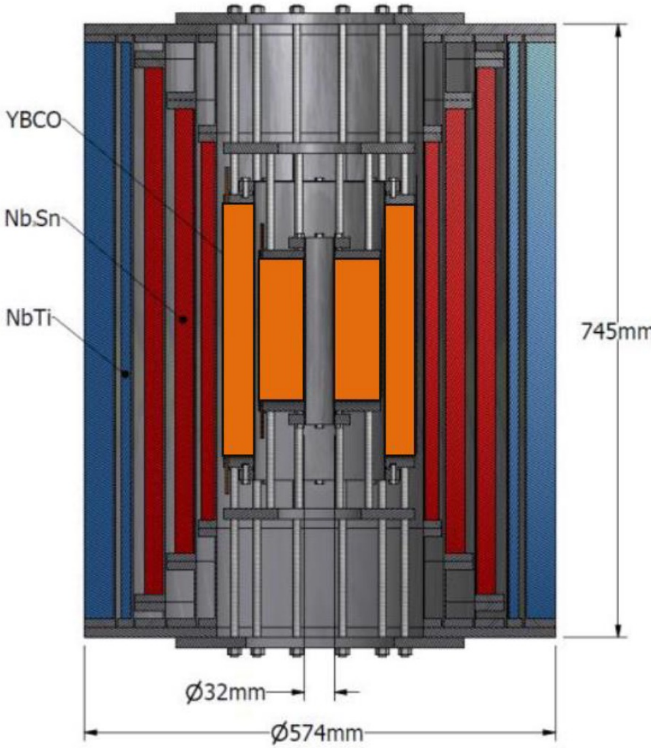
Cross section of **36 T**, **48 mm** **NHFML** user facility (NMR) solenoid
Hybrid Magnet 23 T from resistive insert, 13 T by superconducting Nb_3Sn CICC outsert
14 MW power comsumption

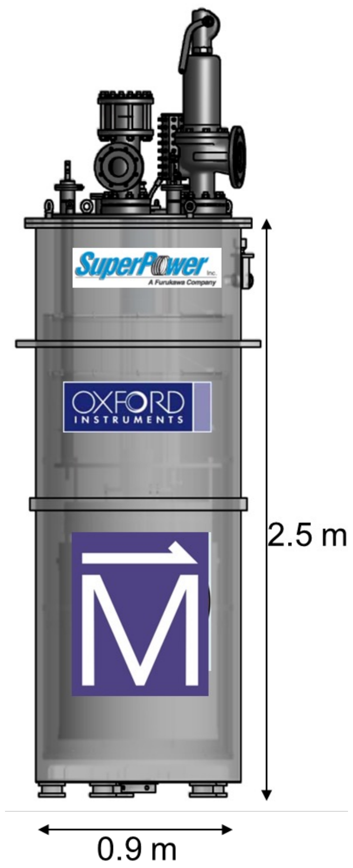


Cross section of **40^*/37 T**, **32/50 mm** **CHMFL** user facility solenoid
Hybrid Magnet 29/26 T from resistive insert, 11 T by superconducting Nb_3Sn CICC outsert
20 MW power comsumption

Getting closer

Cross section of 32 T (15 T LTS, 17 T two ReBCO double pancake coils), 32 mm user facility solenoid
https://nationalmaglab.org/user-facilities/dc-field/magnets-instruments/





Just increase the field and bore
Operate REBCO coils at 20K?

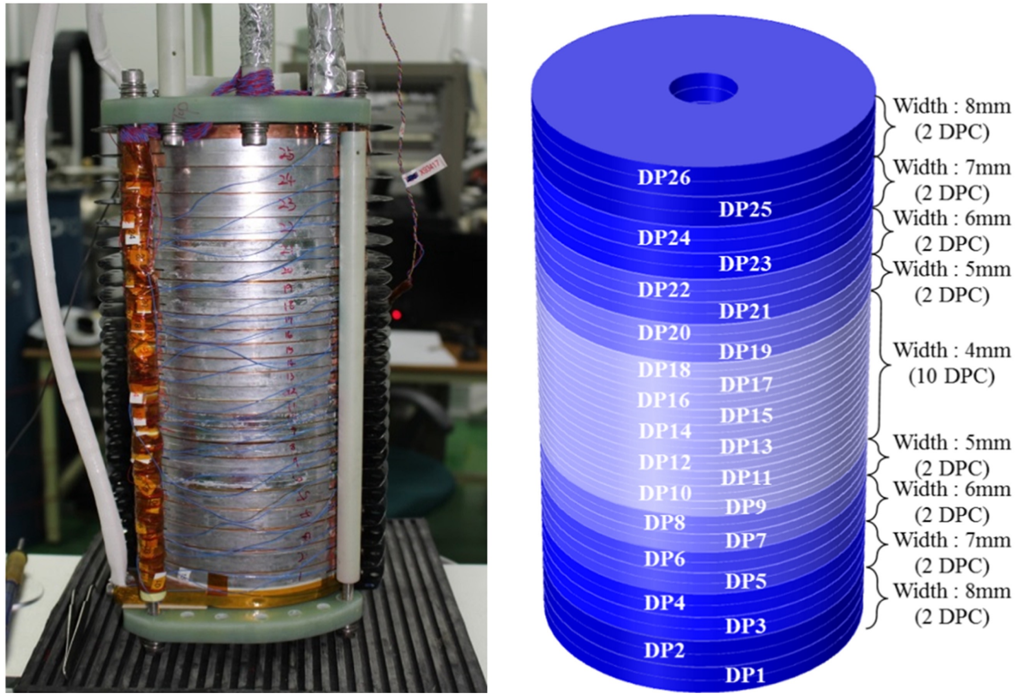
And then the 40T
But will nested coils work for MC?
Low J, mechanical challenges, QP

B. Bordini, CERN

CERN approach

- Single coil, high J_e
  - 40T, 50 mm bore
- Need higher field – but higher tensile radial stress
- Apply precompression to all-HTS NI/MI single coil.
- High potential for future particle accelerators and other societal applications
- Substantial progress on design
- Challenges
  - High stresses
  - Magnet protection – transients to control
  - Charging time

Sunam NI one-body ReBCO magnet
26.4 T in 35 mm, J central pancake 404 A mm^{-2}
(26.4 T HTS multi-width)
overall diameter and height:
172 and 327 mm



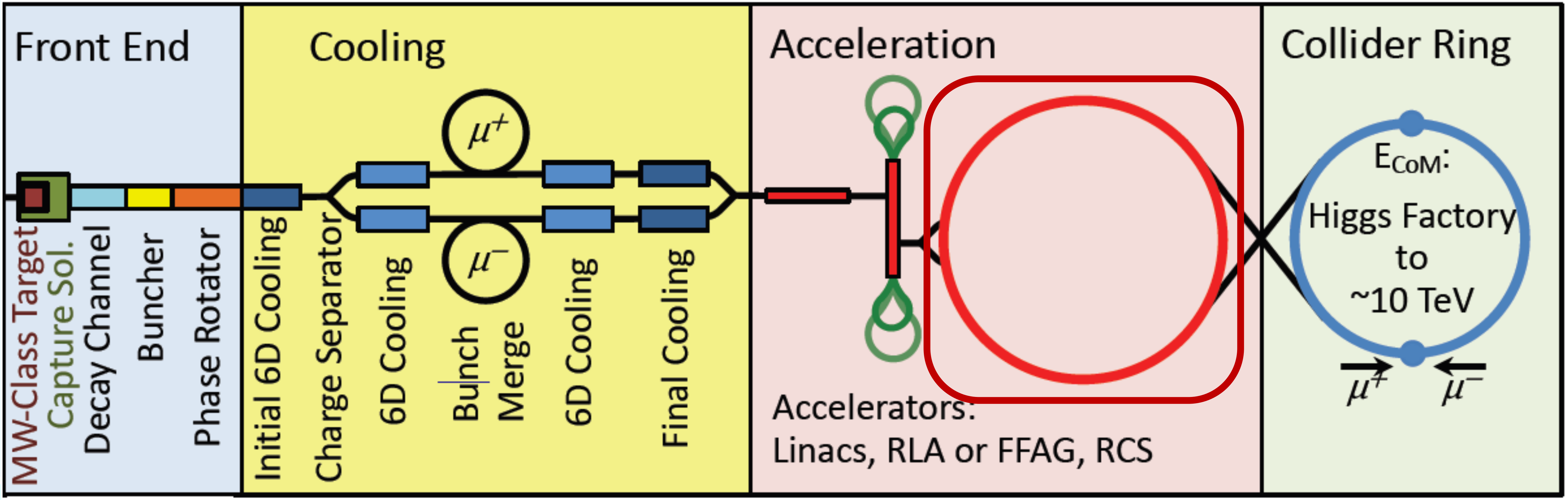
S. Yoon et al. Supercond. Sci. Technol. 29 (2016) 04LT04

B. Bordini, CERN

Accelerator Ring

Accelerator magnets
Field: **±1.8 T (NC),** < 10 T (SC)
Rate: 400 Hz (NC), SS (SC)
Bore: 100 mm(H) x 30 mm(V)
Length: 3 m … 5 m (x 1500)
Radiation heat: ≈ 3 W/m
Radiation dose: TBD

NOTE: **± > 2T** would greatly improve RCS perfomance



Critical systems and main- specifications

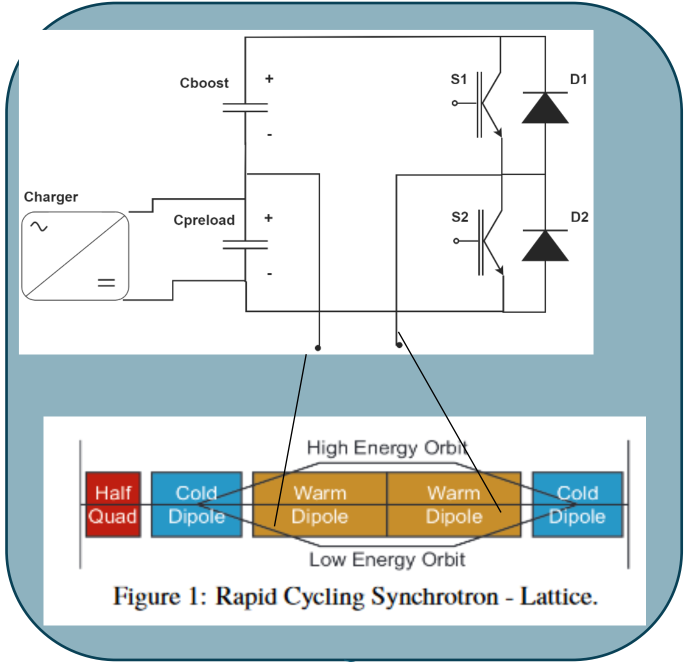
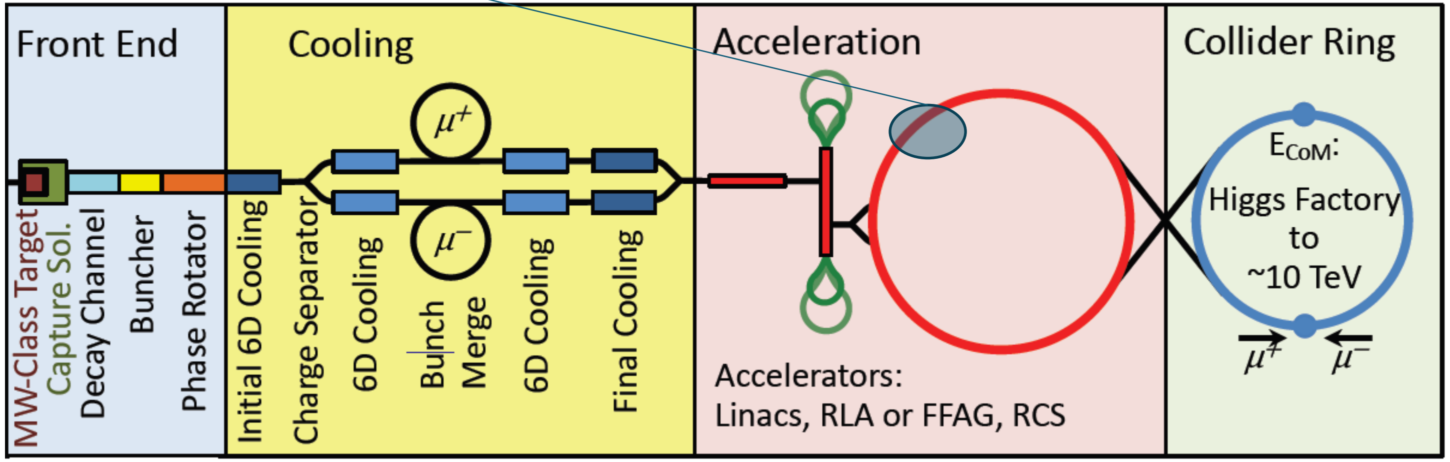


Figure 1: Rapid Cycling Synchrotron - Lattice.

The powering system is very interlinked with the resistive magnets design

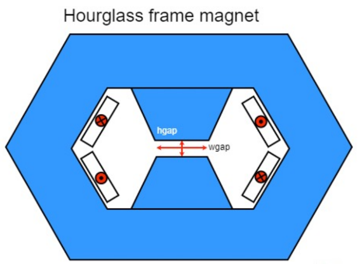
	RCS1	RCS2	RCS3	RCS4
Inj Energy [GeV]	63	314	750	1500
Acc. length [km]	5.99	5.99	10.7	35.0
Res. mags Lm [km]	3.65	2.54	4.37	20.38
Binj in gap [T]	0.36	−1.8	−1.8	−1.8
Bextr in gap [T]	1.8	1.8	1.8	1.8
B ramp time Tramp [ms]	0.35	1.10	2.37	6.37
Trepetition [ms]	200	200	200	200
Dipoles Gap w [mm]	100	100	100	100
Dipoles Gap h [mm]	30	30	30	30
Dipoles Egap@Bext [MJ]	14.1	9.8	16.9	78.8
Dipoles Etot@Bext [MJ]	21.2	14.7	25.3	118.2
Dipoles Pmax [GW]	111	54	43	74

The key performance drivers are directly related to the total energy and power to be delivered to the magnets, but also to the tracking accuracy that will have to be guaranteed. This input should come from the beam studies

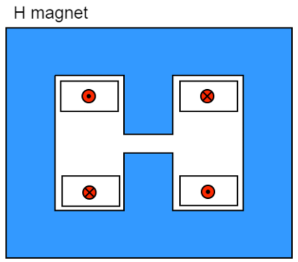


F. Boattini

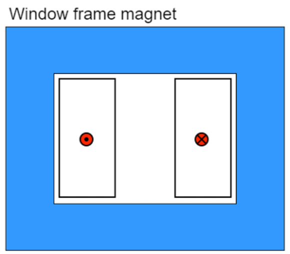
Fast-ramping Magnets



5.07 kJ/m



5.65…7.14 kJ/m

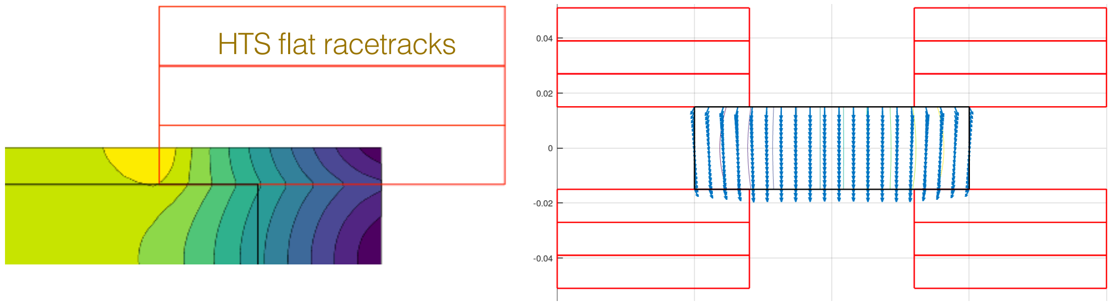


5.89 kJ/m

Main challenge is management of the power in the resistive dipoles (several tens of GW):

- Minimum stored magnetic energy
- Highly efficient energy storage and recovery

Simple HTS racetrack dipole could match the beam requirements and aperture



Rectangular magnet bore 100 mm x 30 mm

1.8T RC with 10T SC

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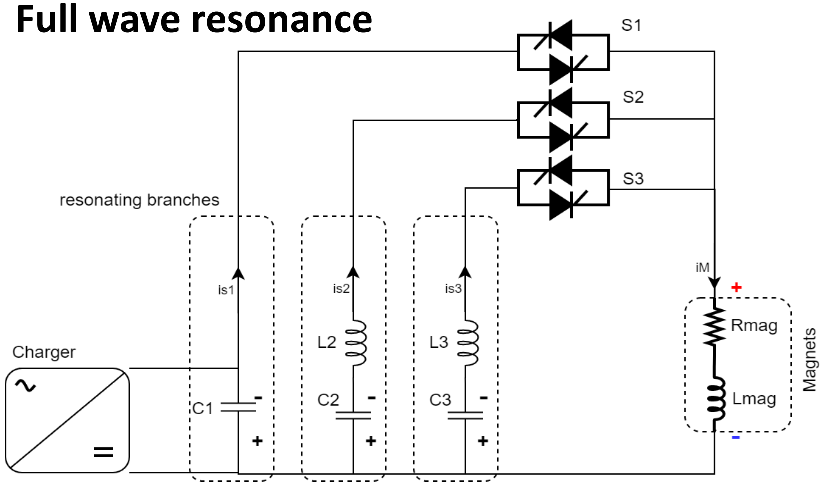
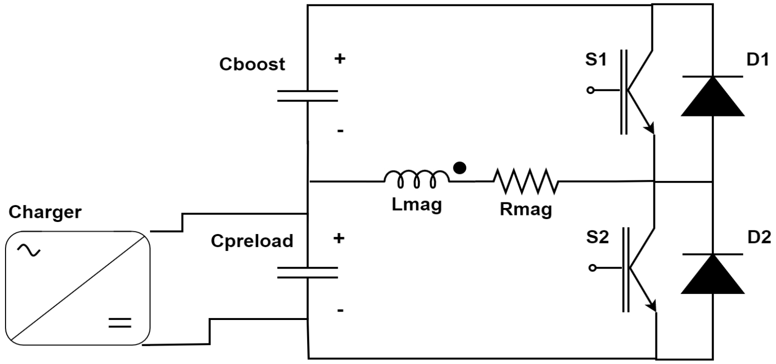
Differerent power converter options investigated

Full wave resonance



Commutated resonance (new)

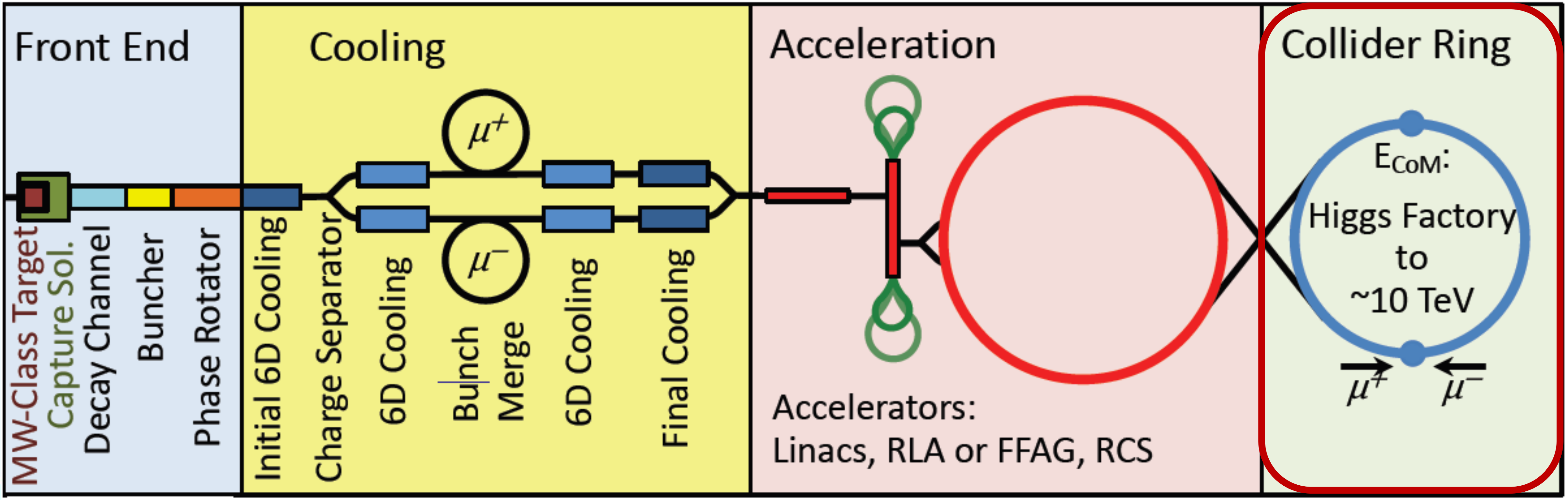


F. Boattini et al.

Collider Magnets

10 TeV IMCC Targets

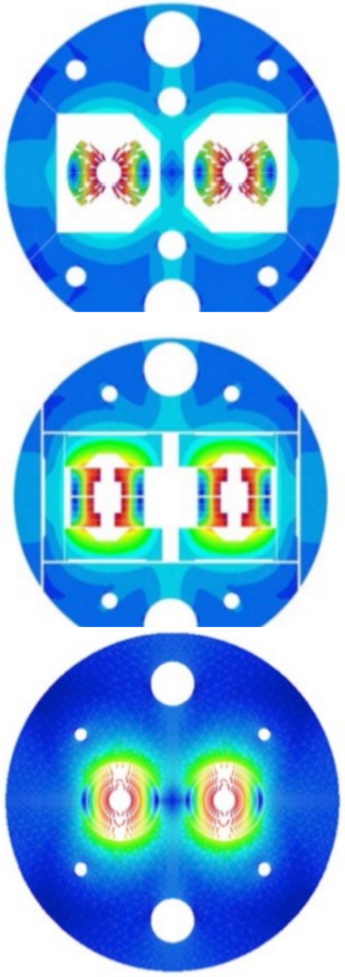
Collider ring magnets
Field: 16 T peak (IR 20 T)
Bore: 150 mm
Length: 10 m … 15 m (x 700)
Radiation heat load: ≈ 5 W/m
Radiation dose: ≈ 20…40 MGy



Material Options

Technology		Pro's	Con's
LTS (Nb-Ti)		• Known and well developed technology (TRL 8)	• Probably do not meet all magnet requirements
LTS (Nb_3Sn)		• Known technology, reaching demonstration level in accelerators (TRL 6/7)	• Probably do not meet all magnet requirements • Brittle/stress limited
Hybrid (LTS Nb_3Sn) + (HTS)		• Lower cost • Exploit potential of both materials	• Low readiness level for HTS insert (TRL 3/4) • LTS/HTS joints and integration to be developed • Temperature limited by LTS
All-SC (HTS)	Insulated	• Most compact solution • Allows operation at high temperature • Profit from on-going R&D activities on insulation/no-insulation windings	• R&D at low readiness (TRL 3/4) • Quench protection to be demonstrated • Field delay and field stability in case of NI winding
	Controlled Insulated		
	Non Insulated		

Design Options (1/2)

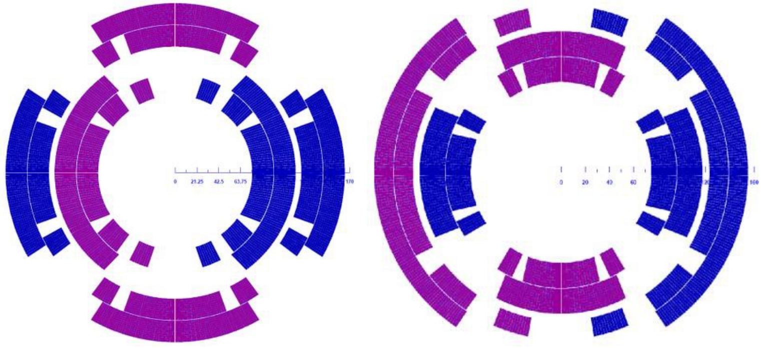


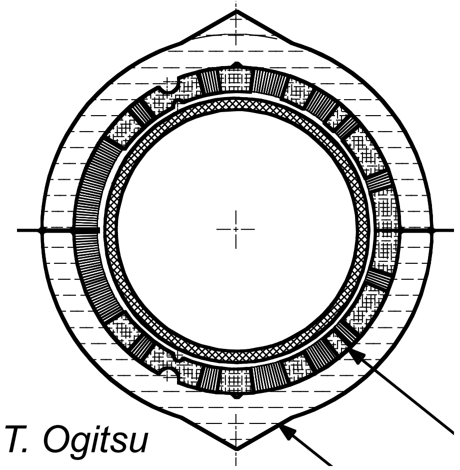
CCT

Technology	Pro's	Con's
Cos-theta Design	• Well known design • Wound around a cylindrical mandrel, end shape already suitable for beam tube insertion	• Mechanical structure can be complex • Not most easy winding geometry for HTS tapes
Block Coil Design	• Known design principles • Mechanical structure simplify stress management • Easier geometry for HTS-tapes	• Difficult stress management on coil ends • Higher ratio conductor length/produced field
Canted Cos-theta Design	• Intrinsic stress management • Low number of parts and tools • Easy winding procedure	• Requires more cable than the other layouts • Quench protection more difficult • R&D needed

Design Options (2/2) Combined function

A. Zlobin





T. Ogitsu

Technology	Pro's	Con's
NESTED Configuration	• Separate Powering Dipole/Quadrupole • Inherit experience on Nb$_3$Sn magnets for HiLumi and LARP-US development program	• High Stress on Internal Coil • Alignment • Higher Costs
Asymmetric Coil Design	• Single type of coil • Optimized margin and field quality	• Fixed Dipole/Quadrupole ratio • Stress on the supporting structure is not balanced

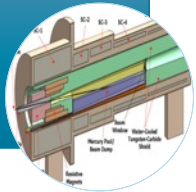
Fields for 3 TeV are high, but 10 TeV very high!

Important negotiation point with machine designers

Summary of the Muon Collider Magnet Pull

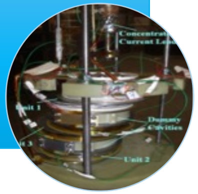
- Characteristics:
  - High field (15-20T)
  - Large bore (meter-scale)
  - Intense radiation environment – NC or HTS insert coil

Capture Solenoid for Simultaneous mu+ & mu- Beams



- Characteristics:
  - Solenoid-based cooling channel (LH_2/LiH absorbers)
  - RF cavities integral to focusing channel
  - Fields ranging from LTS to HTS conductor regime

Muon Ionization 6-Dimensional Cooling Channel



- Characteristics:
  - Emittance exchange channel for TeV-scale colliders – trade increased longitudinal beam emittance for smaller transverse emittance
  - Goal: 40-60 T HTS solenoids with d ~ 50mm

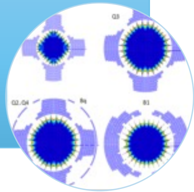
Muon Ionization Final Cooling Channel

- Characteristics:
  - Present baseline based on the use of Rapid Cycling Synchrotrons
  - Requires magnets capable of ~400Hz operation with B>1.5T
  - Novel magnets, suitable modeling, efficient power system

Acceleration to the TeV Energy Scale for Muon Colliders

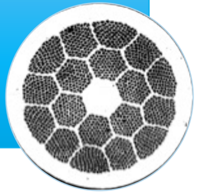
- Characteristics:
  - Decaying muon beams mean that luminosity is inversely proportional to circumference
  - 10T dipole ⇨ 15-20T dipoles improves luminosity
  - Radiation environment
  - Challenging IR magnets

Muon Collider Magnet Needs



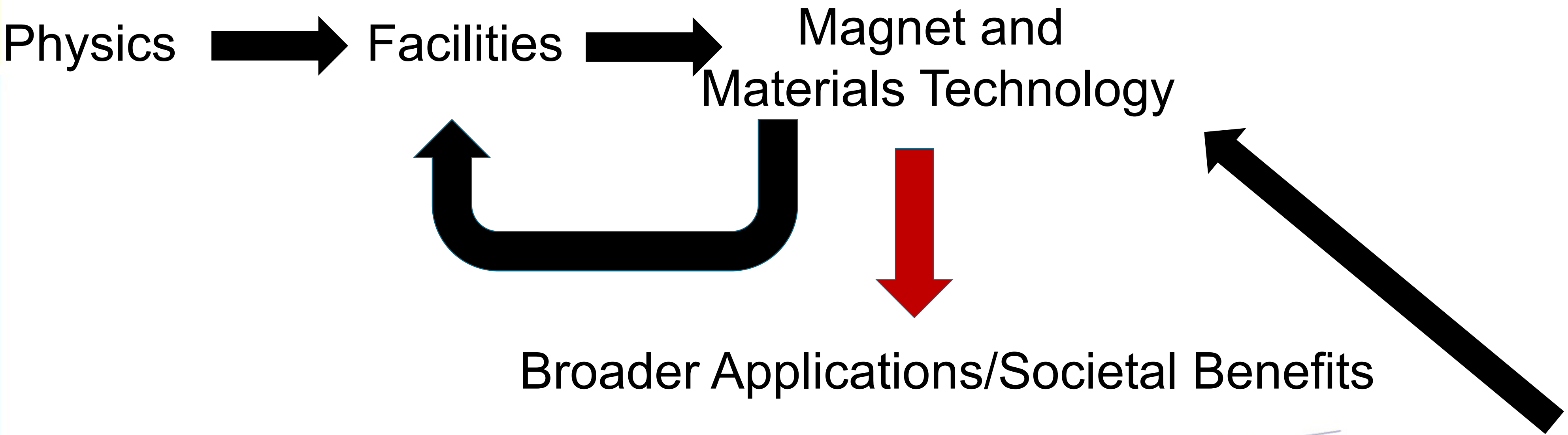
- Characteristics:
  - A MC (w/decaying beams) obtains the greatest performance enhancement of any HEP collider from HTS magnet technology
  - High quality HTS cables and magnets must be a priority

HTS Magnet Development



HEP-Driven Magnet Technology Chain

Benefits more than particle physics

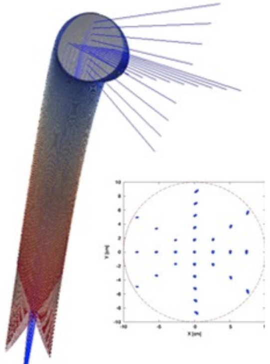


Physics → Facilities → Magnet and Materials Technology

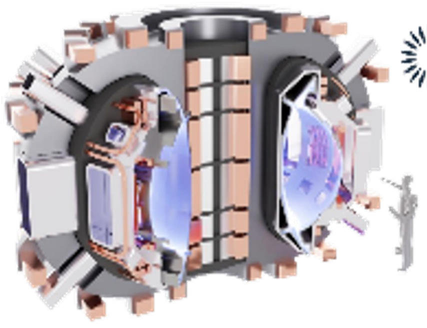
Broader Applications/Societal Benefits

Clean Energy

MRI and High Field Science



Particle Therapy



Commonwealth Fusion Systems

Compact Fusion Reacto

Summary

The accelerator and collider magnet goals for Muon colliders are aggressive but the fundamental machine requirements for a muon collider are more relaxed than those needed for the FCC-hh

Muon colliders will need significant advances in magnet design beyond currently available magnet technologies

Significant development will need to be made in the HTS magnet space

Synergies with compact fusion, high field science magnets help with this development and should be leveraged

Dialogue between machine designers and magnet folks is critical to explore the many trade offs

Current efforts in the US (MDP) and EU (HFM) are inadequate to support muon collider magnet needs in a reasonable timeframe – tradeoff studies needed to define approach

IMCC contends that a 3 TeV Muon Collider could be ready shortly after LHC shutdown in 2041. Technically limited schedule and will need substantial increase in resources on both sides of the Atlantic to be realized