# Progress in the Design of Magnets for a Muon Collider

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# A Muon Collider & the International Muon Collider Collaboration (IMCC)

A **Muon Collider (MuC)** has tremendous potential as a future Higgs factory in terms of footprint, operating costs, and physics reach!

- Given this potential and in response to recommendation from the European Strategy Group, the **IMCC** was formed in 2022 to provide a baseline concept, critical R&D demonstrators, and assess key risks and cost and power consumption drivers of a MuC
- We are considering a fast-track 3 TeV MuC and a 10 TeV MuC

International Muon Collider Collaboration (IMCC)
# Magnets Working Group

**Magnet Technologies** are a crucial technology for all parts of a MuC complex

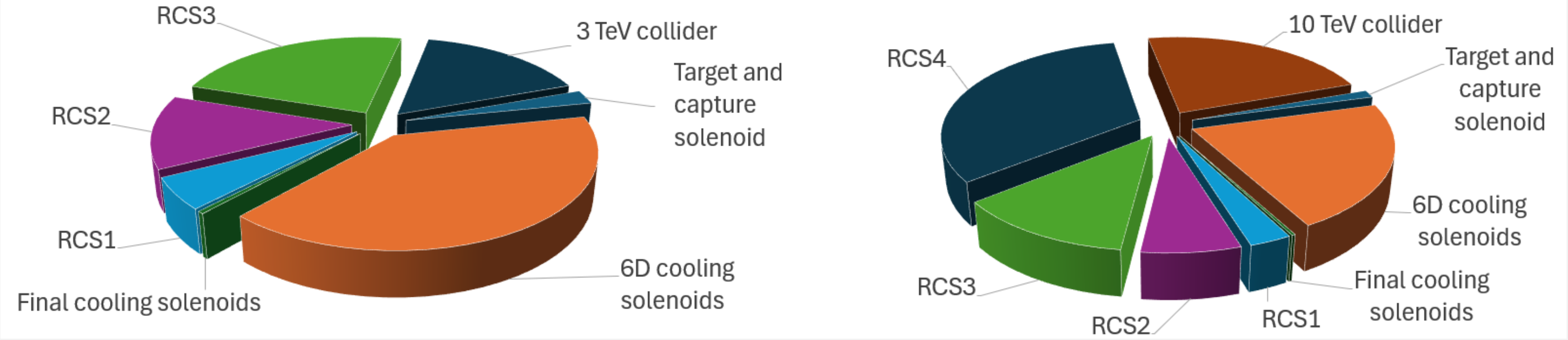
- The U.S. MAP program (2011-2016) provided a baseline MuC magnet configuration
- Focus on **HTS** technologies to enable higher field reaches and other considerations (next slide)

**Recent outcomes** for magnet and powering systems :

## Technically limited schedule

| | |
|---|---|
| 3 TeV | 17 years |
| 10 TeV | 26 years |

**Percentage cost contributions** considering cost of materials, consumables, and labor



# Motivations/Considerations for HTS Technologies

**Sustainability**

**Economics**

**Limited Helium Inventory**

**Synergies & Societal Applications**

2020 update to the European Strategy for Particle Physics:

> "…A detailed plan for the ***minimisation of environmental impact*** and for the ***saving and re-use of energy*** should be part of the ***approval process for any major project***."

**Energy efficient cryogenics! Temperature levels as high as possible**

**6'600 kt** of helium WW estimated reserve according to USGS report in 2021. EU assessment 2023 → **Critical Raw Material**

- A large component of the magnet cost is the **amount of superconductor**
- Cost depends on **material**: High-field superconductors are (significantly) more expensive than Nb-Ti

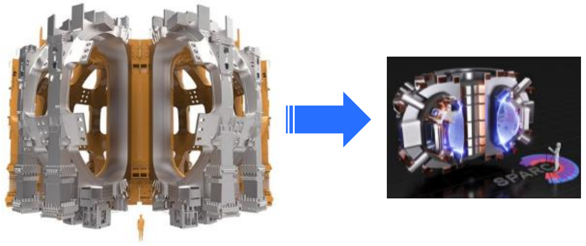
Reduce the coil cross section (**increase J !**)

Reduce the unit conductor cost

**Reduce magnet cost**

Developing **HTS** Technologies = enabling higher field reaches + being more compact!

- Thermonuclear Fusion
- MRI Technology
- High Field Science (e.g. NMR)



https://www.iter.org/mach/Magnets

https://news.mit.edu/2021/MIT-CFS-major-advance-toward-fusion-energy-0908

# Key Challenges

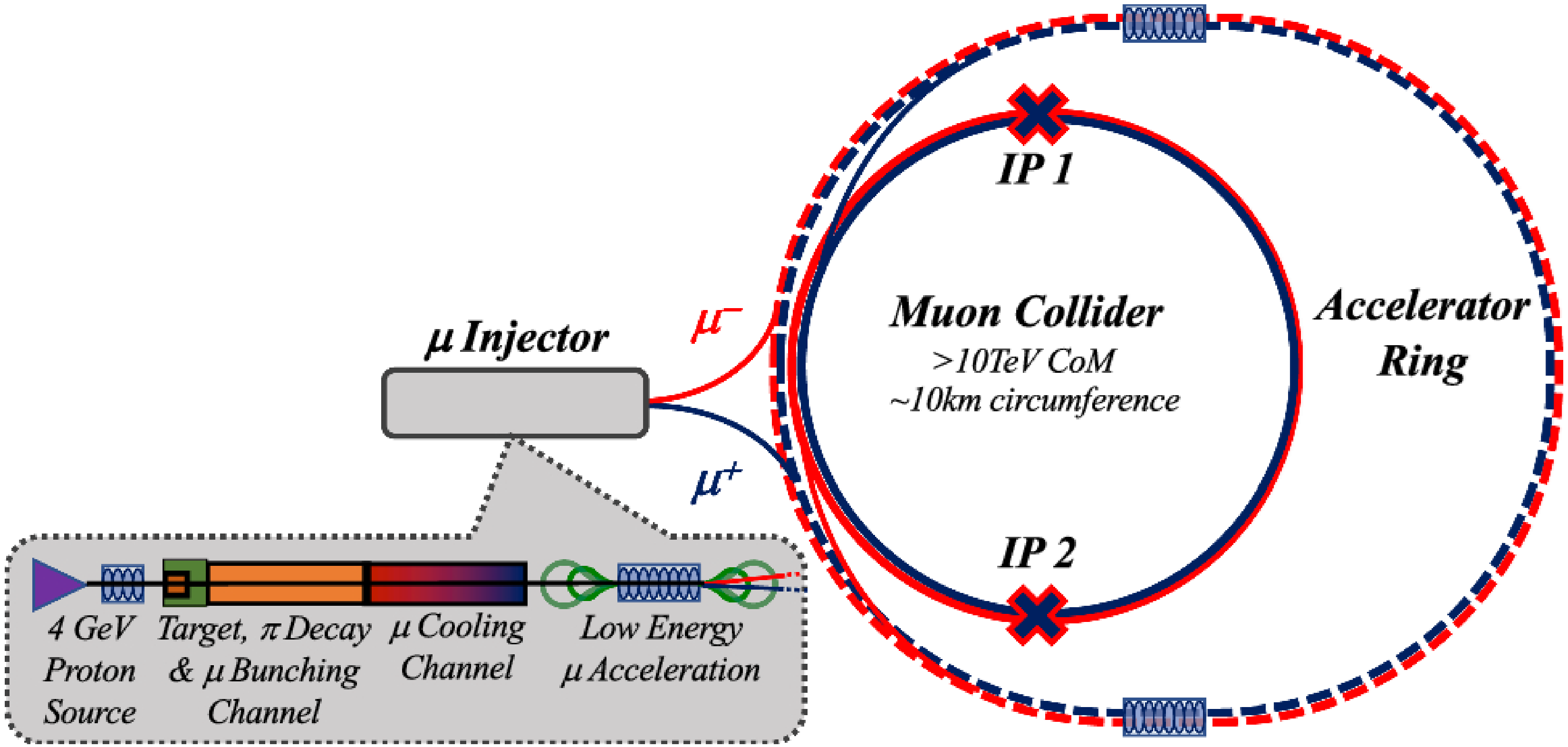
I. **Short muon (2.2 $\mu s$) lifetime**, helped by relativistic time dilation (at 5 TeV, lifetime → ~100 ms )
   - ➢ Rapid production and acceleration of the beam, short collider circumference

II. **Production of bright muon beams**: Luminosity $\propto \bar{B} * (N_{\mu^+} N_{\mu^-})/(\varepsilon_\perp)$, where $\bar{B}$ is avg. bending field, $N_{\mu^+}$ and $N_{\mu^-}$ are the final number of muons per bunch in the collider, and $\varepsilon_\perp$ is the transverse emittance.
   - ➢ Large fields at target to maximize number of captured muons, low final emittance before acceleration, large bending fields in collider

III. **Radiation from their decay products:** ($\mu^+ \rightarrow \nu_\mu + \nu_e + e^+$ and $\mu^- \rightarrow \nu_\mu + \overline{\nu_e} + e^-$ )
   - ➢ Large bore magnets to allow for protective shielding, combined function magnets to minimize straight sections in collider so as not to produce collimated beams of neutrinos

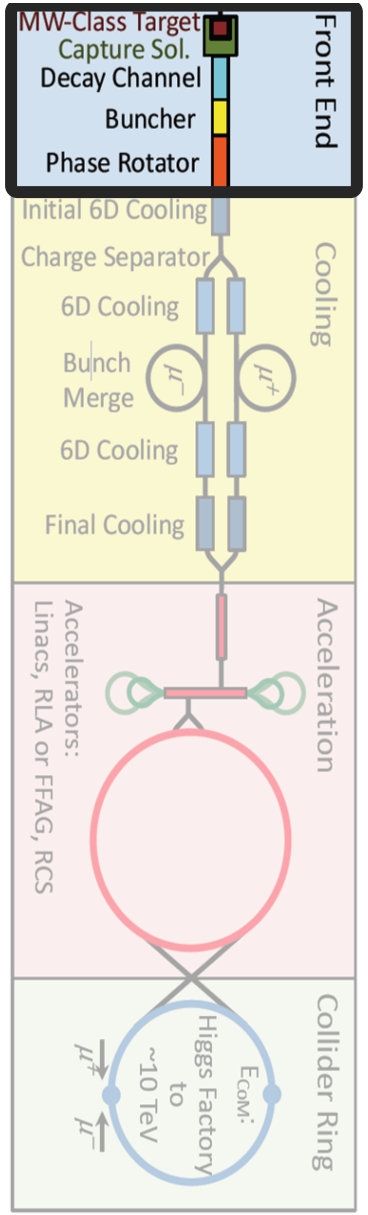
# Key Magnet Systems

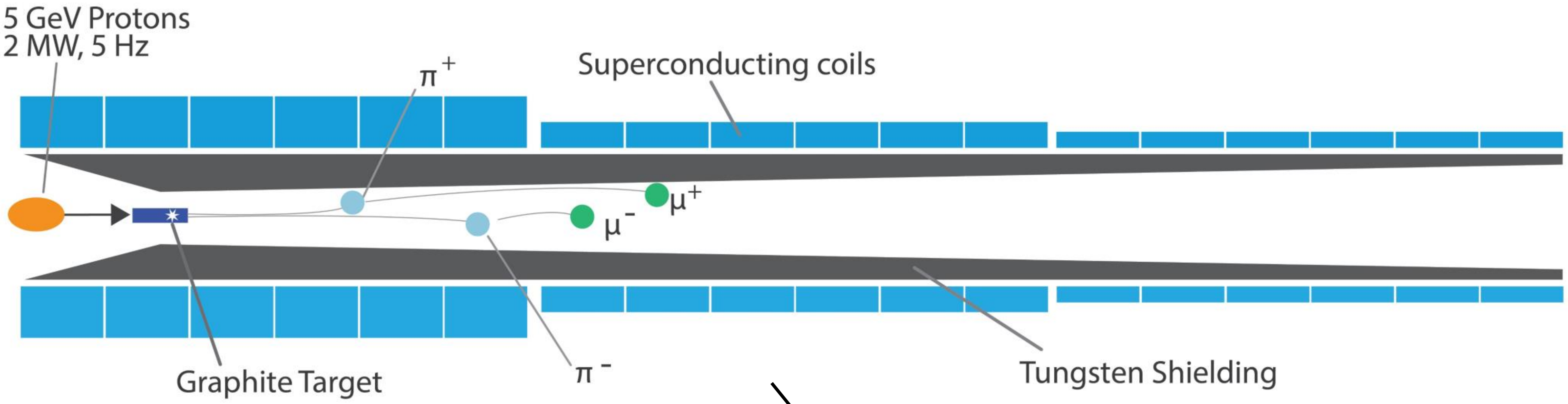
- Target, decay and capture channel
- Cooling
- Acceleration
- Collision

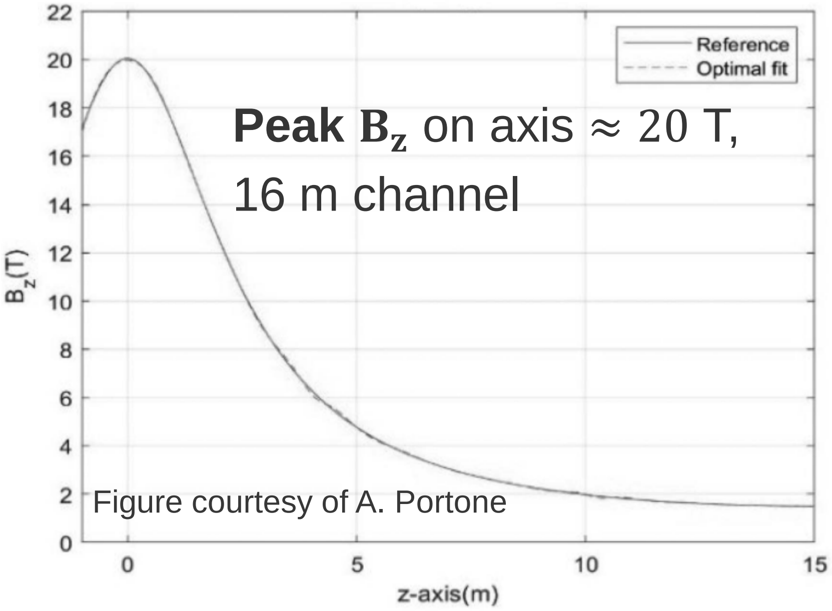


# Key Magnet Systems
## Target

# Configuration Concept



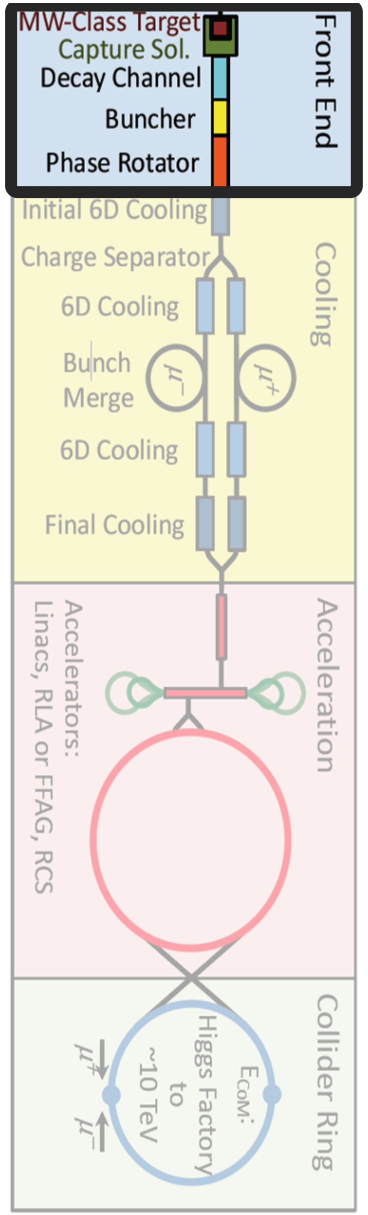




**Peak $B_z$** on axis ≈ 20 T, 16 m channel

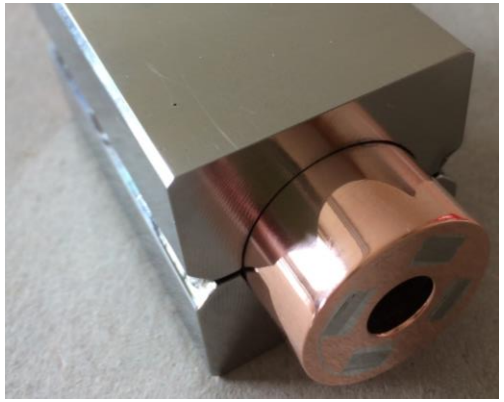
Figure courtesy of A. Portone

# Proposed Design Solution

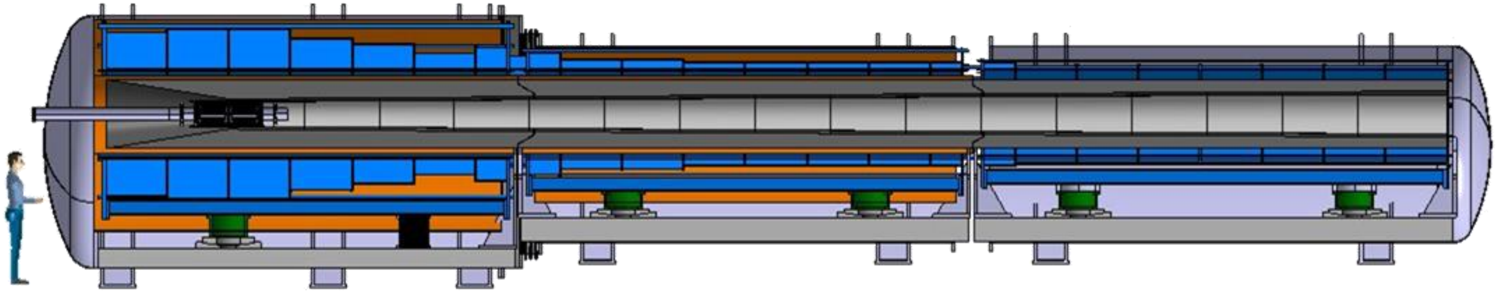


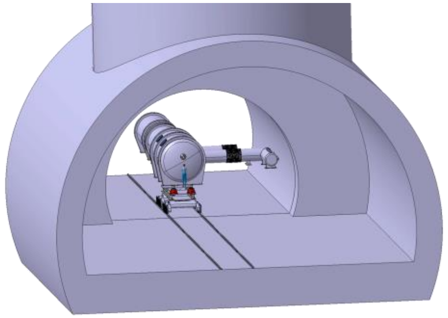
- **23** HTS, ReBCO-based solenoids
- **Peak $B_z$** on axis ≈ 20 T, 16 m channel
- ~1.2 m **bore** diameter
- All coil **currents** $I \cong 61$ kA
- Operating at **20-30 K**
- Total coil weight ~ **100 tons**
- System stored energy ~**1 GJ**
- Power consumption of **~ 1 MW**

Current proposed conductor: MIT “VIPER”



$I_{op}$ = 61 kA
$B_{op}$ = 20 T
$T_{op}$ = 20 K



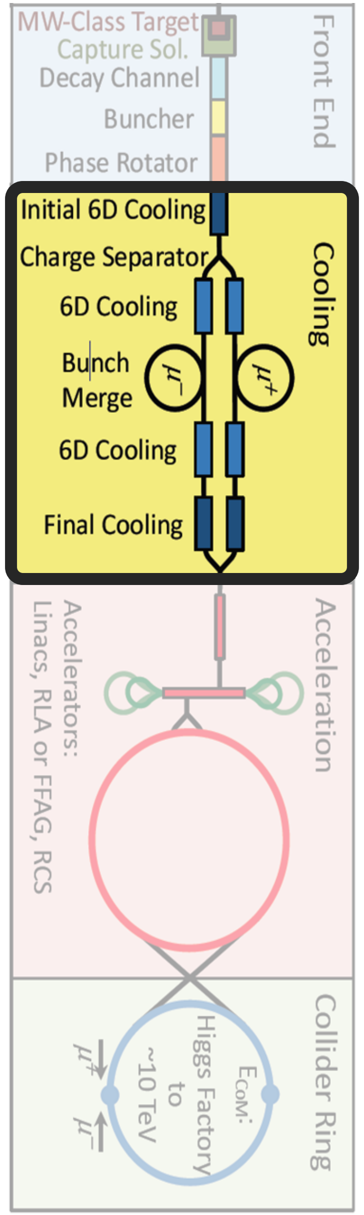


Figures and design by A. Portone, L. Bottura et. al
Accettura, C., et al. "Conceptual design of a target and capture channel for a Muon Collider.“, 2024

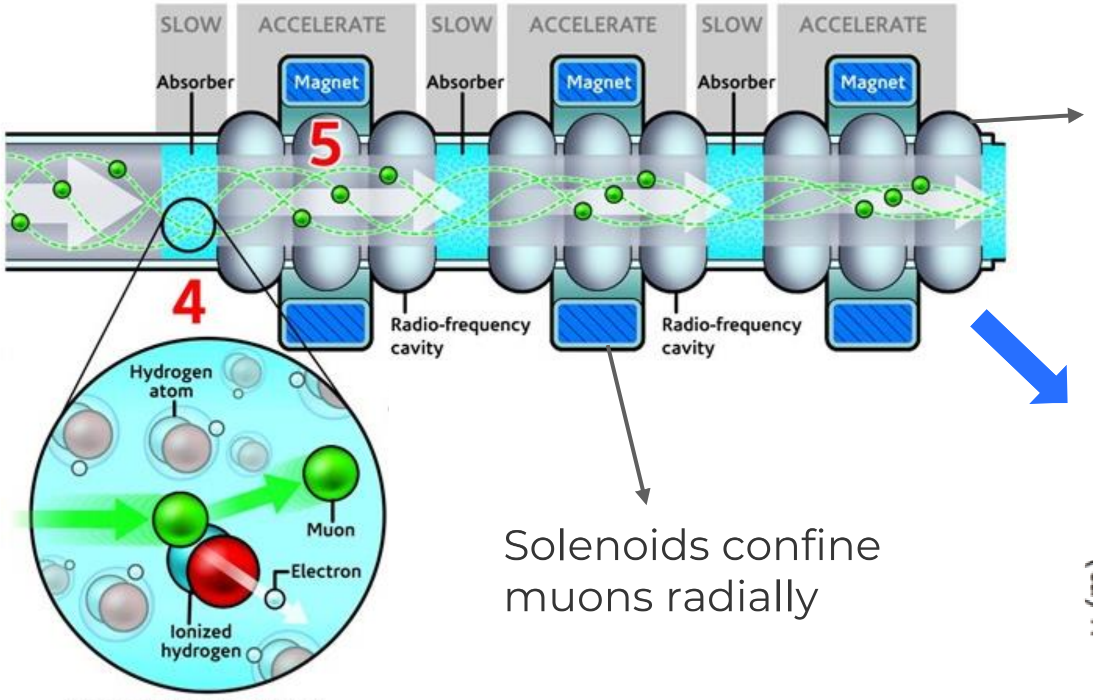
- ✓ Magnetic Design
- ✓ Detailed structural & local analyses
- ➢ Design integration work

# Key Magnet Systems
## Cooling – 6D

## Concept



Cooling system goal is to reduce the normalized rms transverse emittance of the beam by ~ 3 orders of magnitude to roughly 30 μm ·rad



*Infographic: STFC, Ben Gilliland*

RF cavities re-accelerate muons in longitudinal direction

Solenoids confine muons radially

Absorbers slow muons down in all directions

Cooling Cell Example

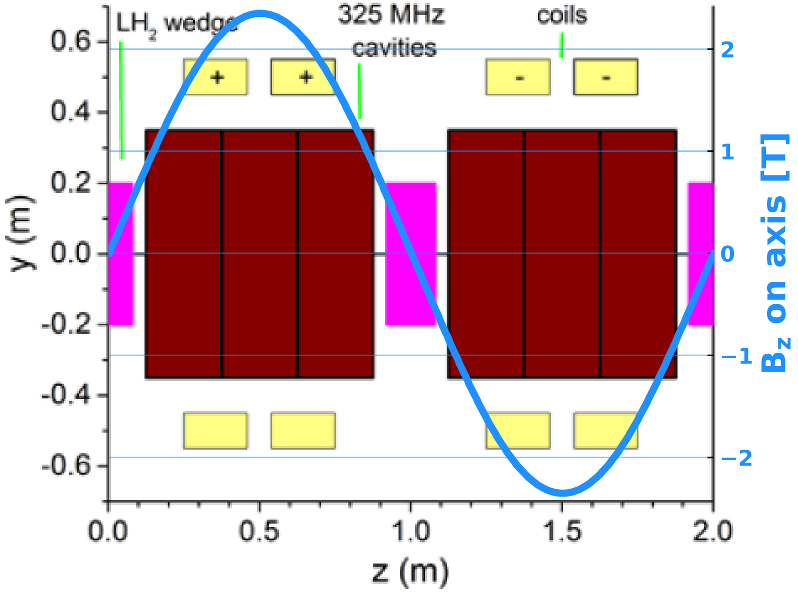


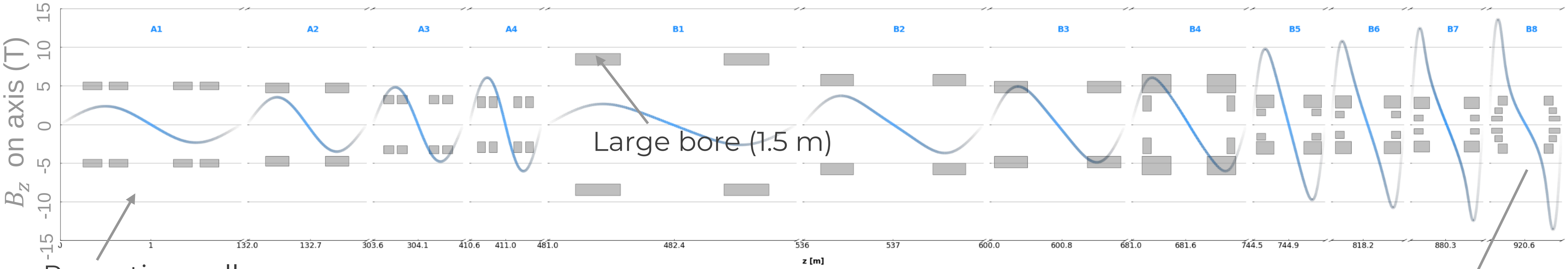
Image from Stratakis, Diktys et al "Rectilinear six-dimensional ionization cooling channel for a muon collider: A theoretical and numerical study." *Physical Review Special Topics-Accelerators and Beams* 18.3 (2015): 031003.

# Key Magnet Systems
# Cooling – 6D

## Baseline Reference (MAP) Evaluation

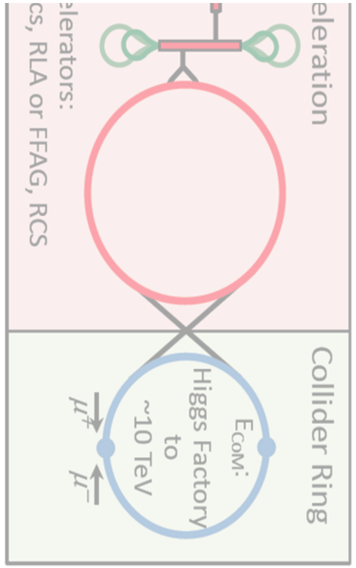
**~3000 solenoids** per ~1 km long cooling chain | **18 unique** solenoid types

**On axis field** 2.4 T to 13.6 T | **Bore size** from 90 mm to 1.5 m



Large bore (1.5 m)

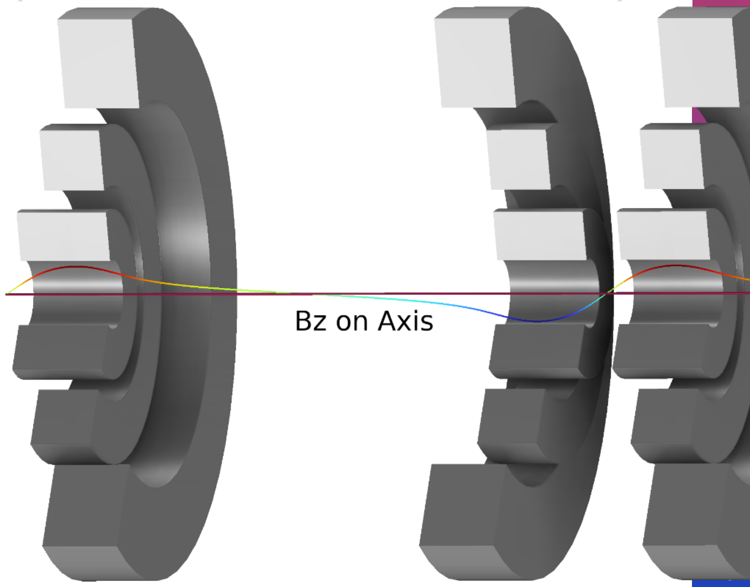
Repeating cells



**Un-optimized** from engineering perspective

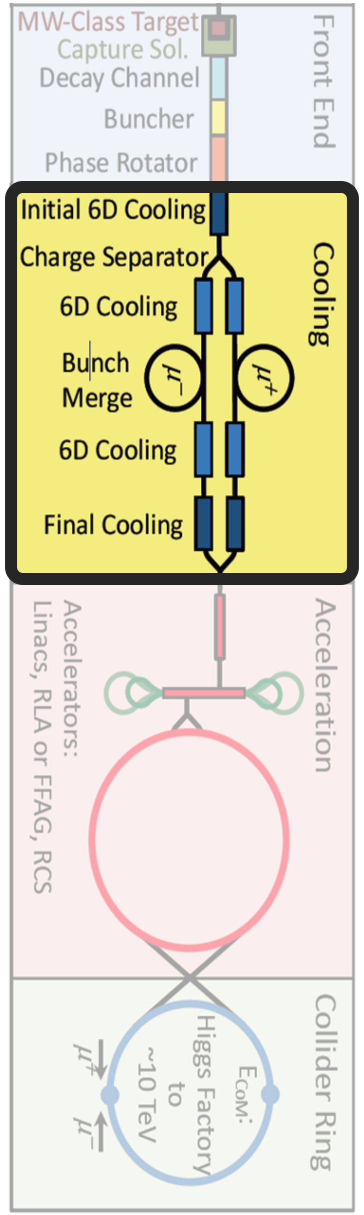
- Large average **hoop stresses** (peak 340 MPa)
- Tensile **radial stresses** (peak 20 MPa)
- Large stored **magnetic energies** (up to 45 MJ in one coil)
- Largest contributor to **cost** of magnets & powering in 3 TeV machine

Repeating cells



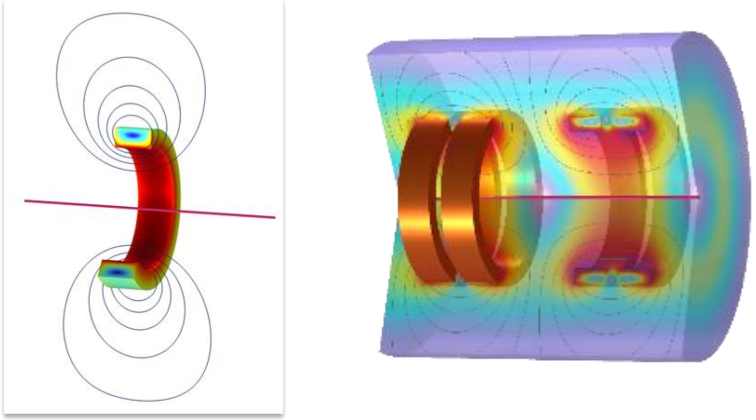
## Key Magnet Systems
## Cooling – 6D

# Unique Problem: Numerical Optimization Routine

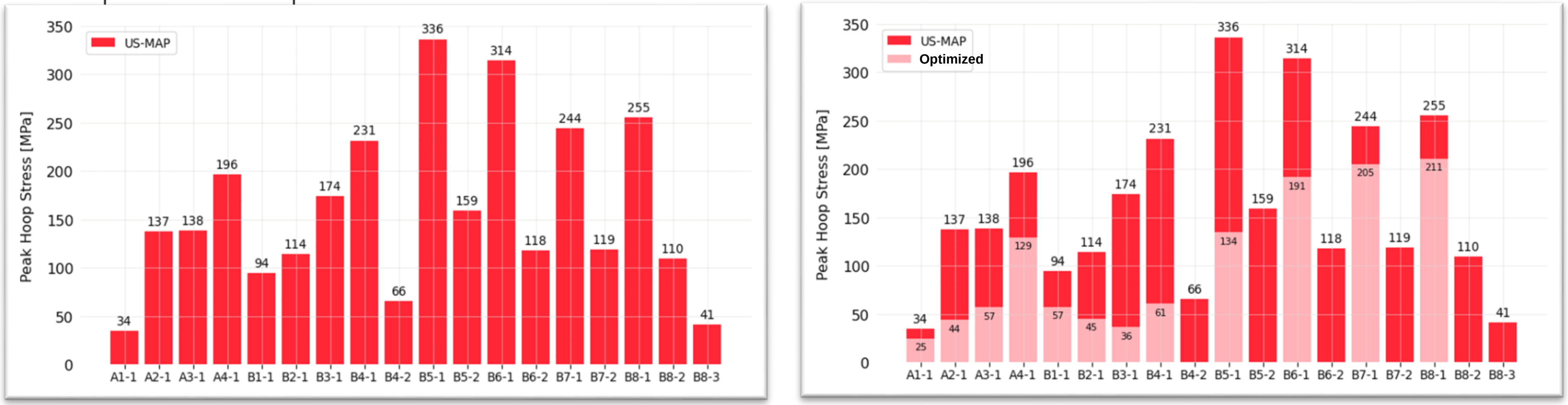


**Input**
- Desired field on axis + some tolerance
- Constraints (**J**, cell length, search resolution, …)

**Output**
- Many solenoid combination solutions and properties (single coil stresses, peak fields, etc.)



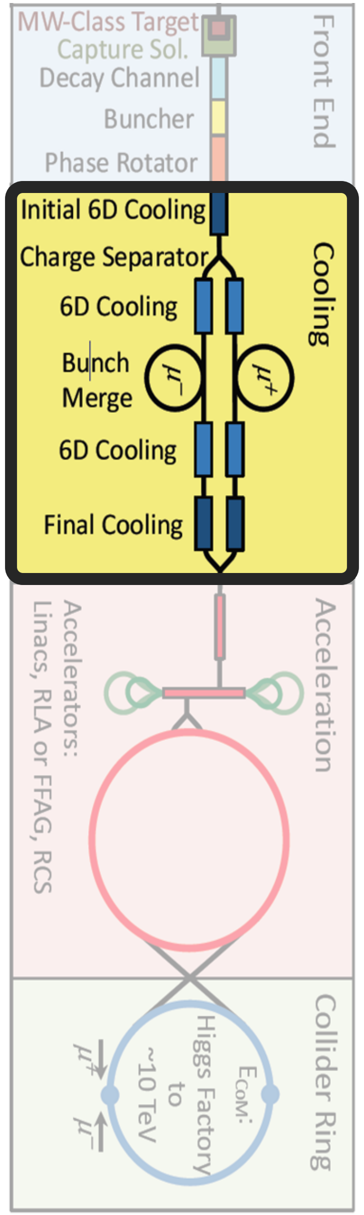
Example: **Stress** optimization



- ➢ **Optimization** is an ongoing iteration with beam optics to improve and realize a realistic solenoid configuration
- ➢ Integrated **cooling cell demonstrator**

# Key Magnet Systems
# Cooling – Final

# Concept & Design Configuration

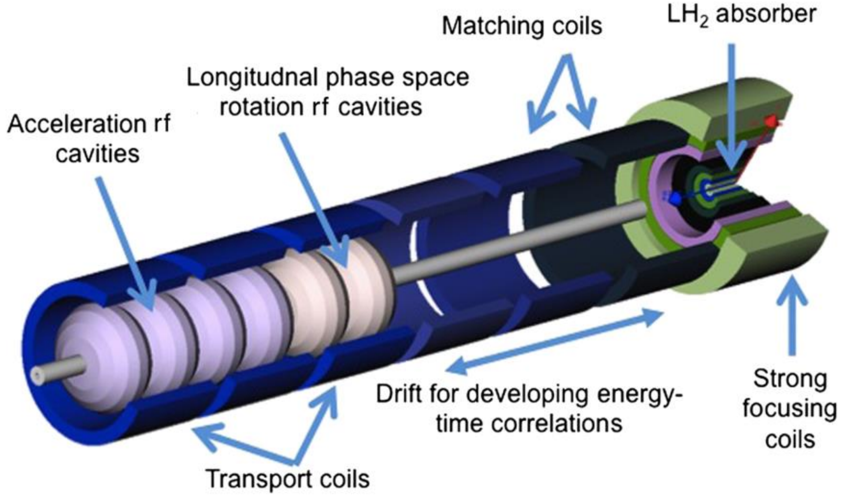


Final **emittance** of muon beam is inversely proportional to final cooling solenoid field strength → considering 14 **very high field** Final Cooling Solenoid Cells

## Current Design

- Magnetic field $\boldsymbol{B_z \geq 40}$ **T**
- Bore diameter **50 mm**
- Not/Metal-Insulated (N/M-I) HTS solenoids
- Field homogeneity w/in 1% over 0.5 m central axis
- Energizing time ≤6 hrs, persistency 0.1 Units/s

### Final Cooling Cell Schematic



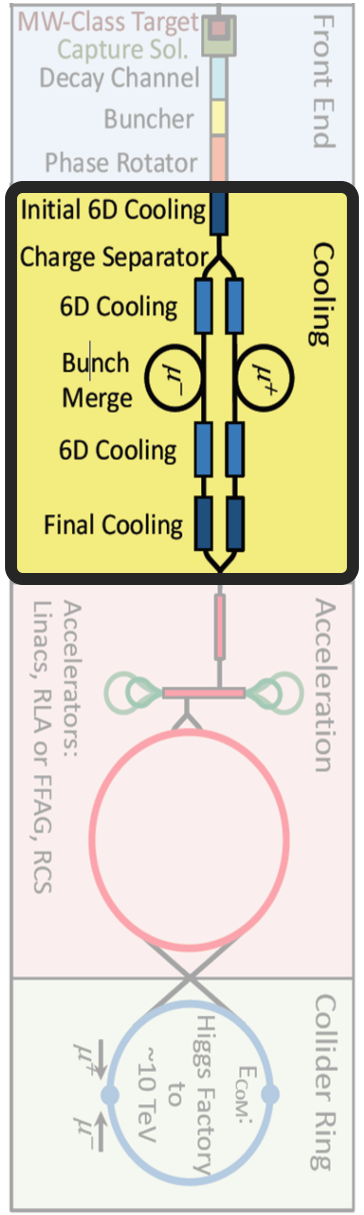
Sayed et al. Phys. Rev. ST Accel. Beams **18**, 091001

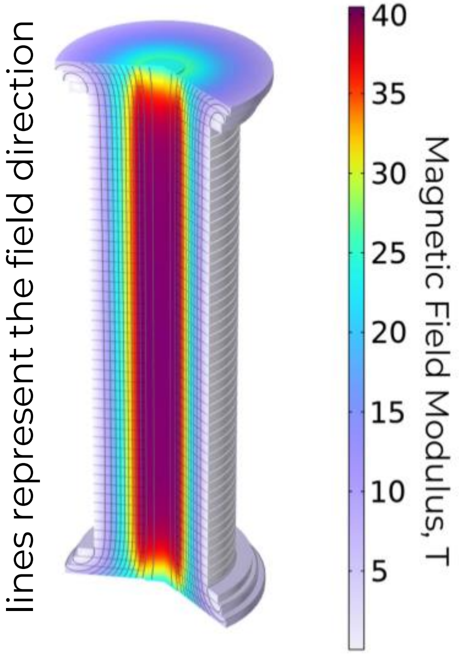
**Critical design parameters:**

- Stress state (no tensile radial stress, hoop stress 600 MPa peak)
- Transverse resistance – low enough for quench protection, but high enough to enable a full ramp < 6 hours

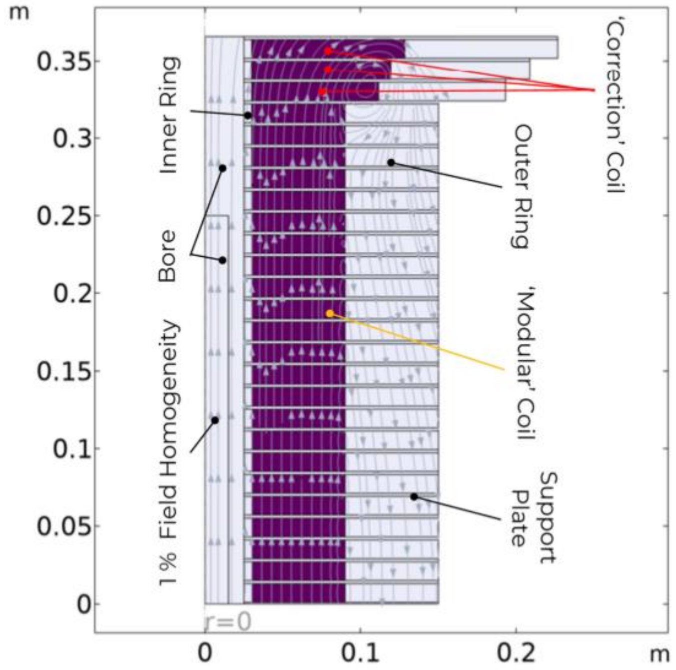
**Key Magnet Systems**
**Cooling – Final**

# Proposed Design Solution





Cross Section of ¼ Solenoid

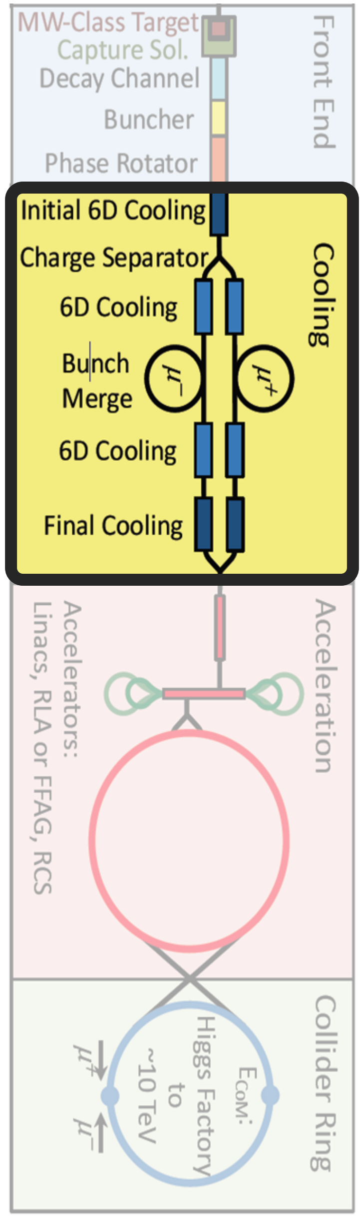


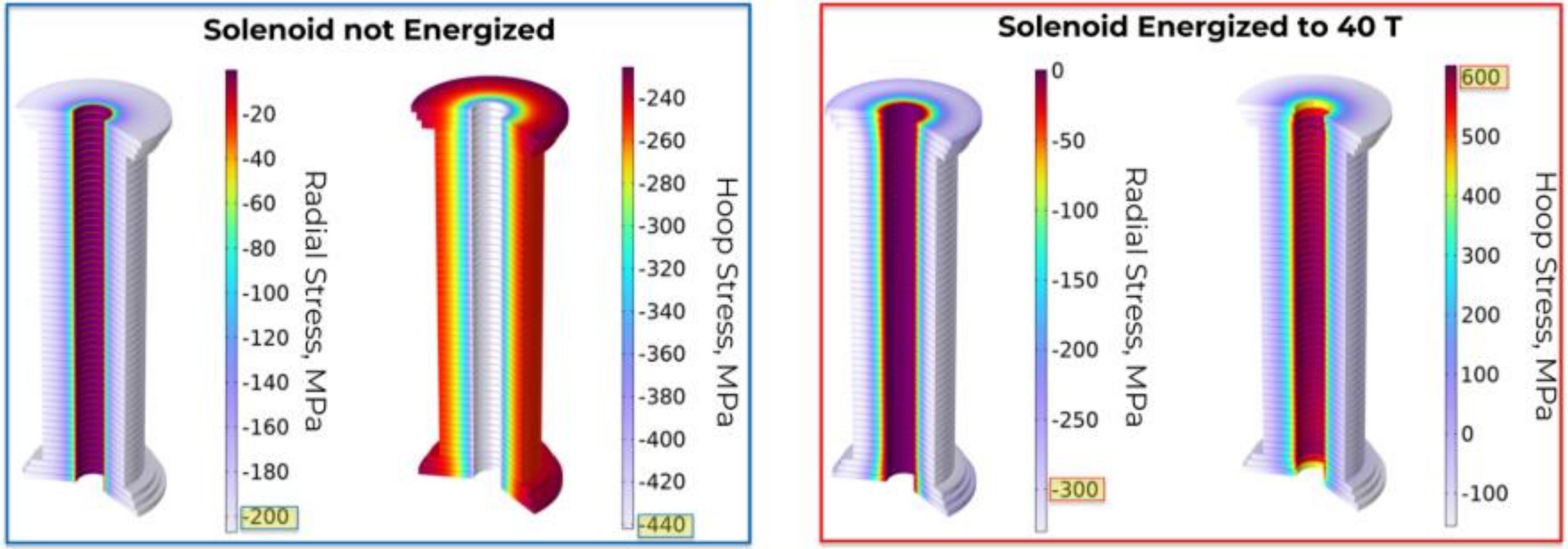
- Modular pancake design
- Supporting outer ring and plates to manage hoop, radial and vertical stresses
- Stack of soft-soldered pancakes
- Outer radius 150 mm
- J = 650 A/mm2
- 12 mm wide tape

Figures courtesy of B. Bordini, CERN. Bordini, B., et al. "Conceptual Design of a ReBCO Non/Metal-Insulated Ultra-High Field Solenoid for the Muon Collider.“ 2024

# Key Magnet Systems
## Cooling – Final

# Proposed Design Solution





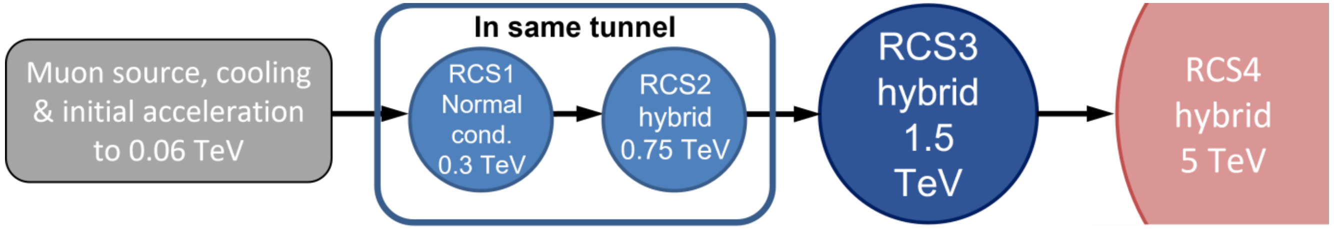
Figures courtesy of B. Bordini, CERN. Bordini, B., et al. "Conceptual Design of a ReBCO Non/Metal-Insulated Ultra-High Field Solenoid for the Muon Collider.“ 2024

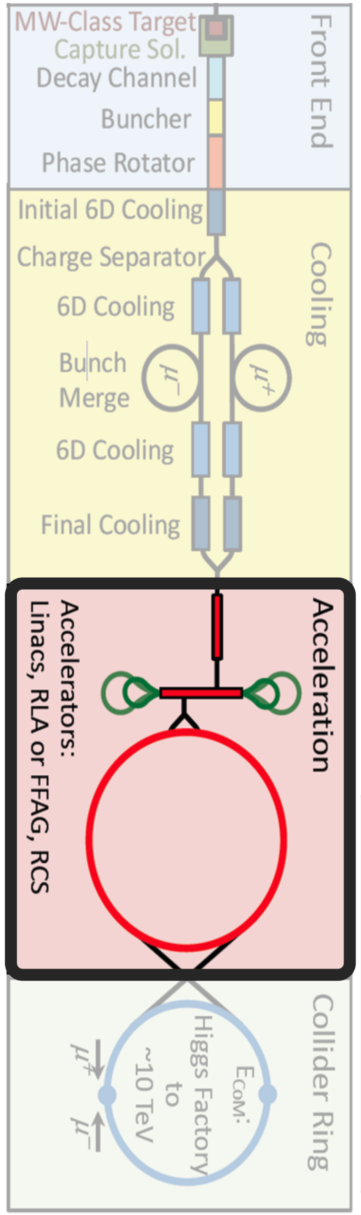
A **radial precompression of at least ~ 200 MPa** is essential to limit the conductor hoop stress to acceptable values and to prevent tensile radial stress.

- Detailed thermo-electromagnetic design and tests are in progress to validate the concept and analyze the coil in transient conditions like quench or ramp-up.
- Significant R&D required, however contributes only <0.5% to cost of magnets and powering systems of a MuC!

# Key Magnet Systems
## Acceleration

## Concept





- Linear accelerator
- Rapid-cycling synchrotron (**RCS**)
  - NC fast-ramping magnets sweep from injection to extraction field levels 0.36 to 1.8 T within 0.35 ms (4 kT/s)
- Hybrid Cycling Synchrotons (**HCS**)
  - Static SC magnets establish field offset of 10 T (or assumed 16 T in final HCS)
  - NC fast-ramping magnets swing from -1.8 to 1.8 T in ramp rates up to 3.3 kT/s

10 T steady state, +/- 1.8 T up to 4 kT/s
30x100 mm aperture

Hybrid Cycled Synchrotron

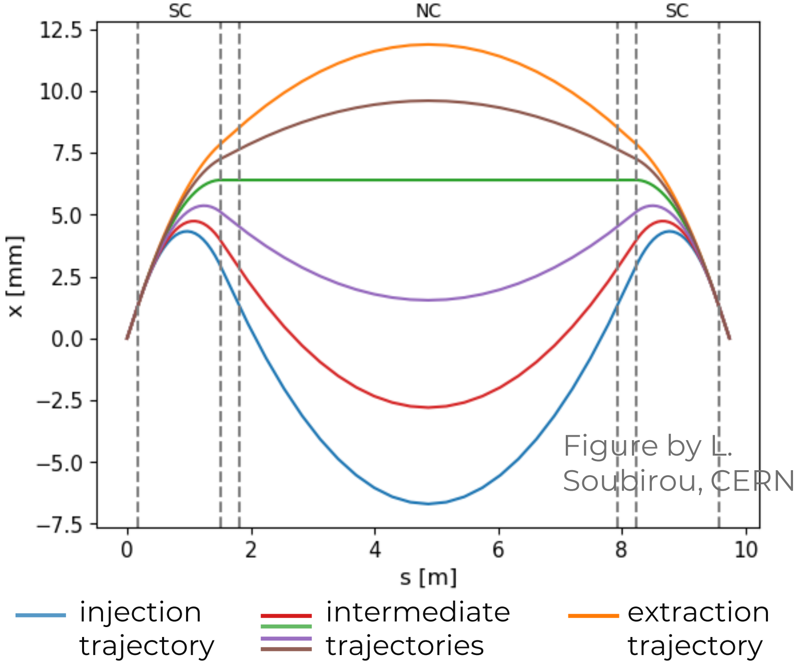


Figure by L. Soubirou, CERN

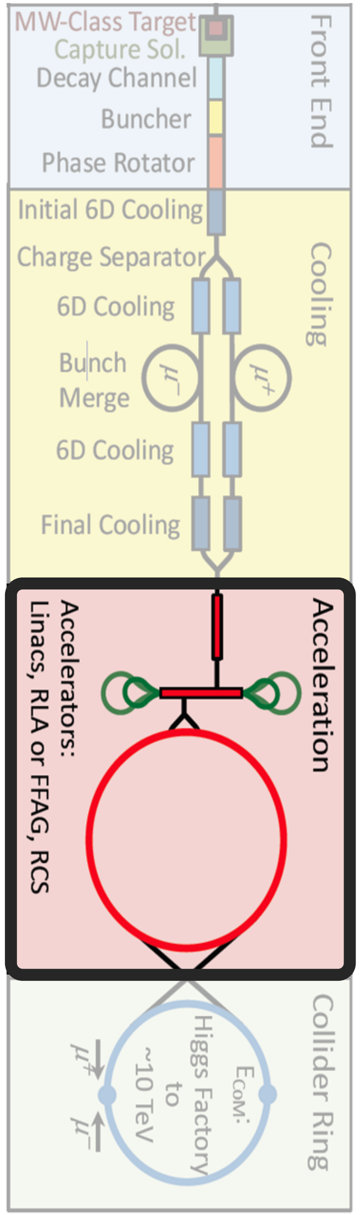
### Challenges

I. **Management of the power** (10s of GW) in the resistive dipoles,
   - Minimize stored magnetic energy (minimizes the stored power)
   - Efficient energy storage and recovery
   - **Limit the total losses** (iron hysteresis, eddy currents, etc.)

II. **Cost**: Magnets + powering in accelerators is largest cost contribution!

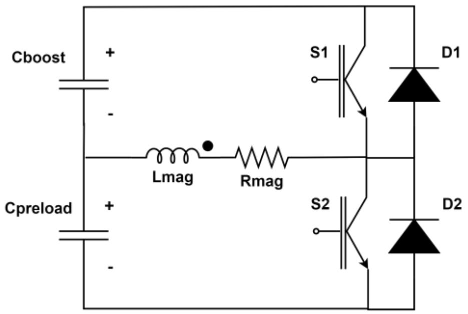
# Ongoing Designs

Breschi, M., et al. "Comparative analysis of resistive dipole accelerator magnets for a Muon Collider", 2024

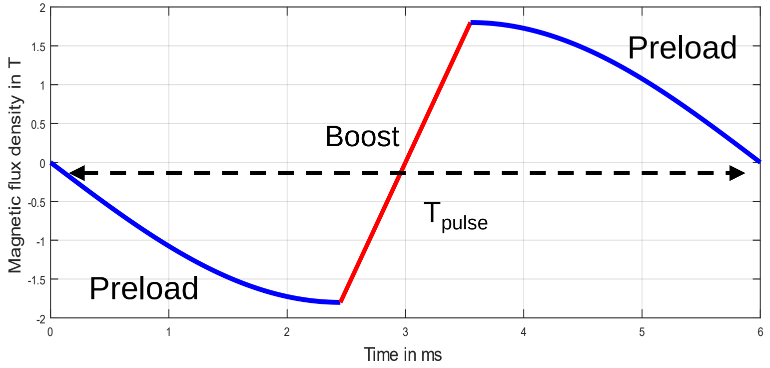


1. **<u>NC Dipole Configuration Optimization</u>** in Matlab (and FEMM) carried out to minimize the stored energy and losses while maintaining the best field homogeneity, considering different configurations, iron cross-sections, materials and current densities.
   - ➢ Best compromise b/w stored energy, losses and manufacturing simplicity is the **H-type magnet.**
2. **Powering system cost optimization carried out** in Python, considering different power converter options

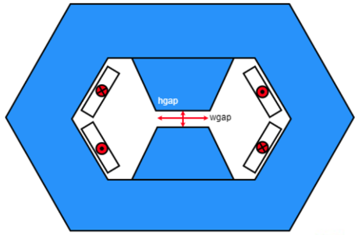
Power converter cell



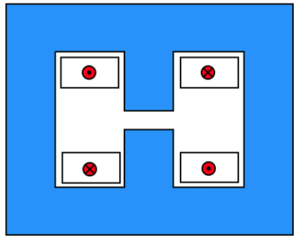
Magnetic field reference



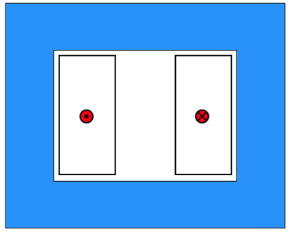
Hourglass frame magnet



H magnet

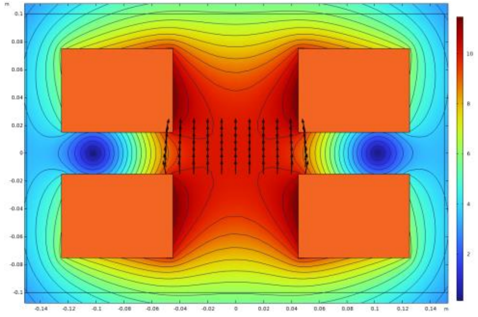


Window frame magnet

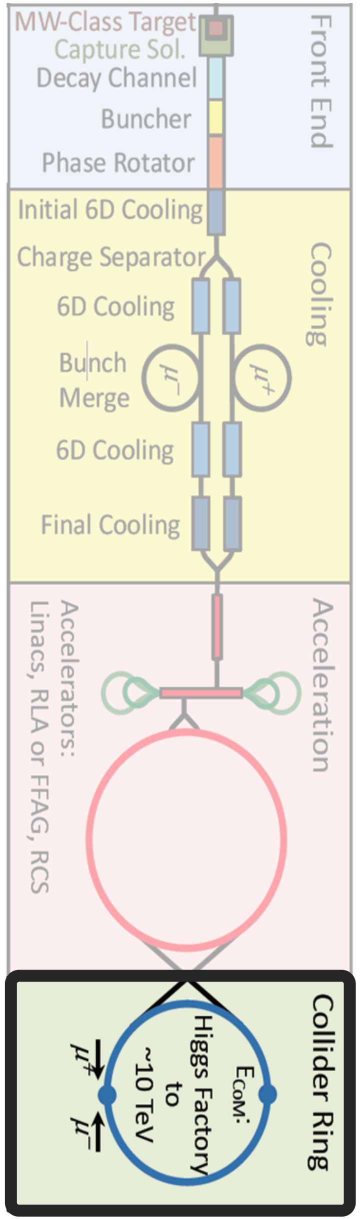


Figures courtesy of M. Breschi, F. Boattini, et al.

3. **<u>SC Dipole Optimization Routine</u>** in progress for rectangular aperture HTS racetrack coils with a target field of 10 T while minimizing cost for a target field quality.



# Current Magnet Requirements (10 TeV, 10 km ring)



## Main bending dipoles

- **16 T, 158 mm aperture**
- 5 m length
- 1200 magnets

## Arc

- Combined function dip. + sext, B1 + B B1~14 T, G ~±7100 T/m2, 100 mm aperture
- Combined function dip. + quad., B1~8T, **G ~±320 T/m**, 100 mm aperture

## IR

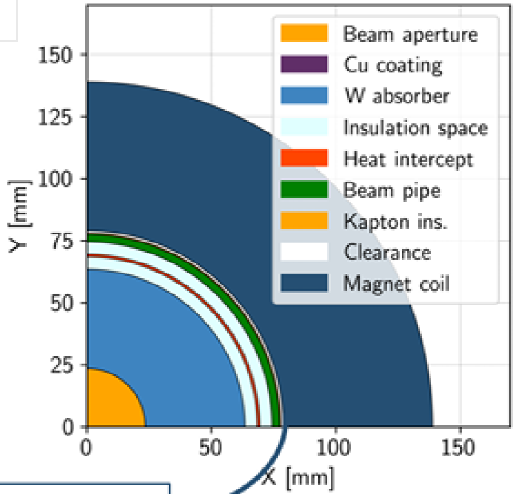
- Quads **G ~±300 T/m**, aperture ~120 mm
- Quads G ~±110 T/m, aperture ~300 mm
- Combined function dip. + quad., B1~8T, G ~±100 T/m, 280 mm aperture

Assuming 10 TeV machine and coil at 4.5 K

| | |
|---|---|
| Beam aperture (5σ) | 23.5 mm radius |
| Cu layer beam screen | 0.01 mm thick |
| Tungsten absorber | 40 mm thick |
| Insulation space | 5 mm thick |
| Heat intercept | 1 mm thick |
| Insulation space | 5 mm thick |
| Beam pipe | 3 mm thick |
| Kapton insulation | 0.5 mm thick |
| Clearance | 1 mm thick |
| Coil pack* | (60 mm thick) |

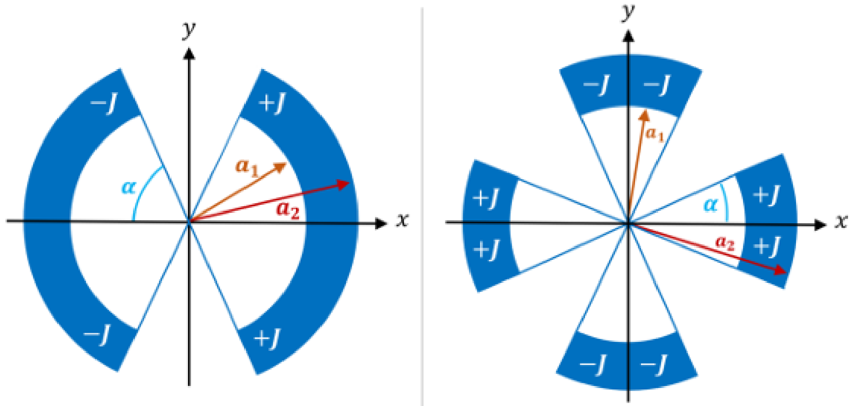
*thickness TBD, placeholder

*Courtesy of Patricia Borges de Sousa*
https://indico.cern.ch/event/1250075/contributions/5357594/



Coil aperture 158 mm

**Analytic Design Study** sector coil approximation dipole and quadrupole



Dipole

Quadrupole

$$B(w,J) = \frac{2\mu_0 J (a_2 - a_1)\sin\alpha}{\pi}$$

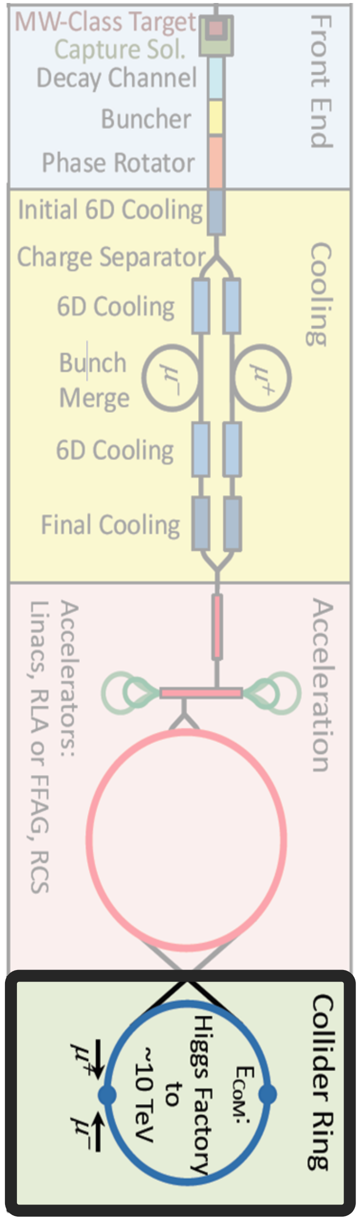
$$G(w,J) = \frac{2\mu_0 J}{\pi} \ln\left(\frac{a_2}{a_1}\right) \sin(2\alpha)$$

$(\,w = coil\ width\,)$

Figures courtesy of D. Novelli, INFN-Genoa

# Analytic design study

Novelli, Daniel, et al. "Analytical evaluation of dipole performance limits for a Muon Collider."



**Ongoing study** considering operating margins, peak stress, quench protection and total cost limit, assuming sector coil geometry with

- NbTi at 1.9 K
- Nb3Sn at 4.5 K
- HTS (ReBCO) at 4.5 and 20 K (*operating at higher temp. also can reduce absorber thickness!)

Summarized into Aperture vs Bore field (AB) plots .

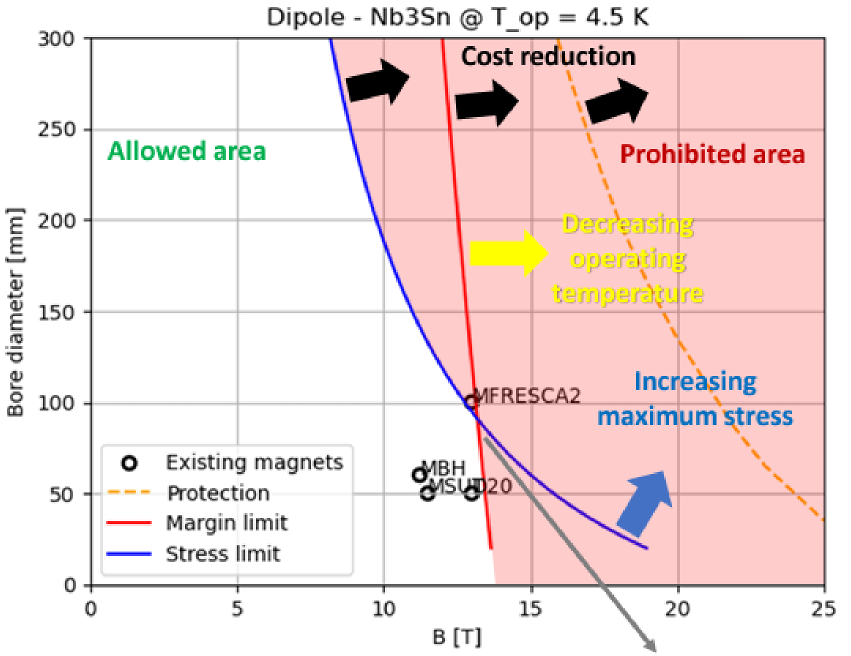


Figure courtesy of D. Novelli, INFN-Genoa

## Conclusions so far (main bending dipoles):

- **$Nb_3Sn$**: limited by peak stress and operating margin, provides feasible solutions only up to 14 T (can be considered for a 3 TeV MuC)
- **Not/metal-insulated ReBCO at 20 K**: limited by balance between total cost of superconductor and quench protection. Two configurations can be 16 T, 100 mm or 14 T, 140 mm

International
MUON Collider
Collaboration

MuCol

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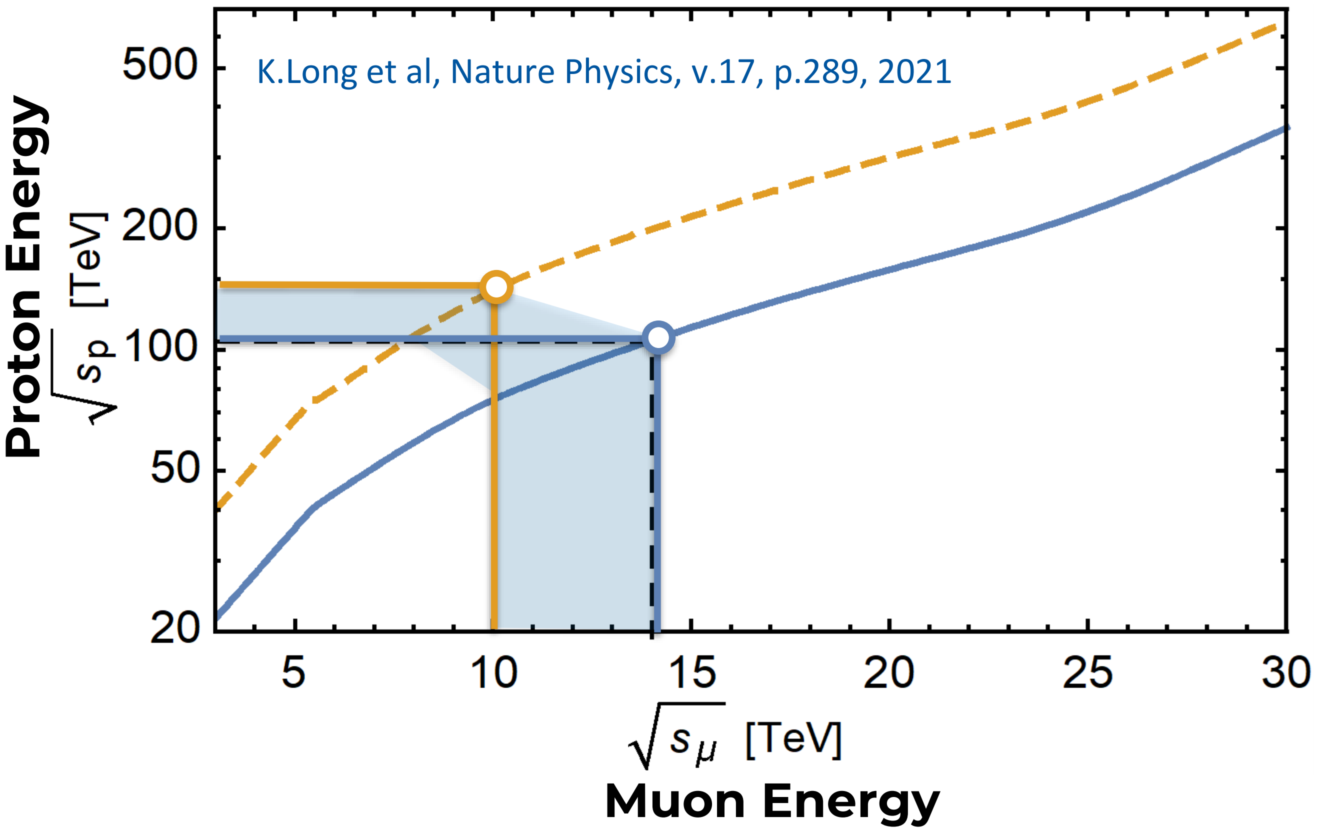
*Funded by the European Union (EU).Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the EU or European Research Executive Agency (REA). Neither the EU nor the REA can be held responsible for them.*

# Back-Up Slides

# Motivation: Muon Collider – Physics Reach

Energy at which the proton (hadron) collider cross-section equals that of muon (lepton) collider for selected production and decay channels



K.Long et al, Nature Physics, v.17, p.289, 2021

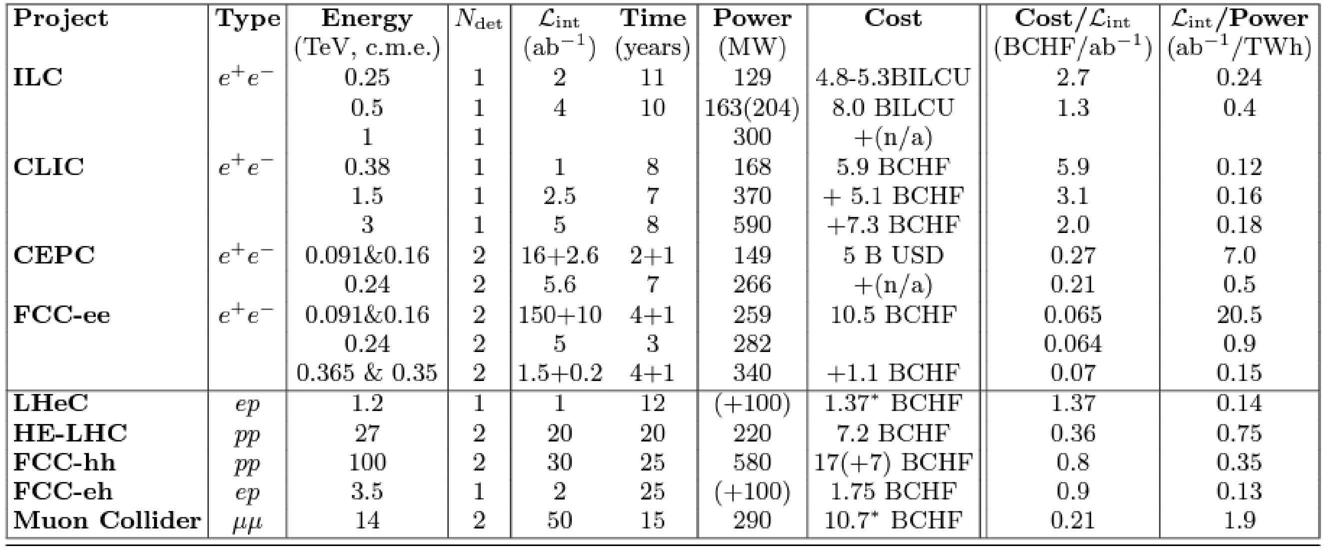
- - - comparable processes from muon and proton production

— possible QCD enhancement of production rates of a proton-proton collider

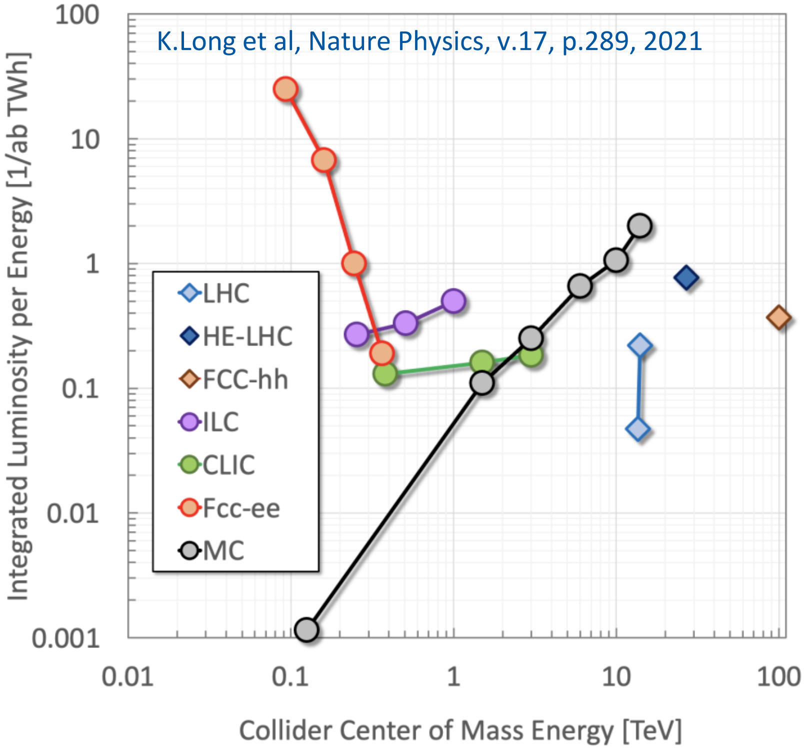
Muon collisions in the range of 10 TeV have comparable discovery potential to hadron collision in the range of 100 TeV

# Future Considerations for the Next HEP Machine

V. Shiltsev et al, Reviews of Modern Physics, v.93, p.57, 2021

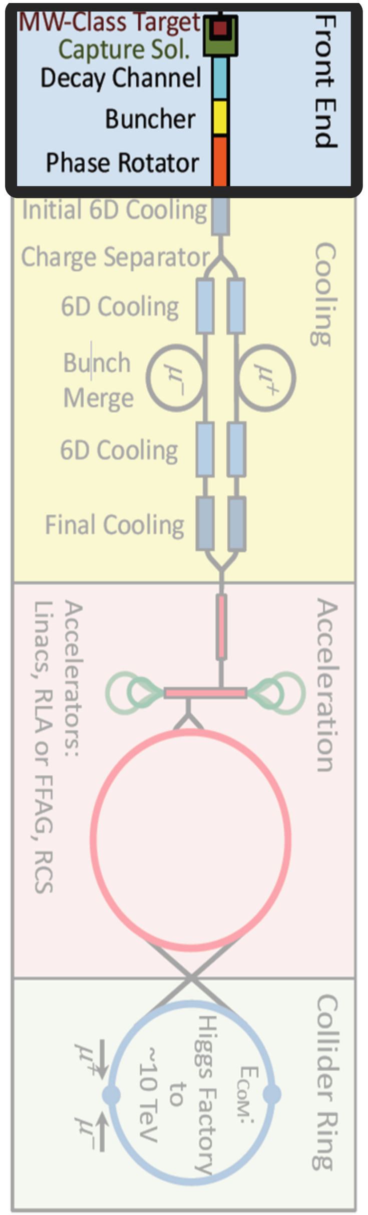


| **Project** | **Type** | **Energy** (TeV, c.m.e.) | $N_{\mathrm{det}}$ | $\mathcal{L}_{\mathrm{int}}$ ($\mathrm{ab}^{-1}$) | **Time** (years) | **Power** (MW) | **Cost** | **Cost/$\mathcal{L}_{\mathrm{int}}$** ($\mathrm{BCHF/ab}^{-1}$) | **$\mathcal{L}_{\mathrm{int}}$/Power** ($\mathrm{ab}^{-1}$/TWh) |
|---|---|---|---|---|---|---|---|---|---|
| **ILC** | $e^+e^-$ | 0.25 | 1 | 2 | 11 | 129 | 4.8-5.3BILCU | 2.7 | 0.24 |
| | | 0.5 | 1 | 4 | 10 | 163(204) | 8.0 BILCU | 1.3 | 0.4 |
| | | 1 | 1 | | | 300 | +(n/a) | | |
| **CLIC** | $e^+e^-$ | 0.38 | 1 | 1 | 8 | 168 | 5.9 BCHF | 5.9 | 0.12 |
| | | 1.5 | 1 | 2.5 | 7 | 370 | + 5.1 BCHF | 3.1 | 0.16 |
| | | 3 | 1 | 5 | 8 | 590 | +7.3 BCHF | 2.0 | 0.18 |
| **CEPC** | $e^+e^-$ | 0.091&0.16 | 2 | 16+2.6 | 2+1 | 149 | 5 B USD | 0.27 | 7.0 |
| | | 0.24 | 2 | 5.6 | 7 | 266 | +(n/a) | 0.21 | 0.5 |
| **FCC-ee** | $e^+e^-$ | 0.091&0.16 | 2 | 150+10 | 4+1 | 259 | 10.5 BCHF | 0.065 | 20.5 |
| | | 0.24 | 2 | 5 | 3 | 282 | | 0.064 | 0.9 |
| | | 0.365 & 0.35 | 2 | 1.5+0.2 | 4+1 | 340 | +1.1 BCHF | 0.07 | 0.15 |
| **LHeC** | $ep$ | 1.2 | 1 | 1 | 12 | (+100) | 1.37* BCHF | 1.37 | 0.14 |
| **HE-LHC** | $pp$ | 27 | 2 | 20 | 20 | 220 | 7.2 BCHF | 0.36 | 0.75 |
| **FCC-hh** | $pp$ | 100 | 2 | 30 | 25 | 580 | 17(+7) BCHF | 0.8 | 0.35 |
| **FCC-eh** | $ep$ | 3.5 | 1 | 2 | 25 | (+100) | 1.75 BCHF | 0.9 | 0.13 |
| **Muon Collider** | $\mu\mu$ | 14 | 2 | 50 | 15 | 290 | 10.7* BCHF | 0.21 | 1.9 |

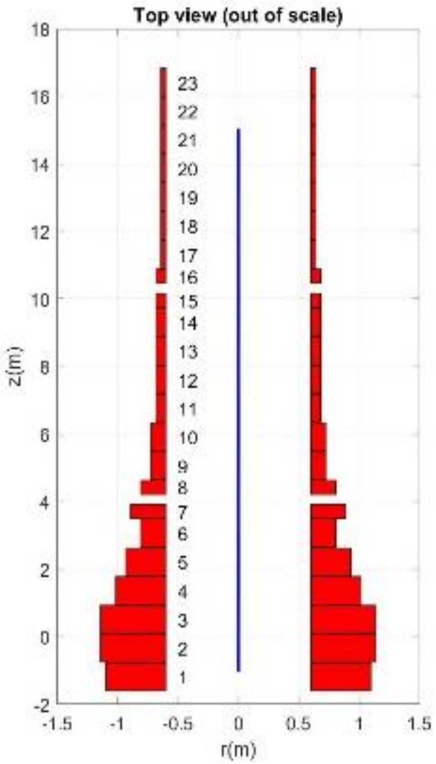

K.Long et al, Nature Physics, v.17, p.289, 2021

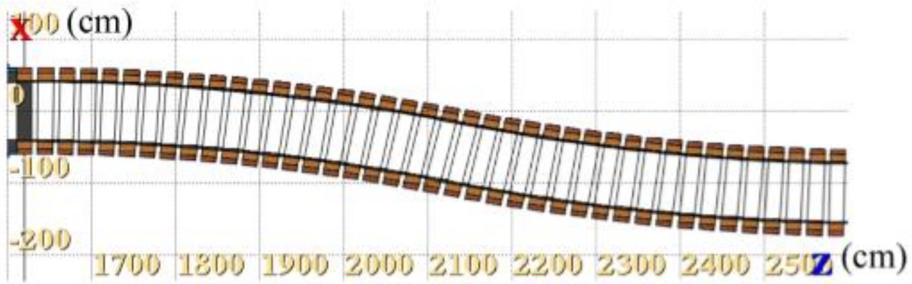
# Key Magnet Systems
## Target

## Back-Up Slide



- 21 T peak field on **HTS cable**
- **Double pancake** winding
- Max **shear stress** in tapes $\tau \approx 30$ Mpa
- **He coolant** $\approx 20$ K, $P \approx 20$ bar
- **3 sections**, ~5.5 m long each, 0.48 m gaps
- Detection and dump strategy for **quenches**, hot spot limit ($T_{HS} \approx 150 - 200$ K), detection threshold in range of 10 mV, dump voltages w/in 5 kV,
- Max **field error** 4.2 %
- HTS cable length 9.65 km
- Tensile stress generally below 10 Mpa
- Dominantly affected by hoop stresses and axial compressive stresses from different coils



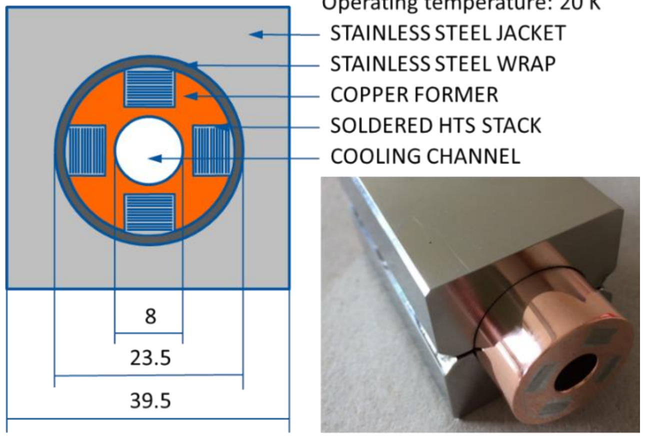


MIT “VIPER” conductor

M. Takayasu et al., IEEE TAS, 21 (2011) 2340
Z. S. Hartwig et al., SUST, 33 (2020) 11LT01

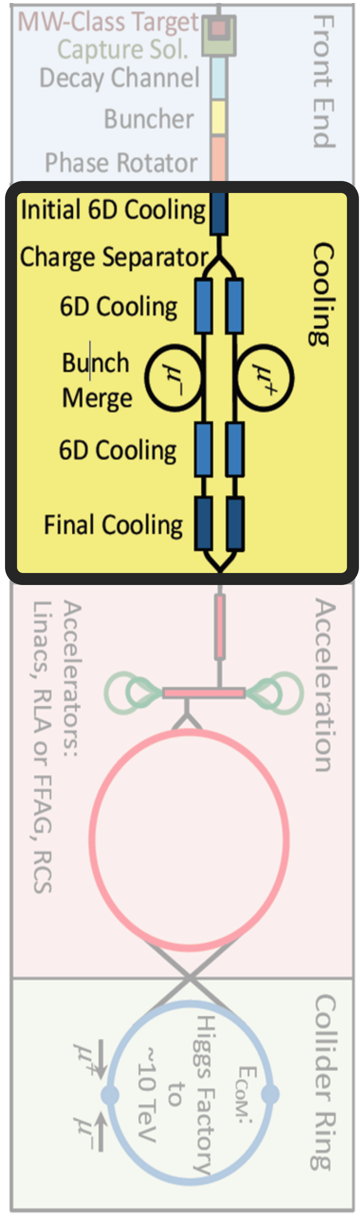
HTS conductor design

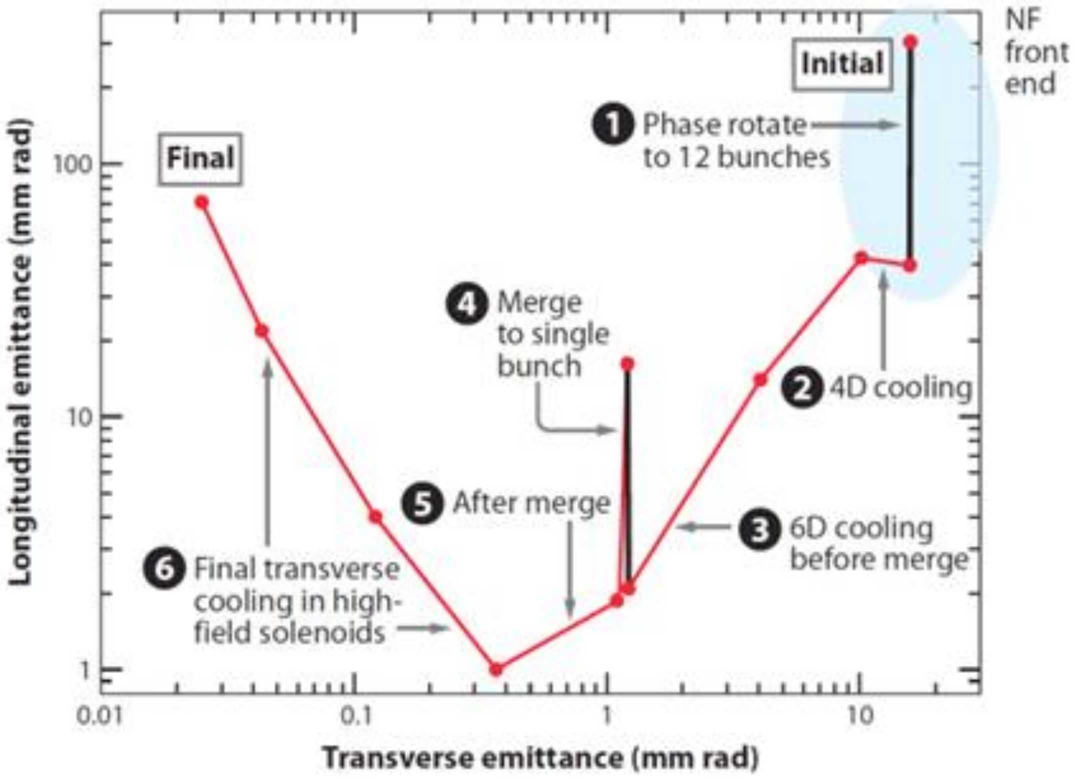
Operating current: 58 kA
Operating field: 20 T
Operating temperature: 20 K



# Key Magnet Systems
## Cooling – 6D

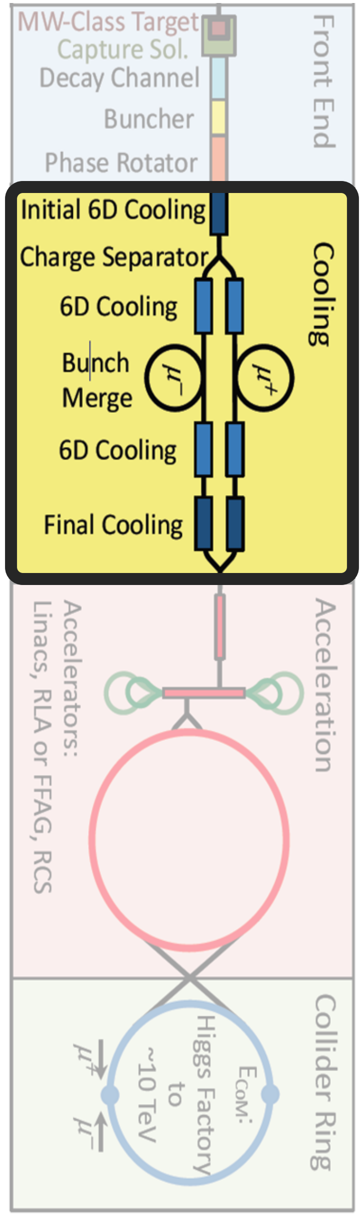
## Concept

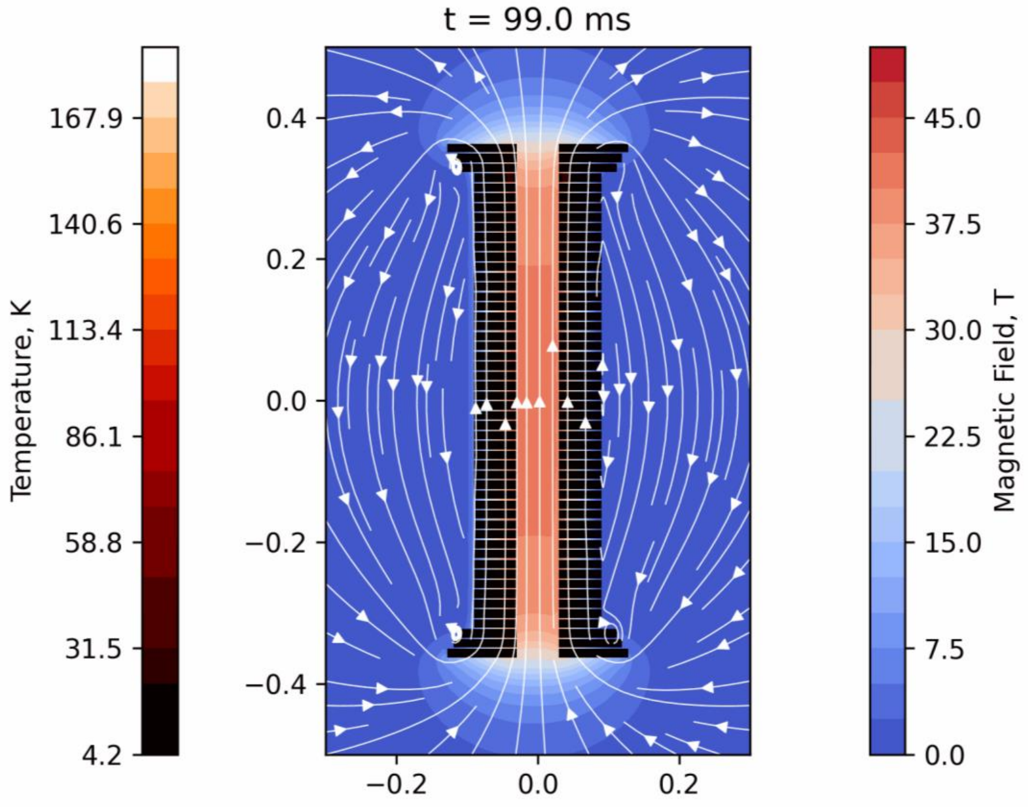


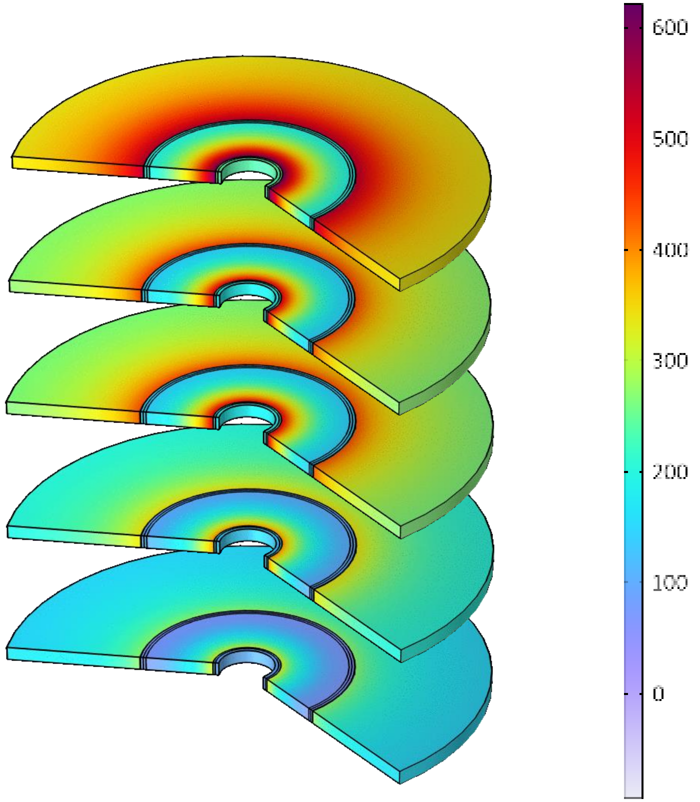


# Key Magnet Systems
## Cooling – Final

## Design



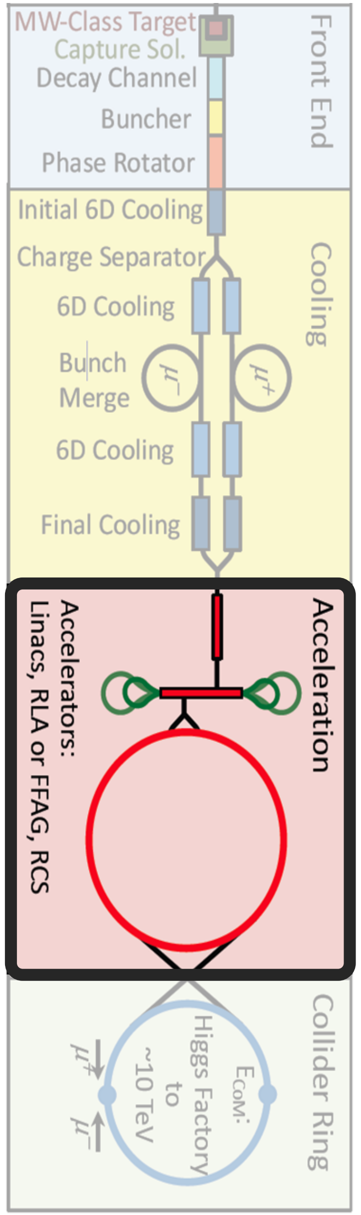


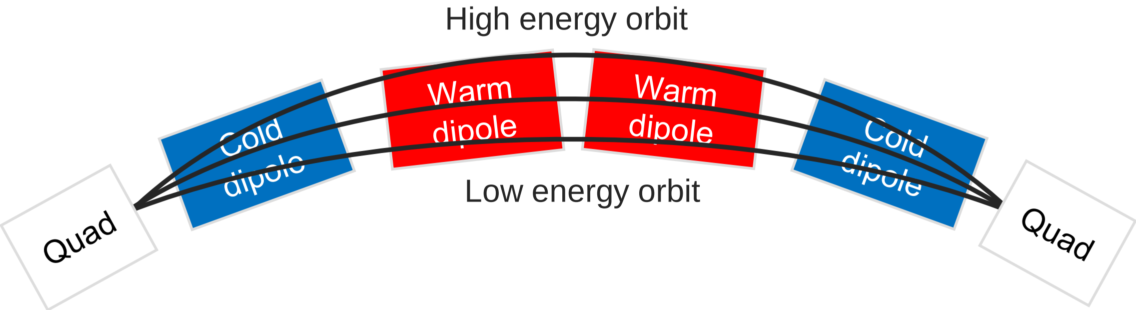


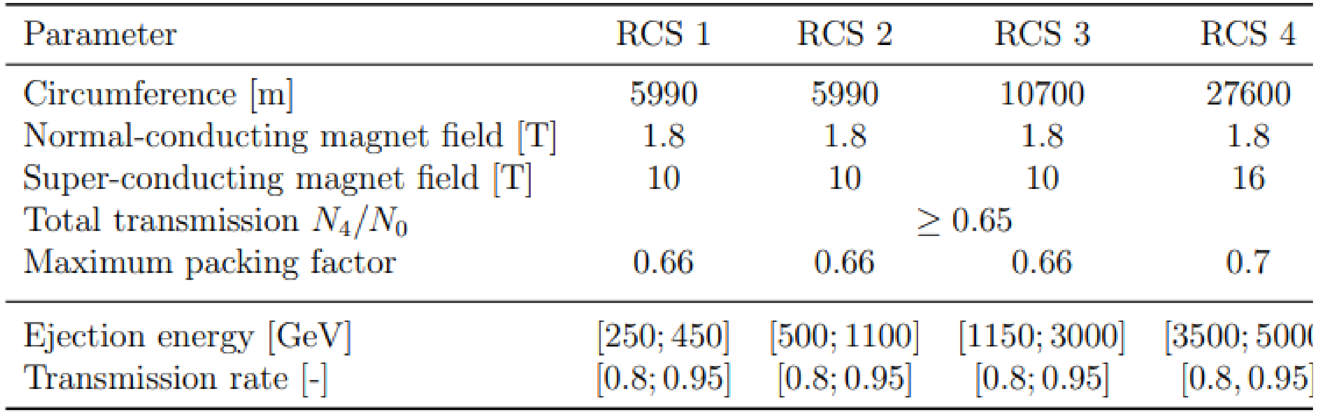
At this magnet scale (i.e. stored energy and size) a **non-insulated winding** seems to be a good option for quench management. Transverse resistance control in a range suitable for operation, balancing protection, mechanics, ramp time and field stability will be crucial (**priority R&D**)

# Key Magnet Systems
# Acceleration

# Backup Slide





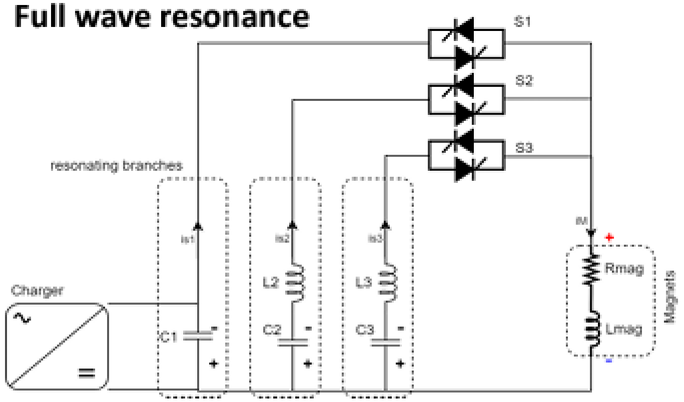


| Parameter | RCS 1 | RCS 2 | RCS 3 | RCS 4 |
|---|---|---|---|---|
| Circumference [m] | 5990 | 5990 | 10700 | 27600 |
| Normal-conducting magnet field [T] | 1.8 | 1.8 | 1.8 | 1.8 |
| Super-conducting magnet field [T] | 10 | 10 | 10 | 16 |
| Total transmission $N_4/N_0$ | | $\geq 0.65$ | | |
| Maximum packing factor | 0.66 | 0.66 | 0.66 | 0.7 |
| Ejection energy [GeV] | [250; 450] | [500; 1100] | [1150; 3000] | [3500; 500 |
| Transmission rate [-] | [0.8; 0.95] | [0.8; 0.95] | [0.8; 0.95] | [0.8, 0.95] |

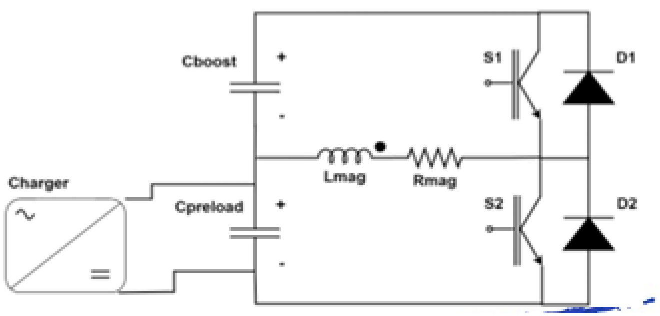
Table 1: Parameters used for the "RCS 4 in LHC tunnel" optimization.

Differerent power converter options investigat

**Full wave resonance**



**Commutated resonance (new)**



# Back-Up Slide – Beam Properties Collider

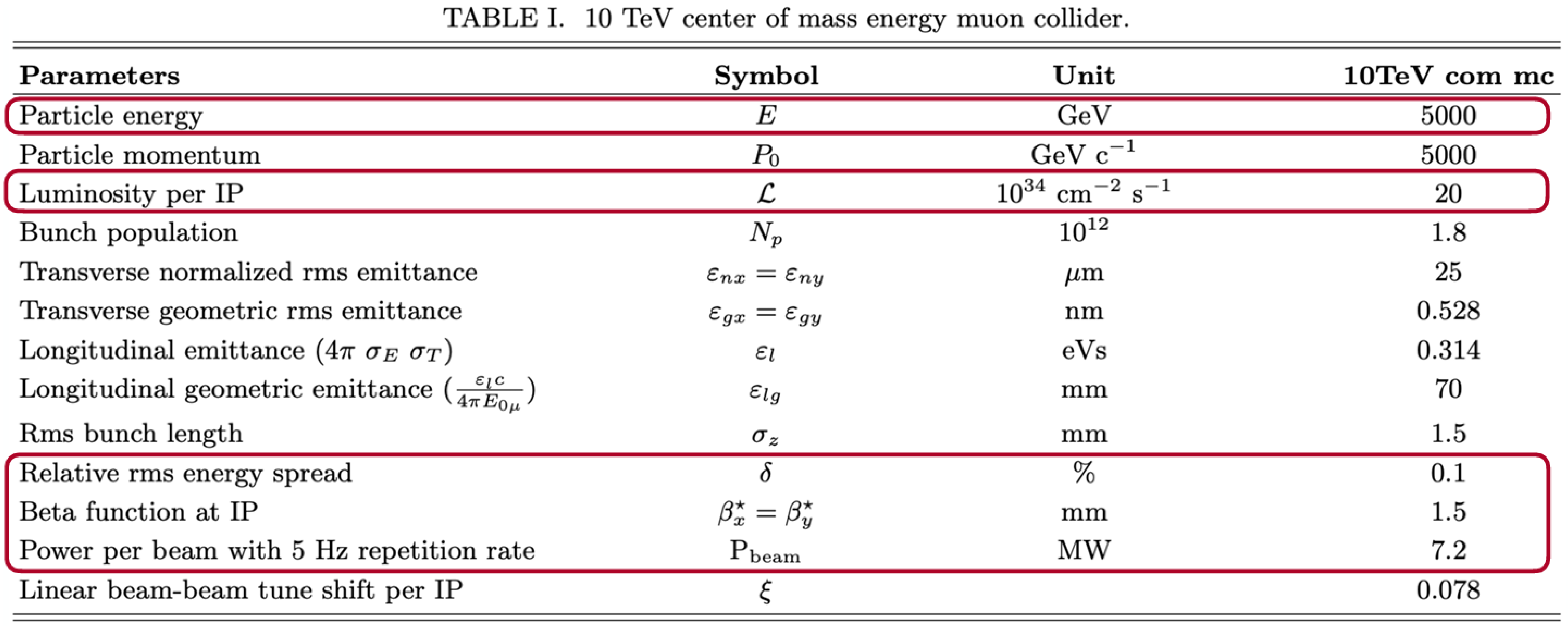
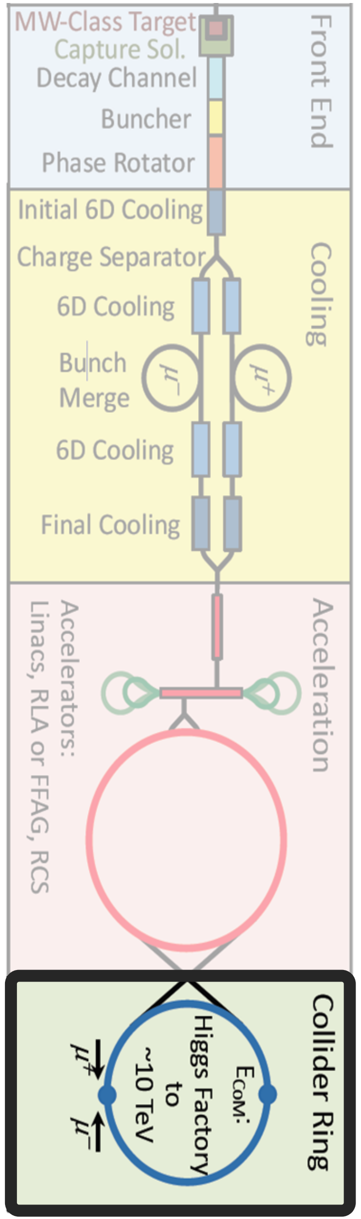


TABLE I. 10 TeV center of mass energy muon collider.

| **Parameters** | **Symbol** | **Unit** | **10TeV com mc** |
|---|---|---|---|
| Particle energy | $E$ | GeV | 5000 |
| Particle momentum | $P_0$ | GeV $c^{-1}$ | 5000 |
| Luminosity per IP | $\mathcal{L}$ | $10^{34}$ cm$^{-2}$ s$^{-1}$ | 20 |
| Bunch population | $N_p$ | $10^{12}$ | 1.8 |
| Transverse normalized rms emittance | $\varepsilon_{nx} = \varepsilon_{ny}$ | $\mu$m | 25 |
| Transverse geometric rms emittance | $\varepsilon_{gx} = \varepsilon_{gy}$ | nm | 0.528 |
| Longitudinal emittance ($4\pi\ \sigma_E\ \sigma_T$) | $\varepsilon_l$ | eVs | 0.314 |
| Longitudinal geometric emittance ($\frac{\varepsilon_l c}{4\pi E_{0\mu}}$) | $\varepsilon_{lg}$ | mm | 70 |
| Rms bunch length | $\sigma_z$ | mm | 1.5 |
| Relative rms energy spread | $\delta$ | % | 0.1 |
| Beta function at IP | $\beta_x^\star = \beta_y^\star$ | mm | 1.5 |
| Power per beam with 5 Hz repetition rate | $\mathrm{P_{beam}}$ | MW | 7.2 |
| Linear beam-beam tune shift per IP | $\xi$ | | 0.078 |

# Analytic design study

Novelli, Daniel, et al. "Analytical evaluation of dipole performance limits for a Muon Collider."



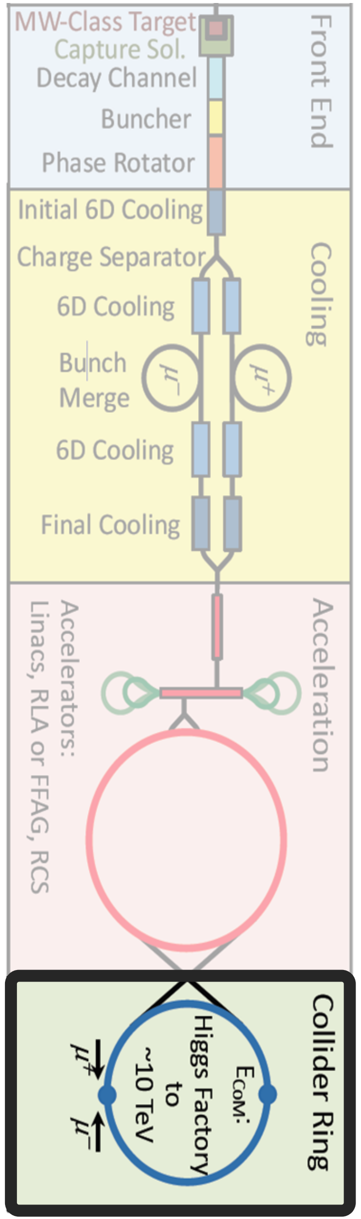
## Assumptions in Analytic Evaluations (see table)

- Quench protection system: quench heaters bring entire volume to resistive state; assumed 40 ms delay between initial quench and coils becoming resistive
- Total cost limit of 175 kEUR/m (FCC)
    - Assumed costs: Labour - 20 kEUR/m (LHC)
    - Other materials - 20kEUR/m
    - See table for conductor cost (*aspirational cost assumed future cost reduction factor of ~3)

| | Critical current fit source | Temp. Margins [K] | Stress Limit (MPa) | SC cost [EU/kg] | SC *aspirational cost [EU/kg] | Hot Spot Temperature Limit [K] |
|---|---|---|---|---|---|---|
| NbTi (1.9 K) | LHC | + 2 | 100 | 330 | | 350 |
| Nb3Sn (4.5 K) | FCC target performance | + 2.5 | 150 | 2000 | 700 | 350 |
| HTS (ReBCO) (4.5 and 20 K | Fujikura FESC AP | + 2.5 | 300 | 8000 | 2500 | 200 |

# Analytic design study

Novelli, Daniel, et al. "Analytical evaluation of dipole performance limits for a Muon Collider."



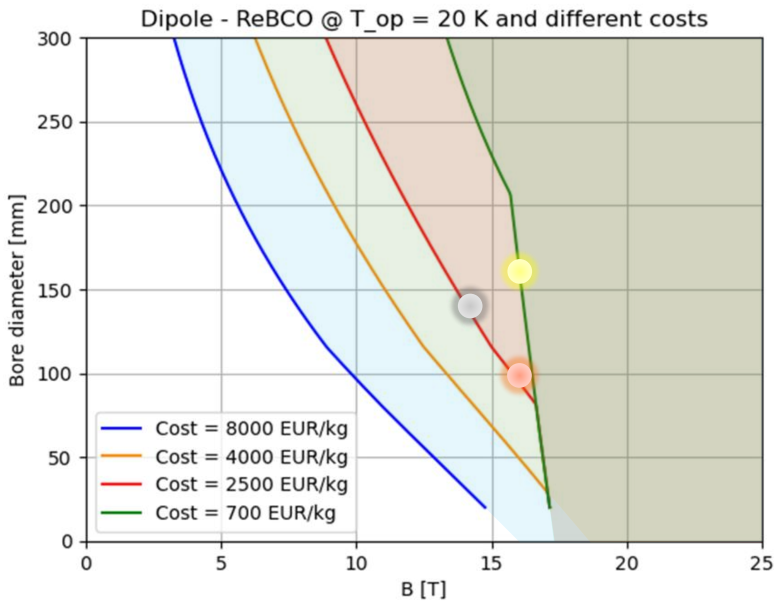
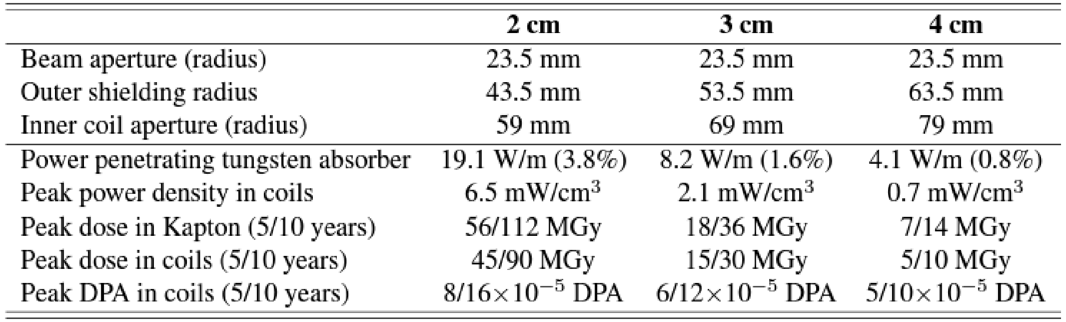


Figure by D. Novelli, INFN-Genoa

- The initial design target (● – 16 T, 158 mm) of the main dipoles.
- Two possible configurations can be 16 T, 100 mm (●) and 14 T, 140 mm (●).



| | 2 cm | 3 cm | 4 cm |
|---|---|---|---|
| Beam aperture (radius) | 23.5 mm | 23.5 mm | 23.5 mm |
| Outer shielding radius | 43.5 mm | 53.5 mm | 63.5 mm |
| Inner coil aperture (radius) | 59 mm | 69 mm | 79 mm |
| Power penetrating tungsten absorber | 19.1 W/m (3.8%) | 8.2 W/m (1.6%) | 4.1 W/m (0.8%) |
| Peak power density in coils | 6.5 mW/cm$^3$ | 2.1 mW/cm$^3$ | 0.7 mW/cm$^3$ |
| Peak dose in Kapton (5/10 years) | 56/112 MGy | 18/36 MGy | 7/14 MGy |
| Peak dose in coils (5/10 years) | 45/90 MGy | 15/30 MGy | 5/10 MGy |
| Peak DPA in coils (5/10 years) | 8/16$\times10^{-5}$ DPA | 6/12$\times10^{-5}$ DPA | 5/10$\times10^{-5}$ DPA |

Power load and damage in arc magnets (10 TeV), as a function of radial tungsten absorber thickness – IMCC Interim Report 2024