International
MUON Collider
Collaboration

MuCol

SAPIENZA
UNIVERSITÀ DI ROMA

INFN
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Funded by
the European Union

Muon Collider Magnets

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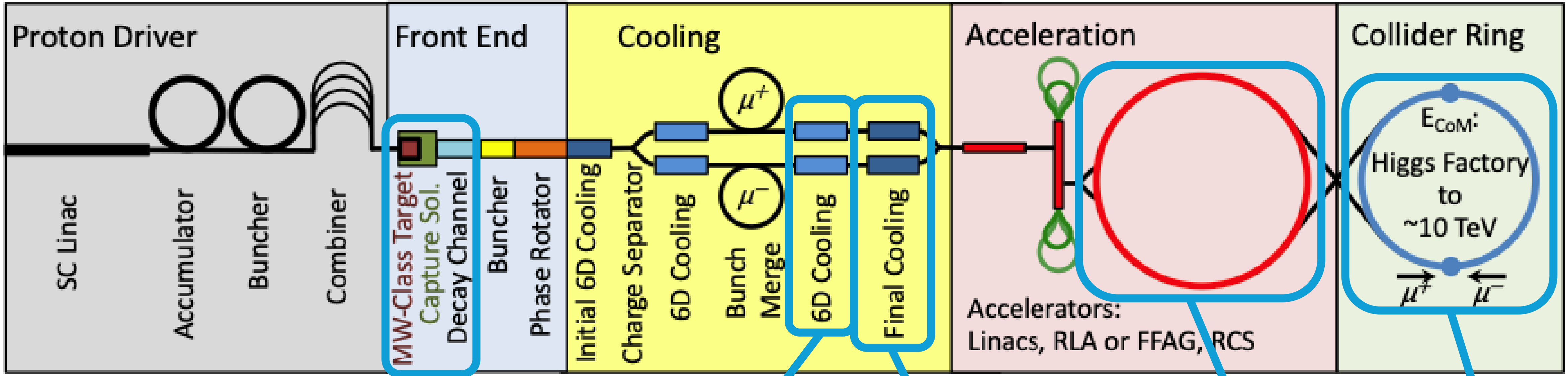
28/08/2024

Outline

- Magnets Overview
  - Target, Decay and Capture Solenoid
  - 6D Cooling Magnets
  - Final Cooling
  - Accelerator RCS & HCS Magnets
  - Collider Ring Magnets
- Design Considerations and Synergies
- Research contribution to the project

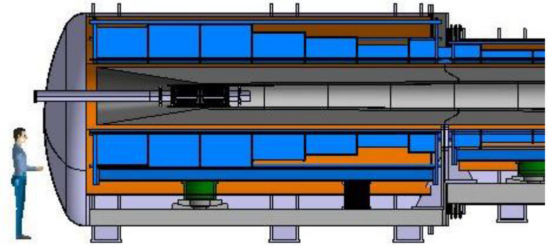
Muon Collider Overview

- → Great variety of magnets in the different sections.
- → Field range along the machine: 1.8 T… > 40 T !!

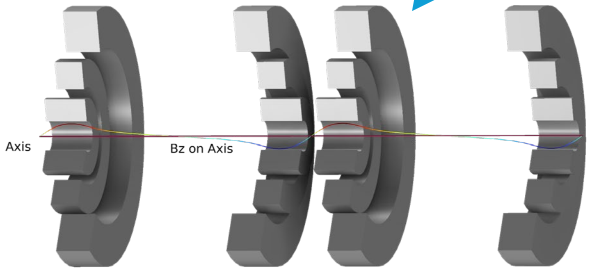


Credits: MAP, US muon accelerator program

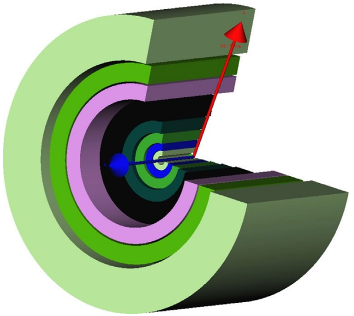
20 T, 1200 mm aperture



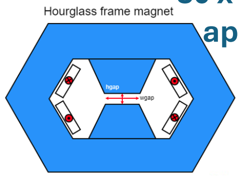
2.4 T to 15 T, 90 mm to 1500 mm aperture



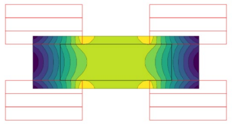
> 40 T, 50 mm aperture



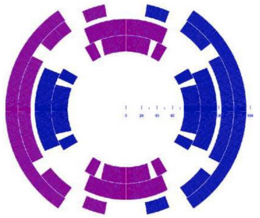
±1.8 T up to 4kT/s, 30 x 100 mm aperture



10 T, 30 x 100 mm aperture



8T to 16T, 320 T/m, 160 mm aperture […]

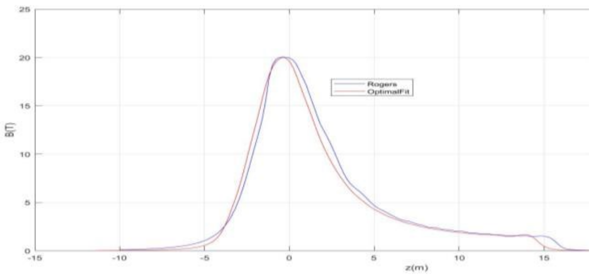


Target, Decay and Capture Solenoid

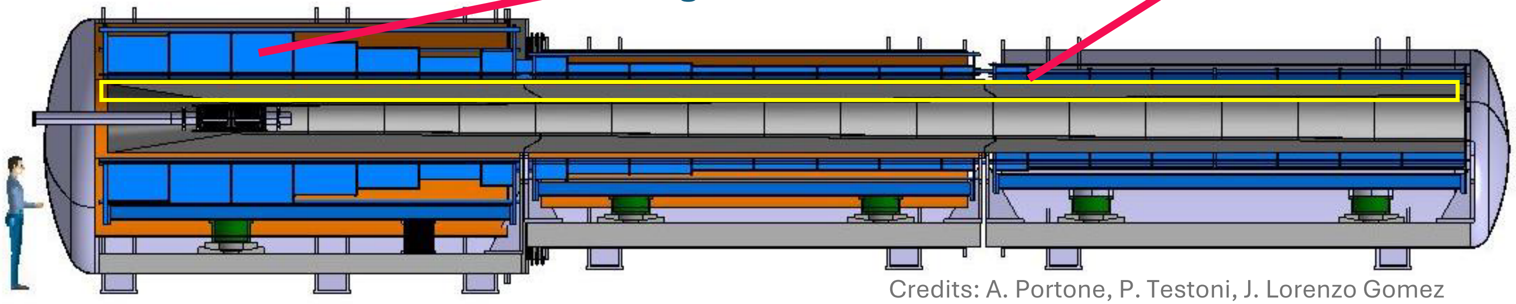
- 1200mm bore, 18m magnetic length, **20 T peak field** on target, 2T at the channel exit.
- **Radiation shield is fundamental**: 500 mm tungsten shield.
- 4kW radiation heat load on coils.
- 80MGy radiation dose, 1e-3 DPA per year.
- **20K operation**: reduced need for radiation heat shielding, improved energy efficiency.

CHALLENGES:

- Radiation damage of superconducting tapes and insulating material.
- Magnet engineering.
- Infrastructure and operating cost (high radiation environment).



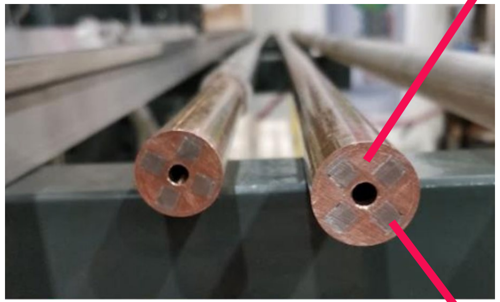
High field solenoids capture and guide pions into decay and capture channel.

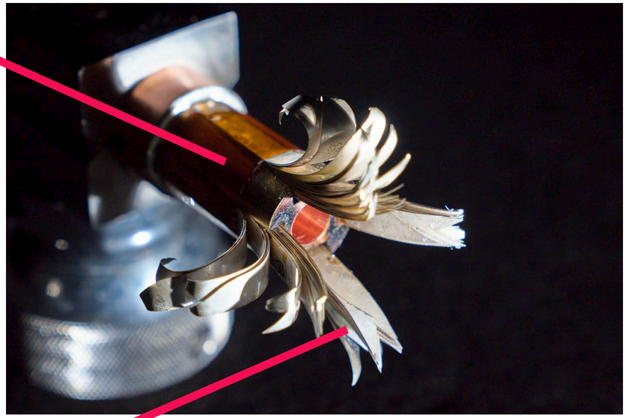

Target solenoid

Radiation shield

Credits: A. Portone, P. Testoni, J. Lorenzo Gomez

Copper


Z.S. Hartwig et al., The SPARC toroidal field model coil program, IEEE Trans. Appl. Supercond. 34 (2024)

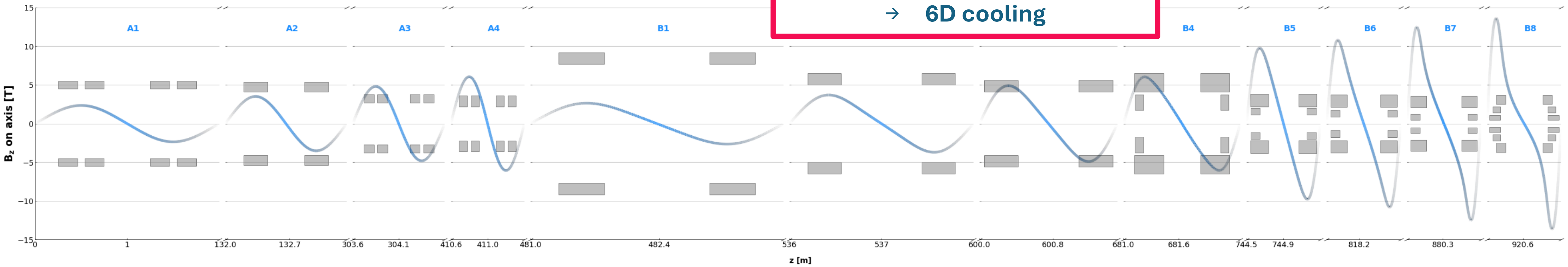

M. Takayasu et al., IEEE TAS, 21 (2011) 2340
Z. S. Hartwig et al., SUST, 33 (2020) 11LT01

ReBCO HTS tapes

6D Cooling Magnets

Solenoids create increasing oscillating field in the beam direction. Combined with absorbers and re-acceleration:
→ **6D cooling**

Credits: MAP, US-DOE muon accelerator program

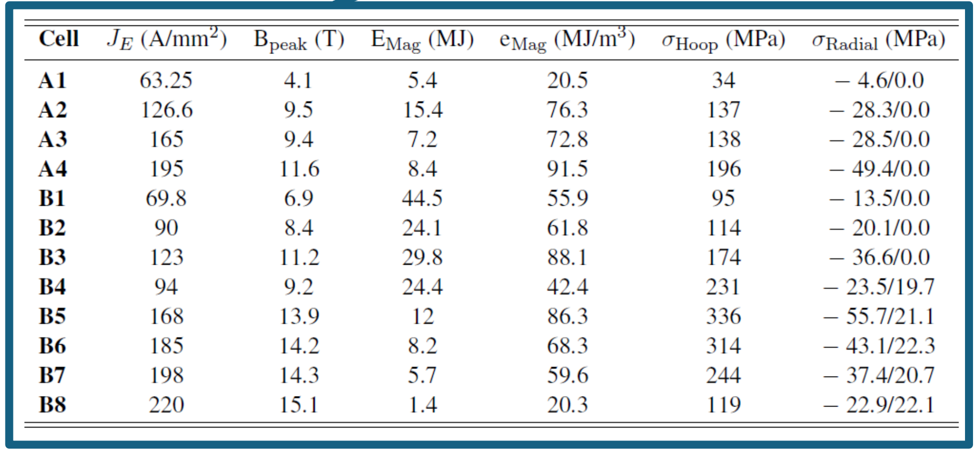


- → 1 km sequence of integrated absorbers, solenoids, RF cavities.
- → MAP design: 2400 solenoids divided into 826 cells.
- → 12 types of cooling cells (A1…A4, B1…B8).

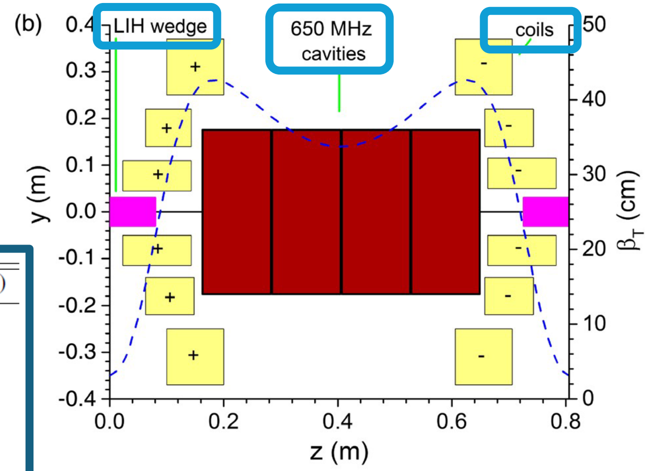
6D magnets baseline from MAP study.
Unoptimized parameters!

CHALLENGES:

- → **Solenoids integration** within the cell.
- → Optimize MAP configuration from an engineering point of view.
- → **Quench management** and protection.
- → Optimize for **standardization**.



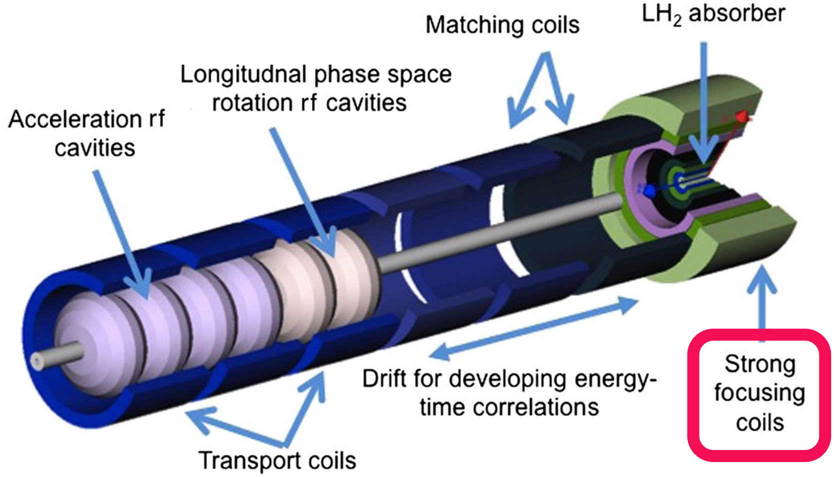
Cell	J_E (A/mm^2)	B_{peak} (T)	E_{Mag} (MJ)	e_{Mag} (MJ/m^3)	σ_{Hoop} (MPa)	σ_{Radial} (MPa)
A1	63.25	4.1	5.4	20.5	34	– 4.6/0.0
A2	126.6	9.5	15.4	76.3	137	– 28.3/0.0
A3	165	9.4	7.2	72.8	138	– 28.5/0.0
A4	195	11.6	8.4	91.5	196	– 49.4/0.0
B1	69.8	6.9	44.5	55.9	95	– 13.5/0.0
B2	90	8.4	24.1	61.8	114	– 20.1/0.0
B3	123	11.2	29.8	88.1	174	– 36.6/0.0
B4	94	9.2	24.4	42.4	231	– 23.5/19.7
B5	168	13.9	12	86.3	336	– 55.7/21.1
B6	185	14.2	8.2	68.3	314	– 43.1/22.3
B7	198	14.3	5.7	59.6	244	– 37.4/20.7
B8	220	15.1	1.4	20.3	119	– 22.9/22.1



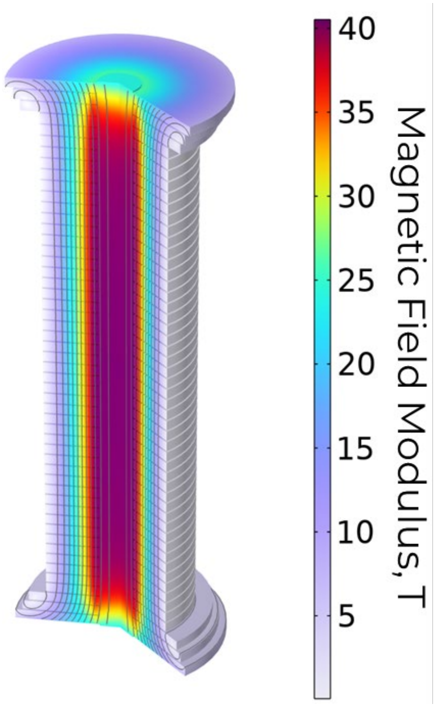
Final Cooling Solenoid

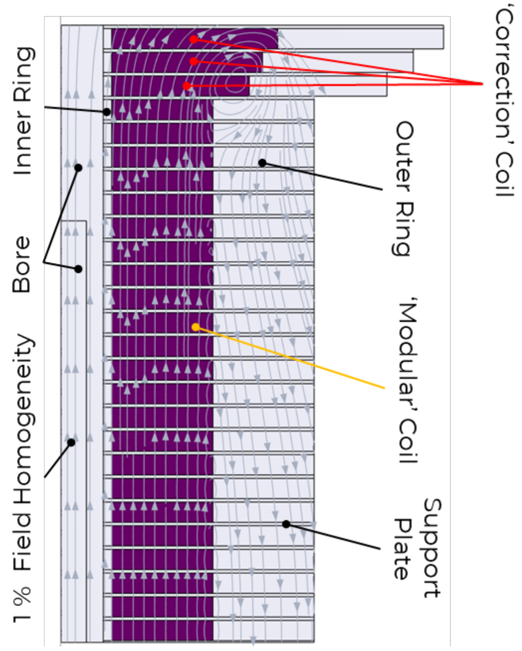
- IMCC design: 12 ultra-high field solenoids.
- **40T, 50mm bore, 500mm length.**
- Compact design to reduce footprint, mass and cost: **non-insulation HTS winding**.
- **Modular design** with supporting rings and plates to manage hoop, radial and vertical stresses.

Strong final focusing minimize the beam emittance.
→ **> 40 T Field !!**



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





Credits: B. Bordini, A. Dudarev

CHALLENGES:

- R&D on solenoids with fields **beyond the state of the art at this scale**.
- Stress management (> 600 MPa hoop stress).
- Contact resistance control in a range suitable for operation.

Accelerator RCS & HCS Magnets

Rapid acceleration to relativistic momentum is key to extend muon lifetime.

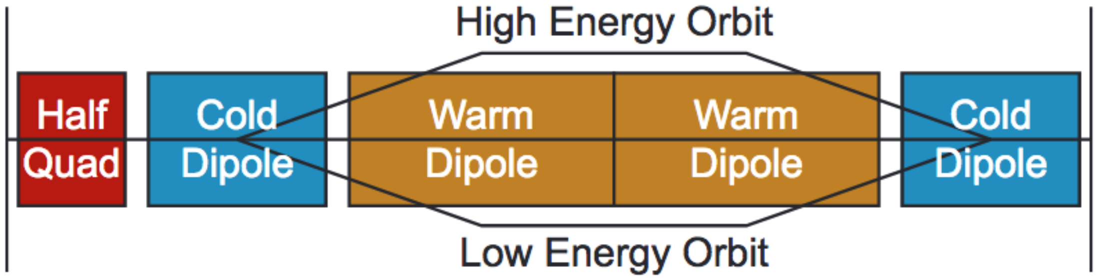
RCS:

→ NC magnets, **0.36T-1.8T**, (**4 kT/s**), 30 x 100 mm aperture.

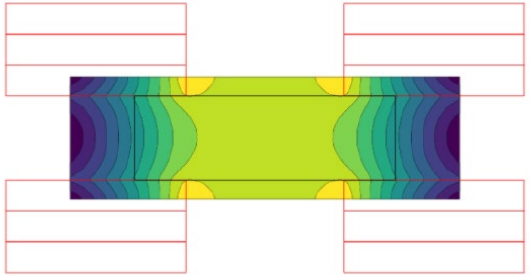
HCS:

→ NC magnets, **±1.8T**, (**560 T/s**), 30 x 100 mm aperture.

→ SC magnets, **10T steady state**, 30 x 100 mm aperture.



Steady state SC dipole: **HTS-based flat racetrack coil.**



CHALLENGES:

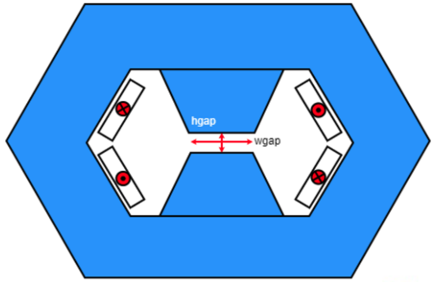
→ Efficiently power the NC magnets at a high pulse rate with effective energy recovering (**tens of GVA**).

→ Mitigate losses (**< 500 J/m** per pulse).

→ R&D on **HCS pulsed magnets** with **ReBCO tapes** and **ferric core**.

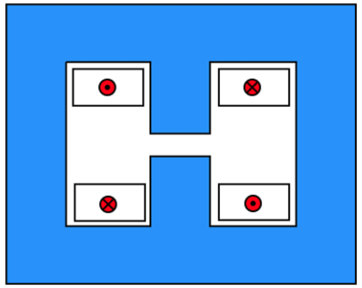
NC pulsed magnets

Hourglass frame magnet



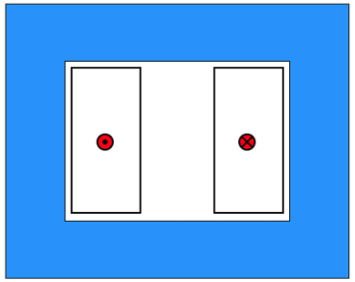
5.07 kJ/m

H magnet



5.65...7.14 kJ/m

Window frame magnet



5.89 kJ/m

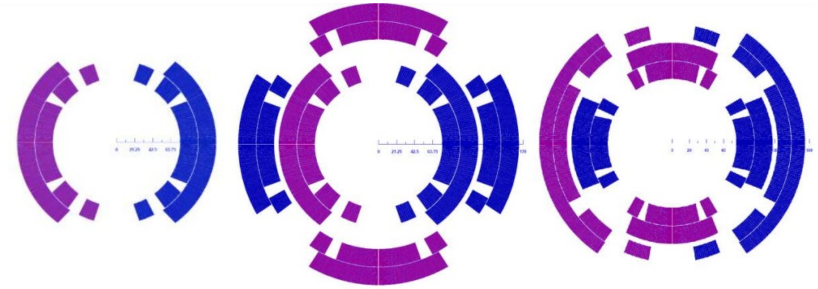
Credits: M. Breschi, P.L. Ribani, R. Miceli

Collider Magnets

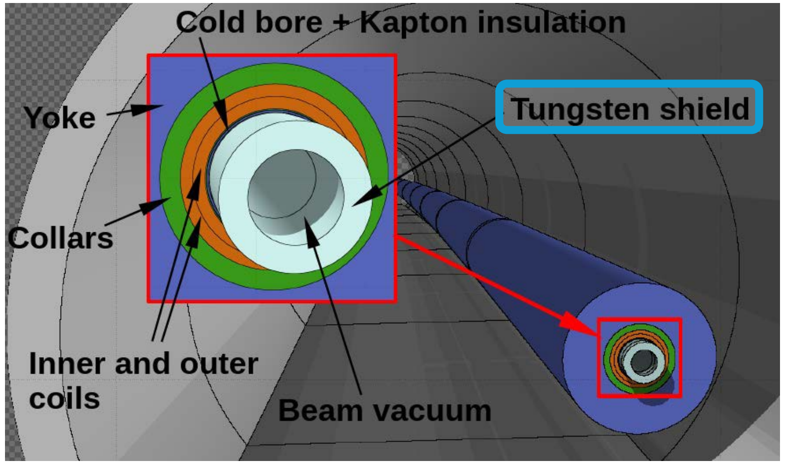
Maximize collision of muon beams with limited lifetime:

→ Minimize collider ring circumference (i.e., **highest possible field in dipoles**)

- → Minimize straight sections by using **combined function magnets** in the arcs.
- → **Radiation shielding** is essential: 40mm thick tungsten shield (<5 W/m, <40MGy at coil level).
- → Arc magnets: 8T…**16T**, **320T/m**, **7100 T/m2**, **160mm aperture**.
- → Final focus: 4T…**16T**, 100…**300T/m**, **12000T/m2**, 120…**300mm aperture**.



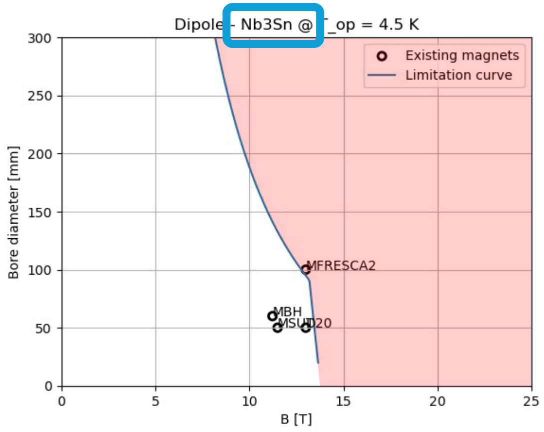
Credits: MAP, US-DOE muon accelerator program

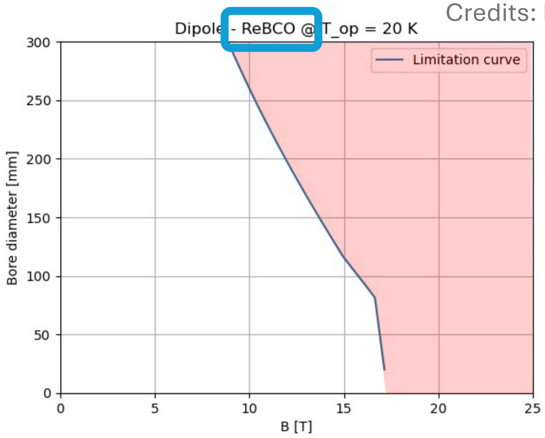


CHALLENGES:

- → Define the **performance limits** of the accelerator dipoles and quadrupoles.
- → Detailed studies on **HTS based magnets** and **Nb3Sn LTS option**.

Credits: D. Novelli





Design Considerations

The **muon collider** promises a **sustainable approach to the energy frontier**:

→ Limited power consumption, cost, land use.

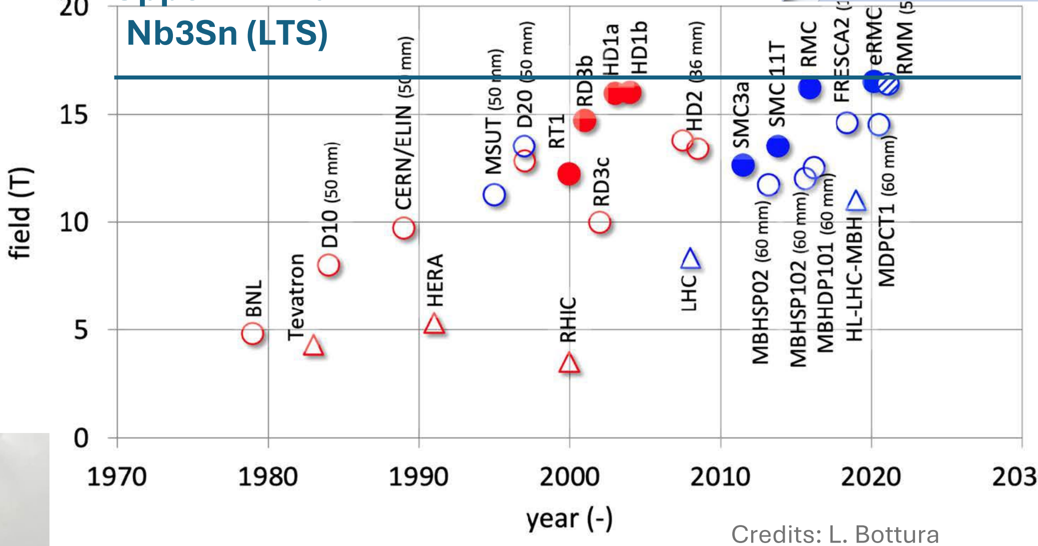
The muon collider as future machine at the energy frontier needs:

→ **High fields** (dipoles, quadrupoles 16T-20T, solenoids up to 40T).

→ **Energy efficiency** (increase operating temperature to 20K, minimize cryogen usage).

→ **Economics** (consider high Je, compact magnets to reduce construction, maintenance and operation cost).

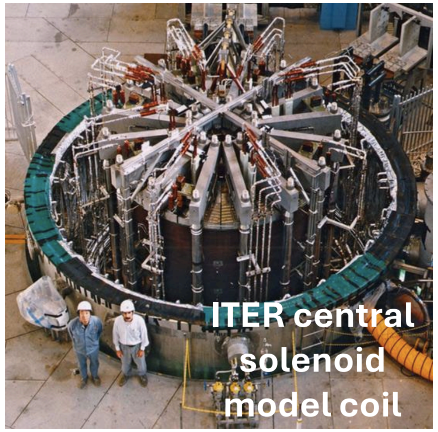
HTS may be the enabler technology!!



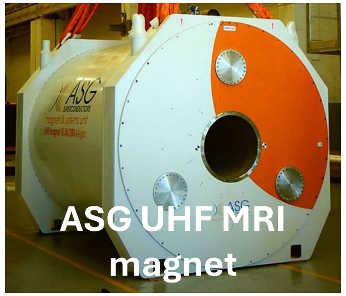
Credits: L. Bottura

Synergies

→ **Important synergies with many technological applications:** thermonuclear fusion, next gen MRI, wind energy generators…


ITER central solenoid model coil


MIT/CFS SPARC TF Coil prototype

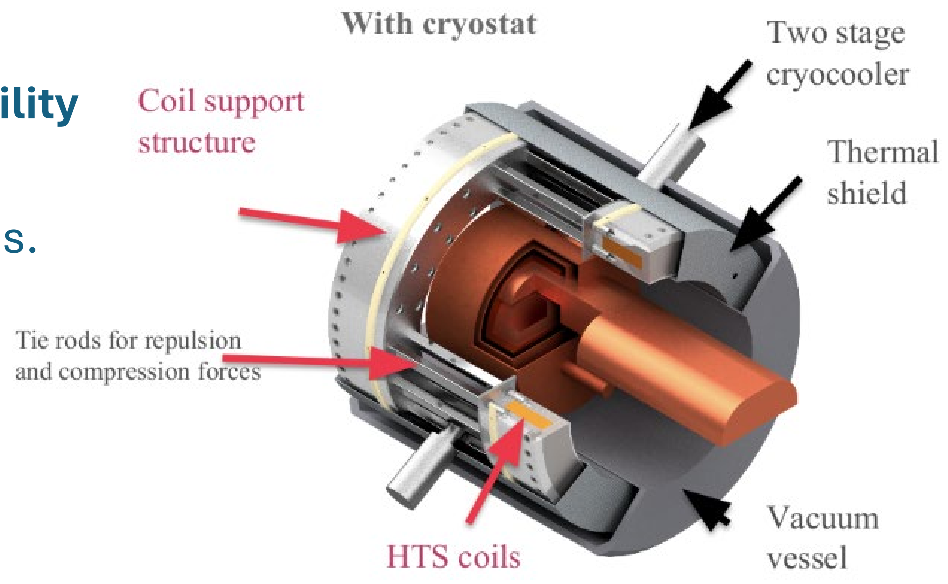

ASG UHF MRI magnet

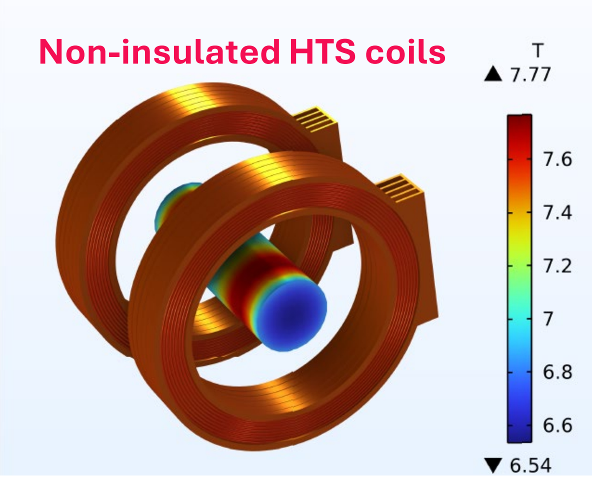

LNCMI/CEA Nougat

My contribution to the project

- → 1st year PhD student in Accelerator Physics at the University of Rome “La Sapienza”, based at the INFN-LASA laboratory in Milan.
- → Focus on the **cooling section magnets for the Muon Collider**.
- → Define the **performance limits** and add detailed **engineering analyses** of the **superconducting solenoids**.
- → Work on the **design** of a **cooling cells demonstrator** and a **test facility for RF cavities** under magnetic field (7T uniform or 40T/m gradient).
- → **Experimental tests** on magnet samples based on ReBCO HTS tapes.
- → The **Muon Collider** is a **challenging** and **stimulating project**, great opportunity to **develop magnets at the technology frontier!**

RFMFTF: Test Facility for radiofrequency cavities




Non-insulated HTS coils


ReBCO HTS tapes

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Funded by
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Credits: Gaia Fontana, @qftoons

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Find more details here:
https://doi.org/10.48550/arXiv.2407.12450