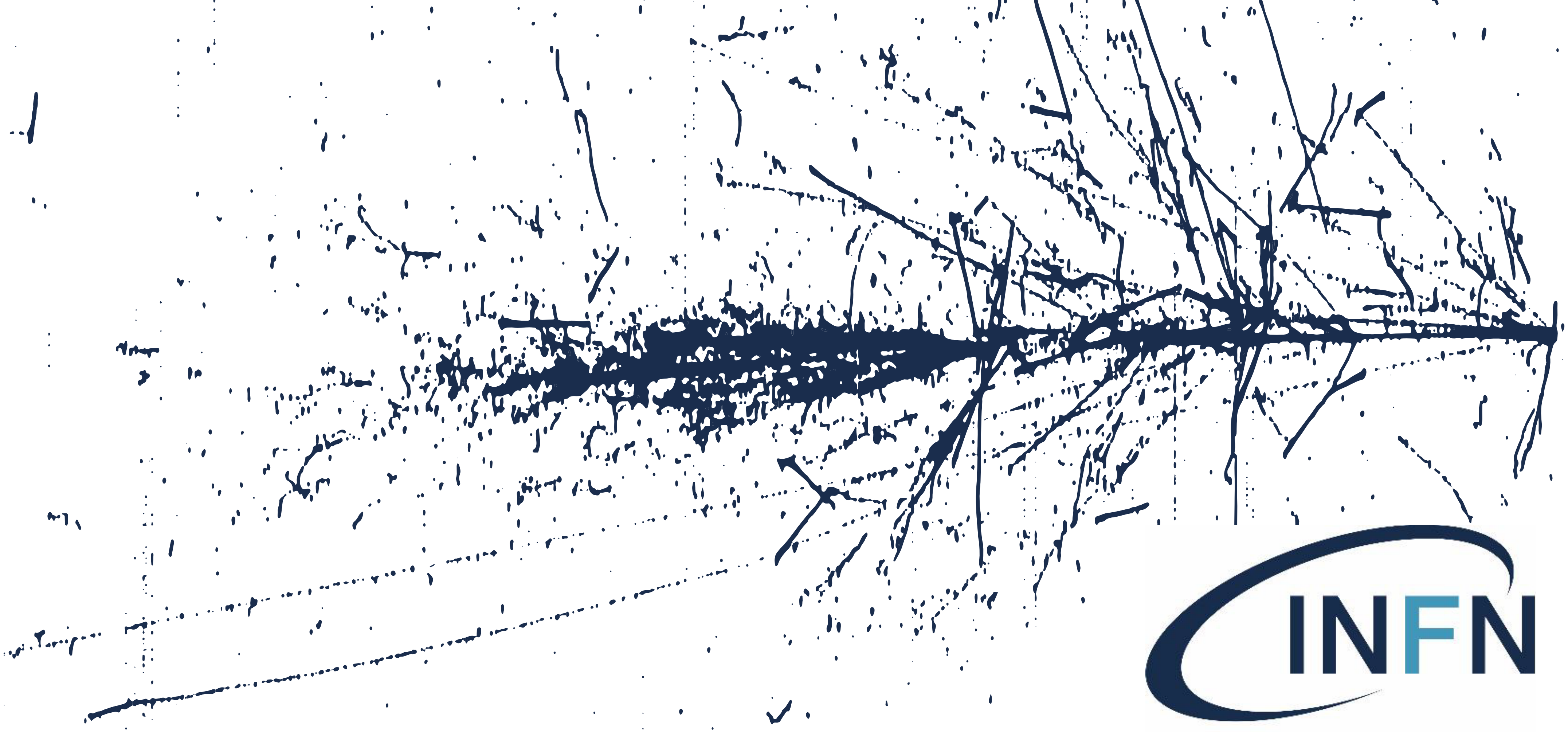


Istituto Nazionale di Fisica Nucleare

HTS magnets challanges for Muon Collider cooling cells

Marco Statera, INFN-MI LASA

INFN e la Strategia Europea per la Fisica delle Particelle, 6.5.2024

Outline

- intro — Motivation; HTS magnets specific requirements
- magnets — Selected examples of HTS magnets
- MuCol — The HTS magnets for International Muon Collider Collaboration and MuCol
- Schedule — Timeline highlights
- Conclusions

Motivation

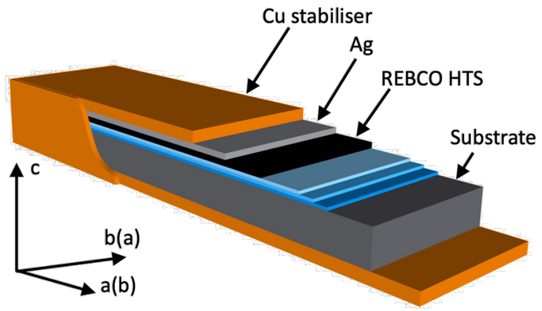
Why

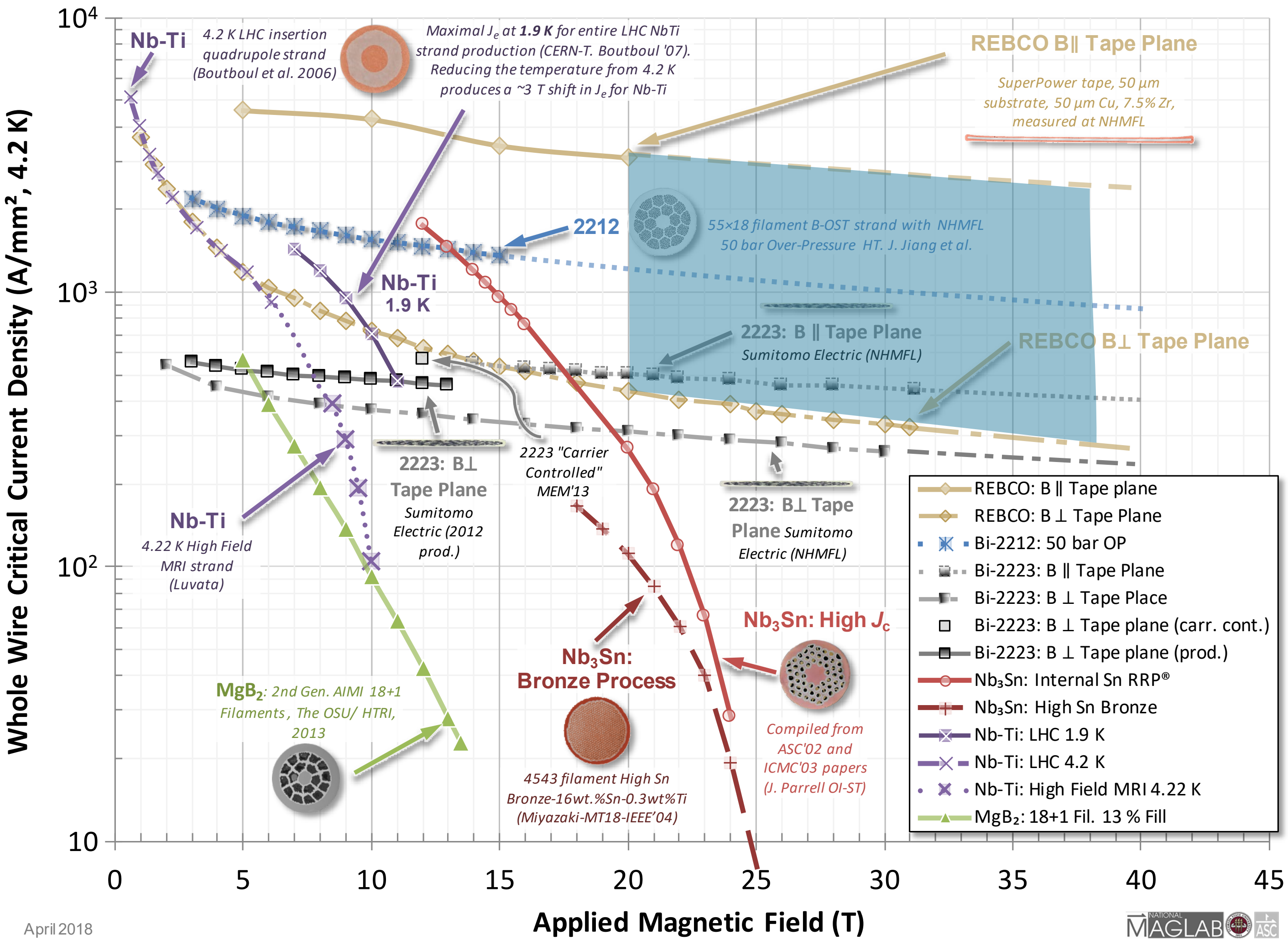
Increase performance and/or sustainability of research institutes

How

High Temperature Superconductors

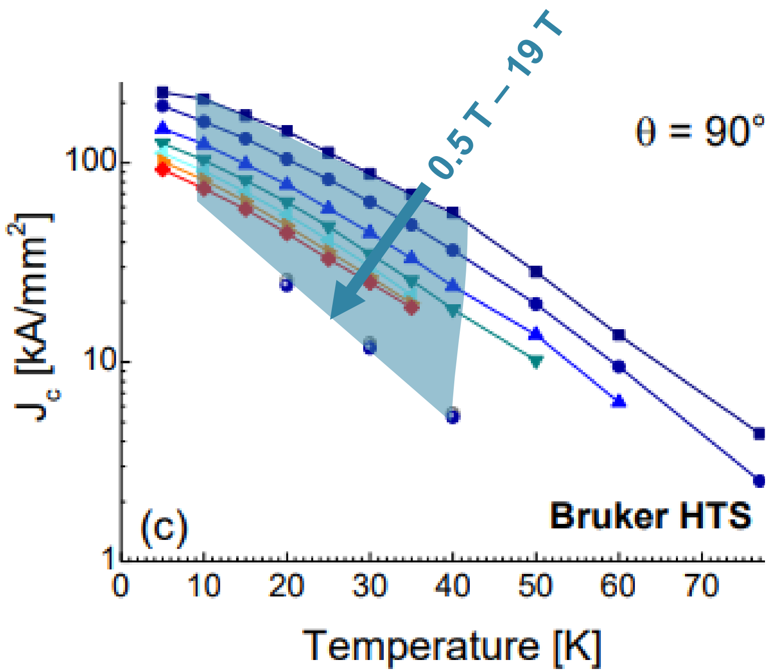
High current densities at higher temperatures



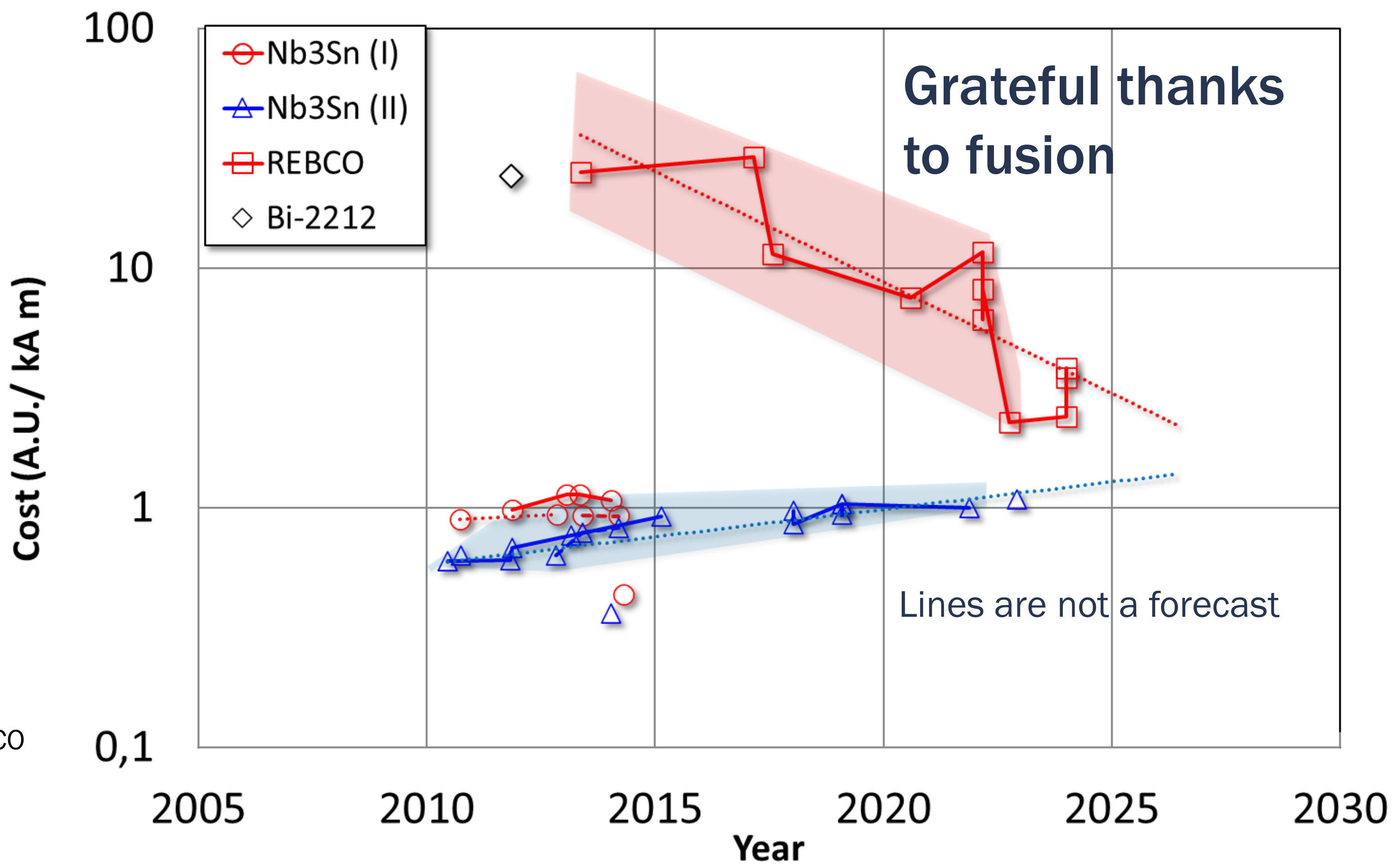


https://nationalmaglab.org/magnet-development/applied-superconductivity-center/plots

Motivation



C. Senatore et al., Field and temperature scaling of the critical current density in commercial REBCO coated conductors - https://arxiv.org/abs/1512.01930

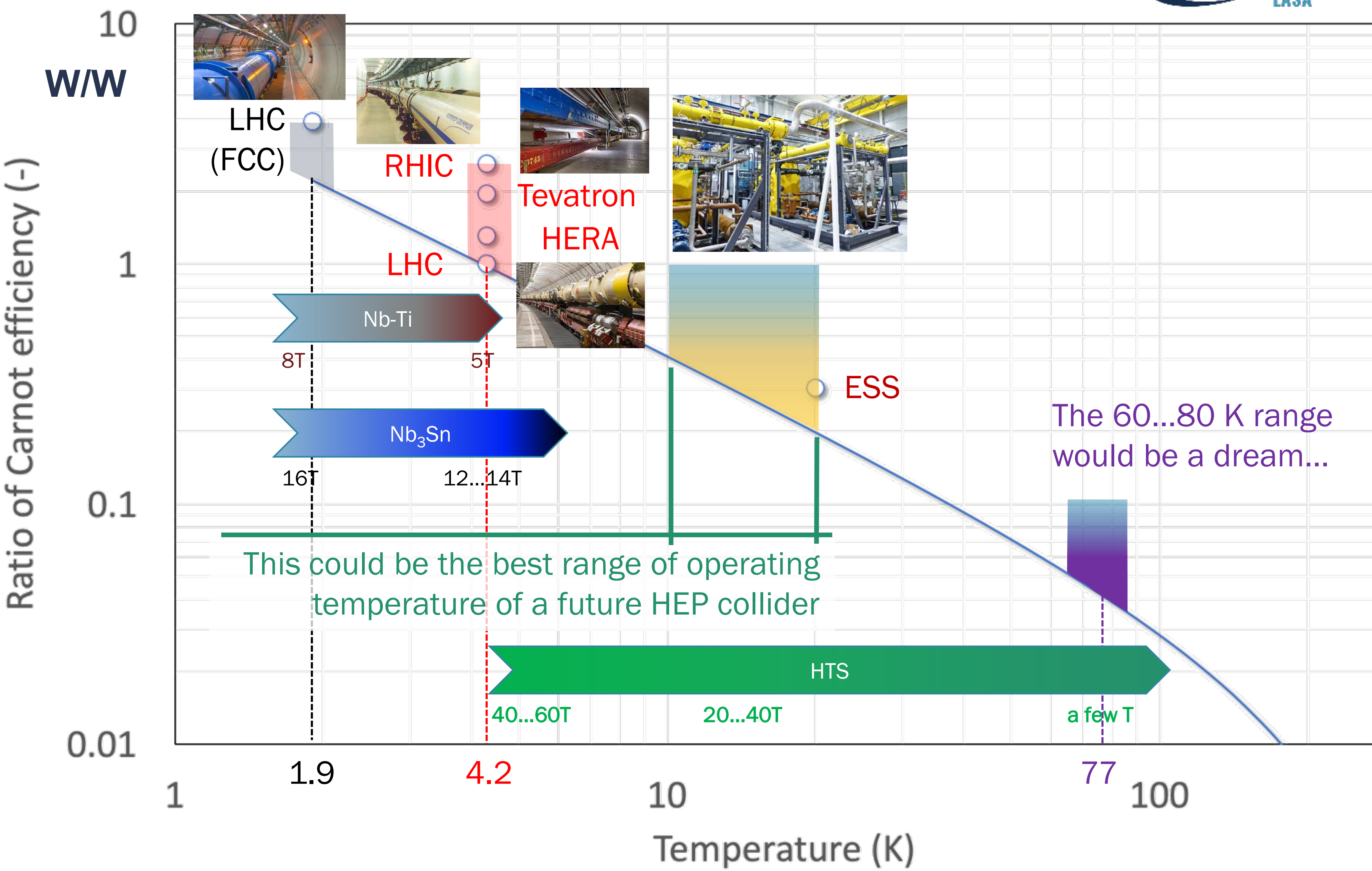


L. Bottura et al, HFM annual meeting https://indico.cern.ch/event/1302031

Motivation

Sustainability is a driver for next generation Research Institutes and projects

HTS may be one important option for the future colliders



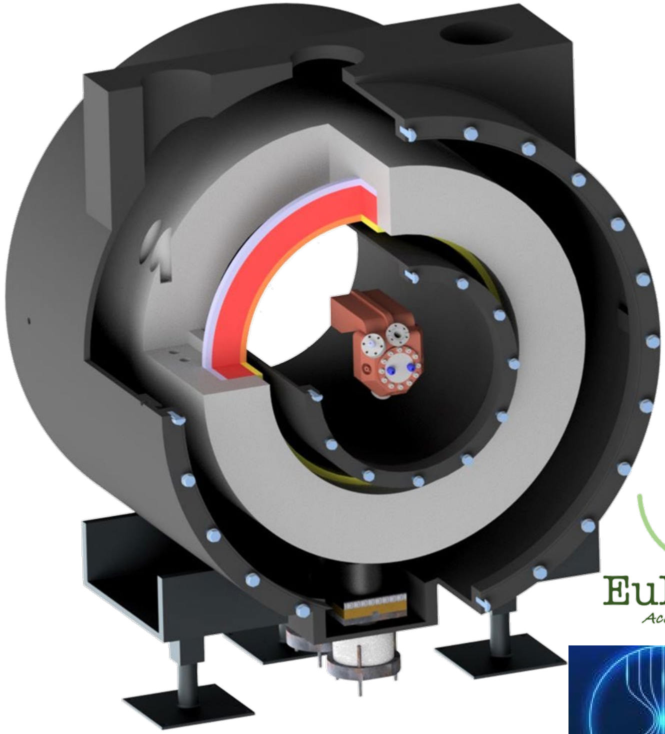
Credits to P. De Sousa and R. Van Weelderen and L. Bottura, CERN

IRIS and Muon Collider are the actual driver for next generation Magnets in HTS

INFN LASA

Split Coil - RFMTF
Magnet Test Facility for RF (and other use)

International MUON Collider Collaboration



10 T gradient
20 K operation
Conduction cooled
300 mm warm bore

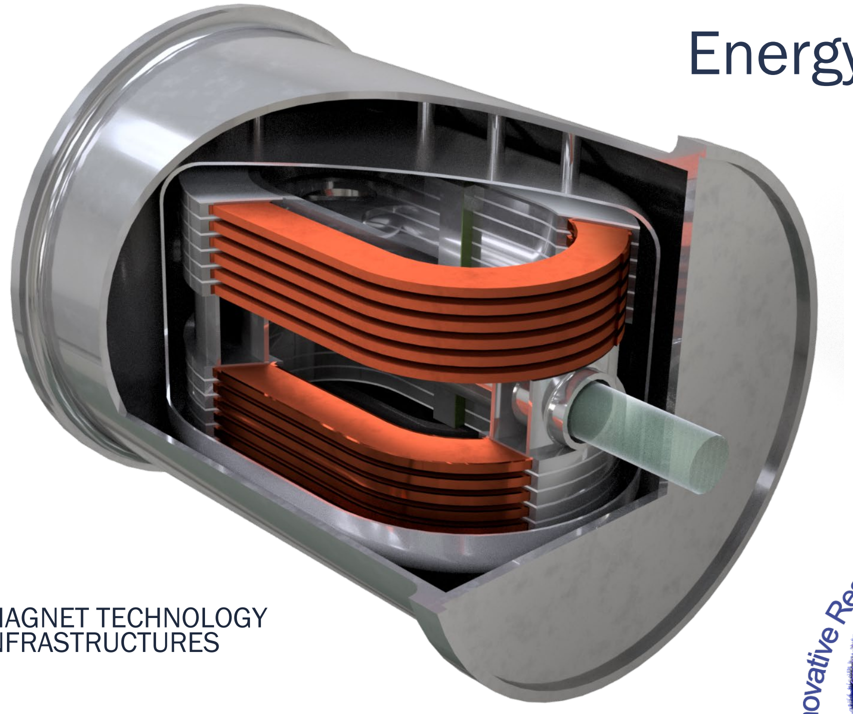
EuMAHTS Accelerating HTS

INFRATECH proposal

EUMAHTS: ADVANCING HTS MAGNET TECHNOLOGY FOR EUROPEAN RESEARCH INFRASTRUCTURES

PI L. Bottura, CERN

Finanziato dall'Unione europea NextGenerationEU | Ministero dell'Università e della Ricerca | Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA



ESMA
Energy Saving MAgnet

10 T dipole
20 K operation
Conduction cooled
70 mm bore

2025

IRIS – Innovative Research Infrastructure on applied Superconductivity

SCIENCE FOR SUSTAINABILITY

HFM High Field Magnets

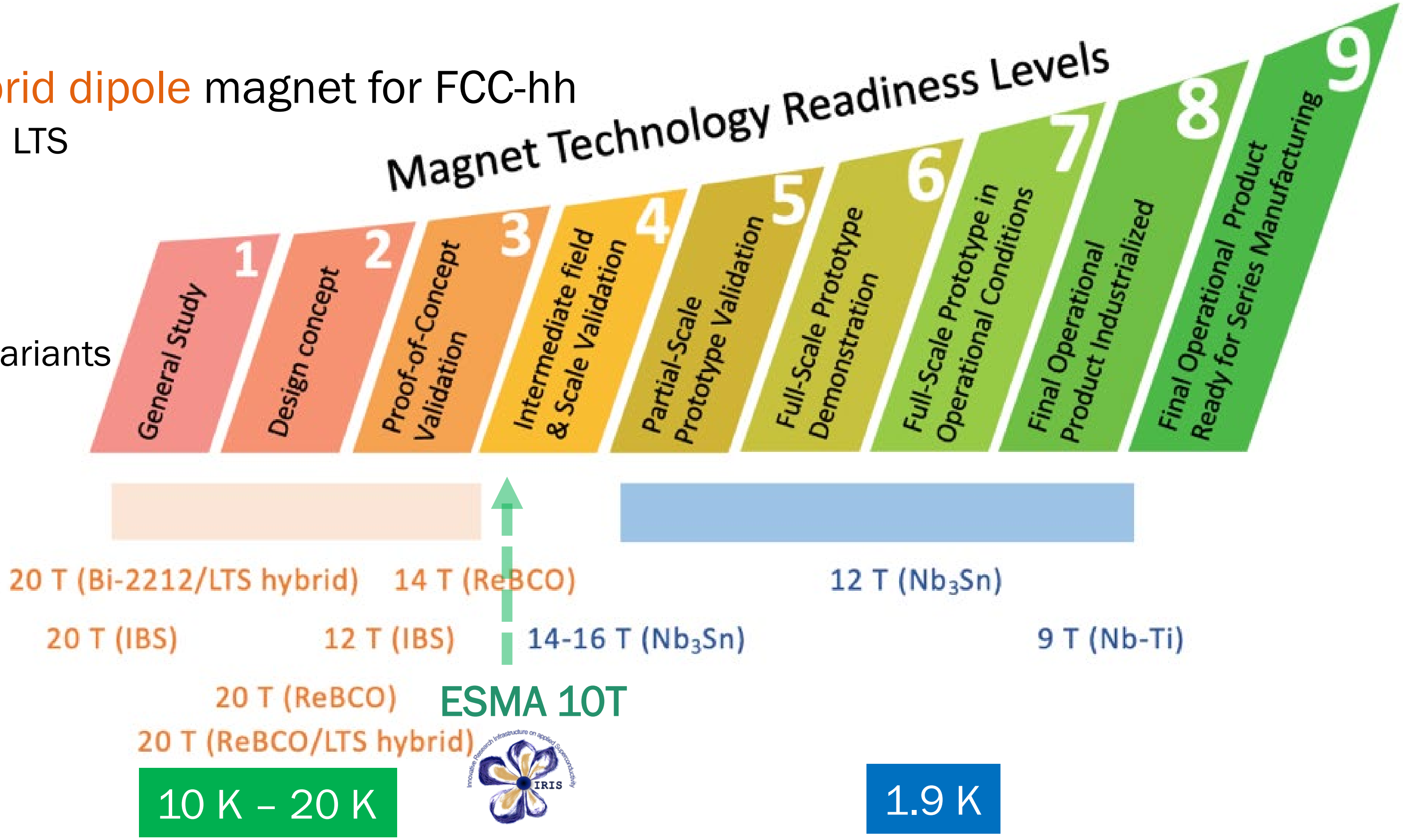
Common R&D to increase TRL of HTS magnet technology

Present R&D Targets of HFM

1. A ~14 T operational field LTS dipole magnets for FCC-hh
   - Establish the operational margins
   - Select the magnet design among multiple variants
   - Scale to 14-m-long magnets
2. A ~20 T operational field HTS or hybrid dipole magnet for FCC-hh
   - Close Technology-Readiness-Level Gap with LTS
     - Establish HTS technology-stack variants
     - Demonstrate accelerator quality
   - Establish the operational margins
   - Select the magnet design among multiple variants
   - Scale to 14-m-long magnets

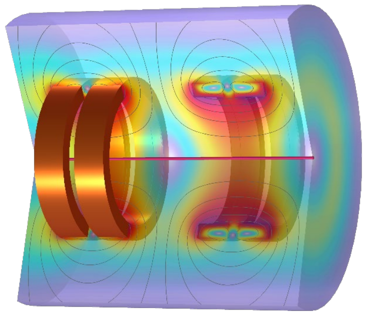
https://hfm.web.cern.ch/

E. Todesco and B. Auchman

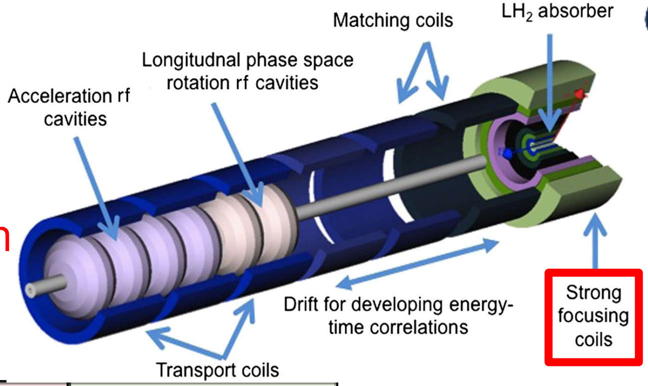


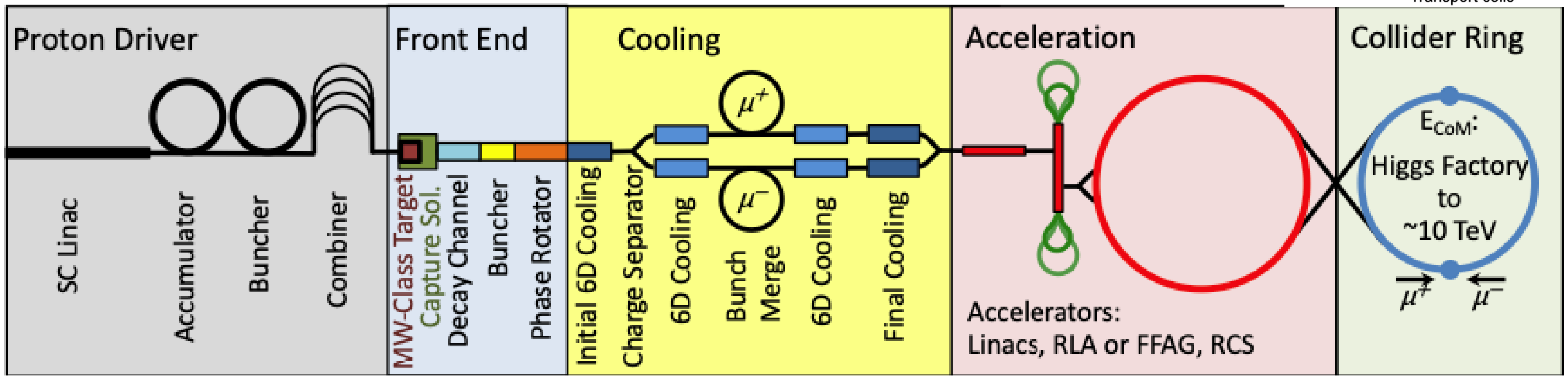
HTS magnets in Muon Collider

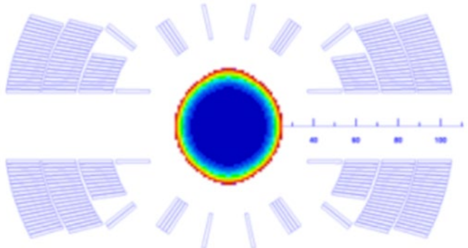
1+1 km of solenoids
Field Up to 20 T – 25 T
Controlled Insulation



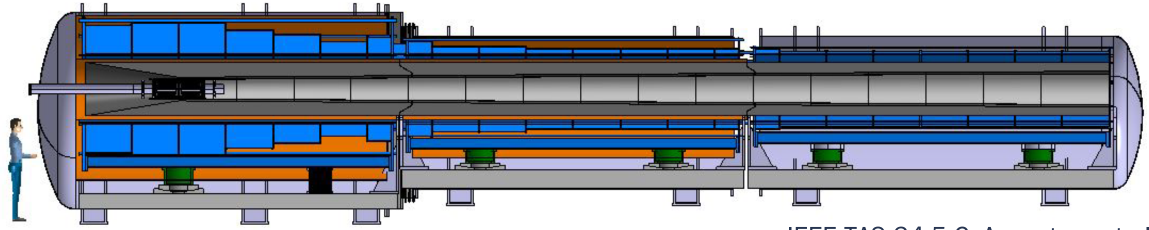
40 T on axis
4 K
Bore size 50 mm
Non Insulated





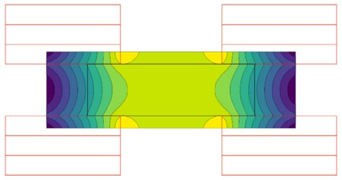


16 T
Bore size 150 mm
Insulated - CI

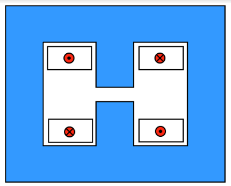


IEEE TAS 34,5 C. Accentura et al.

HTS 10 T steady state
30x100 mm aperture



NC +/- 1.8 T up to 4 kT/s
30 x 100 mm aperture



Field up 20 T, ∅≥ 1.2 m, L ≅ 18 m

Radiation heat load ≈ 5…10 kW Radiation dose: 80 MGy

6D cooling

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 of opposite polarity

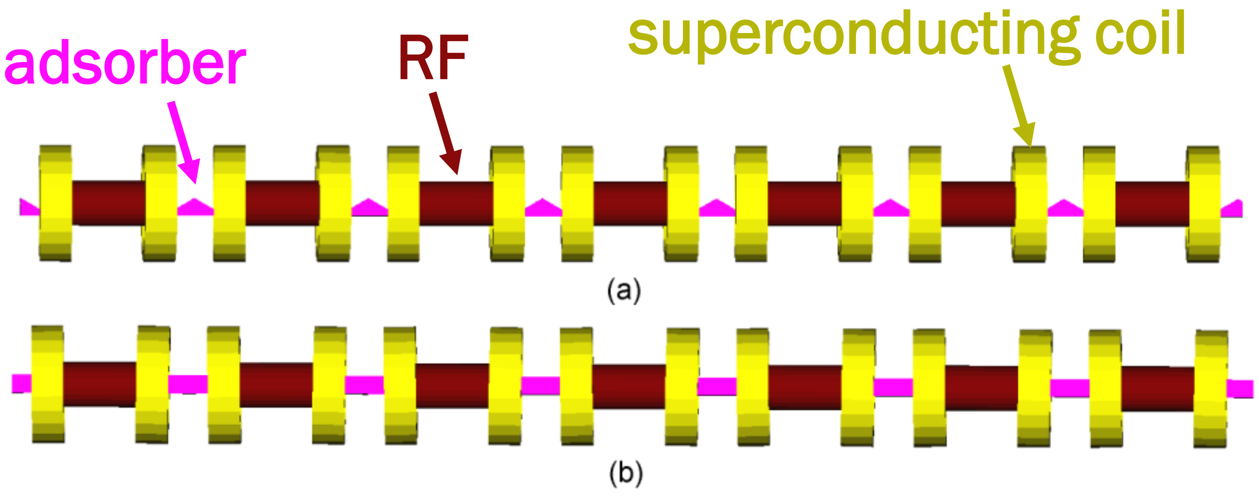
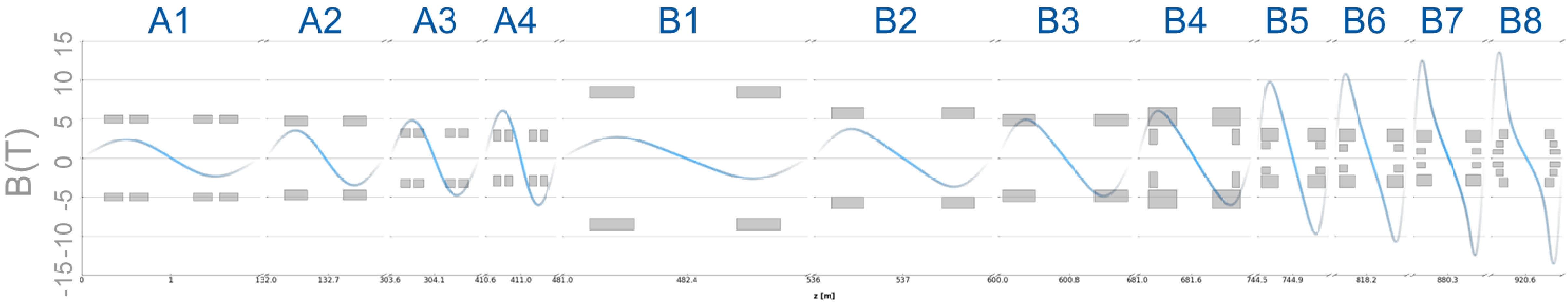
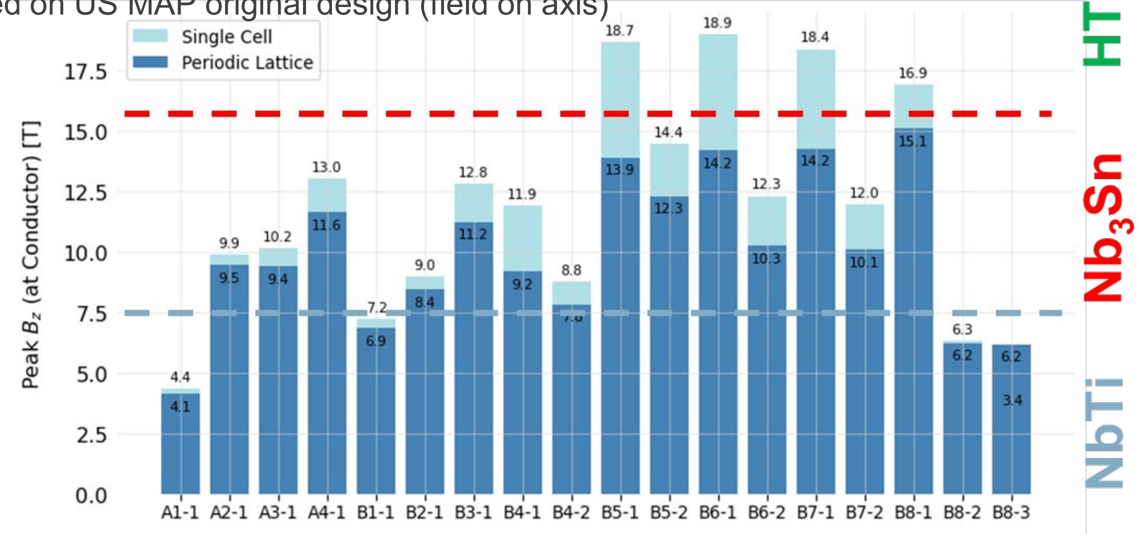


FIG. 2. Conceptual design of a rectilinear channel: (a) top view; (b) side view.



6D cooling solenoids design

based on US MAP original design (field on axis)



J. Pavan, UMIL and S. Fabbri, CERN

Some stats:

Fields on axis: 2 to 15 T

Cell Lengths: 0.8 to 2.7 m

Total length of all Stages: ~ **2 km**

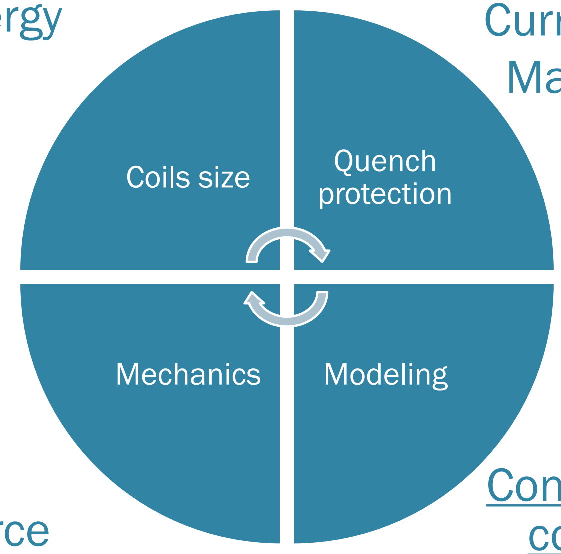
Total number of solenoids: 5000

Design challenges

Stored energy

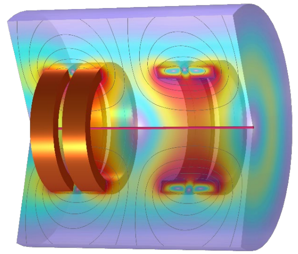
Current density

Magnetic field



Stress/Force

Conductor and coil behavior ↔ R&D ongoing CERN, INFN , CEA.... ↔

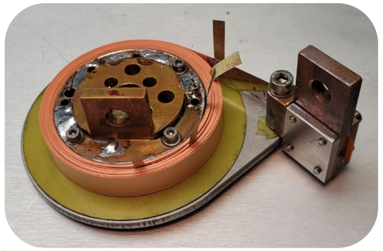


TECHNOLOGY OPTIONS

NbTi

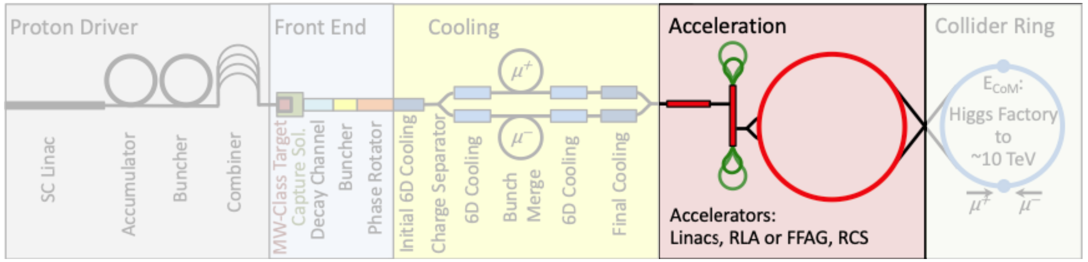
Nb_3Sn @4K ⟷ HTS @20K

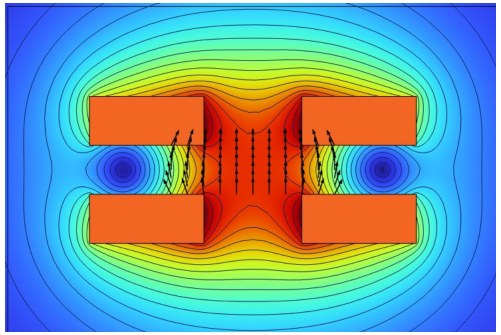
HTS

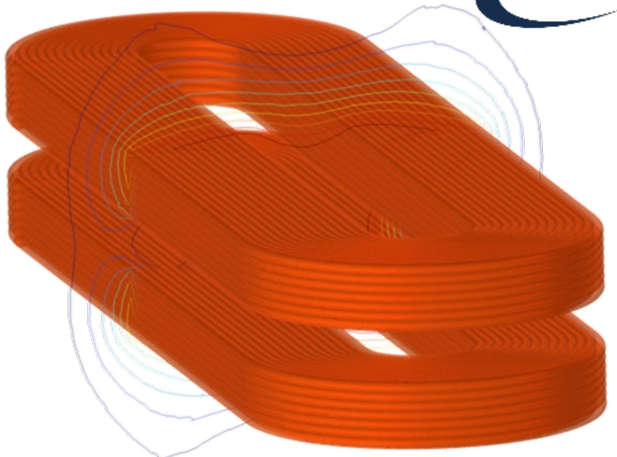


Coil	Technology Options			
	NbTi (4 K)	Nb3Sn (4 K)	HTS (4 K)	HTS (20 K)
A1-1	X	X	X	X
A2-1		X	X	X
A3-1		X	X	X
A4-1		X	X	X
B1-1	X	X	X	X
B2-1		X	X	X
B3-1		X	X	X
B4-1		X	X	X
B4-2		X	X	X
B5-1			X	X
B5-2		X	X	X
B6-1			X	X
B6-2		X	X	X
B7-1			X	X
B7-2		X	X	X
B8-1			X	X
B8-2	X	X	X	X
B8-3	X	X	X	X

Accelerator Superconducting Magnets







Parameters

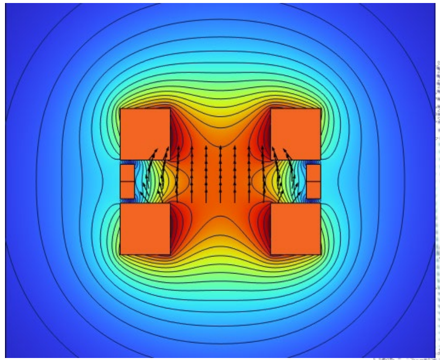
10 T at the center

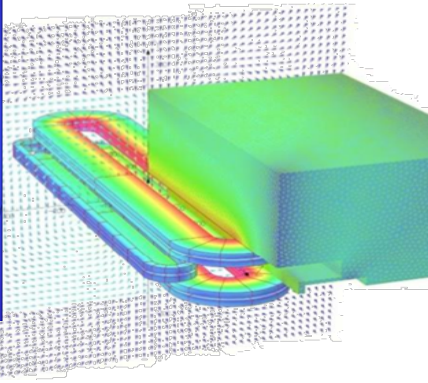
Rectangular aperture **30 mm x 100 mm**

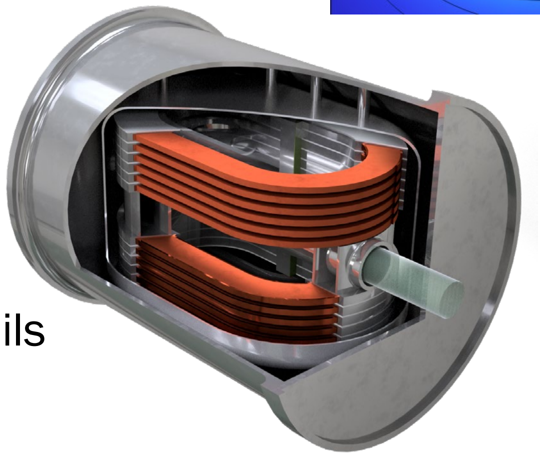
Field quality b_n < 10 units (TBC) in beam diameter (**20 mm**)

Same technology used for ESMA and 6D Cooling solenoids

- HTS windings (for robustness)
- High current density (for cost reasons)
- Operation at high temperature (for energy efficiency)







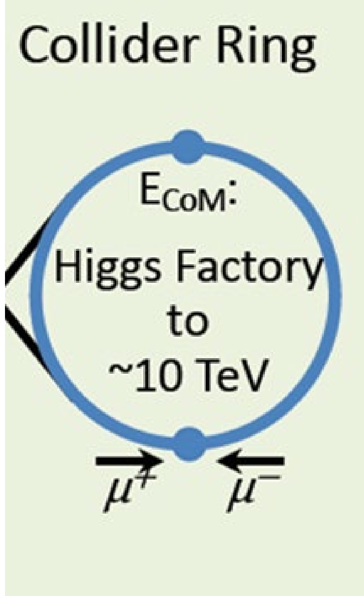
CEA - CERN HFM collaboration
Demonstrator of metal-insulated ReBCO high field coils

ESMA
good field region
400 x 30 x 50 mm^3
1.5% field homogeneity
ϕ 20 mm – b_3 20 units

Collider Magnets Requirements

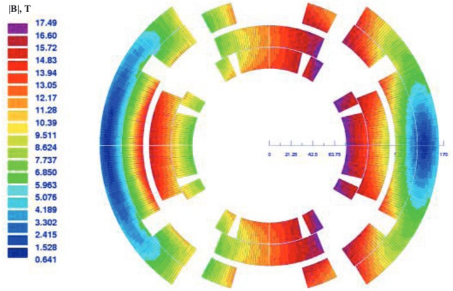
<u>3 TeV collider (5 km ring):</u>
- Close to state of the art
- ~11T / **140 mm (Nb_3Sn)**
- 600 magnets, 5 m length
- Operating temperature: 4.5 K

<u>10+ TeV collider (10 km ring):</u>
- HTS magnets, R&D is required
- ~15T / **140 mm (ReBCO, hybrid)**
- 1200 magnets, 5 m length
- Operating temperature: 4.5…20 K



Challenges

- High field dipoles to minimize collider ring size and maximize luminosity
- Combined function (B1, B2 and B3)
- Large aperture shielding (muon decay)



V.V. Kashikhin et al.

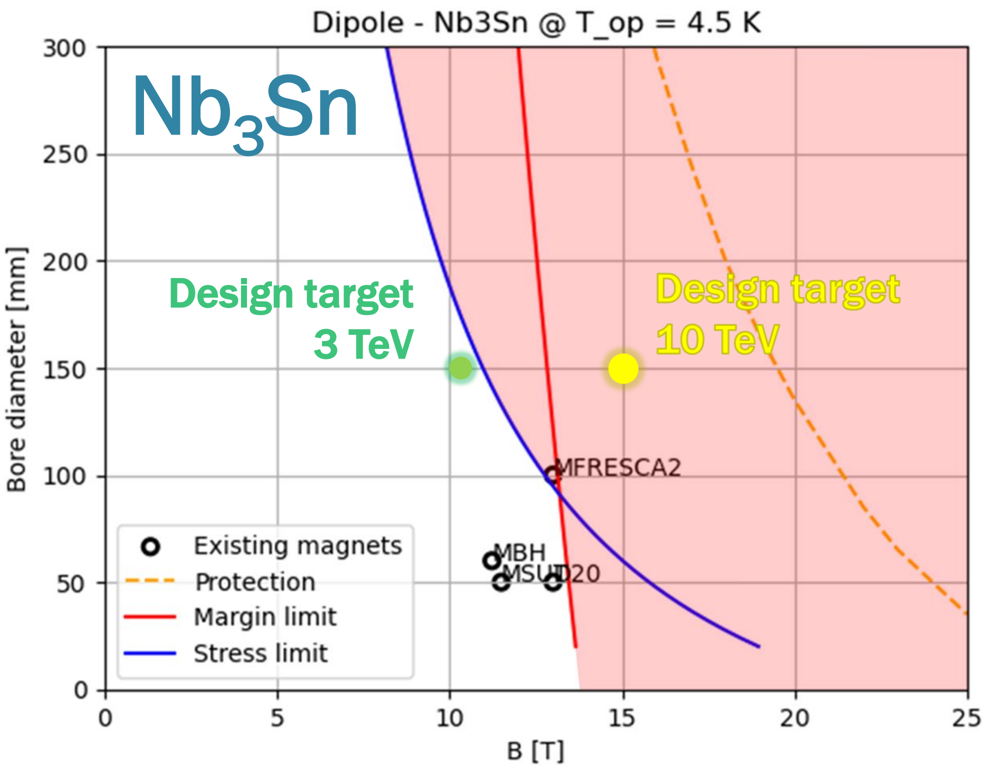
Proposed solution

Nb_3Sn for the 3 TeV machine and HTS (ReBCO) for the 10 TeV collider.

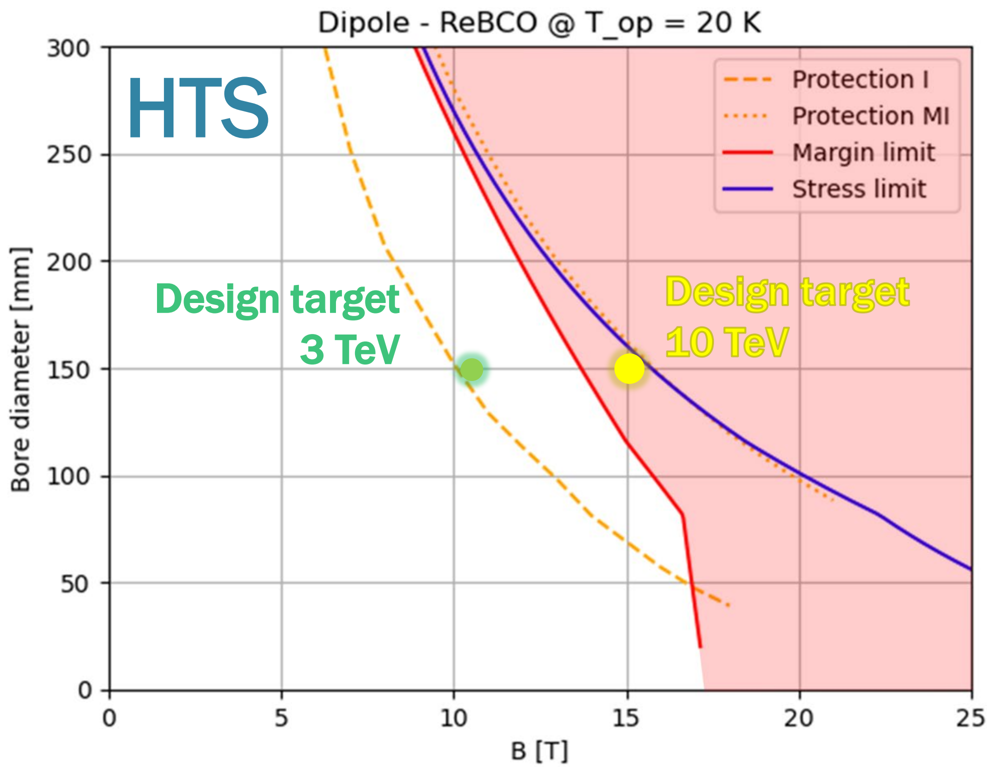
Constraints

Stress limit, mechanical challenges (conductor, force management)
Margin limit, critical current density and stored magnetic energy (quench protection)
Cost, maximum cost per meter of magnet fixed 400 k€/m (about 2 x Eurocircle)

Dipole design charts



Nb_3Sn falls short of required performance because of operating margin and peak stress (at affordable cost !)

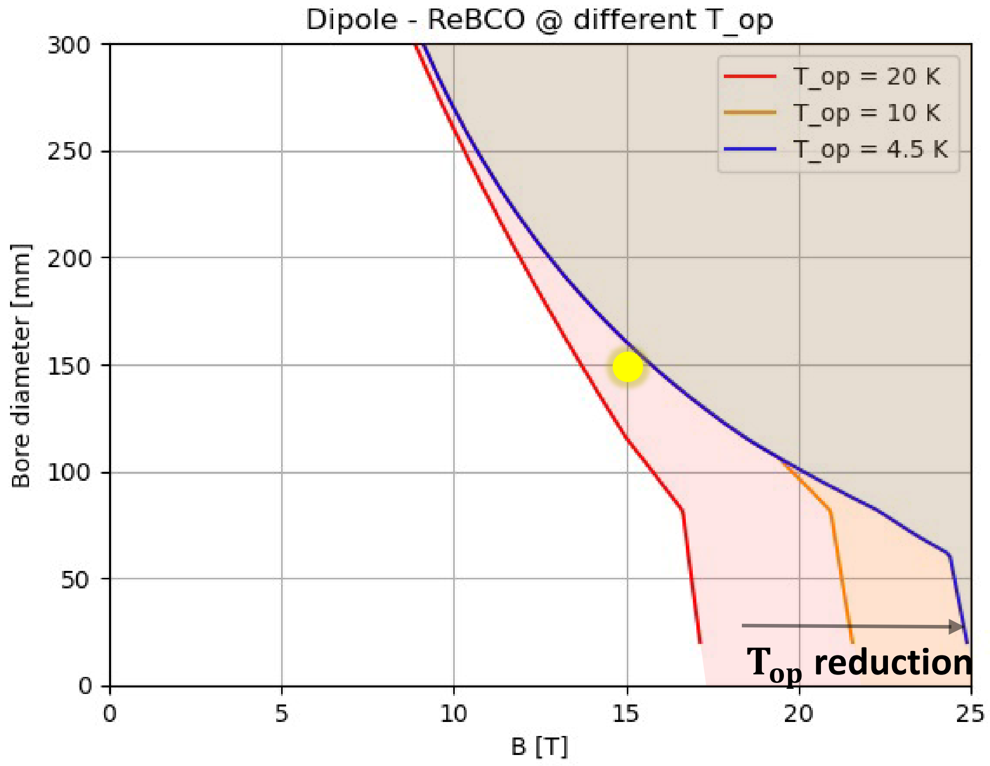


HTS falls short of required performance with classical insulated coils. Assuming MI or NI magnets, the protection limit becomes comparable with the other limits.

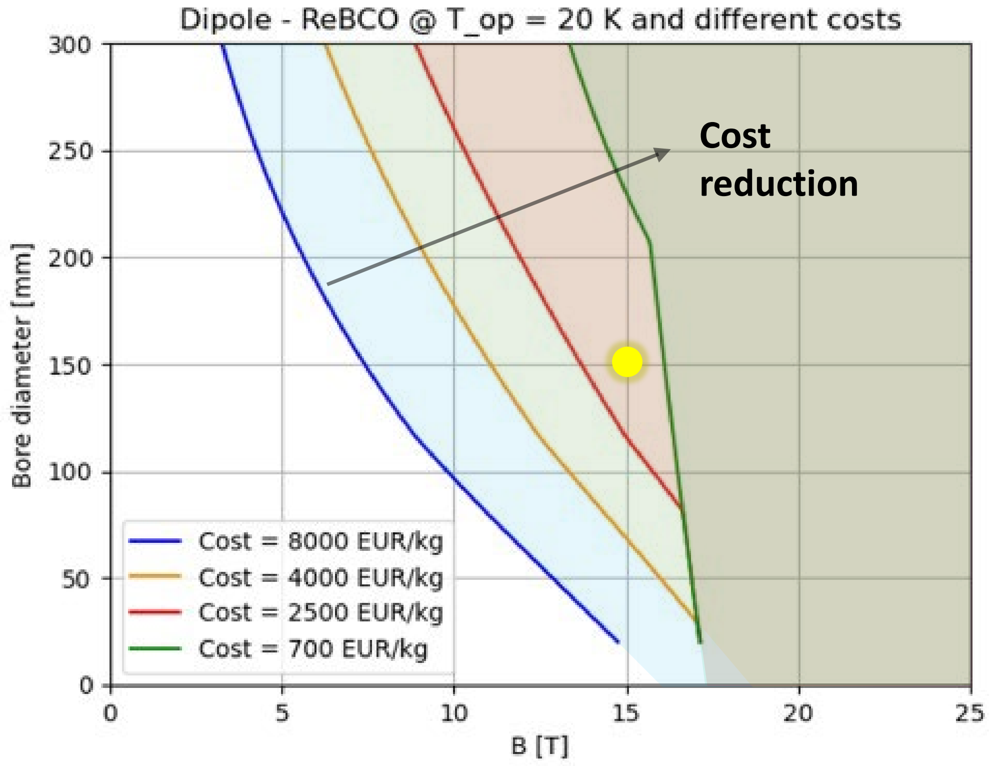
HTS options

What might improve the HTS design?

Fixed the cost per meter of magnet

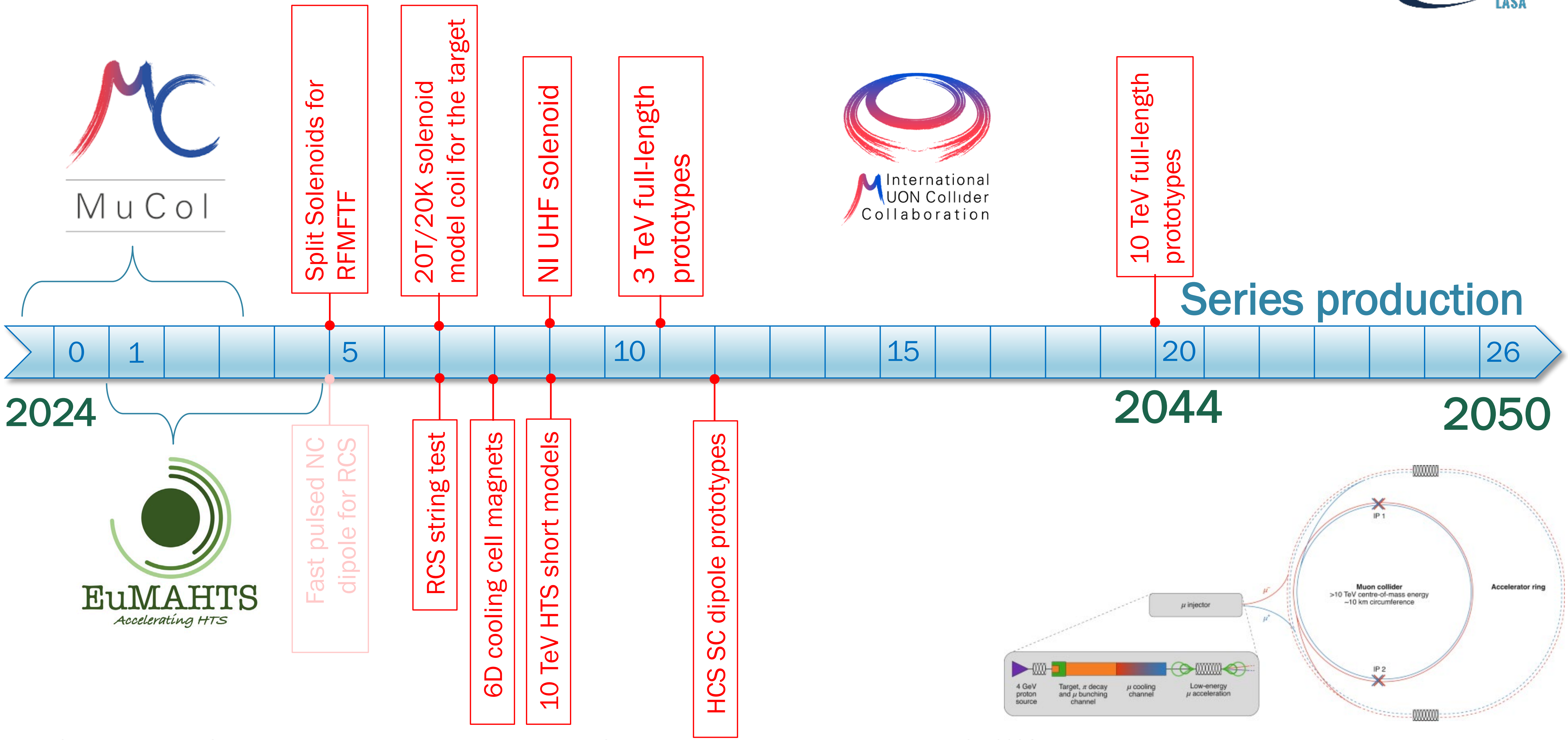


A reduction of operating temperature to 10 K



A reduction of HTS cost
(actually driven by fusion market)

R&D and production schedule



Conclusion

- HTS magnets are feasibile and sustainable for MC (steady state, high field, high operating temperature)
  - Magnetization effects for (slow) ramping and field quality over time are a challenge
  - Further modeling, testing and technology development
- The 2050 goal may be reasonable considering a strong effort (manpower, R&D and funds)
  - The effort involves heavily industry for series production (5k+ magnets)
- A promising path for increasing sustainability is 10 K to 20 K operation of HTS magnets
  - Intensive R&D and modeling is required to increase the TRL
  - Steady state operation is less demanding

Contribution by

CERN: C. Accentura, B. Auchman, B. Bordini, L. Bottura, S. Fabbri, E. Todesco

UMIL: S. Mariotto, J. Pavan, L. Rossi, S. Sorti - INFN: B. Caiffi, D. Novelli, C. Santini - Fusion for Energy: A. Portone

Funded by the European Union (EU). Views and opinions expressed are however those of the author 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.

spares

Existing plants

Temperature	COP^{-1} in W_{power}/W_{cool}	Source
250 K	1	CO_2 plant ATLAS IT
100 K	12	LN_2 plant ATLAS
80 K	16	LN_2 plant ATLAS
20 K	50	20 K/50 kW Frey's plot *
10 K	150	LHC cryoplant data
4.5 K	240	LHC cryoplant data
2.0 K	960	LHC cryoplant data

* Tieftemperatur–Technologie, von H. Frey und R. A. Haefer. Herausgegeben von F. X. Eder. VIII-Verlag, Düsseldorf 1981

Data from:

Cryogenic options for future accelerators: Muon Collider P. Borges de Sousa, M. Rhandi, T. Koettig, R. van Weelderen Muon Collider Magnets WG Meeting 30th March 2023, online

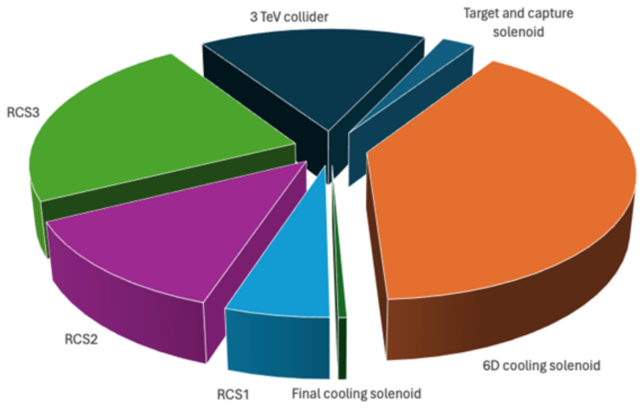
Few considerations on costs

- 6D cooling solenoids are built once
- Acceleration for 10 TeV is the highest relative cost
- More challenging single magnets are few % of the total cost (also for cooling)

We have a cost estimate

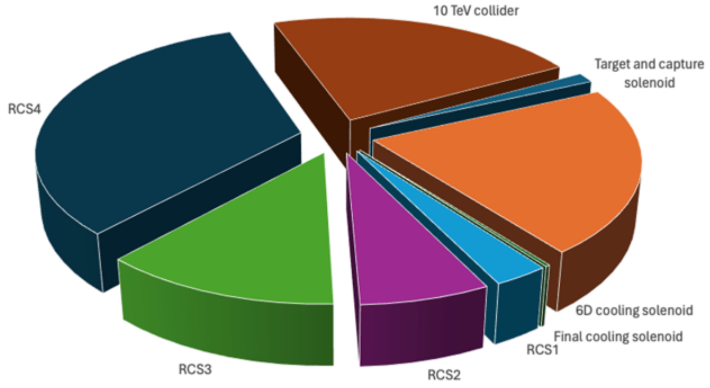
3 TeV

Share in percentage of total cost for the magnet and powering systems



10 TeV

Share in percentage of total cost for the magnet and powering systems



- The **6D cooling and accelerator (RCS)** are the largest cost positions
- RCS4 is the **largest single cost item** in the 10 TeV collider option
- Target and capture (largest stored energy single magnet in the system) and final cooling (largest nominal field) only represent a few % of the total cost

By L. Bottura

9

Comments

- HTS magnets may increase the performance and the sustainability HEP facilities, research institutes and society falicilities
- The cost of HTS tapes is decreasing thanks to higher request (fusion)
- TRL of the magnets have to be increased and the performance have to be demonstrated
- R&D, modeling and test devices are ongoing and in construction
- Dedicated test bed are requested due to the peculiarities of HTS
- A dedicated test station at INFN LASA commissioning starting in 2024 and fully operational mid 2025
- The HTS R&D is common to different scientific projects (HFM, FCC, MuCol) and paves the road for societal applications
- Industry is deeply involved in the construction of new test beds