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NAGASAKI, JAPAN - December 2-4, 2025

REBCO Requirements for Next-Generation HEP High-Field Magnets

Insights from Recent Muon Collider Design Studies

Bernardo Bordini

Acknowledgment to the Muon Collider Magnets Working group and in particular to Luca Bottura

38th International Symposium on Superconductivity

ISS 2025

Funded by the European Union

Outline

- **High Energy Physics & ReBCO Technology**
  - HEP Landscape - Circular Colliders
  - Target Cost for a next Energy Frontier Circular Accelerator
  - ReBCO as an Enabling Technology for High-Energy Physics
  - The Muon Collider (MC): a big pool for ReBCO magnets
- **The MC (ReBCO) Solenoids & cross-sector synergies**
  - The 40 T Final Cooling Solenoids, its demonstrator & on-going R&D
  - The Target and Capture Solenoids & the *20 T @ 20 K* Model Coil
  - Strategic Value of the MC Solenoids' demonstrators

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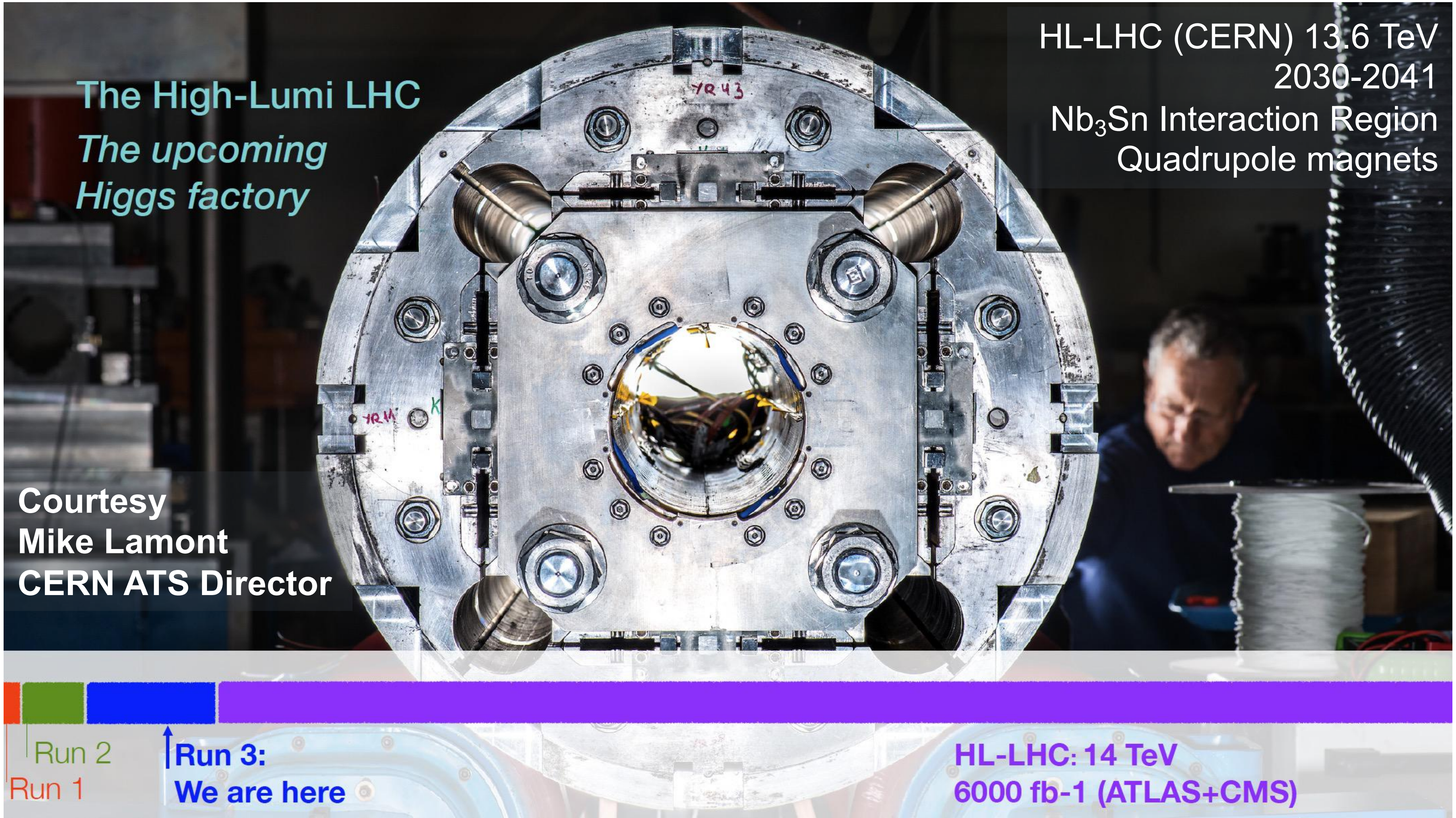
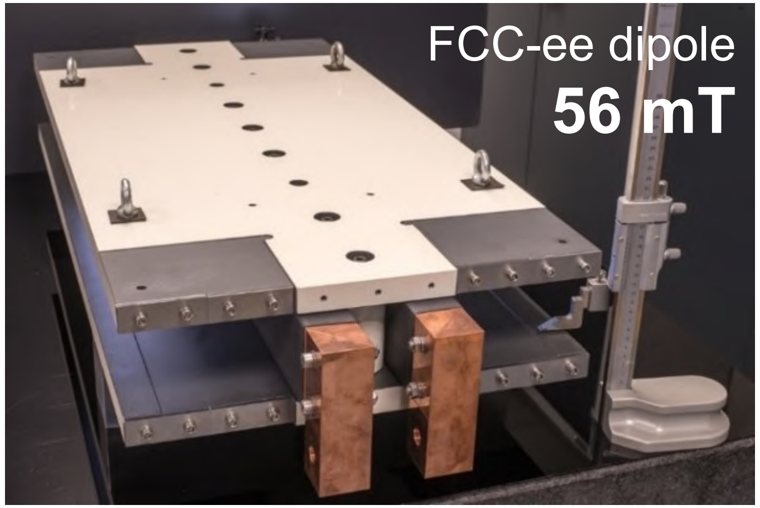
HEP Landscape - Circular Colliders

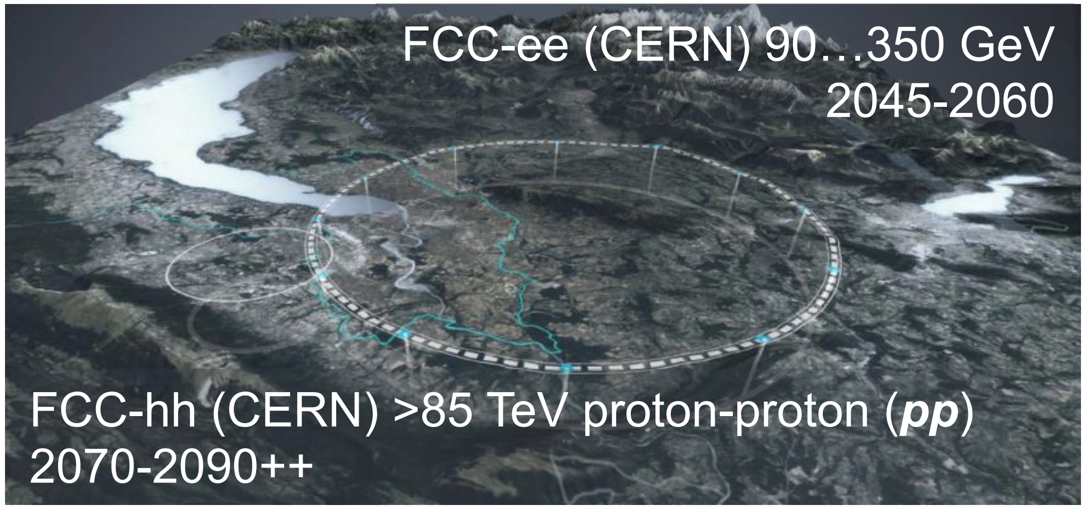
High Luminosity LHC - Hadronic machine (hh)

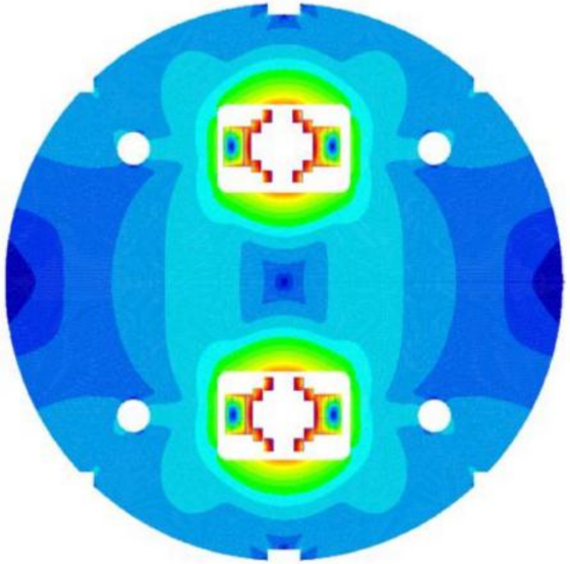


HEP Landscape - Circular Colliders

Electron-Positron (ee) & Hadronic machines (hh)



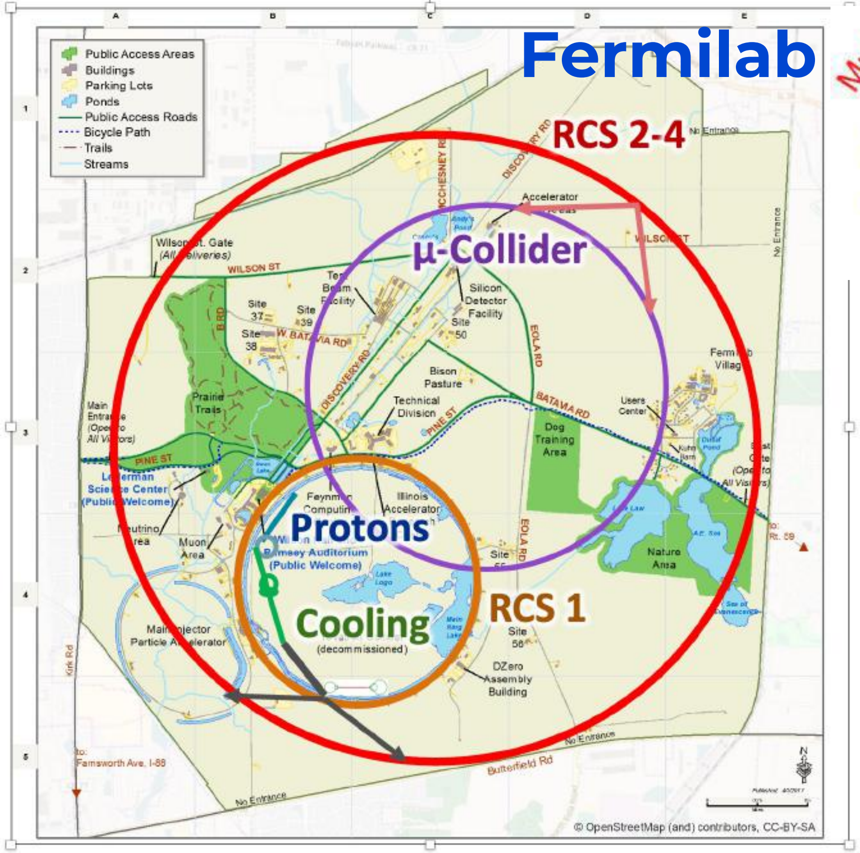


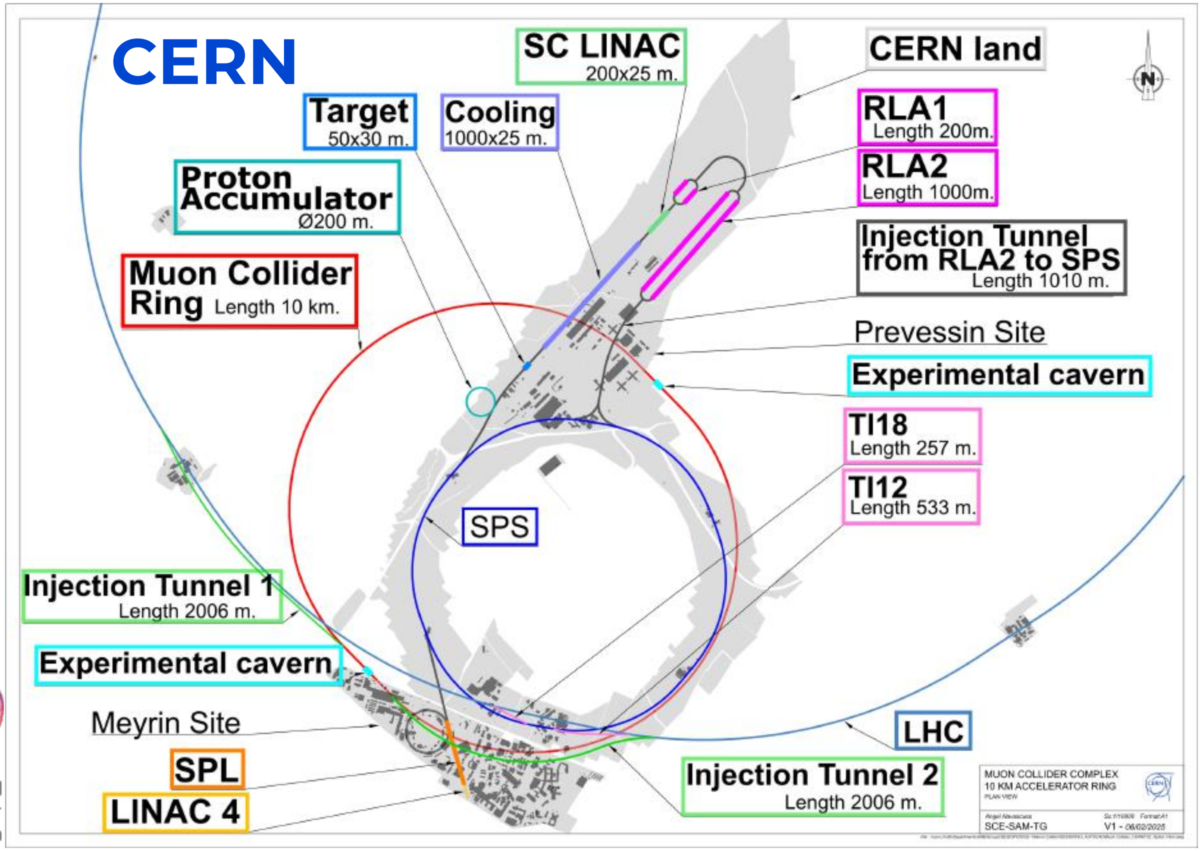


Design of a **20 T** SppC dipole

HEP Landscape - Circular Colliders

Muon (μμ) machines





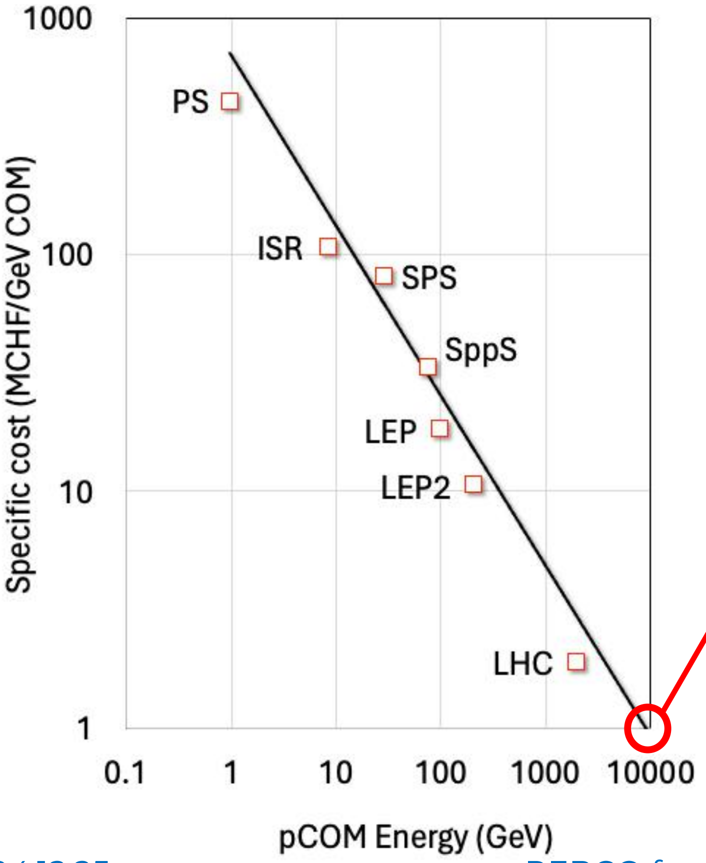
Muon Collider 3…10 TeV > 2040

μ elementary particle, ***p*** made of several elementary particles (partons)→ 14 TeV ***μμ*** ~ 100 TeV ***pp***

Target Cost for a next Energy Frontier Circular Accelerator

Specific cost of technical systems for all colliders built at **CERN**, **normalized** by the **partons** (quarks in hadrons) Center of Mass (pCOM) **energy**

Plot reproduced from **Ph. Lebrun** https://lpsc-indico.in2p3.fr/event/862/



- **Advancements** in accelerator **technology** have been **driven** by the need for
  - higher **energy**, greater **precision**, increased **efficiency**
  - a **reduction** of the **specific costs** to maintain **sustainable** the **overall costs**
- Extrapolating from the plot, the **technical system** of a **~ 10 TeV pCOM accelerator** should have as **target** a
  - **specific cost** of **~ 1 MCHF/GeV**
  - Total Cost **~ 10 BCHF**

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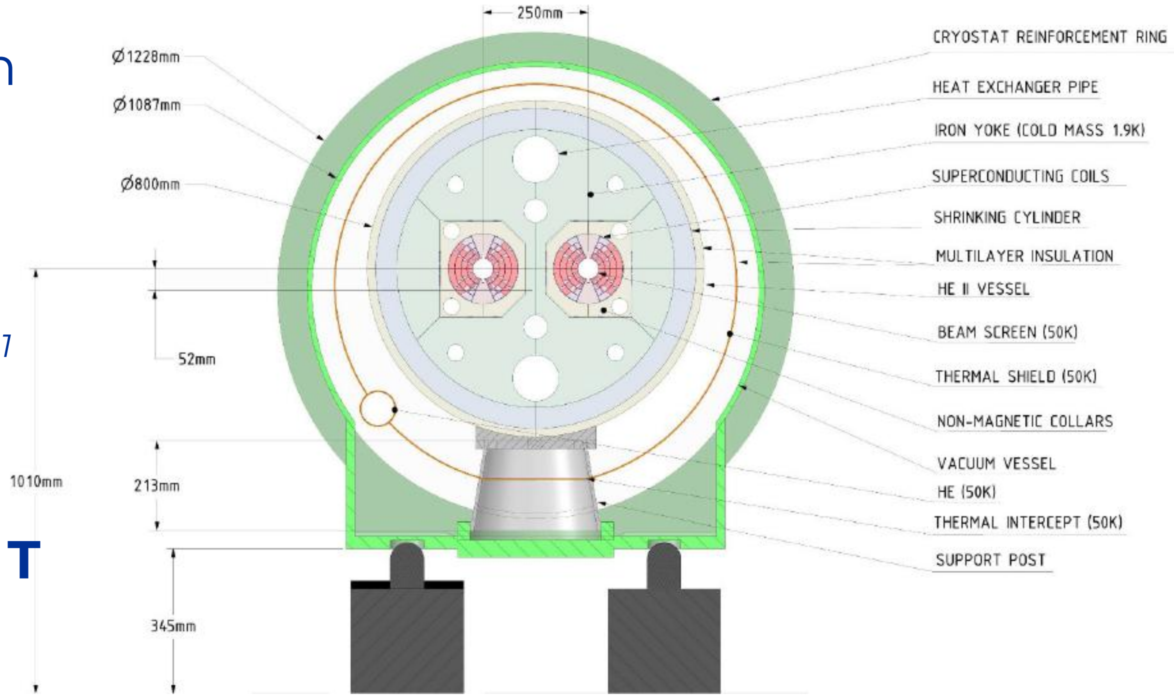
Magnet System Cost for a next Energy Frontier Circular Accelerator

- The **target** cost of **10 BCHF aligns** quite well with the **2018 FCC CDR**
  - For a 100 km ring *"The **major part** of the **accelerator cost** corresponds to the **4700 Nb_3Sn 16 T** main **dipole magnets**, totaling **9400 MCHF**"* [1]

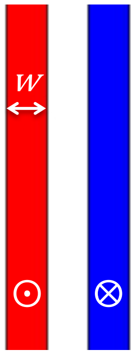
[1] https://cds.cern.ch/record/2651300/files/CERN-ACC-2018-0058.pdf

- The estimated cost of **~ 0.13 MCHF/m** for the **16 T FCC main dipoles** appears to be **beyond** the reach of **current technology**
  - though it could become **feasible with significant** advancements and **R&D** in the **future;** furthermore, **14 T** dipoles are now the project baseline.
  - The **cost** of the **Nb_3Sn wire** should **decrease** of at least a **factor of 3**



Material	Present cost (EUR/kg)	Aspirational cost (EUR/kg)
Nb_3Sn	2200	750
REBCO	8300	2300
Bi-2212	17600	7000

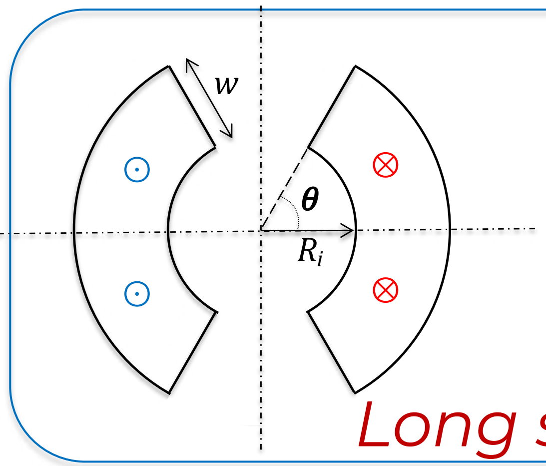
Magnetic Field vs Cost



Long (l >>R$_i$) Solenoid

$$V_{coil} = \pi \cdot l \cdot \left[\left(\frac{B_y}{\mu_0 J}\right)^2 + 2R_i \frac{B_y}{\mu_0 J}\right] \propto \boldsymbol{Cost}$$

If ***J*** is **doubled**, the **conductor cost** is **more** than **halved** !



$$V_{coil} = \theta \frac{\pi}{sin(\theta)} \cdot l \left[\left(\frac{B_y}{\mu_0 J}\right)^2 \frac{\pi}{2\,sin(\theta)} + 2R_i \frac{B_y}{\mu_0 J}\right] \propto \boldsymbol{Cost}$$

Long sector cos-θ dipole

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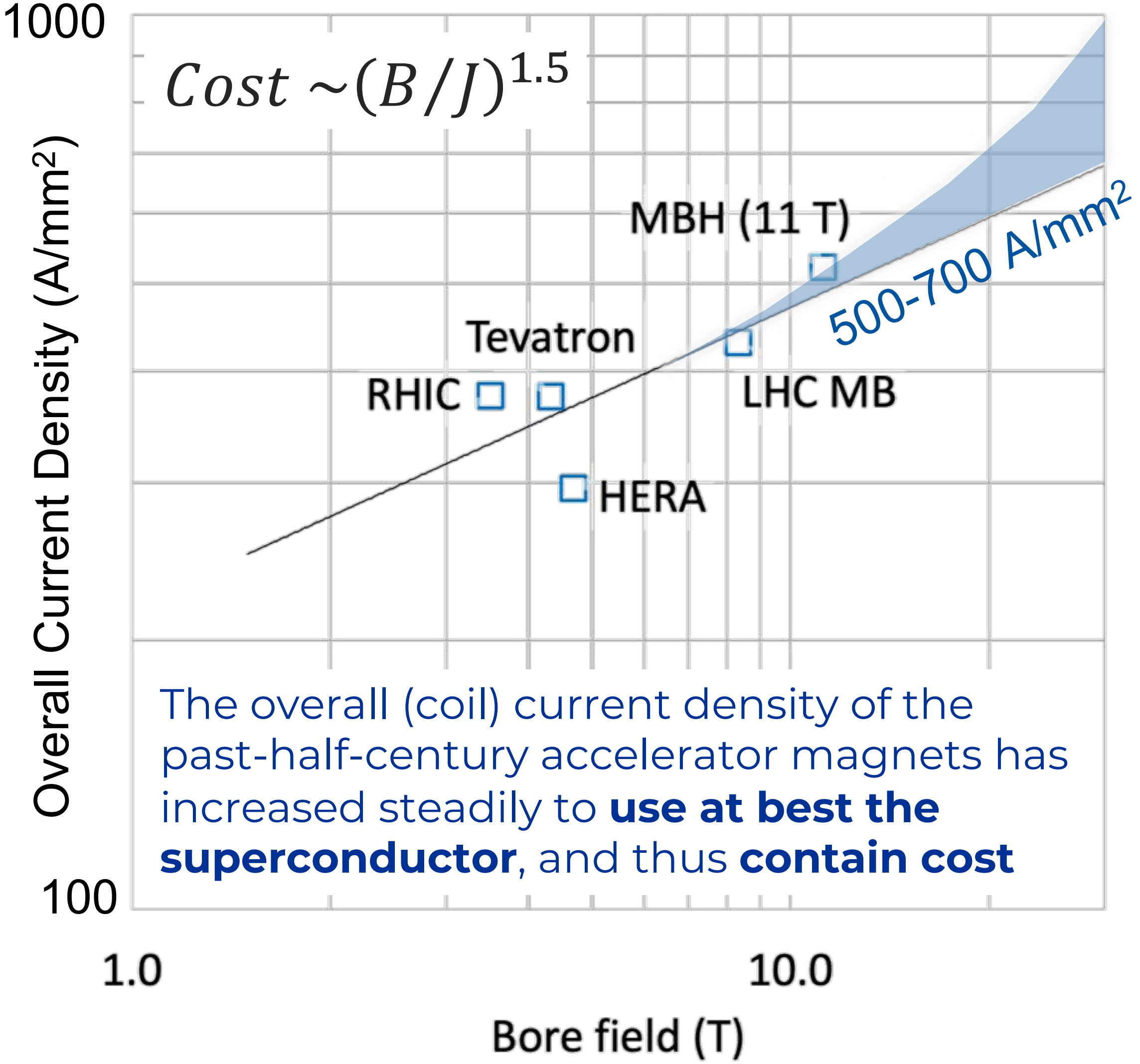
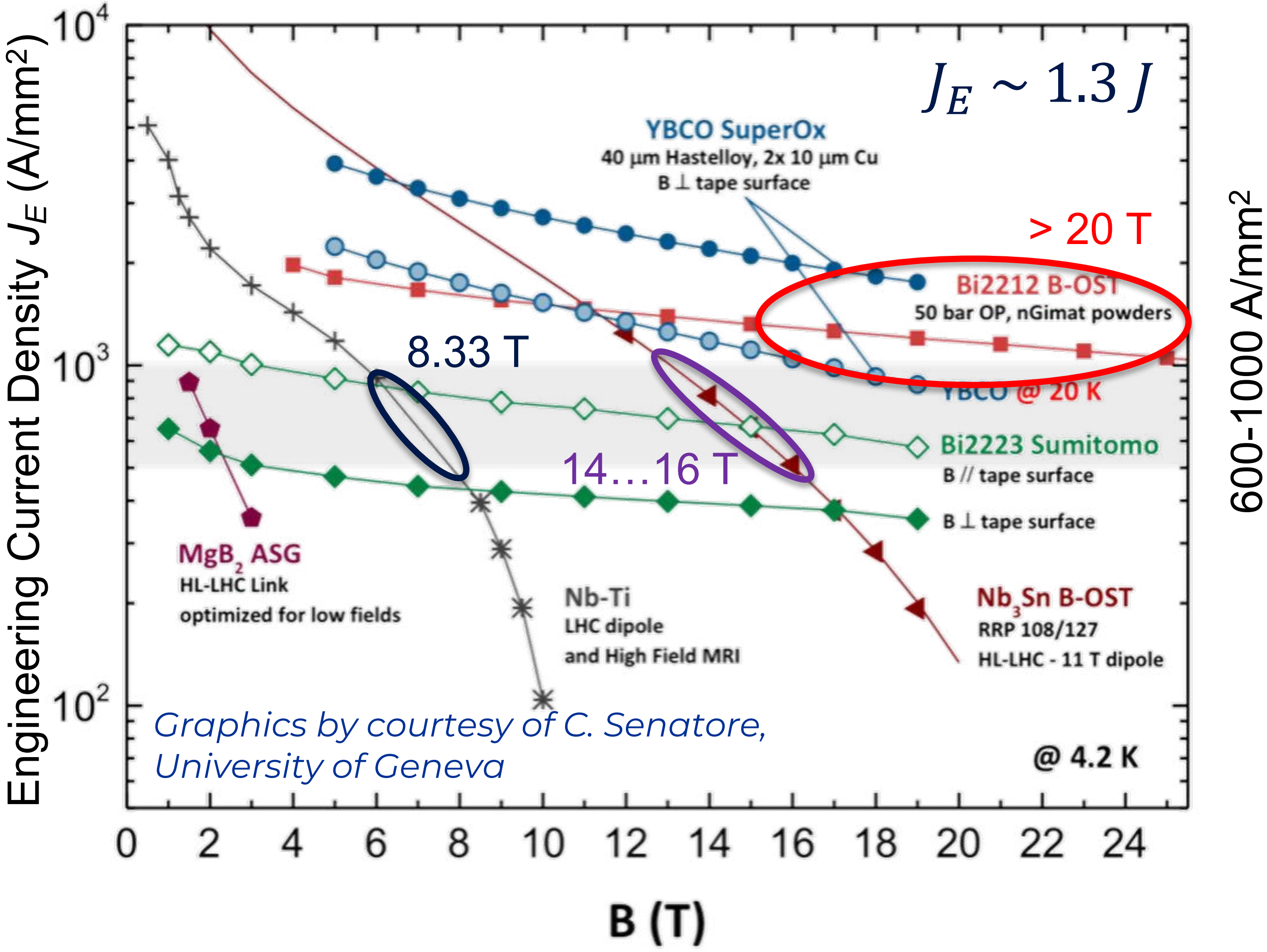
ReBCO - an Enabling Technology for HEP

Overall & Engineering Current Density



The overall (coil) current density of the past-half-century accelerator magnets has increased steadily to **use at best the superconductor**, and thus **contain cost**



Graphics by courtesy of C. Senatore, University of Geneva

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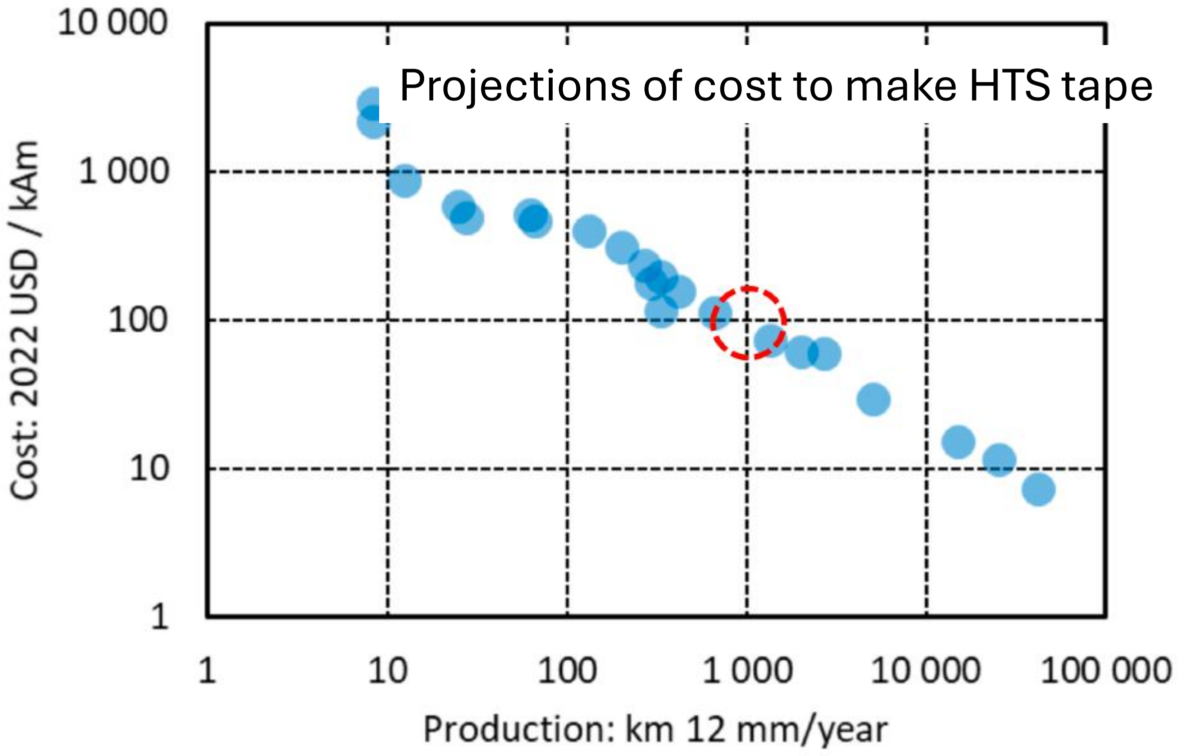
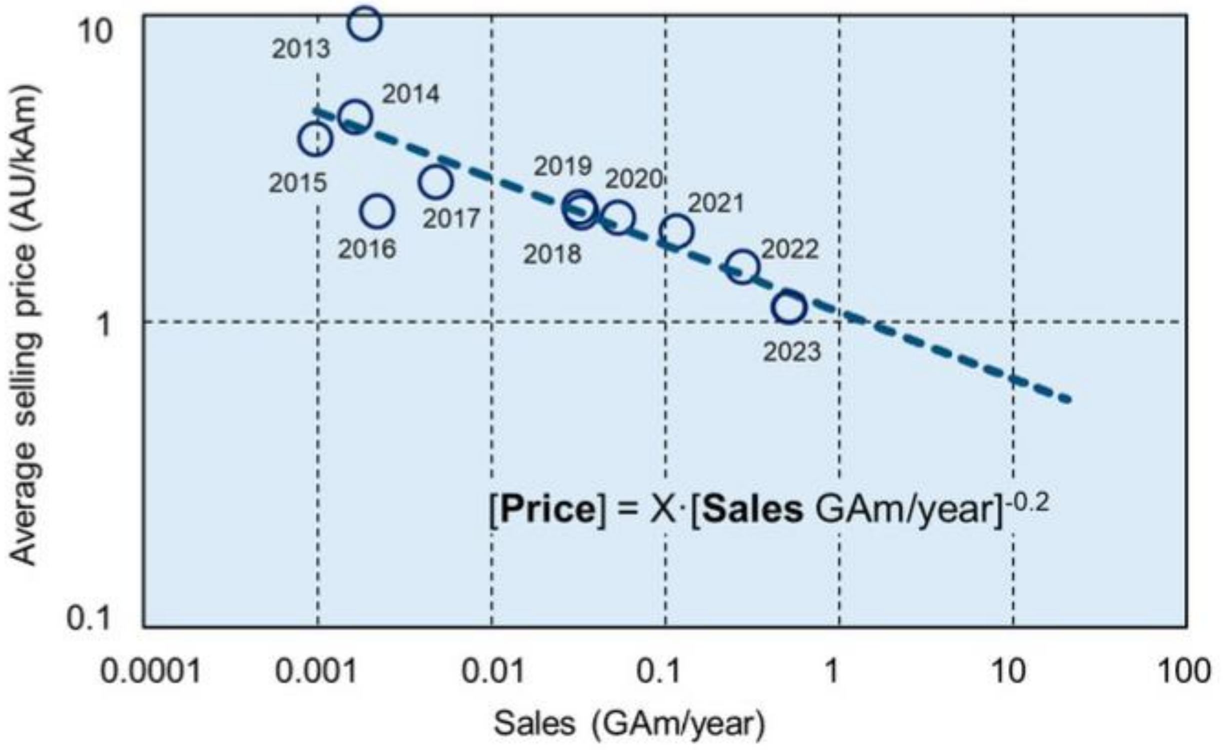
ReBCO - an Enabling Technology for HEP

ReBCO Tapes Cost Projections



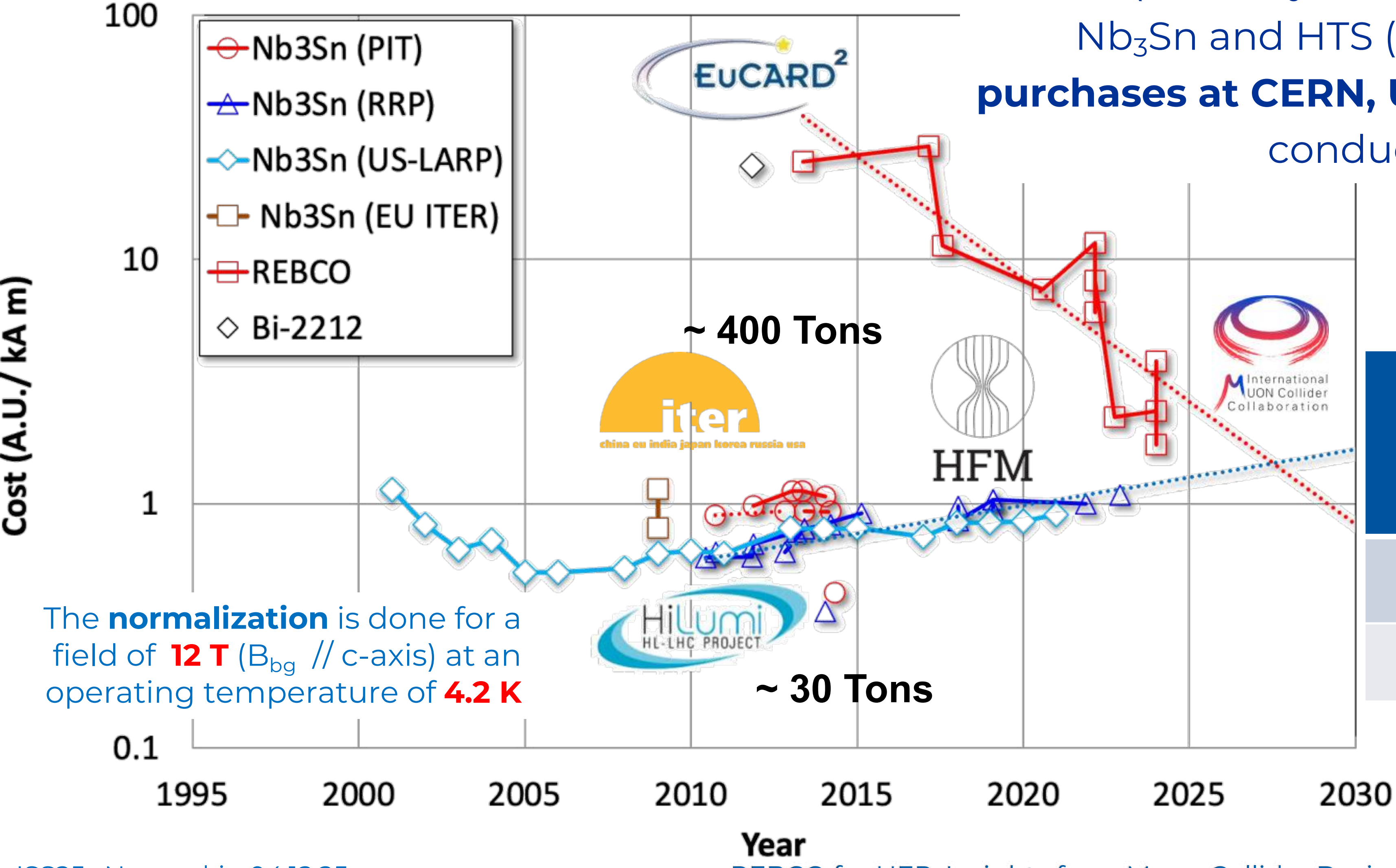
Courtesy of A. Molodyk , FARADAY FACTORY
Presented at ASC Oct. 2022



Courtesy of A. Molodyk , FARADAY FACTORY
Presented at ICSM-9, May 2024

ReBCO - an Enabling Technology for HEP

Nb_3Sn wires vs ReBCO tapes - Price trends



The **normalization** is done for a field of **12 T** (B_{bg} // c-axis) at an operating temperature of **4.2 K**

Cost (arbitrary units) **per unit length** & **current** for Nb_3Sn and HTS (mainly REBCO), derived from **purchases at CERN, US national laboratories** and **ITER** conductor procured in **EU**

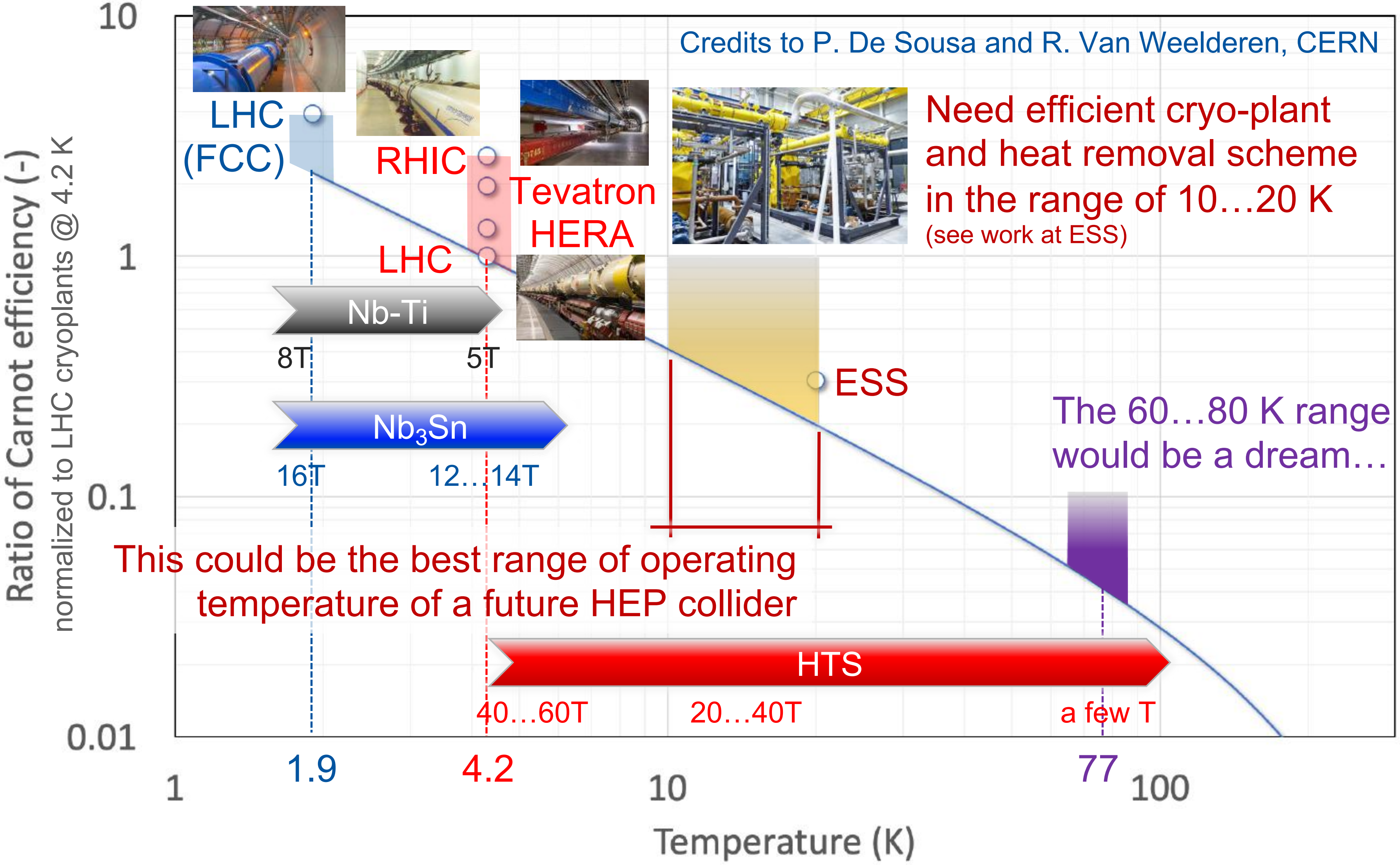
Grateful thanks to fusion for ReBCO cost reduction !

Material	Present cost (EUR/kg)	Aspirational cost (EUR/kg)
Nb_3Sn	2200	750 🙁
REBCO	8300	2300 🙂

Nb_3Sn currently has a limited market, unless fusion applications based on Nb_3Sn technology achieve large-scale success.

ReBCO - an Enabling Technology for HEP

Energy Efficient Cryogenics

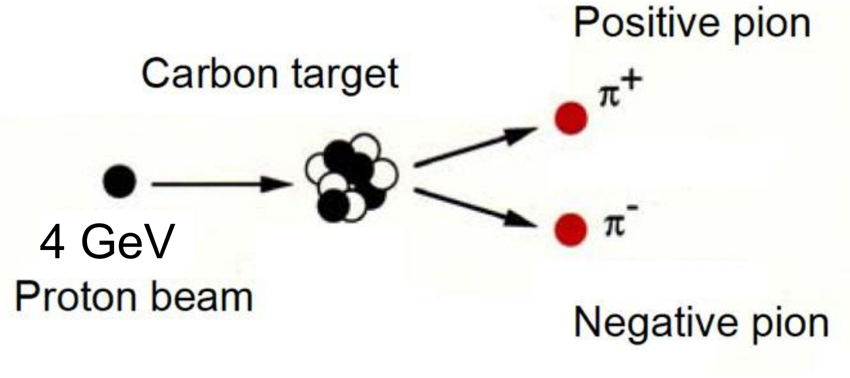


The Muon Collider

Muon production

Pion (π) production:

Proton + carbon target → $\pi^{+/-}$ + X



Pion decay:

$\pi^+ \rightarrow \mu^+ + \nu_\mu$

$\pi^- \rightarrow \mu^- + \overline{\nu}_\mu$

(Lifetime: 26 nsec.)

Muon decay

$\mu^+ \rightarrow e^+ + \nu_e + \overline{\nu}_\mu$

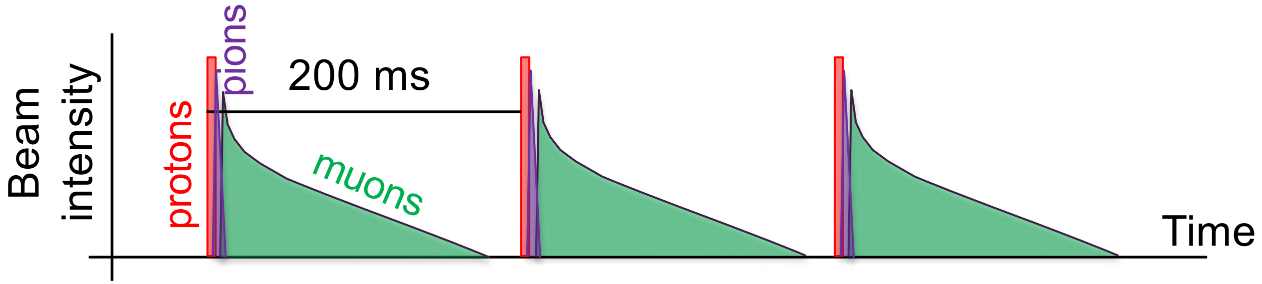
$\mu^- \rightarrow e^- + \overline{\nu}_e + \nu_\mu$

(Lifetime: 2.2 μsec.)

Muon: an **unstable** leptonic elementary particle with a **mass 207 times** larger than that of the **electron** (**synchrotron radiation not** a major **issue**)

At 3 TeV – lifetime is 63 ms

At 10 TeV - lifetime is 210 ms



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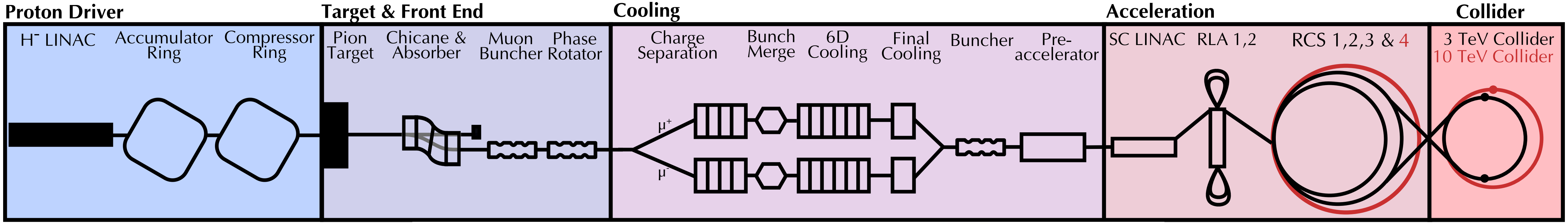
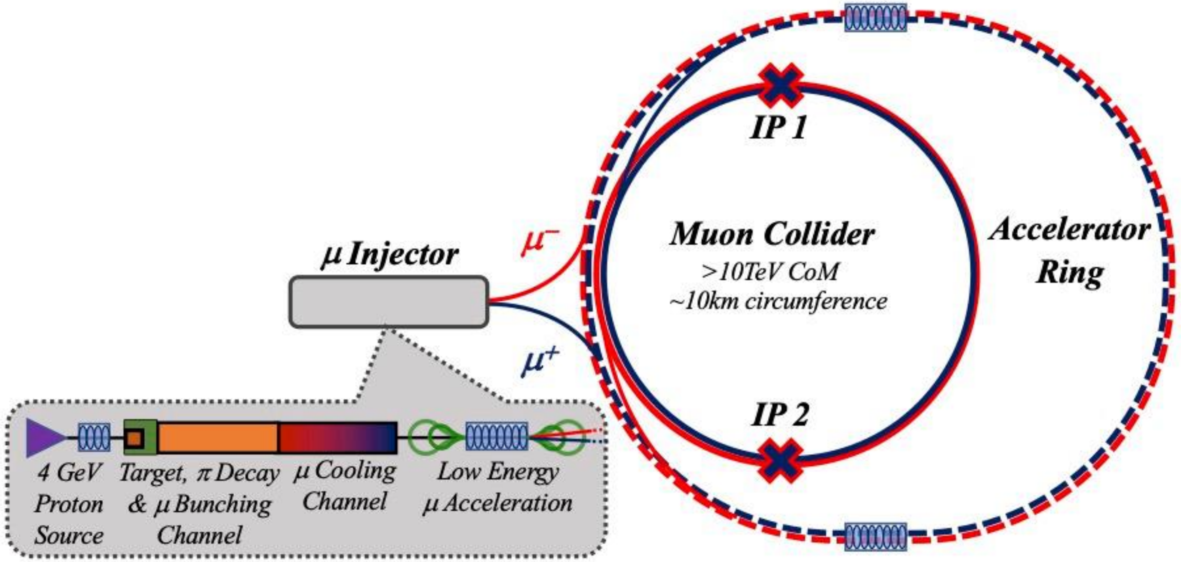
The Muon Collider

Machine Layout

International MUON Collider Collaboration

Short, intense proton bunch	Protons produce pions which decay into muons which are captured	Ionisation cooling of muon in matter	Acceleration to collision energy	Collision

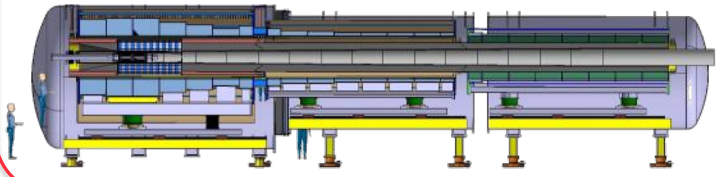




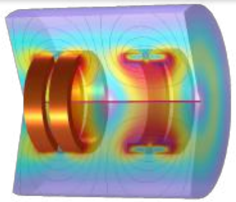
The Muon Collider (ReBCO)Magnets

20 T – 20 K - 1.4 m Aperture

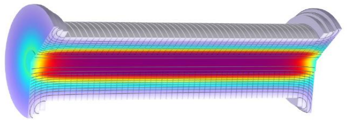
1 solenoid

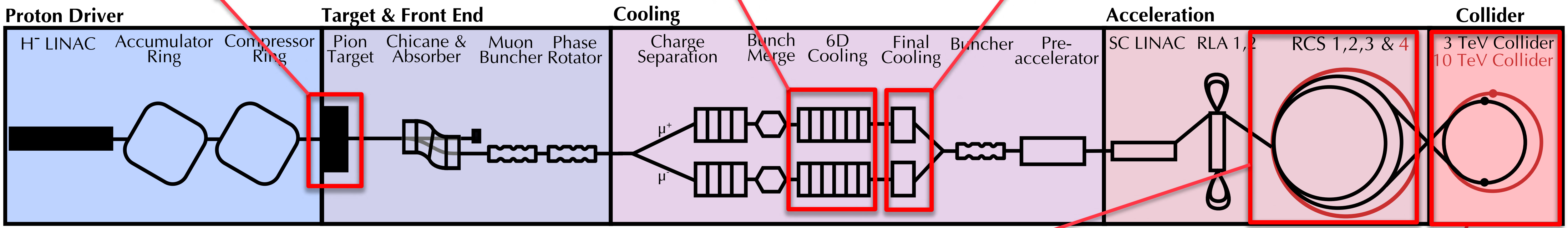


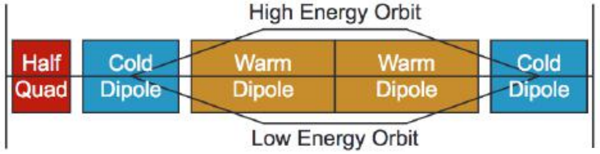
2 to 15 T - 20 K - up to 0.6 m Aperture
1+1 km of solenoids ~**3000 solenoids**



40 T – 4.2 K – 0.05 m Aperture
10+10 solenoids up to 2 m long





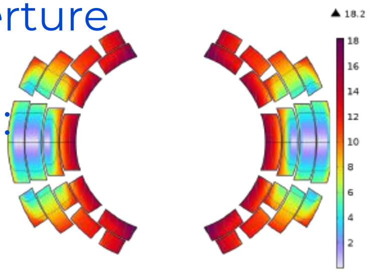


20 K 10 T steady state
30x100 mm aperture

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

14/16 T – 20 K - 0.14 m Aperture

10 TeV collider (10 km ring):
1200 5 m-long arc **dipoles**



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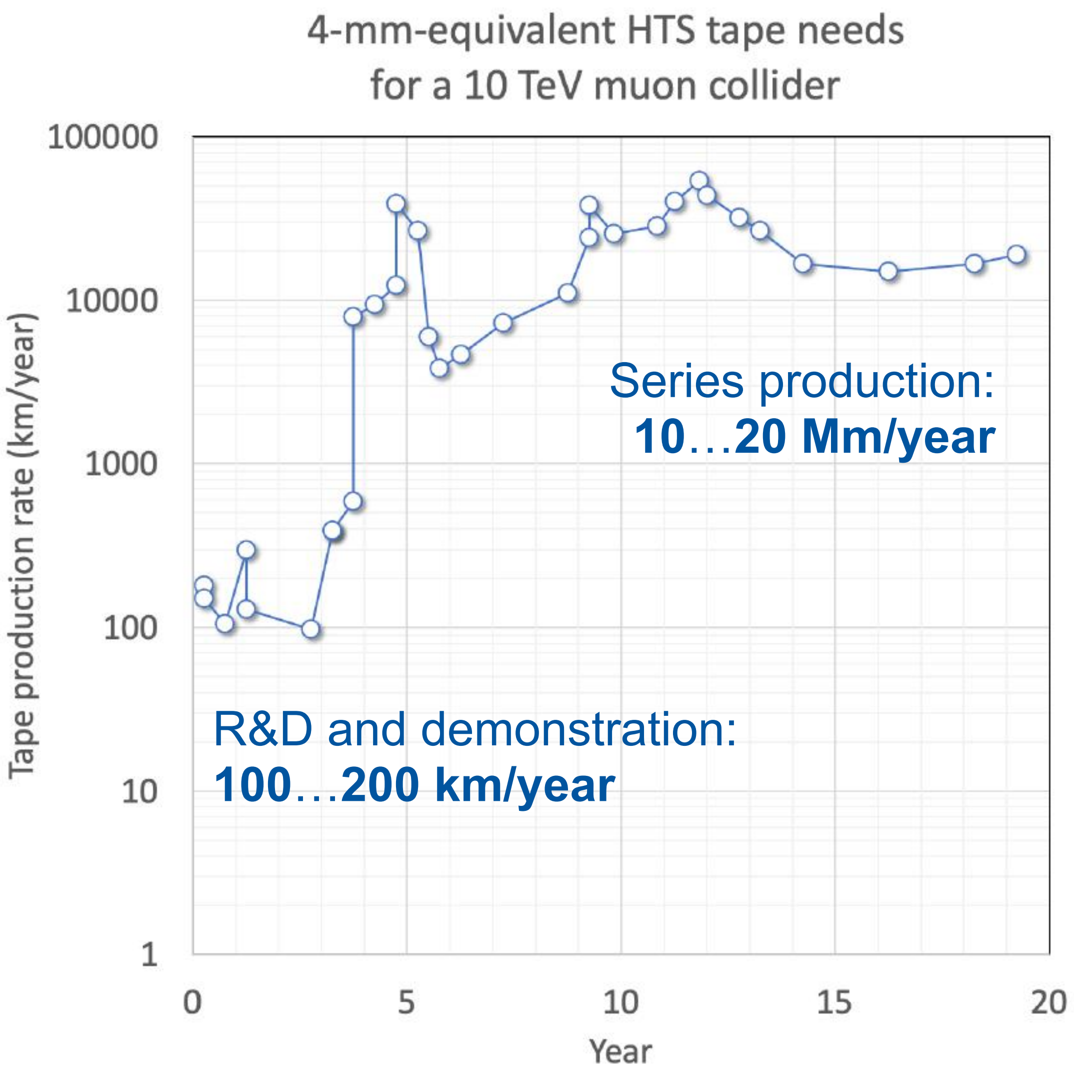
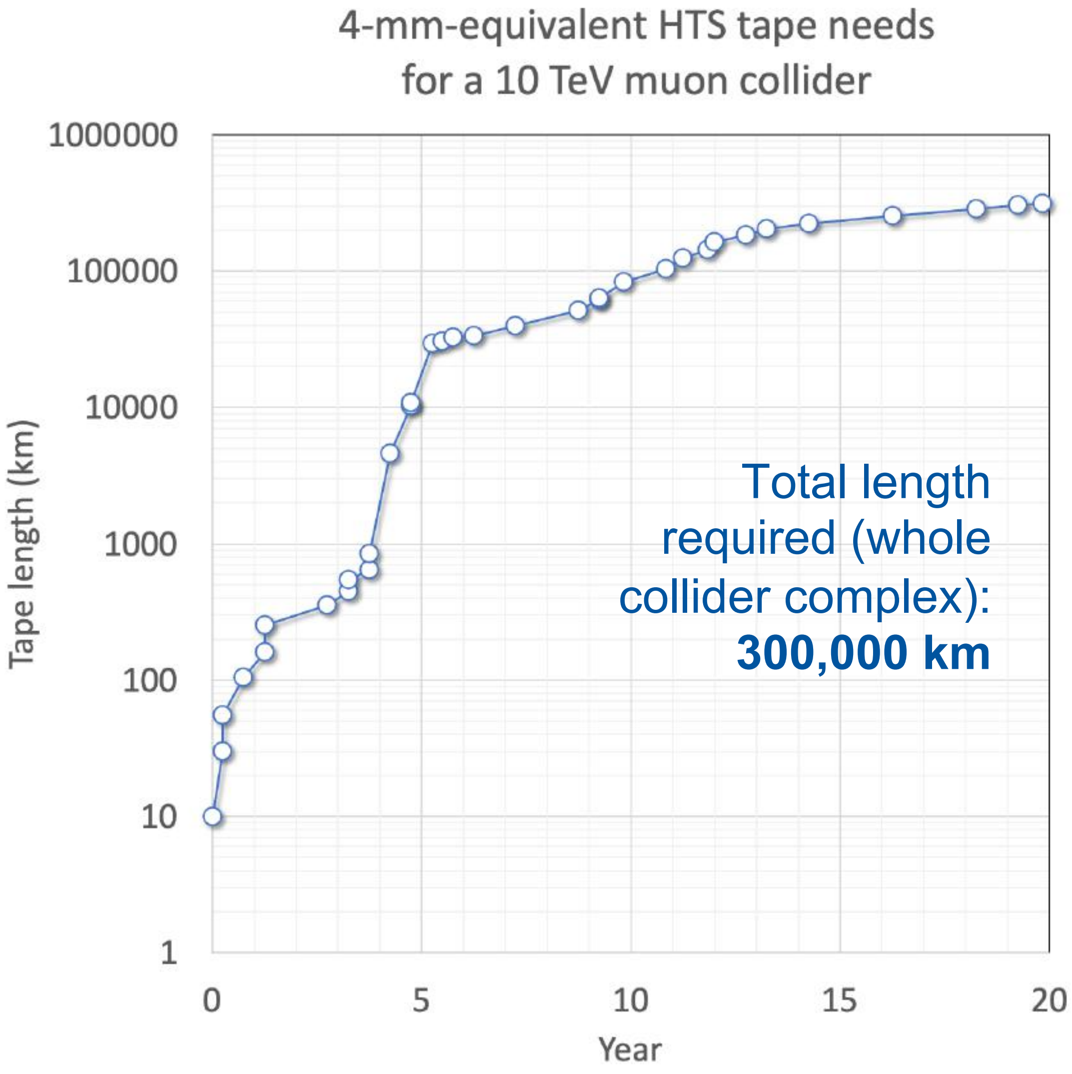
ReBCO needs for a Muon Collider





Outline

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  - The 40 T Final Cooling Solenoids, its demonstrator & on-going R&D
  - The Target and Capture Solenoids & the *20 T @ 20 K* Model Coil
  - Strategic Value of the MC Solenoids' demonstrators

The FC solenoids in the Cooling System

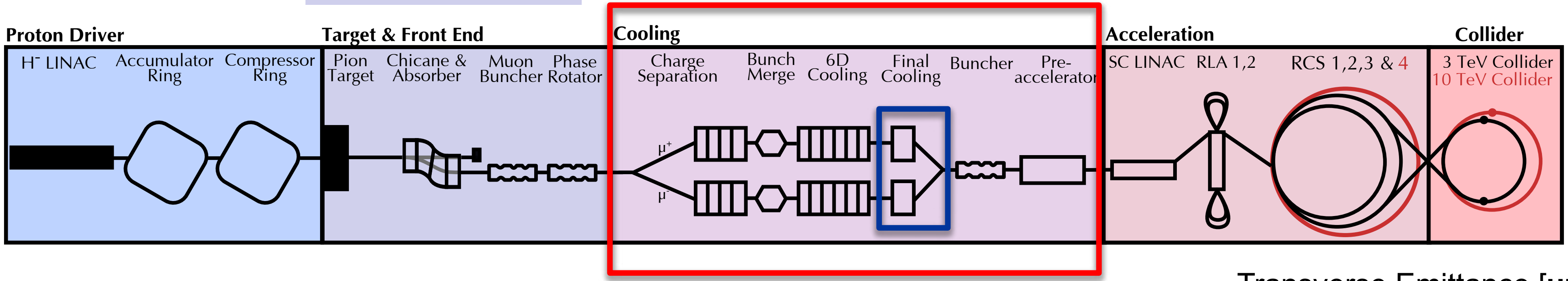
Short, intense proton bunch

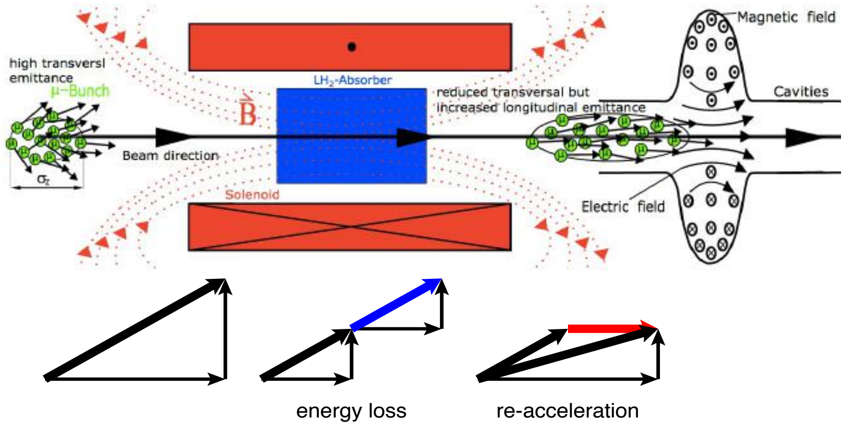
Protons produce pions which decay into muons which are captured

Ionisation cooling of muon in matter

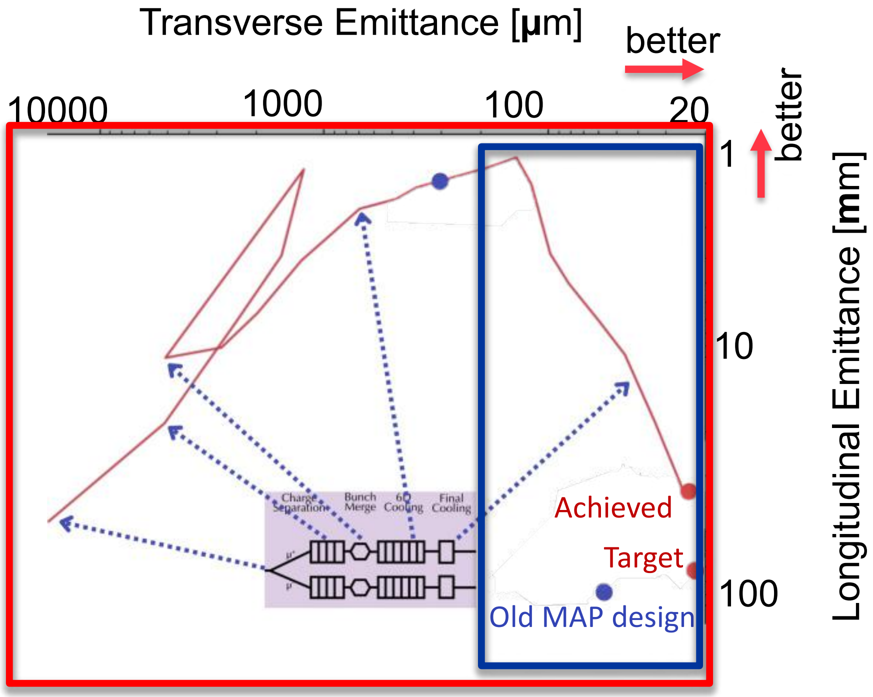
Acceleration to collision energy

Collision





- The final cooling magnets are part of the **Cooling System**, specifically within the **two Final Cooling Channels**



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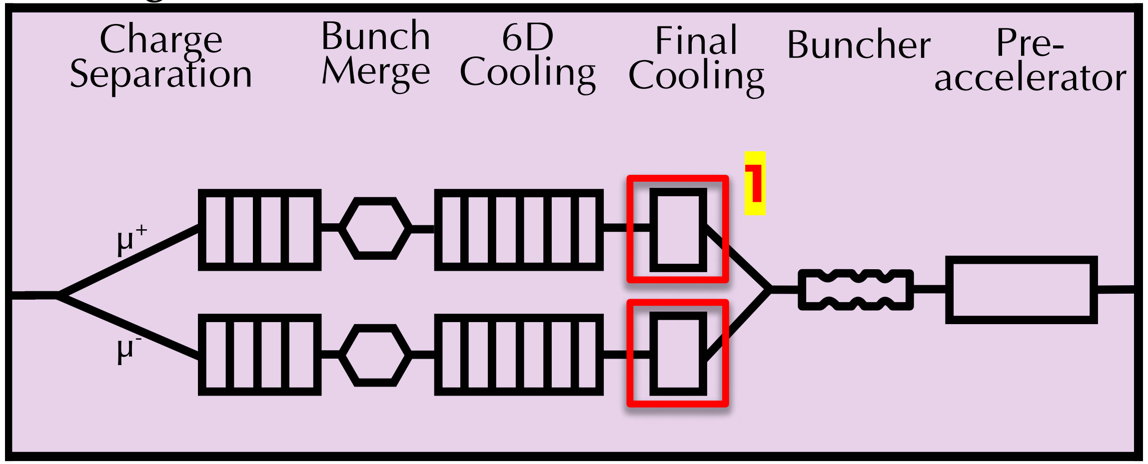
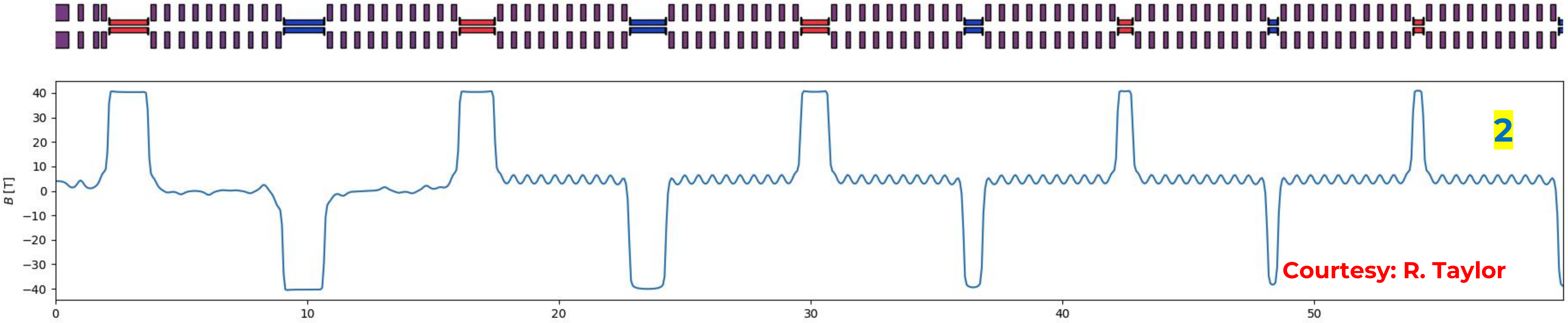
The FC Channels

Cooling



- The **two Final Cooling Channels**[1] consists of **several cooling cells** arranged in sequence
  - the latest configuration consists of **10 cells**[2]
  - **Each cell** presents **one 40-T-solenoid** of different lengths



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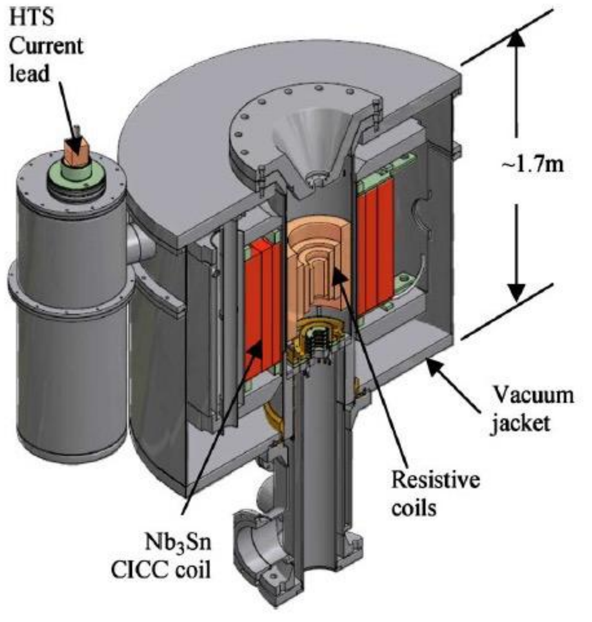
State of the Art Ultra High Field Solenoids

Superconducting (LTS) + Resistive (Cu)

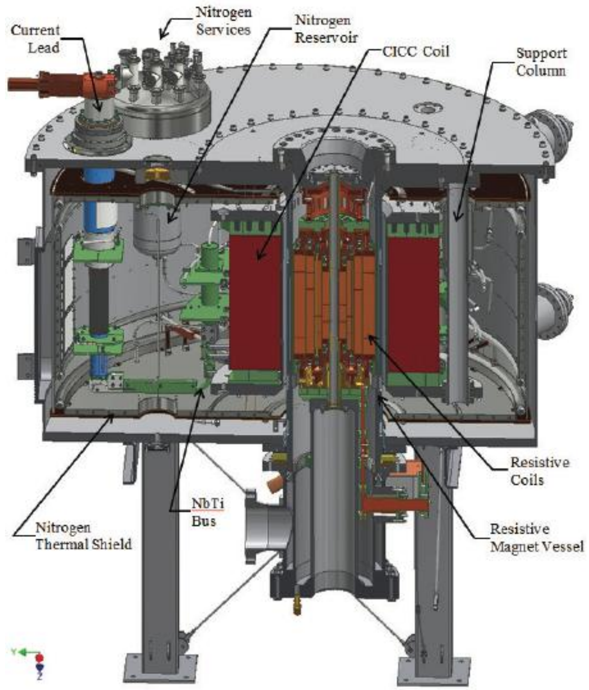
https://nationalmaglab.org/user-facilities/dc-field/magnets-instruments/

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

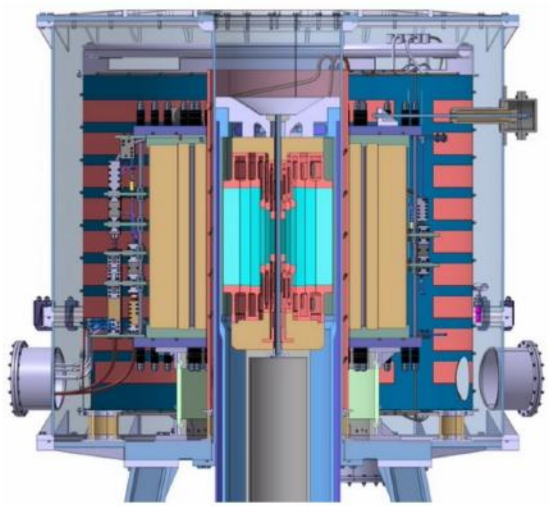


Tallahassee magnet system.

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



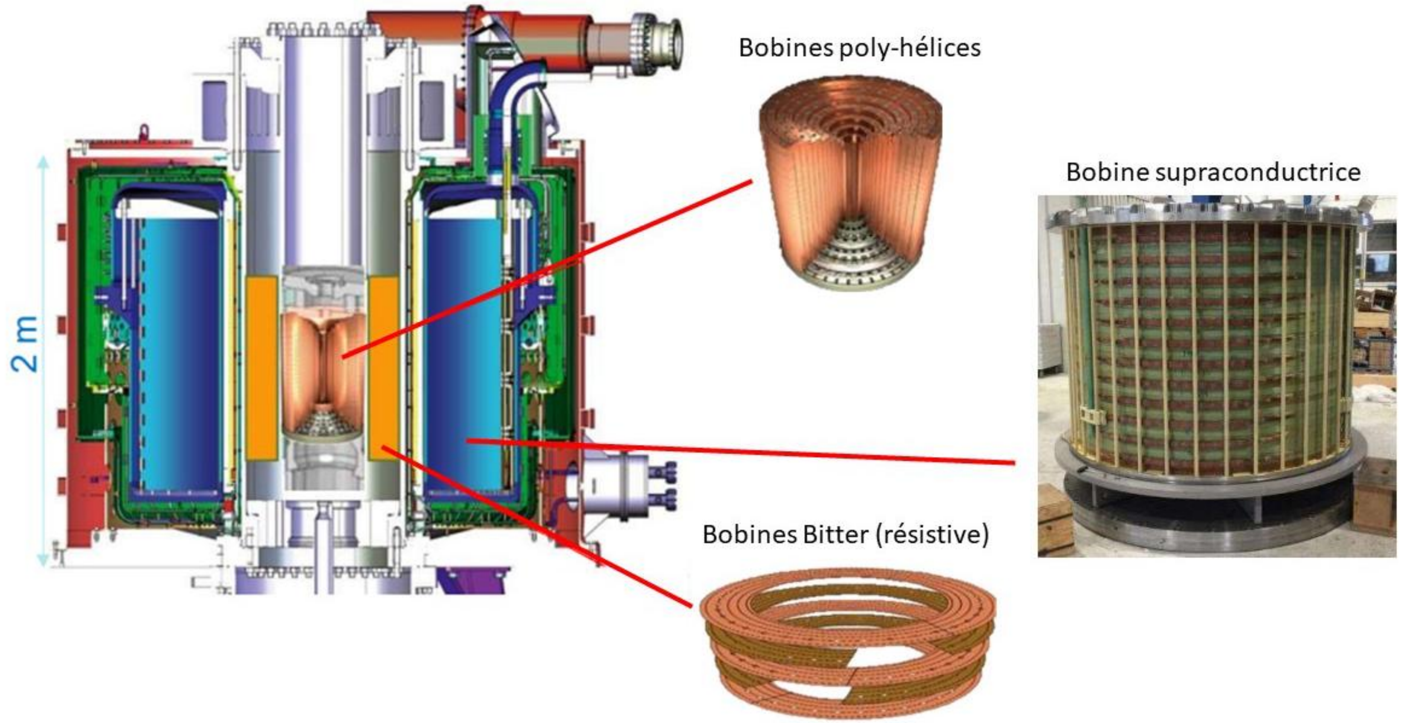
Cross section of **45/37 T**, **32/50 mm**
CHMFL user facility solenoid
Hybrid Magnet 29/26 T from resistive insert, 11 T by superconducting Nb_3Sn CICC outsert
20 MW power comsumption

State of the Art Ultra High Field Solenoids

Superconducting (LTS) + Resistive (Cu)

International MUON Collider Collaboration

42 T Reached on November 2024

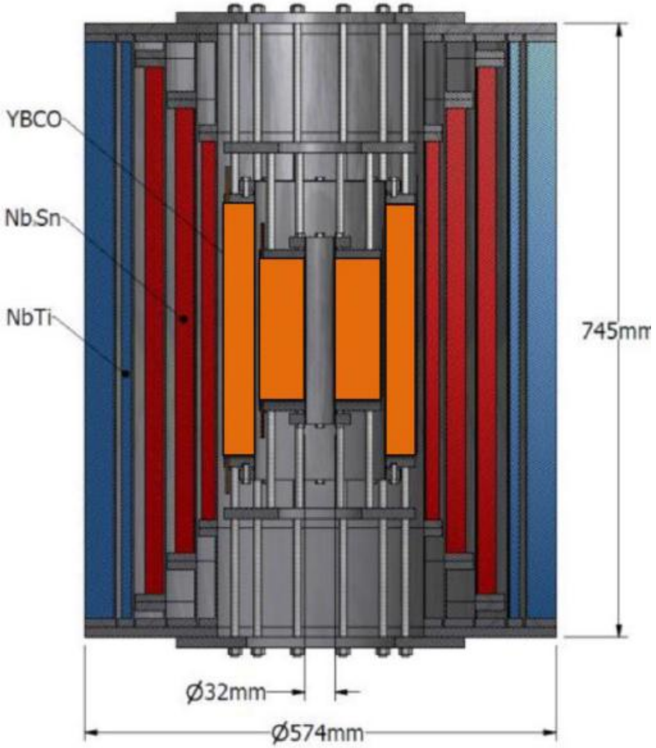


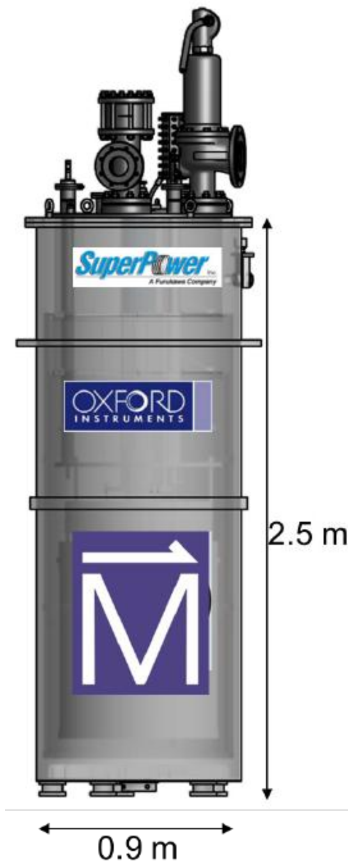
Cross section of 42 T, **34 mm LNCMI** solenoid
Hybrid Magnet 33.5 T from resistive insert, 8.5 T (1.8 K) by superconducting outsert
21 MW power comsumption

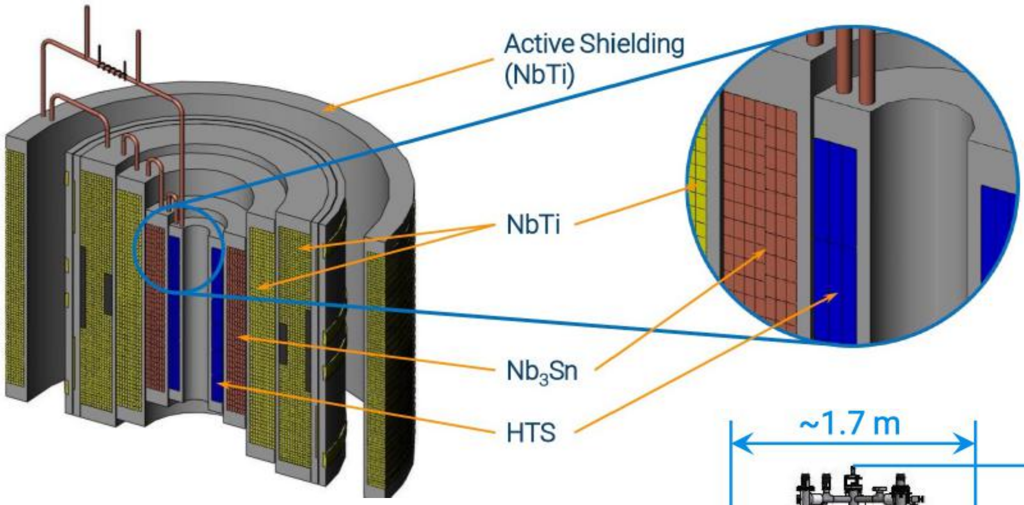
State of the Art Ultra High Field Solenoids

All-Superconducting (LTS+HTS) Solenoids

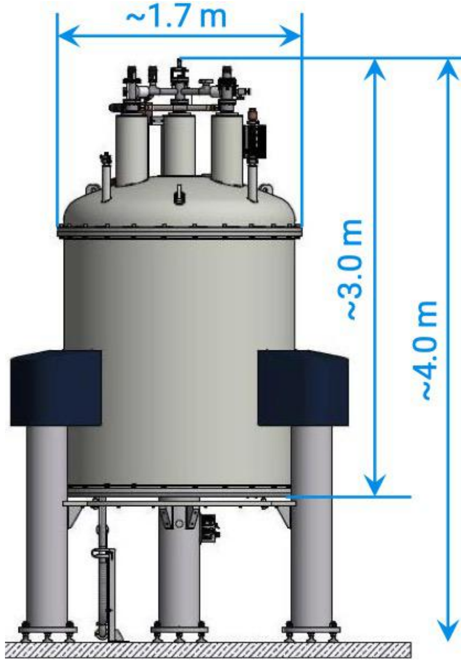
Cross section of **32 T** (15 T LTS, 17 T two ReBCO double pancake coils), **32 mm** user facility solenoid
https://nationalmaglab.org/user-facilities/dc-field/magnets-instruments/







Artistic impression of a UHF NMR magnet by Bruker:
1.3 GHz-NMR (Bruker)
30.55 T – 54 mm RT
https://snf.ieeecsc.org/sites/ieeecsc.org/files/documents/snf/abstracts/MT27%20PL1%20Bruker%20High%20Field%20NMR.pdf



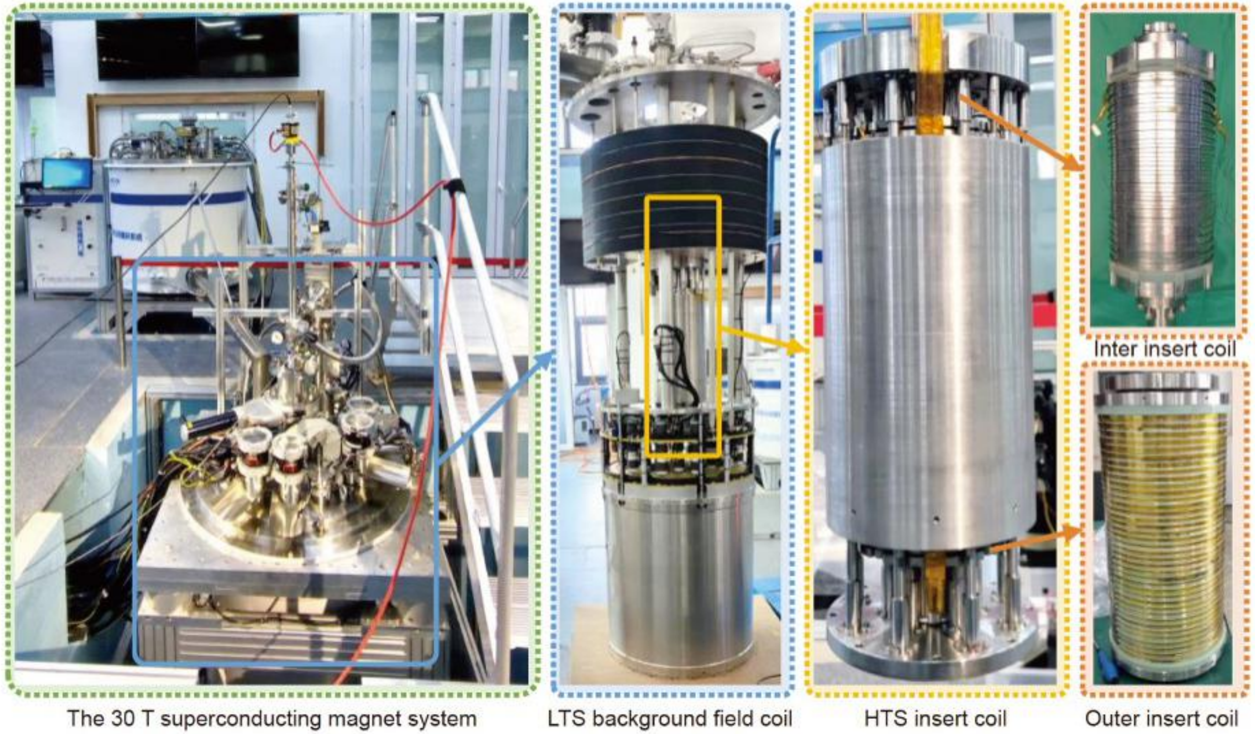
State of the Art Ultra High Field Solenoids

All-Superconducting (LTS+HTS) Solenoids

Total field	30 T
Insert magnet	15 T
Background magnet	15 T
Cold inner bore	35 mm
Operating current	140.1 A
Superconducting tape	YBCO
Co-wound tape	stainless steel tape
Coil structure	Double pancake
HTS conductor length	9290 m
Homogeneity	8 ppm @DSV 30 mm

Zhou, B., Dai, Y., Zhang, Z. *et al.* Achievement of a high-performance 30-tesla metal-as-insulated user superconducting magnet. *Sci. China Technol. Sci.* **67**, 1974–1978 (2024).

Synergetic Extreme Condition User Facility (SECUF), Huairou Science City, Beijing



30 T User Facility in SECUF

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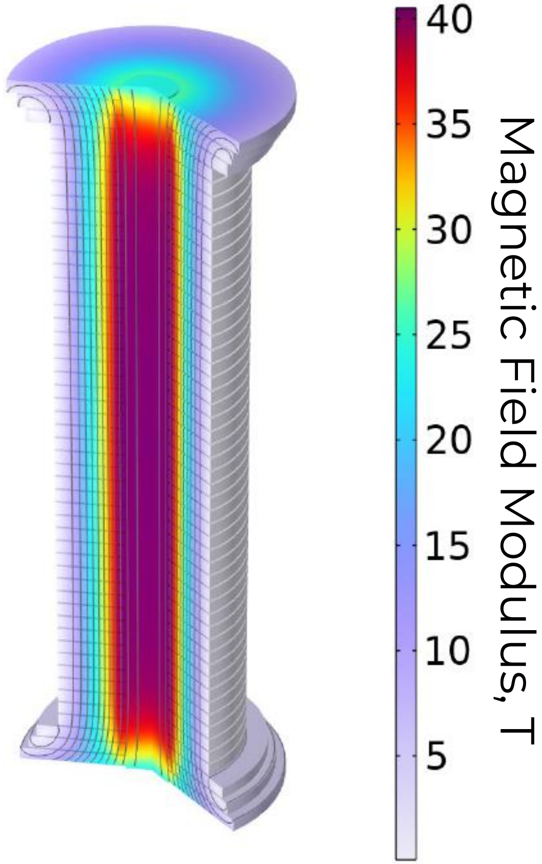
The 40 T FC Solenoid Conceptual Design

Ultra Compact Full ReBCO Solenoid

International MUON Collider Collaboration

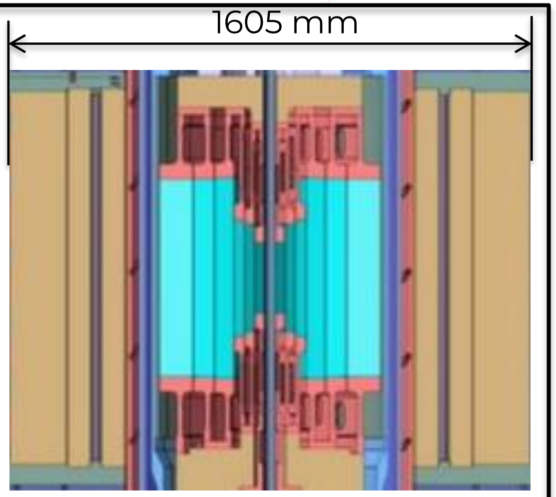
73 cm height, 46 modular single pancakes +6 pancakes for the heads

J = 632 A mm^{-2} → 40 T

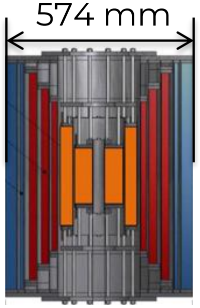


Main Dimensions, mm	Free Bore	50
	Winding ID	60
	Modular Winding OD	180
	Tape Width	12
Current, A	Conductor (single tape)	~ 650
Magnetic Energy, MJ/m	Overall	~ 5
Temperature, K	Conductor Innermost layer	4.5
Current Margin, %	Current, B//a-b	> 100

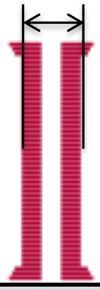
Windings of the **Hybrid 45 T, 32 mm** user facility solenoid at **CHMFL**



Winding of the **full superconducting** (15 T LTS, 17 T ReBCO) **32 T, 32 mm** user facility solenoid



Winding of the **full ReBCO 40 T- 50 mm** solenoid proposed for the Final Cooling



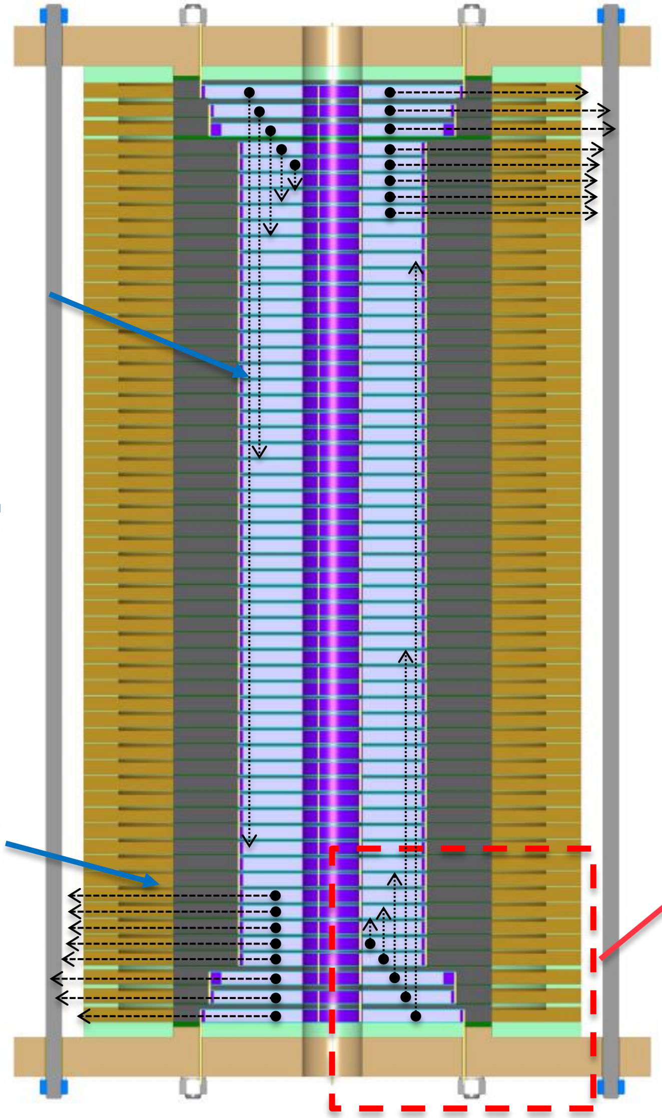
*B. Bordini *et al.*, "Conceptual Design of a ReBCO Non/Metal-Insulated Ultra-High Field Solenoid for the Muon Collider," in *IEEE Transactions on Applied Superconductivity*, 2024

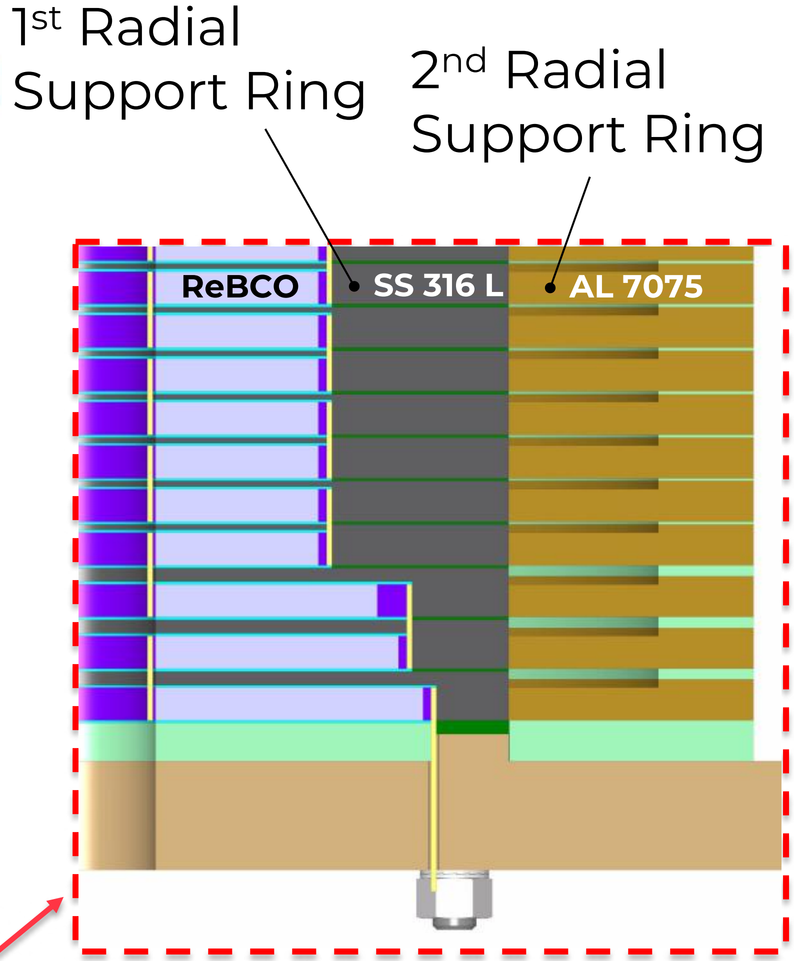
A Preliminary Engineering Design

200 MPa Radial Precompression

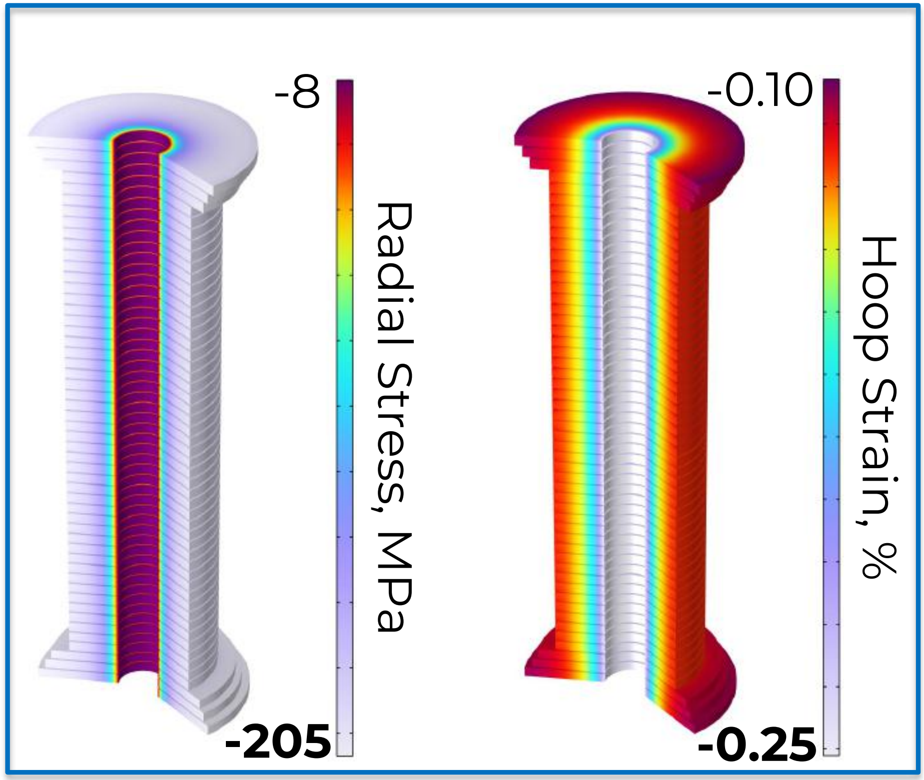
International MUON Collider Collaboration

Radial Lorentz Forces **scaled down** by a **factor** of **3** with **respect** to **axial** forces





Precompression at Room Temperature (RT) via **shrink fitting** of Radial Support Rings

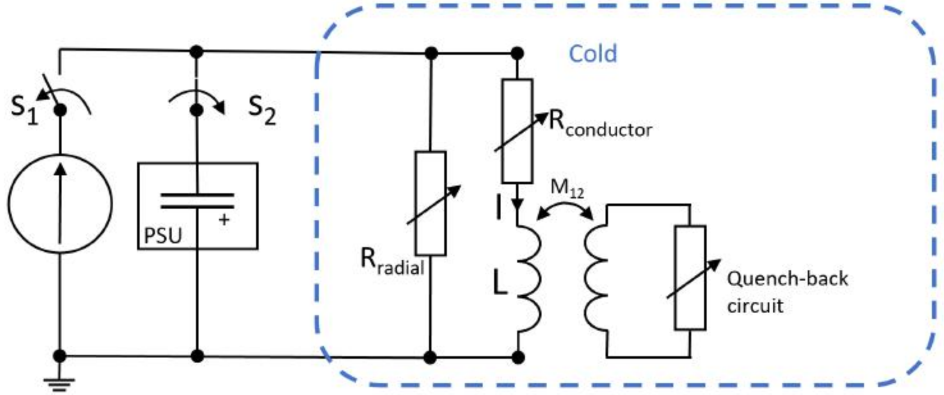


B. Bordini *et al.*, "Development of a ReBCO Non/Metal-Insulated 40 T Solenoid for a Muon Collider," TAS 2025

C. Accettura *et al.*, "Mechanical Design of a ReBCO Non/Metal-Insulated 40 T Solenoid for the Muon Collider," TAS 2025

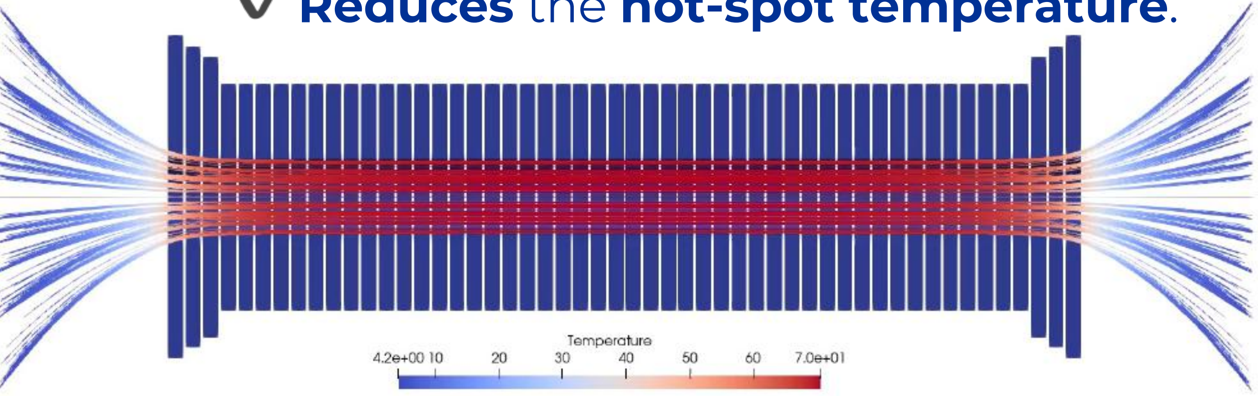
The 40 T FC Solenoid
Protection Studies

- The **Capacitor Discharge** (CD) quenches the full magnet to **normal state** within **milliseconds** without the need of additional electrical infrastructure.
  - **opening the breaker** and **injecting** additional **current** to **heat the magnet**

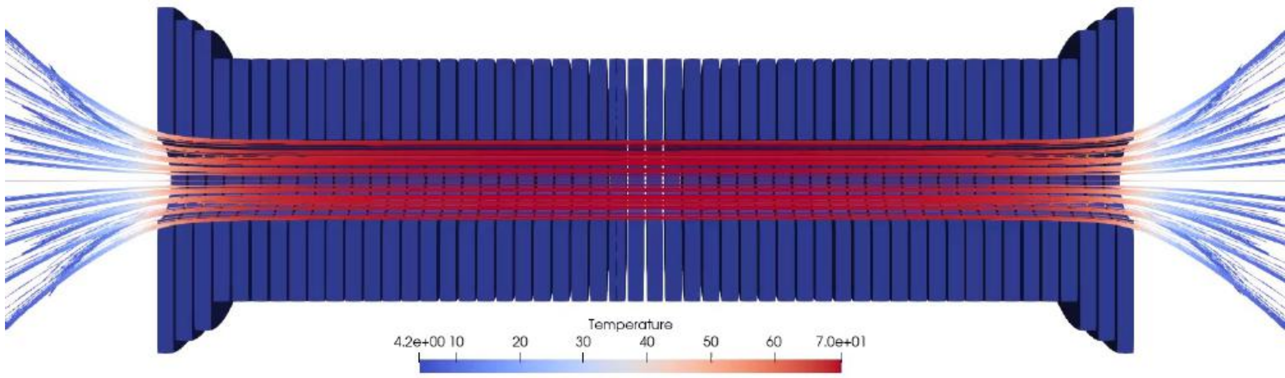


[1] *T. Mulder, M. Wozniak, A. Verweij, Quench Protection of Stacks of No-Insulation HTS Pancake Coils by Capacitor Discharge, IEEE Trans. Appl. Supercond., Vol 34, Nr 5, 2024.*

Benefits:
✓ Controlled **predictable quench**.
✓ **Reduces** the radial and axial **forces**.
✓ **Reduces** the **hot-spot temperature**.



No Protection



Capacitor Discharge (CD) Protection

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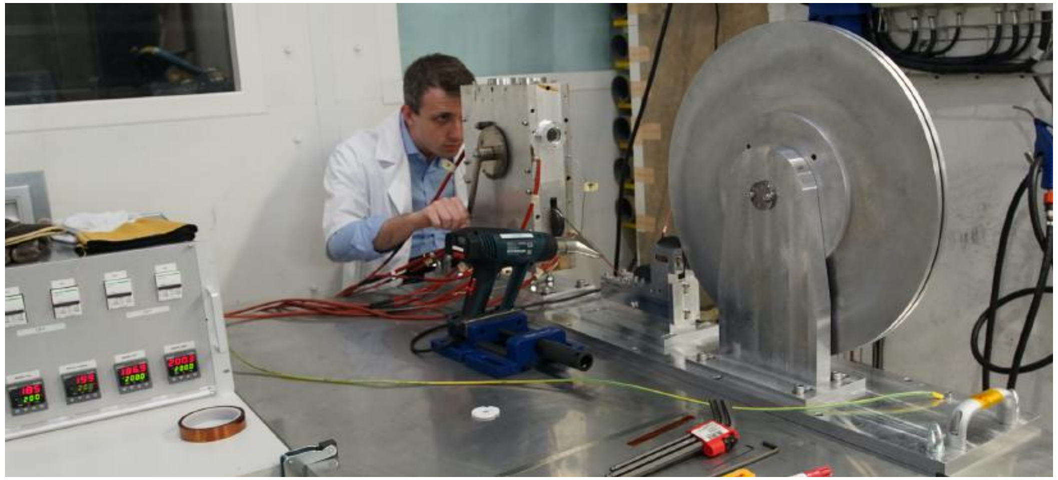
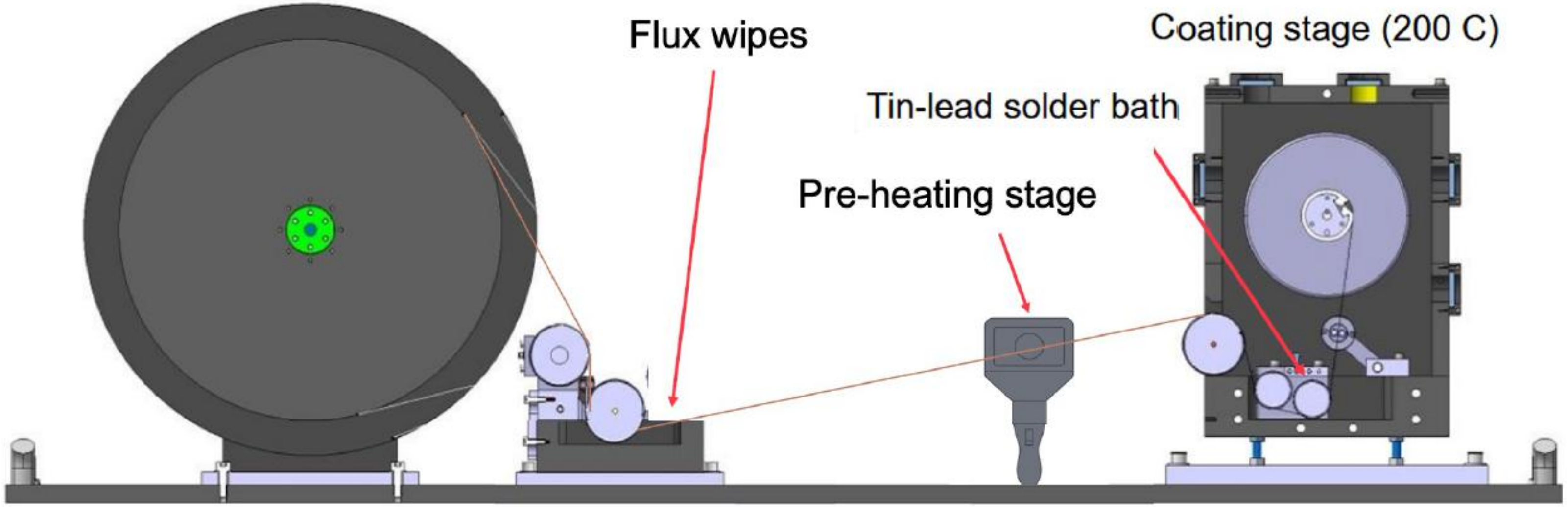
The 40 T FC Solenoid

Conductor & Winding Technology

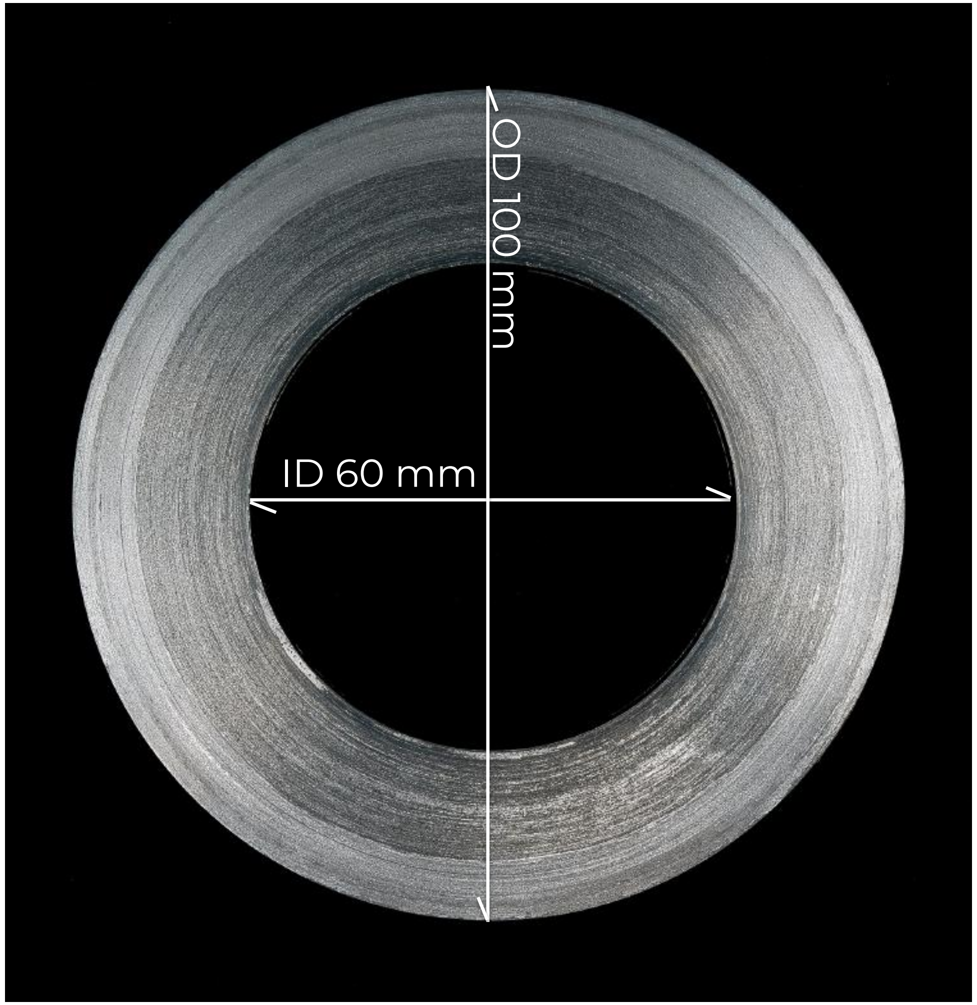


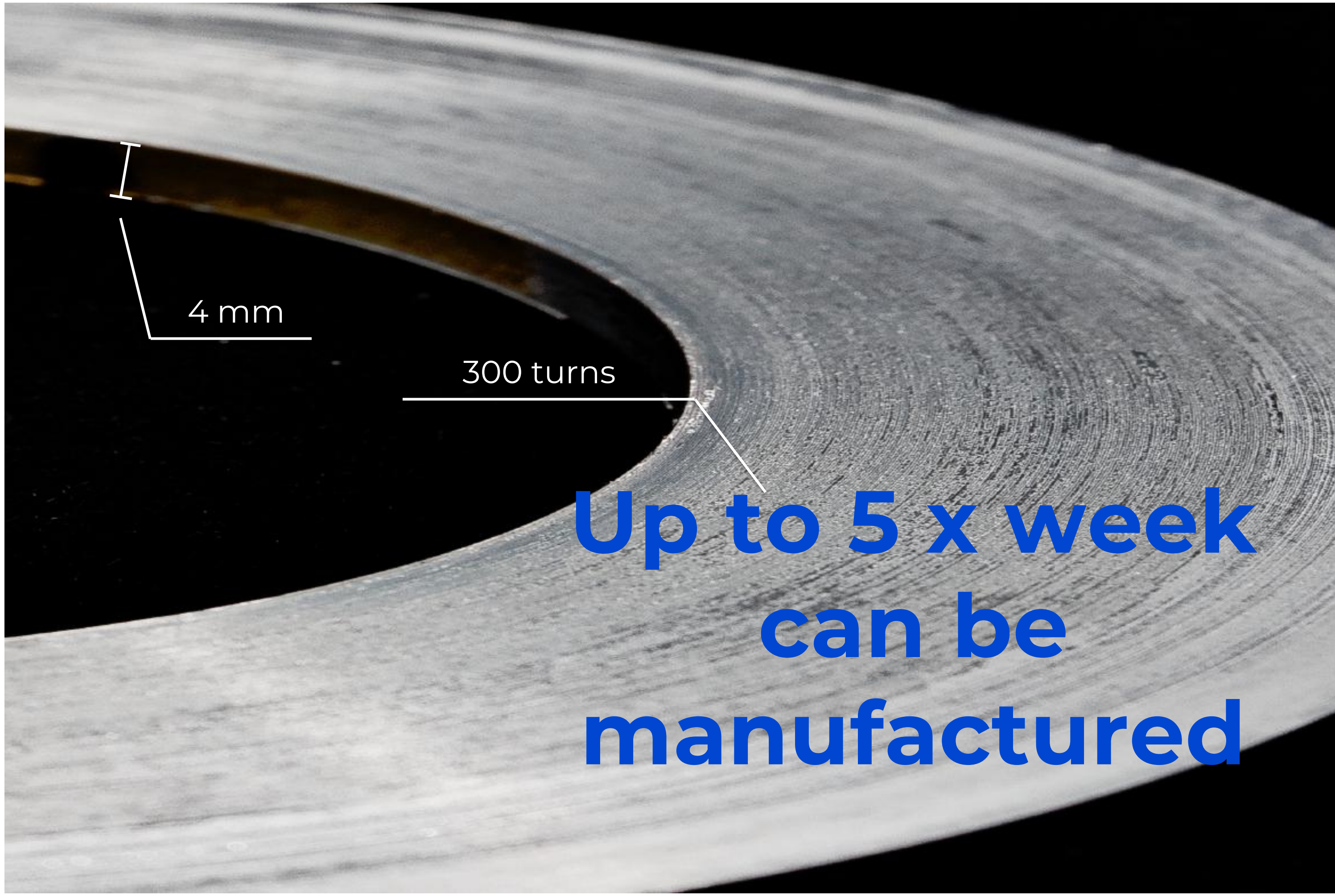
Fully Soldered pancakes via Hot Winding



The 40 T FC Solenoid

Subscale Pancakes





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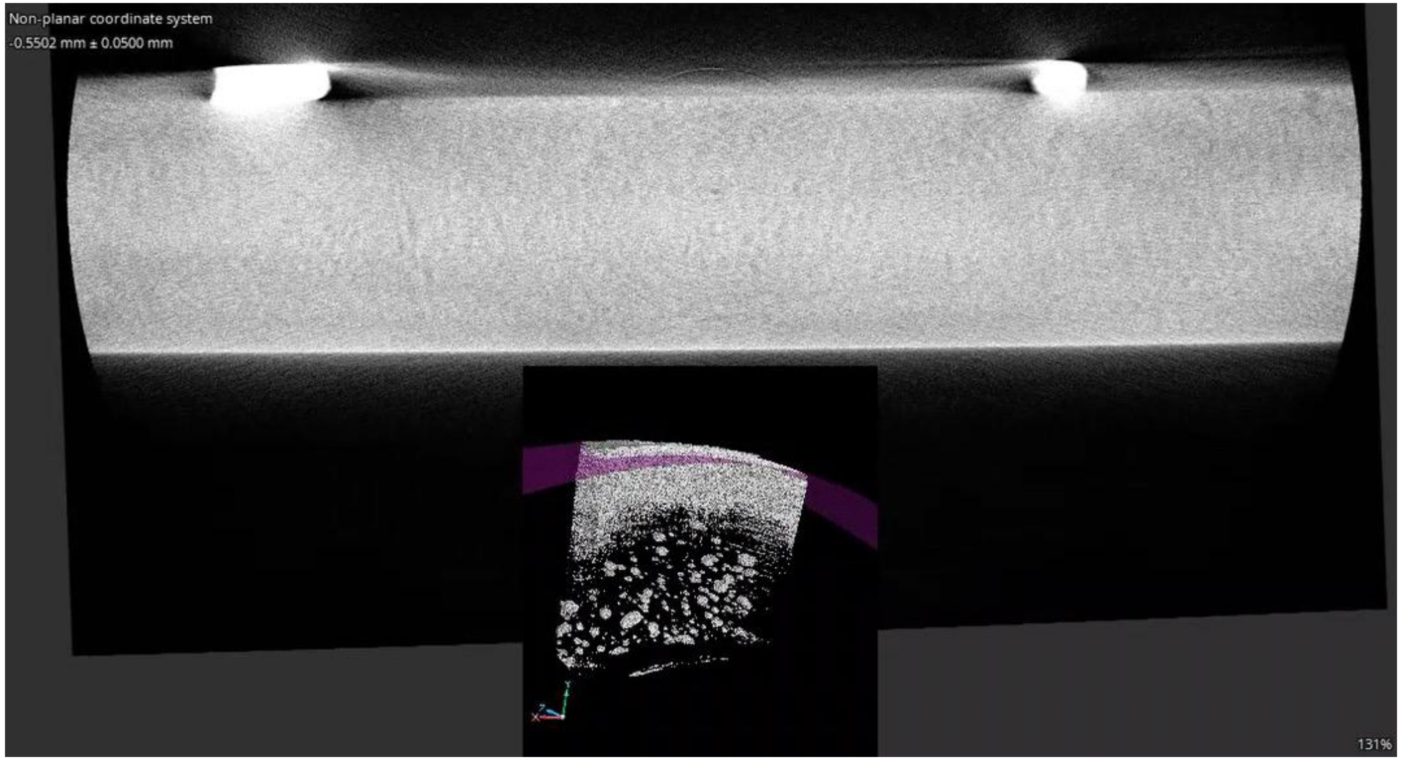
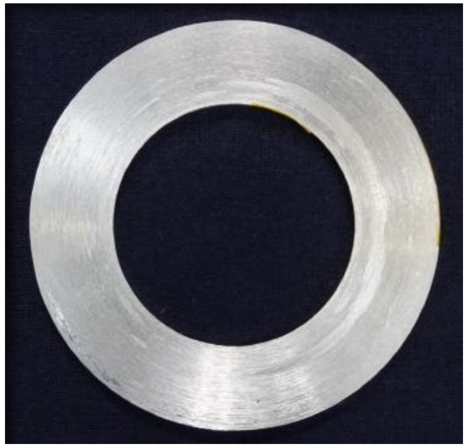
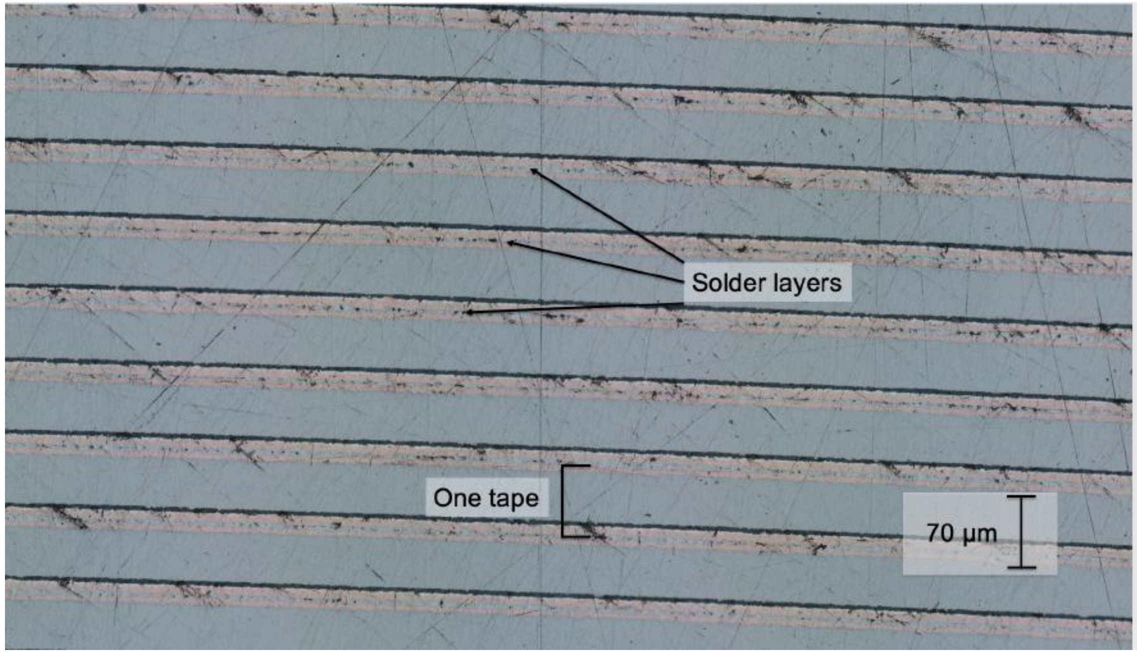
40 T Subscale coils Characterization

Tomography & Micrographs

Assessing **porosity**, interface quality, and **geometric consistency**.

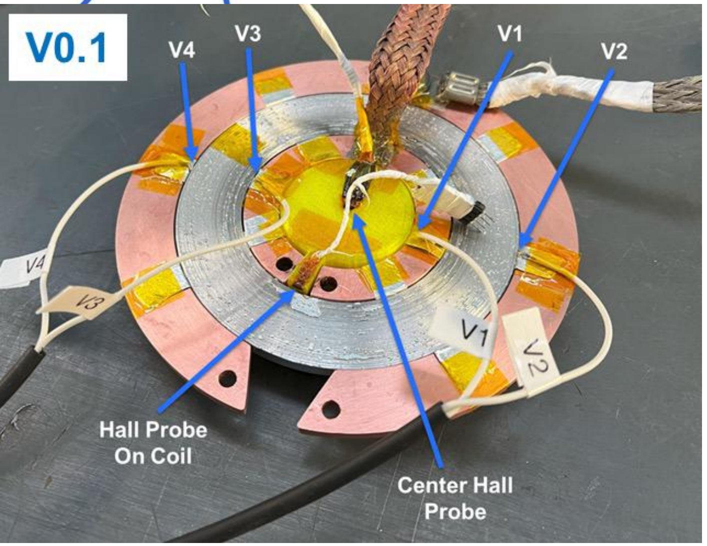


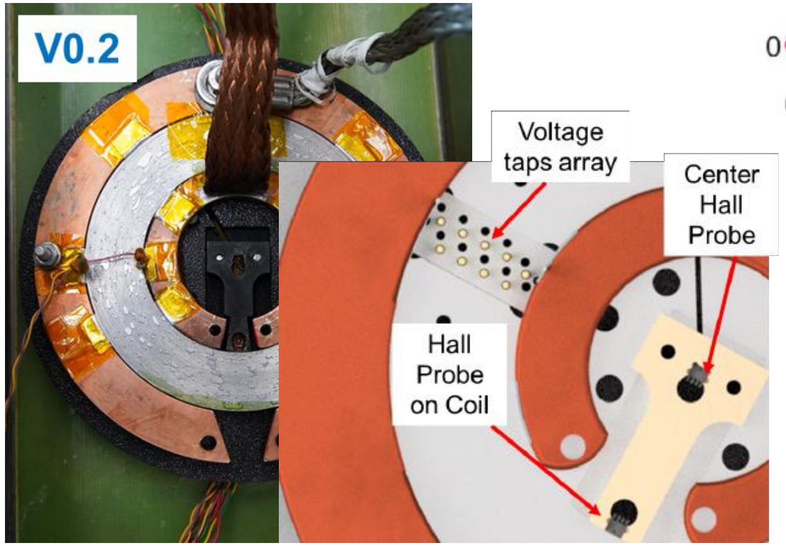


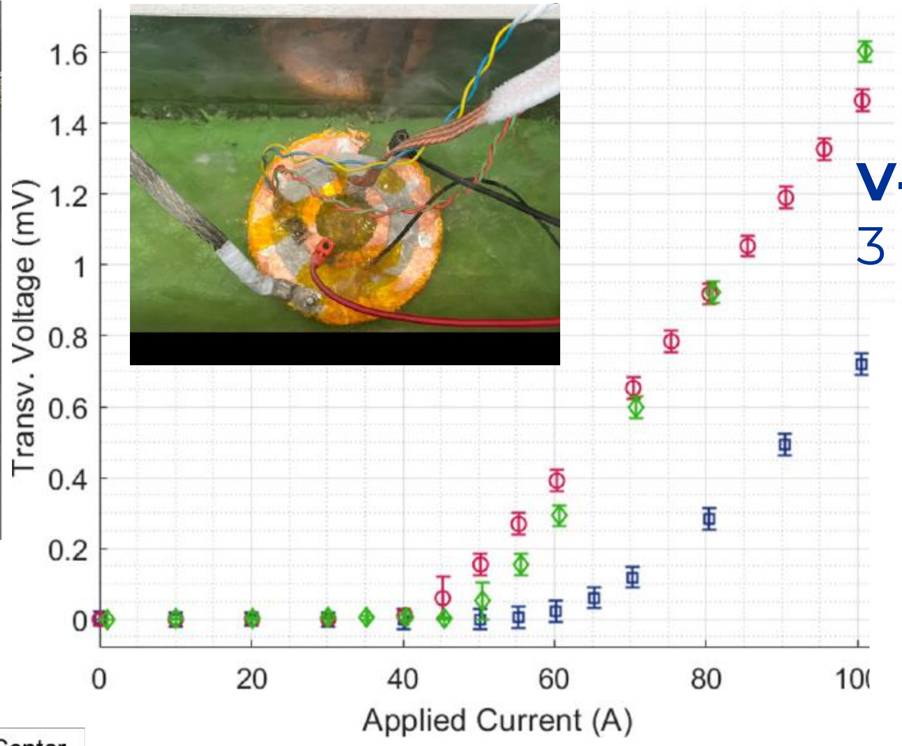


40 T Subscale Coils Characterization

77 K Electric & Magnetic Measurements

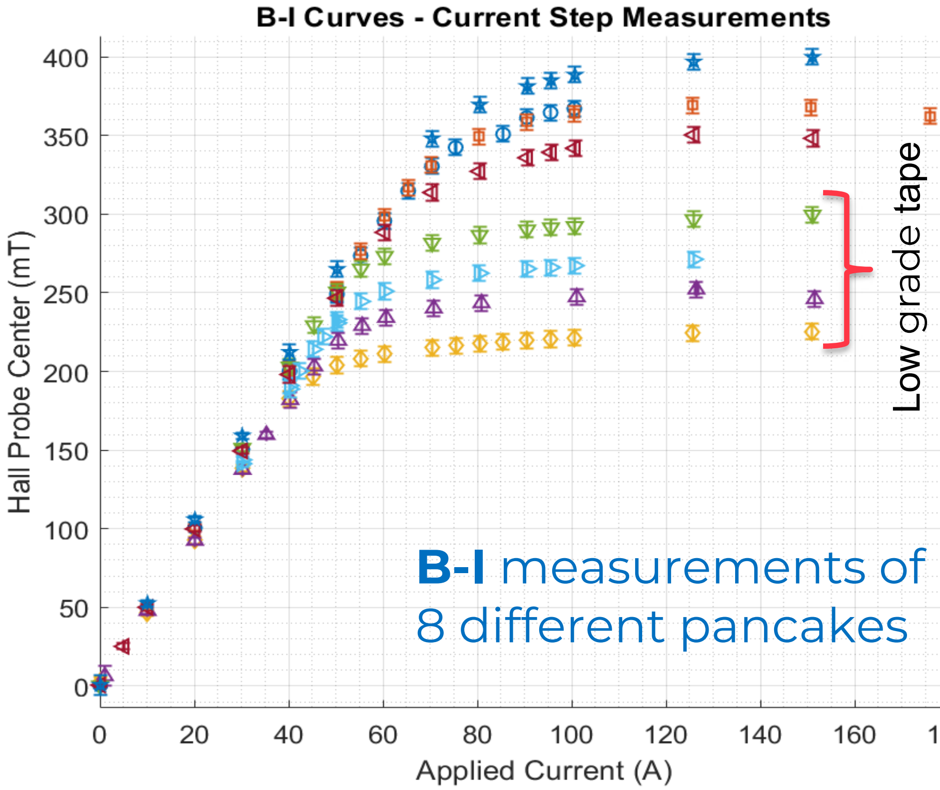






V-I measurements of
3 different pancakes

All results in line with tape manufactures' I_c measurements



B-I measurements of
8 different pancakes

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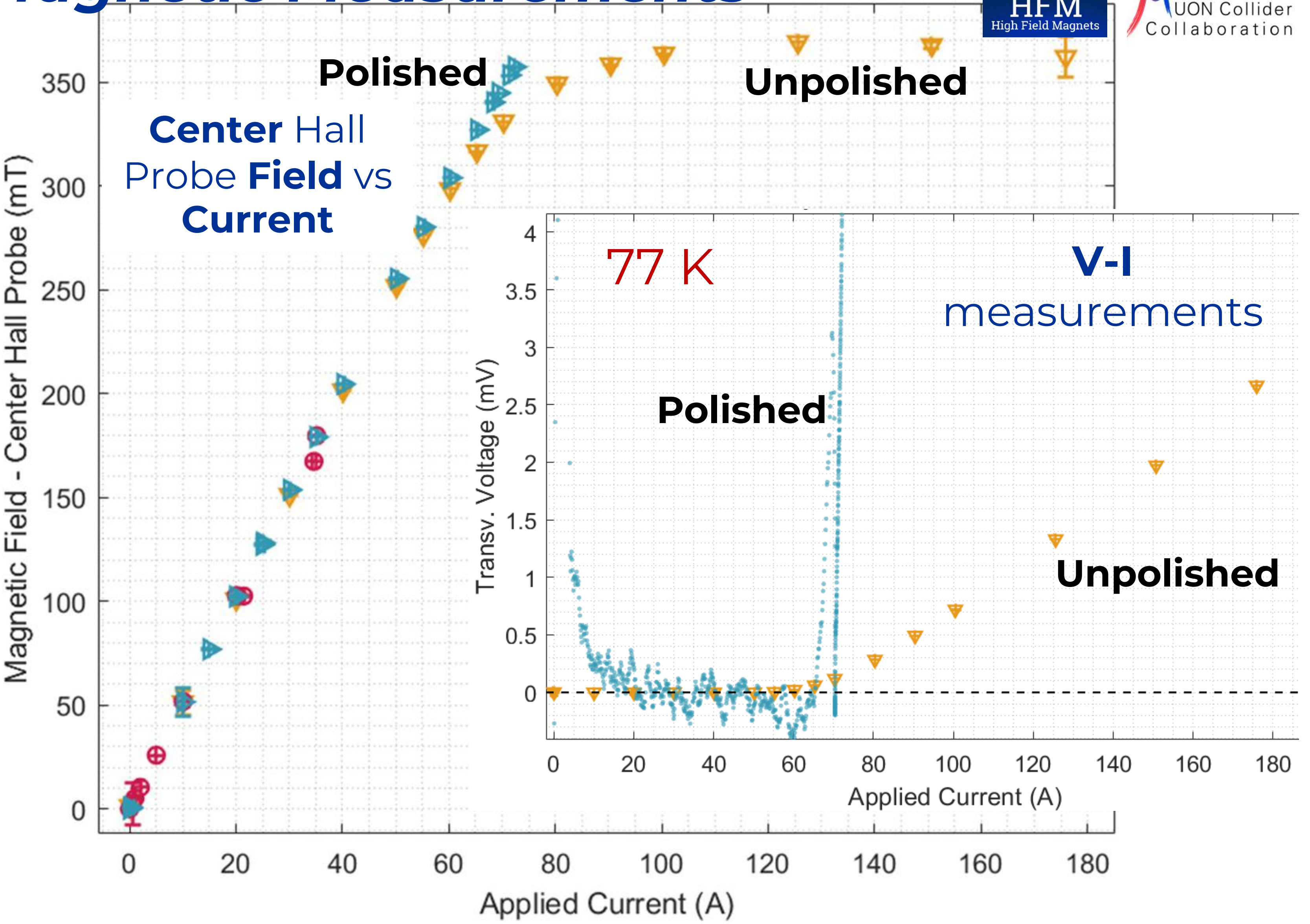
40 T Subscale Coils Characterization

77 K Electric & Magnetic Measurements

Characteristic time reduced from **300** to **2 seconds**

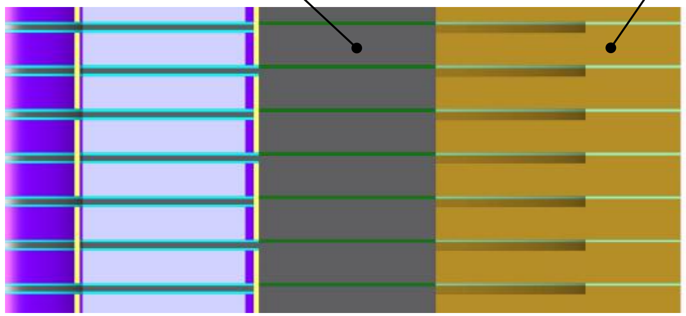


IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 63, Mar. 2026. Presentation given at ISS 2025, Nagasaki, Japan, Dec. 2025.

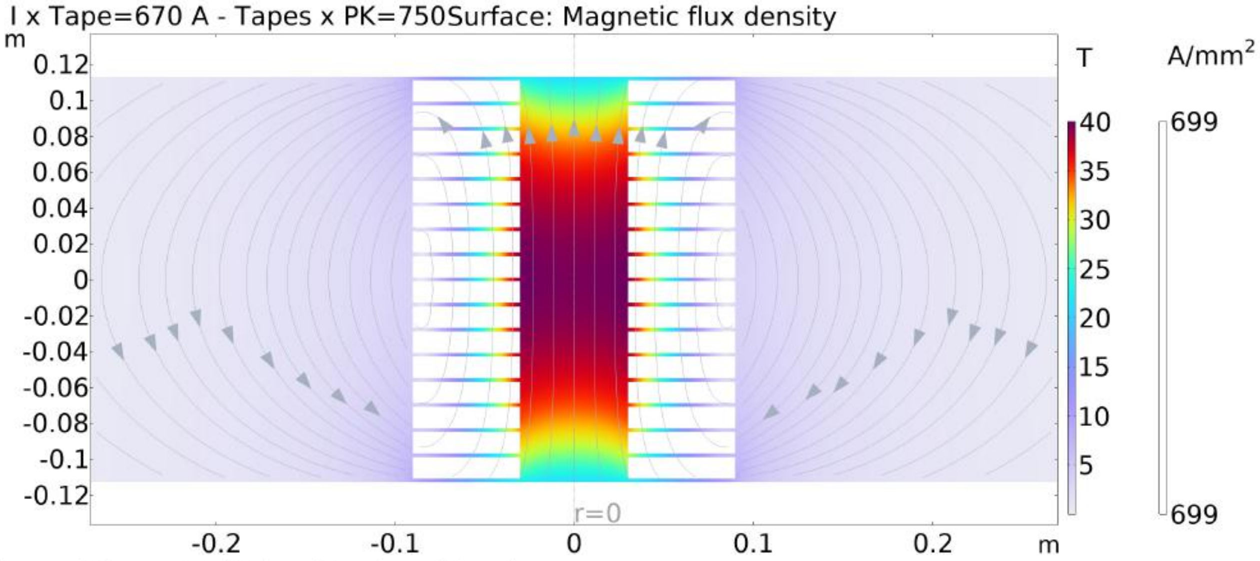
40 T Demonstrator

Design parameters

Main Dimensions, mm	Free Bore	50
	Winding ID	60
	Winding OD	180
	1st Radial Disk OD	~ 300
	2nd Radial Disk OD	~ 540
	Solenoid Height	~ 220
Precompression, MPa	Radial on the outermost layer	~200
Field, T	Peak	40
Current Density, A/mm^2	Overall	~ 650
Current, A	Conductor	~ 650
Magnetic Energy, MJ	Overall	1.8
Temperature, K	Conductor Innermost layer	4.5
Current Margin, %	Current, B//a-b	> 100



Conductor	# tapes	1
	Tape width, mm	12
	piece length, m	250-300
	Insulation	No
Pancakes	#	16
	Eletrical Connection	Series
	Impregnation	Solder
	Technolgy	Hot-Winding



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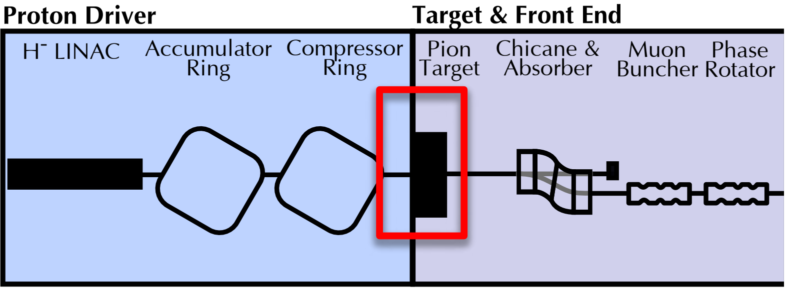
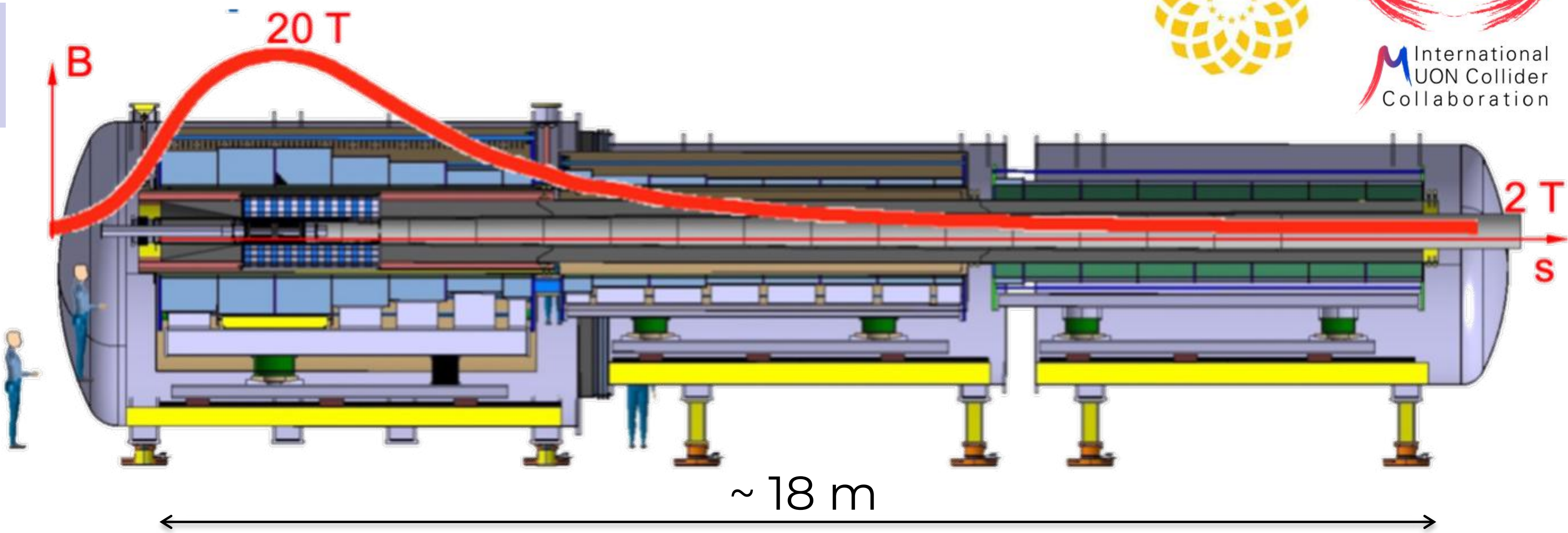
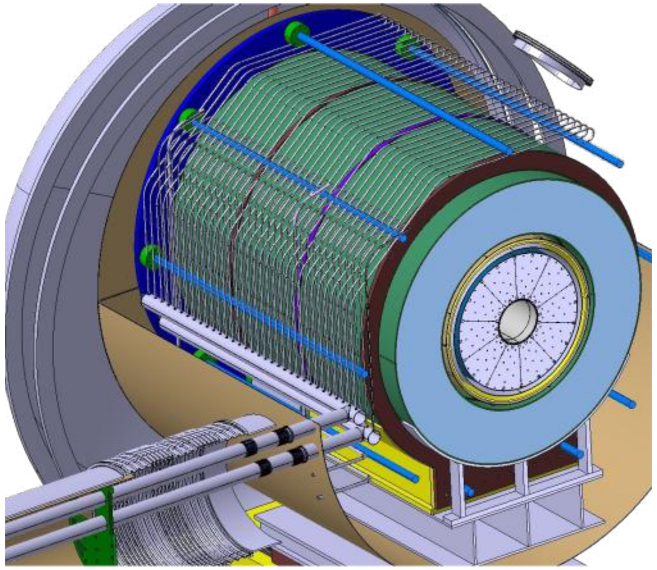
Target and Capture solenoids

Protons produce pions which decay into muons which are captured







Double pancake wound with ReBCO Cable in Conduit Conductor (CiCC)

- Conductor Made of ReBCO **HTS** (**23 SC coils**, **~1.4 m** bore ∅)
- Operating Temperature **20 K**; Bore peak field **20 T**; energy **> 1 GJ**
- Radiation heat load on coils ≈ 4 kW; Radiation dose ≈ 80 MGy

This magnet shares many similarities with next generation fusion magnets currently under development

Target and Capture Demonstrator

20 T @ 20 K Model Coil

- The **performance** required of the Target Decay and Capture Solenoid goes well **beyond** the current **state of the art**
  - This is why we are **proposing** to build and test a **20 T @ 20 K model coil**—a **critical step** to raise the **technology readiness** level and provide sufficient confidence that the full system can indeed be built and operated.
  - **Beyond** its direct application to the **Muon Collider**, this **development** is also **aligned** with the **needs** of **other scientific domains**, such as **high-field physics**, as well as **societal applications**, including **fusion** energy.
  - Several **major European players** in **HEP** and **fusion** are **associating** in this effort (and others have expressed interest in joining),
    - **contributing** to the definition of **performance requirements** and **coil geometry**, as well as to the **development** of a **design** that includes **initial engineering** & **analysis** of the 20 T @ 20 K **model coil**.

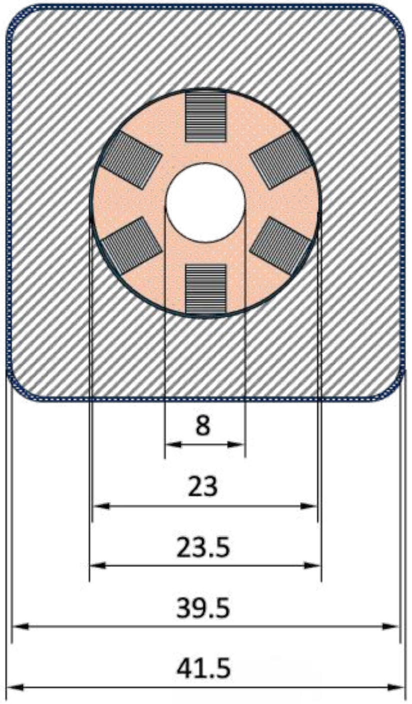
CERN

20K-20T Feasibility study

Baseline Conductor Design

International MUON Collider Collaboration

- Initial Design Principles:
  - **Target field**: 20 T @ 20 K
  - **Operating current**: 30–60 kA to minimize inductance and dump voltage
  - **Superconductor**: REBCO tapes (industrial-grade)
  - **Operating margin**: ~10 K, adjustable to optimize tape cost
  - **Mechanical support**: Stainless-steel jacket for EM load containment
  - **Copper current density**: < 200 A/mm² to limit Joule heating and enable standard quench detection/dump

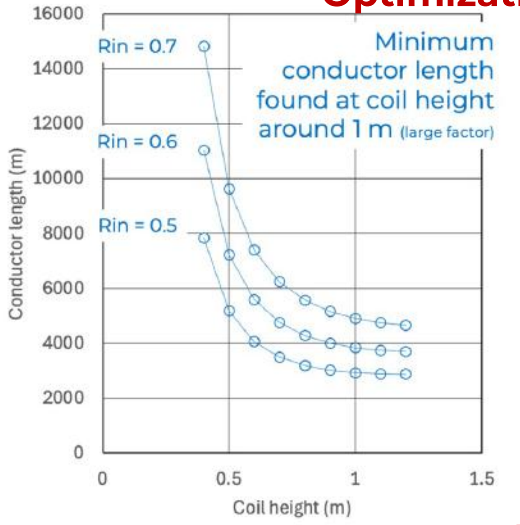


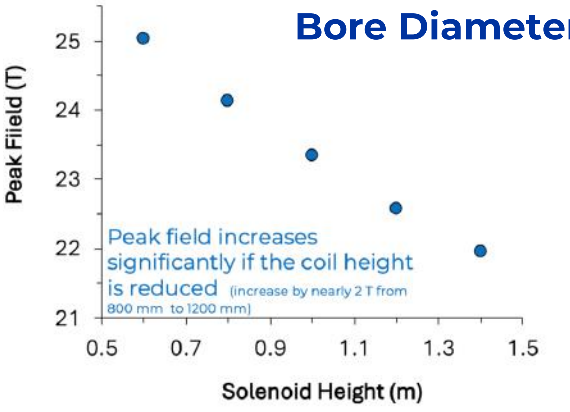
Conductor design, quench detection and protection

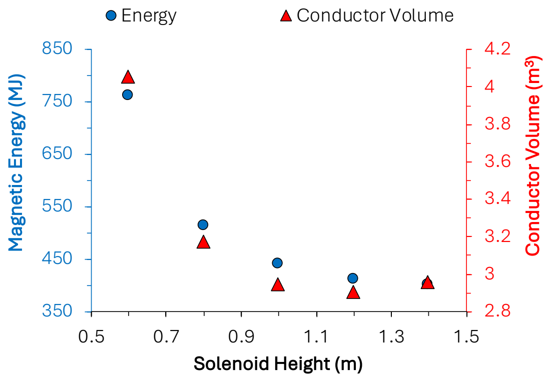
20K-20T Feasibility study

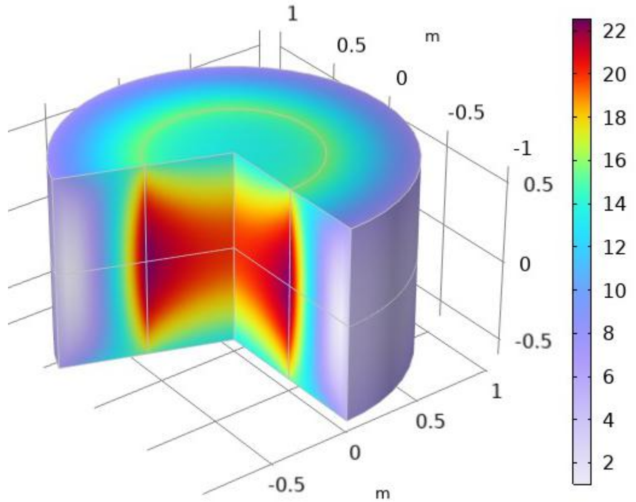
Electromagnetic design and optimization

Optimization 1: Cost-Oriented — 20 T on the Bore

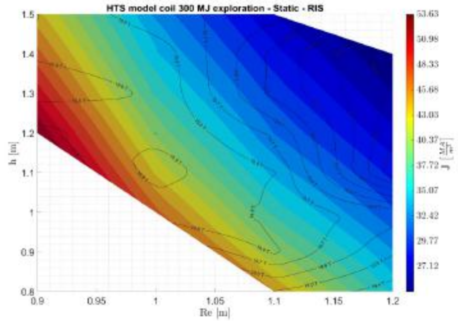


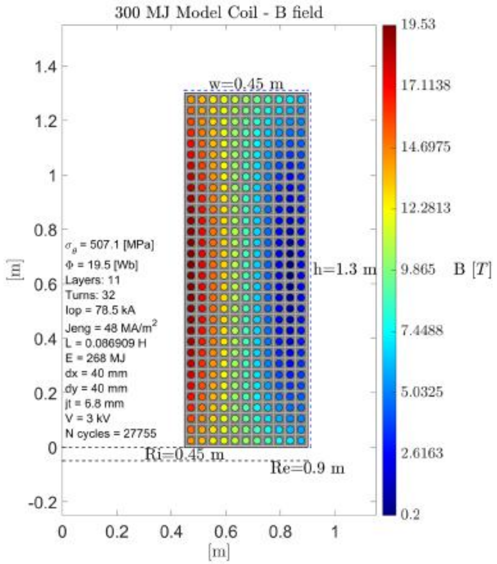




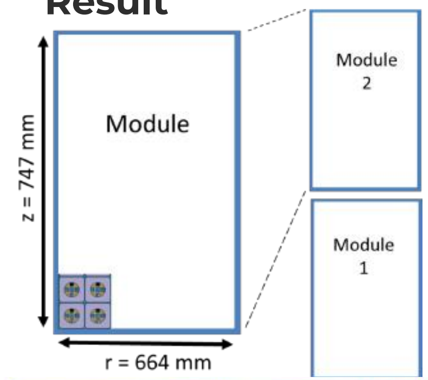


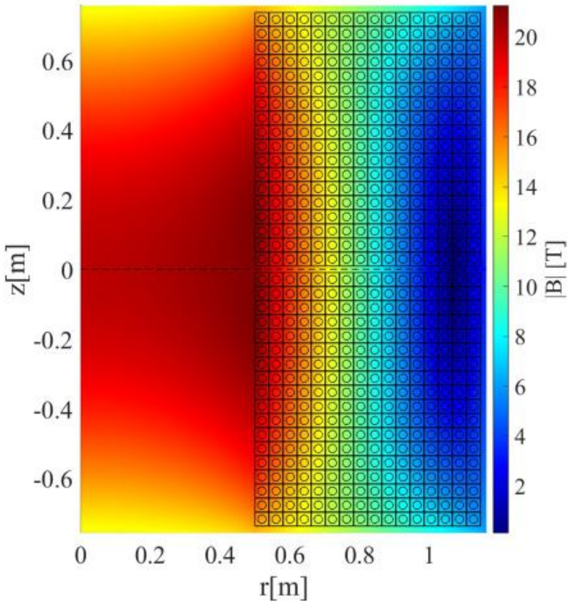
Optimization 2 : Robust 300 MJ Coil





Result





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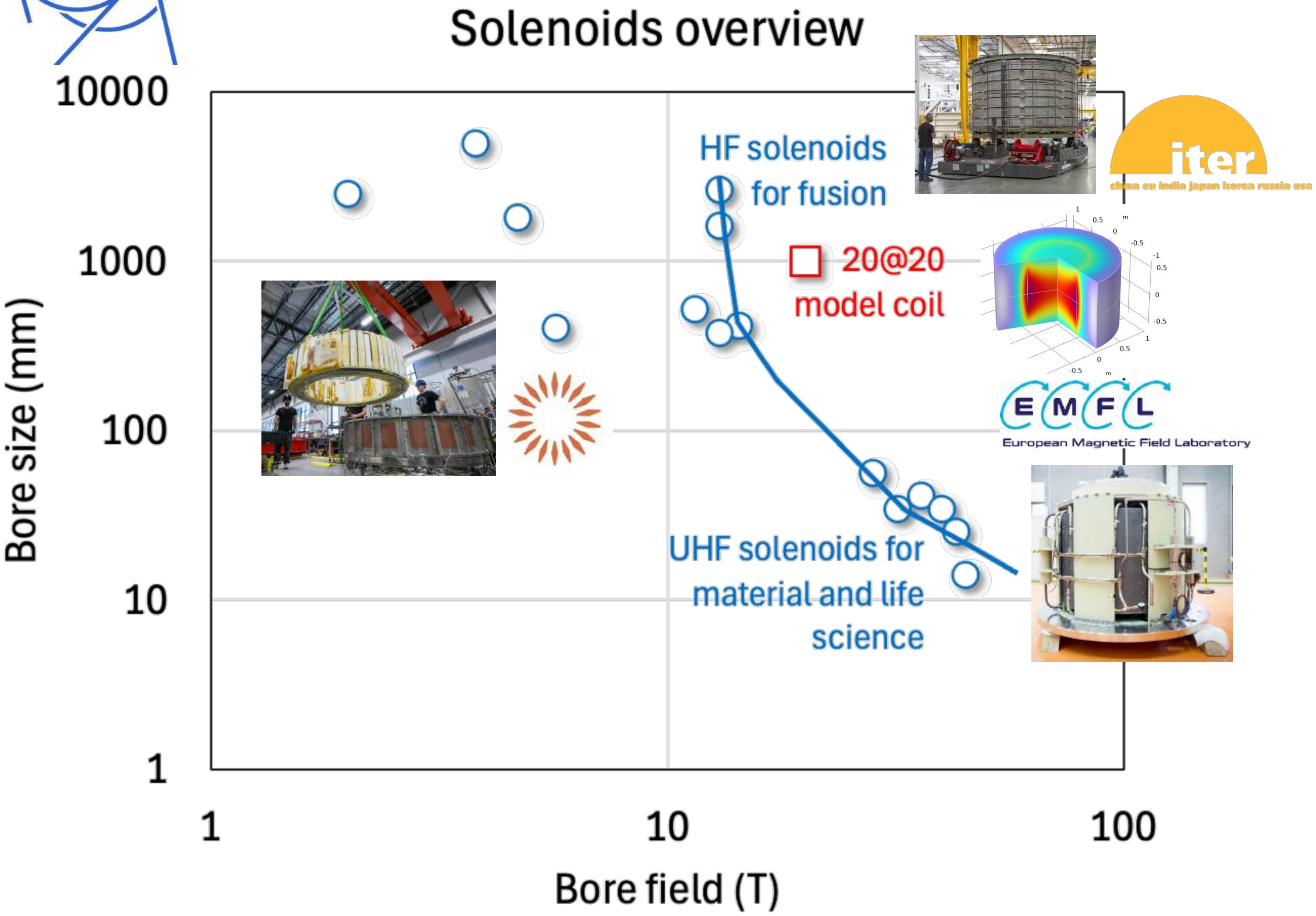
20K-20T in worldwide perspective



The **20@20 model coil outperforms** existing SC magnets **by over 50 % in field** (at comparable bore dimension) and by **one order of magnitude** in **bore dimension** (at comparable field)

No other **project worldwide** matches the **proposed geometry** and **performance targets**

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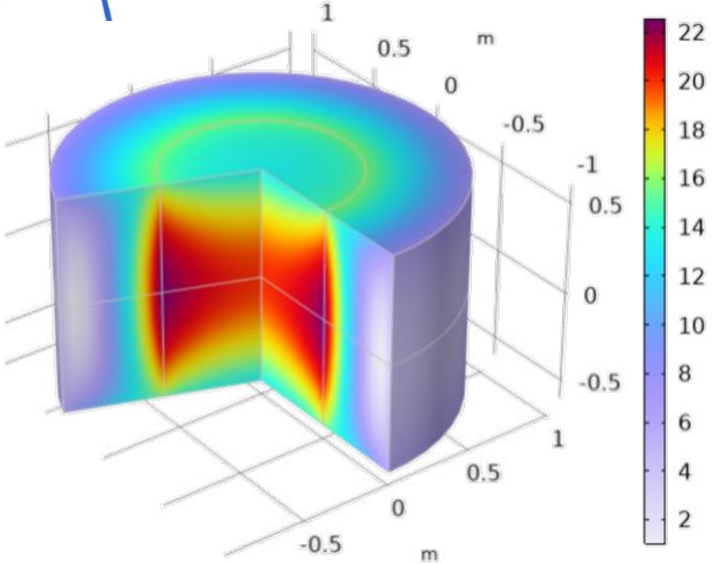
Strategic Value of the demonstrators

20 K, 20 T, 1 m-bore



- 20@20 is a **demonstrator** of mature HTS magnet **technology** for the **target solenoid of the Muon Collider**
  - HTS conductor development
  - Construction of large bore magnets
  - Management of forces and stress at material limits
  - Protection strategy for magnets with large stored magnetic energy
- **Engage and prepare EU industry** for a possible construction **(e.g. THEVA, BNG, ASG)**
- 20@20 will be **a world-wide unique test facility**
- **Shared technology development with fusion** (same objective, same technology)
  - Declared interest and on-going collaboration with partners from the public sector (F4E, EUROFusion) as well as **private sector (Eni, GFG)**
- Potential application for **high field science**

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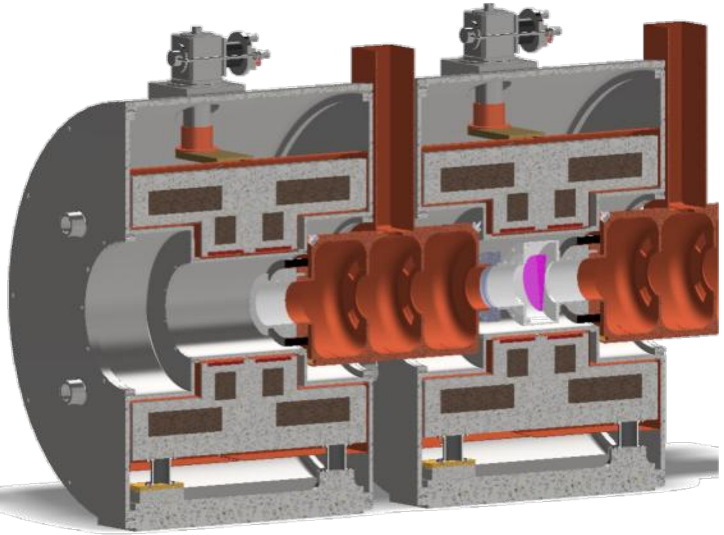
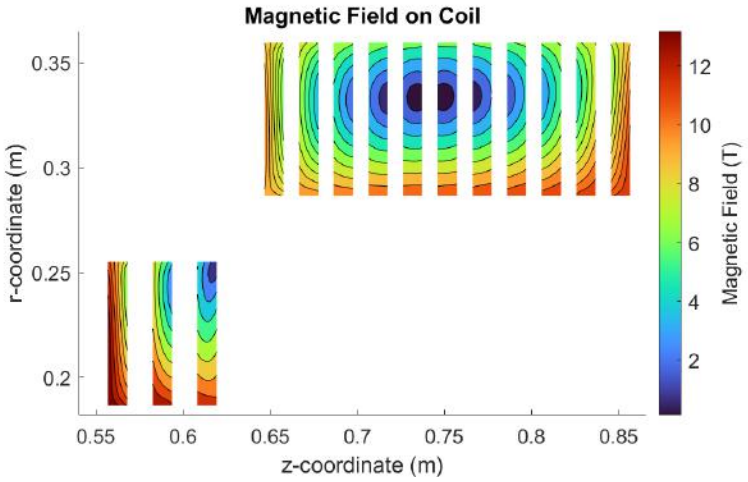
Strategic Value of the demonstrators

Split 7 T, 20 K in 350 mm bore

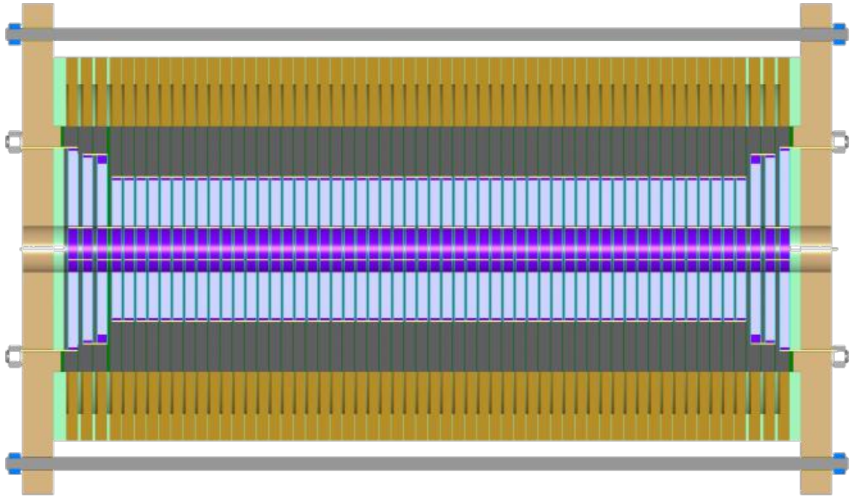


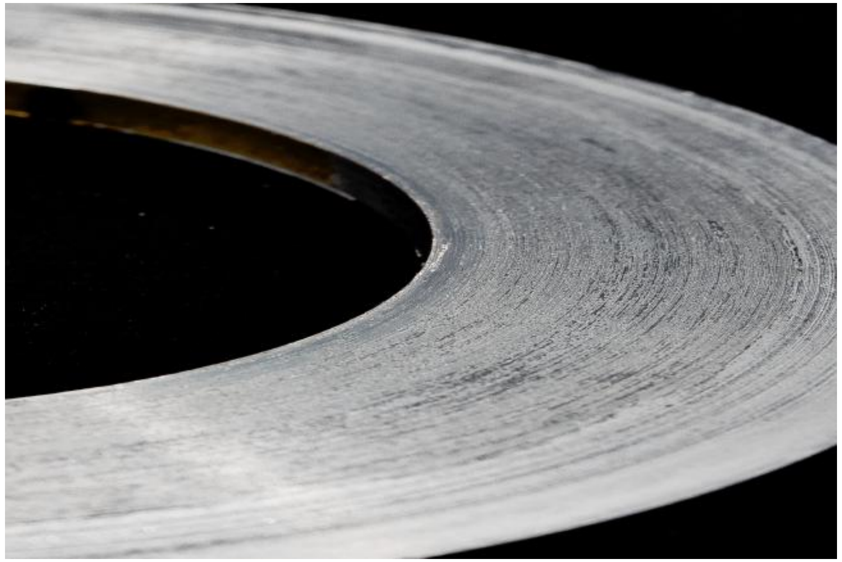


- The 7T split solenoid demonstration magnet is the **steppingstone** towards the **6D magnets of the Muon Collider**
  - Dry-cooled, partial-insulation, novel HTS magnet technology operating at 20 K
  - Protection of HTS magnets with high stored energy and high current density
  - Complex system integration, management of large forces and thermal gradients
- **Technology relevant to next generation MRI machines**
  - Helium-free, lower consumption, simpler engineering, easier maintenance
  - Suitable to improve healthcare in remote world regions
  - Opportunity for increasing market penetration, seeking interest from the big three (Siemens, GE, Philips)

Strategic Value of the demonstrators

40 T, 4.5 K, 60 mm bore





- The UHF 40 T demonstration magnet is a **crucial milestone** towards **achieving** the **luminosity of the Muon Collider**
  - Field level is at the frontier of magnet science
  - Ultra-compact, partial-insulation novel HTS magnet technology
  - Management of forces and stress at material limits
  - Requires characterization of material properties at unprecedented levels of field and detail
  - Development of novel design and analysis tools

- **Shared technology development with high magnetic field science/NMR**
  - Structural biology and proteomics
  - Drug discovery
  - Solid-state physics for scientific and societal applications
  - Collaboration with high magnetic field laboratories **(EMFL and NHMFL)**

Conclusions

International MUON Collider Collaboration

- A **Muon Collider** is one of the very interesting **options** for **HEP** at the energy frontier
  - **Precision** measurements and **energy frontier**, **small footprint**, **cost-effectiveness, sustainability**
- **ReBCO** technology could be **pivotal** in realizing an **affordable** and **efficient MC**
  - Aim for **high operating current density** (up to 1000 A/mm^2) and operation at **high cryogenic temperature** (up to 20 K)
  - This is likely true **also** for **other HEP colliders** at the **energy frontier**
  - Muon Collider **magnets** are **designed** to use **currently available commercial ReBCO** tapes
- There are **many challenges** and crucial developments ahead however **Magnet technology R&D** for a **Muon Collider**:
  - Has close and **tight relation** to the **advances needed** for **other science** and **societal applications** (e.g. fusion, material and life sciences, NMR, energy)
  - **Will provide a sure return of investment** not only for **particle accelerators** but also to several other **societal applications**


38th International Symposium on Superconductivity (ISS2025)
02-04 December 2025
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Thank you for your attention!