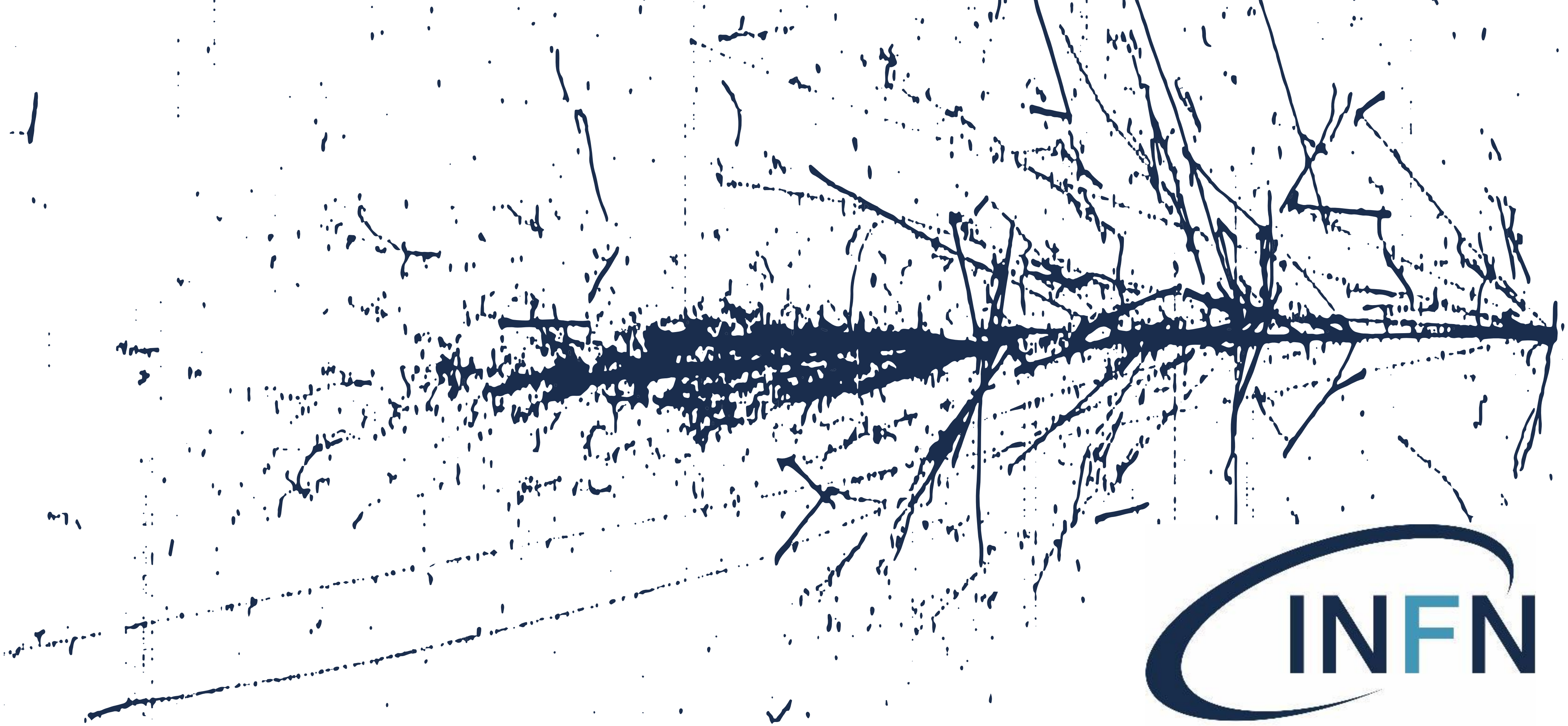


INFN
Istituto Nazionale di Fisica Nucleare

iFAST

Challenges of cryogenics for HTS magnets test station

Marco Statera and Carlo Santini, INFN-MI LASA

Industry Workshop on Cryogenics in Big Science, 16.4.2024

iFAST

Outline

INFN LASA

- **intro**
  - Motivation
  - HTS magnets specific requirements
- **magnets**
  - Selected examples of HTS magnets
  - The IFAST HTS CCT
- **test**
  - 20 K test station at LASA
  - Performance and timeline
- Conclusion

Motivation

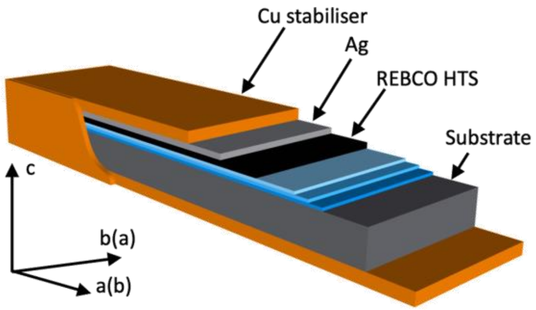
Why

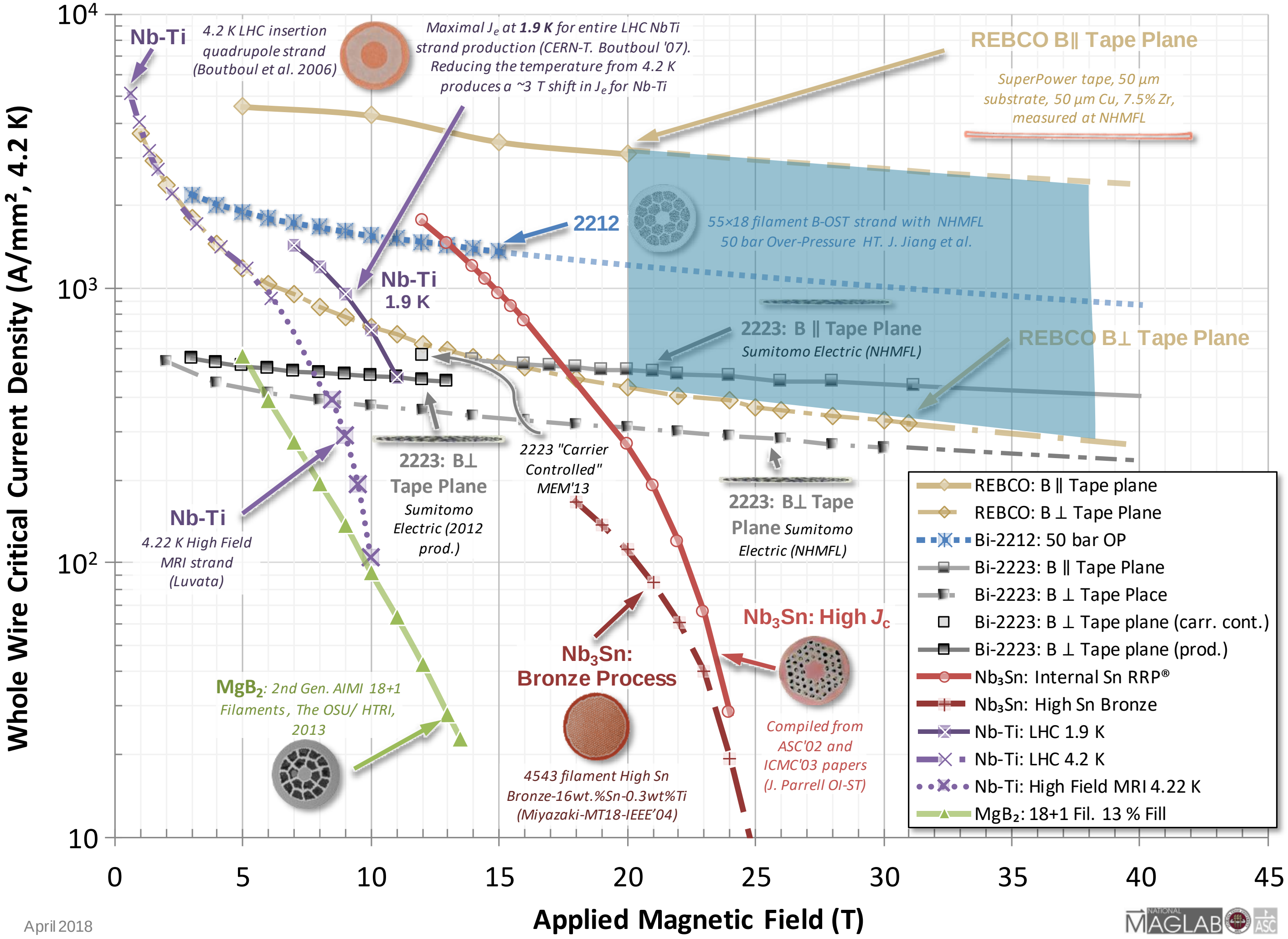
Increase performance and/or sustainability of research institutes

How

High Temperature Superconductors

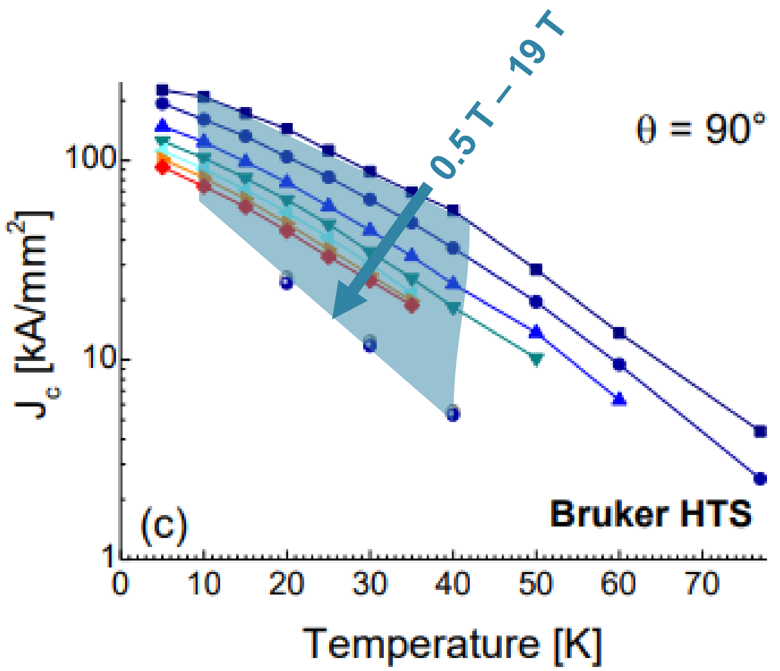
High current densities at higher temperatures



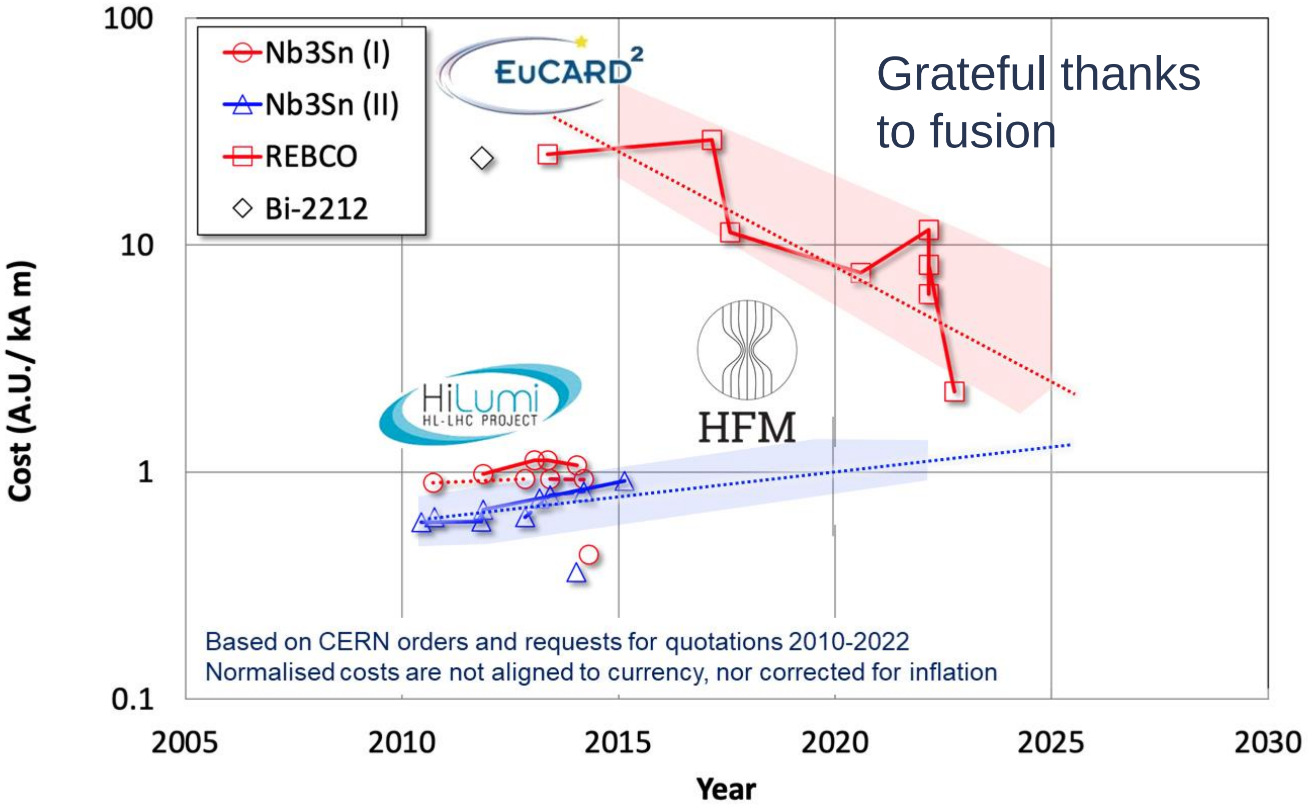


https://nationalmaglab.org/magnet-development/applied-superconductivity-center/plots

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

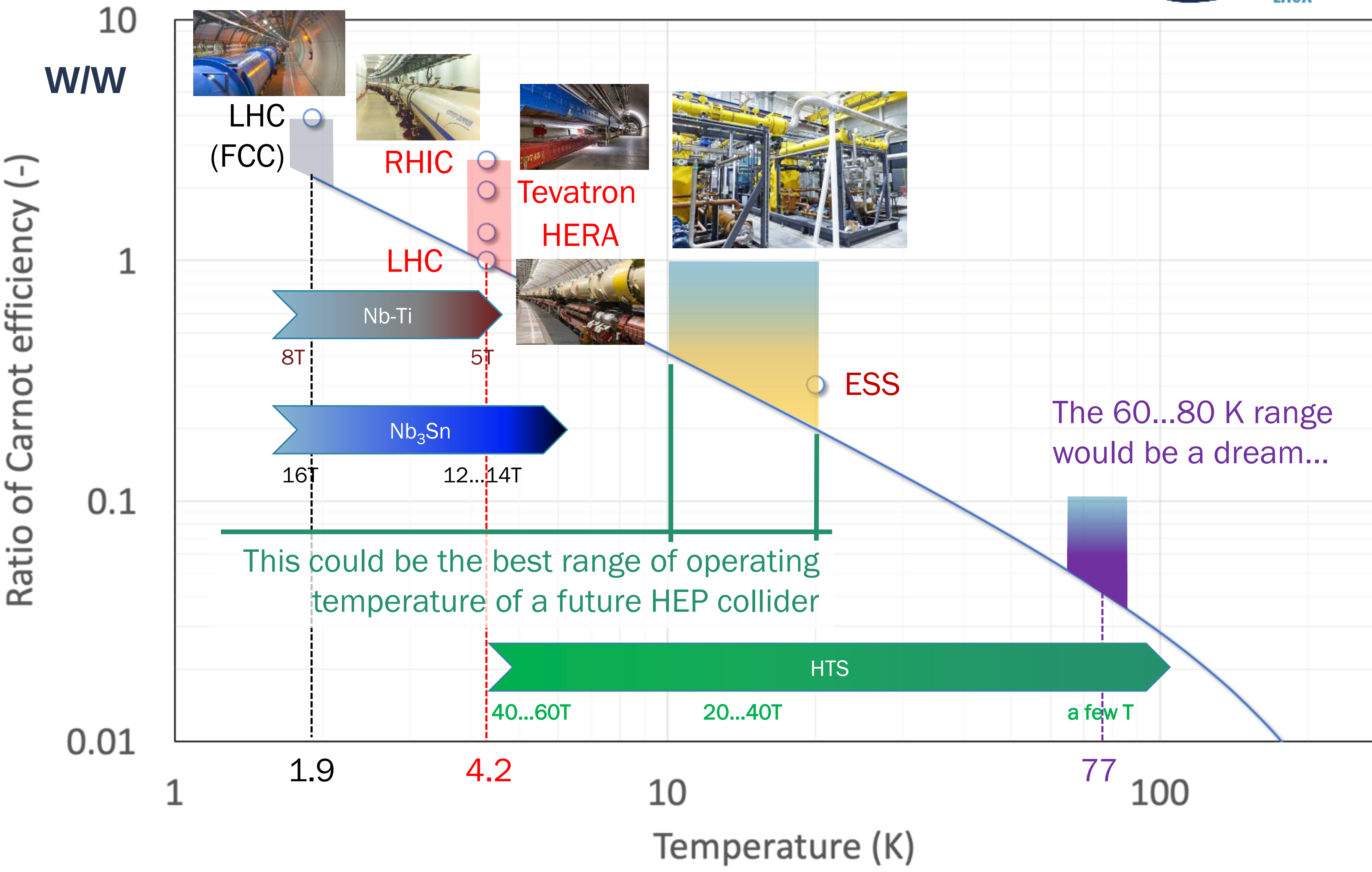


L. Bottura et al, HFM annual meeting https://indico.cern.ch/event/1302031

Motivation

Sustainability is a driver for next generation Research Instituites and projects

HTS may be one important option for the future colliders



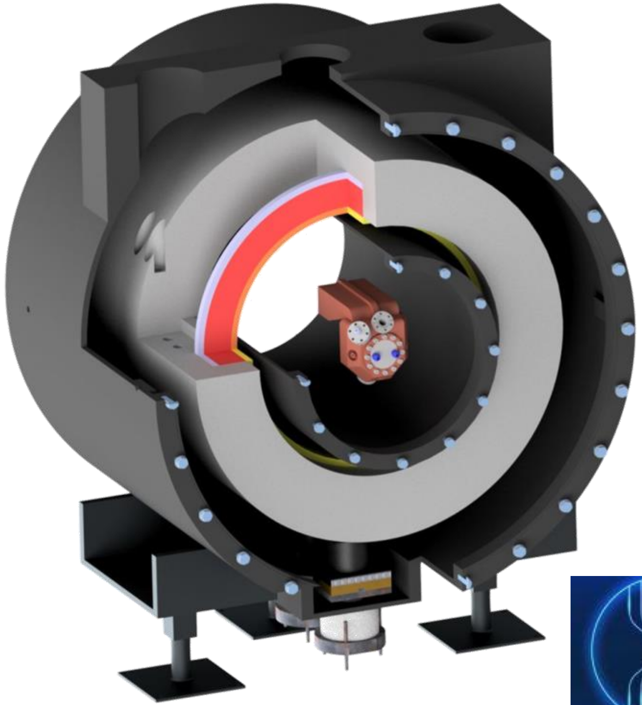
Credits to P. De Sousa and R. Van Weelderen and L. Bottura, CERN

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

Finanziato dall'Unione europea NextGenerationEU | Ministero dell'Università e della Ricerca | Italiadomani Piano Nazionale di Ripresa e Resilienza

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

International MUON Collider Collaboration

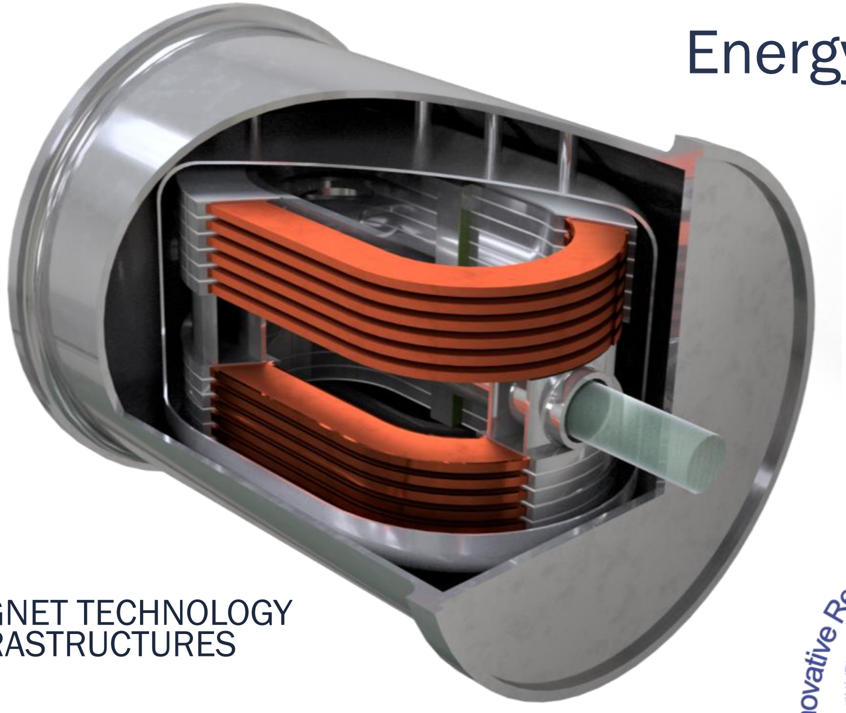


10 T gradient
20 K operation
Conduction cooled
300 mm warm bore

INFRATECH proposal

EUMAHTS: ADVANCING HTS MAGNET TECHNOLOGY FOR EUROPEAN RESEARCH INFRASTRUCTURES

PI L. Bottura, CERN



ESMA
Energy Saving MAgnet

10 T dipole
20 K operation
Conduction cooled
70 mm bore

2025

Innovative Research Infrastructure on applied Superconductivity IRIS

HFM High Field Magnets

Common R&D to increase TRL of HTS magnet technology

SCIENCE FOR SUSTAINABILITY

I.FAST WP8 – Innovative superconducting magnets

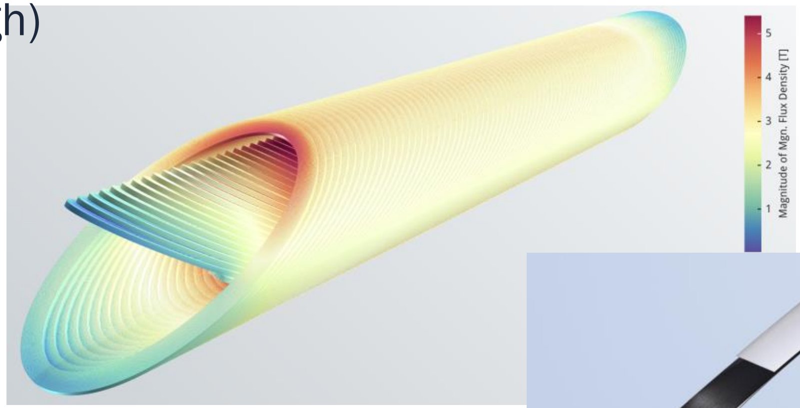
Exploring <u>Canted Cosine Theta with HTS superconductor (main goal),</u> preceded by a <u>combined function CCT based on LTS</u> → involving the industries that want to learn about the CCT magnets;

Construction of the two demonstrators: winding and magnet assembly, magnet test and validation

Courtesy of E. De Matteis

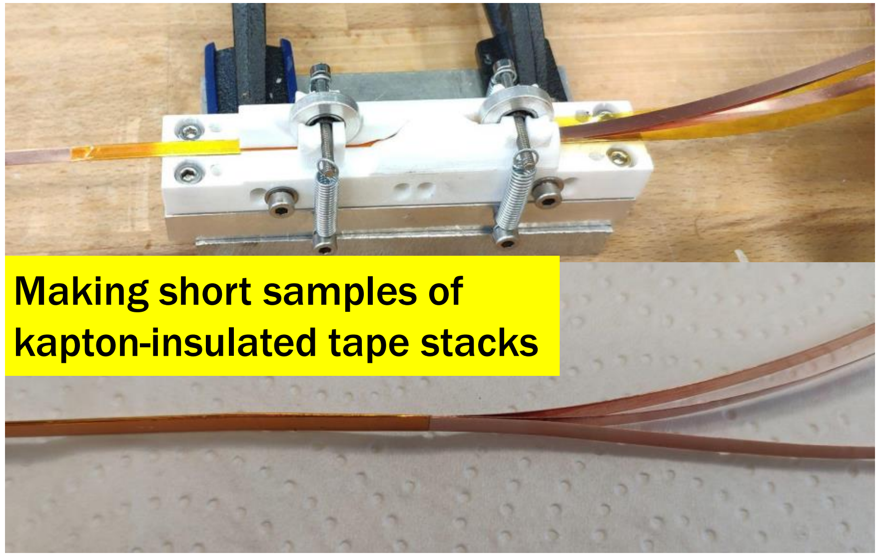
- **CCT based on HTS** (REBCO tape 4 mm wide)
  - **4 T dipole** with a new Top of **20 K** (> 10 K of margin)
  - Frenet-Serret frame used for the conductor (avoid hard way bending)
  - **Straight geometry** just to start the study (HTS is already difficult enough)
  - **Two design options:** <u>2-tapes (980 A)</u> and 4-tapes cable (1990 A)
  - Quench protection is demanded (Cu stabilizer added for this)
- Company Elytt Energy (Spain) in charge of the construction of demo
  - Delivery within October 2024
  - Test at LASA (INFN) – first half of 2025

CCT dipole
4 T target
Ø =80 mm;
L <= 1000 mm



I.FAST WP8 – status

The **AC-losses (ramping at 0.4 T/s)** during operating for both designs are on average **50 W.** This is compatible with a conduction cooling system at 20 K.

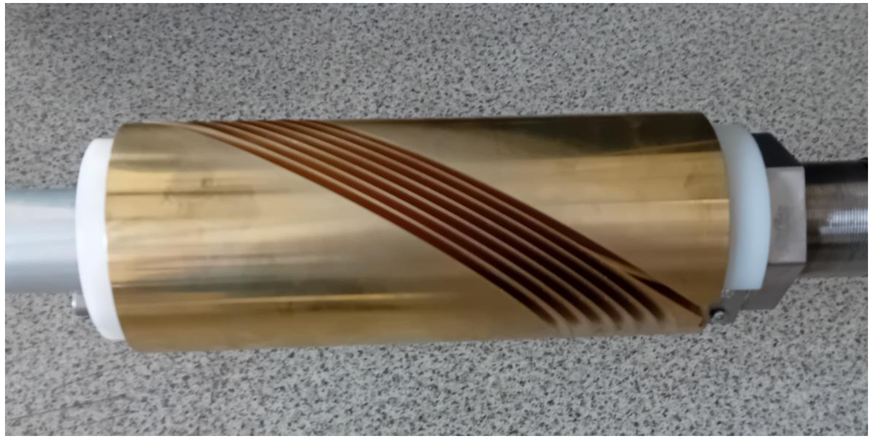


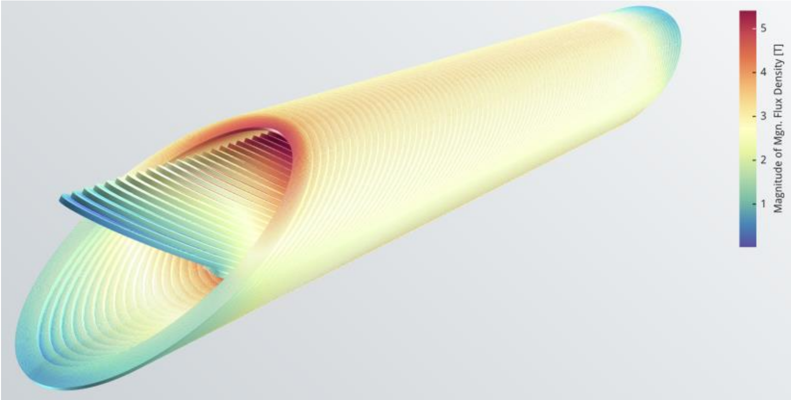
TEST AT LASA IN 2025

20 K conduction cooled

I 980 A

See E. De Matteis on Thursday





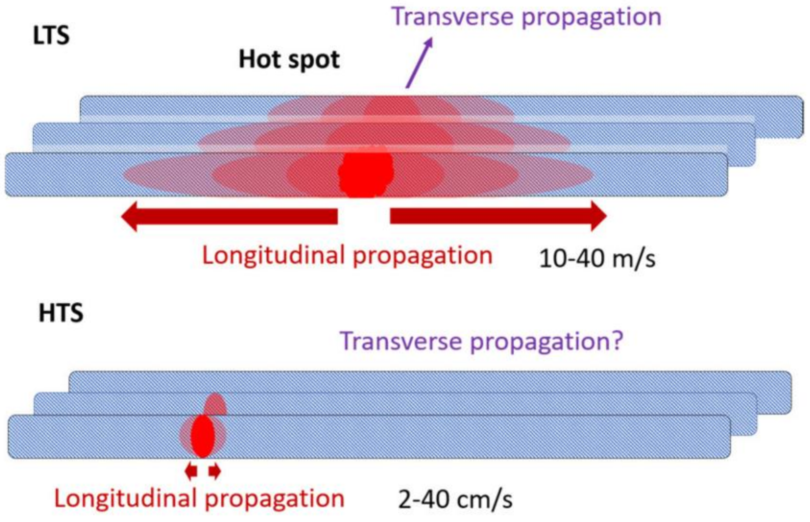
CCT dipole
4 T target
Ø =80 mm;
L <= 1000 mm

T. Lecrevisse, ''Conceptual Design of HTS Magnet''
IFAST WP8.3

Technological challenges of HTS magnets

MODELING I

One main difference in behavior is **protection**: *mechanical events associated with conductor motion and/or impregnation material fracturing – a major source of quenching in LTS accelerator magnets are not likely to cause quenching in HTS.*[1]
→ HTS quench by **over-heating** or **over-current**



Both can be caused by to **defects** or **degradation** in conductor. For this reason, Quality Assurance (QA) is very important. A lot of QA is possible (and needed) at 77 K [2].
→ HTS are extensively **tested in liquid nitrogen**

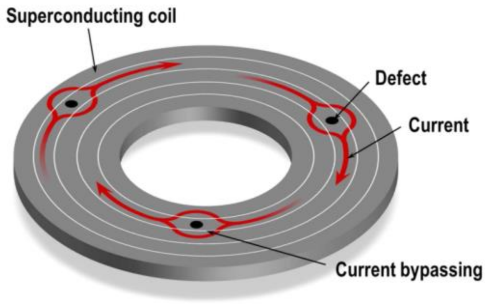
THERMO-MECHANICAL PROPERTIES

HTS, even in high-field applications (20 T) can be operated at higher temperatures than liquid helium. Cryogen free cooling is not only possible but needed for the sake of sustainability. This poses a limit to the cooling budget
→ HTS magnets should be dapperly investigated also on their **thermodynamics**

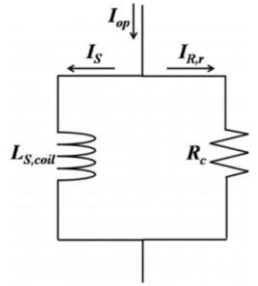
[1] M. Marchevsky, LBNL, Quench detection and protection for HTS accelerator magnets
[2] R. Gupta et al., High field HTS solenoid for a muon collider—Demonstrations, challenges, and strategies. IEEE TAS, 2013

Technological challenges of HTS magnets

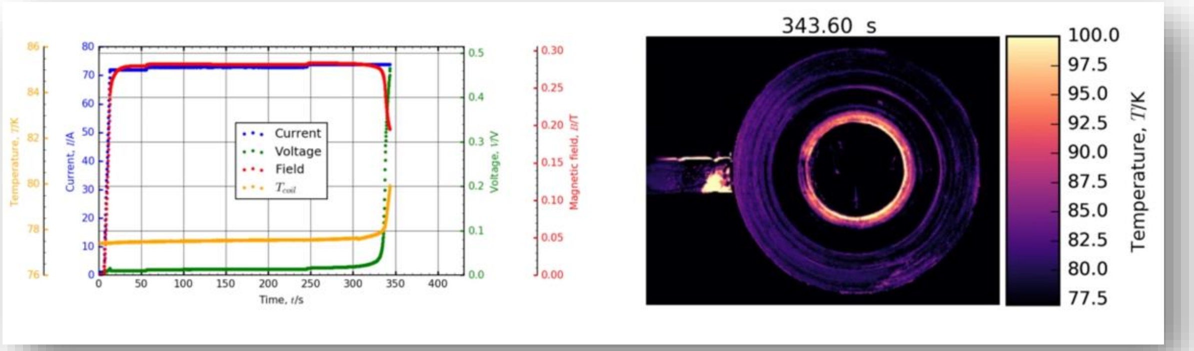
MODELING II



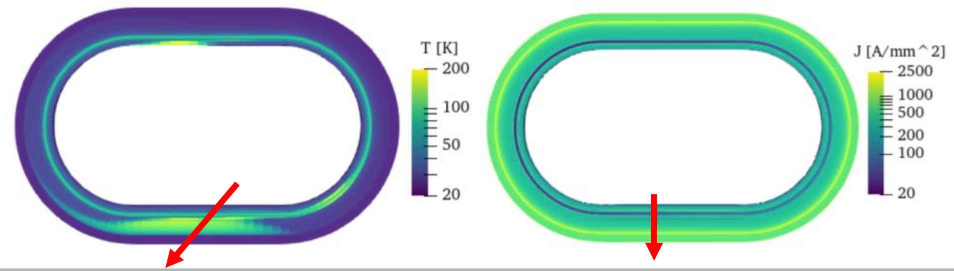
One of the most promising solution for the sake of HTS protection is **non/partial insulation** of coils [3]. This is not possible with LTS [4]. This approach brings in the magnet completely new phenomena which we must model and measure:



1. **"Charging" time** (current flowing radially in transients) → measure field response to ramps/steps
2. **Defect/hotspot bypassing** with local current redistribution → measure a map of voltage/field in/on the coil
3. Less control over **field quality** among different cycles (especially warming to RT) → test many cycles
4. **Novel quench phenomena**, due to current re-distribution, not burning the coil but damaging it → explore novel testing approaches, even thermal imaging [5]

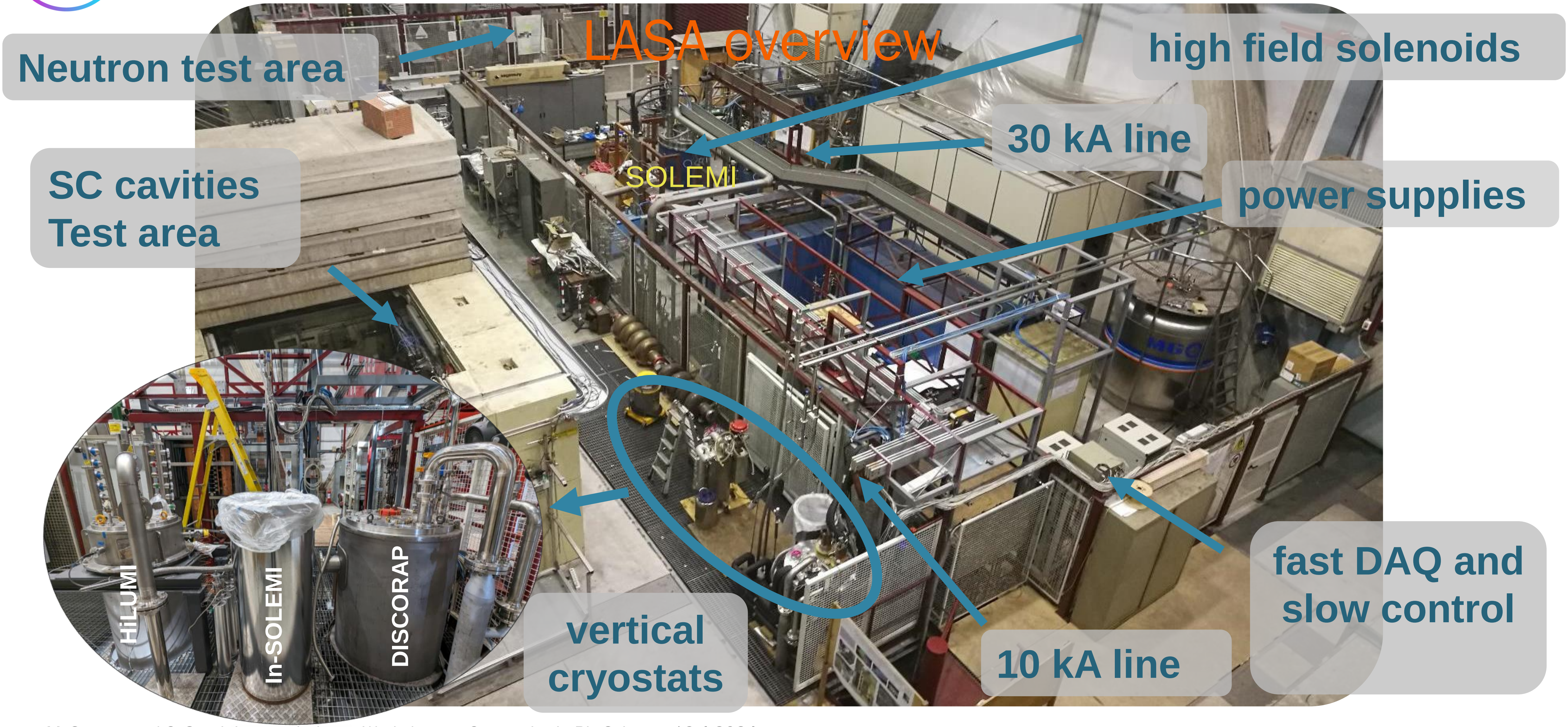


High-J shock-wave propagation during discharge for quench protection



[3] Hahn, Seungyong, et al. "HTS pancake coils without turn-to-turn insulation." IEEE TAS 2010
[4] Keilin, Victor E., and Lev B. Lugansky. "Analysis of the behaviour of superconducting windings with short-circuited turns." IEEE TAS 2011
[5] R Gyuráki et al 2019 Supercond. Sci. Technol. 32 105006

How are we testing HTS magnets?



INFN-LASA Test Facility Upgrade (through 2025)

New closed loop G-He **Variable T Cooling Plant**

- Cooling power by cryocooler
- Gas Helium circulation
- Easy to move, no liquid helium required
- 20 W at 20 K – 200 W at 55 K

New pre cooling system down to 100 K

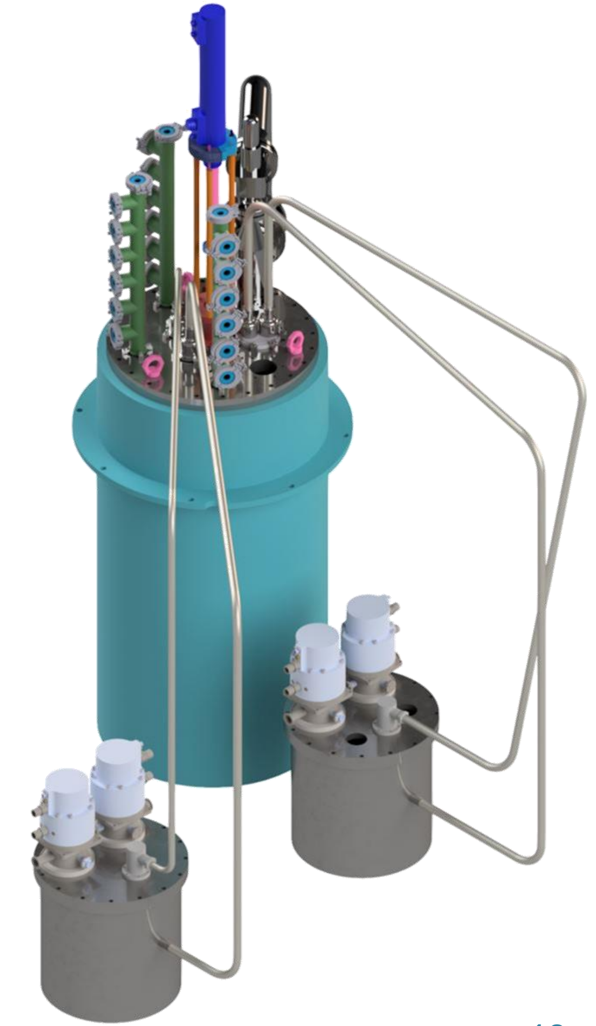
- Open loop LN_2 and gas

New **Cold Masses (2x)** to test HTS Coils and Magnets

- Hilumi
- Solemi insert (two configurations)

Innovative Research Infrastructure on applied Superconductivity
IRIS

SCIENCE FOR SUSTAINABILITY

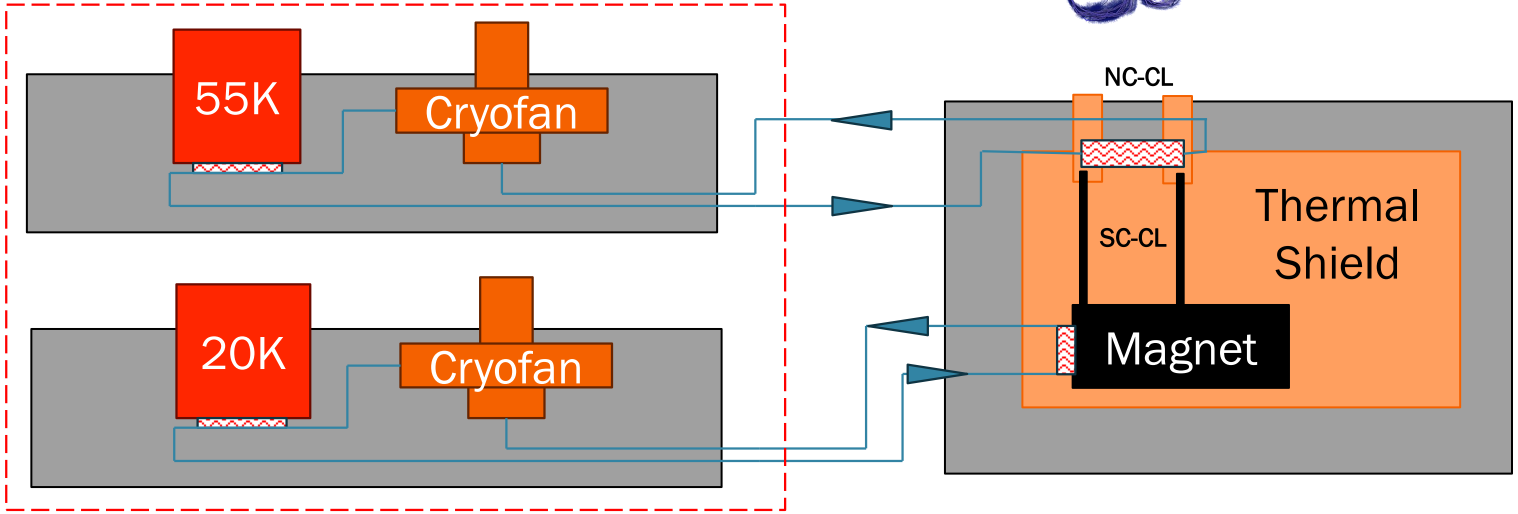


Finanziato dall'Unione europea NextGenerationEU
Ministero dell'Università e della Ricerca
Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

INFN-LASA Variable Temperature Cooling Plant

Circuit B - cooling **Current Leads** and **Thermal Shield** to **55K.** Power extraction **200W** (1kA Current Leads) – possibility to upgrade the system for Power extraction 600W (5kA Current Leads)

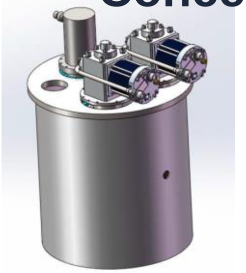
Circuit A - cooling **SC coils** and **SC magnets** between 15K and 50K (variable temperature). Power extraction **@20K 20W.**



Good choice for a test bed, a cryo plant has a much better COP of 50

	Load A (SC Magnet)	Load B (TS+ CLs)
Temperature	20 K	55 K
Cooling power from cryocoolers	80 W	360 W
Cooling power from line	23 W	310 W
Total consuption	18 kW	18 kW
COP^{-1} cryocoolers	220	19
COP^{-1} line	740	22

Conceptual Design



20K

Coolant: Helium Gas
10g/s mass flow
DeltaTmax: 2K

55K

Coolant: Helium Gas
10g/s mass flow
DeltaTmax: 8K

The cooling plant will be at LASA in May 2025

INFN-LASA Hilumi Cold Mass

Cryostat:

- D 515mm
- H 2950mm

Cold Mass Conduction Cooled (Cooling Plant) to:

- 15K-50K (Variable T) – Magnets
- 55K – Shield + Current Leads (1kA)

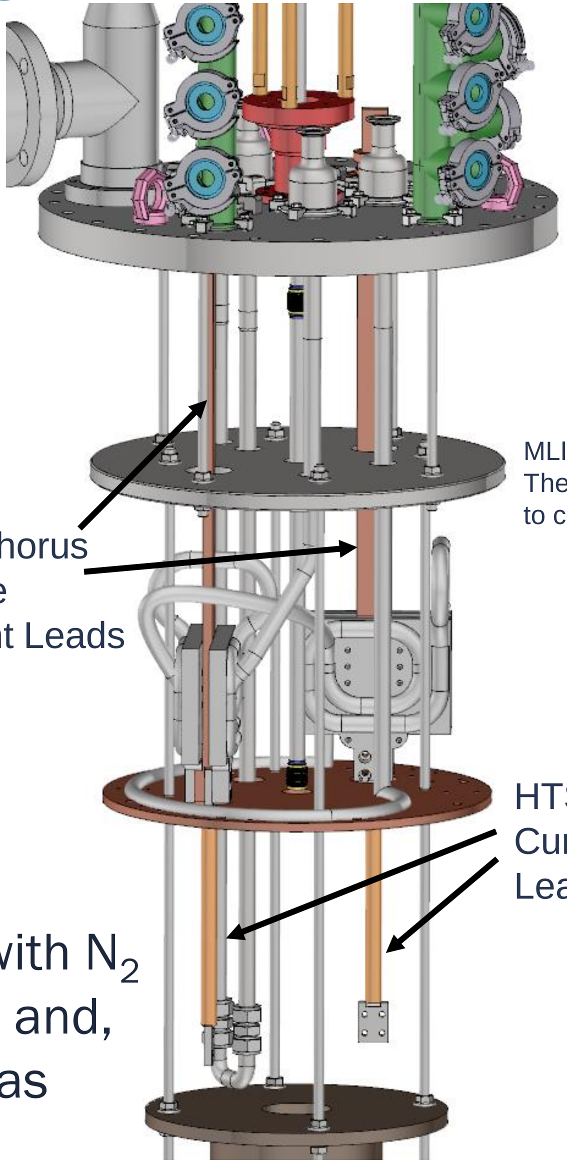
Copper Thermal Shield

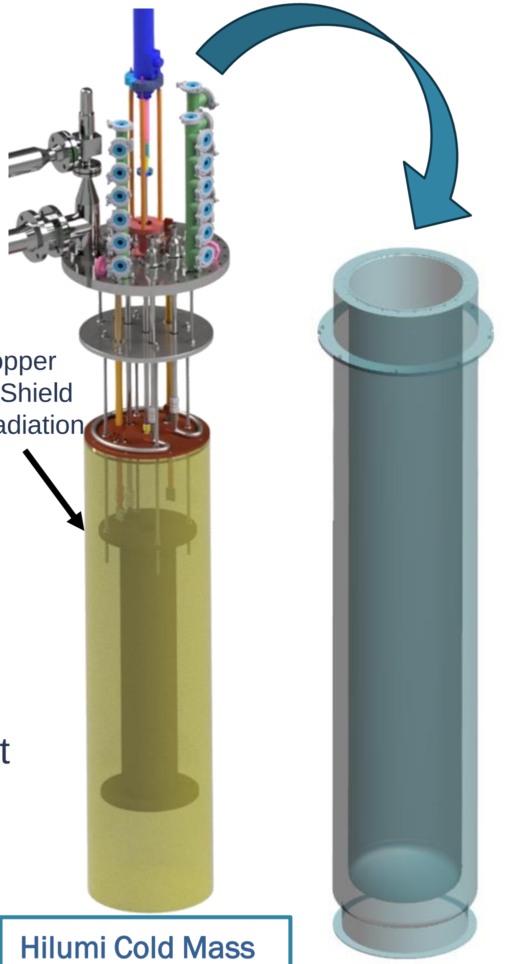
- D 450mm
- H 1800mm

Free Test Volume

- D 400mm
- H 1400

To speed up the cooling process, the Cryostat will be filled with N_2 gas and cooled down to 100K, then the gas will be pumped and, once reaced a good vacuum (10^{-5} 10^{-6} mbar), the Helium Gas Cooling Plant will be started.





The Hilumi Cold Mass will be at LASA in December 2024

INFN-LASA Hilumi Cold Mass: Current Leads Cooling

Thermal wise, the most critical components of the Cold Mass are the Current Leads

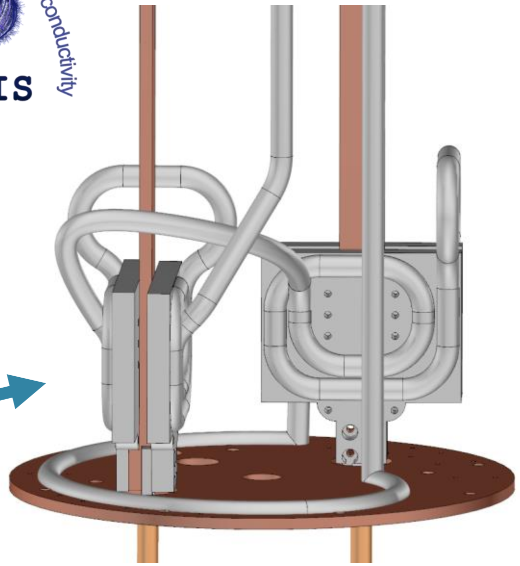
- 1kA Phosphorous Bronze CLs will introduce 100W (50W each) in the system
- The Temperature constrain is given by the HTS Current Leads: Max Temperature 64K

To remove it via conduction is challenging considering the dualism:

- **High thermal conduction** (to better remove the heat)
- **Electrical insulation** (you don't want to short your CLs)

Two options are considered to achieve the heat removal:

- **Flat surfaces CL hold in two Copper Plates** soldered directly to the Helium Gas Pipe. In order to have enough heat exchange surface between pipes and copper plate, the pipes must be shaped in a circular spiral path.
  - Electrical Insulation: the CL are insulated with a Kapton sheet
  - CL Max Temperature (HTS CL Level): 60K
- **Cylindrical CL soldered directly to the Helium Gas Pipe** (helix shape). The direct contact between CL and Pipes makes the system more compact and easier to assembly.
  - Electrical Insulation: the Pipe section will be insulated by the rest of the Pipe by insulation connectors.
  - CL Max Temperature (HTS CL Level): 58K



The two options are under discussion with Industry (SAES RIAL Vacuum) to understand the most valuable

INFN-LASA SOLEMI Insert Cold Mass Conf-A

SOLEMI is a 8T NbTi Solenoid installed at LASA

With SOLEMI Insert we will be able to test Coils in an 8T Magnetic Field

Cryostat:

- D 480mm
- H 1200mm

Cold Mass Conduction Cooled (**Cryocooler**) to:

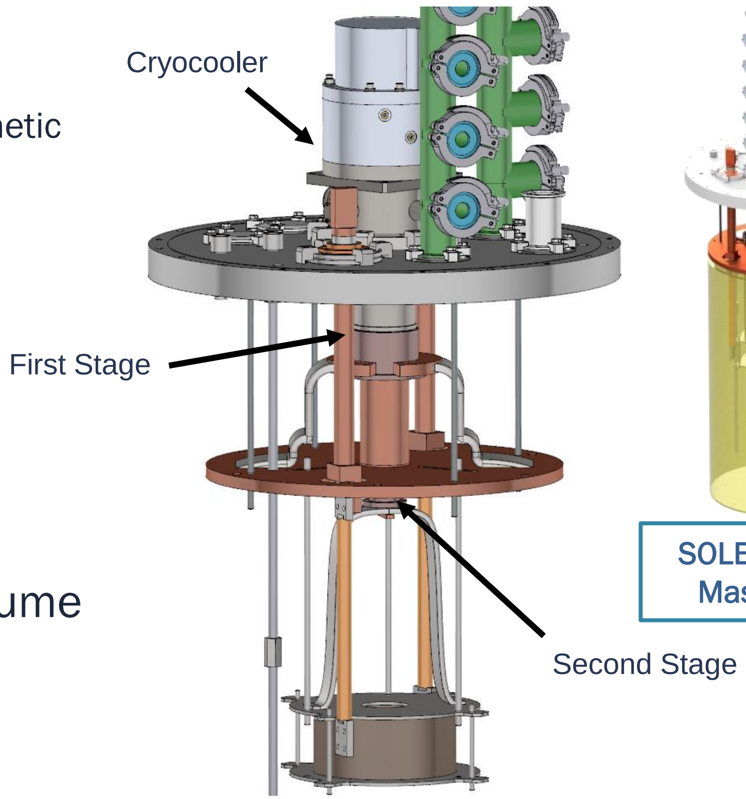
- 15K – Coils (**Magnetic Field up to 8T**)
- 55K – Shield + Current Leads (500A)

Copper Thermal Shield

- D 450mm
- H 825mm

Free Test Volume

- D 400mm
- H 425mm



SOLEMI In Cold Mass Conf-A

SOLEMI In Cryostat

SOLEMI Test Magnet

The 8T background field is challenging for the HTS Current Lead (HTS-110):

- in a 2T parallel field, the maximum transportable current is 25% of nominal (@64K)
- in a 1T perpendicular field, the transportable current drop to 0A (@64K)

To overcome this problem, we though about two solutions:

- to shield the HTS Current Leads with a **SC magnetic shield** – field total shielding
- To produce in house oversized HTS Current Leads with **HTS ReBCO tapes in parallel**

The SOLEMI Insert Cold Mass Conf-A will be at LASA in October 2024

INFN-LASA SOLEMI Insert Cold Mass Conf-B

SOLEMI is a 8T NbTi Solenoid installed at LASA

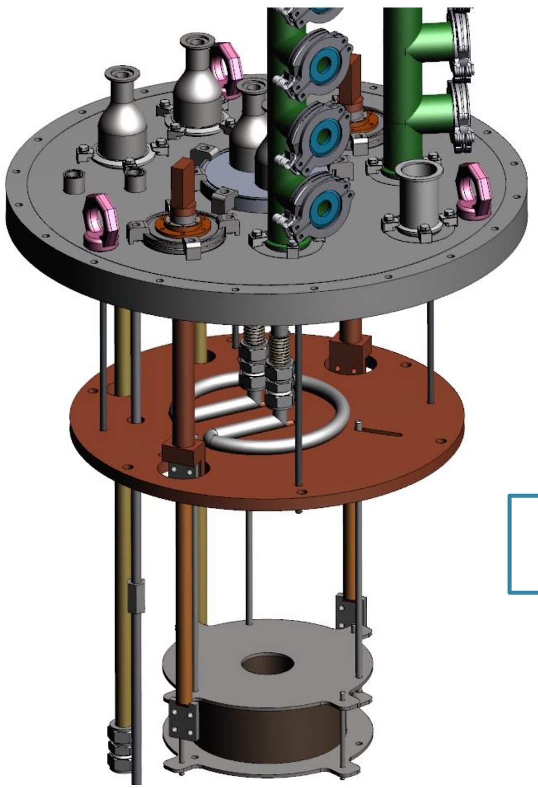
With SOLEMI Insert we will be able to test Coils in an 8T Magnetic Field

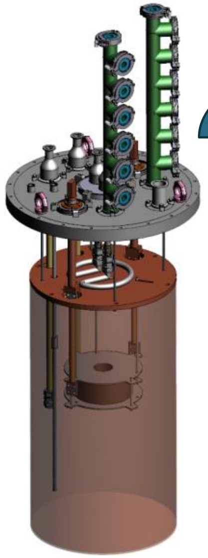
Cryostat:
- D 480mm
- H 1200mm

Cold Mass Conduction Cooled (**Cryocooler**) to:
- 15K – Coils (**Magnetic Field up to 8T**)
- 55K – Shield + Current Leads (500A)

Copper Thermal Shield
- D 450mm
- H 825mm

Free Test Volume
- D 400mm
- H 425mm





SOLEMI In Cold Mass Conf-B

SOLEMI In Cryostat

SOLEMI Test Magnet

The Conf-A Cold Mass will be assembled in October 2024 with the existing Cryocooler. Thanks to this Configuration we will be able to perform tests (500A) during the six months Cooling Plant waiting time. Once the Cooling Plant will be delivered at LASA (May 2025), the SOLEMI Insert Cold Mass will be converted to the final configuration CONF-B.

The SOLEMI Insert Cold Mass Conf-B will be at LASA in October 2024

Conclusion

- 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

Ph. by G. Fornasier

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