Roma 6-7 maggio 2024
Centro Congresso Frentani

Istituto Nazionale di Fisica Nucleare

L'INFN e la
Strategia Europea
per la
Fisica delle Particelle

HTS Magnet status & plan for FCC-hh

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UNIONE EUROPEA
Fondo Sociale Europeo

Ministero
dell'Università
e della Ricerca

PON
RICERCA
E INNOVAZIONE
2014 - 2020

REACT EU

Outline

- **HTS R&D State of the Art**
- **High Field Magnet Program**
- **INFN efforts on HTS magnet development**
- **HTS for FCC-ee**
- **Conclusions**

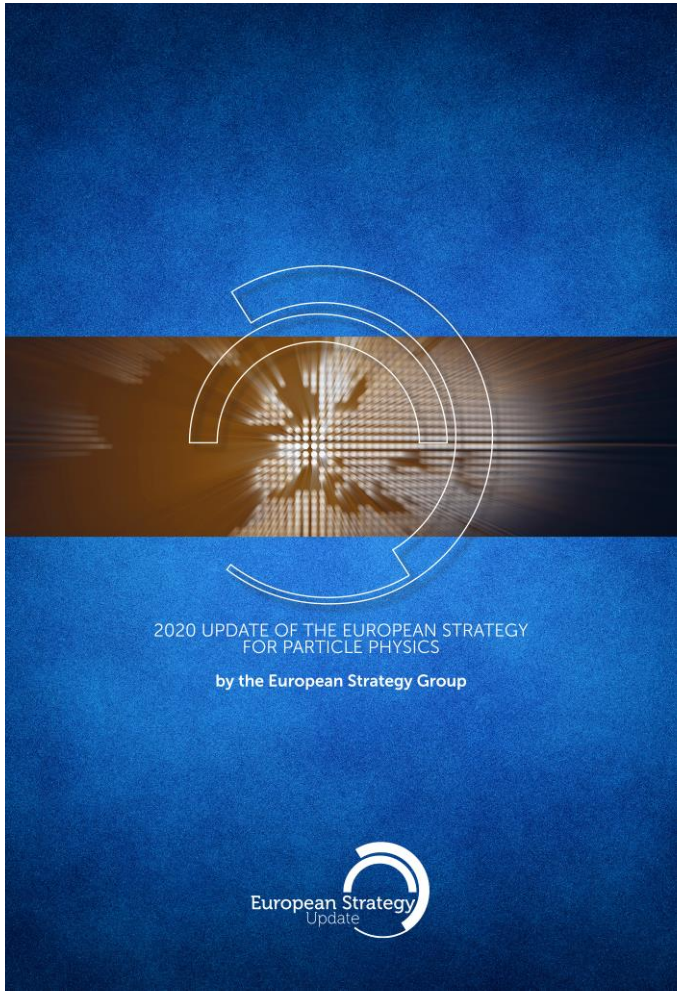
2020 European Strategy Update

Which machines to build?

- Electron-positron **Higgs Factory** (highest priority)
- **Proton-proton collider** @ highest achievable energy

High Priority future initiatives:

"The particle physics community should ***ramp up its R&D effort*** *focused on advanced accelerator technologies, in particular that for* ***high-field superconducting magnets****, including* ***high-temperature superconductors****"*


2020 UPDATE OF THE EUROPEAN STRATEGY FOR PARTICLE PHYSICS

by the European Strategy Group

http://cds.cern.ch/record/2721370

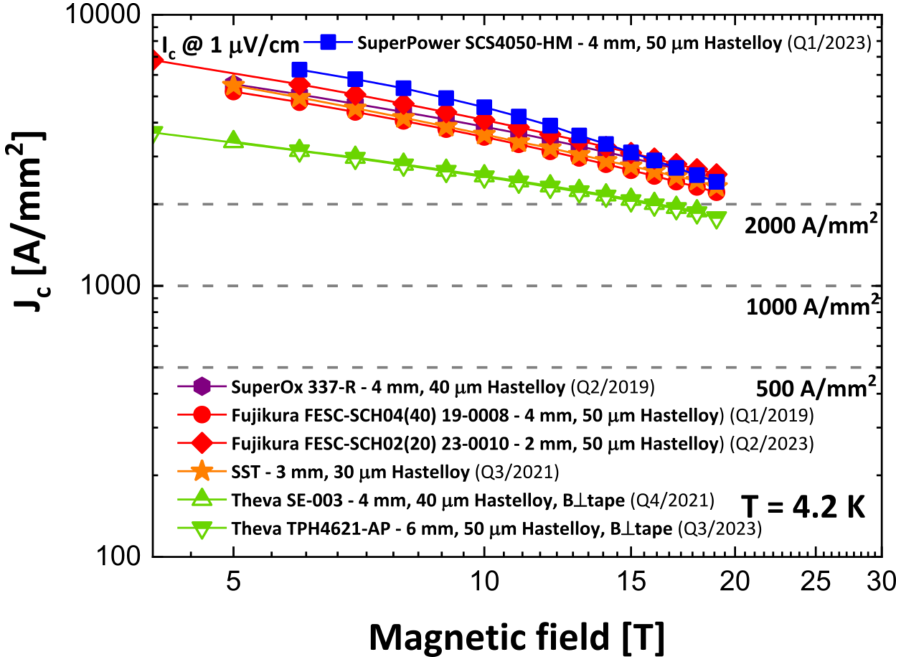
Why HTS technology?

- High Magnetic Field (B < 25 T) operating at 1.9 K or 4.2 K
- Magnetic Field up to 16 T with higher T_{op} (10-20 K)

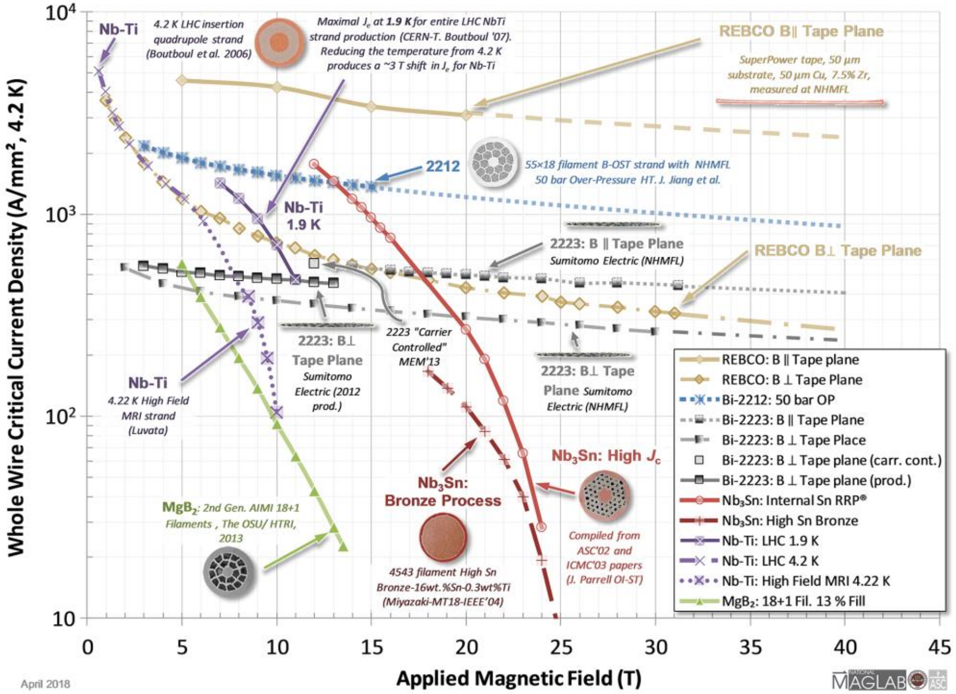
HTS ReBCO Conductor: State of the Art

ReBCO ($ReBa_2Cu_3O_{7-x}$) coated conductor is a potential enabling technology for magnets beyond 16 T

- J_c is sufficient for most application requirements: **J_c (4.2 K, 20 T) > 2000 A/mm²**
- Main conductor development driver: **Fusion Applications**



Courtesy of C. Senatore "HFM annual meeting 2023"

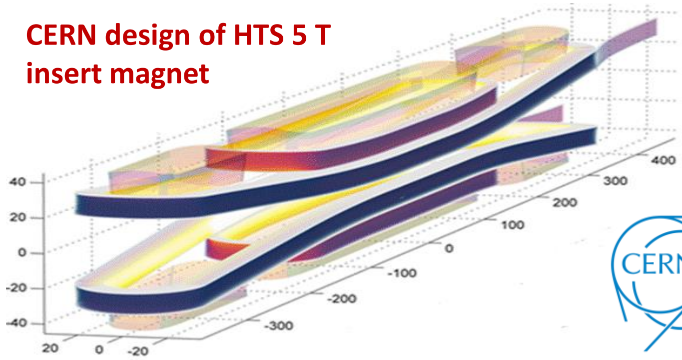


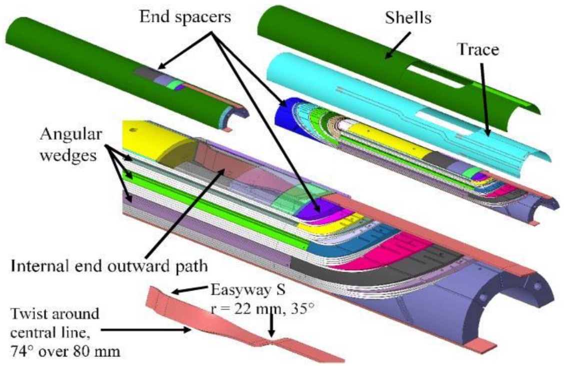
HTS Accelerator Magnet State of the Art

The broader **HTS magnet technology, including cable design, coil design, joints, quench detection and magnet protection** remains at an **early stage of development**

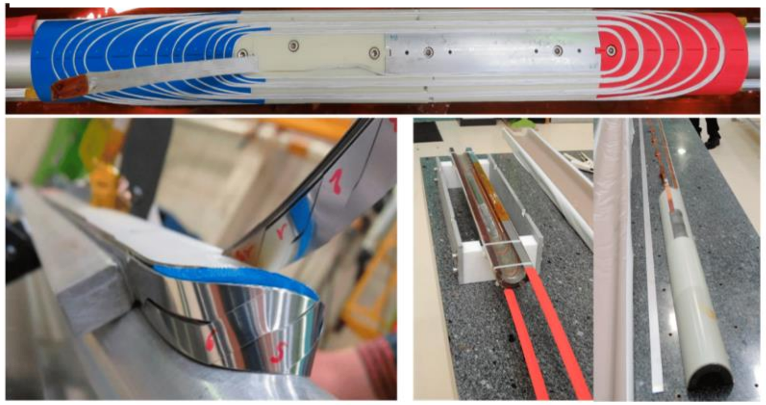
- **Many small experimental solenoid** magnets have been built
- **Few coils for accelerator-type dipole magnets** in ReBCO or Bi-2212 cables*
  - **5 T HTS inserts** for hybrid dipole demonstrators at CERN and CEA
  - LBNL **3T CCT dipolar inserts**
  - Significant performance limitations

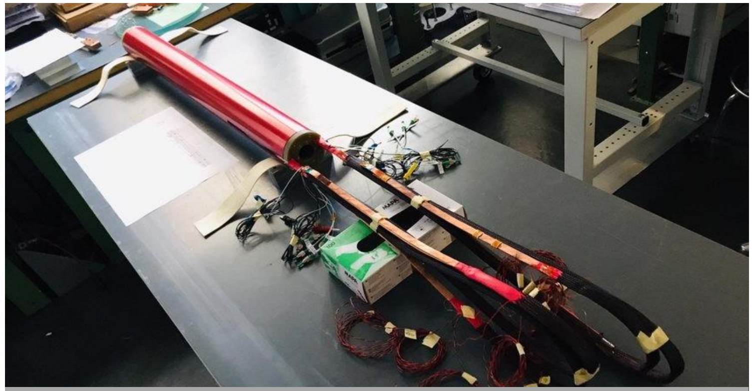
CERN design of HTS 5 T insert magnet





CEA Cos-theta HTS 5 T insert magnet





Courtesy of G. Kirby, J. Van Nugteren

*See: Andrzej Siemko - "Status of HFM R&D Programme", HFM Annual Meeting 2023

High Field Magnet Program

HFM
High Field Magnets
Programme

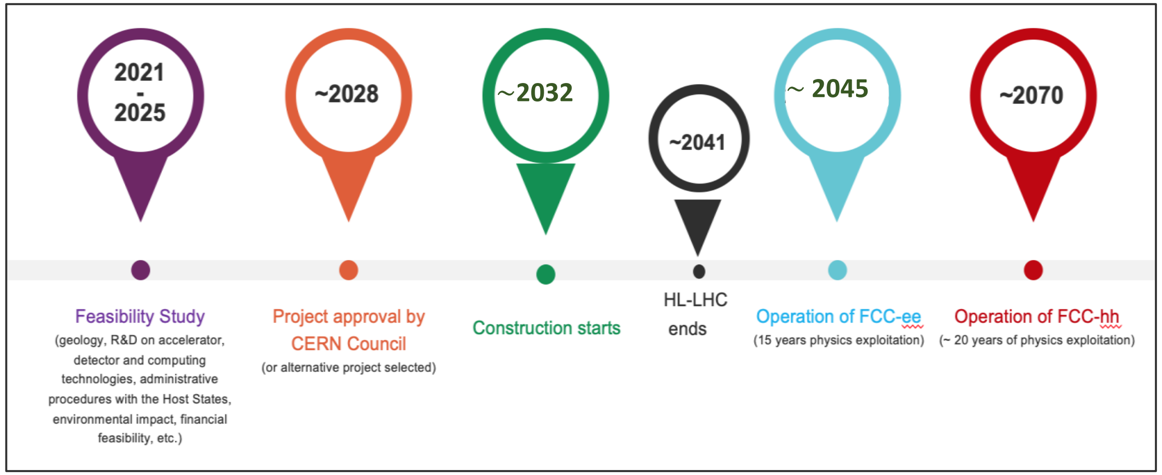
Research and Development program @ CERN with National Laboratories

- Explore the performance limits of LTS magnets with a focus on robust large-scale implementation
- Explore the HTS magnet technologies for accelerator application beyond the limits of Nb_3Sn
- Develop the next generation of accelerator magnets for future colliders

https://cern.ch/hfm

Targets and goals:

- For the Nb_3Sn option:
  1. Establish the **operational margins**
  2. **Select the magnet design**
  3. **Scale to 14-m-long** magnets
- For **HTS, prove the viability** for accelerator dipoles



Magnet performances:

- 14 T Nb_3Sn magnet for FCC at $\sqrt{s} > 80$ TeV
- **20 T HTS magnet for FCC** at $\sqrt{s} \sim 120$ TeV

Technology Readiness Level

20 T operational field HTS or hybrid dipole magnet for FCC-hh

- Close Technology-Readiness-Level Gap with LTS
  1. Establish HTS technology-stack variants
  2. Demonstrate accelerator quality

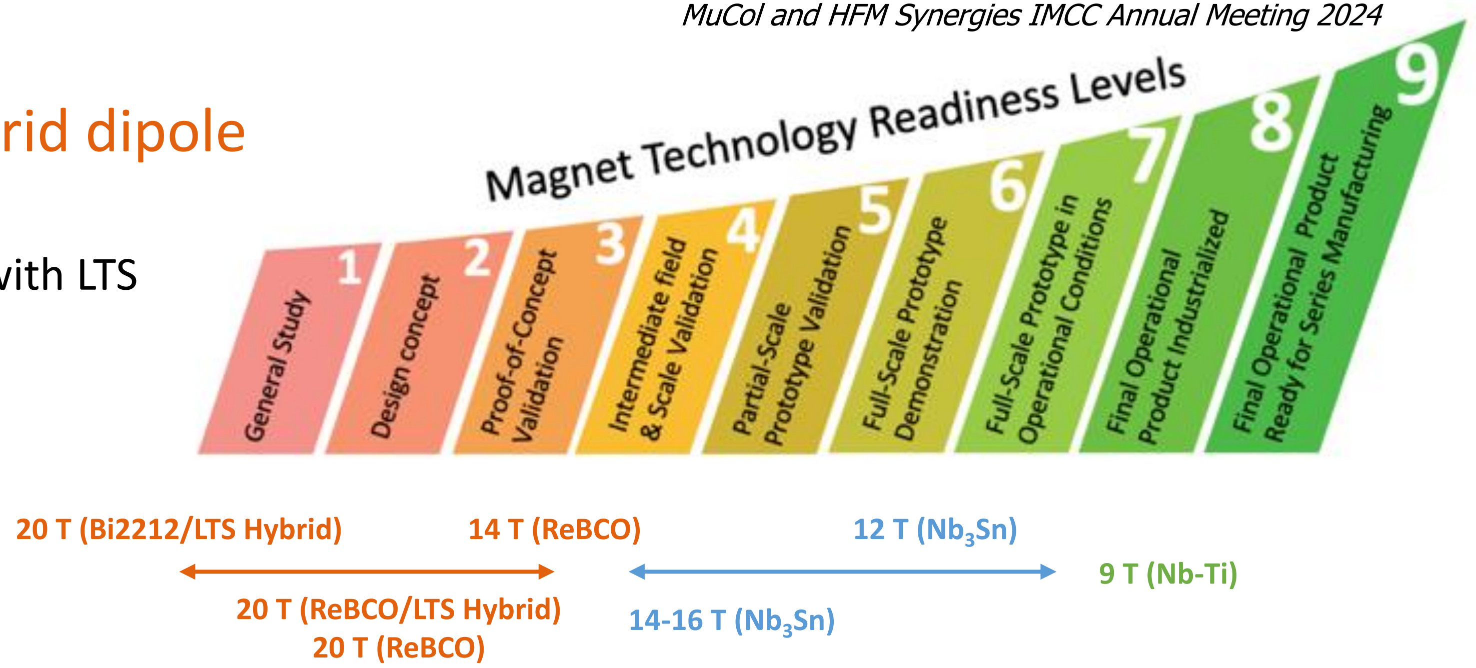
➢ HTS Conductors

- ReBCO for low AC loss and magnetization
- Novel practical HTS cables
- Alternative HTS such as IBS

➢ HTS Magnets

- Subscale HTS inserts (hybrid LTS/HTS)
- Stand-alone all HTS demonstrator

Courtesy of B. Auchmann, E. Todesco
MuCol and HFM Synergies IMCC Annual Meeting 2024

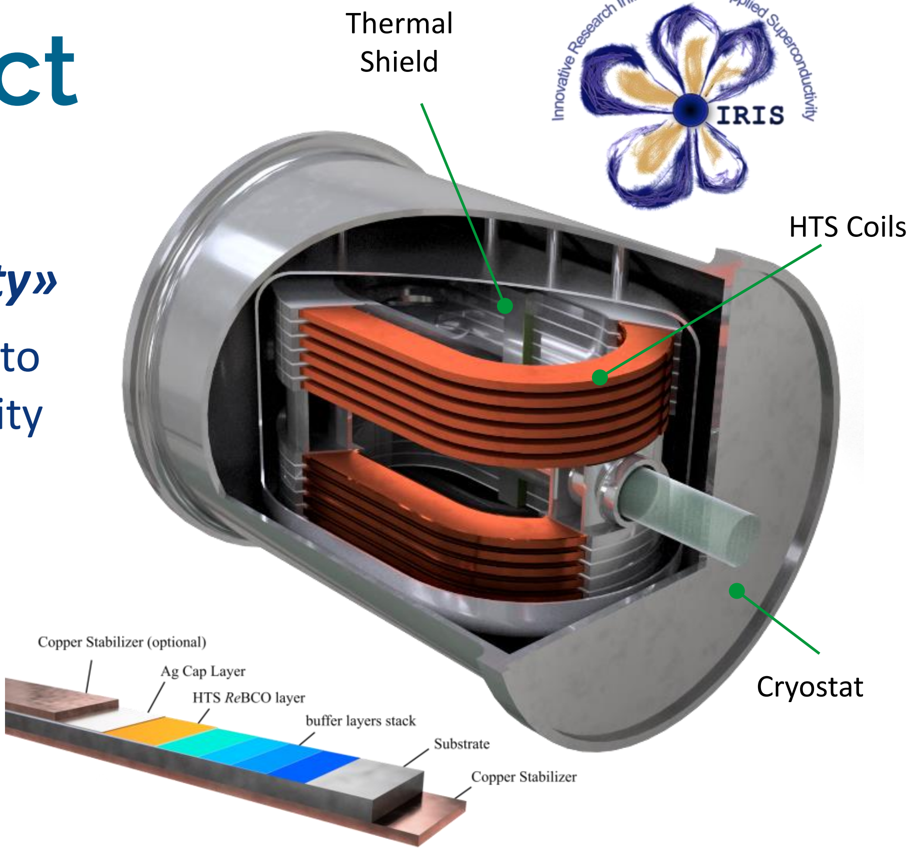


INFN Contribution

«Discussion for new collaboration for HTS research and development activity in parallel with Nb3Sn magnets»

See S. Farinon talk

10 T HTS Dipole for IRIS project

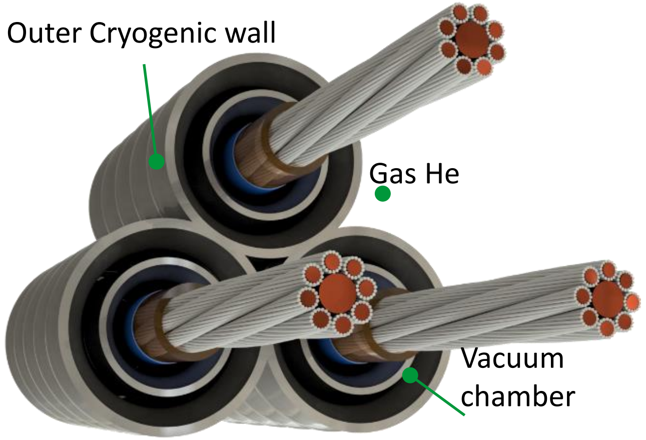


New development project (PNRR-IRIS) 2022-2025
«Innovative Research Infrastructure on applied Superconductivity»

- Improvement of **6 national research laboratories and university labs** to perform cutting-edge technology research activity on superconductivity

DEMONSTRATORs:

1. **1 GW Green Superconducting line in MgB_2 (25 kV, 40 kA)**
2. **10 T HTS dipole «Energy Saving Magnet for Accelerators» @ 20 K**



Courtesy of M. Statera, S. Sorti, S. Maffezzoli, L. Balconi

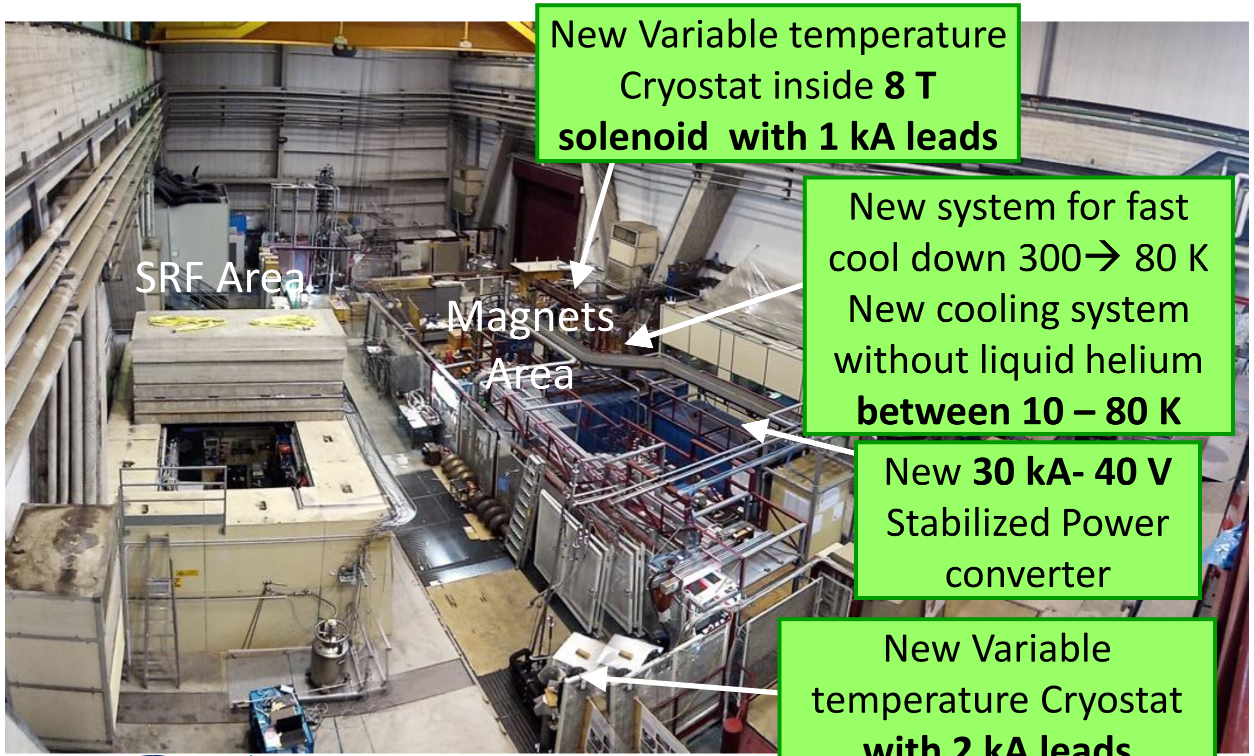
Parameter	Unit	Value
Central field	tesla	10
Free bore dimensions	mm	70
Magnet length	mm	1000
Good field region uniformity	N/A	1.5%
Operating temperature	K	20
Minimum op. temper. for test	K	10
Maximum current	A	<1000

INFN-LASA Upgrade

New Test Station Infrastructure and equipment

Construction of **two new laboratories** 400 m^2 each

1. **Superconducting Magnet Laboratory**
2. **Advanced Accelerator Test Facility**



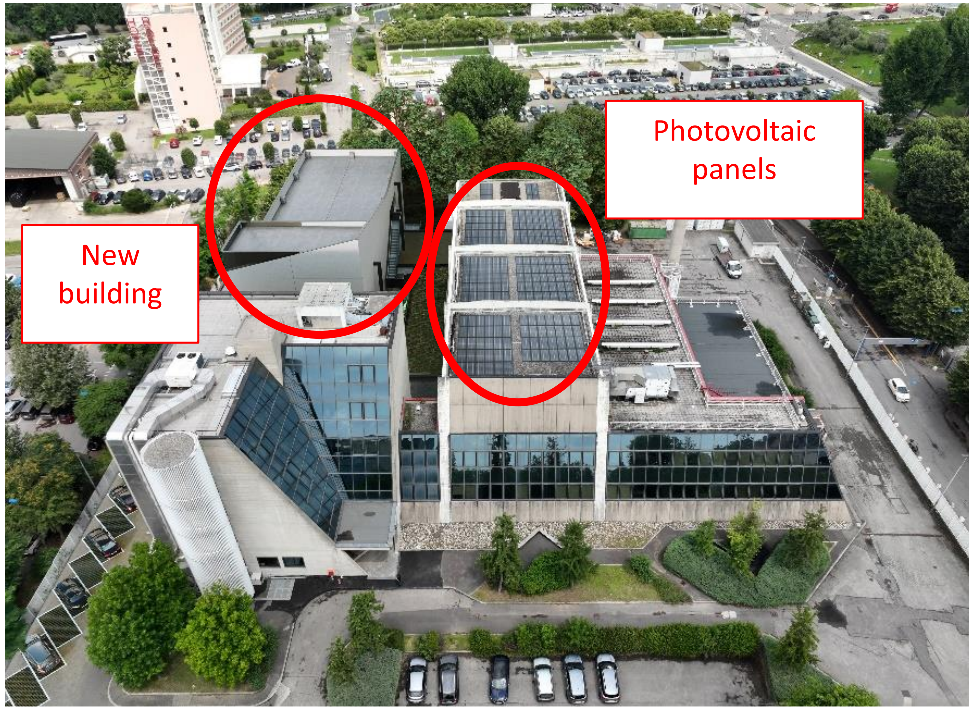
New Variable temperature Cryostat inside **8 T solenoid with 1 kA leads**

New system for fast cool down 300→ 80 K

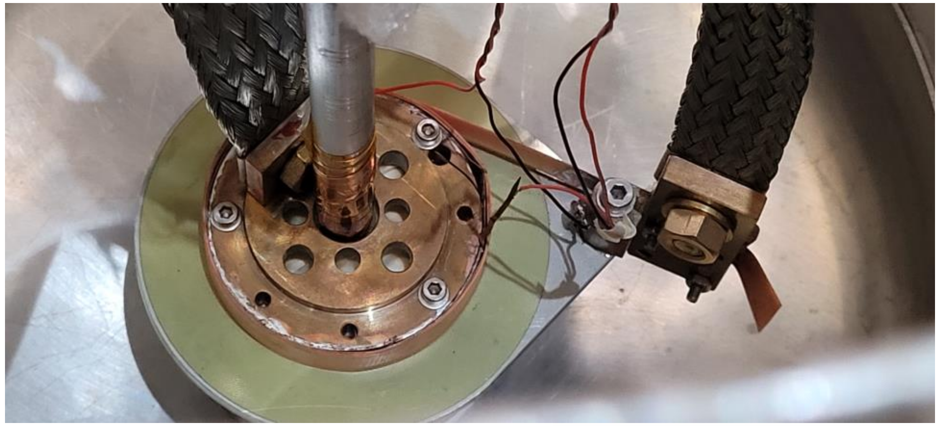
New cooling system without liquid helium **between 10 – 80 K**

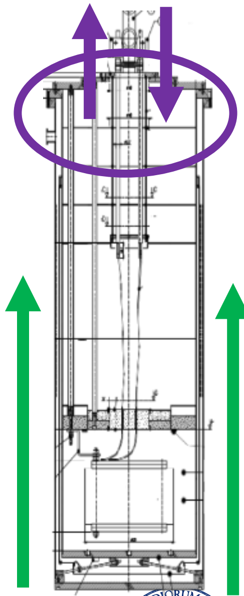
New **30 kA- 40 V** Stabilized Power converter

New Variable temperature Cryostat **with 2 kA leads**



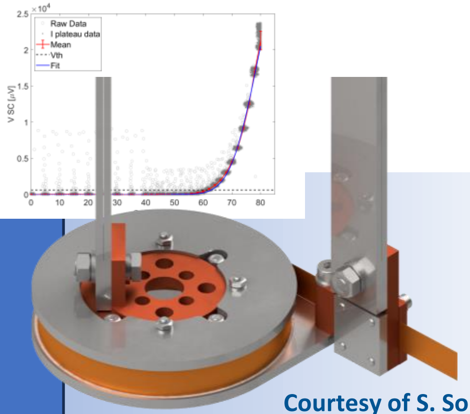
INFN-LASA HTS Program





New cooling system 20-50K Closed loop He (IRIS)

8 T field Solemi1 (IRIS)



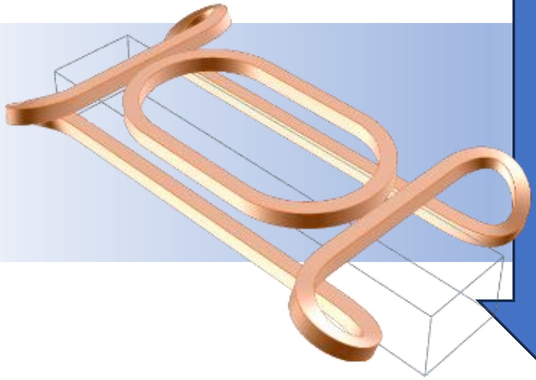
Courtesy of S. Sorti

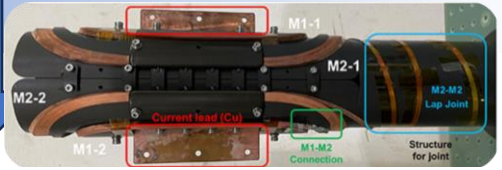
1 Test of small HTS coils to handle tapes and test in LN_2

2 New technologies development (splicing, CI/MI windings)

3 Experience with racetracks in magnet-like design at variable-T.

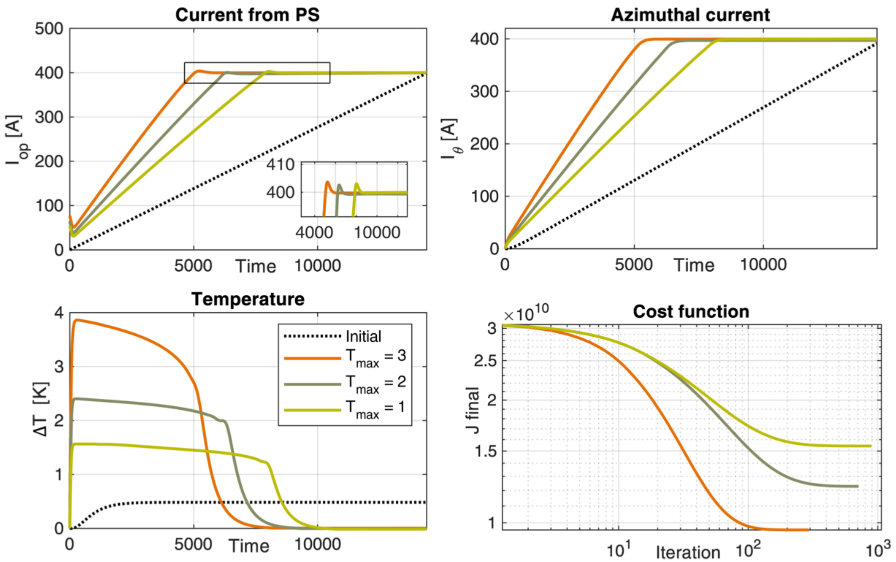
4 Non-planar coils: accelerator grade magnets





Small HTS tape dipole : Prof. S. Hahn (Seoul U.)

Numerical Models for HTS Coils



2 matrices and 4 scalars to set!

$$\Phi(t_f) = (\boldsymbol{X}(t_f) - \boldsymbol{X}_{\mathrm{ref}}(t_f))^{\mathrm{T}}[P](\boldsymbol{X}(t_f) - \boldsymbol{X}_{\mathrm{ref}}(t_f))$$

$$L(t) = (\boldsymbol{X} - \boldsymbol{X}_{\mathrm{ref}})^{\mathrm{T}}[Q](\boldsymbol{X} - \boldsymbol{X}_{\mathrm{ref}}) + U \exp\left(V\frac{\boldsymbol{X}-\boldsymbol{X}_{\max}}{\boldsymbol{X}_{\max}}\right) + W \exp\left(Z\frac{U-U_{\max}}{U_{\max}}\right)$$

Penalty to reach a target or following a trajectory (i.e. target azimuthal current)

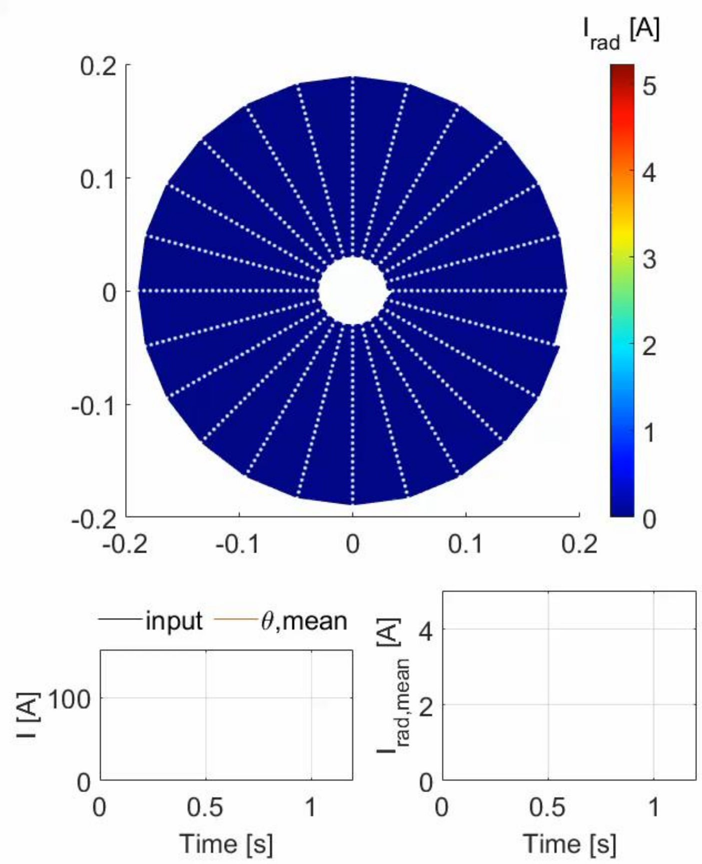
Constraints on state (i.e. limiting temperature)

Saturation of input (i.e. maximum current from power supply)

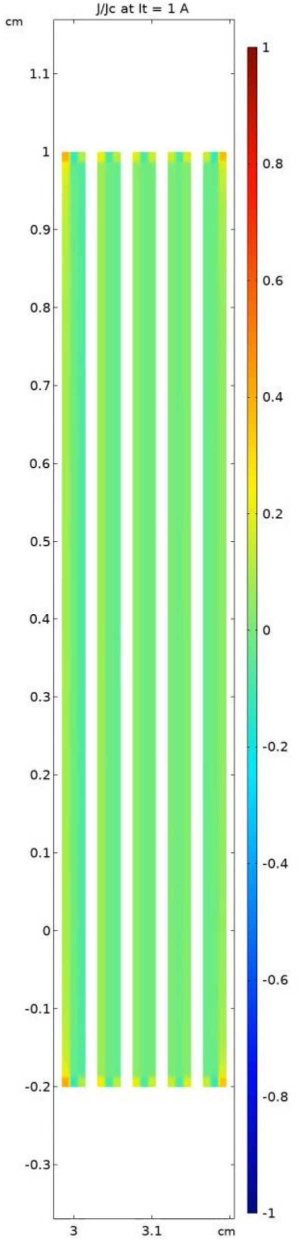
Lumped circuit employed in **Optimal Control of ESMA**.

- Cost minimization

Need for accurate model and comprehensive description of HTS behaviour



Courtesy of S. Sorti, L. Balconi



INFN efforts on HTS program

Different **on-going R&D Projects** on HTS magnets:

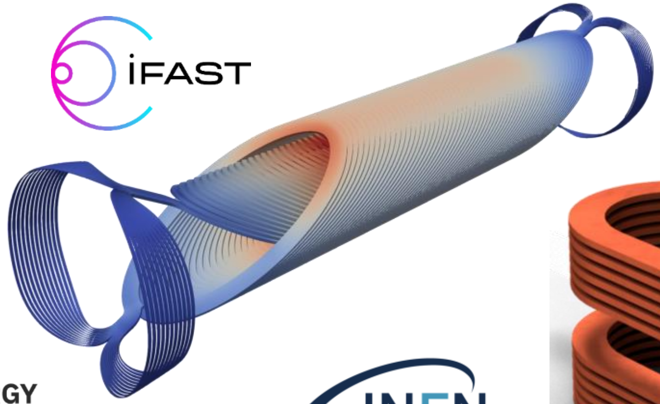
- 4 T all-HTS, 80 mm bore CCT dipole **(IFAST)**
  - **Collaboration with Industry**
  - **Demonstrate to work @ T=20 K**
  - **TRL 5**
- 10 T dipole **IRIS**
  - **Collaboration with Industry**
  - Planar coils handling
  - Interconnections
  - **TRL 4**

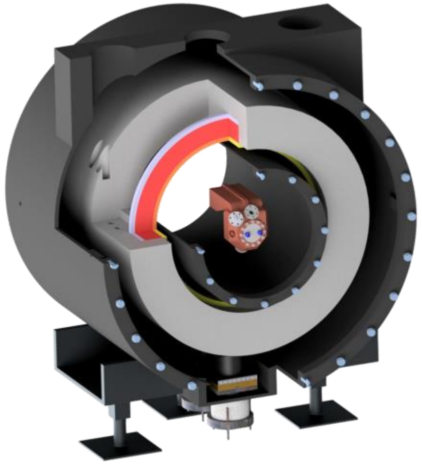
Synergies on HTS conductor R&D with MuonCollider

- MuCol Split Coil – RFMTF (RF Magnet Test Facility)
  - ***See M. Statera talk next***

NEW R&D development programs: EuMAHTS

- **INFRATECH proposal**
- PI: L. Bottura, CERN





iFAST

Innovative Research Infrastructure on applied Superconductivity IRIS

ELYTT ENERGY

wigner

INFN LASA

MuCol

EuMAHTS Accelerating HTS

What about FCC-ee ???

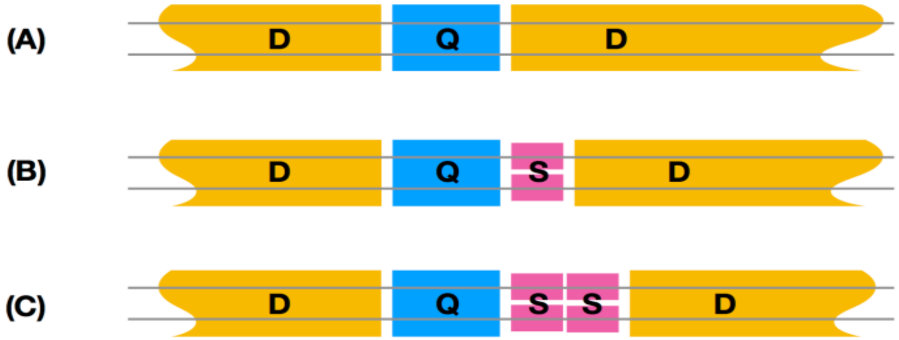
Main goal: develop **superferric** configurations able to work **@ 50 K** without thermal-shield with **HTS** superconductors

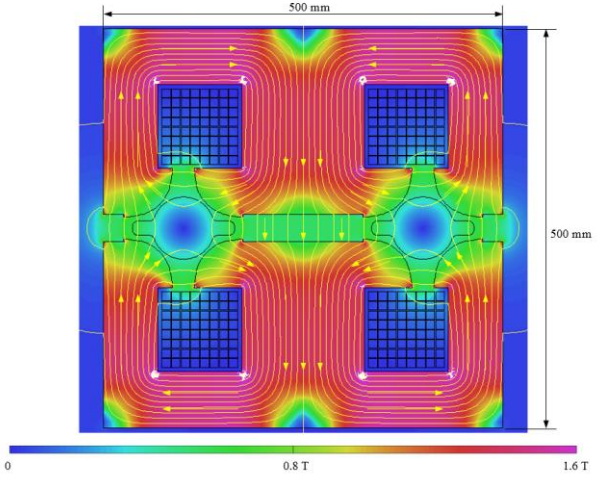
“ENERGY SAVING APPLICATION”

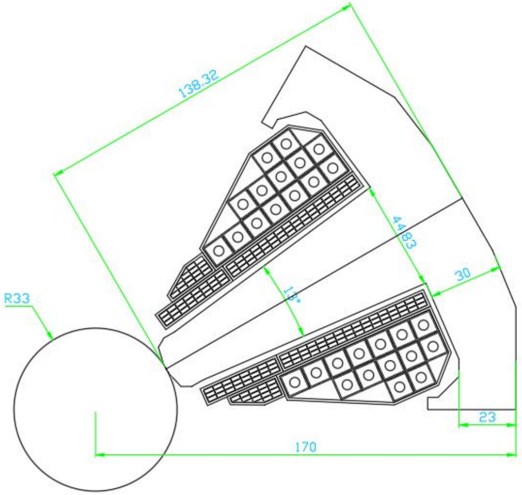
CDR: 2900 quads & 4700 sextupoles

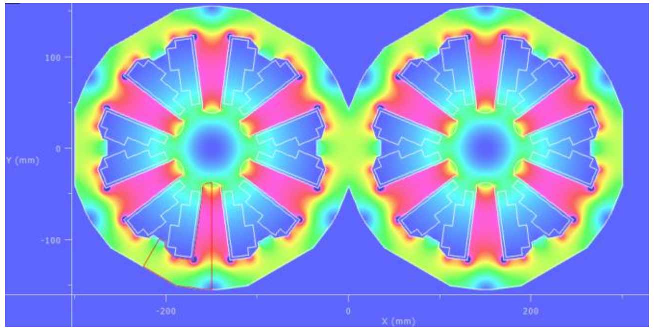
- Normal conducting, ~50 MW @ $t\bar{t}$
- 3 different types of short straight sections

CDR arc lattice







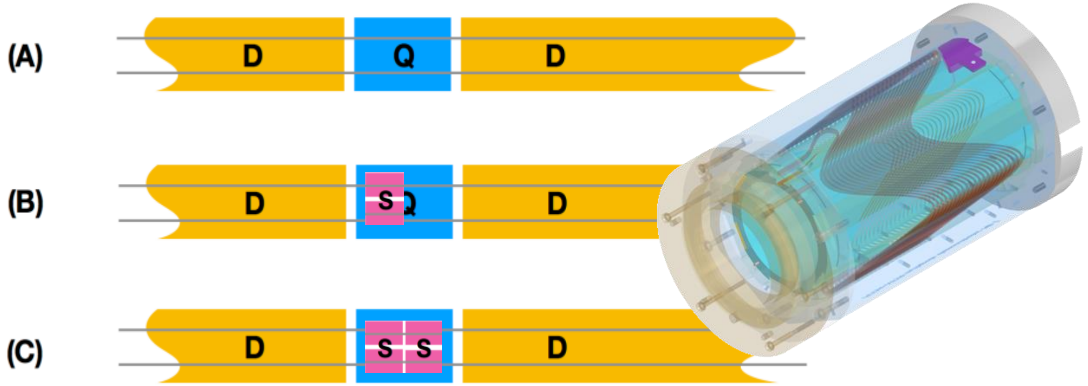


FCC-ee HTS magnets

“CHART” collaboration started to evaluate different solutions based on Nested SC quadrupole and sextupole with CCT design

Swiss Accelerator Research and Technology

HTS option



- **HTS could work @ 40 K** and providing **good field quality**
- **Dipole filling factor improved** with optic flexibility
- **Cryo-cooler** supplied cryostat
- **1 m long demonstrator** before 2026

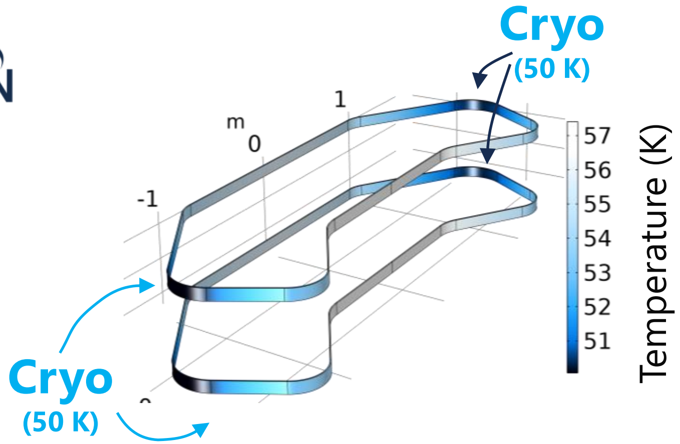
CONS:

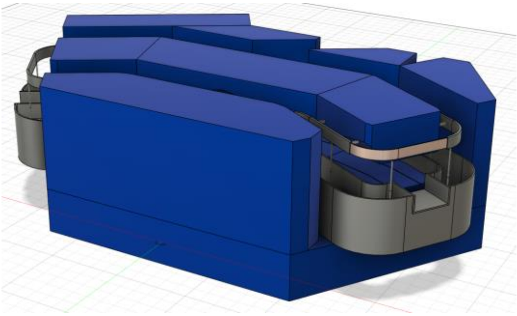
- High quantity of HTS conductor **(high cost of the magnet)**
- **Redundancy of cryocoolers**: distributed cryogenic is mandatory

Possible INFN expertise contribution

Energy Saving Accelerator and Beamline Magnets

Development of **Superferric** magnet configurations using **HTS** conductors optimized to work at **T < 50 K without thermal shield** and with **high energy efficiency**





Conclusions

R&D on HTS is a key aspect for advanced accelerator technologies

- Enable of very **high field magnet** (20 T, 4.2 K) for FCC-hh
- Key technology beyond Nb3Sn to **reduce accelerators power consumption** (T~10-20 K)
  - Possible application of next years HTS technology for FCC-ee design
- Strong effort on **R&D needed for technology readiness** increment
  - Conductor characterization in operating magnet to be explored
  - Validation of HTS compatibility with FCC-hh requirements: high priority
- **INFN** strongly **involed in High Field Magnet** program
  - Considerable effort of R&D on HTS conductor and HTS magnets in parallel to Nb3Sn high field magnets development
  - **New infrastructure @ INFN-LASA** for HTS magnets testing **(IRIS)**
  - **HTS R&D is common to different scientific projects (HFM, FCC, MuCol)**

INPUTS from many collaborators: INFN: L. Rossi, M. Sorbi, M. Statera, S. Farinon CERN: E. Todesco, B. Auchmann et al.

Thank you for the Attention!

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