HFM FCC Program - Italian activities

Current Status, Challenges, and Developments

Stefania Farinon

For the INFN LASA and Genova Collaboration

ESPP flagship project: FCC

- FCC is currently split in two stages:
  - FCC-ee
    - no need for high field magnets
    - HTS can enhance the performance and sustainability of detectors (refer to S. Mariotto's presentation on the IDEA magnet) as well as other specialized components of accelerators.
  - FCC-hh
    - requires nearly 4700 high field dipoles
    - the major part of FCC-hh cost is driven by the cost of each dipole (2MCHF/magnet, source: https://arxiv.org/pdf/2203.07804, 2022)

→ critical role of HFM superconducting magnet developments

FCC IN A NUTSHELL

Timeline

- **2025**: Completion of the FCC Feasibility Study
- **2027–2028**: Decision by CERN Member States and international partners

Tunnel

- **90.7 km** circumference
- **200 m** average depth
- **8 surface points** (7 in France, 1 in Switzerland)

Two stages

- **FCC-ee** (precision measurements) about 15 years from the **mid-2040s**
- **FCC-hh** (high energy) about 25 years from the **2070s**

Costs/benefits

- **15 billion CHF**, spread over at least **15 years** for FCC-ee with four experiments
- Estimated benefit–cost ratio of **1.66**
- About **800 000** person-years of employment created

https://home.cern/science/accelerators/future-circular-collider

Challenges in high-field dipole development

- **Superconducting Materials:**
  - Practical superconductors have limitations in reaching and sustaining fields in the range 14—16 T, needed for a 90-100 TeV accelerator.
- **Engineering Challenges:**
  - Managing stresses, cooling, and quench protection becomes increasingly difficult at higher fields.
- **Cost and Reliability:**
  - High-field magnets are expensive to produce and maintain, and reliability is crucial in long-term experiments.

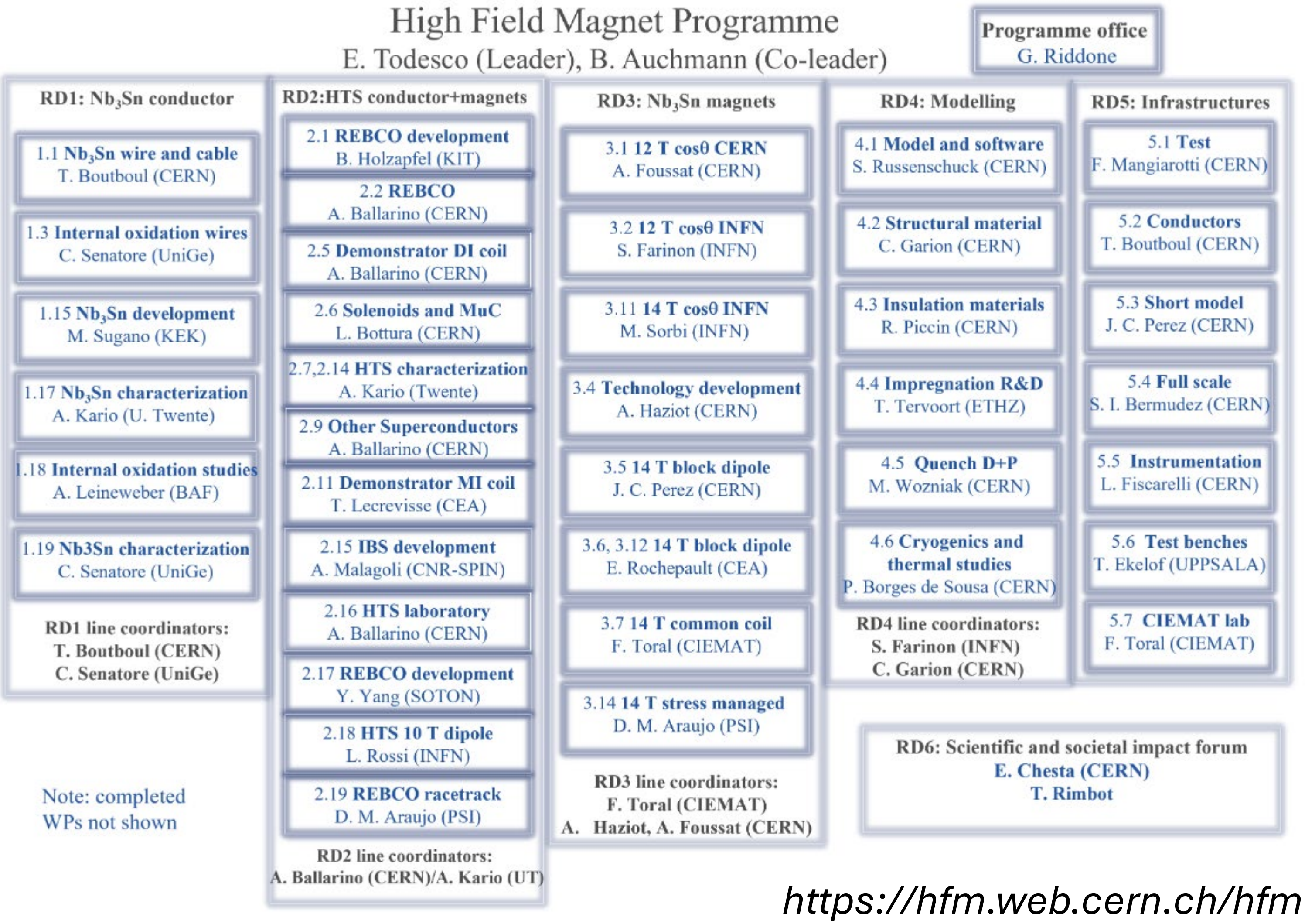
Superconducting material choice

- **NbTi:** this technology has reached its **peak potential**.
  - The LHC dipoles (operating at 8.33 T, with an ultimate field of 9 T) represent the upper limit of NbTi's capabilities in accelerator dipole magnets.
- **Nb_3Sn:** this technology is **mature but not consolidated**.
  - The upcoming High Luminosity LHC upgrade will rely on 24 Nb_3Sn quadrupoles for the triplets.
  - However, the 11 T Nb_3Sn dipole project for HL-LHC has been paused following degradation over time observed in several full-size magnets, with the cause still under investigation.
- **ReBCO:** this technology is in its **early stage of development**.
  - Very promising:
    - ★ Very high magnetic field (≤25 T) at low temperature (≤4.5 K)
    - ★ High magnetic field (≤16 T) at intermediate temperature (10— 20 K)
  - Significant R&D efforts are underway globally.

Pros and cons of Nb_3Sn in HFM

- **Pros:**
  - Magnetic properties:
    - Nb_3Sn enables access to dipole fields in the 12-16 T range, which NbTi cannot achieve.
  - Strands & cables availability
    - Nb_3Sn strands are commercially available, with High-Luminosity (HiLumi) LHC performance improvements of 10-15%.
    - Nb_3Sn is available as round strands and can be formed into Rutherford cables, enhancing compatibility with accelerator designs.
- **Cons:**
  - Brittleness:
    - Nb_3Sn is a brittle ceramic-like material, unlike NbTi, which is ductile.
    - This brittleness makes it difficult to handle and susceptible to fracture, complicating manufacturing and assembly, especially in high-stress environments.
  - Complex Fabrication and Heat Treatment:
    - Nb_3Sn coils require a challenging fabrication process, including a high-temperature heat treatment (typically above 650°C) after winding.
    - This process is time-consuming, costly, and introduces risks like deformation or damage to the windings.
  - Mechanical Strain Sensitivity:
    - Nb_3Sn superconducting properties degrade under mechanical strain, which can occur during cool-down, magnet energization, or operational fluctuations.
    - This sensitivity requires careful mechanical design and stress management to maintain performance over time.
  - Higher Cost:
    - Nb_3Sn is more expensive than NbTi, partly due to the complex fabrication and heat treatment processes, as well as the increased material costs.
    - This makes large-scale adoption or replacement more costly in projects.

HFM Program @ CERN



https://hfm.web.cern.ch/hfm-programme-structure

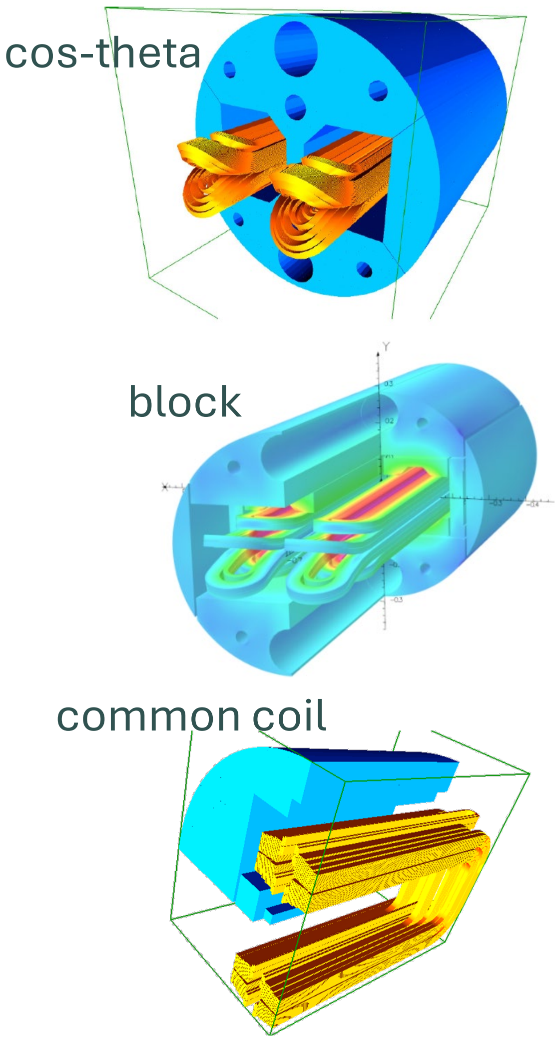
HFM Program RD3: Nb_3Sn magnets

- HFM RD3 focuses on Nb_3Sn magnets
- INFN is contributing in two main areas:
  - The development of a 12 T dipole in a cos-theta configuration through a collaborative effort with CERN (FalconD project).
  - The development of a 14 T dipole in cos-theta configuration (details of the CERN/INFN agreement still under discussion)

RD3: Nb_3Sn magnets

- 3.1 **12 T cosθ CERN** — A. Foussat (CERN)
- 3.2 **12 T cosθ INFN** — S. Farinon (INFN)
- 3.11 **14 T cosθ INFN** — M. Sorbi (INFN)
- 3.4 **Technology development** — A. Haziot (CERN)
- 3.5 **14 T block dipole** — J. C. Perez (CERN)
- 3.6, 3.12 **14 T block dipole** — E. Rochepault (CEA)
- 3.7 **14 T common coil** — F. Toral (CIEMAT)
- 3.14 **14 T stress managed** — D. M. Araujo (PSI)

RD3 line coordinators:
F. Toral (CIEMAT)
A. Haziot, A. Foussat (CERN)

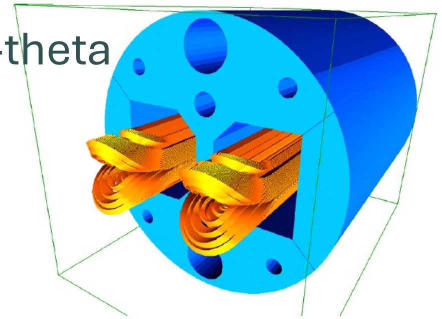


https://hfm.web.cern.ch/hfm-programme-structure

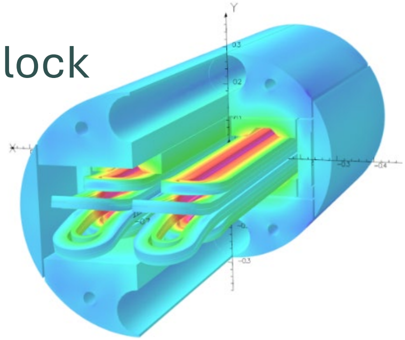
HFM Program RD3: Nb_3Sn magnets

- HFM RD3 focuses on Nb_3Sn magnets
- Italy is contributing in two main areas:
  - The development of a 12 T dipole in a cos-theta configuration through a collaborative effort with CERN (FalconD project).
  - The development of a 14 T dipole in cos-theta configuration (details of the CERN/INFN agreement still under discussion)

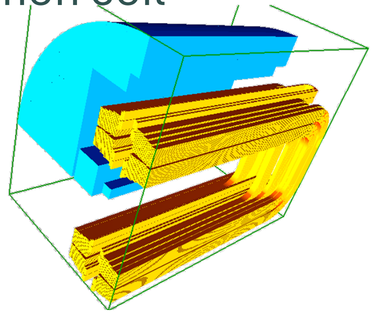
cos-theta



block



common coil



https://hfm.web.cern.ch/hfm-programme-structure

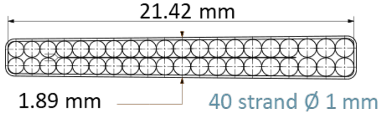
Nb_3Sn dipoles: 12 T vs 14+ T

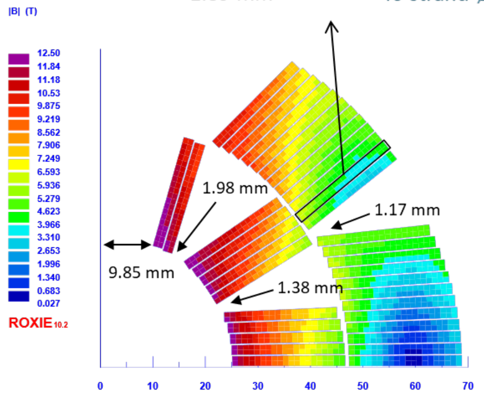
- There is a significant technological leap between achieving a magnetic field strength of 12 T and that of 14+ T

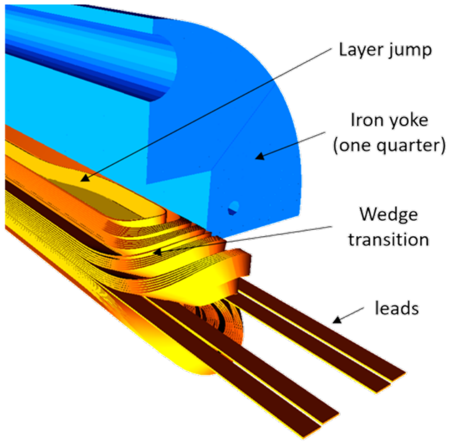
FALCON DIPOLE

12 T

Reacted cable
Width +2%
Mid-thick +4.5%





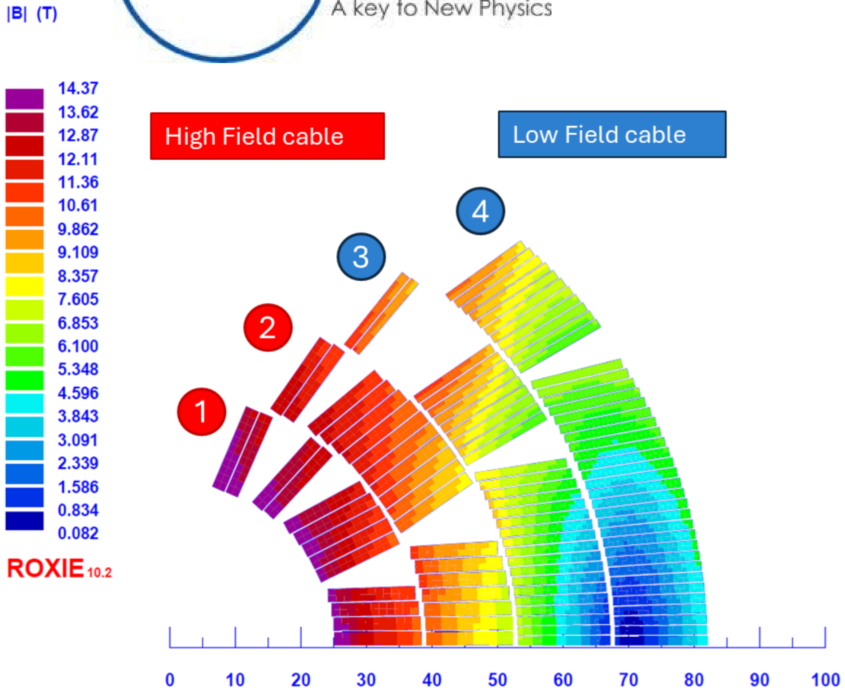


Bore Field	Operating Current	Margin on Loadline @ 1.9 K
12 T	20180 A	24.4%
*13.5 T	23000 A	15%

*intended as mechanical limit

EuroCirCol
A key to New Physics

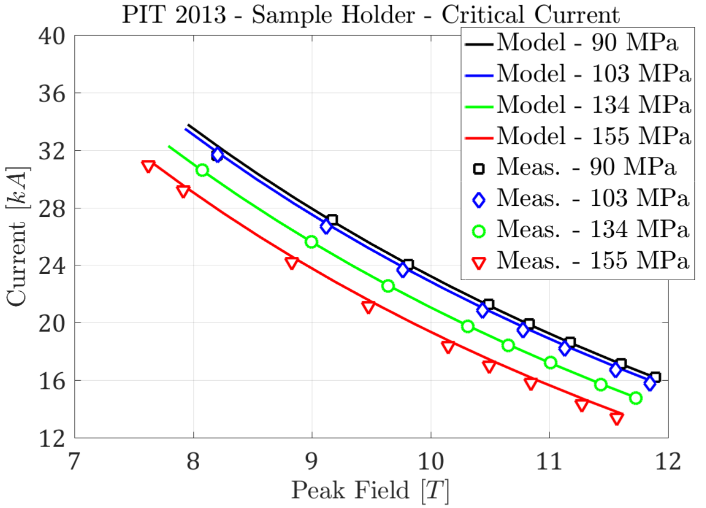
16 T

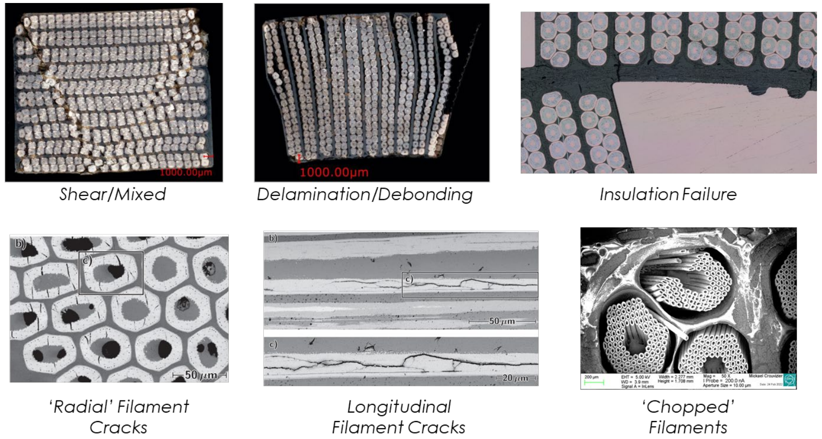


Parameter	HF cable (DEM-1.1)	LF cable (11T dipole)
Operating current (A)	9820	9820
Margin @ 1.9 K	21%	25%

Why is the 16 T target no longer the baseline objective?

- R&D efforts are essential not only for magnets but also for conductors. Key aspects include:
  - transport properties:
    - J_C(16 T, 4.2 K)=1200 A/mm^2 state of the art of Nb_3Sn strands (HiLumi)
    - **J_C(16 T, 4.2 K)=1500 A/mm^2 target performance for FCC-hh @ 16 T**
  - mechanical sensitivity:
    - *reversible effects*: the critical current density decreases as applied stress increases, but these effects are reversible within certain limits.
    - *irreversible effects*: excessive stress can lead to coil failures due to irreversible damage.
- The current FCC-hh **baseline** is set at **14 T**, achieving the minimum goal of 90 TeV with dipole magnets operating at 1.9 K. This baseline also includes enough margin to operate at 4.2 K, which would help reduce energy costs.
- The **12 T step** facilitates quicker industrialization if FCC-hh development is accelerated relative to the current timeline.

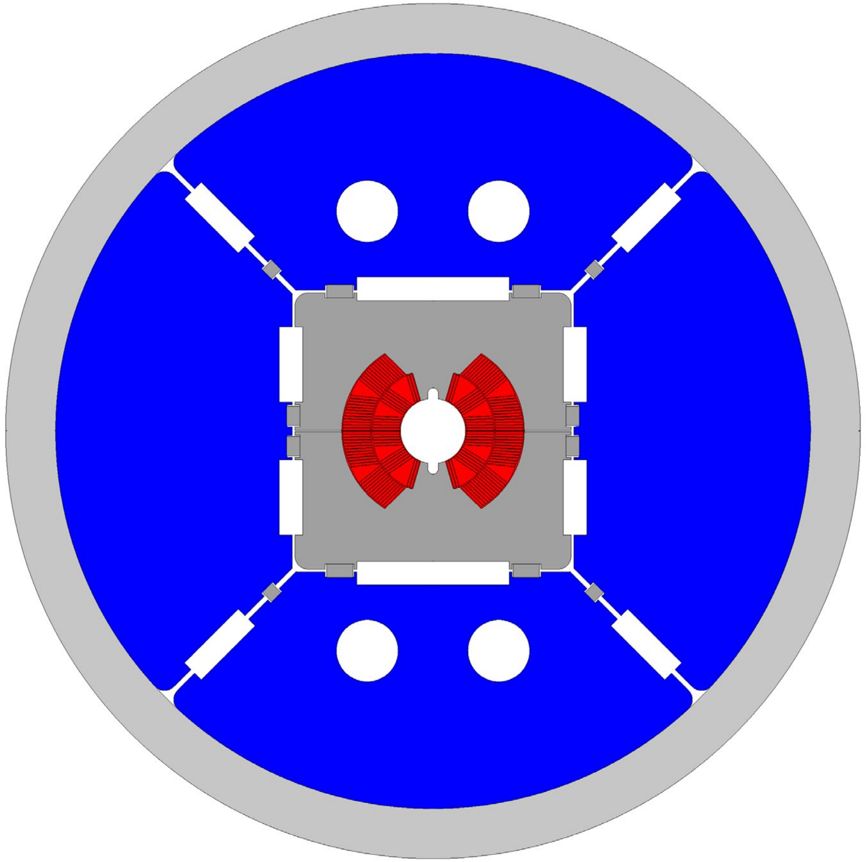




G.Vallone
https://indico.cern.ch/event/1177999/

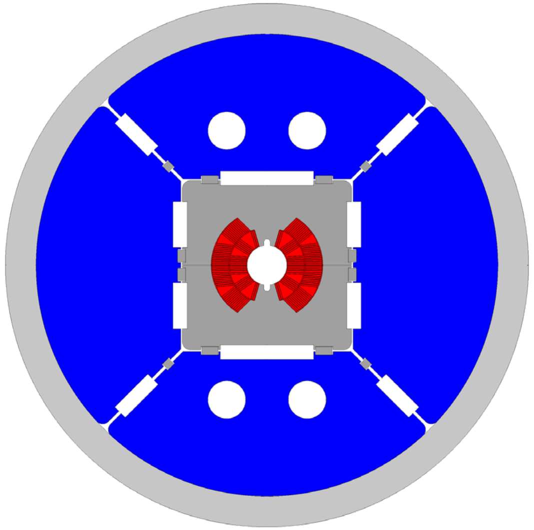
12 T Nb_3Sn FalconD dipole

- The FalconD program, signed in 2018, is being developed in accordance with the CERN/INFN KE 4102 agreement.
- An amendment was issued on March 2023 to update the project's scope and schedule.
- The project involves the development and construction of a short model Nb_3Sn dipole with the following specifications:
  - Single aperture with an inner bore of 50 mm.
  - 2-layer cos-theta coil, providing a bore field of 12 T at 1.9 K.
  - Mechanical assembly using bladder & key technology.
  - The total coil length is 1.5 m.



12 T Nb_3Sn FalconD dipole

- The FalconD project includes the following activities:
  - At ASG-Superconductors, the manufacturing of:
    - 1 dummy pole wound with copper cable
    - 2 practice poles wound with Nb3Sn cable
    - 5 poles wound with Nb3Sn cable for the single aperture dipole
  - At INFN-LASA Lab
    - the mechanical assembly and testing @ 4.2 K of the FalconD magnet



CERN supports all activities and supplies the magnet **components**, including the cable, spacers, and other necessary items.

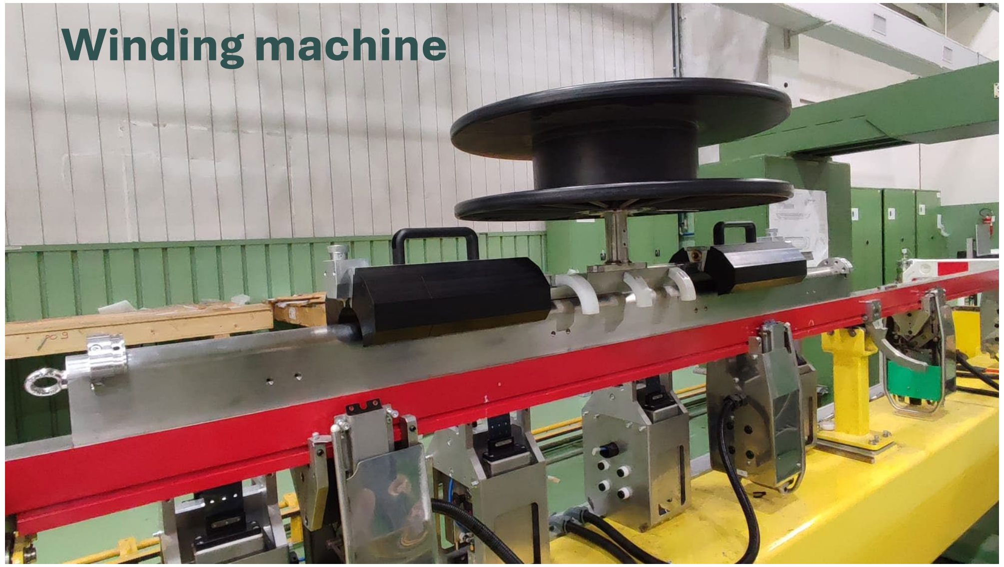
ASG Superconductors is responsible for manufacturing the **coils**, which include 7 Nb_3Sn coils and 1 dummy copper coil.

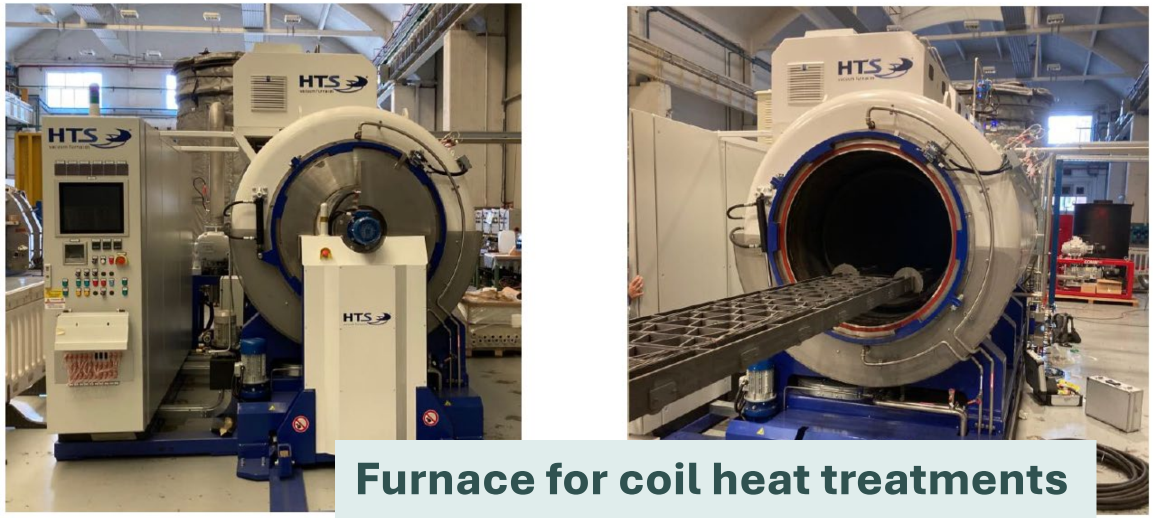
INFN is responsible of the magnet design, **B&K assembly**, and preliminary **test** @ 4.2 K
at LASA laboratory in Milan.

Coil production status

- All components required to start winding tests are scheduled for delivery to ASG by the end of the year.
- In 2025, ASG is expected to produce one dummy copper coil and one or two Nb_3Sn coils.
- Following the production of 2 coils, magnet assembly at LASA is anticipated to begin in 2026.

SS end spacers


Winding machine



Furnace for coil heat treatments

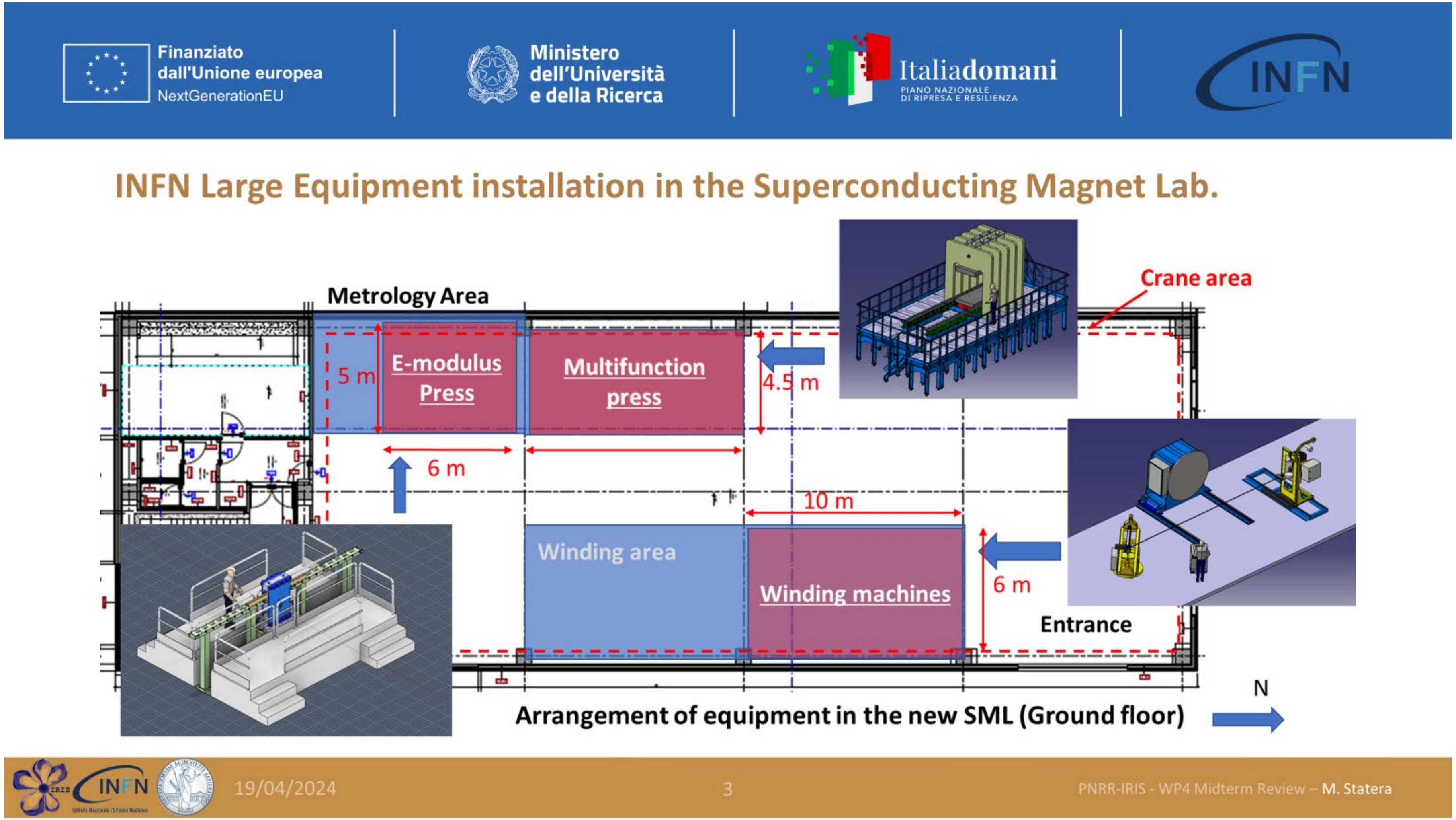
Toward the 14 T Nb_3Sn program

- Lucio Rossi on behalf of INFN collaboration is discussing with CERN and is close to finalizing a 6-year proposal within the HFM R&D Program framework.
- A primary goal is to construct a 14 T demonstrator in a cos-theta configuration.
- Key innovation is that fabrication will occur at the new IRIS program facilities in the LASA lab.

Milestones	Months after agreement start
Electromagnetic design and conductor choice	M6
Technical design report	M12
Coil engineering design report	M18
Winding test completion and tooling assessment	M24
Coil construction readiness review	M30
Magnet engineering design report	M42
Manufacture of RMC	M30
Manufacture of 1 dummy (copper) coil	M36
Manufacture of 1 Nb_3Sn practice coil	M48
Manufacture of 2 Nb_3Sn coils	M54
Magnet assembly	M60
Manufacture of 2 Nb_3Sn coils	M66
RMC test at LASA at 4.5 K	M42
14 T magnet preliminary test at LASA at 4.5 K	M66
14 T magnet final test at CERN with test report	M72

IRIS Infrastructure at LASA

- the new laboratory complements the test facility, which we are upgrading as part of IRIS.



HFM Program RD2: HTS

- **Pros:**
  - **Magnetic properties**: HTS enables access to dipole fields in the 16-20 T range.
  - **Operating temperatures:** operating temperatures can be in the range 10-20 K
- **Cons:**
  - **Unfavorable Aspect Ratio**: ReBCO tapes have a high aspect ratio (very thin but wide), which makes them challenging to stack and wind tightly. This shape complicates the magnet design, requiring special handling and limiting flexibility in coil structures.
  - **Anisotropic Conductivity**: ReBCO tapes exhibit anisotropy in their critical current, meaning their performance varies with the angle of the magnetic field
  - **Mechanical Stress and Strain Sensitivity** : ReBCO tapes are sensitive to stress and strain, which can lead to performance degradation or irreversible damage under the high mechanical loads present in high-field magnets.
  - **Quench Detection and Protection** : Detecting and managing quenches is difficult with ReBCO, as it has a low normal zone propagation velocity, meaning quench development is slow. This requires advanced protection systems to prevent damage.
  - **High Cost and Manufacturing Complexity** : ReBCO tapes are expensive to produce, and the fabrication of high-quality, defect-free tapes in large quantities remains challenging and costly.
  - **Joining and Splicing Techniques**: Reliable joints between ReBCO tapes are difficult to achieve, impacting overall current-carrying capability and increasing electrical resistance, which can lead to heat generation and instability.

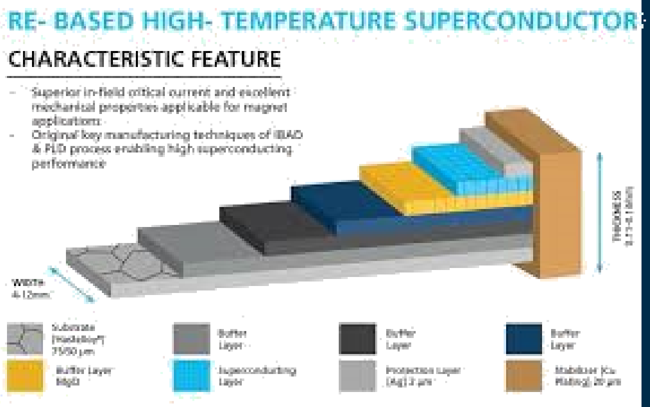
RD2:HTS conductor+magnets

- 2.1 **REBCO development** — B. Holzapfel (KIT)
- 2.2 **REBCO** — A. Ballarino (CERN)
- 2.5 **Demonstrator DI coil** — A. Ballarino (CERN)
- 2.6 **Solenoids and MuC** — L. Bottura (CERN)
- 2.7,2.14 **HTS characterization** — A. Kario (Twente)
- 2.9 **Other Superconductors** — A. Ballarino (CERN)
- 2.11 **Demonstrator MI coil** — T. Lecrevisse (CEA)
- 2.15 **IBS development** — A. Malagoli (CNR-SPIN)
- 2.16 **HTS laboratory** — A. Ballarino (CERN)
- 2.17 **REBCO development** — Y. Yang (SOTON)
- 2.18 **HTS 10 T dipole** — L. Rossi (INFN)
- 2.19 **REBCO racetrack** — D. M. Araujo (PSI)

Nb_3Sn Rutherford cable

https://h2020-tarantula.eu/

ReBCO tape

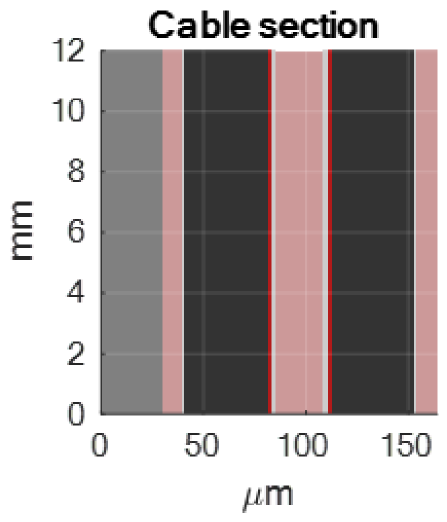


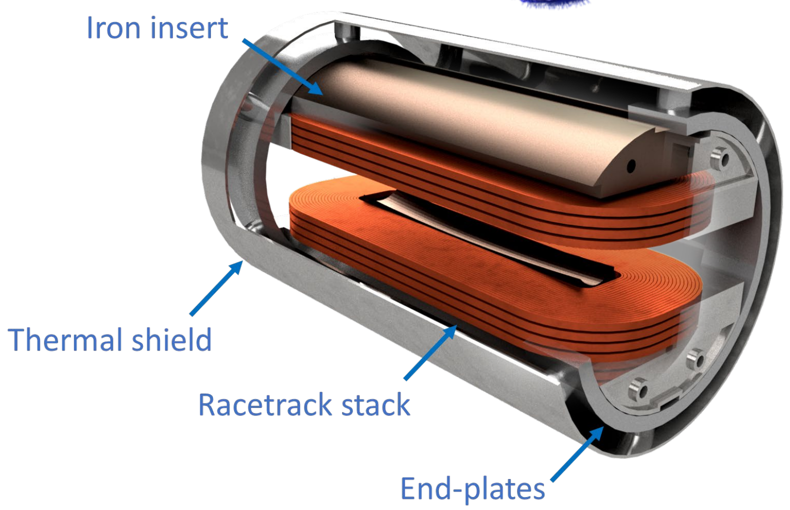
https://www.fujikura.co.uk/

INFN ongoing HTS program

- Within the IRIS framework, INFN is actively involved in several ongoing projects related to HTS.
- WP9 IRIS ESMA dipole: a 10 T HTS dipole (split coil racetrack design, controlled insulation with metal tape).
- A cold test of the first ESMA pancake is scheduled for early 2025.

Parameter	Unit	Value
Central field	T	10
Free bore dimensions	mm	H80 x V50
Magnet length	mm	1000
Good field region uniformity	N/A	1.5%
Good field region extension	mm	H50xV30xL400
Operating temperature	K	20
Minimum op. temper. for test	K	10
Maximum current	A	<1000





Courtesy S. Sorti and L. Balconi
Univ. of Milano & INFN-Milano-LASA

INFN future HTS programs

- The current proposal within the HFM R&D Program framework under discussion with CERN also includes activities focused on HTS.
- The objectives are:
  - To study and evaluate multiple configurations (three or more) of HTS-based (REBCO-type) dipole magnets designed with characteristics suited for accelerator applications.
  - To design, construct, and test a single-aperture, subscale HTS dipole model targeting a central field of 10 T, operating at temperatures between 10 and 20 K.

Milestones	Months after agreement start
Report on the comparative study of 3 different designs	M12
Technical design report of the subscale model of the selected design	M18
First coil of the subscale model	M24
Readiness review to start assembly of the subscale model	M30
Power test at LASA at 20 K	M42

Conclusions

- Significant progress and contributions by the INFN team in advancing high-field magnet technology for the FCC have been achieved.
- INFN through collaborative efforts with CERN, is pushing boundaries in Nb_3Sn and HTS technologies to meet the challenging requirements of FCC-hh.
- With continued R&D, the success of these advancements will play a pivotal role in realizing the FCC's ambitious objectives, consolidating Italy's position in the forefront of superconducting magnet technology for particle physics.

Thanks for the attention