Etienne Rochepault
on behalf of the magnet group of CEA-Paris
Stefania Farinon
on behalf of applied superconductivity groups of INFN Genova and Milano

High-Field Magnets Program in Italy and France

Joint FCC-France & Italy Workshop
Lyon, November 22nd 2022

DE LA RECHERCHE À L'INDUSTRIE
cea
INFN
Istituto Nazionale di Fisica Nucleare

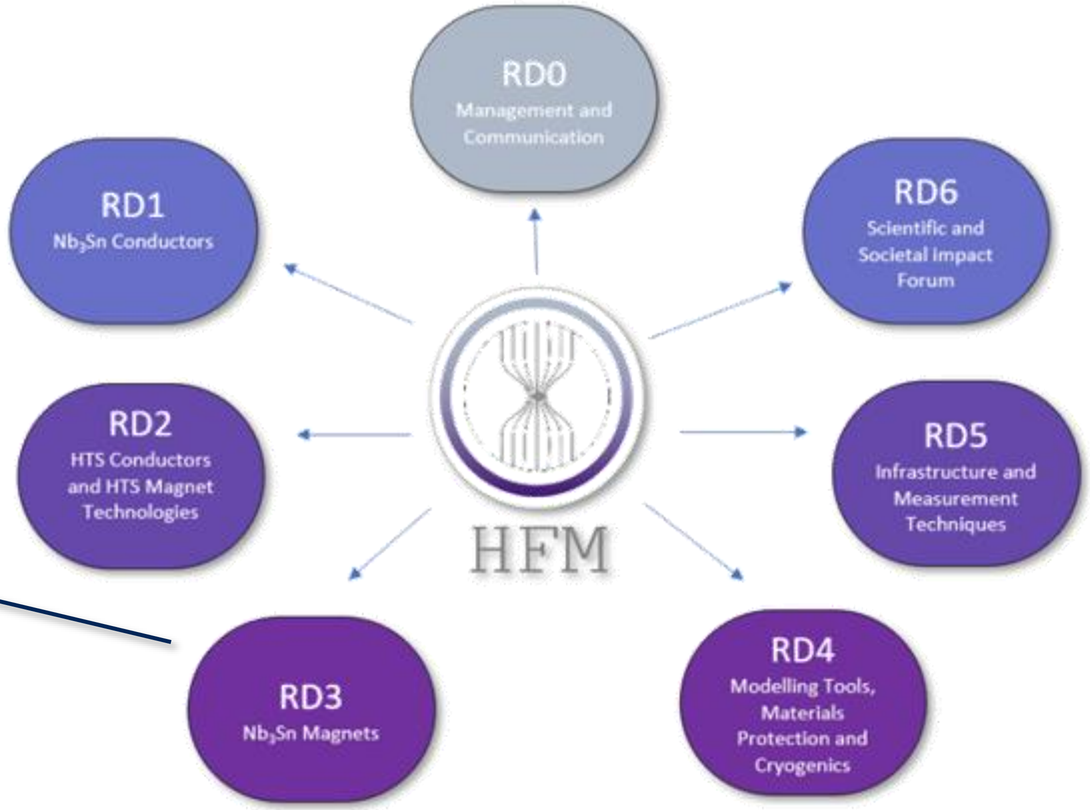
The HFM Program at CERN https://hfm.web.cern.ch/

- INFN and CEA programs are part of the general HFM program at CERN
  - INFN is involved in the development of a robust dipole in the range of 12 T (cos-θ configuration)
  - CEA is involved in exploring the ultimate Nb_3Sn magnet technology towards 16 T dipole (block-coil configuration)

RD3 - Nb3Sn Magnets

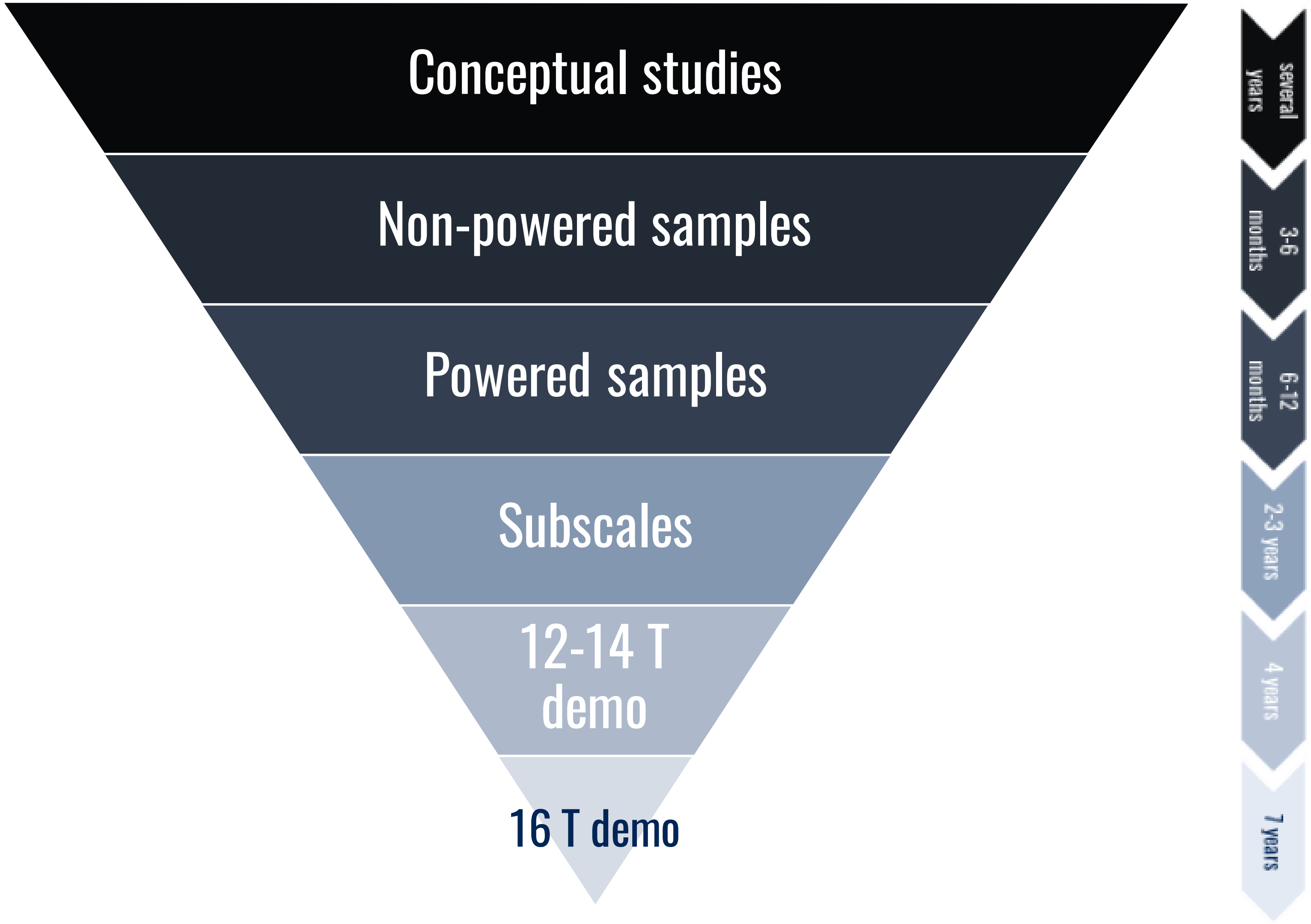
The main goals of the RD3 Line are:

- Robust Nb_3Sn Accelerator Magnet
- Design and demonstrate a long dipole magnet with robust performance in the range of 12T
- Seek cost-effective engineering solutions, suitable for large-scale production
- Ultimate Nb_3Sn Magnet Technology
- Pursue and accelerate the work started in the frame of the FCC Magnet Development Program towards 16T dipole models (through collaborations)
- Explore alternatives and develop design and technology for ultimate performance Nb_3Sn magnets



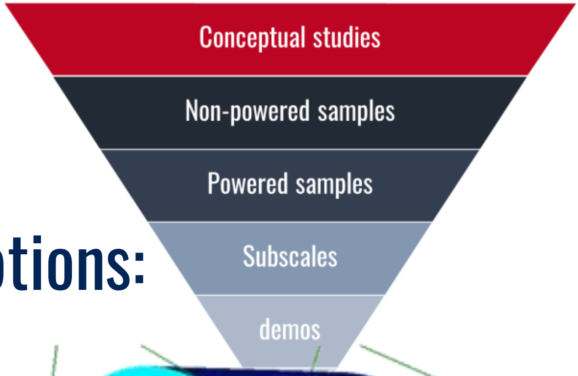
towards 16 T Nb_3Sn magnets

Development Pyramid for Nb_3Sn High Field Magnets



Conceptual studies: EuroCirCol (2014-2019)

- The EuroCirCol project focused on the key design issues that determine the feasibility of a 100 TeV hadron collider in a 100-km-long tunnel
- WP5, devoted to high-field dipoles, involved exploring different design options:



cos-theta

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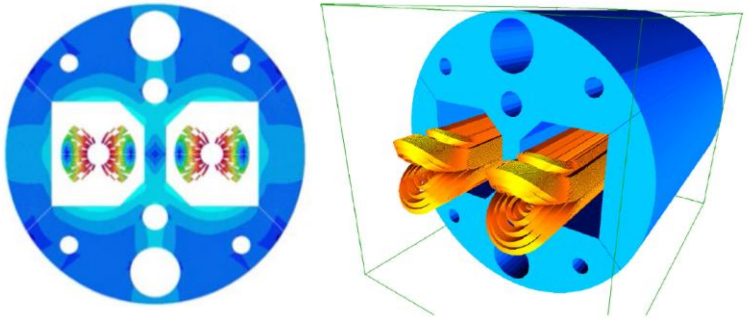
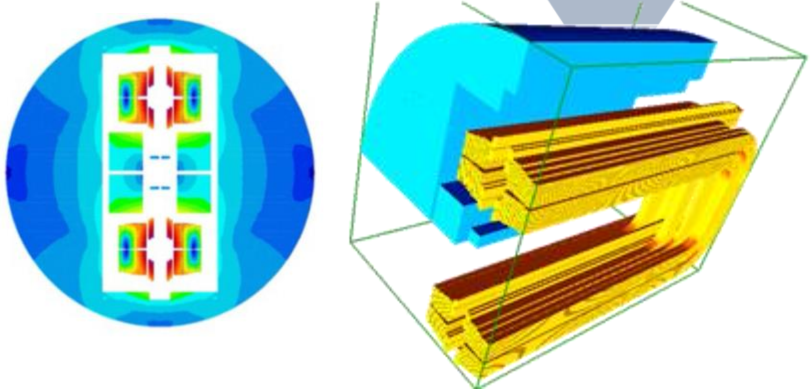
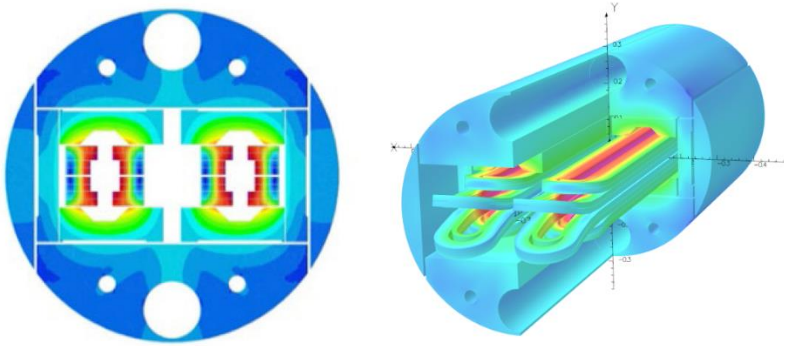


common coil

Laboratorio Nacional de Fusión

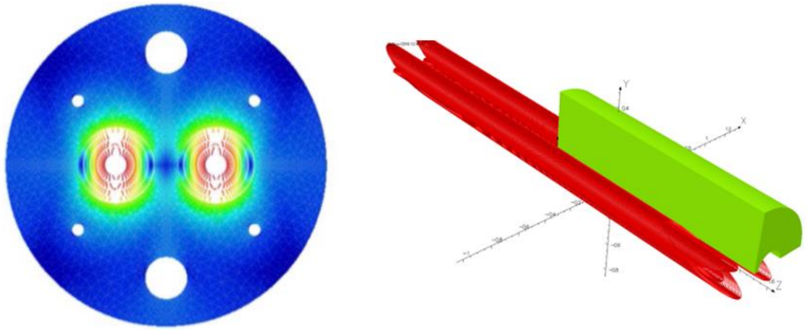


block coil



canted cos-theta

PAUL SCHERRER INSTITUT



Conceptual studies: EuroCir[...]

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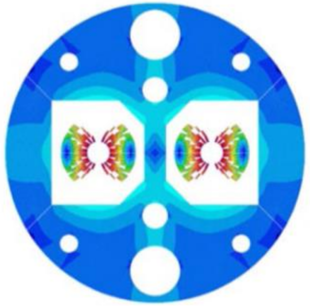
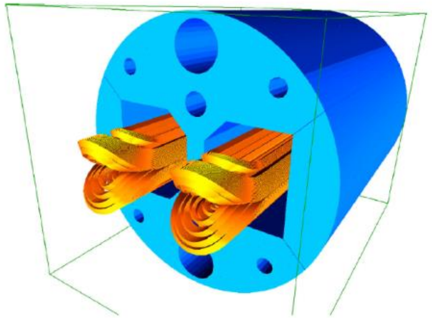
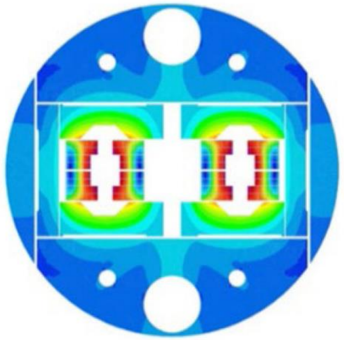
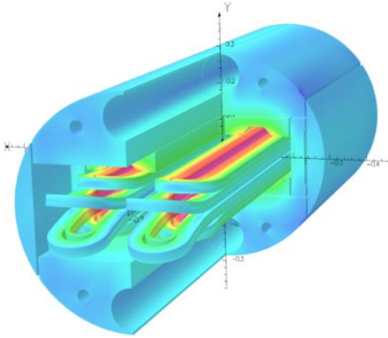
cos-theta

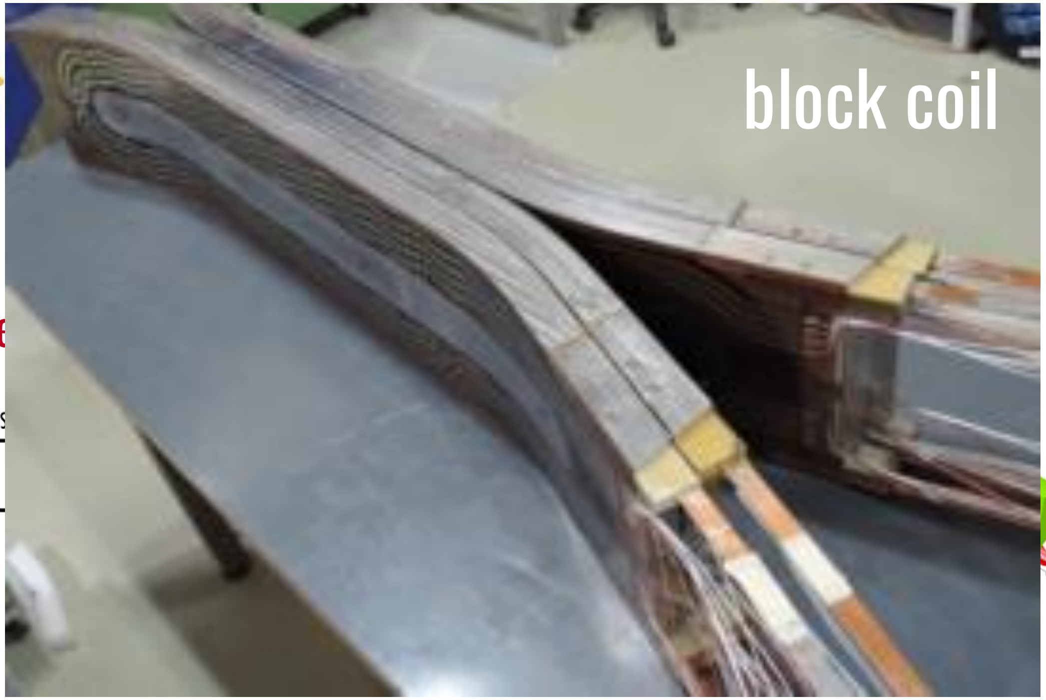
block coil





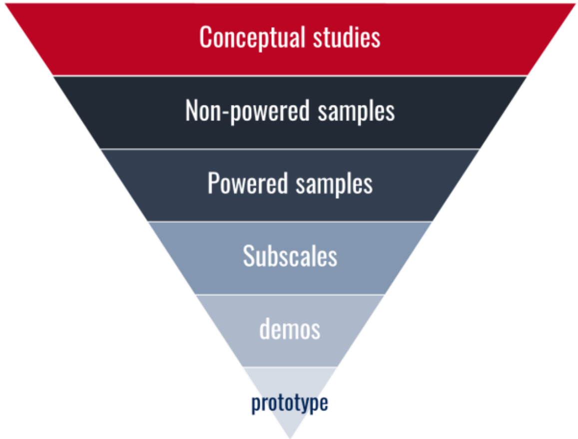






EuroCirCol Conceptual Design Report

- The INFN option was chosen as the baseline for the CDR published in 2019 mainly because accelerator dipoles were usually wound in a cos-theta configuration.
- However, the conclusion was that each configuration could not be selected/abandoned on the basis of design alone.
- The CEA and INFN teams then started working on demonstrators.



Eur. Phys. J. Special Topics 228, 755–1107 (2019)
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https://doi.org/10.1140/epjst/e2019-900087-0

THE EUROPEAN PHYSICAL JOURNAL
SPECIAL TOPICS

Regular Article

FCC-hh: The Hadron Collider

Future Circular Collider Conceptual Design Report Volume 3

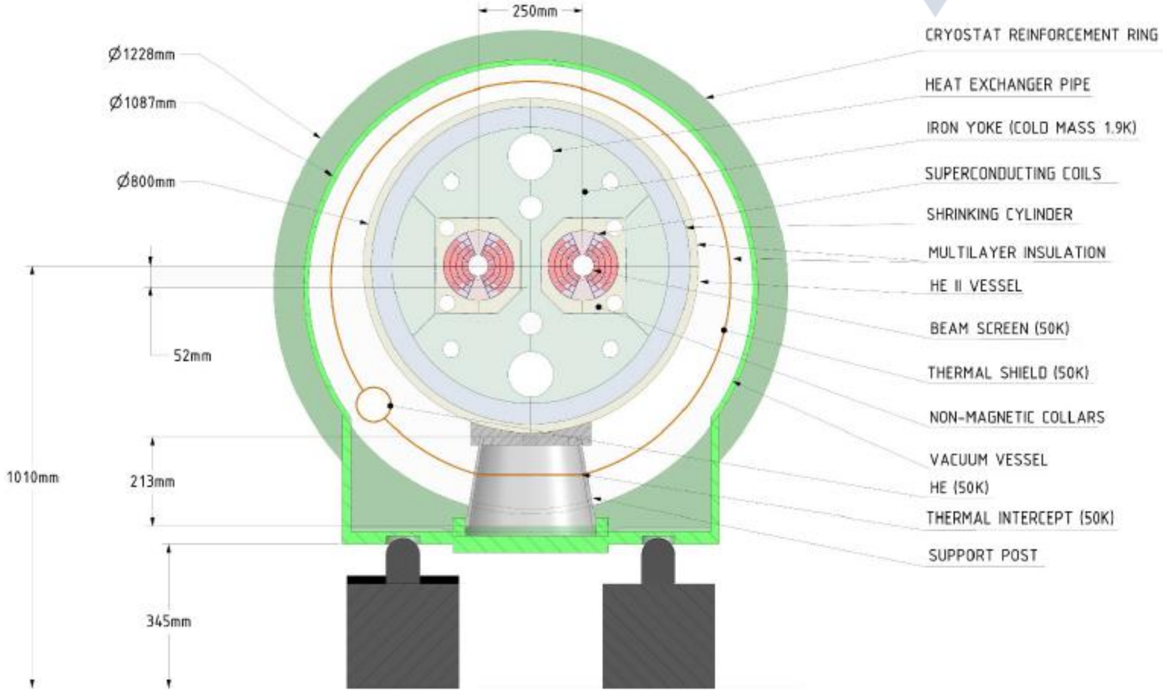
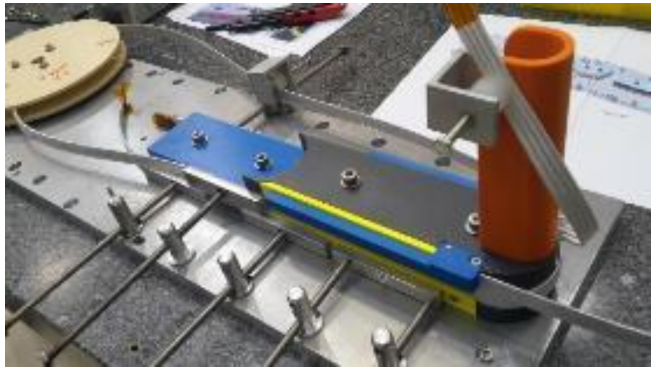
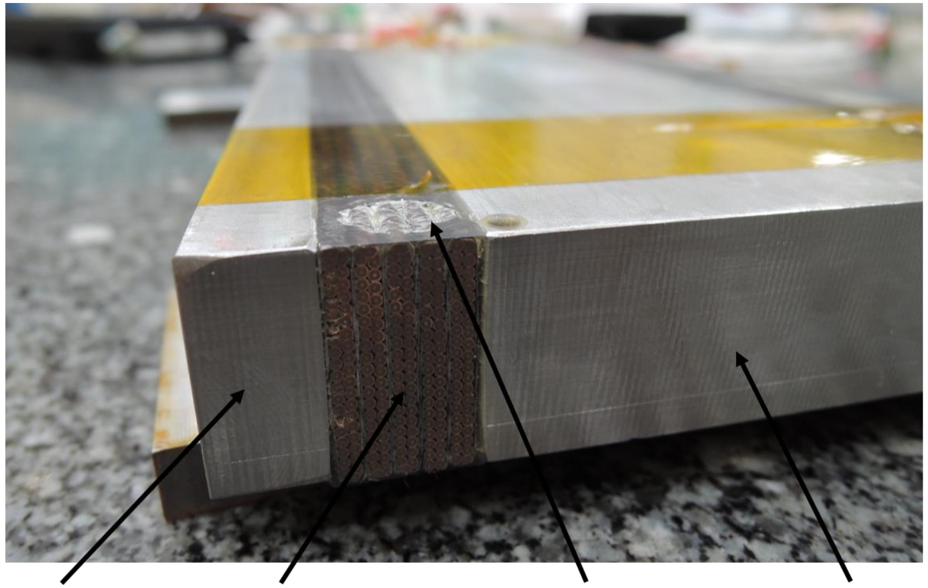


Fig. 3.1. Main dipole cross-section.

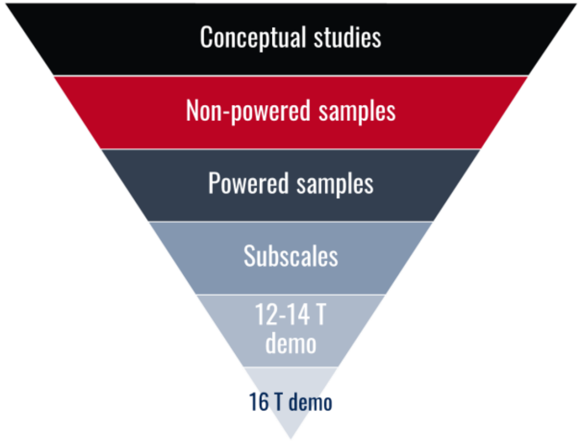
CEA: non-powered samples

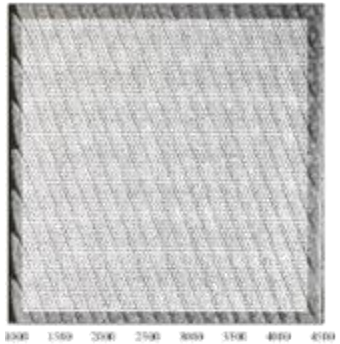


Winding mockups
(test state of the art cables in prototype coils)

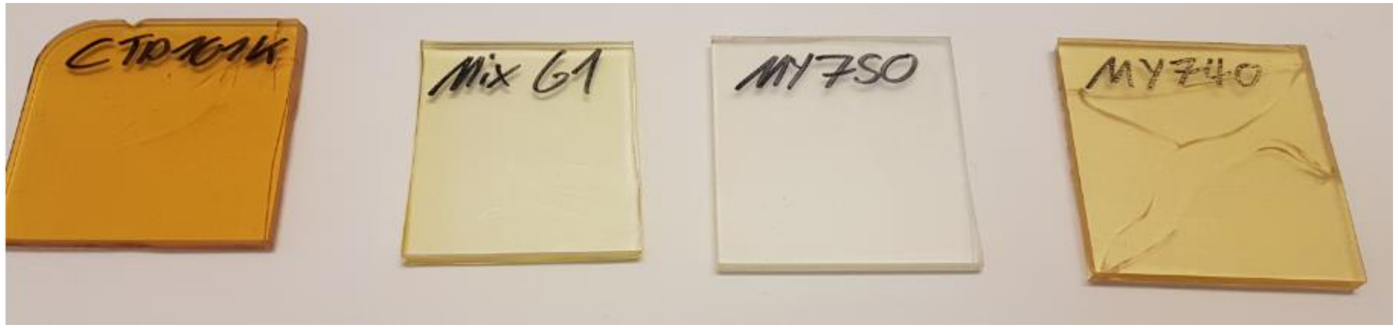


Characterization of dummy coil blocks
(in representative conditions at room-temperature and at cold)





Characterization of cables during the heat treatment at 650°C

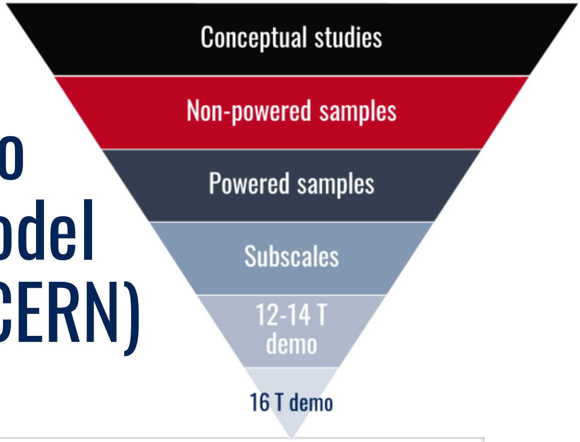


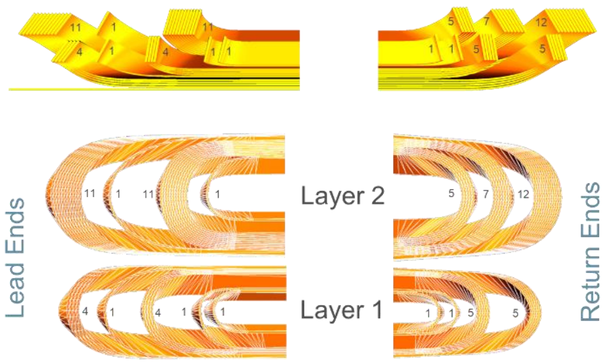
Characterization of resins

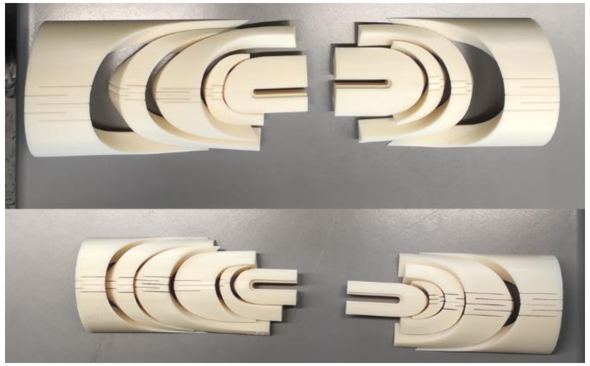
Joints mockups
(test the grading technology before implementing it into coils)

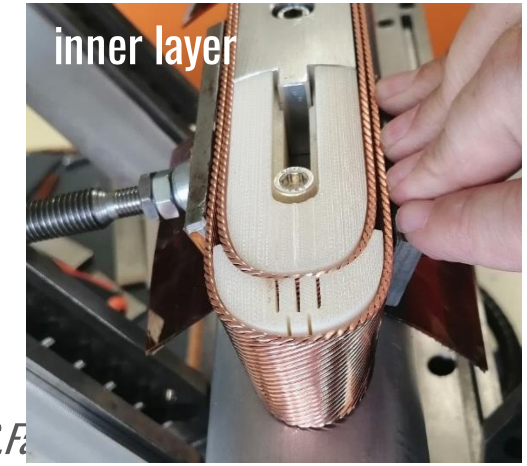
INFN/CERN: non-powered samples

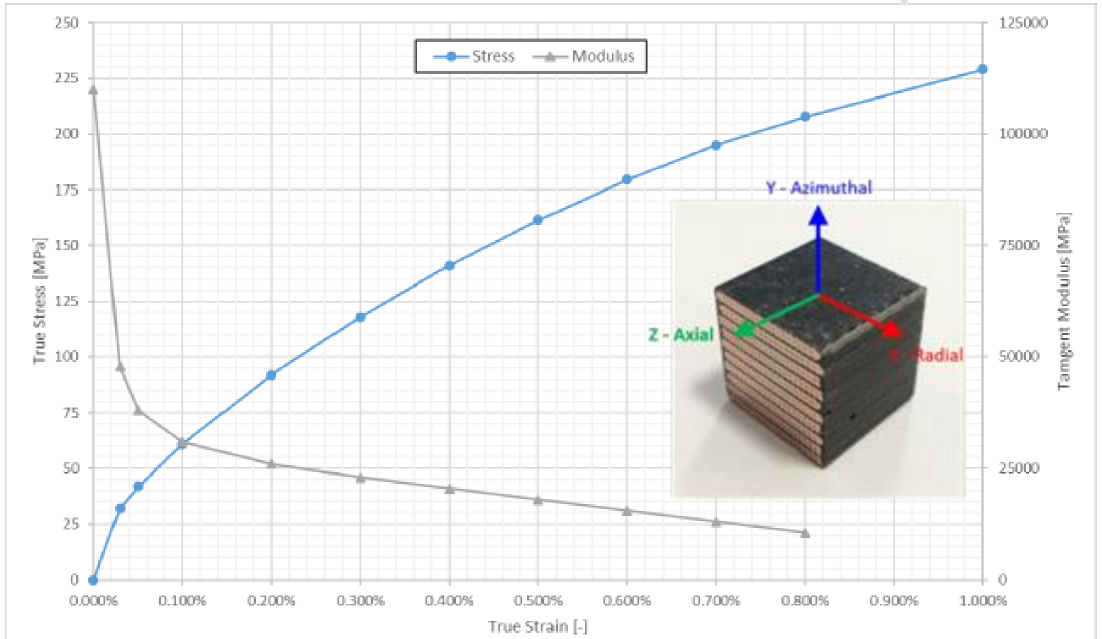
- 3 run of winding trials were performed to:
  - optimize the conductor parameters (CERN)
  - optimize the shape of spacers (INFN)
- Measurements of mechanical properties to overcome the elastic model in numerical analyses (CERN)





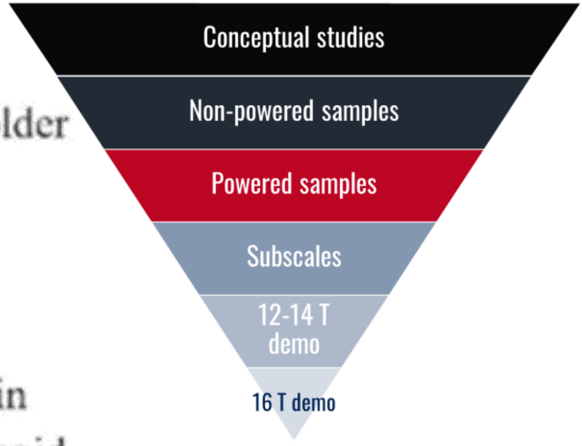




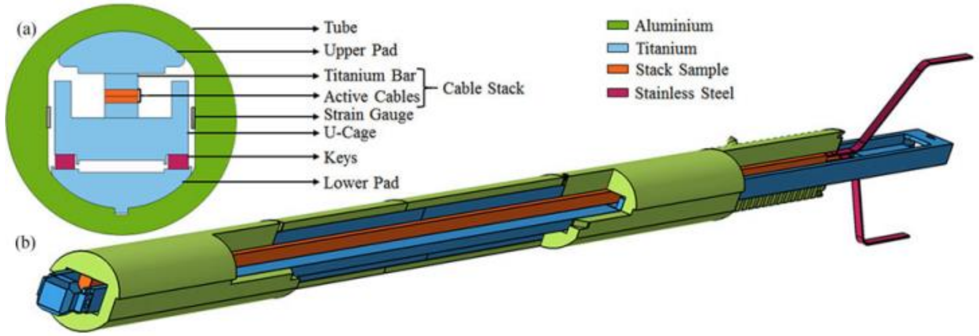


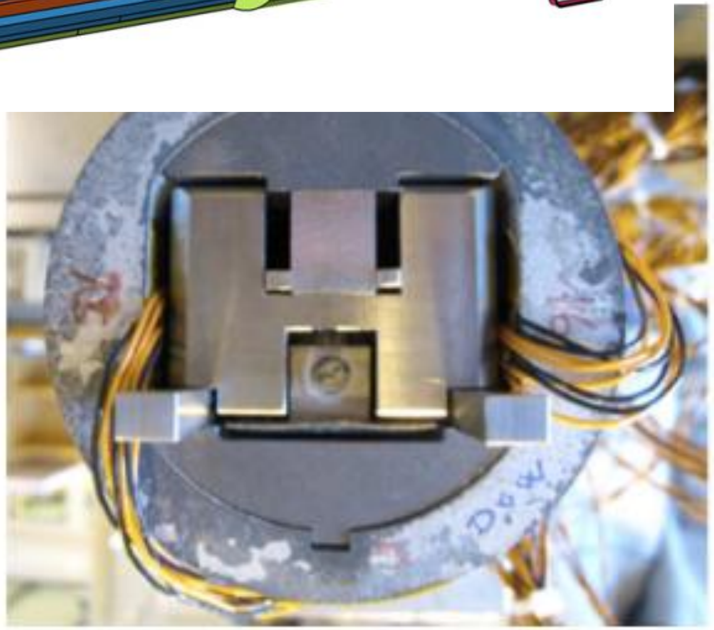
Courtesy CERN

CEA in collaboration with other institutes: powered samples

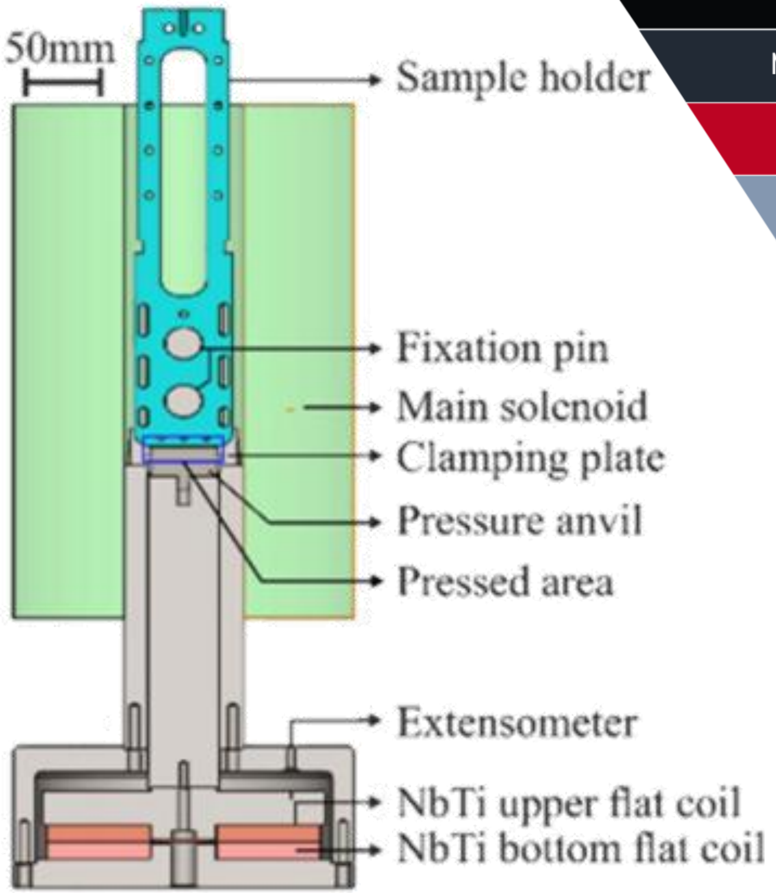


- The goal is to measure the behavior of Nb_3Sn cables in conditions representative of magnets.





Characterization of cables at high field/high current/high stress
Courtesy CERN



Characterization of cables when debonding at high field/high current
Courtesy University Twente

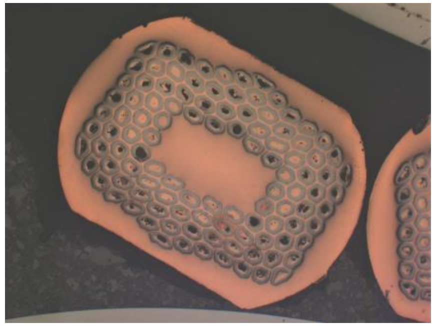
INFN: powered samples

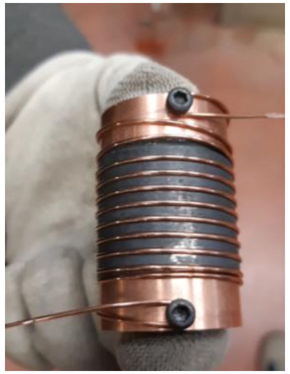
- INFN activity dedicated to Nb_3Sn powered samples:

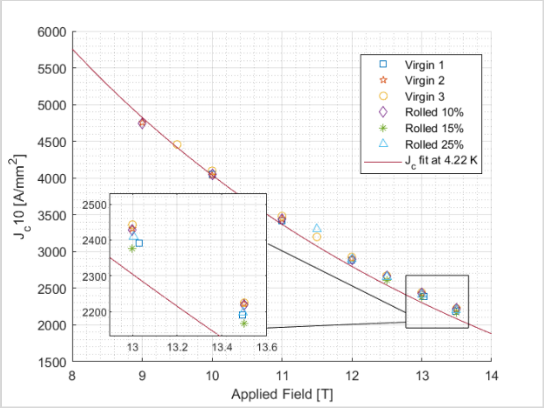
ASTRACT Analysis of STrain Affected CharacTeristics of brittle sc cables

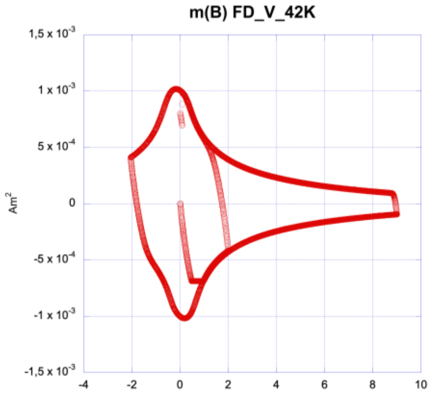
Conceptual studies
Non-powered samples
Powered samples
Subscales
12-14 T demo
16 T demo

- critical current and magnetization mesurements of virgin and rolled Nb_3Sn strands

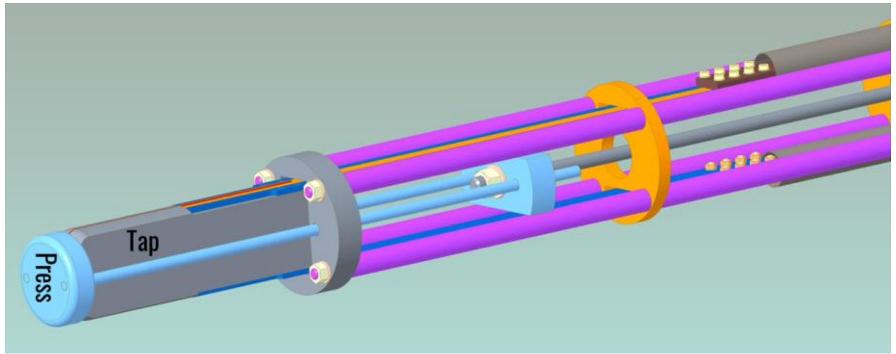






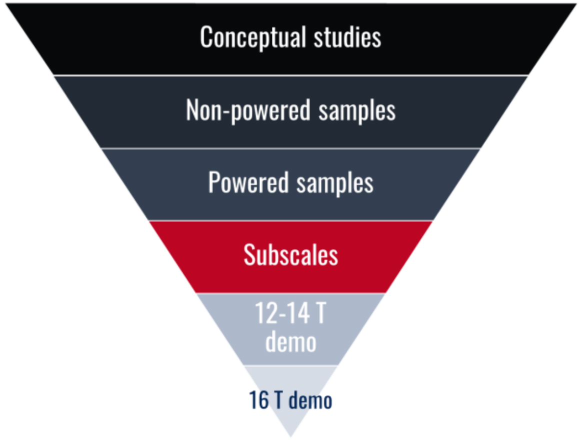


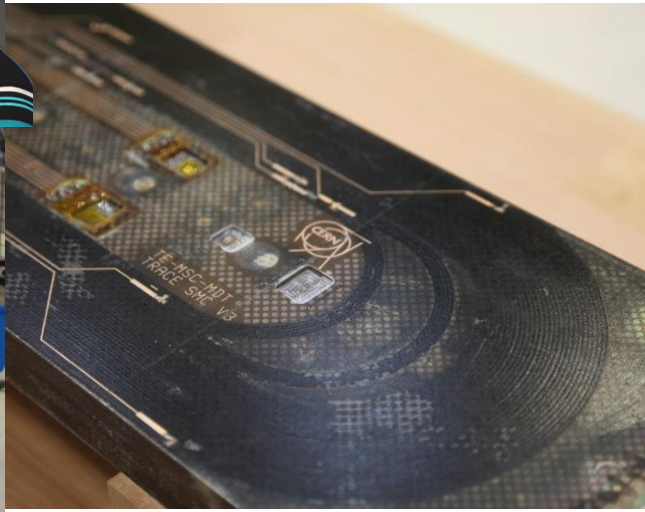
- development of a sample holder to perform measurements under transverse strain at 4.2 K
  - The wire is fixed on the tap
  - By pulling up the press, the wire deforms along the transverse direction.
  - Capacitive displacement sensors (CDS) measure the distance between the press and the tap, which is related to the transverse deformation.
  - Production of the components is underway at the Galli & Morelli (LU) workshop.
  - The electric motor, actuator, CDS and current conductors have been purchased.



CEA: subscale - SMC-11T-CEA

- 1st Nb_3Sn coil entirely manufactured at CEA Paris-Saclay since 10 years!

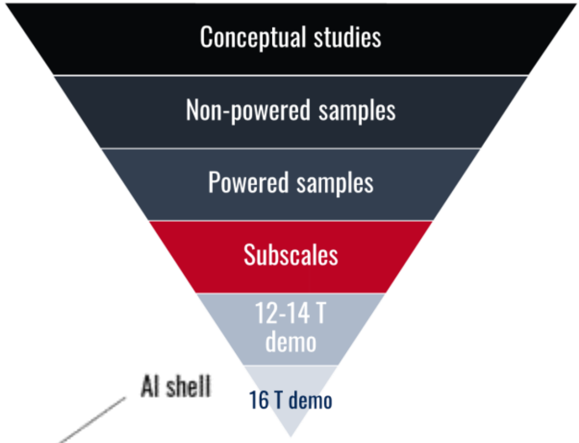


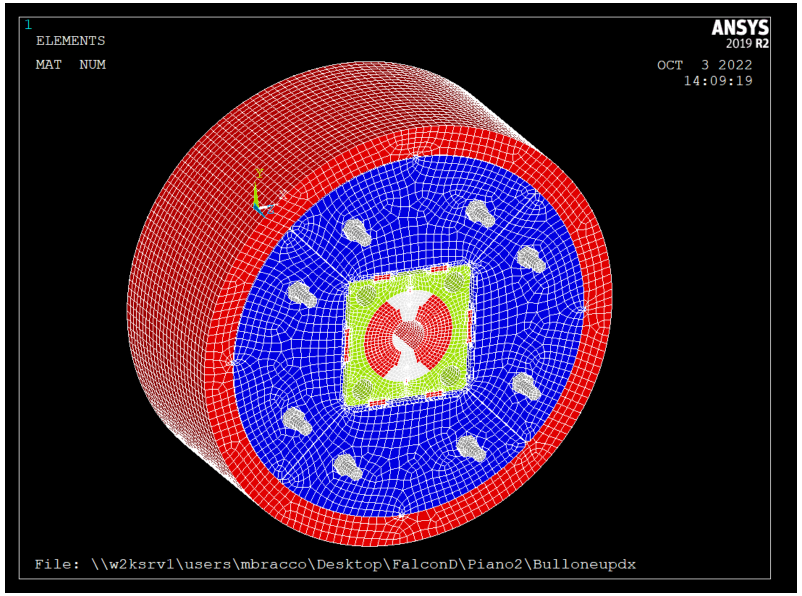


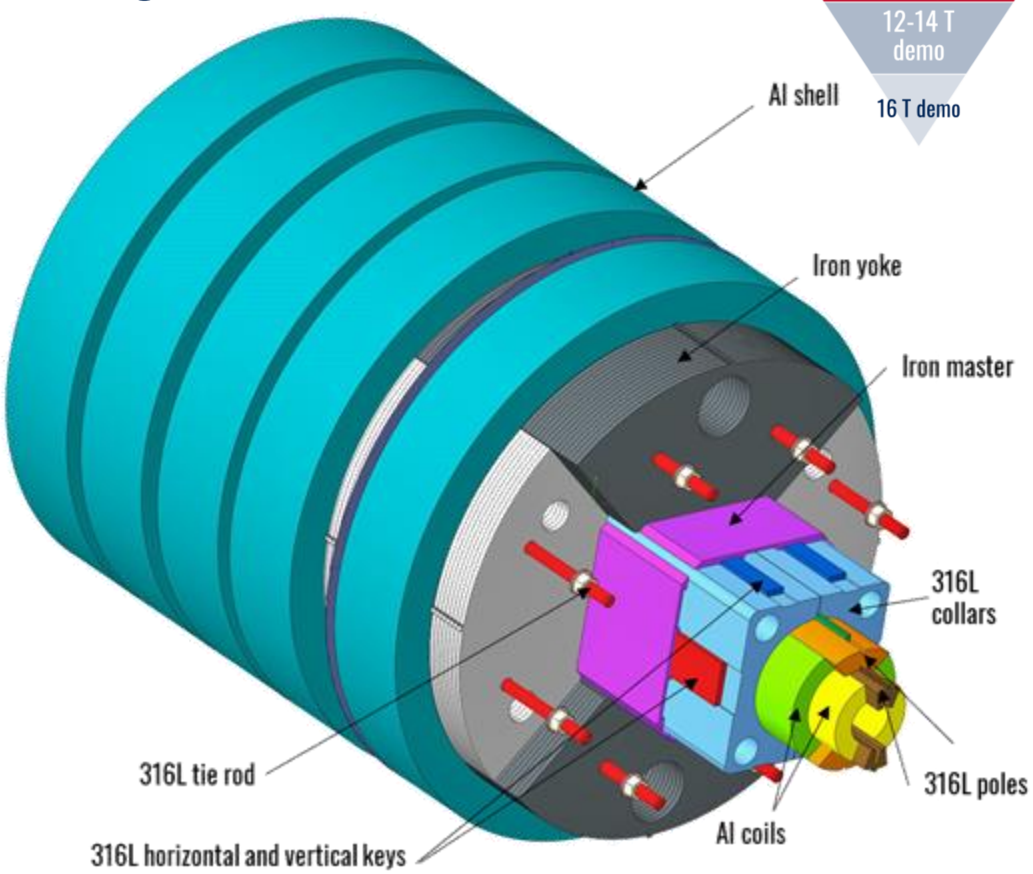
- In order to train and develop the required infrastructure, CEA has built a Short Model Coil, namely SMC, with the help of CERN.
- CERN has sent the parts and procedures, and CEA has built the coil entirely at Saclay.
- The coil has then been tested at CERN with success, demonstrating that CEA is now mastering the state-of-the-art technology.

INFN – non powered subscale

- INFN is developing a 1:1 scale section, 500 mm long, of the real model to gain expertise on mechanical aspects and related issues:
  - Dummy aluminum coil instead of Nb_3Sn cable
  - Bladder&key process verification during assembly and cooling to 77 K
  - Instrumentation with resistive strain gauges (SG)
  - Tolerance measurement on individual components

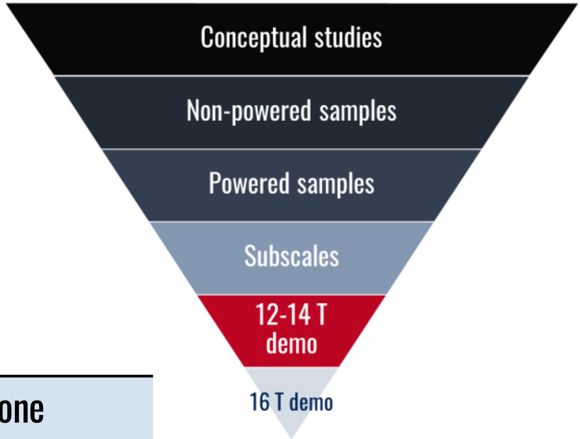




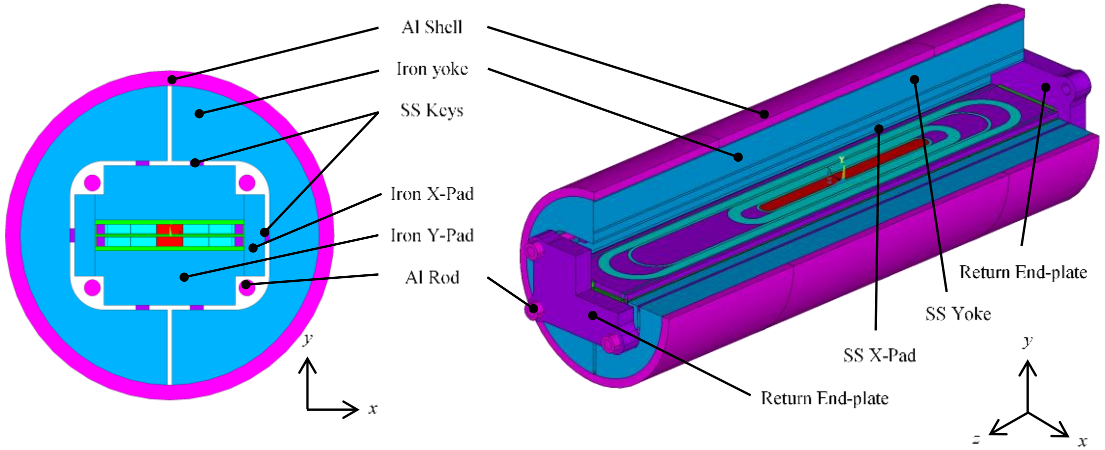


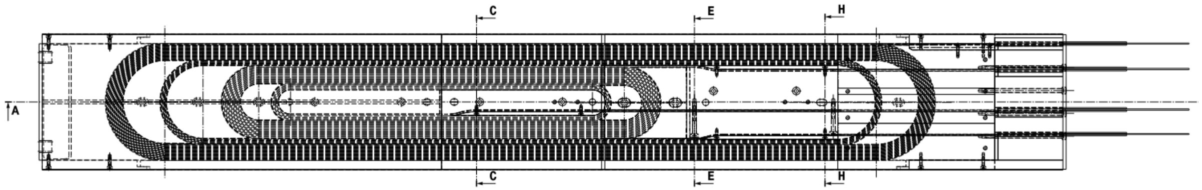
CEA: 12 T demo R2D2

- CEA is developing R2D2, the « Research Racetrack Dipole Demonstrator ».
- The goal is to prove the « grading » technology in block-coils, which is the use of 2 different conductors in the same coil, in order to be more compact and use less conductor.
- The technological concepts have been 1st validated using mockups, as presented before.
- The design has been made at CEA and the coil components have been manufactured and should be delivered soon.
- Then the fabrication of the coil will start early next year.
  The magnet will be fully assembled at CEA and tested at CERN.



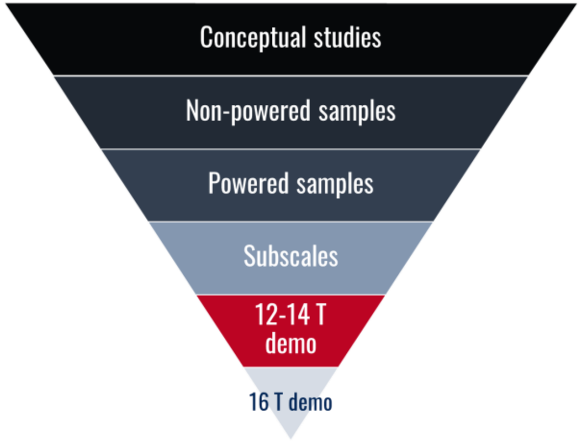
Aperture	None
Outer diameter	480 mm
Structure length	2.0 m
Nominal central field	11.1 T
Ultimate central field	12.0 T
Nominal peak field	12.7 T
Ultimate peak field	13.7 T

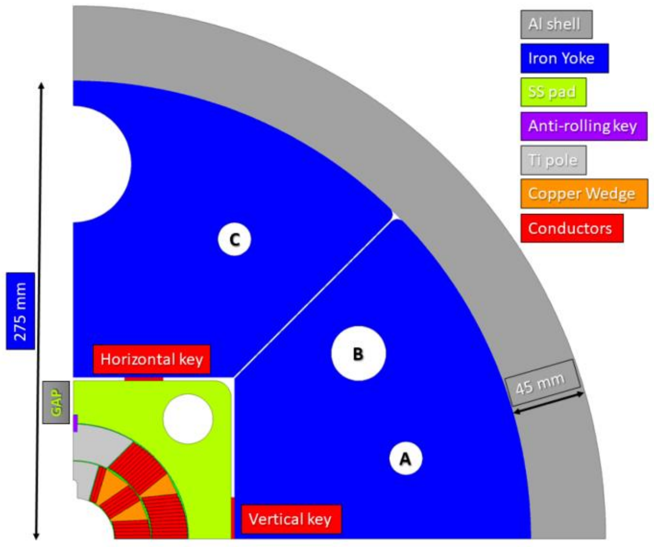




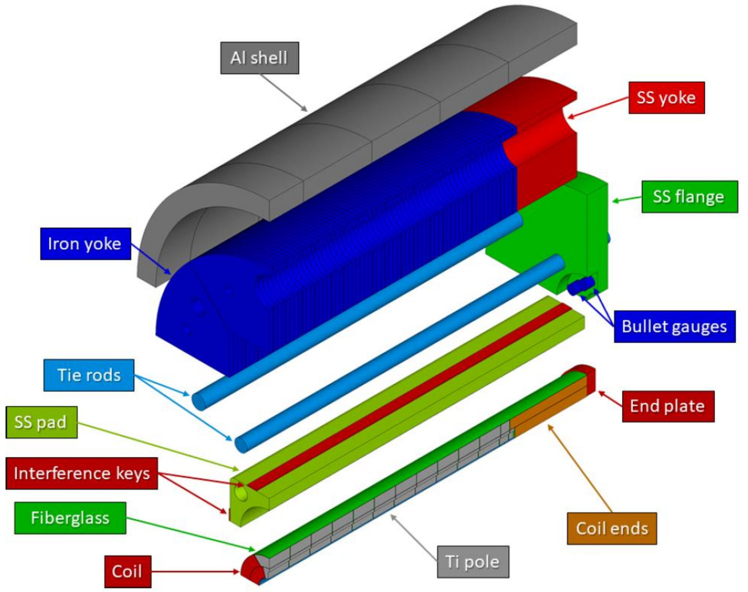
INFN: 12 T demo FalconD

- For the 12 T demonstrator, INFN's choice was to go directly to industry.
- After an international tender, the fabrication of the coils was awarded to ASG Superconductors (Genova, Italy).
- The assembly with the bladder&key technique will be performed at the INFN LASA laboratory in Milan.
- Magnet completed and tested by the end of 2025.



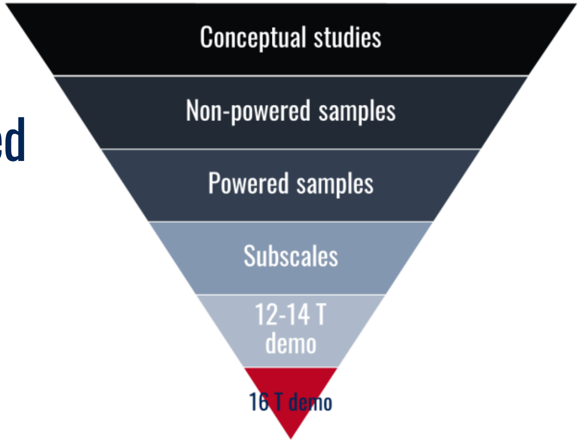


Aperture	50 mm
Outer diameter	650 mm
Structure length	1.5 m
Nominal central field	12 T
Nominal peak field	12.5 T
Margin on the loadline	23.6%
Ultimate central field	13.5 T

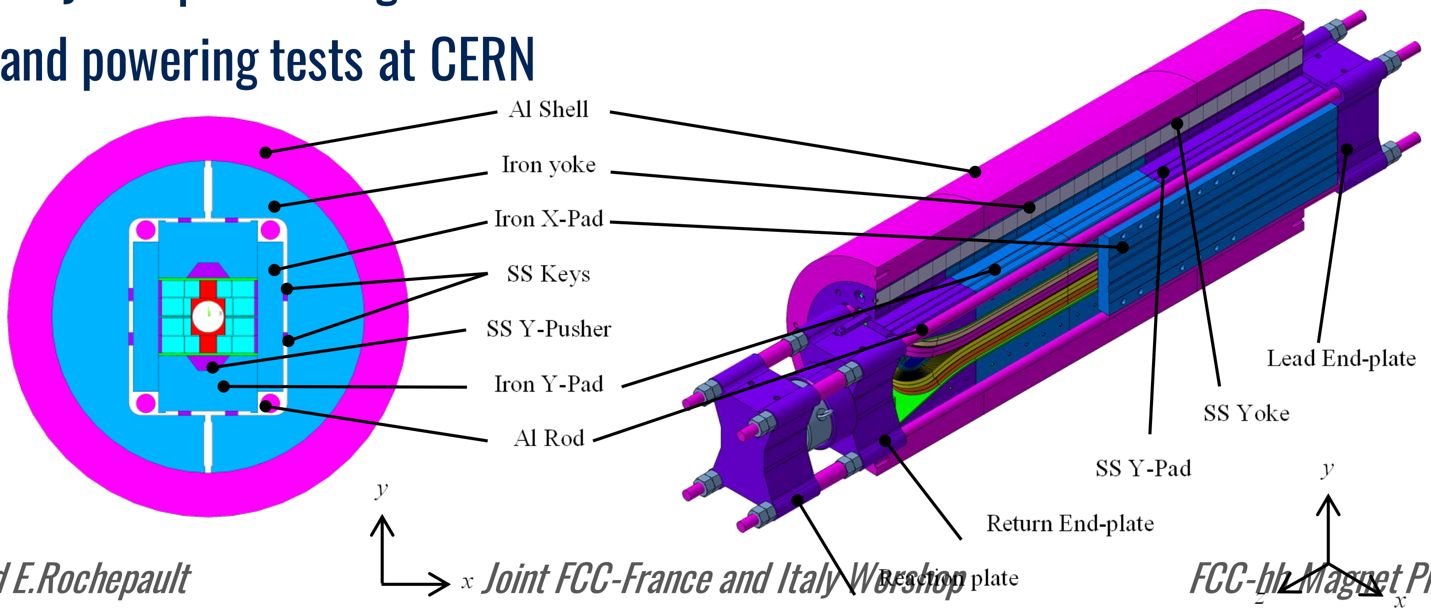


CEA: 16T F2D2

- F2D2, « Future Flared-ends Dipole Demonstrator », is the CEA development plan towards 16 T
- The conceptual design, done by CEA, involves the « grading » technology that is being developed in the R2D2 program.
- The design will use the same cables as for R2D2 to minimize the cable development.
- Waiting for proof-of-concept R2D2 and technology development
- Fabrication planned 2026-2027 at CEA
- Assembly and pre-loading in the structure at CEA
- Cold and powering tests at CERN



Aperture	50 mm
Outer diameter	650 mm
Structure length	2.0 m
Nominal central field	15.5 T
Short sample central field	17.8 T
Nominal peak field	16.2 T
Ultimate peak field	18.6 T



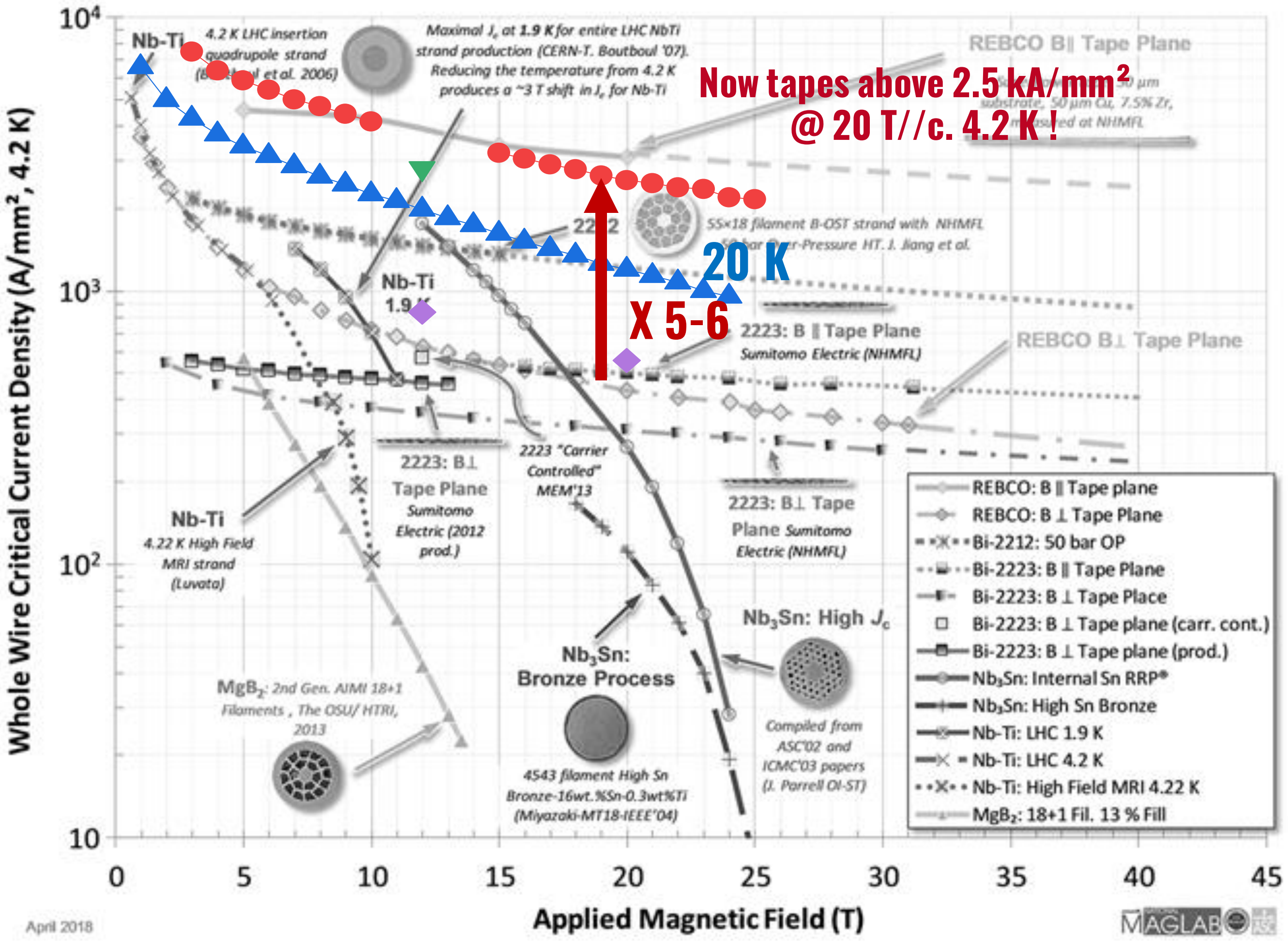
towards 16+ T HTS magnets

REBCO Conductor performance update

- SuperOx 4.2 K B//c [1]
- SuperOx 20 K B//c [1]
- SuperPower 4.2 K B//c [2]
- SuperPower 4.2 K CORC [2]

[1] Molodyk. A. et al 2021 Scientific Reports vol. 11. 2084

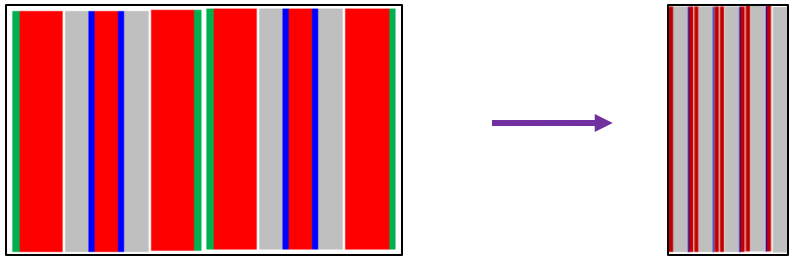
[2] J D Weiss *et al* 2020 *Supercond. Sci. Technol.* **33** 044001



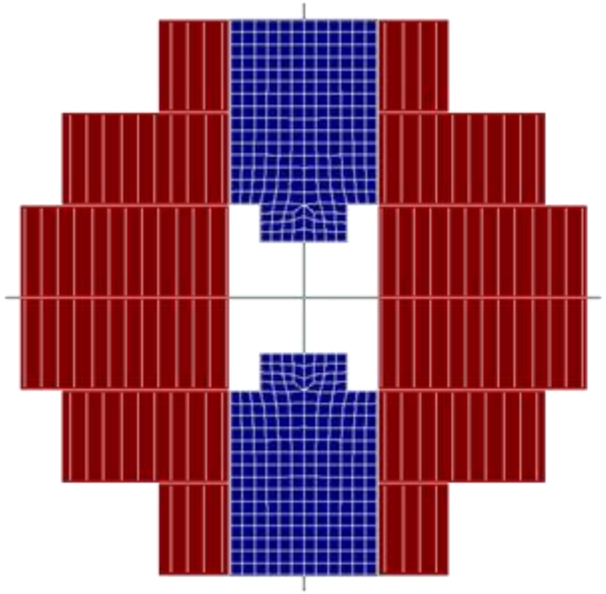
https://nationalmaglab.org/images/magnet_development/asc/plots/Je_vs_B-041118_1024x743_PAL.png

CEA: development proposal toward 20 T

- Use Metal-Insulated (MI) tapes:
  - No need for insulation and Cu stabilization
  - **Increase considerably the current density** in the coil to reach very high fields using very compact coils
- Design concepts:
  - **20 T @ 4.2K**
  - Or **16 T @ 20 K** → opportunity to lower exploitation cost or simplify the cryogenics
- Test the concept in short racetrack coil models:
  - **Lower risks/cost**
  - **shorter time** developments
  - Possibility to change the central coil to add aperture
- First phase (2023-2024): development, fabrication, and test of a mockup



Insulated : **J_e = 250 A/mm²** MI : **J_e = 850 A/mm²**



Example of a cross-section of the magnet mockup

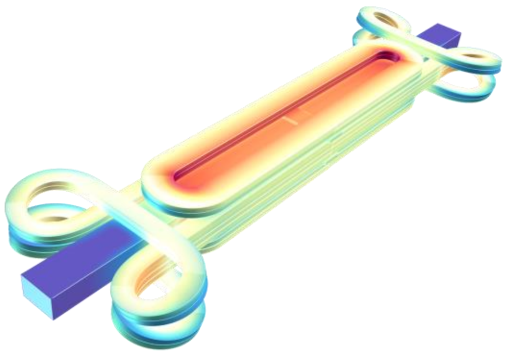
Courtesy of T. Lecrevisse, CEA

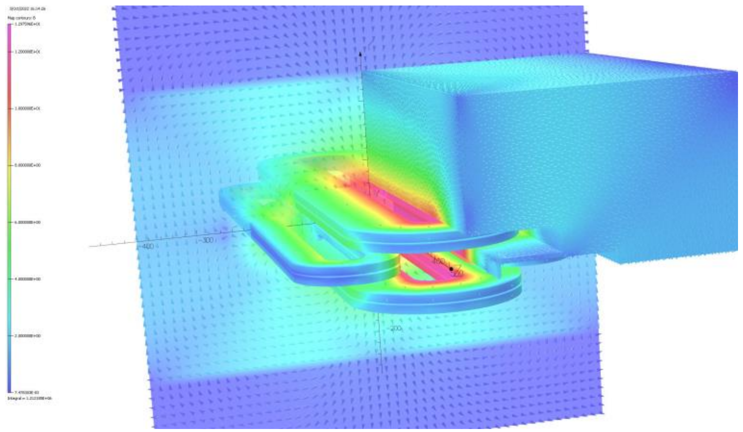
INFN: development proposal

- there are 2 running programs

PNRR_IRIS

development of a HTS (REBCO) dipole, 8-10 T , 10-20 K cryogen-free, 50mm x 80 mm free bore, Controlled Insulation technology, to be installed in the user facility for Genova pole of IRIS





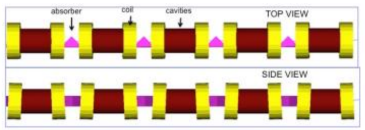
MU_COL

International MUON Collider Collaboration

- design study of high-field (20 T) and large aperture (150 mm) target solenoid with heavy shielding to withstand heat (100 kW/m) and radiation loads
- design study of ultra-high-field solenoids (40-60 T) to achieve desired muon beam cooling
- development of a Solenoid Coil Demonstrator (SCD), a representative test configuration (20 T, 50 mm, 500 MPa) to support the conceptual design with a strong experimental basis.

Solenoid zoo for Muon Collider

- Target solenoid
  1.5 m 20 T 2MW
- Muon cooling
  1km 2 T to14 T
- Final cooling
  8.5 m – 40 T or 60 T



Conclusions

- Italy (INFN) and France (CEA) are involved with CERN in a global strategy towards 16T Nb_3Sn Magnets:
  - INFN: robust concepts using a partnership with industry
  - CEA: technology developments in the lab
- « Development Pyramid » used within the HFM program
  - Non-powered samples → material and technology
  - Powered samples → fast turnover representative tests
  - Subscale models → proof-of-concepts
  - 12 T demonstrators → implementation of technology
  - 16 T demonstrator → ultimate goal
- CEA/CERN strategy for 20 T HTS Magnets:
  - MI (Metal-Insulated) HTS tapes for very high current densities
  - Relying on fast turn-over / reduced-risk subscales
- INFN strategy for HTS Magnets
  - PNNR_IRIS: development of a HTS (REBCO) dipole in the range 8-10 T
  - MU_COL: development of a 20 T Solenoid Coil Demonstrator

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Merci

DE LA RECHERCHE À L'INDUSTRIE

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Grazie

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