HITRI plus
Heavy Ion Therapy Research Integration

Advancements in Superconducting Magnet Design for Carbon Ion Therapy

HITRIplus WP8 – Superconducting Magnet Design

ERNESTO DE MATTEIS (WP8 COORDINATOR)

4TH PROJECT MEETING AND HADRONTHERAPY WORKSHOP - FROM INNOVATION TO IMPLEMENTATION

25 MARCH 2025, PODGORICA, MONTENEGRO

ON BEHALF OF MY WP8 HITRIPLUS COLLEAGUES

INFN LASA

Innovative Research Infrastructure on applied Superconductivity IRIS

Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

Finanziato dall'Unione europea NextGenerationEU

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101008548

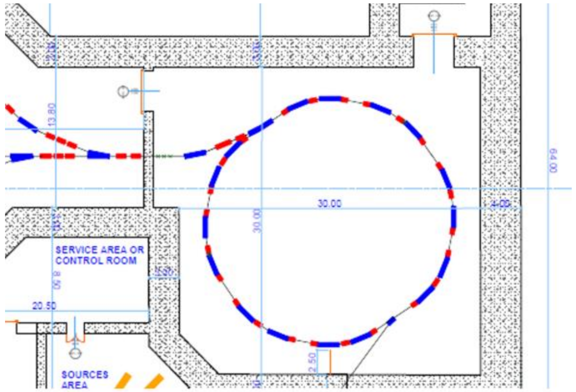
Superconductivity can reduce the footprint of medical facilities

HIT - Heidelberg Ion Beam Therapy Center

25 m long
13 m diameter
600 tons rotation
670 tons total

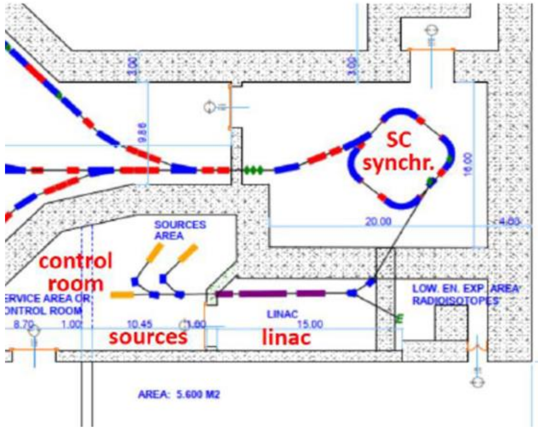
Accelerator hall → standard resistive magnet synchrotron vs SC magnets

Resistive dipoles 1.5 T
Curvature radius of about 4.5 m

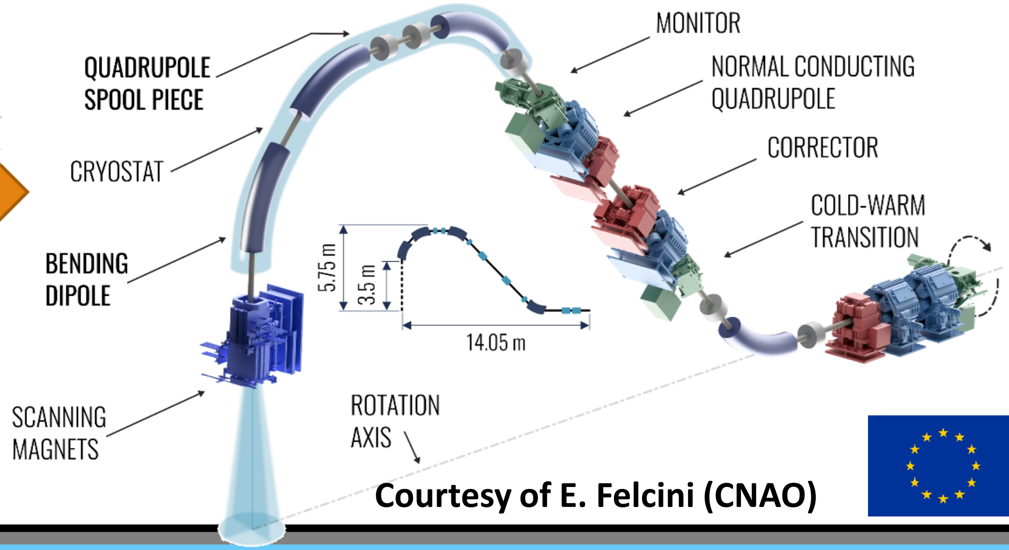


Courtesy of E. Benedetto (TERA, SEEIST study)

Four 90 degree dipoles at 3.5 T
Curvature radius of about 2 m



Heavy Ion Therapy Rotating Gantry



Courtesy of E. Felcini (CNAO)

Footprint and cost reduction;

Reduce the power consumption;

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Superconducting magnet technology: EU initiatives

Application of the Superconducting magnet technology for size and cost reduction (energy saving)

EU initiatives started by CERN in 2018-2020:
1) Concept of GaToroid (CERN);
2) Concept of compact rotatable gantry SIGRUM(TERA, CERN);

End 2020: review to decide between GaToroid and Sigrum rotatable gantry→ decision to explore more in detail rotatable gantry and continue the study on the Gatoroid;

2021: setting up of the HITRIplus and IFAST projects with WPs for accelerator and gantry based on superconducting magnets (CCT dipoles);

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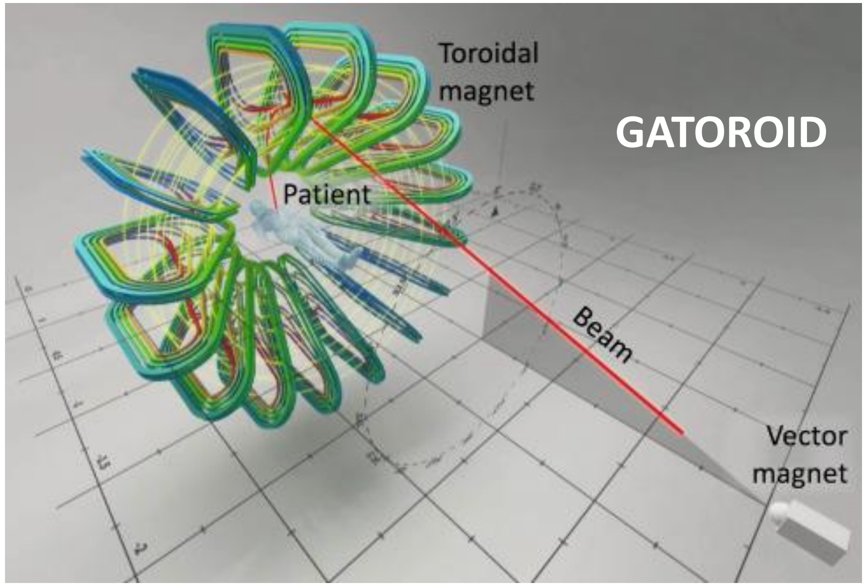
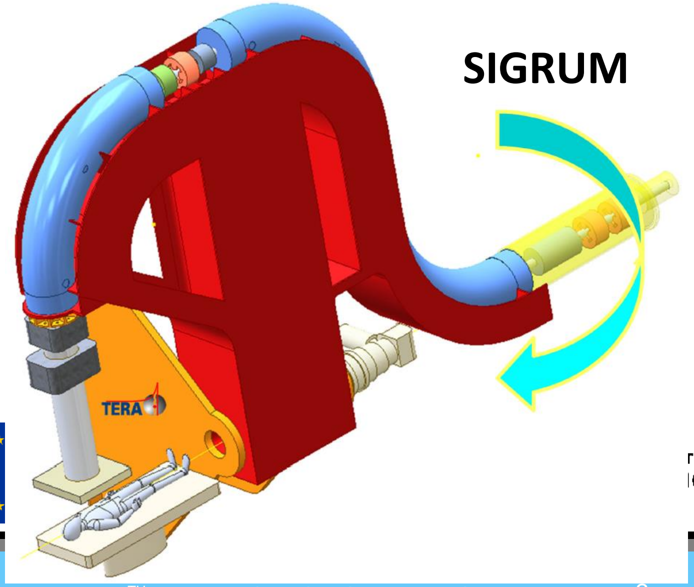
2022: setting up of INFN call SIG, then EUROSIG, focused on the study of a rotatable superconducting gantry based on Curved CosTheta magnet.

HITRIplus – Heavy Ion Therapy Research Integration   Superconducting Ion Gantry   EuroSIG – European Superconducting Ion Gantry





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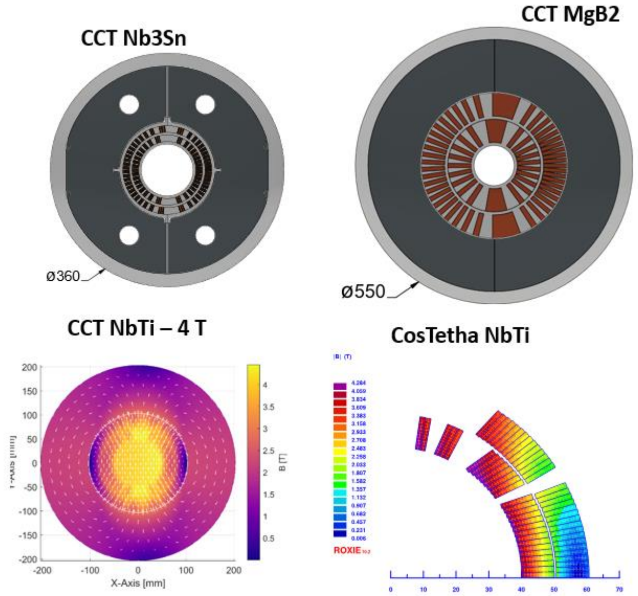
HITRIplus WP8 – Superconducting magnet design

First technical and financial assessment of various magnet designs: Canted cosine theta and Cosine theta layouts with several superconductors (NbTi, Nb3Sn and HTS);

Preliminary engineering design for the new concept of accelerator magnets and innovative gantry magnet;

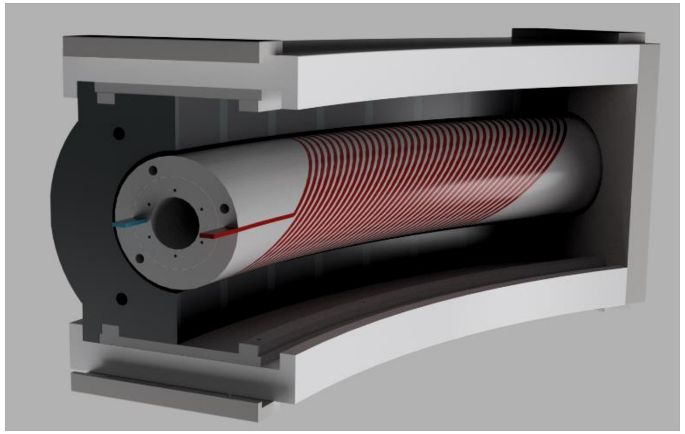
Construction and test of a small demonstrator for feedback useful for accelerator as well as gantry final magnet design.

Comparison of various magnet designs



The decision[1] to explore a **curved Canted Cosine Theta layout magnet based on NbTi** (Low losses strand) and conductor (rope 6+1 strands):

Final magnet design



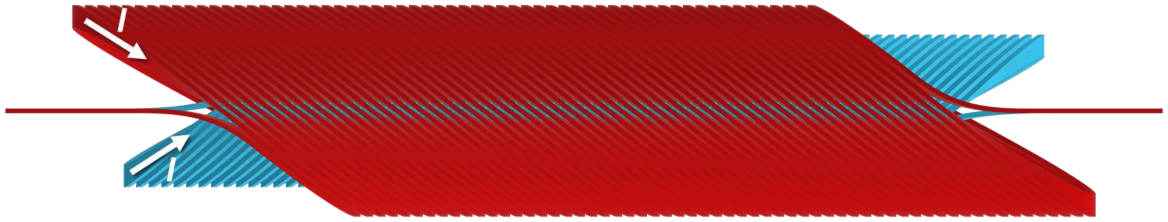
[1]E. De Matteis, S. Mariotto, T. Lecrevisse, M. Prioli, S. Sorti, M. Statera, L. Rossi, **"Magnet Assessment for SC accelerator and gantry",** HITRIplus WP8 - Deliverable 8.1, Zenodo. https://doi.org/10.5281/zenodo.7875298

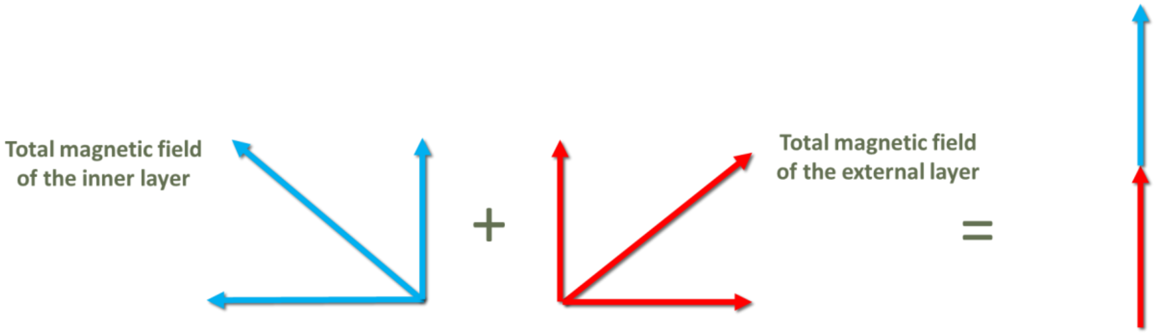
Canted-Cosine-Theta (CCT) Magnet

The CCT design is based on pairs of canted conductor layers:

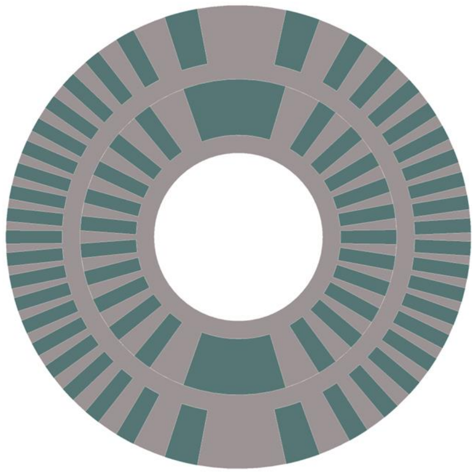
G. Ceruti – CERN (ex INFN-Milano-LASA)

Current I flows in the two conductors so that the transverse magnetic field components sum and axial field components cancel each other.

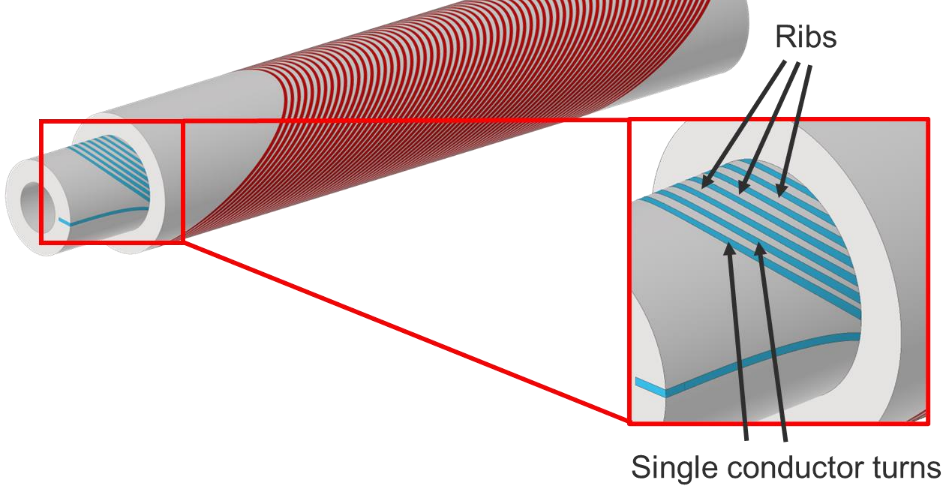




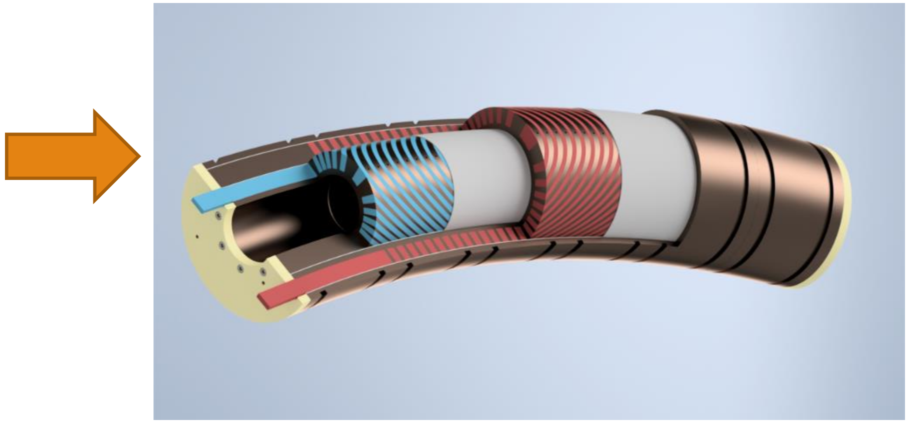
Canted Cosine Theta schematics



Straight



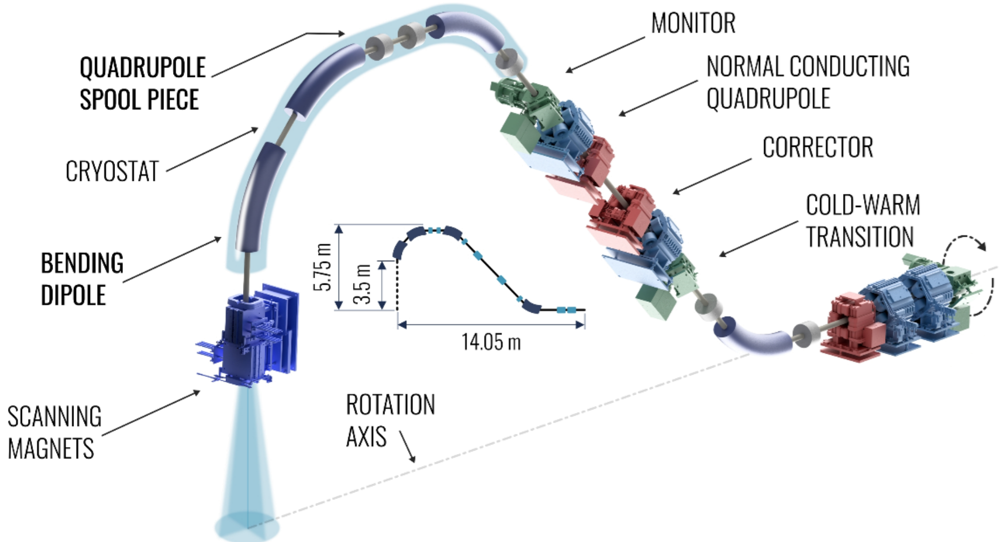
Curved CCT



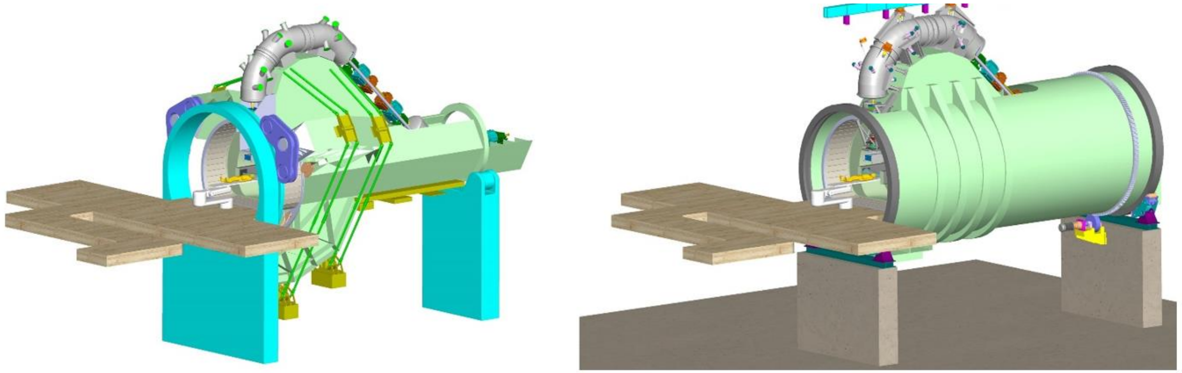
Parameters of demonstrator magnet

Carbon Ion Beam rigidity (6.6 Tm)

Parameters	Values	unit
Magnet type	CCT + Iron	-
Geometry	**Curved**	-
Central magnetic field B_0	**4**	**T**
Curvature radius ρ	**1.65**	**m**
Bending angle	**30°**-45°	degree
Magnetic and physical length	0.8, 1	m
Bore diameter	**80**	mm
dB/dt	**0.4**	**T/s**
Operation temperature	**4.7**	**K**
Loadline margin (@4.7 K) static	25	%
Superconductor	**NbTi**	-



Superconducting Rotating Gantry



Courtesy of M. Vretenar (CERN) and L. Piacentini (RTU)- WP7 HITRIplus

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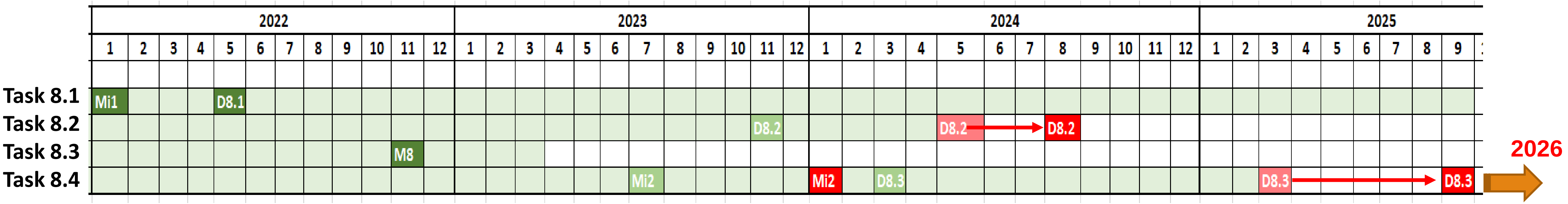
WP8 Timeline – MLS and DLVs

HITRI+ WP8: Superconducting Magnet Design
Task 8.1 - Coordination and Assessment of magnet design
Task 8.2 - Technical and Financial evalaution of various magnet designs
Task 8.3 - Preliminary engineering design for accelerator and gantry magnets
Task 8.4 - Construction of a small size magnet demonstrator for accelerator and gantry



Deliverables

- D8.1 (05/2022): Magnet Assessment for SC accelerator and gantry (**ACHIEVED**)
- **D8.2 (08/2024): TDR (Technical Design Report)** (**ACHIEVED)**
- D8.3 (03/2025→09/2025→2026): Magnet Demonstrator (we need an additional extension);
  - **The postponement of the deliverables was necessary due to the difficulty to machine the curved formers.**

De Matteis, E., Lecrevisse, T., Mariotto, S., Prioli, M., Sorti, S., Statera, M., & Rossi, L. (2022). Magnet Assessment for SC accelerator and gantry (1.0). Zenodo. https://doi.org/10.5281/zenodo.7875298

Milestones:

- Mi1 – Internal (01/2022): Decision on layout of demonstrator magnet (**ACHIEVED**);
- M8 (11/2022): Magnet Layout decision and Engineering design (**ACHIEVED**)
- Mi2 – Internal (01/2024): Manufacturing readiness of demonstrator(**ACHIEVED**):
  - **Conductor, curved formers and part of the tooling are defined – simplified assembly without Iron yoke.**

Barna, D., Ceruti, G., De Matteis, E., Sorti, S., Felcini, E., & Benedetto, E. (2023). Magnet Layout decision and engineering design report of the curved CCT dipole magnet demonstrator (1.0). Zenodo. https://doi.org/10.5281/zenodo.8096053

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Conductor layout, Materials and Procedures (TDR[1] – D8.2)

Rope Conductor Design

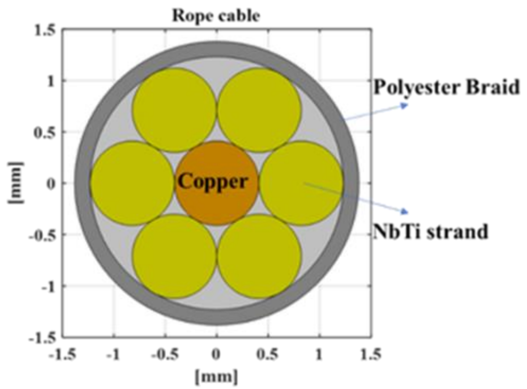
- 6 NbTi strands + 1 copper core
- Double braided polyester insulation
- Low-loss NbTi strand
- Industrial low-cost cabling

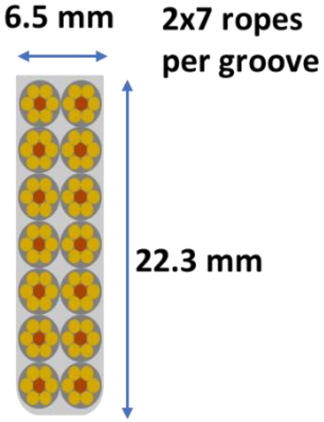
Simplified Manufacturing

- Easy winding with minimal tooling
- Reduced tool count for fabrication

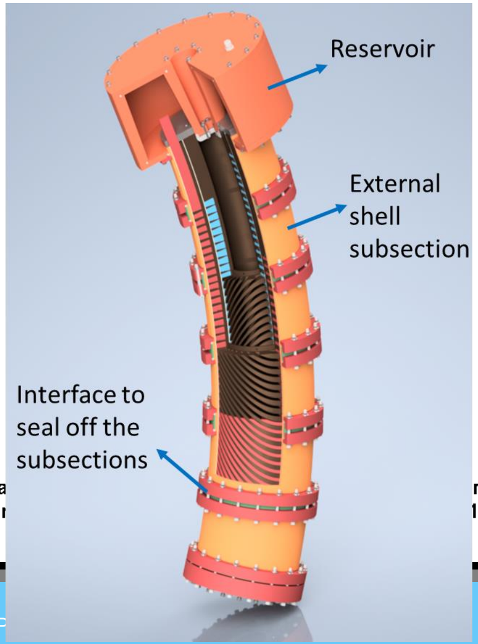
Wax-Based Impregnation

- Magnet structure serves as impregnation mold;
- Reversible process – allows recovery of components;
- Enables non-quench operation;
- Excellent thermal conductivity – ideal for conduction-cooled systems (e.g., gantries).





Parameters	Value	Unit
Rope diameter	3.15	mm
Number of ropes in a groove	2 x 7	-
Groove width	6.5	mm
Groove dept	22.3	mm
Spar thickness	8	mm
Minimum rib thickness	0.5	mm
Bending angle	34.8	degree
Magnet current	1670	A
Pitch (φ_0)	10.4813	mrad
Number of turns	40	-
Total rope length	850?	m



[1] E. De Matteis, D. Barna, M. Castoldi, N. Ciarchi, G. Ceruti, S. Sorti, F. Toral (2024). **Technical Design Report: Final report on Magnet design for SC synchrotron and SC gantry.** to be submitted on Zenodo.

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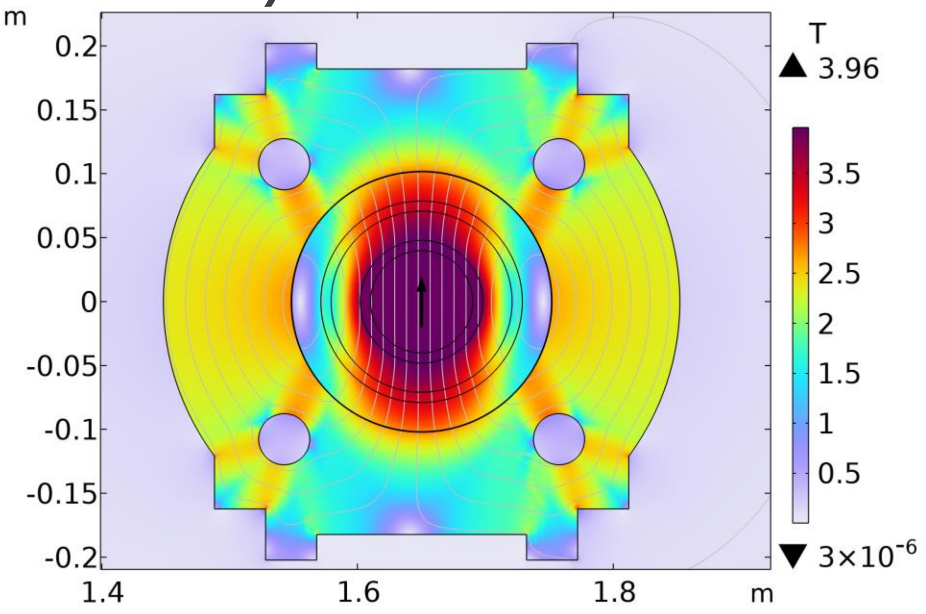
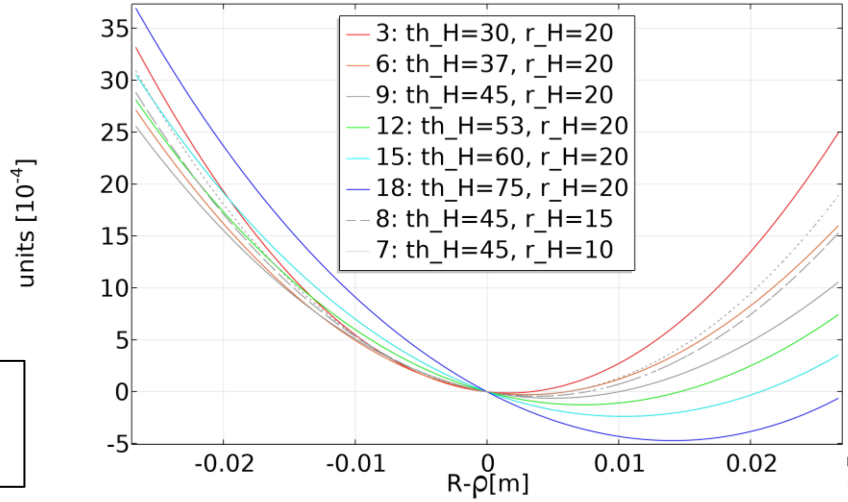
Magnetic design and field quality (TDR[1] – D8.2)

- **Yoke Optimization Challenge:**
  - Coil optimization handles linear sources
  - Iron yoke introduces nonlinearities (e.g. sextupole component)
- **Sextupole Mitigation Strategy:**
  - Cannot be corrected by coil tuning
  - Requires **active yoke shaping**
- **Optimization Techniques:**
  - Insertion of holes in specific yoke regions (e.g. ~60° from midplane)
  - **Pole shaping** as complementary method
- **Modeling Approach:**
  - **2D asymmetric model** with homogenized coils
- **Results:**
  - **2D optimization**: homogeneity ~25 units
  - **3D model (30° section)**: final homogeneity <7 units





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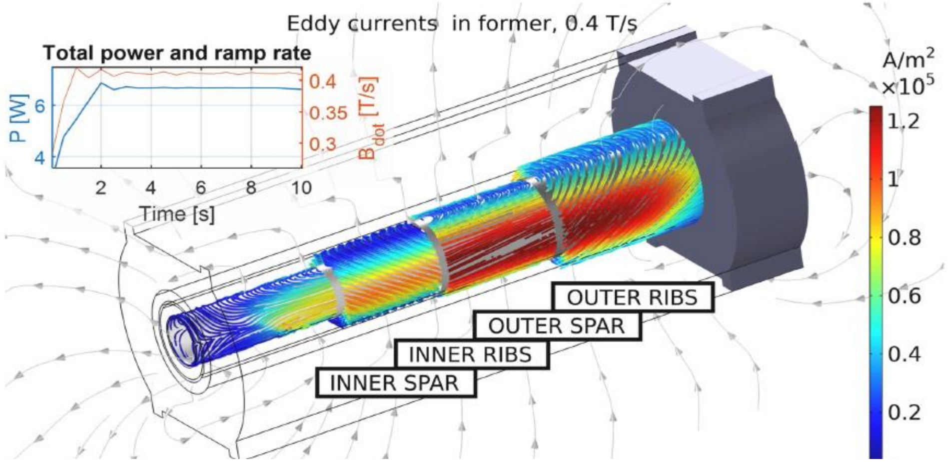
Electromagnetic losses[1] due to fast ramping (0.4 T/s) (TDR – D8.2)

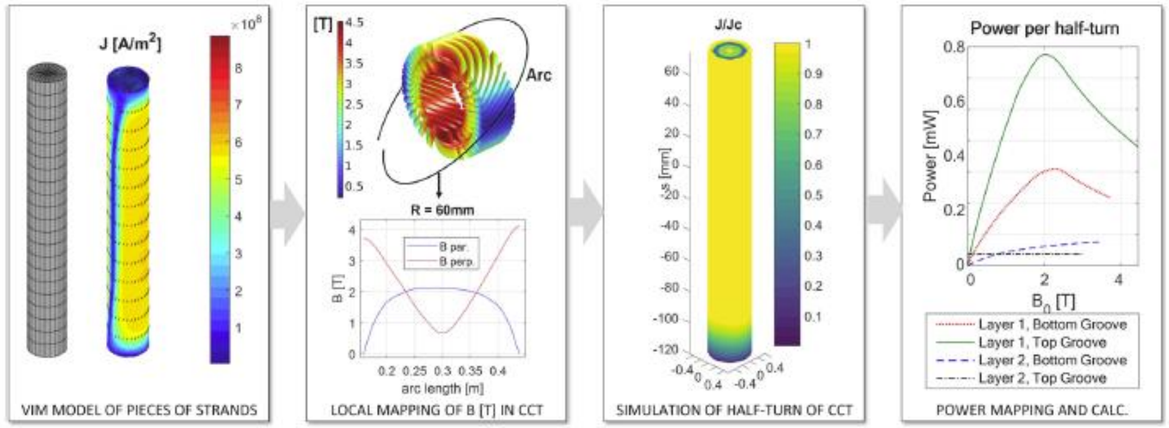
- **AC Loss Estimation Method**:
  Based on 3D time-domain FEM simulation in COMSOL 6.1.
- **Material Considerations:**
  - Eddy losses ∝ 1/ρ → resistivity sensitivity
  - Aluminum-Bronze chosen for the former
- **Total Estimated Losses**:
  ~15–16 W during ramping at 0.4 T/s

Source	Ramp-average [W]
Former	10
Superconductor	<5
Yoke	<1

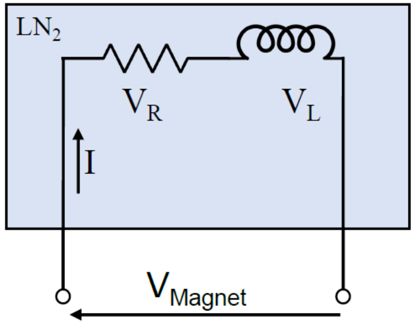
Power losses due to metallic Al-Br formers



Calculation Workflow of interfilament coupling losses in the superconductor



AC losses measurement system (IRIS project)



$$P = \frac{1}{N}\sum_{n=0}^{N-1} v(n)i(n)$$

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NI-9239

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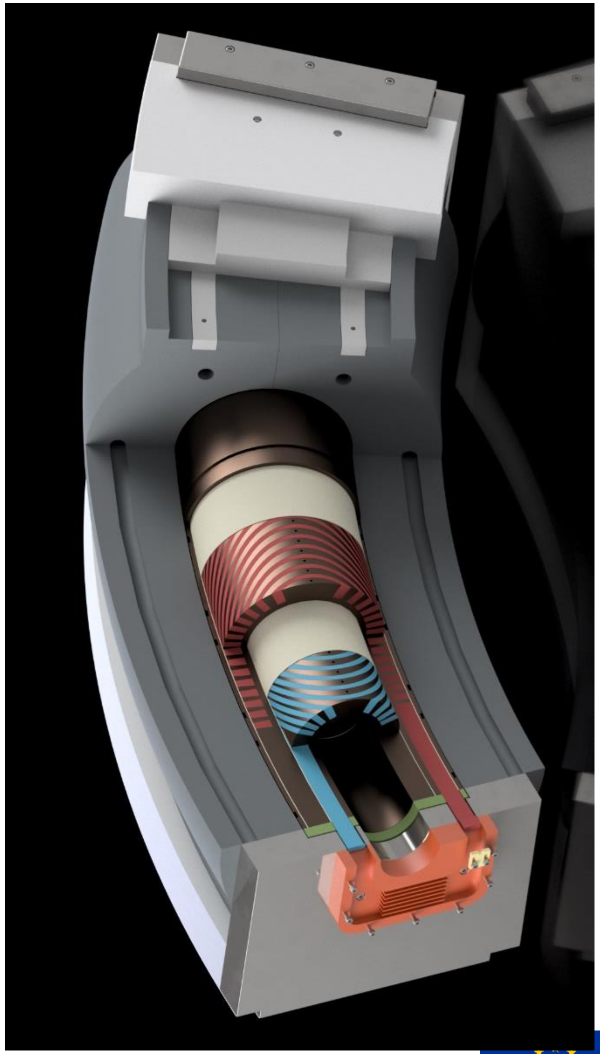
[1]S. Sorti et al., "Electromagnetic Losses in Fast-Ramped Canted-Cosine-Theta Magnets," in IEEE Transactions on Applied Superconductivity, vol. 34, no. 3, pp. 1-6, May 2024, Art no. 4003506, doi: 10.1109/TASC.2024.3360933.

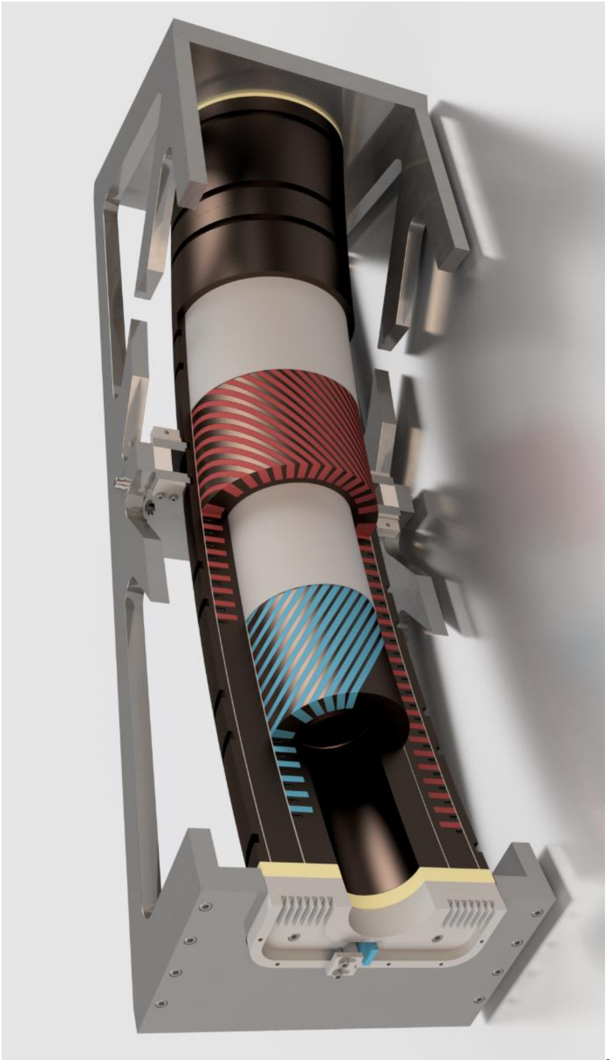
Final and Simplified assembly

Courtesy of N. Ciarchi (INFN-LASA)

Final Assembly of the magnet demonstrator without the Iron Yoke:

- The magnet will reach 2.8 T without the iron yoke;
- The iron yoke needs resources (funds + R&D);
- To reach the target of the deliverable for the HITRIplus project (D8.3 Magnet demonstrator);
- CERN workshop will manufacture the assembly parts;
- The R&D of the Iron yoke will continue with the CERN (we have budget available just for a prototype).





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Mechanical study- Assembly magnet

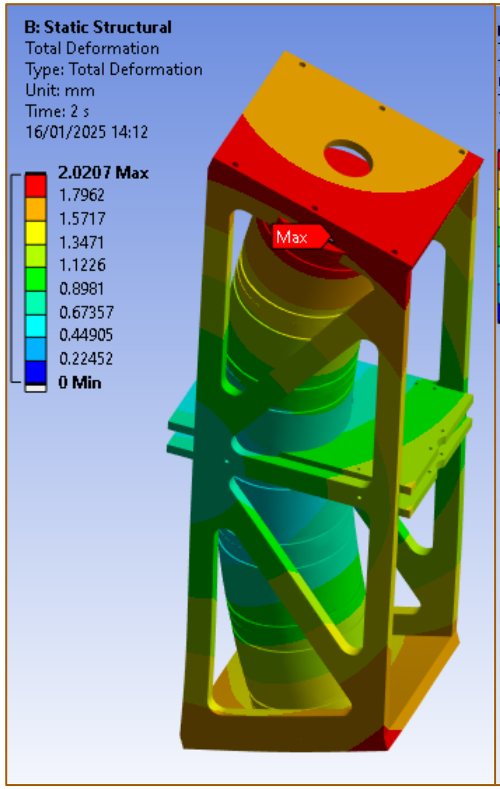
<u>Courtesy of L.Dassa and G. Ceruti (CERN)</u>

FEM Analysis of the CCT structure by Ansys simulations:

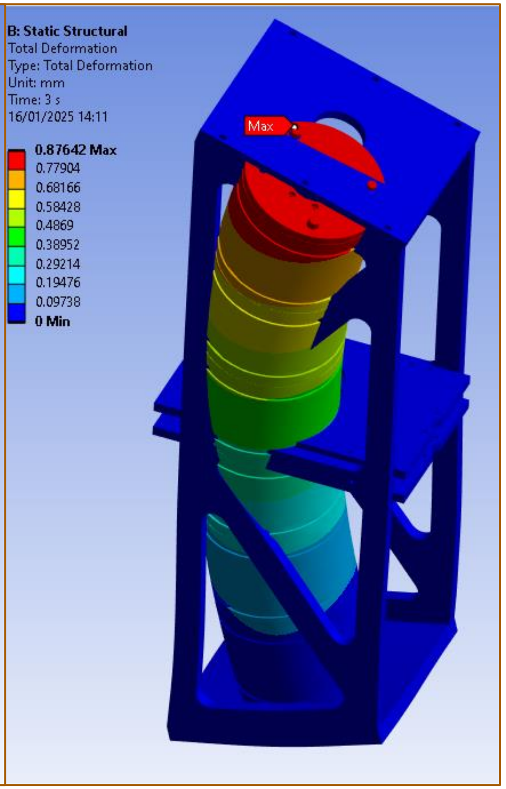
- Linear models,
- Magnet is entirely made in Aluminum Bronze
- Structure is entirely made in stainless steel (Rp0.2 = 200 MPa / fadm=200 MPa /1.5= 133 MPa)
- Only the bottom face of the magnet is bonded to the structure

Net forces are evaluated for simplicity (conductor is not considered);

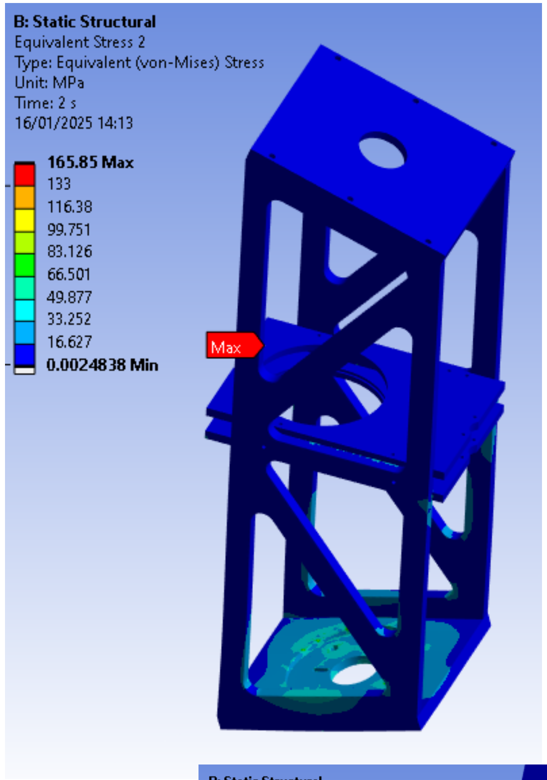
A numerical error of the net force due to the asymmetry of the magnet→ solution could be a full 3D simulation (very heavy to run).



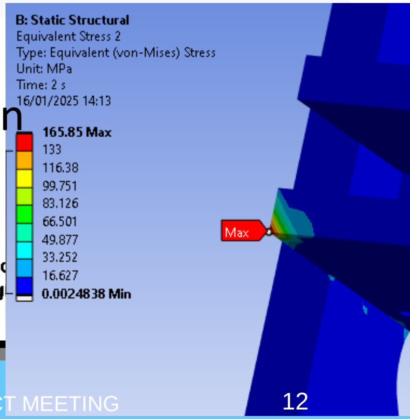
Thermal + Energization



Energization



Thermal + Energization



<u>Work in progress!!</u>

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This project has received fund
research and innovation prog

Construction aspects – curved formers (key parts of the magnet)

Partner Selection Challenge

- Difficulty in finding companies with required expertise;
- Tosti Srl (Castelpiano, Italy) selected after successful prototyping.

Progress Overview

- 3D model of curved formers completed
- Technical drawings for first formers delivered
- 3 inner former segments produced
  - One remade (initially out of tolerance)
  - One under correction

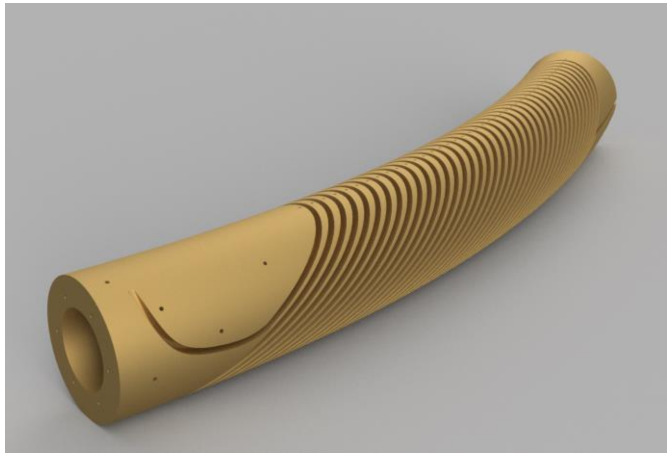
Production Insights

- **Machining more time-consuming than expected**;
- Multiple steps needed to minimize vibrations
- **Measurements is not trivial !!**

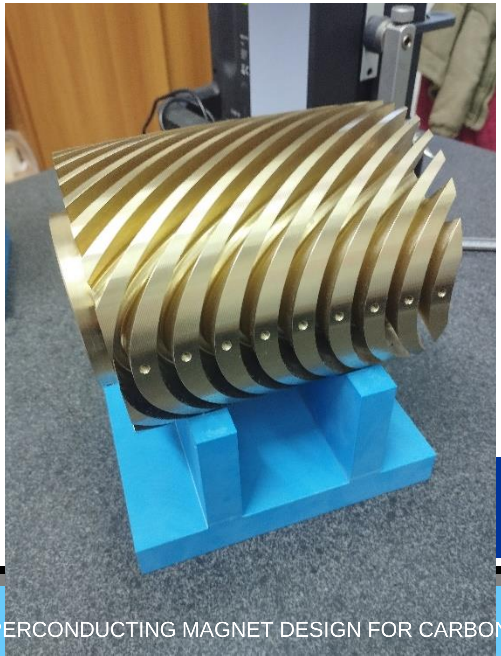
Next Milestones (by July 2025)

- Complete first and second layer formers;
- Final assembly using slotted pins.

3D model of the inner former



One segment on the meas. step



Assembly of #3 segments (inner former)

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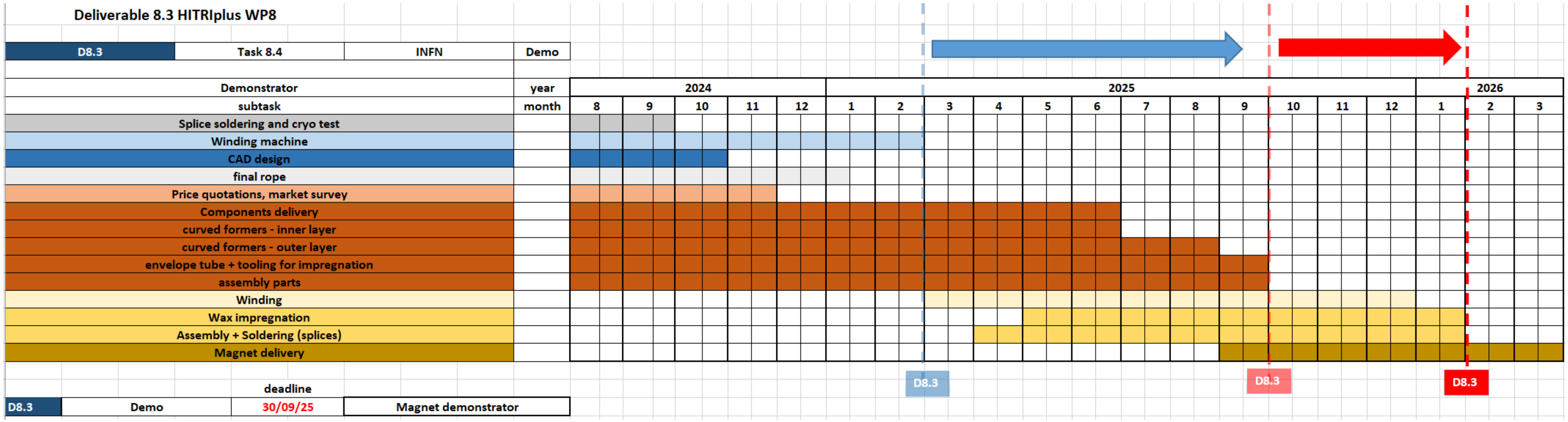
Timeline of D8.3 Magnet demonstrator



Critical points for this magnet are the construction of the curved formers and the overlapping with the construction of the combined function CCT (I.FAST) → both are foreseen at CIEMAT

Additional extension up to March 2026 for finalizing the magnet!!

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Conclusions and next steps

- **Summary of Progress**
  - WP8 superconducting magnet design advanced significantly
  - TDR – D8.2 highlights presented:
  - Conductor design, fabrication procedures
  - Magnetic design, field quality, AC losses
  - Final assembly without iron yoke (Plan B) due to resource limitations
  - CERN workshop will produce assembly components (and R&D of Iron yoke)
- **Current Status**
  - Curved formers production delayed – machining more complex than expected
  - Extension required to complete magnet construction
- **Next Steps**
  - Complete curved formers, envelope tube, and impregnation tooling
  - Finalize assembly parts with CERN support
  - Final conductor rope delivered by CIEMAT
  - Winding & impregnation at CIEMAT – winding machine adaptation ongoing
  - Magnetic measurements at warm with Senis (INFN-LASA) – pending
  - Cold test at 4.2 K at INFN-LASA (planned for late 2026 – post-HITRIplus)

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Thanks for the attention!!!

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