Heavy Ion Therapy Research Integration

WP8 – Superconducting Magnet Design Report for 3rd project and 2nd Reporting Period meeting

ERNESTO DE MATTEIS (WP8 COORDINATOR)

3RD PROJECT AND 2ND REPORTING PERIOD MEETING

23 MAY 2024, MARBURG, GERMANY

ON BEHALF OF MY WP8 HITRIPLUS COLLEAGUES

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

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);

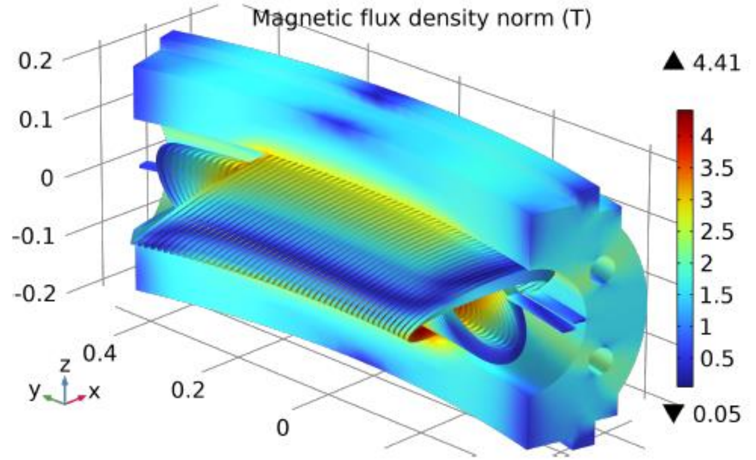
Preliminary engineering design for the new concept of accelerator magnets and innovative gantry magnet;

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

BERKELEY LAB

Program based CCT layout led by S. Prestemon

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

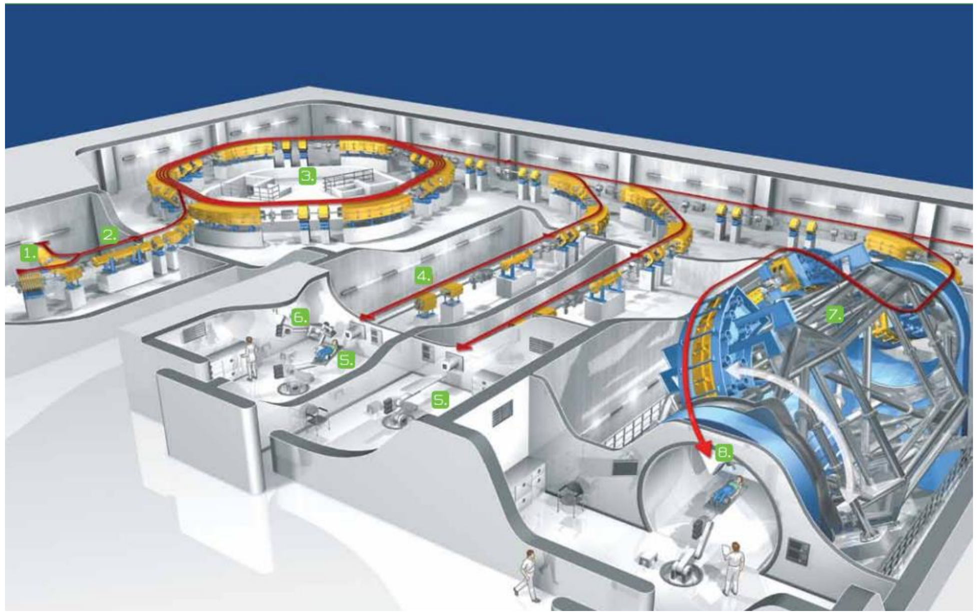


[1]E. De Matteis, S. Mariotto, T. Lecrevisse, M. Prioli, S. Sorti, M. Statera, L. Rossi, **"Magnet Assessment for SC accelerator and gantry",** HITRIplus WP8 - Deliverable 8.1, Zenodo. https://doi.org/10.5281/zenodo.7875298

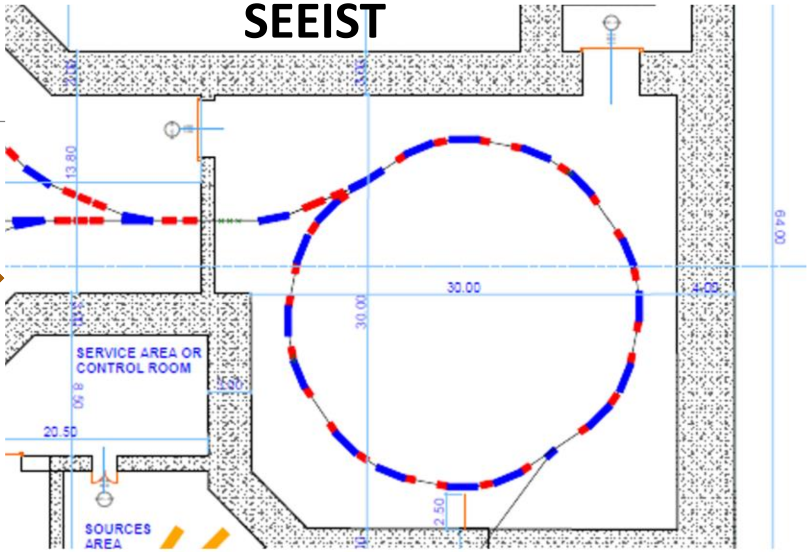
Medical Facilities – dimensions strictly depend on the magnetic field

Accelerator hall in case of standard resistive magnet synchrotron vs case of using SC magnets

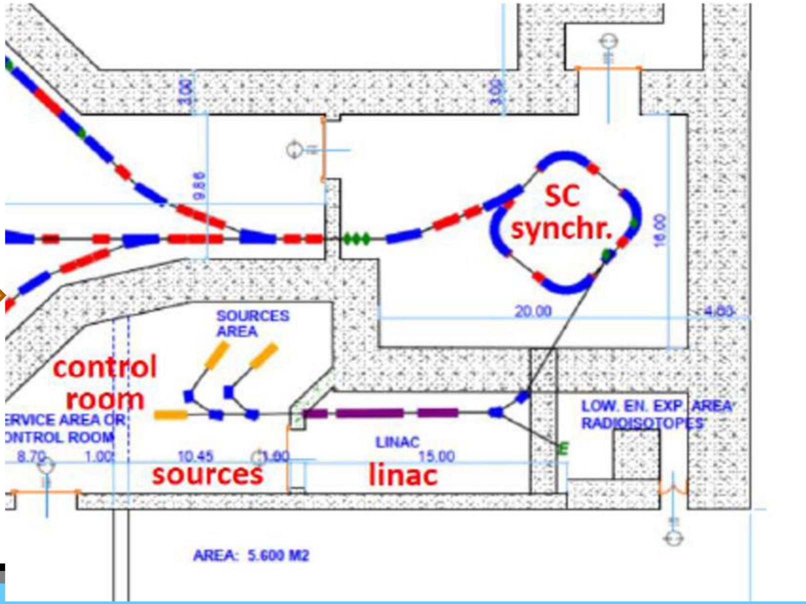
HIT - Heidelberg Ion Beam Therapy Center



Resistive dipoles 1.5 T
Curvature radius of about 4.5 m



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



Courtesy of E. Benedetto (SEEIST)

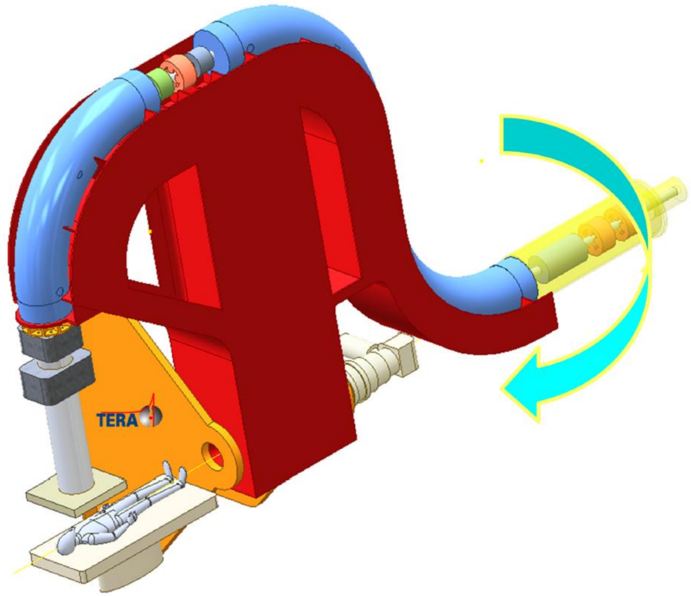
Footprint and cost reduction;

Reduce the power consumption;

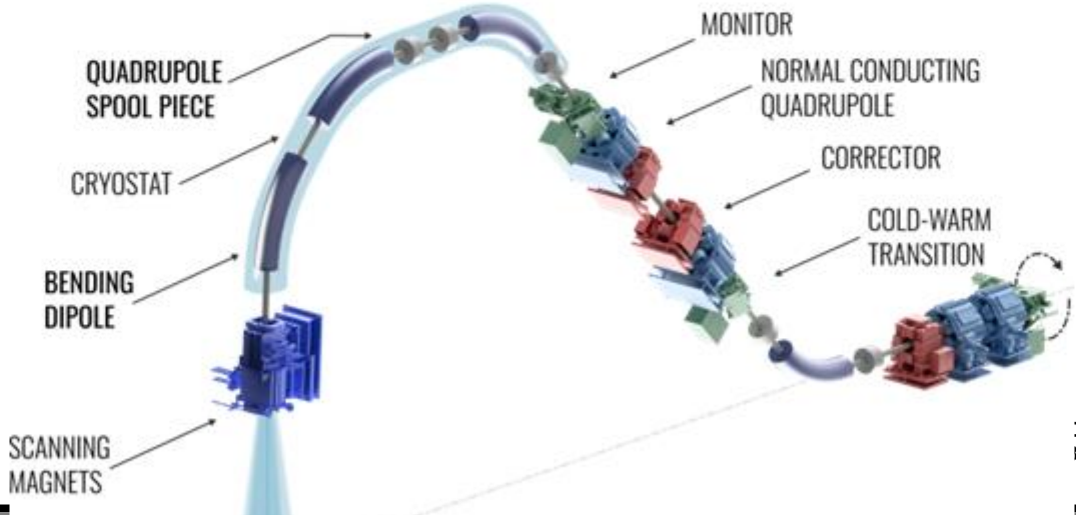
Parameters of demonstrator magnet

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



Carbon Ion Beam rigidity (6.6 Tm)



Courtesy of E. Felcini (CNAO)

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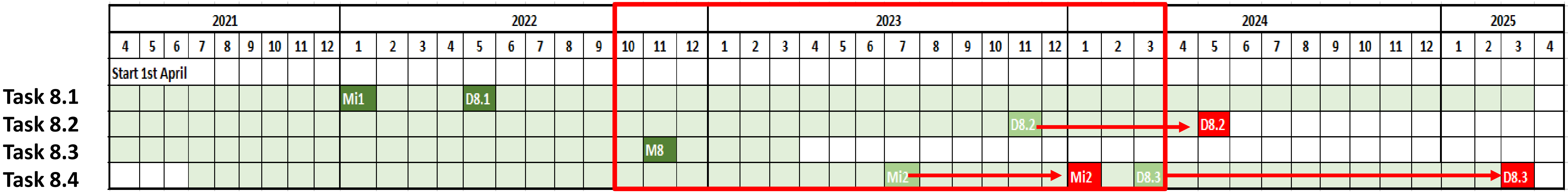
WP8 Timeline – MLS and DLVs

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

19 – 36 months activities



Deliverables

- D8.1 (05/2022): Magnet Assessment for SC accelerator and gantry (**ACHIEVED**);
- D8.2 (05/2024): TDR (Technical Design Report) (writing);
- D8.3 (03/2025): Magnet Demonstrator (postponed of 12 months);
  - The postponement of the deliverables was necessary due to the difficulty to find companies able to machine the curved formers.

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(almost **ACHIEVED**):
  - Conductor, curved formers and part of the tooling are defined – iron yoke and assembly under study.

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

HITRIplus WP8 – activities of last 18 months

- Task 8.1: Coordination and assessment of magnet design
  - From the 4th of October 2022 we had n. 9 general meetings and more than 25 dedicated weekly meetings about the demonstrator (every Monday);
  - **Survey** for machining of the **curved formers** and related tests;
  - Collaboration with the other WPs (WP4 and WP7);
- Task 8.2: Technical and financial evaluation of various magnet designs for synchrotron and gantry
  - Magnet designs concerning electromagnetic losses, field quality optimization and mechanical simulations;
  - Preparation of the **Technical Design Report (TDR)** – Deliverable D8.2;
- Task 8.3: Preliminary Engineering Design for Accelerator and Gantry magnets
  - Submission of the **Milestone 8(MLS 8)**: "Magnet Layout decision and Engineering design of the synchrotron-gantry dipole magnet";
  - Engineering design: Various materials for formers were considered, with Aluminium-Bronze chosen for its machinability and conductivity. Successful winding and impregnation tests led to using wax as a baseline filler and an Aluminium-Bronze external shell for conductor protection during impregnation.
- Task 8.4: Construction of a small size magnet demonstrator for accelerator and gantry
  - Definition of the final conductor rope (6 NbTi +1 copper core strands), and of the curved formers construction;
  - Assembly procedure and tooling for the impregnation;
  - First wax- impregnated magnet (SUSHI magnet – Wigner RCP).

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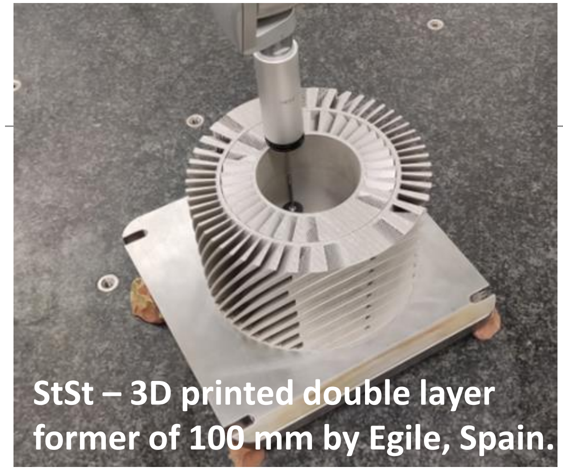
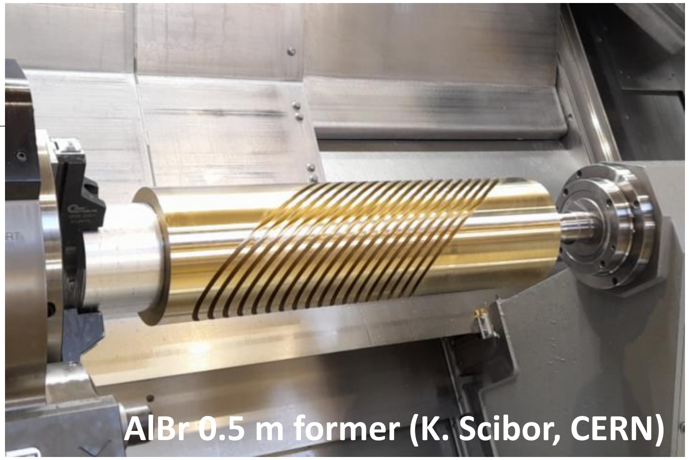
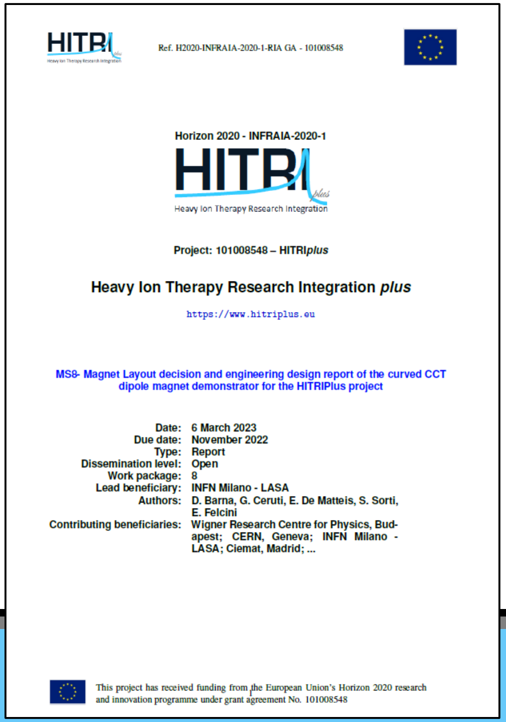
Milestone 8 - Magnet Layout decision and Engineering design[1] (Task 8.3)

- Former material tests: StSt, Al-Br and PEEK;
  - **Aluminium-Bronze** could be the final one;
- Conductor:
  - **Low losses NbTi strand and rope(6+1) cable;**
- Winding parameterization and optimization (dedicated algorithm);
- Winding and Impregnation procedure and setup;
- Magnetic and mechanical design;
- Magnet Assembly.


StSt – 3D printed double layer former of 100 mm by Egile, Spain.


AlBr 0.5 m former (K. Scibor, CERN)


HITRI Ref. H2020-INFRAIA-2020-1-RIA GA - 101008548

Horizon 2020 - INFRAIA-2020-1

HITRI plus

Heavy Ion Therapy Research Integration

Project: 101008548 – HITRI*plus*

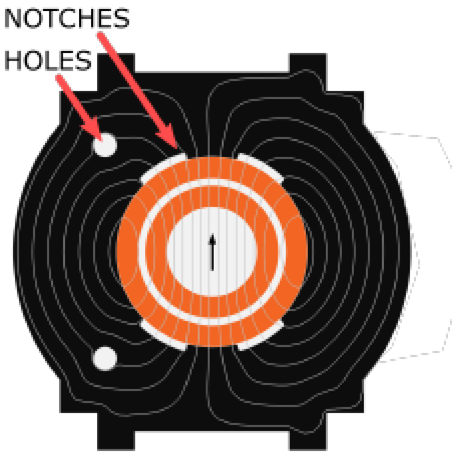
Heavy Ion Therapy Research Integration *plus*

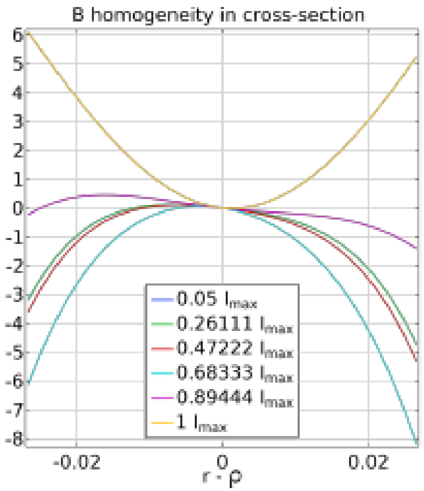
https://www.hitriplus.eu

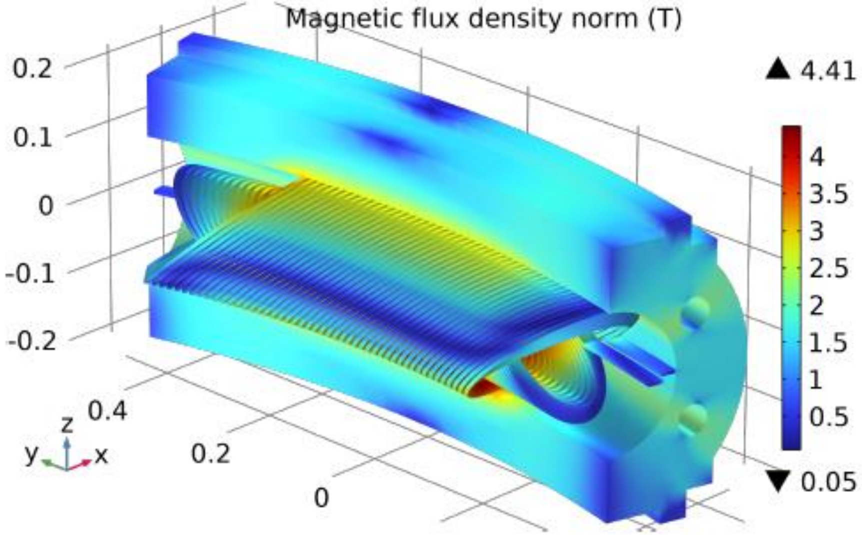
MS8- Magnet Layout decision and engineering design report of the curved CCT dipole magnet demonstrator for the HITRIPlus project

Date: 6 March 2023
Due date: November 2022
Type: Report
Dissemination level: Open
Work package: 8
Lead beneficiary: INFN Milano - LASA
Authors: D. Barna, G. Ceruti, E. De Matteis, S. Sorti, E. Felcini
Contributing beneficiaries: Wigner Research Centre for Physics, Budapest; CERN, Geneva; INFN Milano - LASA; Ciemat, Madrid; ...

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







[1]D. Barna, G. Ceruti, E. De Matteis, S. Sorti, E. Felcini, **"Magnet Layout decision and engineering design report"**, HITRIplus WP8 - Milestone 8.

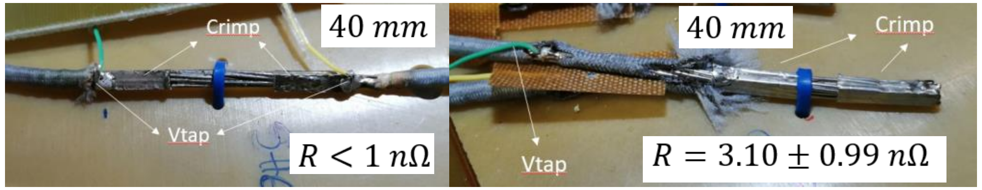
Milestone 8: Rope conductor and Winding tests (Task 8.3)

Rope (6 NbTi strands +1 copper core strand) with double braid made of polyester: qualified with several critical current measurement test campaigns (Common conductor in synergy with I.FAST program);

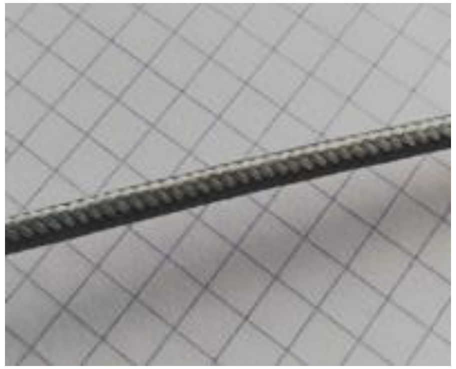
Winding and High Voltage tests performed at Wigner RCP;

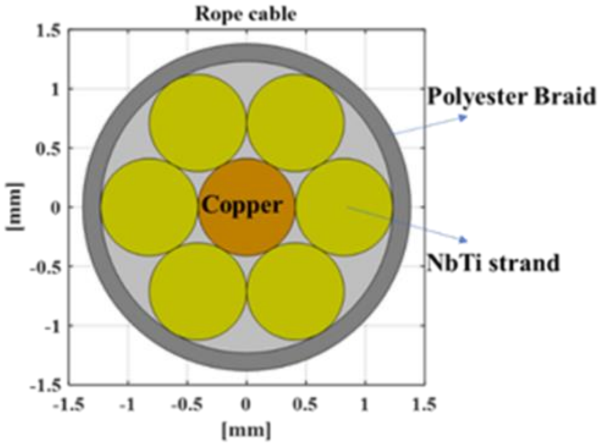
Ic measurements and splice test at LASA(INFN);

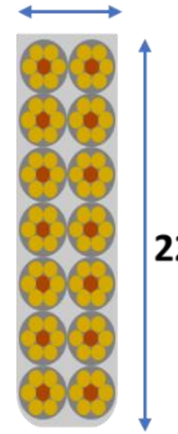
Final order has been launched→ ready for production.



Made by Texcavi srl (Inzago, Milan, Italy)





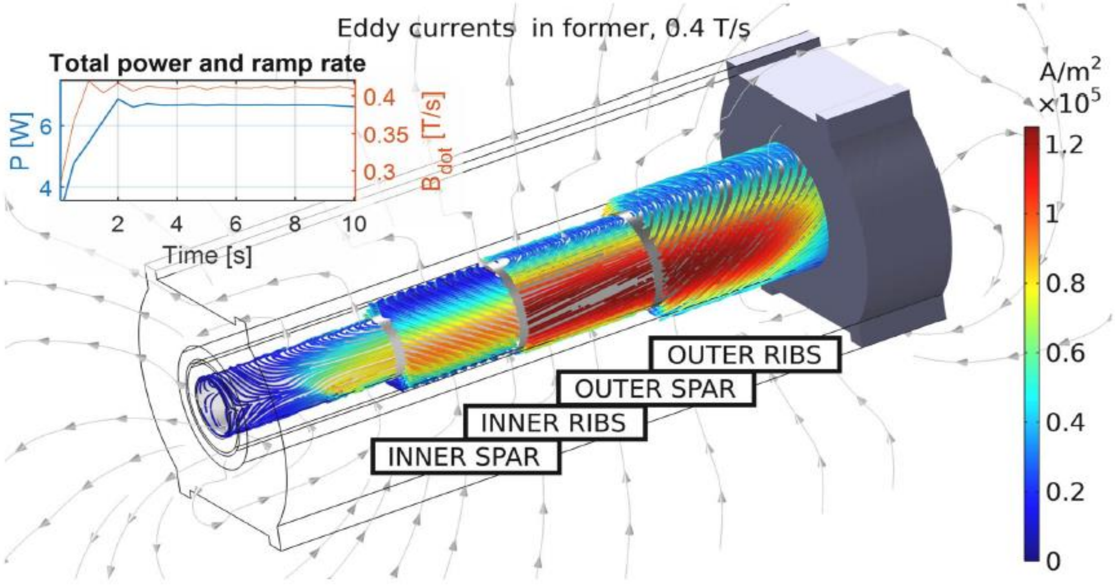


Electromagnetic losses[1](Task 8.2)

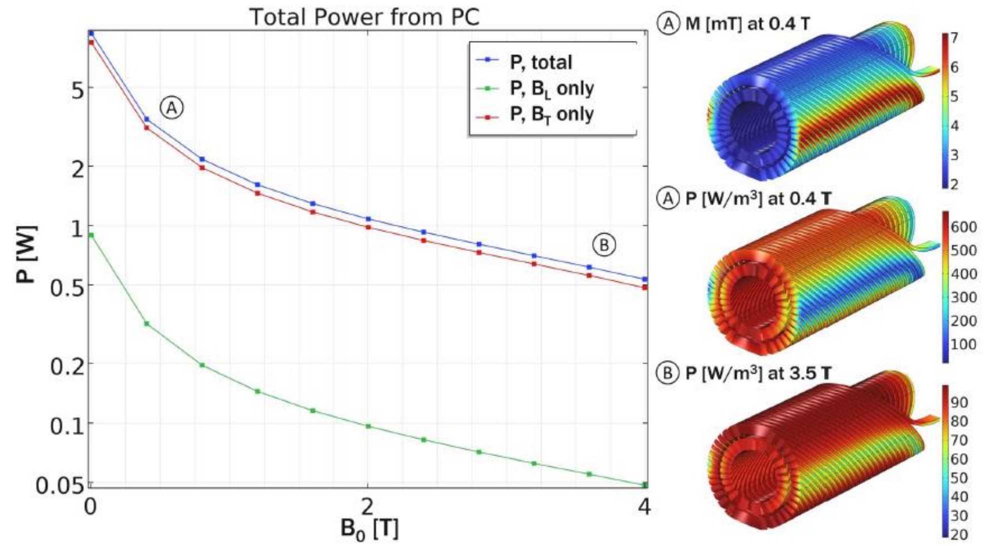
- Electromagnetic losses are critical in **fast-ramped superconducting magnets** as the conduction-cooled CCT proposed for hadron therapy.
- Critical sources of losses are the **metallic formers and multifilamentary superconductors**;
- establishing the cooling budget and discussing the thermal design;
- The main heat source is identified as the CCT metallic former, providing a ramp-averaged power of 6 W.
  - non-conducting former is considered, though it may complicate heat extraction from the conductor;
- Losses in the superconductor amount to 2.1 W from persistent currents and 3 W from interfilament currents.
- **Measurements of losses** on the demonstrator are scheduled once it is built.

[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.

Power losses due to metallic Al-Br formers



Power losses due to magnetization of the filaments



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IRIS project – collaboration with HITRIplus

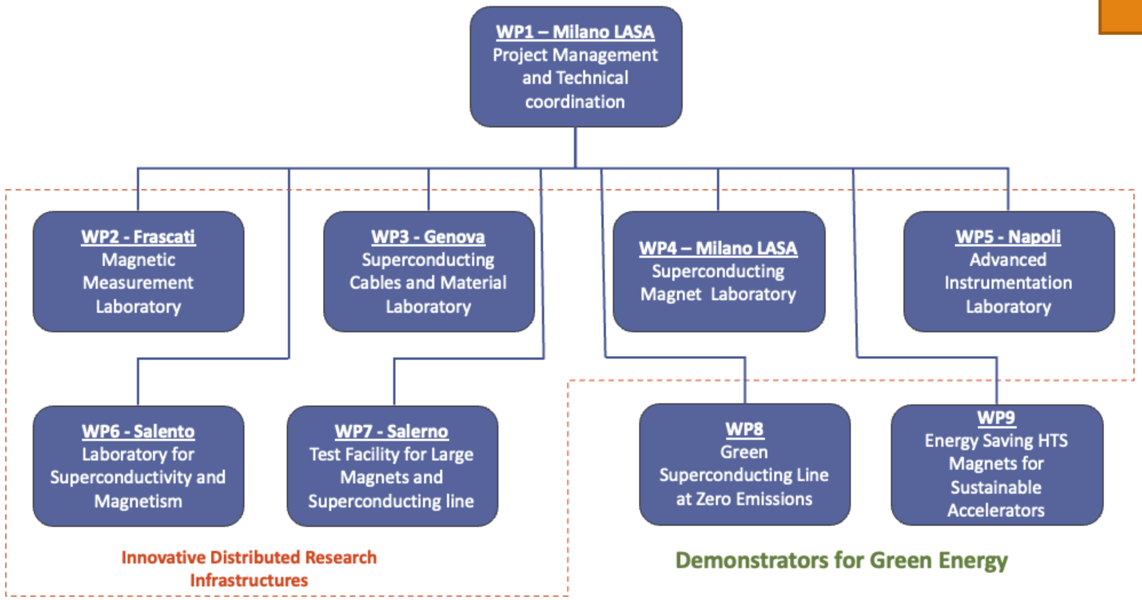
Italiadomani
PIANO NAZIONALE DI RIPRESA E RESILIENZA

Finanziato dall'Unione europea
NextGenerationEU

Innovative Research Infrastructure on applied Superconductivity – Next generation EU project

6 poles for the new or renewed infrastructures: Frascati (INFN), Genova (INFN, CNR-Spin, Unige), Milano (INFN, Unimi – LASA lab), Napoli (Unina), Salento (Unisalento) e Salerno (INFN e Unisa).

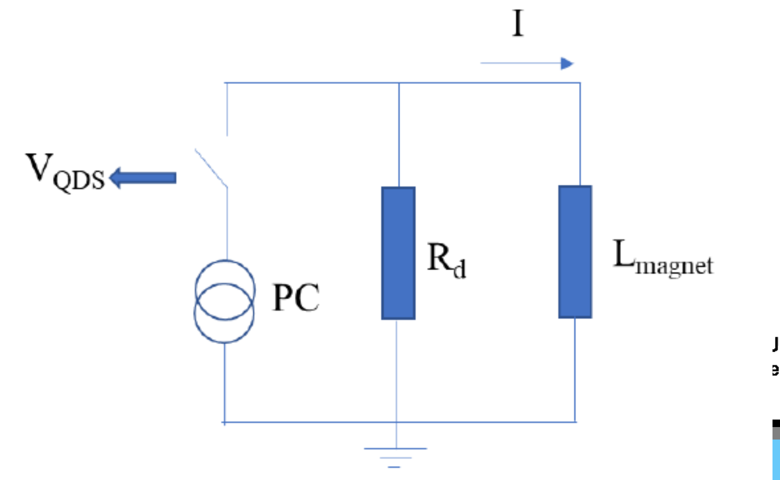
LASA (Milano) is the hub and coordinates the activity



Implementation for **AC loss measurement system** for superconducting magnets (LASA-INFN and Univ. of Naples)

Voltamperometric measurements method

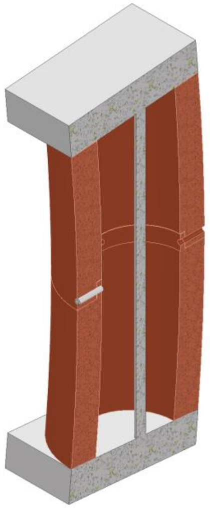
$$Q(t_1, t_0) = \int_{t_0}^{t_1} V \cdot I dt \approx \Delta t \sum_{j=1}^{n} V_j \cdot I_j$$

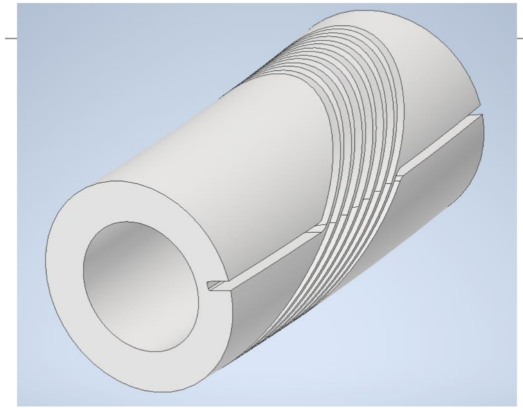


Jnion's Horizon 2020
ement No 101008548

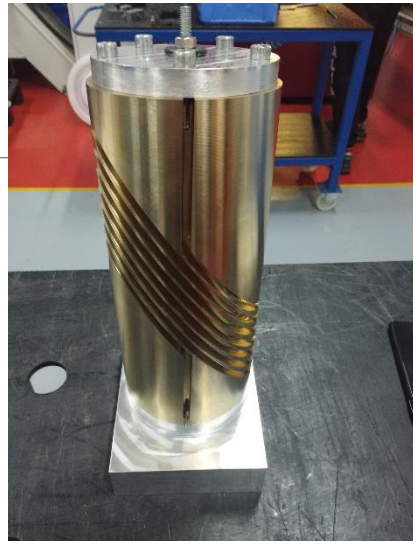
Curved formers construction (Task 8.4)

- <u>Two Solutions Explored:</u>
  - Bending a straight Aluminium bronze tube and machining surfaces and grooves.
  - **<u>Constructing curved subsections from straight tubes, machining the grooves and joining them with slotted pins.</u>**
- <u>Comprehensive Survey:</u> Conducted across Europe in collaboration with INFN and CERN to find suitable partners for this specialized research.
- <u>Challenges in Finding Partners:</u> Difficulty in identifying companies capable of handling the specialized research.
- <u>Selected Partner:</u> Tosti srl in Castelpiano, Italy, was chosen after successful testing of the second construction procedure.
- <u>Current Status</u>: orders for construction launched and technical drawings are being implemented at INFN-LASA.

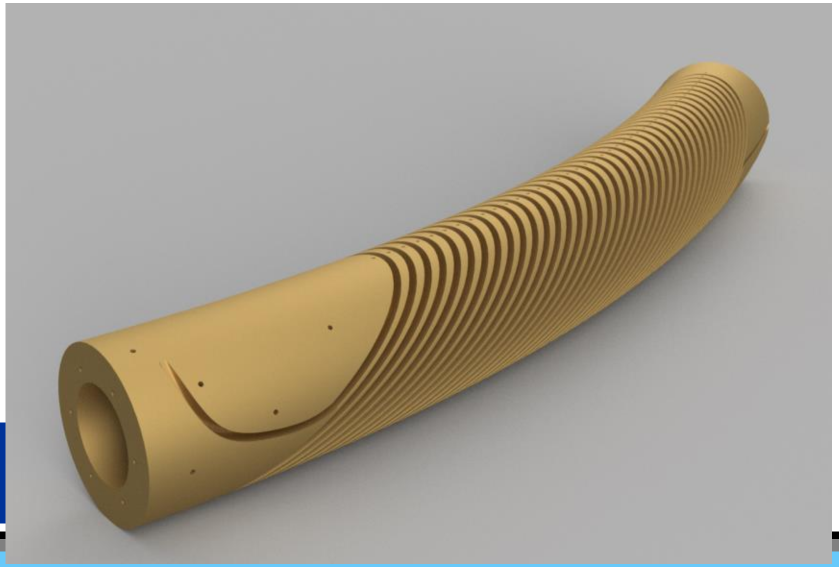




Curved former test



Inner curved former with slotted pins



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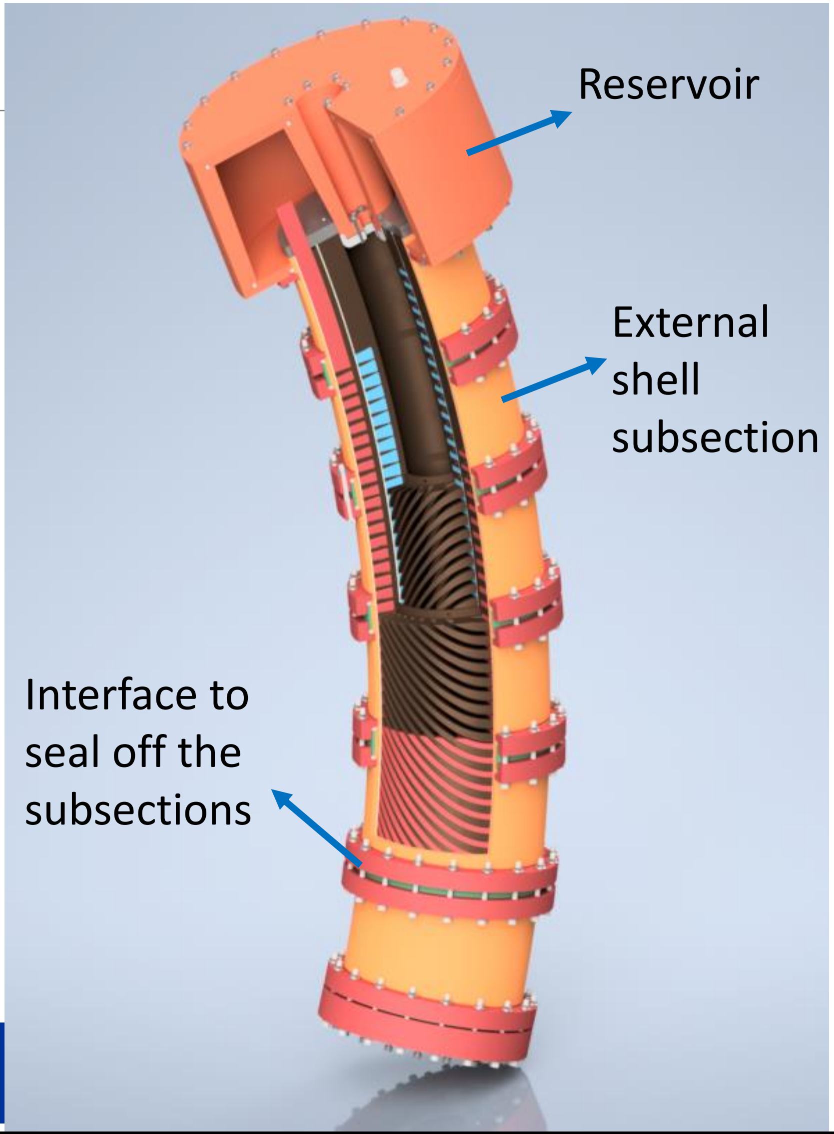
Tooling for impregnation with wax (Task 8.4)

- **Impregnation Setup**: The magnet serves as the mold with wax injected from the bottom, filling the magnet and a local reservoir without needing an external vacuum system:
  - Following the Sushi magnet experience (next slide);
  - Inserting an external shell made of Al-Br (6 curved subsections)
- **Wax will be injected under vacuum** and maintained above exit slots until impregnation will be complete.
- **Cooling Process:** Cooling will start from the bottom and inside the bore, progressing upwards to ensure a continuously progressing solid-liquid interface.
- Removal of Reservoir Parts: The inner and outer walls of the reservoir are conical for easy removal from the solidified wax, with mechanical removal of remaining wax as the final step.



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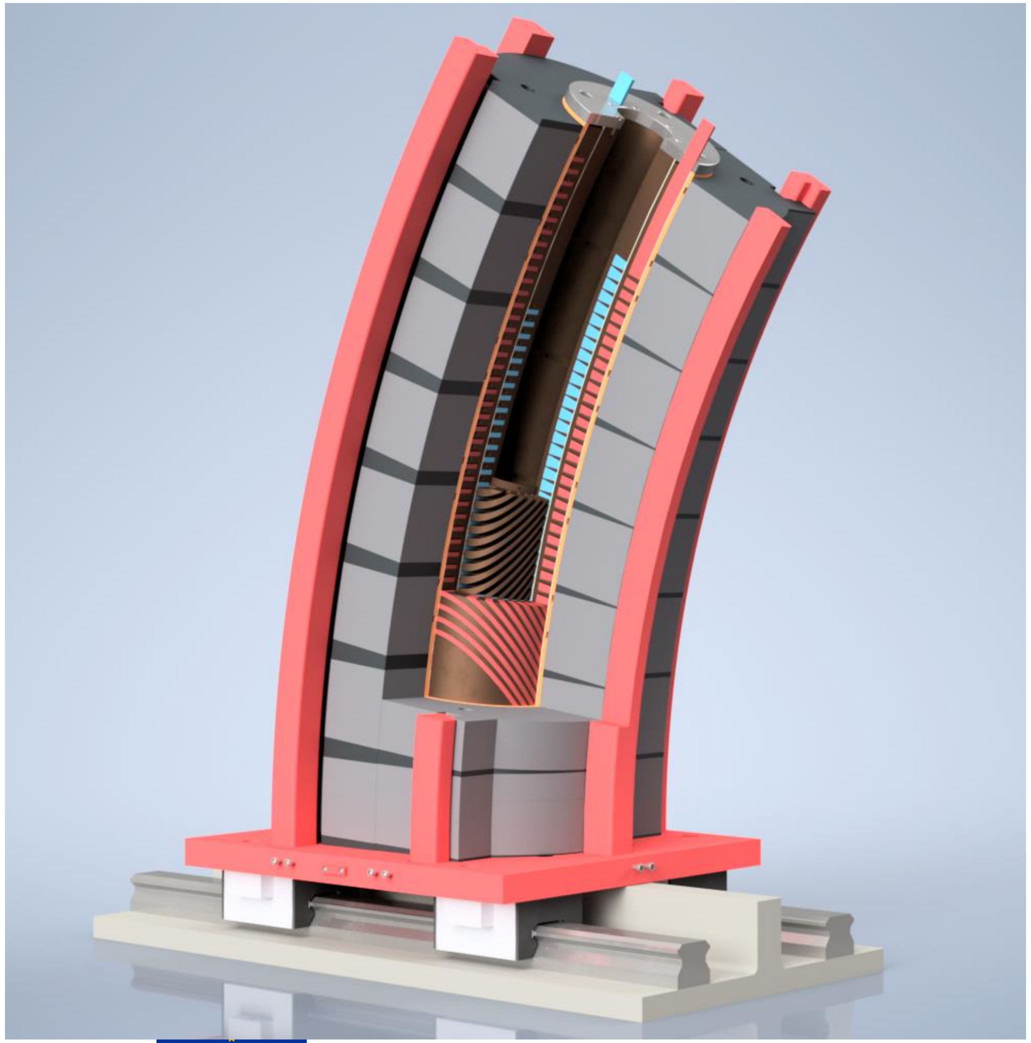
Assembly procedure and setup (Task 8.4)

- **Vertical assembly setup:** Significant effort was invested in exploring the transition from a horizontal to a vertical concept for magnet assembly.
  - This exploration included meticulous consideration of logistical feasibility, structural integrity, and ease of implementation.

- Primary Structural Components as the base and the two trolley structures with curved guides to support the two halves of the iron yoke;

- Two iron yoke options were investigated:
  1. One with single lamination being considered but deemed costly for machining.
  2. The alternative involves assembling straight glued laminations before machining (INFN, CERN, CIEMAT, and Wigner RCP);



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Wax impregnation of the SuShi CCT magnet

Superconducting Shield (SuShi) septum magnet, supplying the background field of the zero-field superconducting magnetic channel (test mentioned in Task 8.4);

Epoxy → Wax impregnation (After the great results of the BOX experiment (PSI))

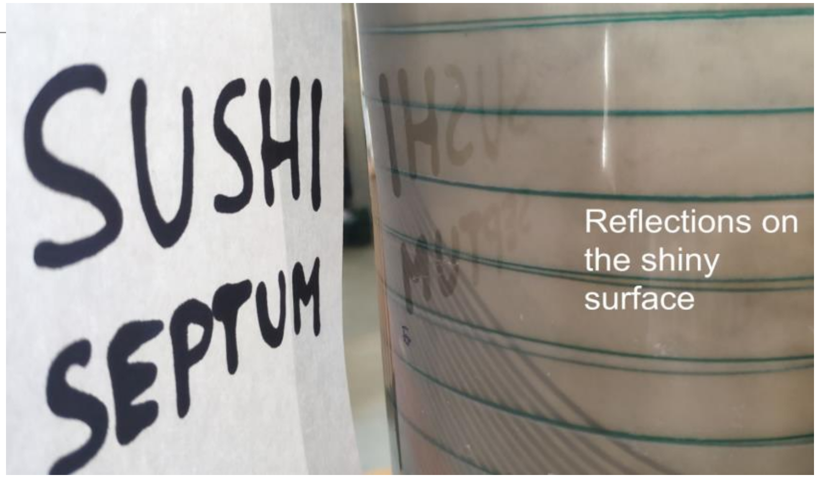
Wax is cheap, easy to work with (55 °C melting), undoable in case of an error (!!!), and shows no quench training at all;

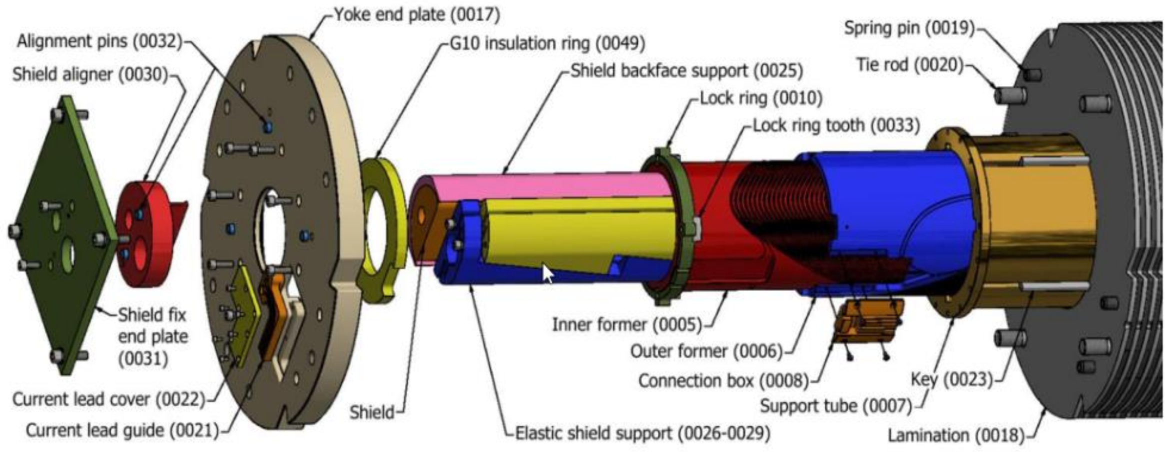
Several months spent on experimentation to master the contraction of wax when solidifying (15%);

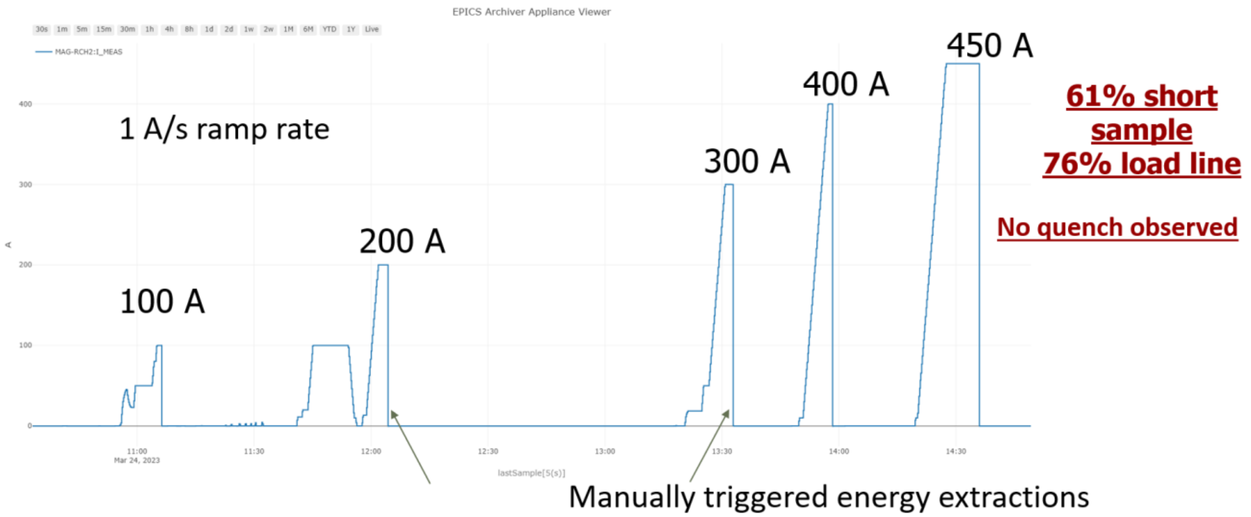
A lot of information can be found in the video documentation: https://youtube.com/playlist?list=PLeCOFQnTJU_WG1woGvIBHH3dHW06fohE

For further questions: barna.daniel@wigner.hu

D. Barna and Kristof Brunner (Wigner RCP)







Conclusions and next steps

- Milestone 8: Magnet Layout decision and Engineering design (achieved)(Task 8.3 – Wigner RCP, INFN, CIEMAT, CERN, CNAO):
  - Former material tests (Al-Bronze could be the final one), Conductor (qualification of the rope), Winding parameterization (dedicated algorithm), Winding and Impregnation procedure and setup, Magnetic and mechanical design, and Magnet Assembly.
- Finalized the rope conductor by Ic meas., HV tests and splice tests (INFN and Wigner RCP) :
  - Launched the order for the final production at Texcavi company;
- Finalized the construction procedure for the curved Al-Br former in collaboration with Tosti srl;
  - Constructing curved subsections from straight tubes, machining the grooves and joining them with slotted pins.
- Defined the tooling for the winding and the impregnation (INFN, CIEMAT and Wigner RCP);
  - Winding machine is in order to CIEMAT, and impregnation tooling drawings are ready (INFN-LASA);
- Technical Design Report (TDR) – Deliverable D8.2 (05/2024) is in preparation:
  - Report on the last design updates and construction readiness of the final demonstrator.

Open points and next steps:

- Complete the magnet assembly tools and iron yoke construction (INFN and CERN).
- Final test of the demonstrator will be done at Uppsala (Deadline for the demonstrator is March 2025)

Magnetic measurements (in synergy with EuroSIG project + involvement of Senis for warm measurements).

Other activities of WP8

HITRIplus WP8 Meetings indico page:

https://indico.cern.ch/category/13726/

Papers published

Type	Author(s), *Title*, References, Date	Link
Scientific article	L. Rossi et al., "A European Collaboration to Investigate Superconducting Magnets for Next Generation Heavy Ion Therapy" in IEEE Transactions on Applied Superconductivity, vol. 32, no. 4, pp. 1-7, June 2022, Art no. 4400207, doi: 10.1109/TASC.2022.3147433.	https://ieeexplore.ieee.org/document/9701444
Scientific article	D. Veres, T. Vaszary, E. Benedetto and D. Barna, "A New Algorithm for Optimizing the Field Quality of Curved CCT Magnets," in IEEE Transactions on Applied Superconductivity, vol. 32, no. 5, pp. 1-14, Aug. 2022, Art no. 4900914, https://doi.org/10.1109/TASC.2022.3162389.	https://ieeexplore.ieee.org/document/9743490
Scientific article	E. De Matteis et al., "Straight and Curved Canted Cosine Theta Superconducting Dipoles for Ion Therapy: Comparison Between Various Design Options and Technologies for Ramping Operation," in IEEE Transactions on Applied Superconductivity, vol. 33, no. 5, pp. 1-5, Aug. 2023, Art no. 4401205, doi: 10.1109/TASC.2023.3259330.	https://ieeexplore.ieee.org/document/10077410
Scientific article	L. Rossi, et al. "Magnet Technology and Design of Superconducting Magnets for Heavy Ion Gantry for Hadron Therapy." Journal of Physics. Conference Series, vol. 2687, no. 9, 2024, pp. 92009-, https://doi.org/10.1088/1742-6596/2687/9/092009.	https://iopscience.iop.org/article/10.1088/1742-6596/2687/9/092009
Scientific article	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.	https://ieeexplore.ieee.org/abstract/document/10418266
Scientific article	F. Toral et al., "Status of Nb-Ti CCT Magnet EU Programs for Hadron Therapy," in IEEE Transactions on Applied Superconductivity, vol. 34, no. 5, pp. 1-5, Aug. 2024, Art no. 4401705, doi: 10.1109/TASC.2023.3349252.	https://ieeexplore.ieee.org/document/10379464
Scientific article	De Matteis, E. New technologies: superconducting magnets. Health Technol. (2024). https://doi.org/10.1007/s12553-024-00849-4.	https://link.springer.com/article/10.1007/s12553-024-00849-4

Big list of outreach talks (19 – 36 months)

Public event	L. De Curtis, L. Rossi, M. Boselli, E. Calore, E. Diociaiuti, "What's next – Giovani che incontrano il futuro", organised by INFN-Communcation, Ferrara 5th of October 2022
Conference talk	E. De Matteis et al., "Straight and curved Canted Cosine Theta superconducting dipoles for ion therapy: comparison between various design options and technologies for ramping operation", Applied Superconductivity Conference 2022 (ASC22), Honolulu, USA, 26 October 2022.
Public talk	L. Rossi, "I grandi acceleratori di particelle e il super-collider post-LHC al CERN. Dall'infinitamente piccolo alle tecnologie per la salute e la transizione verde." Castel San Giovanni, "Scienza in Valle" (Valtidone) event, 18th March 2023.
Outreach to students	E. De Matteis, "CERN and INFN: general overview and LASA activities", Liceo Scientifico "Giordano Bruno", Melzo, Italy, 23rd March 2023.
Outreach	L. Rossi, "I grandi acceleratori di particelle e il super-collider post-LHC al CERN. Dall'infinitamente piccolo alle tecnologie per la salute e la transizione verde.", Institute Mochi, Arezzo, Italy, 24th March 2023.
Conference talk	L. Rossi, et al., "Magnet technology and design of superconducting magnets for heavy ion gantry for hadron therapy", 14th International Particle Accelerator Conference IPAC 23, Venice, Italy, 11th May 2023.
Newspaper article	L. Rossi, interview of L. Benacchio, "Dentro l'infinitamente piccolo al servizio dell'umano – Tecnologie Innovazione", Il Sole 24 ORE, pag. 24, 14th May 2023.
Conference talk	F. Toral et al., "Status of Nb-Ti CCT Magnet EU Programs for Hadron Therapy", MT28 – International Conference on Magnet Technology, Aix-en-provence, France, 14 September 2023.
Workshop talk	E. De Matteis, "New Technologies: Superconducting Magnets", Workshop on Hadron therapy: status and perspectives. Development of a hadron therapy facility: learning from the existing and Scientific day on BNCT, CNAO, Pavia, Italy, 12 October 2023.
Public talk	L. Rossi, et al., "La Tecnologia Superconduttiva tra ricerca e green deal", Festival della Scienza, Genova, Italy, 3rd November 2023.
Public talk	L. Rossi, "Nuova fisica, difesa della salute e vita nello spazio: temi d'attualità per un'informazione responsabile", "Edoardo Amaldi e la sfida del CERN" organized by UGIS (Unione Giornalisti Scientifici Italiani), Piacenza, 25th November 2023.
Outreach to students	L. Rossi, "I grandi acceleratori di particelle e il super-collider post-LHC al CERN. Dall'infinitamente piccolo alle tecnologie per la salute e la transizione verde", Fondazione Vasilij Grossman, Liceo Scientifico e classico, Milano, Italy, 15th December 2023.
Public talk	L. Rossi, "Dal bosone di Higgs alla transizione energetica ed alla medicina: il PNRR come volano tecnologico per la superconduttività.", public conference "Venerdi' dell'Universo", Univerisità degli Studi di Ferrara and INFN-Ferrara, Ferrara, Italy, 26th January 2024.
Outreach to students	I convegno dell'associazione su L. Rossi, "Università: il fascino indiscreto del Maestro… Ma gli allievi ci sono ancora?", association conference Universitas-University, Cremona, Italy, 24th Febbruary 2024.
Outreach to students	L. Rossi, "Un errore mi ha cambiato la vita - Caduta e ripresa dell'LHC al CERN", ITI e Liceo Enrico Fermi, Desio, Italy, 18th March 2024.

Heavy Ion Therapy Research Integration

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Thanks for the attention!!!

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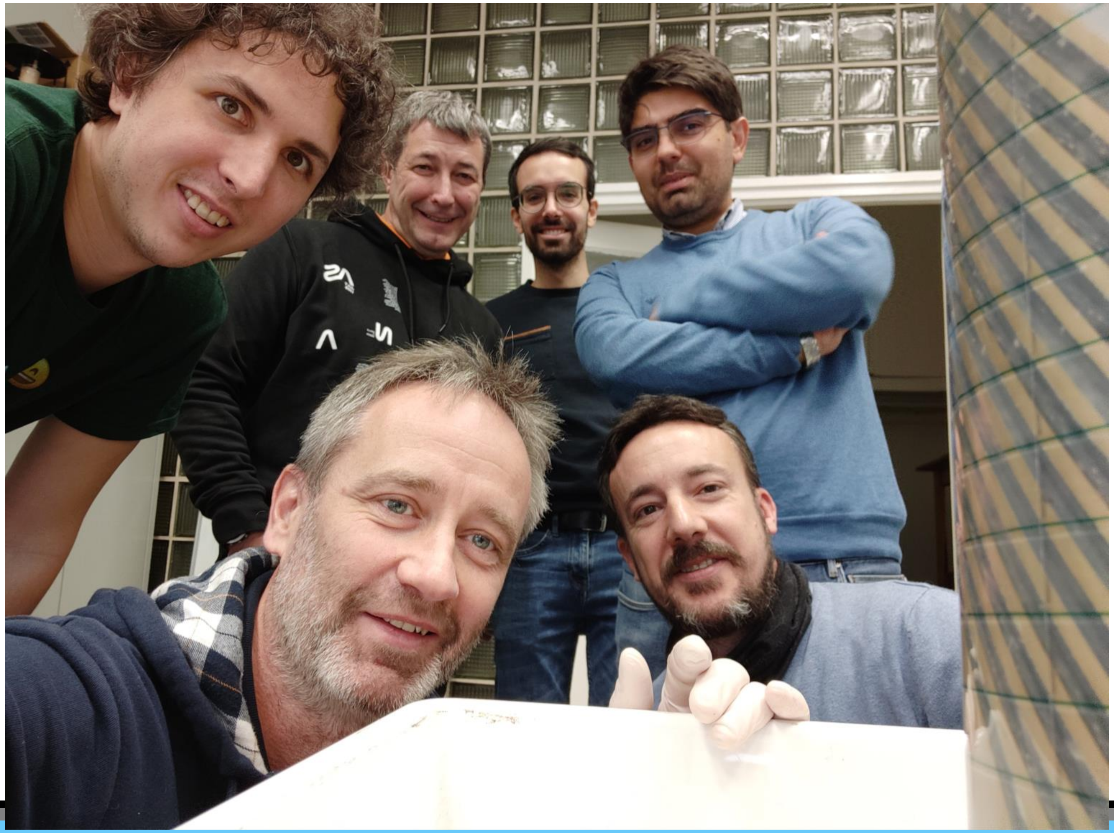
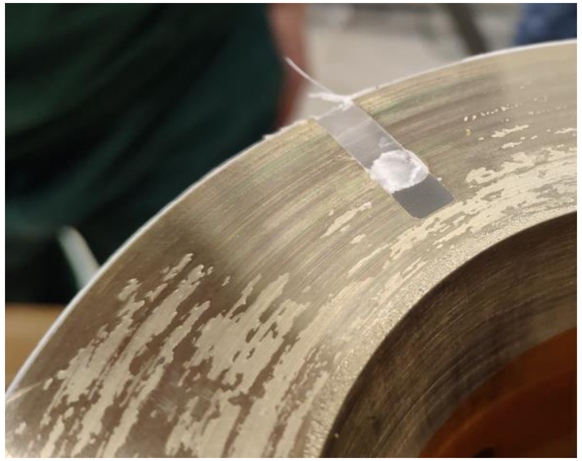
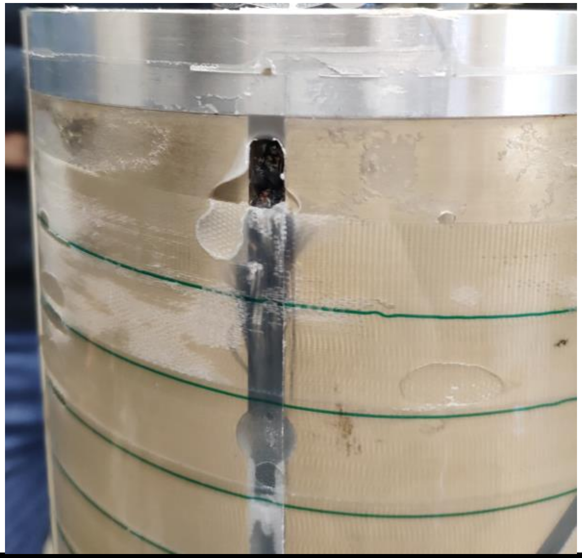
2x8 ropes impregnation test with wax (Task 8.3)

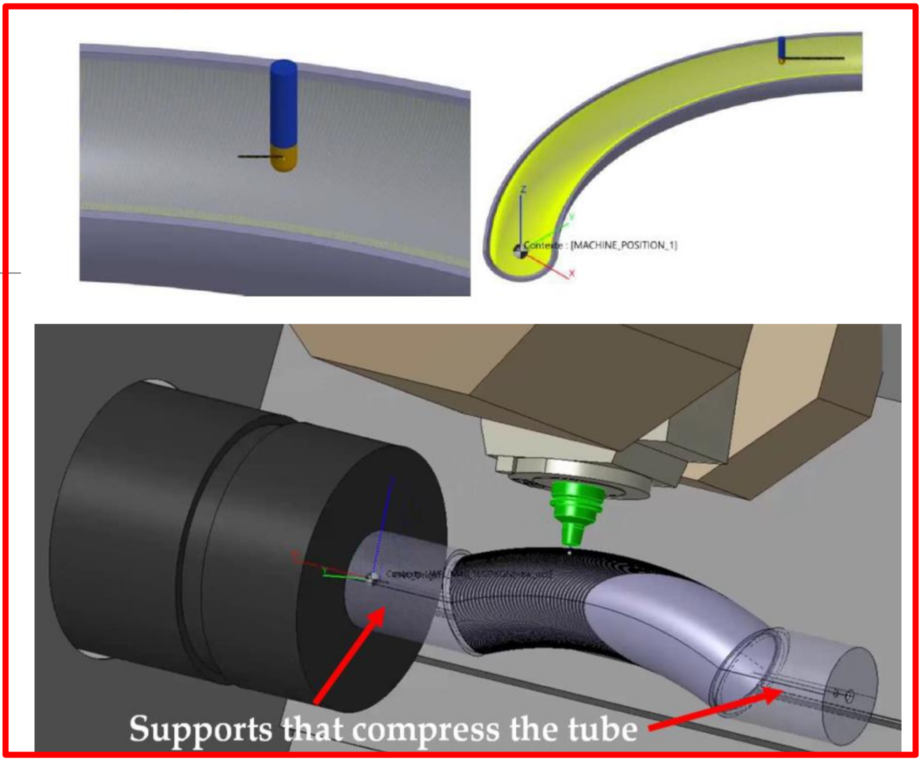
Test impregnation of HITRIplus former prototype with 2x8 polyester insulated ropes showed good filling of the groove.







Curved Al-Br formers machining (Task 8.4)

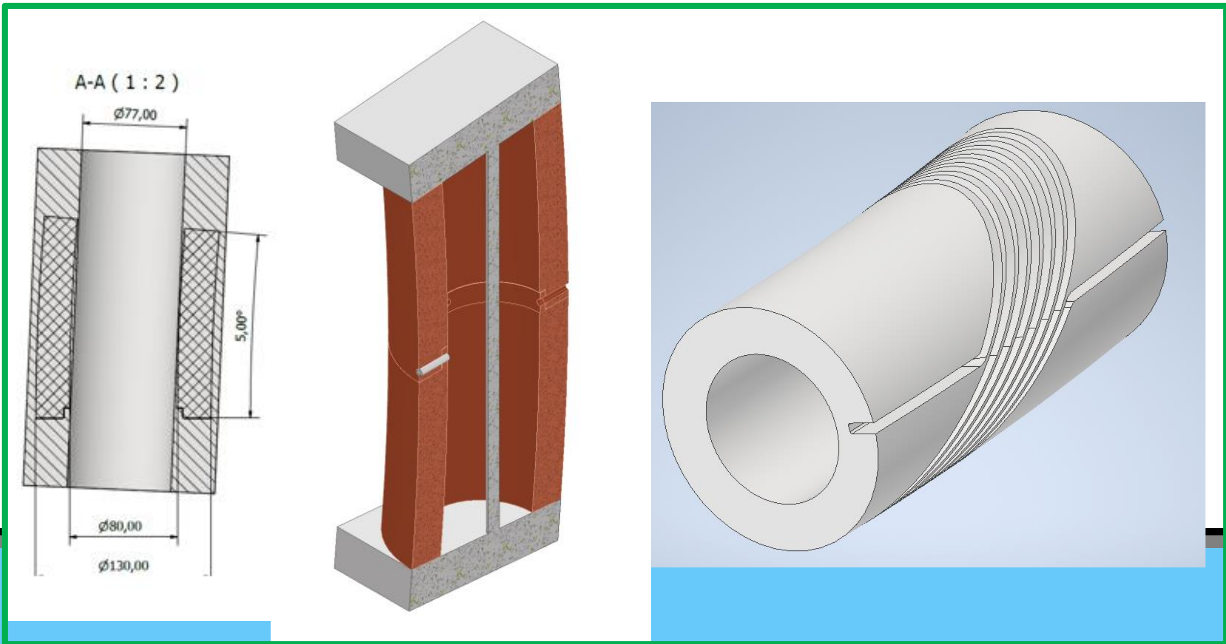


First construction procedure based on CERN-INFN preliminary study:

- 1)Supply of raw straight tubes of AlBr, 2)Bent tubes, 3)Split the bent tube along the longitudinal direction, 4) Machining of internal part, 5)Brazing of the two halves, 6) Machining of the formers' groove;
- Long survey contacting several companies around Europe;
- Difficulties finding a unique company able to do this kind of construction or a chain of companies capable of doing it.

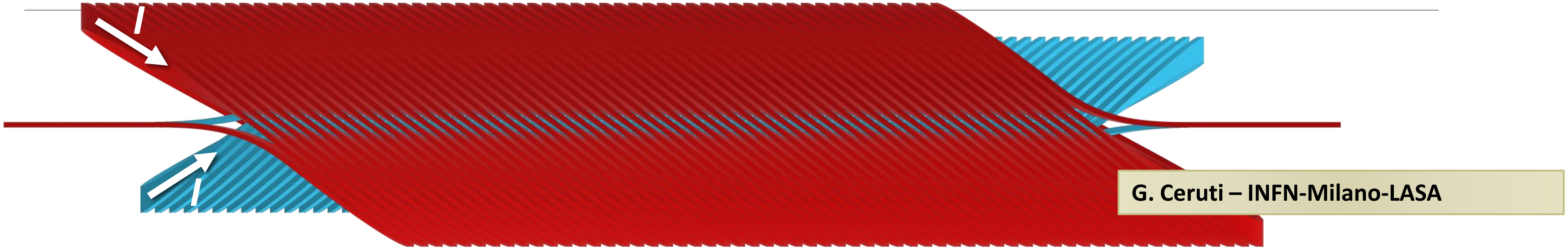
Second construction procedure based on curved subsections joined by slotted pins:

- Build the curved tube subsections from a straight AlBr tube with extra wall material, join the subsections by slotted pins, and then machine the grooves;
- Tosti srl (Castelpiano, Grosseto, Italy) is in charge of the tests (waiting for the order);

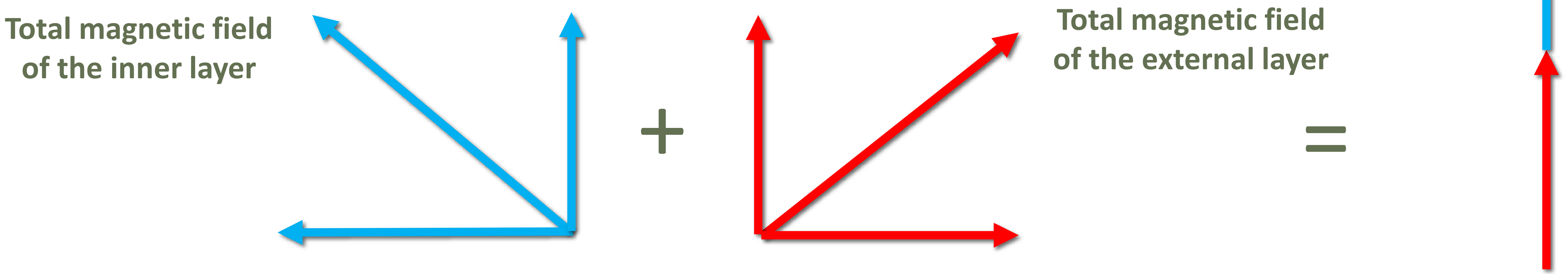


Canted-Cosine-Theta (CCT) Magnet (1)

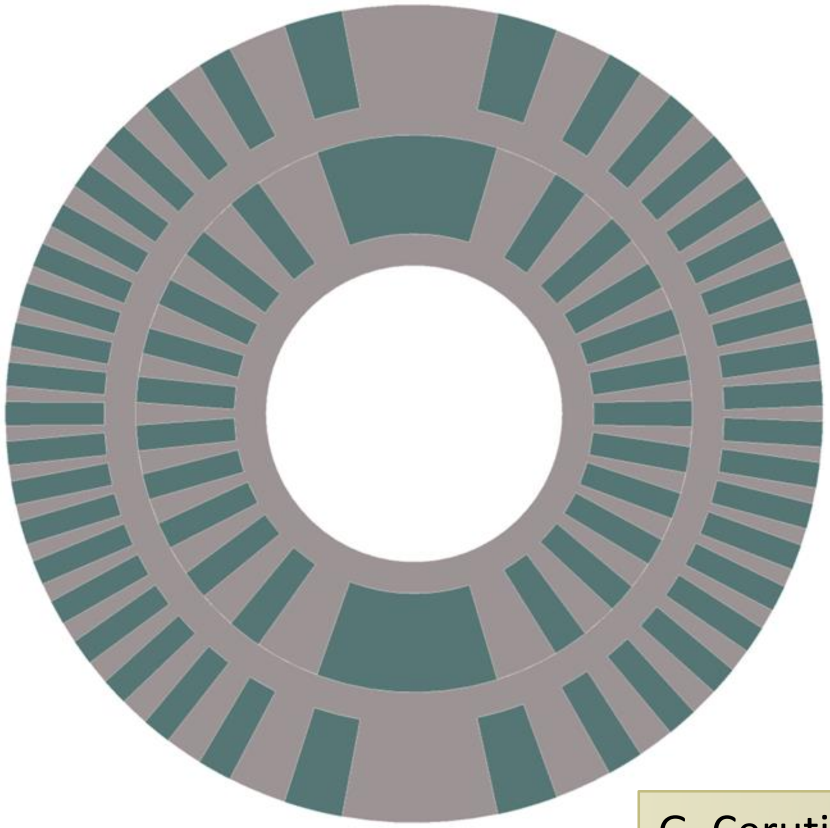
- The CCT design is based on pairs of canted conductor layers:

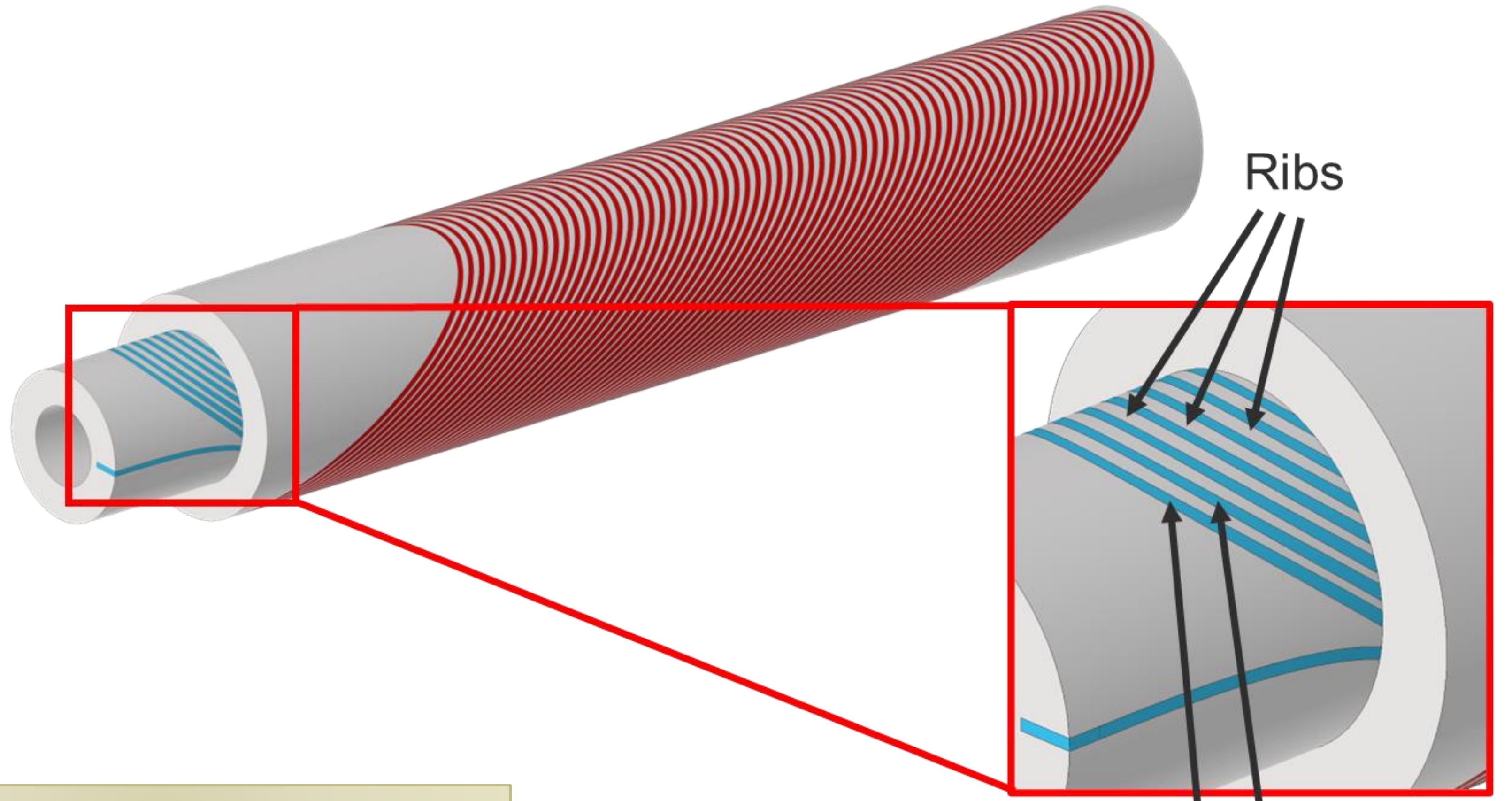


- **Current *I* flows in the two conductors so that the transverse magnetic field components sum and axial field components cancel each other.**



CCT schematics





G. Ceruti – INFN-Milano-LASA

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HITRIplus WP8 – Superconducting magnet design members

HITRIplus & I.FAST

HITRIplus

	Coordination	Task	Task leader	Deputy-task leader
WP8 Superconducting Magnet Design	E. De Matteis (INFN) T. Lecrevisse (CEA)	8.1 - Coordination and Assessment of magnet design	E. De Matteis (INFN)	D. Barna (Wigner Inst.)
		8.2 - Technical and Financial evaluation of various magnet designs	S. Sorti (INFN)	D. Barna (Wigner Inst.)
		8.3 - Preliminary engineering design for accelerator and gantry magnets	D. Barna (Wigner Inst.)	F. Toral (CIEMAT)
		8.4 - Construction of a small size magnet demonstrator for accelerator and gantry	F. Toral (CIEMAT)	S. Sorti (INFN)

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