This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under GA No 101004730.

WP8 - Innovative Superconducting Magnets report on Tasks 8.1 – 8.5

Ernesto De Matteis, INFN of Milan (Italy) – LASA laboratory

and all WP8 collaborators

I.FAST – 3rd Annual Meeting

18.April.2024 – Paris, France

SCIENCE FOR SUSTAINABILITY

I.FAST WP8 – Innovative superconducting magnets

Scope

Form a permanent **European Strategy Group**, open to worldwide partners, to discuss the European strategy **for HTS magnets for accelerators**, and to improve Industry involvement in this technology;

Exploring **Canted Cosine Theta with HTS superconductor (main goal),** preceded by a **combined function CCT based on LTS** □ involving the industries that want to learn about the CCT magnets;

Construction of the two demonstrators: winding and magnet assembly, magnet test and validation

Magnet Members of Task 8.1 – 8.5

cea, CERN, Ciemat, WIGNER, INFN Istituto Nazionale di Fisica Nucleare, PAUL SCHERRER INSTITUT PSI, UPPSALA UNIVERSITET, BILFINGER Bilfinger Noell GmbH, UNIVERSITÉ DE GENÈVE, ELYTT ENERGY, SCANDITRONIX

BERKELEY LAB

Program based on CORC and CCT layout led by X. Wang & S. Prestemon

CCT dipole
4 T target
Ø =80 mm;
L <= 1000 mm

CORC®

By Advanced Conductor Technologies

Courtesy of Xiaorong Wang

Relevance of objectives and impact

- Coordinate and foster initiatives towards High-Temperature superconductivity (HTS) for accelerators:
  - HTS is the new frontier for superconductivity, promising higher magnetic fields and smaller cryogenics systems, but has still to face challenges in terms of cable production schemes, magnet design, and cost.
  - The Strategy group will collect data, identify promising directions, and propose future R&D plans.
- Design a new magnet for medical applications in both classic superconductor and HTS, and build and test a demonstrator:
  - Reduce dimensions and cost of synchrotrons and gantries for research and for cancer therapy.
  - *WP8 will construct prototypes of advanced components to be used, among others, for medical accelerators.*
- Develop HTS magnet for energy saving: cooling system based on conduction cooling are more efficient at high temperature (20 K) with respect to Low temperature (LTS at 4.2 K):
  - The COP^{-1} is 240 W_{elect}/W_{cool} at 4.5 K → 50 W_{elect}/W_{cool} at 20 K (5 times less)

R. van Weelderen (CERN)
CAS-Austria 2023-11-27/28

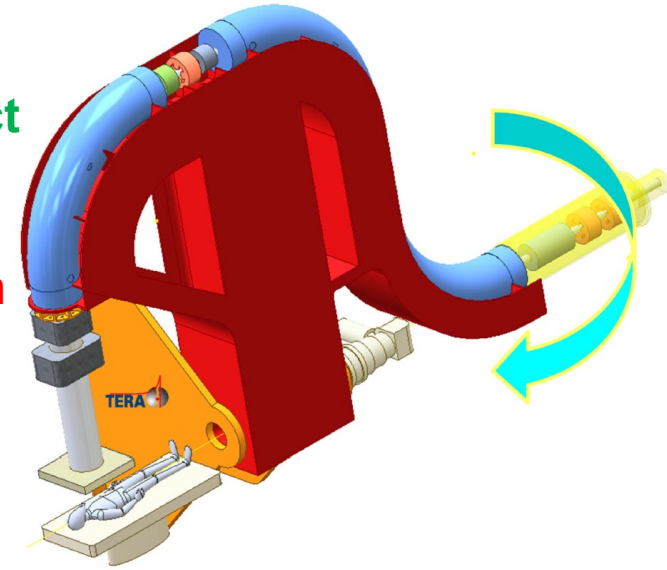
Temperature level	COP^{-1} in W_{elect}/W_{cool}	FOM (%)
20 K	50	
10 K	150	
4.5 K	240	28
2.0 K	960	16

Parameters of demonstrator magnets

Parameters	Values		unit
Magnet type	CCTs		-
	LTS	HTS	
Geometry	**Straight**		-
Central magnetic field B_0	**4**		**T**
Magnetic and physical length	0.8, 1		m
Bore diameter	**80**		mm
dB/dt	**0.4**		**T/s**
Operation temperature	**4.7(4.2)**	**20**	**K**
Loadline margin (@4.7 K) static	25		%
Superconductor	**NbTi**	**RebCo tape**	-

Superconducting Rotating Gantry

Light and compact
weight<100 ton
Cost reduction
Cryogenic system



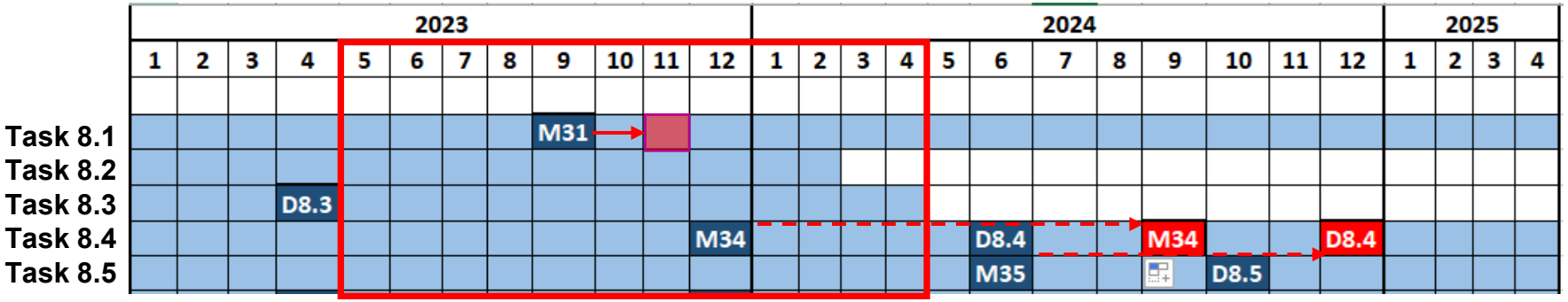
Carbon Ions beam rigidity

Magnet parameters as HITRIplus and SIG/SIGRUM programs (Hadron Therapy magnet)
Straight geometry → HTS is already difficult enough!

WP8 – Timeline, Milestones and Deliverables

IFAST WP8: Innovative Superconducting Magnets
Task 8.1 - Coordination and High-Temperature Superconductor (HTS) Strategy Group
Task 8.2 - Preliminary Engineering design of combined Canted Cosine Theta (CCT) magnet
Task 8.3 - Preliminary Engineering design of HTS CCT
Task 8.4 - Construction of combined CCT magnet demonstrator
Task 8.5 - Construction of the HTS CCT magnet demonstrator

24-36 months activities



Deliverables

- D8.1 (04/2022): HTS European Strategy Group (**ACHIEVED**) (CERN and INFN)
- D8.2 (02/2022): Conceptual Design of combined CCT in LTS (**ACHIEVED**) (INFN);
- D8.3 (04/2023): First Engineering design of HTS demonstrator (**ACHIEVED**) (INFN)
- D8.4 (06/2024→12/2024) : Construction of combined CCT demonstrator (Postponed) (CIEMAT):
  - **Delay accumulated by the change of beneficiaries from BNG to CIEMAT.**

Milestones:

- M32 (10/2021): Characterization of the first length of superconductor for low losses (**ACHIEVED**) (INFN, Univ. Geneva, and CERN)
- M33 (06/2022): Conceptual design of HTS magnet (**ACHIEVED**) (CEA)
- M31 (12/2022 → 11/2023): Construction readiness of combined CCT demonstrator (**ACHIEVED**) (INFN, CIEMAT, Wigner RCP)
- M34(12/2023 →09/2024): Construction of the formers for combined CCT winding (Postponed) (CIEMAT)
  - **Delay accumulated by the change of beneficiaries from BNG to CIEMAT+change of the strategy.**

I.FAST WP8 – activities of last year (24-36 month)

- From the 27th of April 2023 we had n. 6 general meetings and more than 40 dedicated weekly meetings about the demonstrators (n. 20 for the combined CCT, each Monday and n. 20 for the HTS CCT, each Tuesday);
- Task 8.1, 8.2 and 8.3 have reached all the objectives (MLSs and DLVs);
- Construction readiness of combined CCT demonstrator (Task 8.1 –INFN, CIEMAT, Wigner RCP):
  - The report highlights the key components and procedures of the magnets – **MS31 MLS**
- Construction of combined CCT demonstrator (Task 8.4 – CIEMAT):
  - CIEMAT started the activities (formers and winding) in the construction of the combined function formers (ongoing tests) – **MS34 MLS;**
  - 3D model and conductor are ready, started the activities at CIEMAT – **D8.4 DLV;**
- Construction of HTS CCT demonstrator (Task 8.5 - ELYTT):
  - R&D activities concerning cabling, winding, soldering, and splicing – **MS35 MLS, D8.5 DLV;**
  - CERN delivered and measured the HTS tape (FFJ) for the final demonstrator

Milestone MS31: Construction readiness of combined CCT demonstrator[1]

Task 8.1 – (INFN, CIEMAT, Wigner RCP)

IFAST

Innovation Fostering in Accelerator Science and Technology

Horizon 2020 Research Infrastructures GA n° 101004730

MILESTONE REPORT

Construction readiness of combined CCT demonstrator

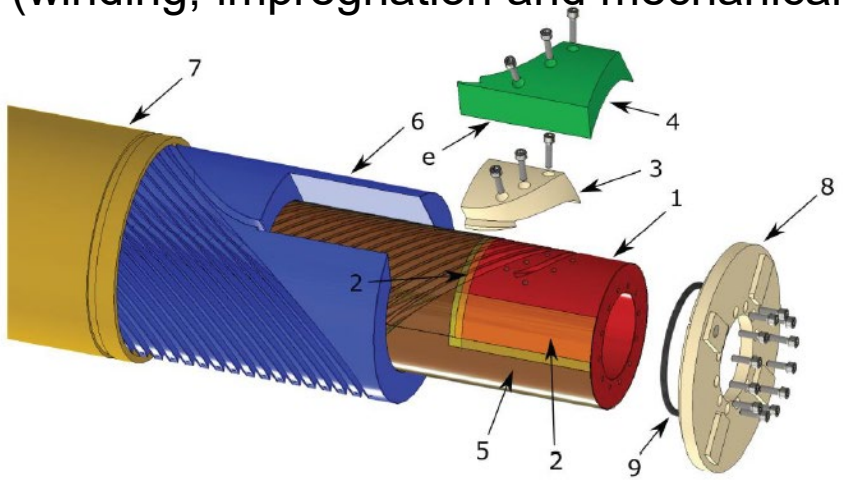
MILESTONE: MS31

Document identifier:	MS31
Due date of milestone:	End of Month 20 (December 2022)
Justification for delay:	Change of the beneficiary responsible
Report release date:	31/10/2023
Work package:	WP8: Innovative superconducting magnets
Lead beneficiary:	INFN
Document status:	Draft 1.0

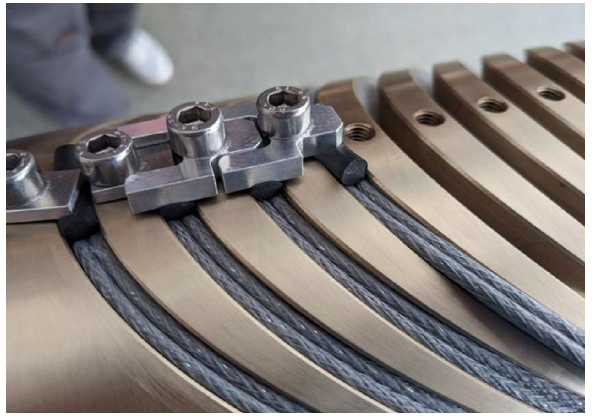
ABSTRACT

The report presents the construction readiness of the combined function CCT demonstrator. The document summarizes the components and the procedures that should be done to productively start and sustain magnet construction operations.

Report on the assembly process of the demonstrator magnet with detailed 3D illustrations, and listing the main components (conductor, formers, envelope tube, end plates, and splice box) and the main procedures (winding, impregnation and mechanical assembly).



Components	Readiness status	Comments
Conductor	ready	Final production launched
Formers	ready	Company for the final production to be found
Envelope tube	medium	Missing mechanical simulation for establishing the final thickness
End plates	ready	
Splice box	medium	To verify the production by CNC-machining and material (G10)
Procedures		
Winding	ready	Winding techniques ready, 3D model ready, fabrication drawings ongoing
Impregnation	ready	Design ready, components to be manufactured with the other parts.
Assembly	medium	To be defined the interlayer and the external surfaces of the formers.



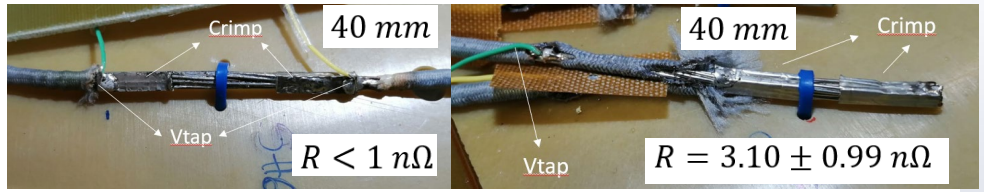
[1]E. De Matteis, D. Barna, F. Toral, R. U. Valente, **"Construction readiness of combined CCT demonstrator",** submitted for publication on Zenodo, 2023.

Task 8.4 - Construction of combined demonstrator (1/2)

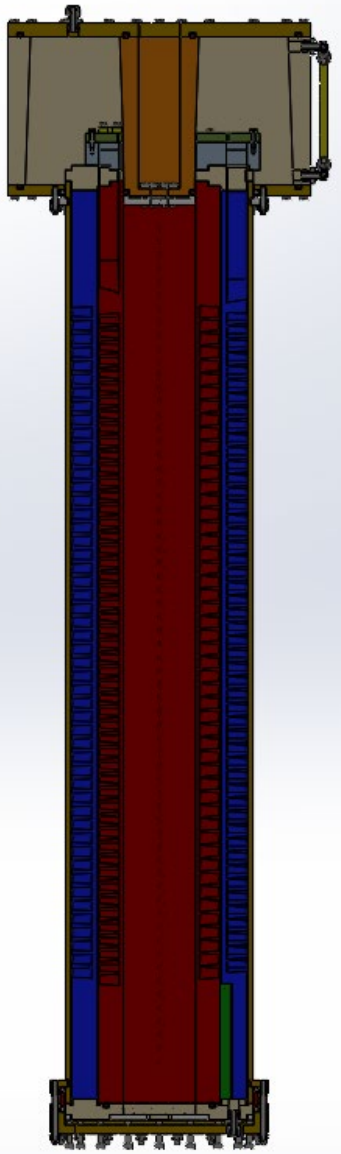
Task 8.4 – J. Munilla (CIEMAT)

Strategy

- Test former using copper rope including wax impregnation
- Validation tests: splices (INFN)
- Real size magnet

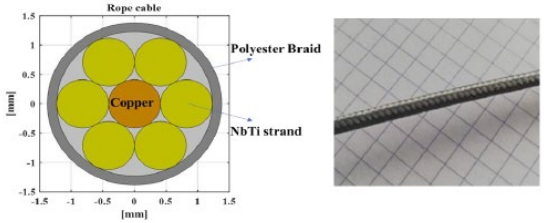


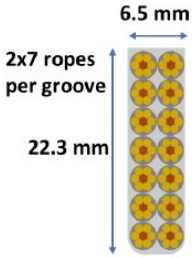
Real size magnet with impregnation tooling



Status

- Conductor ready (#14 spools of rope NbTi)
- A new winding machine is being commissioned
- Design and fabrication drawings are ongoing
- Some parts are already in fabrication



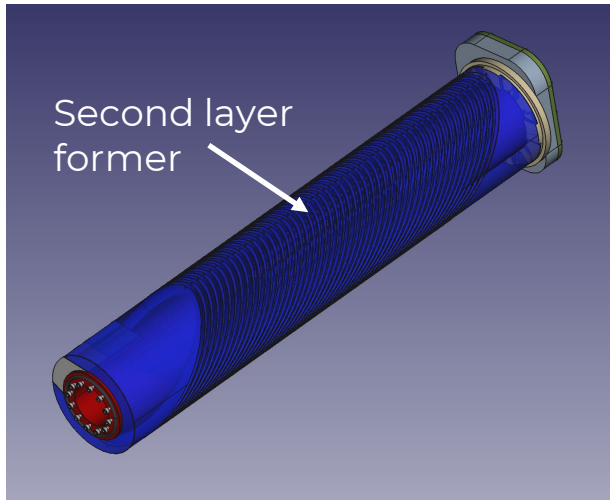


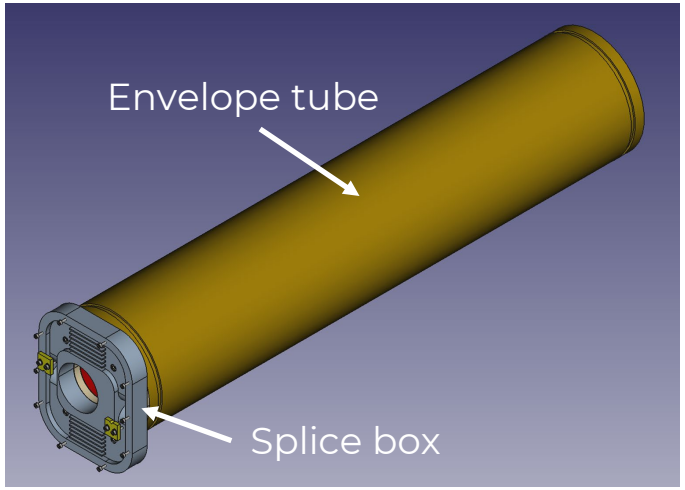
New winding machine

Task 8.4 - Construction of combined demonstrator (2/2)

Schedule

- Winding machine: April 2024
- Test former:
  - Drawings: April 2024
  - Fabrication: May 2024
  - Winding: June 2024
  - Impregnation: July 2024
- Real size magnet:
  - Drawings: July 2024
  - Fabrication: October 2024
  - Winding: November 2024
  - Impregnation: December 2024 (from June 2024).
- Cold tests of the magnet:
  - FREIA facility (Uppsala University): beginning of 2025.





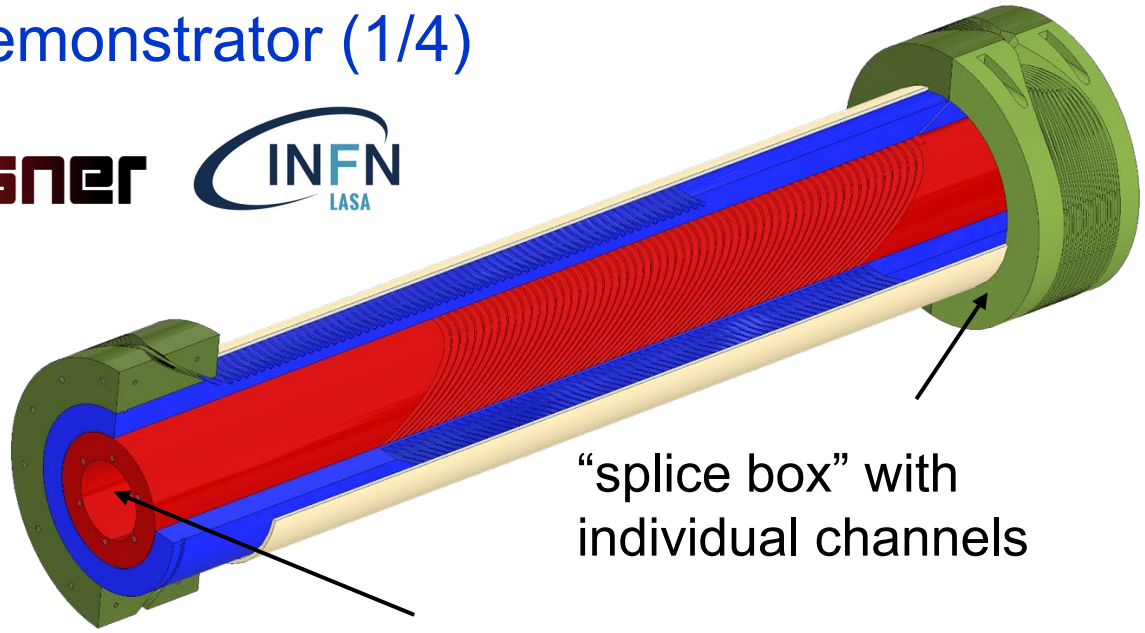
Final **TRL 5** wrt TRL6
Technology validated in (industrially) relevant environment (as CIEMAT facility) but tested in laboratory (Uppsala).

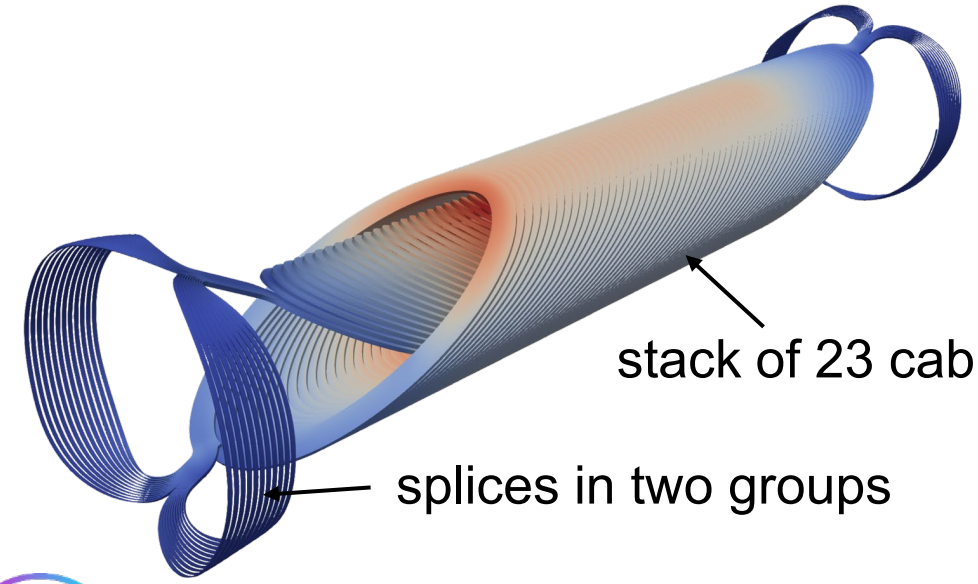
Task 8.5 - Construction of the HTS CCT demonstrator (1/4)

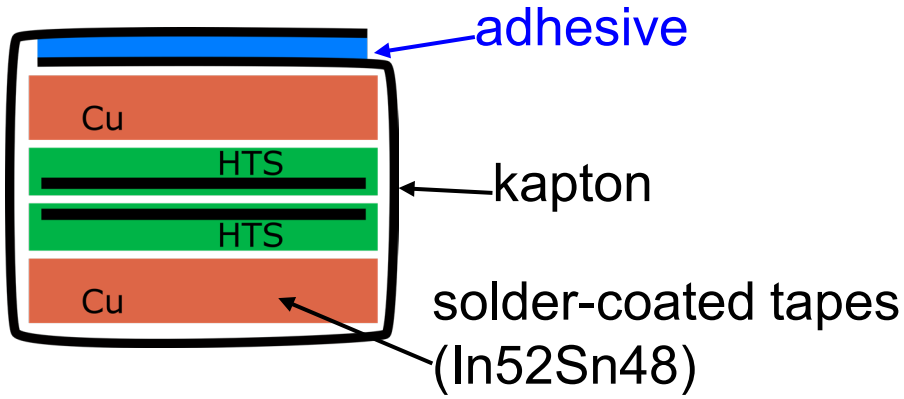
Task 8.5 – A. Echeandia (ELYTT)

Winding geometry

- Routing the tapes highly non-trivial.
- Winding path optimized/constructed by own C++ code
- Simulation, harmonic corr. by RAT



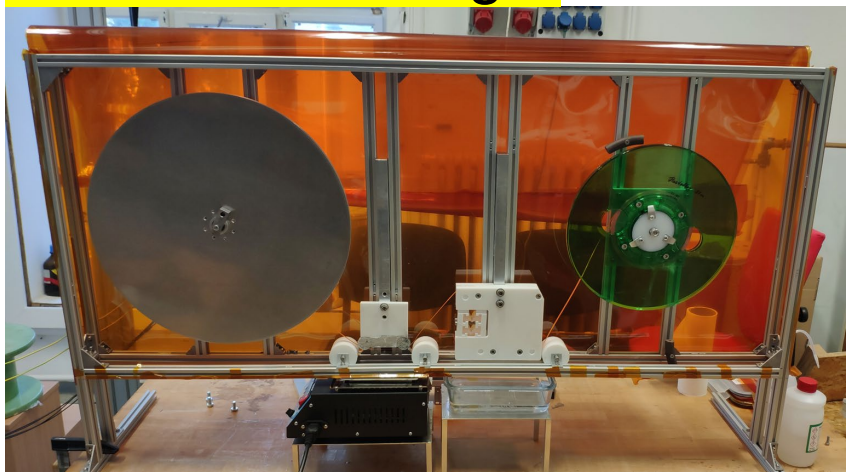




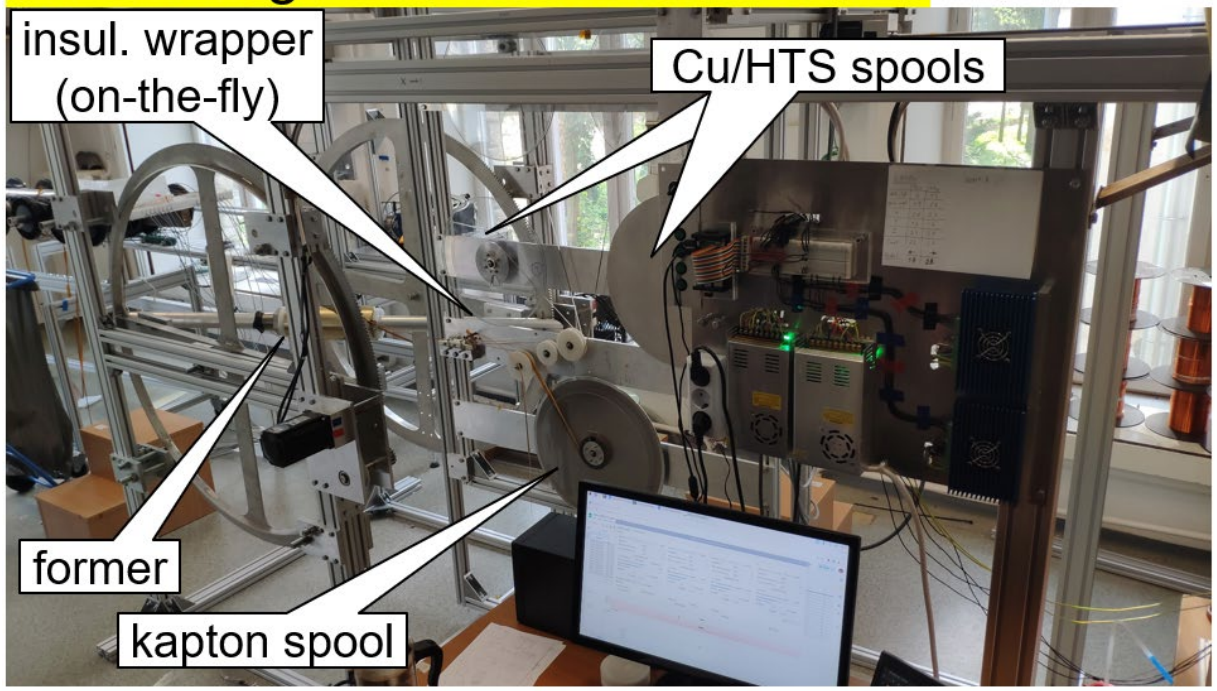
Task 8.5 - Construction of the HTS CCT demonstrator (2/4)

Cabling/winding

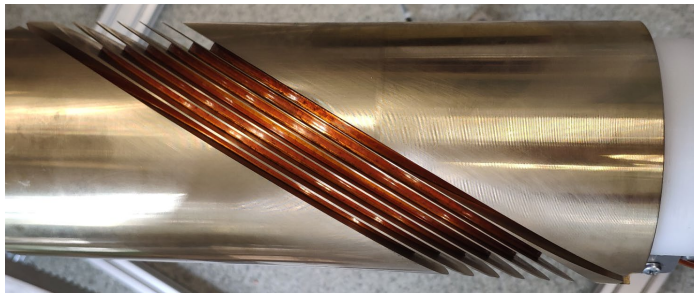
1. solder-coating



2. winding: custom-built machine



Mockup coil (2 cables yet) completed



tight fit, no problem

3. soldering in-situ

satisfactory bonding

Task 8.5 - Construction of the HTS CCT demonstrator (3/4)

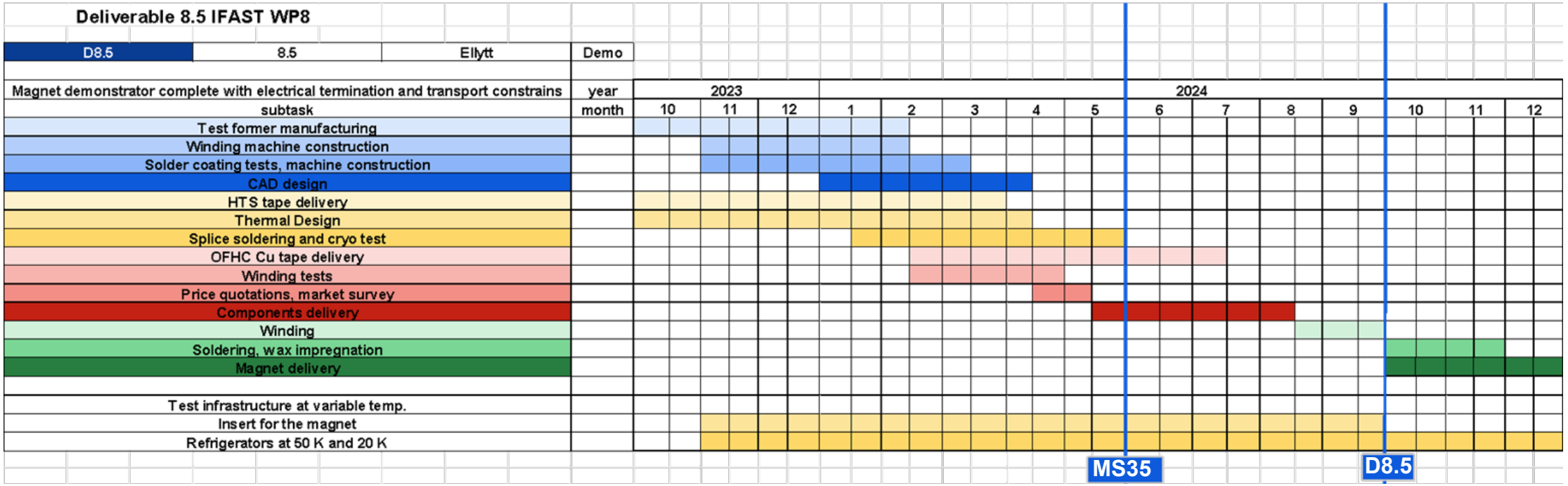
Status

- Choice of solder (In52Sn48 - melting point @ 118 °C < 200 °C !) & flux ✓
- Solder coating machine ✓ tests ✓ and coating parameters (~40-50 um) ✓
- Test mandrel manufacturing ✓, ultimate manufacturer chosen (not easy!) ✓
- Winding machine ✓, winding a mock-up coil ✓
- In-situ soldering: small test ✓, with mock-up coil: in progress (**MS35 – MLS in time!!**)
- Transfer of winding path from C++ to CAD ✓
- CAD design: concept ✓ final model in progress (~1 month)
- Splice soldering tests in progress
- CERN procured and measured 2.5 km of 4 mm HTS tape from FFJ (now at LASA for splice tests) ✓
- Wax impregnation R&D and method (from SuShi septum) ✓
- Conduction cooling system design in progress
- Test facility at 20 K (INFN-LASA) in progress

Final **TRL 5** wrt TRL6
Technology validated in (industrially) relevant environment but tested in laboratory

Task 8.5 - Construction of the HTS CCT demonstrator (4/4)

Schedule



		deadline	
M35	Rep. Test and Ass.	01/06/24	Test of mock up coils with dummy cable
D8.5	Demo	01/10/24	Construction of HTS CCT demonstrator

D8.5 is without time margins
The cold test is foreseen in 2025

I.FAST WP8 – collaboration with IRIS project

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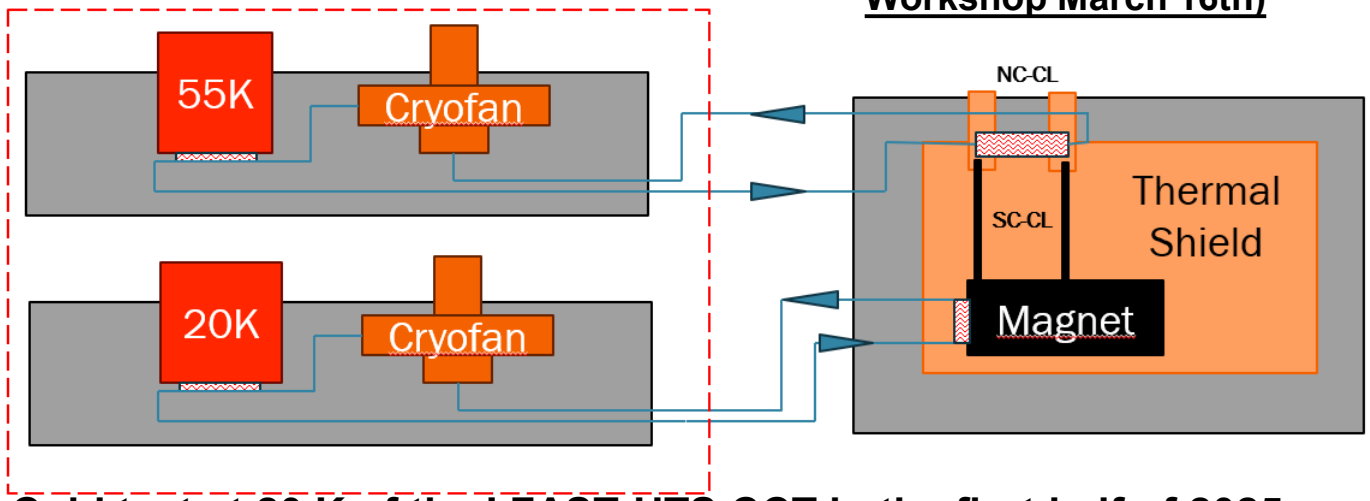
Finanziato dall'Unione europea NextGenerationEU

Variable Temperature Cooling Plant

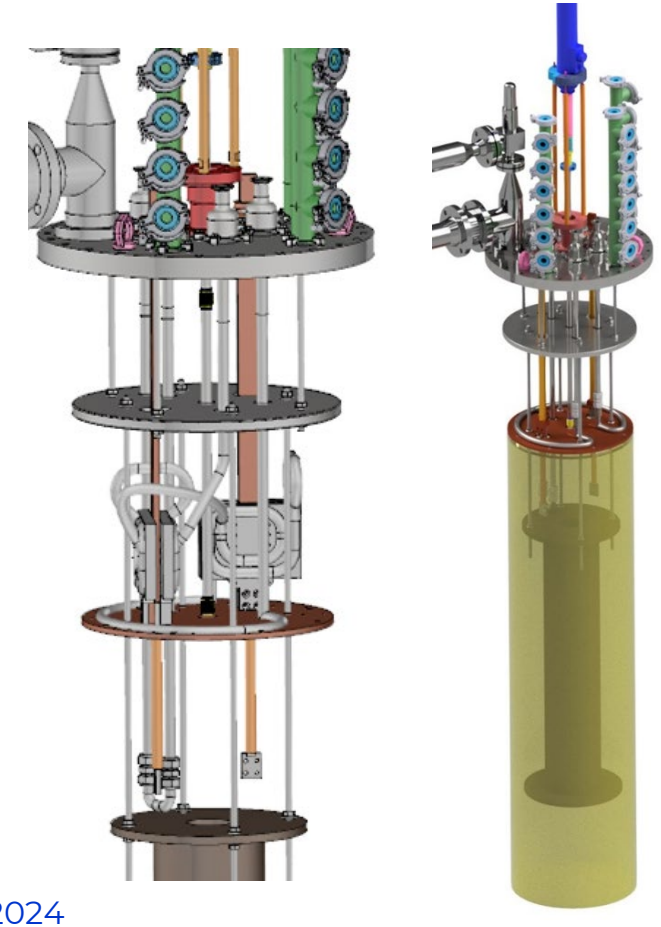


See talk of M. Statera (Industry Workshop March 16th)

Insert and Conduction Cooled System:

15K-50K (Variable T) – Magnets;

55K – Shield + Current Leads (1kA);

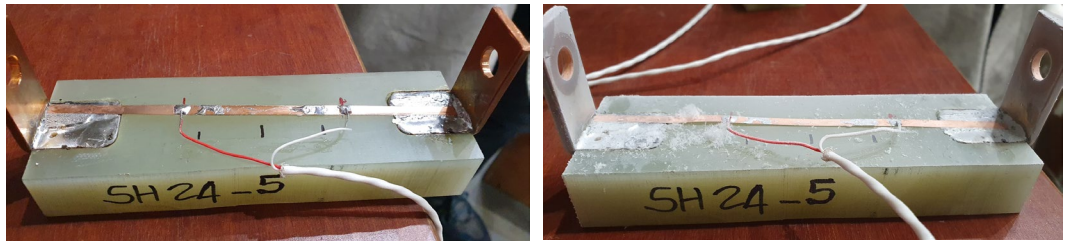


Cold test at 20 K of the I.FAST HTS CCT in the first half of 2025:

- Conduction cooling system are more efficient at high temperature (20 K);
- *COP^{-1} is **240 W_{elect}/W_{cool}** at 4.5 → **50 W_{elect}/W_{cool}** at 20 K (5 times less).*

Junction/Splice Tests (ongoing)→ definition of the splice length (min. Resistance)

Courtesy of L. Balconi



Conclusions and next steps

- Activities of the first three tasks completed (Task 8.1, 8.2 and 8.3):
  - Milestone **MS31**: Construction readiness of combined CCT demo (Done - 11/2023);
- Task 8.4 - Combined function CCT based on NbTi (first demo):
  - Activities are delayed for the construction (CIEMAT is paying the accumulated delay in the change of beneficiary);
  - Milestone **MS34**: Construction of the combined formers for CCT winding (delayed 09/2023).
  - Deliverable 8.4: Magnet delivery – (postponed from 06/2024 to 12/2024) more time for testing;
- Task 8.5 – CCT dipole based on HTS (second demonstrator):
  - R&D activities are ongoing and well progressing;
  - Procurement of the HTS tape (CERN) has been done;
  - Actual deadline for the **MS35** (06/2024) will be respected, more critical the **DLV 8.5** (10/2024)→**R&D is very challenging!!! We don't have time for contingencies;**
  - Test facility at 20 K is in preparation at INFN-LASA (IRIS collab.)→ test in the first half of 2025;
- We should increase the TRL of the demonstrators up to TRL5 (no TRL6 as GA).

Other activities of WP8

IFAST WP8 Meetings indico page:

https://indico.cern.ch/category/13096/

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	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	E. De Matteis et al., "Conceptual Design of an HTS Canted Cosine Theta Dipole Magnet for Research and Hadron Therapy Accelerators," in IEEE Transactions on Applied Superconductivity, vol. 34, no. 5, pp. 1-5, Aug. 2024, Art no. 4402505, doi: 10.1109/TASC.2024.3360210.	https://ieeexplore.ieee.org/document/10416714
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 (24 – 36 months)

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.
Conference talk	E. De Matteis et al., "Conceptual Design of an HTS Canted Cosine Theta Dipole Magnet for Research and Hadron Therapy Accelerators", 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.
Workshop talk	E. De Matteis, "Innovative Superconducting Magnets: IFAST's approach with Canted Cosine Theta based on High-Temperature Superconductor", Workshop on Superconductivity for Sustainable Energy Systems and Particle Accelerators, GSI, Darmstadt, Germany, 19 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 Scientific 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	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.

Thank you for your attention!

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This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under GA No 101004730.

WP8 – magnets members

(WP8 comprise also Task 8.6 on special SC cable for fast ramping led by GSI)

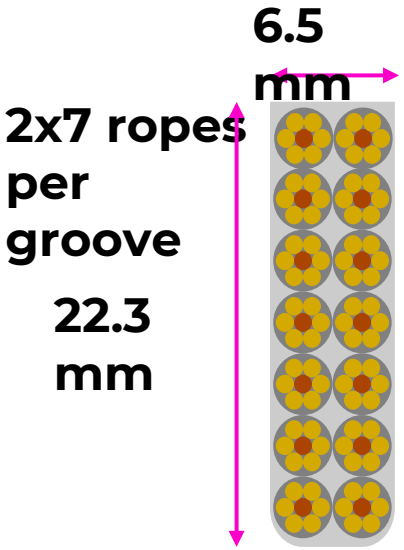
See the next talk by Tiemo Winkler (GSI)

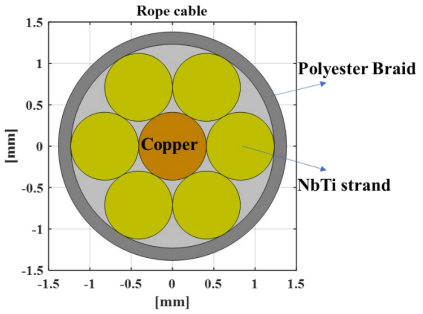
	Coordination	Tasks	Task leader	Deputy-task leader
WP8 Innovative superconducting magnets	E. De Matteis (INFN) T. Lecrevisse (CEA) C. Roux (GSI)	8.1 - Coordination and HTS Strategy Group	E. De Matteis (INFN)	A. Ballarino (CERN)
		8.2 – Preliminary Engineering design of combined CCT magnet	E. De Matteis (INFN)	D. Barna (Wigner Inst.)
		8.3 – Preliminary Engineering design of HTS CCT	S. Sorti (INFN)	A. Ballarino (CERN)
		8.4 - Construction of combined CCT magnet demonstrator	J. Munilla (CIEMAT)	D. Barna (Wigner Inst.)
		8.5 – Construction of HTS CCT magnet demonstrator	A. Echeandia (Elytt)	S. Sorti (INFN)
		8.6 – Development of ReBCO HTS nuclotron cable	T. Winkler (GSI)	C. Roux (GSI)

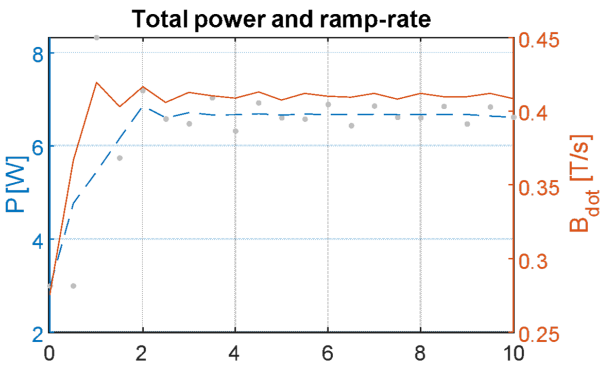
I.FAST WP8 – Highlights and status

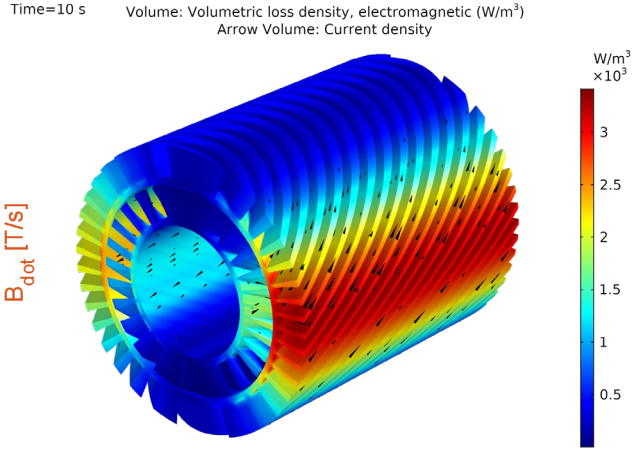
Combined CCT based on LTS (rope 6 NbTi + 1 copper strand as HITRIplus):

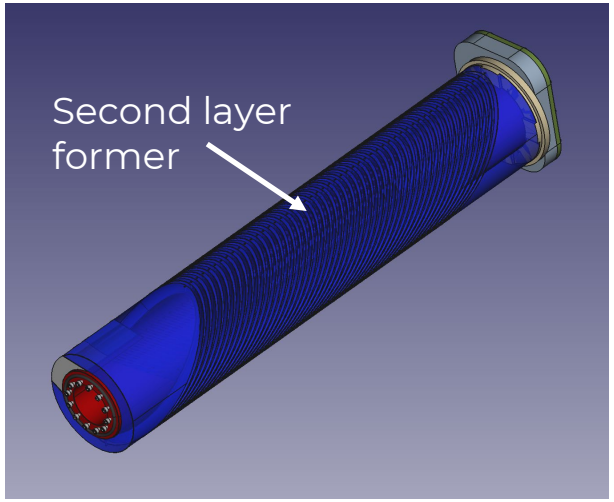
- **4 T dipole + 5 T/m quadrupole (important feature to test it for CCT);**
- **Ramped at 0.2- 0.4 T/s** challenge is the heat extraction generated by superconductor, and former;
- Straight geometry, Top of 4.2 K, nominal current of 1.5 kA;
- **Demonstrator for testing the combined feature of CCT and thermal study of AC losses;**
- Former made in Al-Br, wax impregnation;
- No iron yoke on the final demonstrator;
- **<u>Assembly ready for production</u>** (middle of 2024 test)-CIEMAT (responsible).

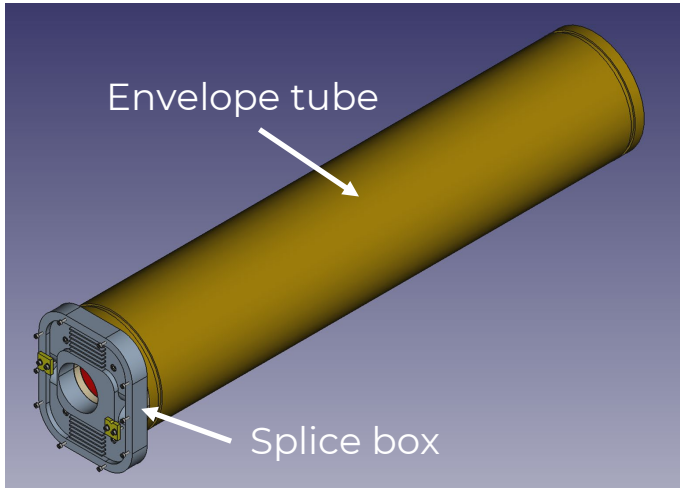












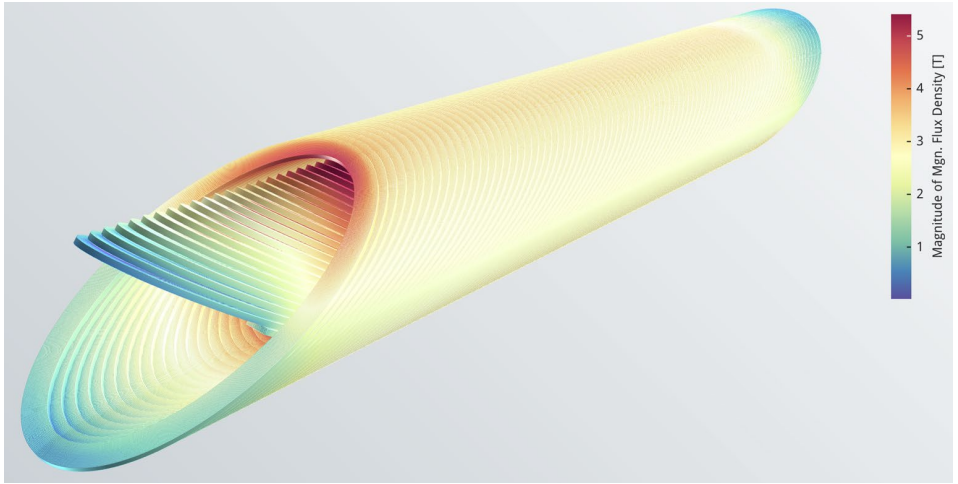
I.FAST WP8 – Highlights and status

CCT based on HTS (REBCO tape 4 mm wide):

- **4 T dipole** with a new Top of **20 K** (> 10 K of margin);
- Frenet-Serret frame used for the conductor (avoid hard way bending);
- **Straight geometry** just to start the study (HTS is already difficult enough);
- **Two design options:** 2-tapes (980 A) and 4-tapes cable (1990 A);
- Quench protection is demanded (Cu stabilizer added for this);

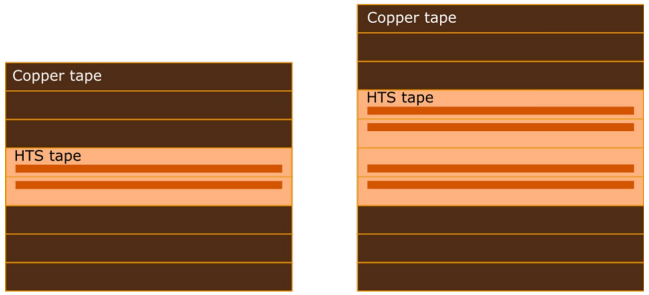
Company Elytt Energy (Spain) in charge of the construction of demo;

- Delivery within October 2024.

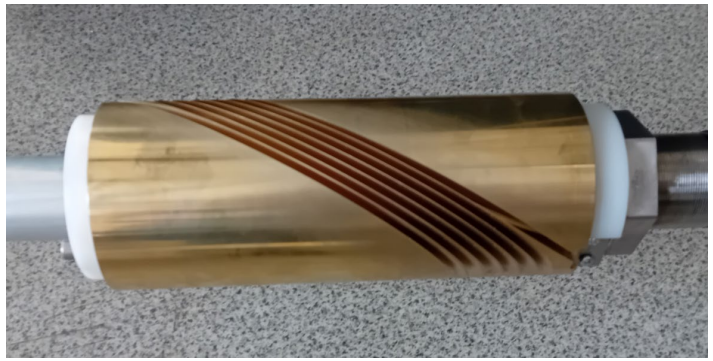


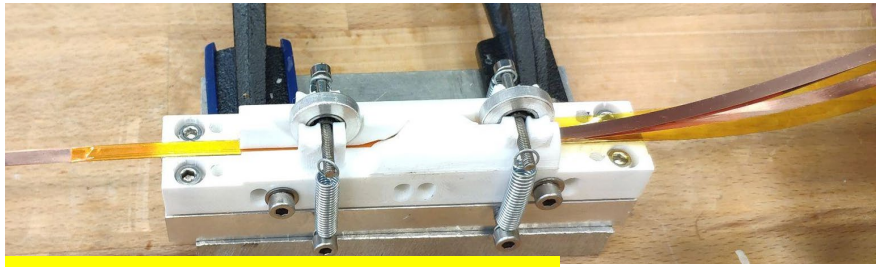
The **AC-losses (ramping at 0.4 T/s)** during operating for both designs are on average **50 W.** This is compatible with a conduction cooling system at 20 K.

1) No need of helium gas;
2) Power efficiency of cryocooler higher at 20 K wrt 4.5 K;



Short test





Making short samples of kapton-insulated tape stacks