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Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

INFN

Innovative Superconducting Magnets: IFAST's approach with Canted Cosine Theta based on High-Temperature Superconductor

Ernesto De Matteis,

INFN of Milan (Italy) – LASA

On behalf of my colleagues I.FAST WP8 and INFN-LASA

Superconductivity for Sustainable Energy Systems and Particle Accelerators

INFN LASA

Innovative Research Infrastructure on applied Superconductivity IRIS

iFAST

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

Superconductivity for Sustainable Energy Systems and Particle Accelerators

19. October.2023 – GSI, Darmstadt, Germany

IRIS

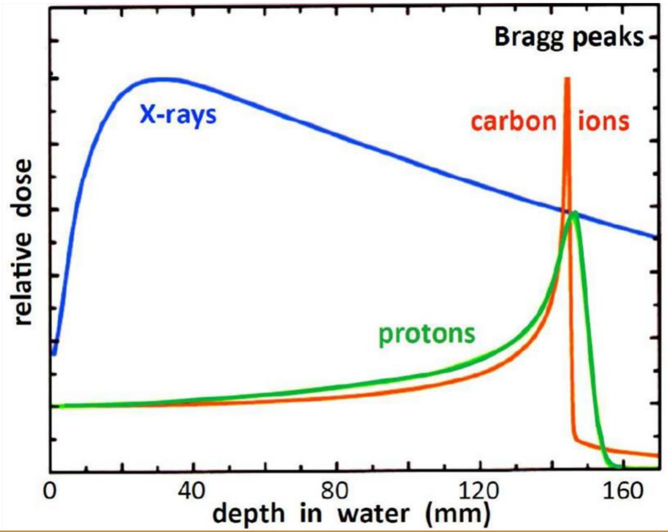
Summary

- Hadron therapy application: Magnet parameters
- IFAST WP8: Scope and demostrators;
- CCT based on HTS:
  - Preliminary design
  - Geometry, magnetic design, quench protection analysis
  - AC losses, R&D advancements, Test in the frame of IRIS
- Sinergy IRIS-I.FAST
- Conclusions

Medical application: Hadron Therapy

- Hadron therapy is a medical treatment that uses carbon ions and protons to cure cancer.
- Carbon ions are more effective for tumours resistant to traditional therapy and protons, but their use is limited by the size and cost of the needed infrastructure.

Relative dose versus depth for different radiations[1].



The treatment room at CNAO (National Centre for Oncological Hadrontherapy).

[1]Collings, Edward W., et al. "Accelerators, Gantries, Magnets and Imaging Systems for Particle Beam Therapy: Recent Status and Prospects for Improvement." *Frontiers in Oncology* 11 (2022): 737837

Medical Facilities – dimensions strictly depend on the magnetic field

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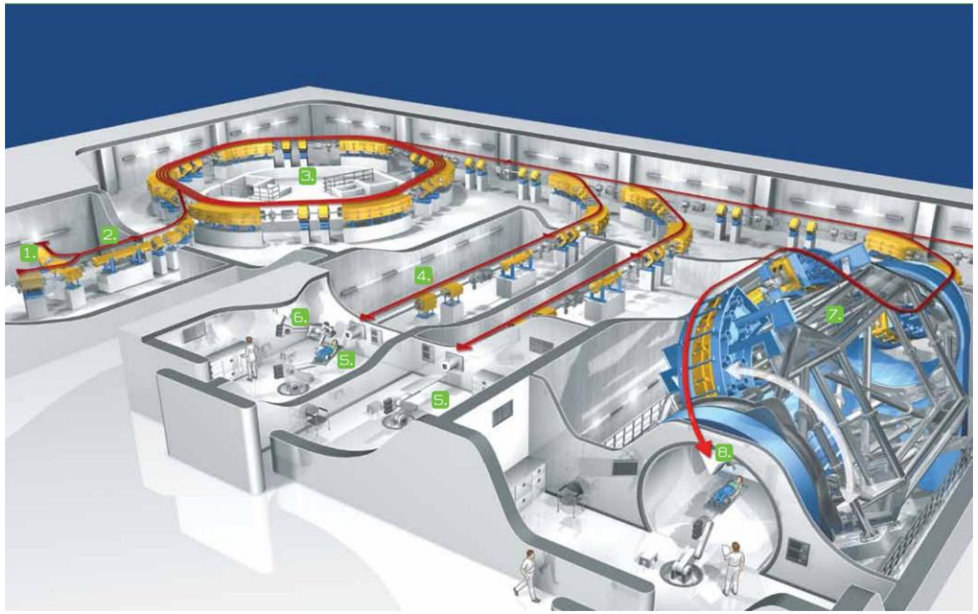
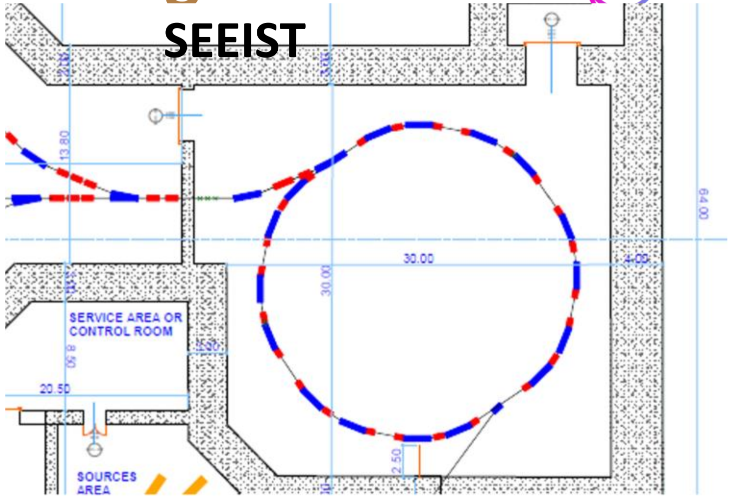
Accelerator hall in case of standard resistive magnet synchrotron vs case of using SC magnets

HIT - Heidelberg Ion Beam Therapy Center

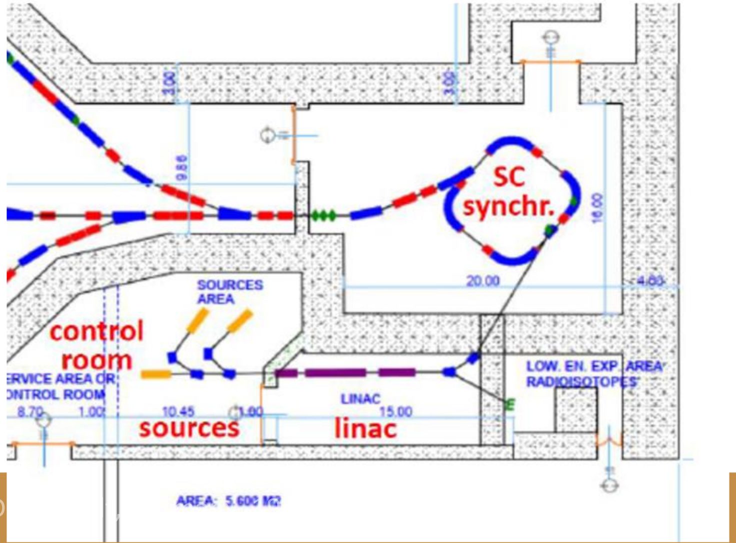


Resistive dipoles 1.5 T
Curvature radius of about 4.5 m

SEEIST



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



Courtesy of E. Benedetto (SEEIST)

Heavy Ion Therapy Rotating Gantries in the world

HIT - Heidelberg Ion Beam Therapy Center
(first in EU) – normal conducting magnets (B<2 T)

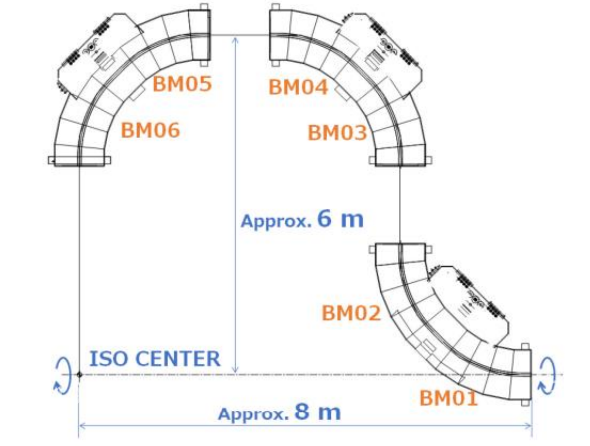
25 m long
13 m diameter
600 tons rotation
670 tons total

Japan - HIMAC (Heavy Ion Medical Accelerator in Chiba):
First SC Gantry in operation 2018 (B < 3 T);
Yamagata University Gantry:
Second Gantry in operation 2023 (Bmax 3.5 T).

Cryocooled dry SC magnet

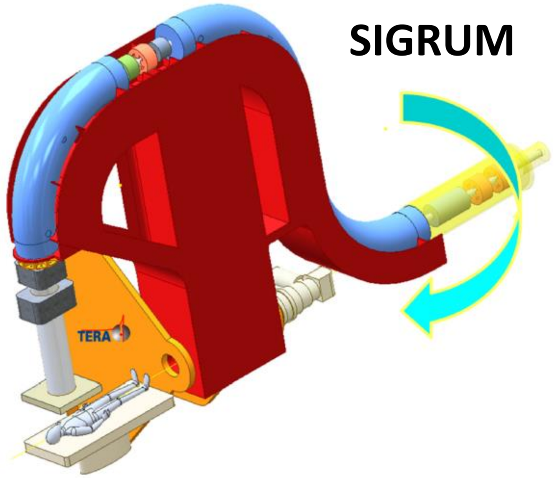
HIMAC

Yamagata



Superconducting magnets for Ion Therapy Gantries and Accelerators

SIGRUM



Main advantages:

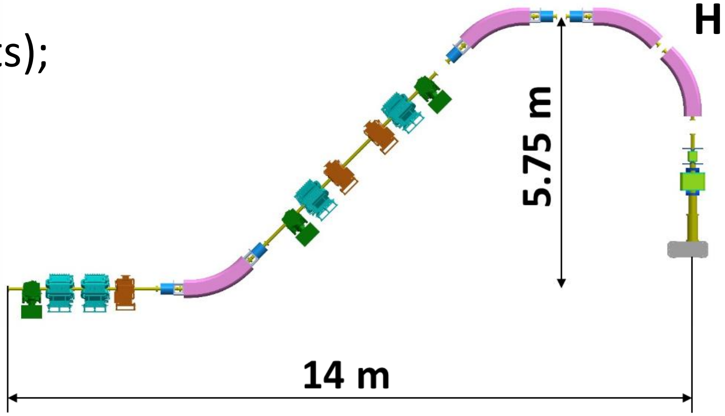
- Reduction of weight (300 → 50 ÷100 tons)
  - Reduce the number of magnets (B = 3→4 T)
- Footprint and cost reduction
  - Gantry cost is about 25% of facility cost;
  - Total cost of facility is about 200-250 Meuro (50 Meuro for the gantry);
  - Compact accelerator and gantry → less civil construction.
- Reduce Power consumption (SC vs NC magnets);

SC Magnet Target
B = 4 T
Θ=45°
Top = 4.7 K
dB/dt =0.4 T/s
Curv. Radius = 1.65 m

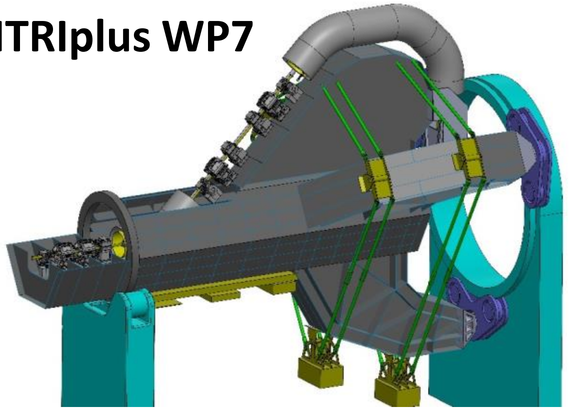
Carbon Ion Beam rigidity Bρ= 6.6 Tm

Main disadvantage:

- Need of cryogenic system (Top > 4.7 K, no liquid helium);



HITRIplus WP7



Courtesy of E. Felcini, M. Pullia (CNAO) and L. Piacentini (CERN - Riga)

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I.FAST WP8 – Innovative superconducting magnets

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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

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

CORC® By Advanced Conductor Technologies

Courtesy of Xiaorong Wang

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

12 mm HTS REBCO tape

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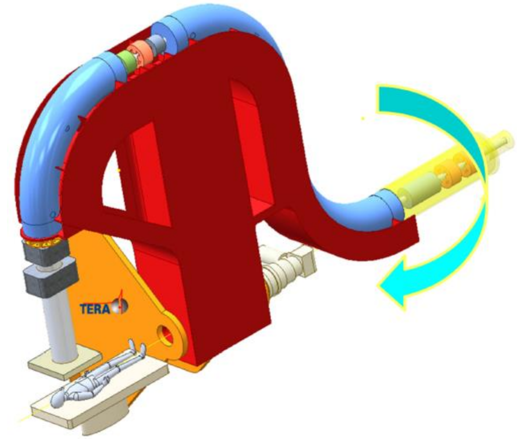
I.FAST - Parameters of magnet demonstrators

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**	**10 – 20**	**K**
Loadline margin (@4.7 K) static	25		%
Superconductor	**NbTi**	**RebCo tape**	-

Superconducting Rotating Gantry

Light and compact
weight<100 ton
Cost reduction
Energy saving
Cryogenic system



Carbon Ions beam rigidity

Magnet parameters as HITRIplus and SIG/SIGRUM (now EUROSIG) programs focused on Hadron Therapy magnet

Straight geometry → HTS is already difficult enough!

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Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

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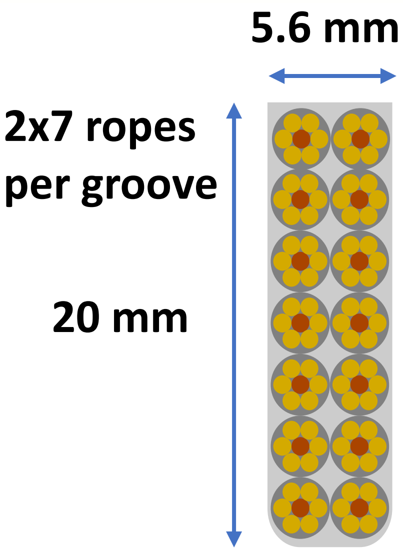
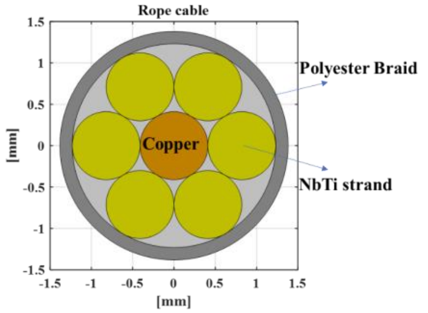
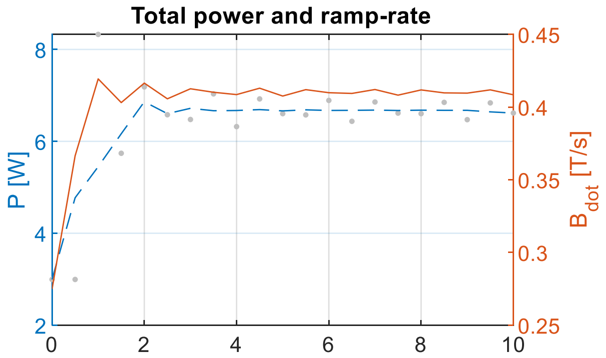
I.FAST WP8 – CCT based on LTS

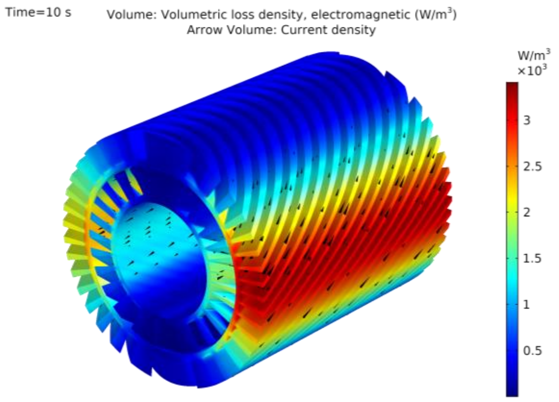
Combined CCT based on LTS (rope 6 NbTi + 1 copper strand as HITRIplus):

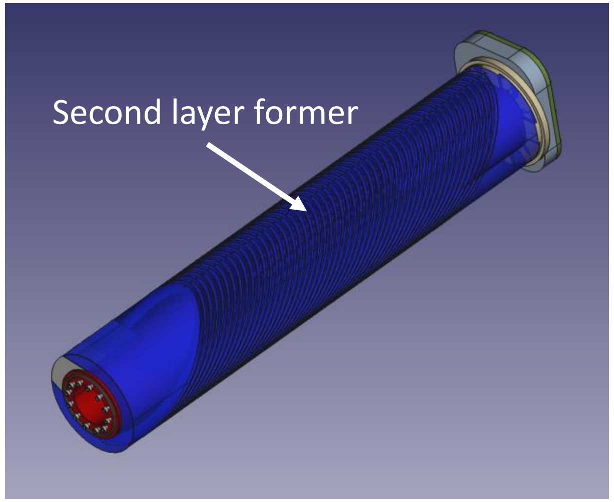
- **4 T dipole + 5 T/m quadrupole (important feature to test it for CCT);**
- **Ramped at 0.2- 0.4 T/s** → challenge is the heat extraction generated by superconductor, and former;
- Straight geometry, Top of 4.5 K, nominal current of 1.5 kA;
- **Demonstrator for testing the combined feature of CCT and thermal study of AC losses;**
- Former made in Al-Br, wax impregnation;
- No iron yoke on the final demonstrator;
- **Assembly ready for production** (middle of 2024 test).

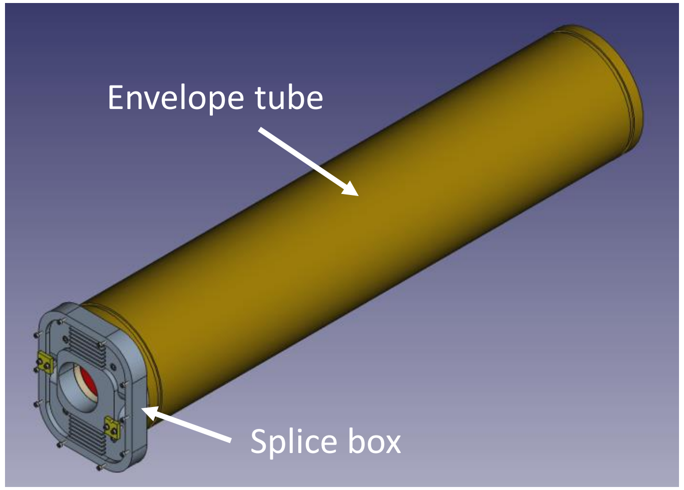












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Preliminary Design of HTS CCT Magnet

Work done by Thibault Lecrevisse (CEA)

Report[1] on the conceptual design study of the HTS CCT:

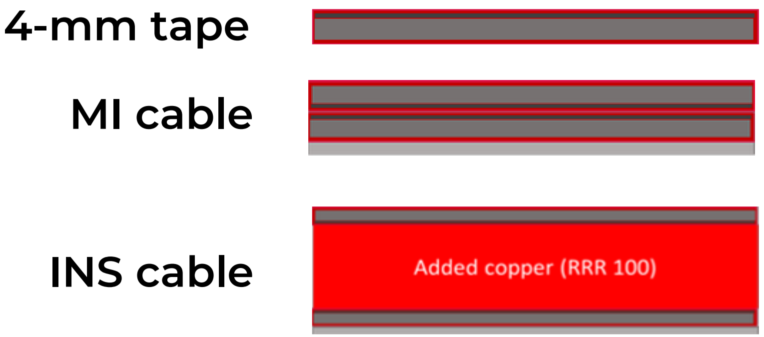
- Baseline (**4 T dipole** @ **10 K**, > 15 K of margin);
- Superconductor ReBCO (Tapes) – SST Ic = 650 A @ (15 K, 5 T);
- Cooling with cryocoolers → low current (< 2kA) to avoid high losses in current leads.

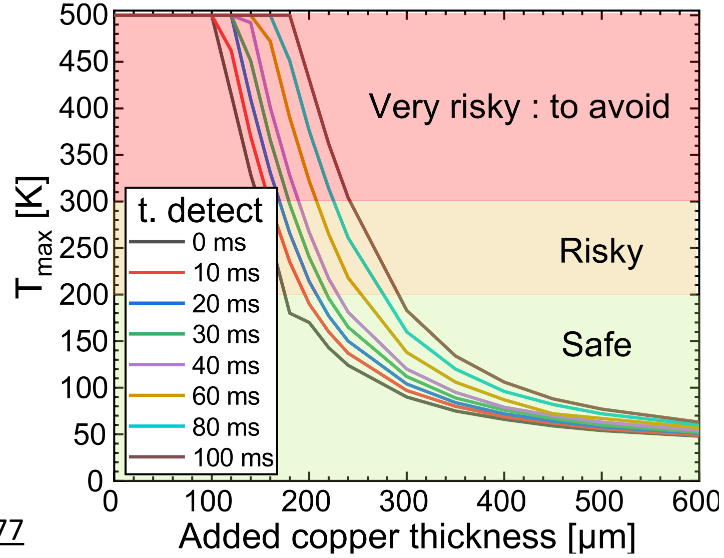
Two preliminary designs (No iron):

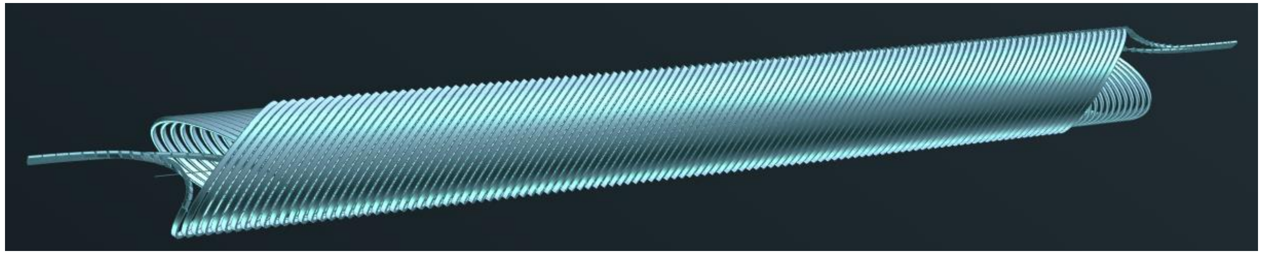
- "**Metal Insulation-like**" design with 2 tapes cable (550 A x 2 tapes x 14 cables)
- "**Insulated-like**" design (added copper to the conductor);

The protection aspect is the critical point for both:

- No classical protection for the MI;
- Vd<5 mV in 13 V, <60 ms detect for the INS, adding more than 260 µm of copper.



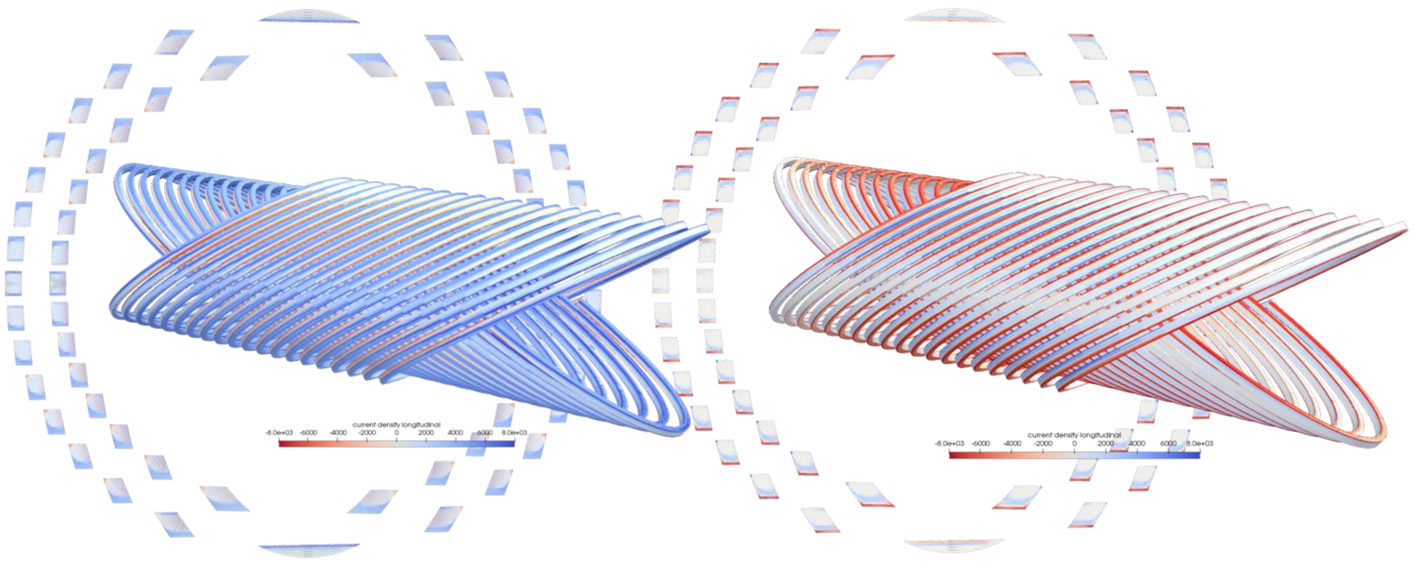




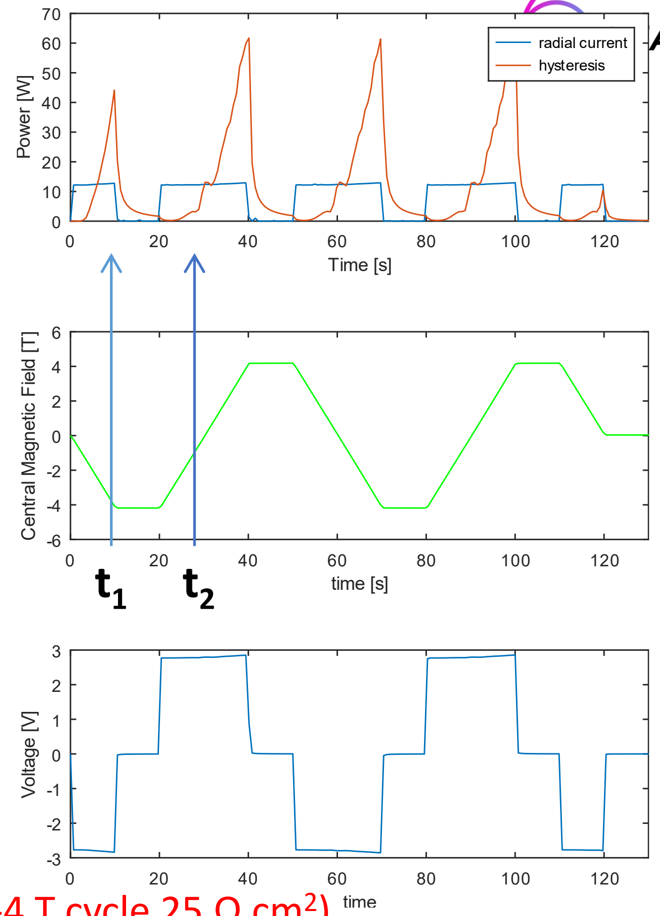
[1]T. Lecrevisse, "**Conceptual Design of HTS Magnet**", IFAST WP8.3 Milestone 33, Zenodo, https://doi.org/10.5281/zenodo.6979877

AC losses calculation for preliminary design HTS Magnet

current distribution in subscale model (20 turns) for a ±4 T cycle



End of 1° ramp (t_1) **Passing at 0 A (t_2)**



- High AC losses for the full scale magnet (~100 W peak for ±4 T cycle, ~50 W peak for 0-4 T cycle 25 Ω cm^2)
- Estimated adiabatic heating in one cycle gives + 8 K
- Difficult to extract by cryocoolers at 10 K

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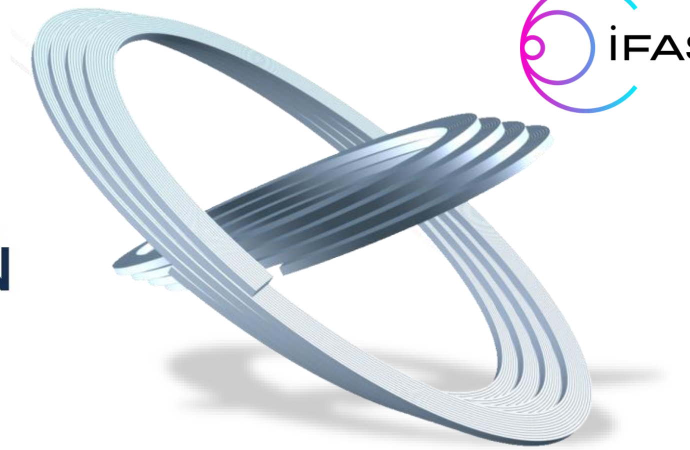
Further design[1] of the HTS magnet

Collaboration between Little Beast Engineering (Jeroen van Nugteren) and INFN LASA



4T dipole with a new Top of 20 K (> 10 K of margin):

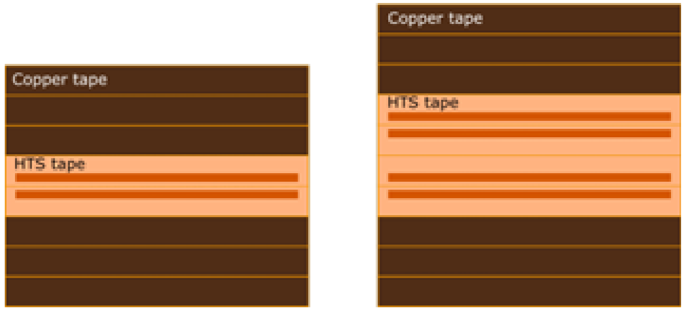
- Superconductor ReBCO (Tapes) -Fujikura 660 A @ (20K, 5T);
- Frenet-Serret frame used for the conductor geometry;

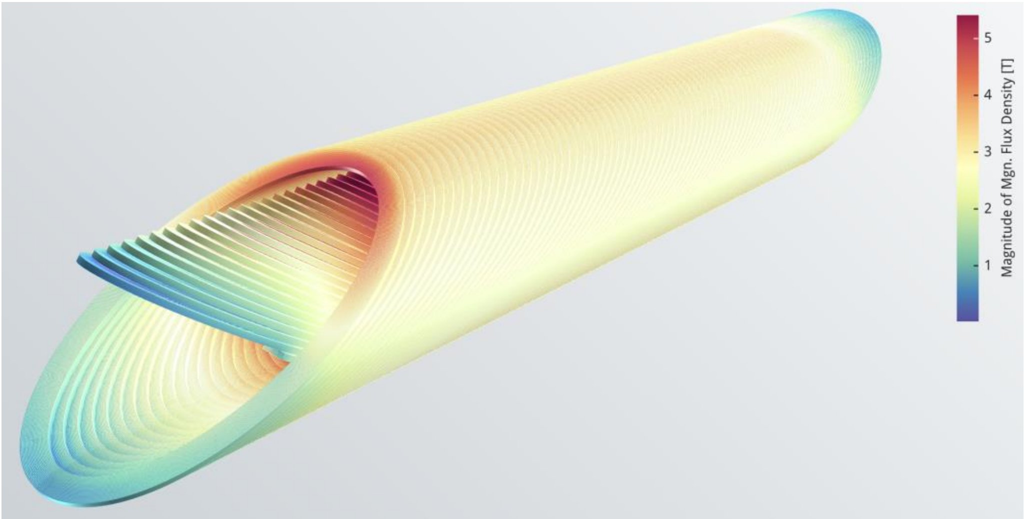
Insulation option for the conductor with Cu stabilizer is pursued.

Two further design options:

- 2-tapes cable (980 A)
- 4-tapes cable (1990 A)

Soldering all tapes inside the cable under consideration;





[1]S. Sorti, E. De Matteis, ''**First Engineering design of HTS demonstrator** '', IFAST WP8 Deliverable 8.3, Zenodo, https://doi.org/10.5281/zenodo.7930115

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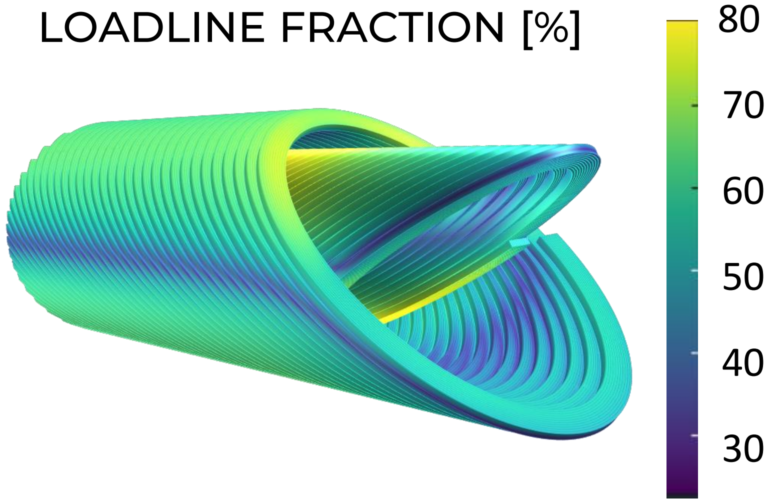
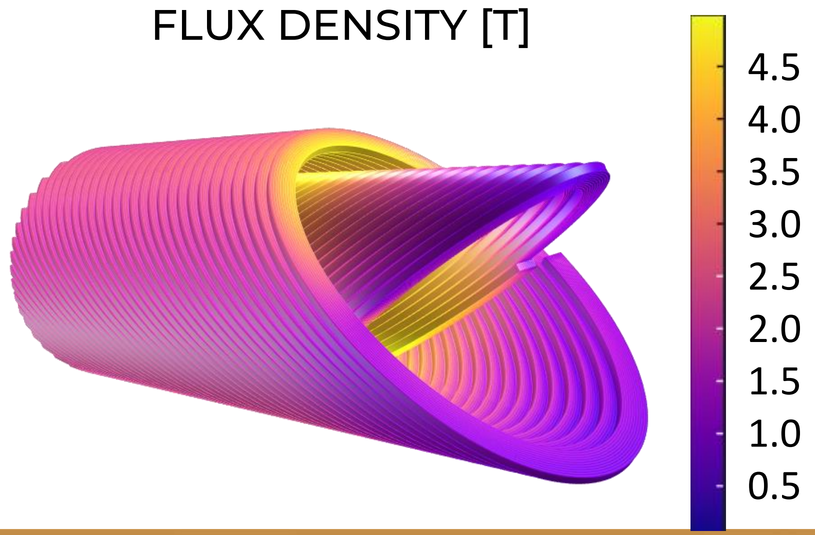
Magnetic design

- Accelerator-level **field-quality** (integral below-unit), no iron yoke (shielding open problem);
- **Loadline margin** expectably 20-25% (reference tape has 660 A at 20 K, 5 T with a current-per-tape in cable of 500 A);

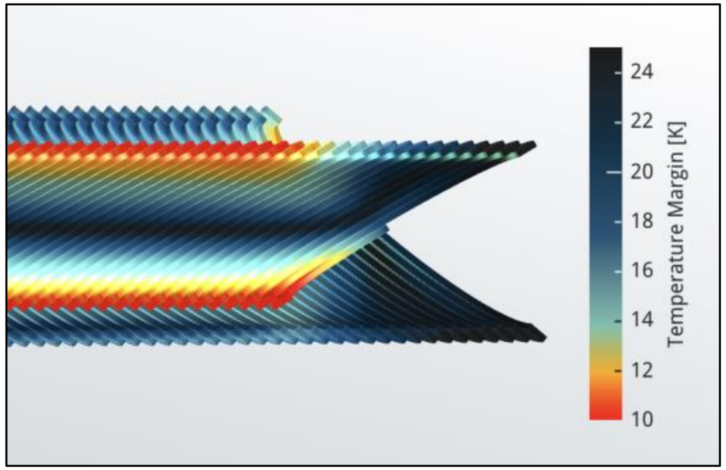
harmonics given at a reference radius of: 20.000 [mm]

Order	An [T.m]	an	Normalized Shape	Order	Bn [T.m]	bn	Normalized Shape
A1	4.14e-05	0.12		B1	3.40e+00	10000.00	
A2	2.99e-05	0.09		B2	-1.93e-04	-0.57	
A3	1.31e-05	0.04		B3	1.70e-04	0.50	
A4	4.55e-06	0.01		B4	-5.32e-05	-0.16	
A5	2.07e-06	0.01		B5	-3.96e-05	-0.12	
A6	4.73e-07	0.00		B6	1.75e-06	0.01	
A7	3.48e-07	0.00		B7	6.73e-06	0.02	
A8	-2.70e-07	-0.00		B8	1.04e-08	0.00	
A9	5.55e-08	0.00		B9	-1.36e-07	-0.00	
A10	-3.93e-07	-0.00		B10	6.84e-09	0.00	





Temperature margin and Quench protection



	Two HTS tapes	Four HTS tapes	
	350 µm	600 µm	700 µm
V_{Th}	0.2 V	0.2 V	0.3 V
t_d [s]	$T_{hot\text{-}spot}$ [K]	$T_{hot\text{-}spot}$ [K]	$T_{hot\text{-}spot}$ [K]
0.01	224	224	241
0.02	235	238	252
0.03	242	252	264
0.04	253	268	277
0.05	263	284	290
0.06	275	302	304

- Temperature margin of 10 K but most of the conductor with even higher margin;
- **Quench protection** system is being demanded for better performances:
  1. Inductive signal to be compensated;
  2. Higher V_d, above AC losses voltage (which is ∼50 mV);
  3. Push the detection time to the lowest limit possible.
  4. Varistor unit?

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Quench analysis

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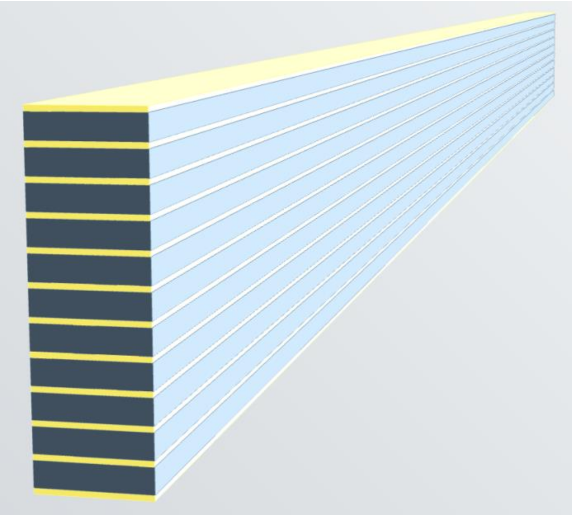
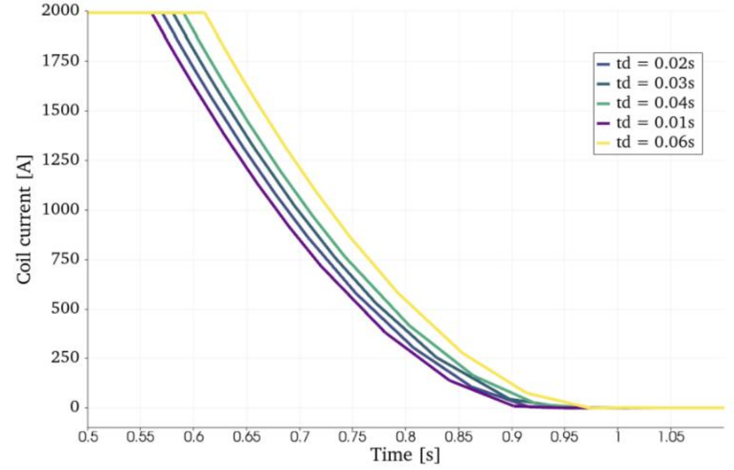
Adiabatic quench analysis:

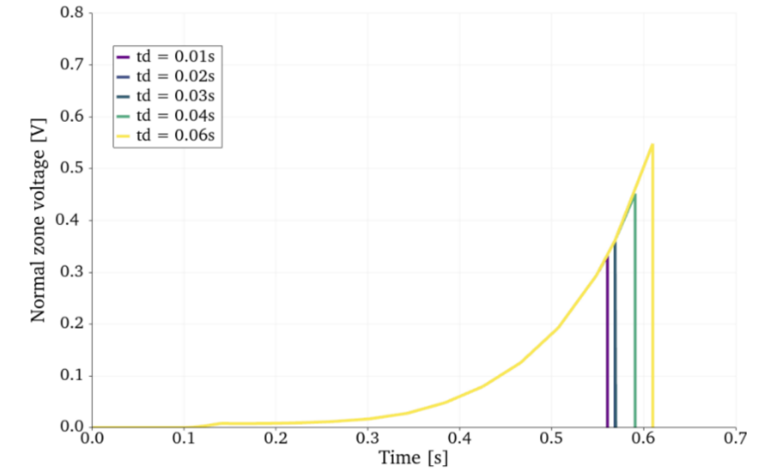
- A transverse background field of 4 T is applied. The magneto resistance of the copper is also taken into account during.
- quench detection voltage threshold of 0.3 V, a protection delay of 20 ms and a protection voltage of 500 V using a varistor unit;
- 350 µm and 700 µm of Cu stabilizer for the two-tape and four-tape designs, (peak temperature within **250 K**).



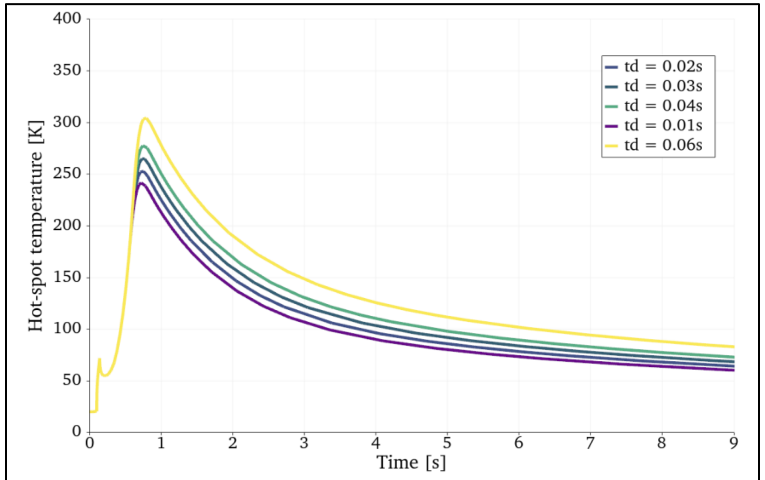
200 mm long CCT layer with 11 sub-layers, four HTS tapes per sub-layer and 700 µm copper stabilizer, for different quench protection delays.



(b) Current in the coil.



(c) The normal zone voltage.



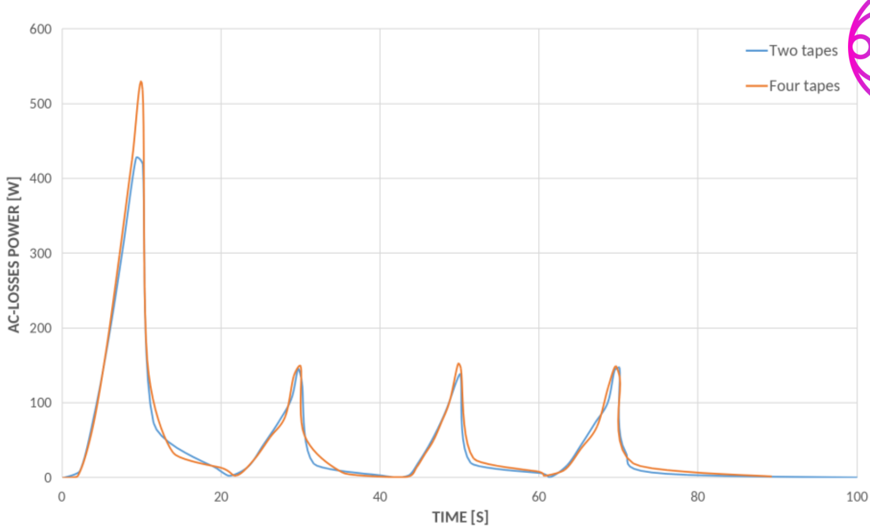
(a) Hot-spot temperature.

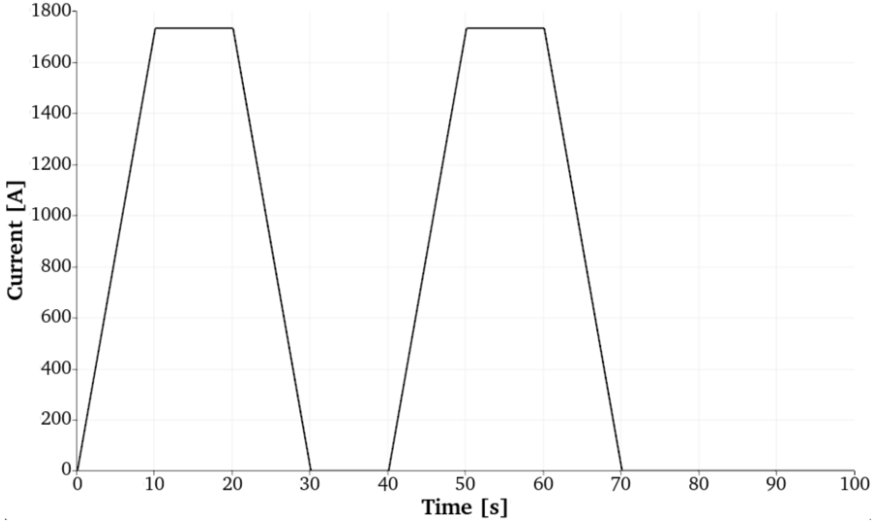
AC losses

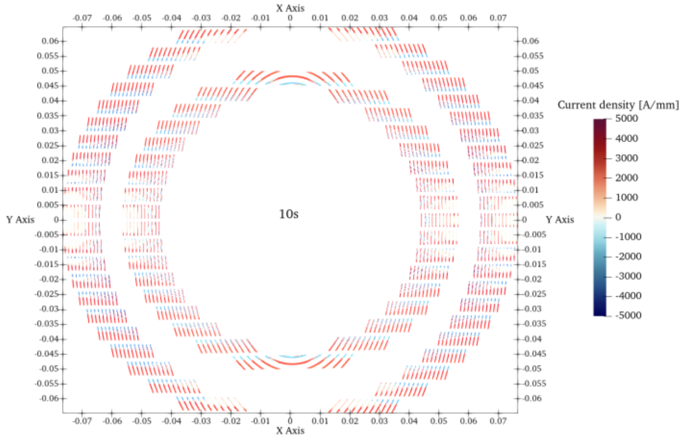
The **AC-losses** during operating for both designs are on average **50 W.** This is compatible with a conduction cooling system at 20 K.

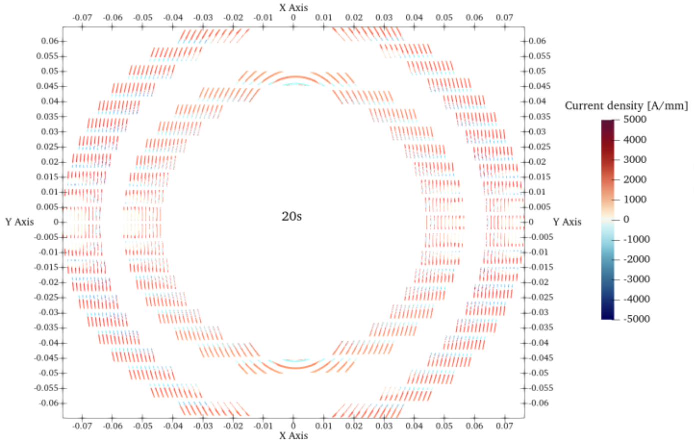
1) No need of helium gas;

2) Power efficiency of cryocooler higher at 20 K wrt 4.5 K;









Cabling and former progress

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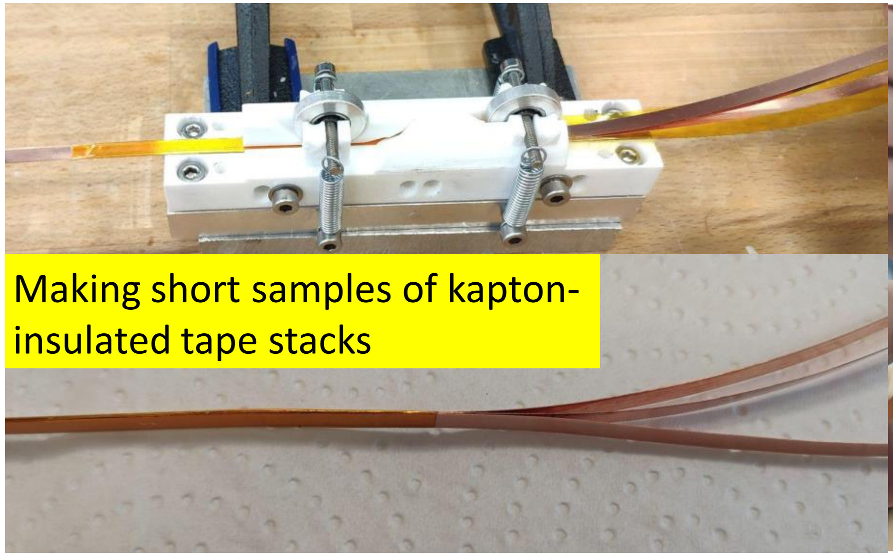
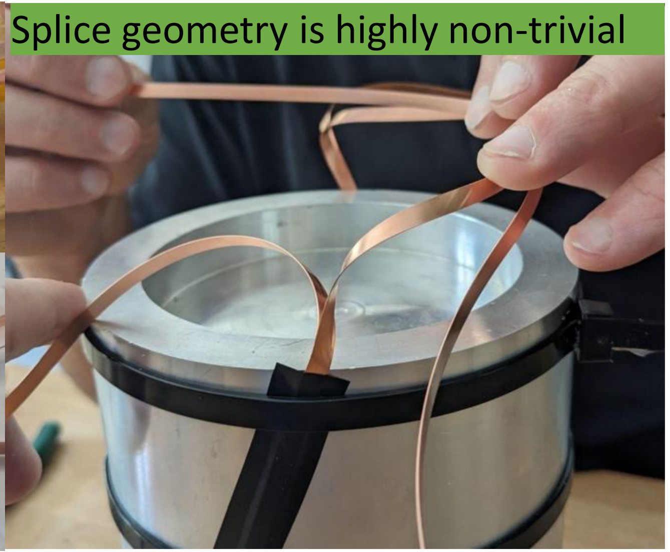
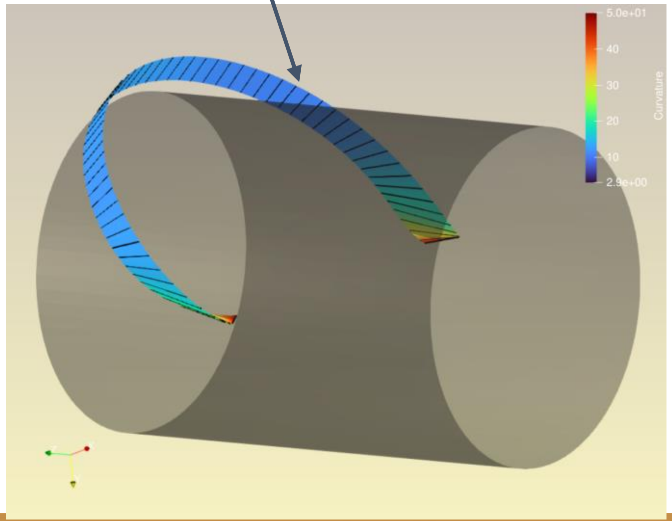


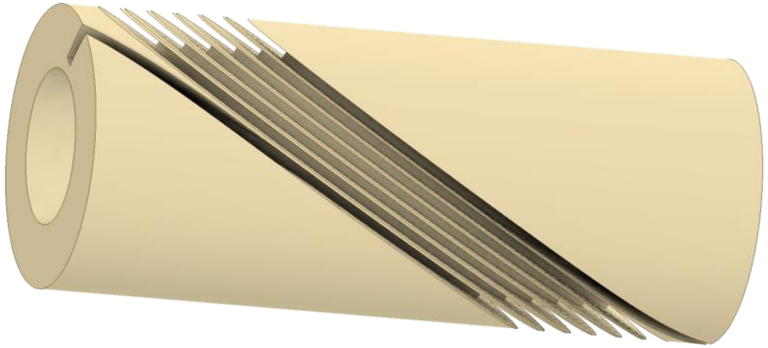


C++ library development for tape geometry optimization

Looking for possible splice geometries



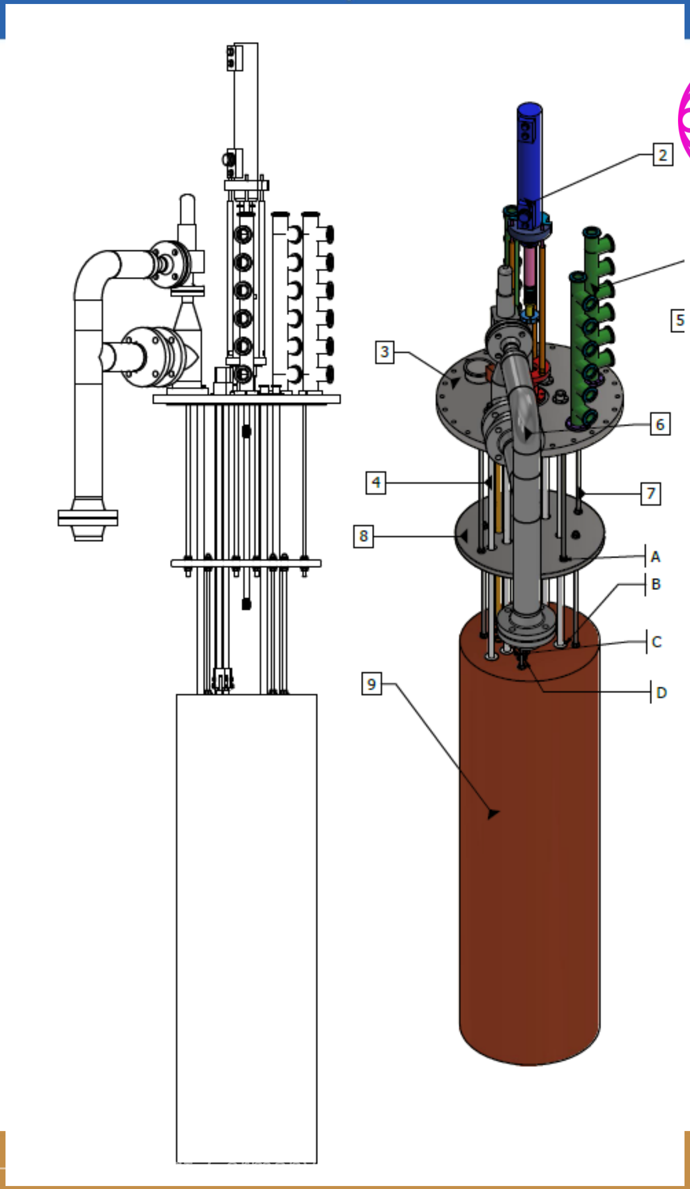
- VBScript macro to build 3D grooves (C++ → Inventor CAD)
- Variable-pitch test former designed w/ optimized start/end sections



Test facility and HTS tape

- Magnet test programmed at INFN-LASA (Milan):
  - Upgrade of one test facility at INFN-LASA:
  - Customized insert for the HTS CCT (1 kA,10 -50 K);
  - Funded in the frame of EU recovery project IRIS (presented this morning by L. Rossi);

- The procurement of HTS tape is underway by CERN (A.Ballarino);
  - Faraday Factory Japan (about 2.5 km);
  - Delivery foreseen in the next months.



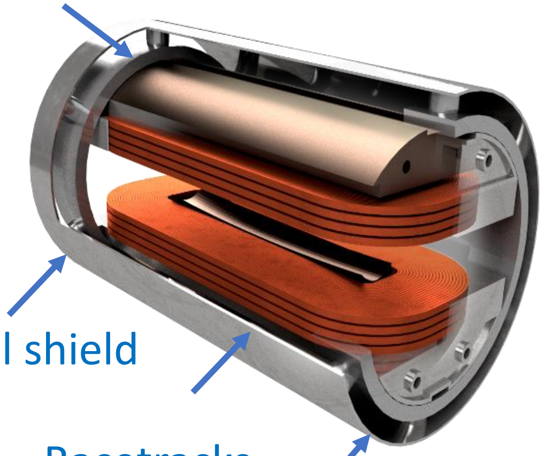
Innovative Research Infrastructure on applied Superconductivity (IRIS) project

ESMA: Energy Saving Magnet for Accelerators to be an HTS, conduction-cooled magnet.

Three main scopes:

1. Start a focused program with **basic R&D on HTS;**
2. **demonstrator** for accelerator-like magnets (transverse fied with accessible bore) employing HTS operating above LHe temperature: 10-20K;
3. **User magnet** for conductor and large current cable testing at INFN Genova (providing background fields in the 2 – 10 T range).

See talk of L. Rossi (this morning)



Technology-wise it serves both for FCC or Muon-C magnets, but in general for <u>future Accelerator magnets oriented to Energy saving.</u>

Central field B_0 (min. accept)	tesla	10 (8)
Free aperture	mm	Ø70
Good field region uniformity	N/A	±1.5%
Good field region extension	mm	H50xV30xL350
Operating temperature	K	20

Synergy IRIS - I.FAST (and beyond)

- Preparation of the facility for cold measurements;
  - I.FAST CCT based on HTS will be a conduction-cooled magnet as ESMA dipole;
- Common studies related to the joint/splice technology;
  - Tests ongoing at LASA for ESMA;
  - Cold measurements for the I.FAST CCT;
- Superconducting Magnet Laboratory (SML) – IRIS at LASA:
  - New equipment for manufacturing small/medium size SC magnets: winding machines, ovens for heat treatment and impregnation, presses for curing, collaring and welding;
  - Additive manufacturing machines (metallic and plastic);
  - Mechanical and electrical qualification of the magnets.
- Great synergy with projects as I.FAST (especially looking at the future prospects of this and other projects).

iFAST

Innovative Research Infrastructure on applied Superconductivity IRIS

Conclusions

- Research and medical accelerators need big size and cost infrastructure;
- Superconducting magnets, as CCT, based on superconductor can help make these structures compact and economically sustainable (reduce the power consumption);
- IFAST WP8 is oriented to explore CCT magnets based on LTS and HTS (main goal);
- IFAST CCT magnet based on ReBCo tape will operate at 20 K, conduction cooled without helium gas temperature range where the power efficiency of the cryocooler increases;
- IRIS research infrastructure can work in synergy with projects as I.FAST (especially looking at the future prospects of this and other projects).

Thank you for your attention!

INFN LASA

Innovative Research Infrastructure on applied Superconductivity IRIS

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Finanziato dall'Unione europea NextGenerationEU

iFAST

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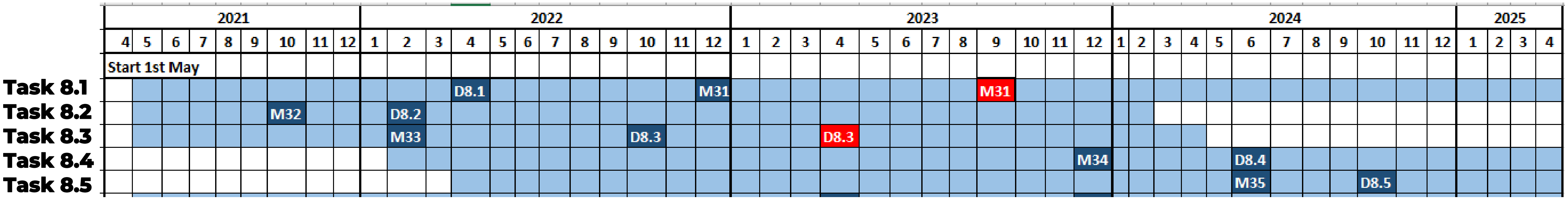
I.FAST WP8 – Task and timeline (magnets)

	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	Fernando Toral (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)



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PIANO NAZIONALE DI RIPRESA E RESILIENZA

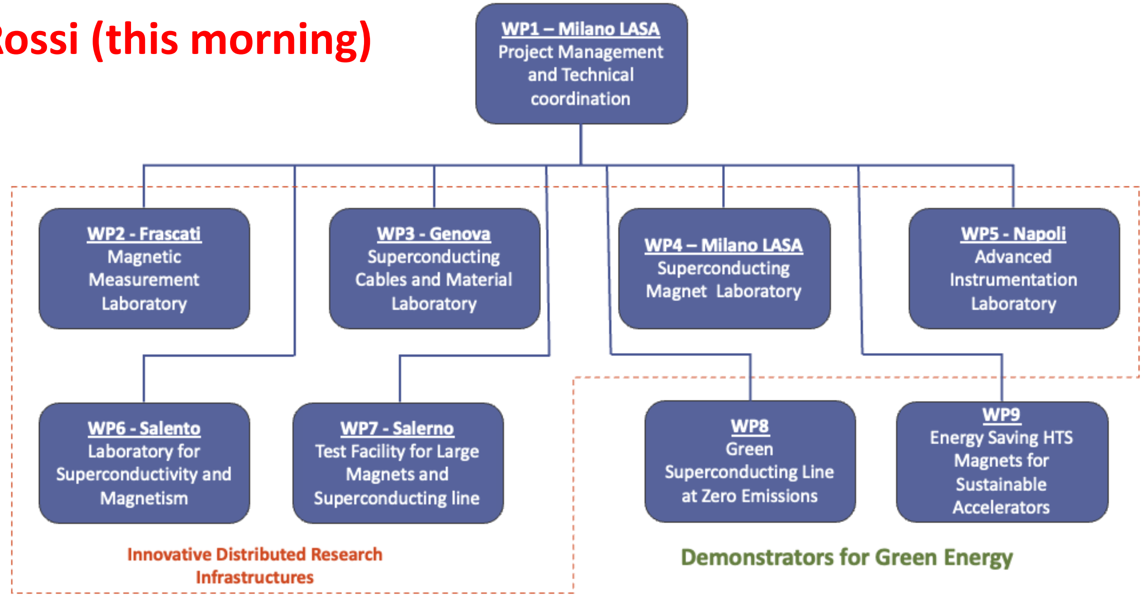
INFN

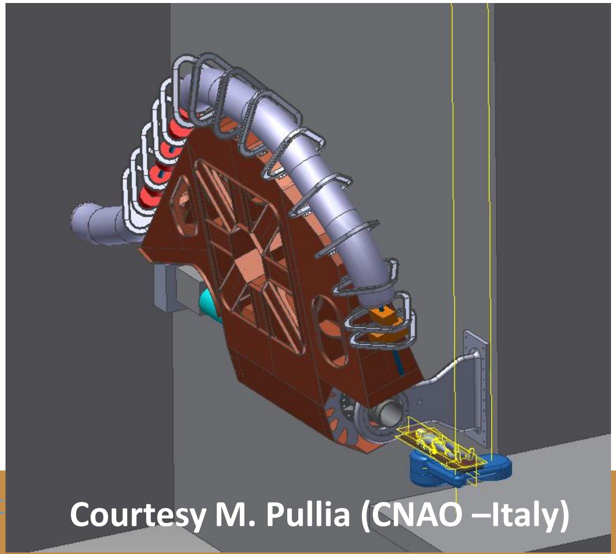
Innovative Research Infrastructure on applied Superconductivity (IRIS) project

Next Generation EU project (PNRR)

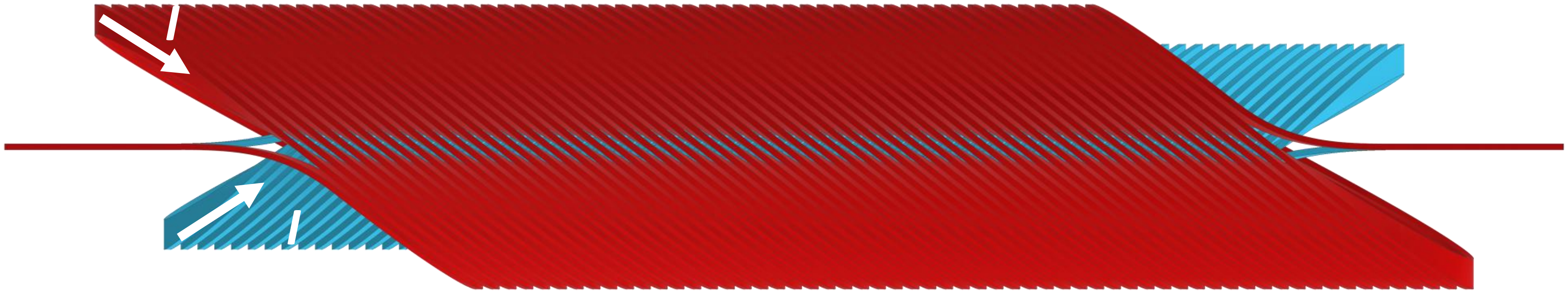
- **Ultimate goal** to contribute to Fundamental Physics instrumentation (particle accelerators for post-LHC era) and to Societal Applications for green energy and medical applications.
- **6 poles** for the new or renewed infrastructures: Frascati (INFN), Genova (INFN, CNR-Spin, Unige), Milano (INFN, Unimi – LASA lab), Napoli (Unina), Salento (Unisalento) e Salerno (INFN e Unisa).
  LASA (Milano) is the hub and coordinates the activity

See talk of L. Rossi (this morning)



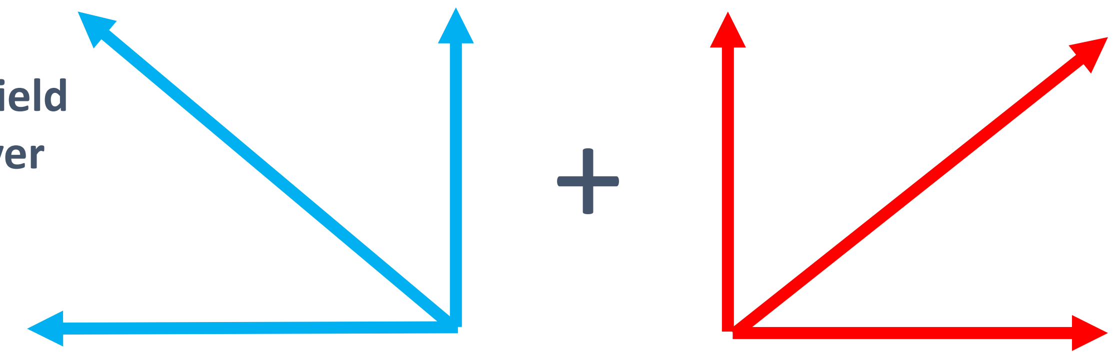


Canted-Cosine-Theta (CCT) Magnet



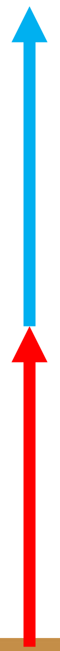
- Current *I* flows in the two conductors so that the transverse magnetic field components add up and axial field components cancel each other out.

Total magnetic field of the inner layer

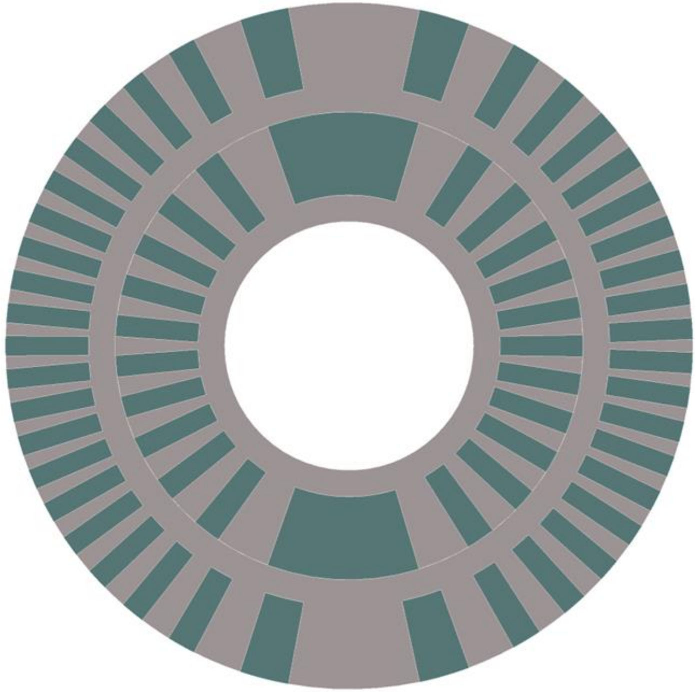


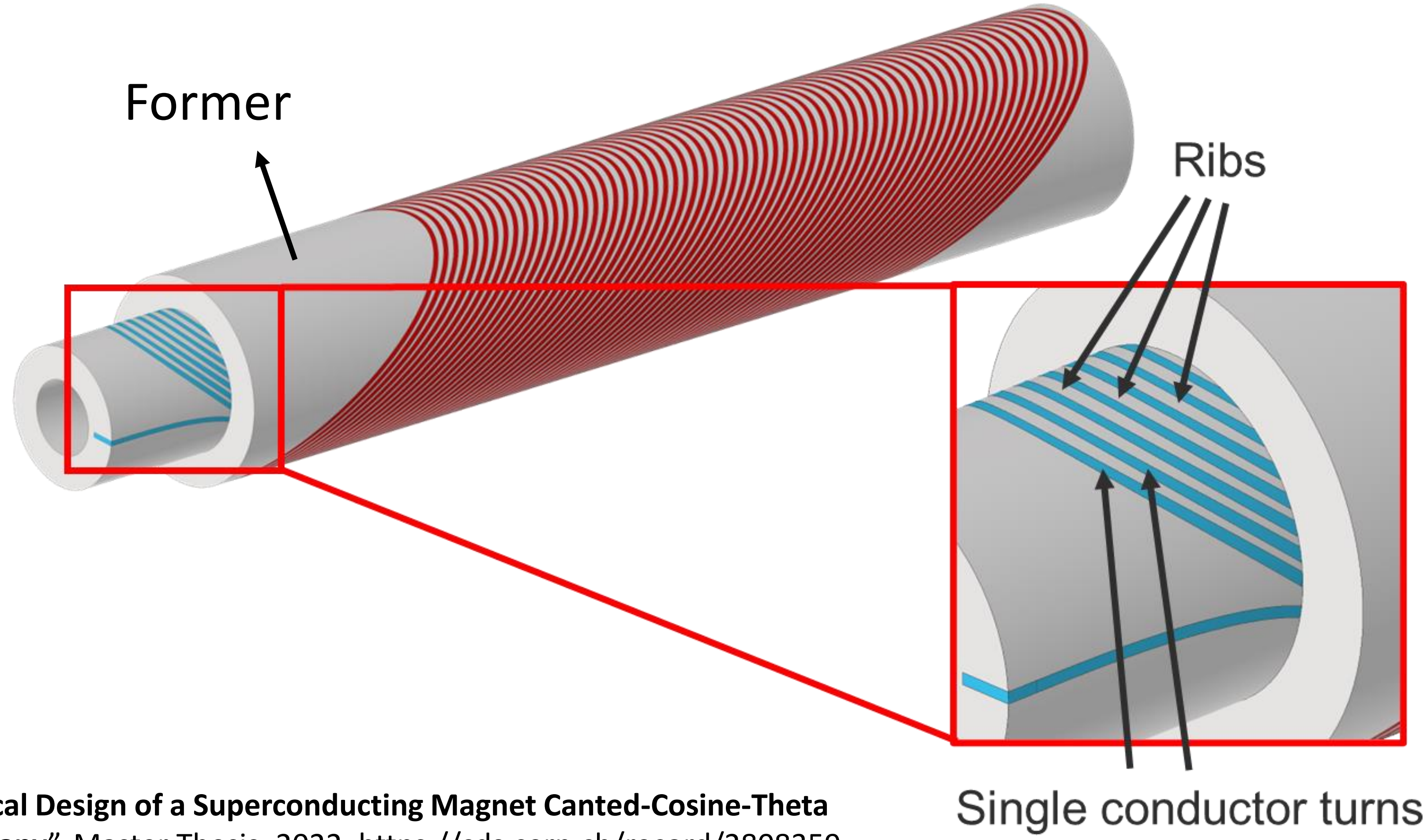
Total magnetic field of the external layer

=



CCT schematics[1]





[1]Gabriele Ceruti, “**Preliminary Mechanical Design of a Superconducting Magnet Canted-Cosine-Theta (CCT) for a New Gantry for Hadron Therapy**”, Master Thesis, 2022. https://cds.cern.ch/record/2808359