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Magnetization and other losses in CCT SC magnets for hadrontherapy and perspecitve for IRIS

Highlight Talk Nr1

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iFAST

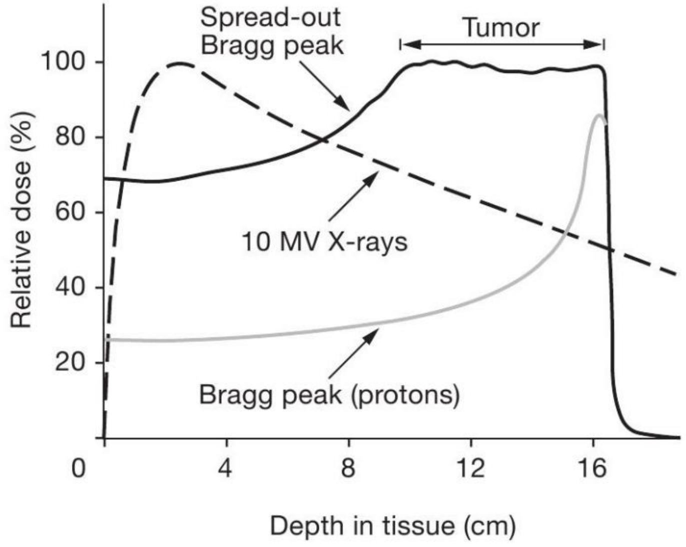
Outline

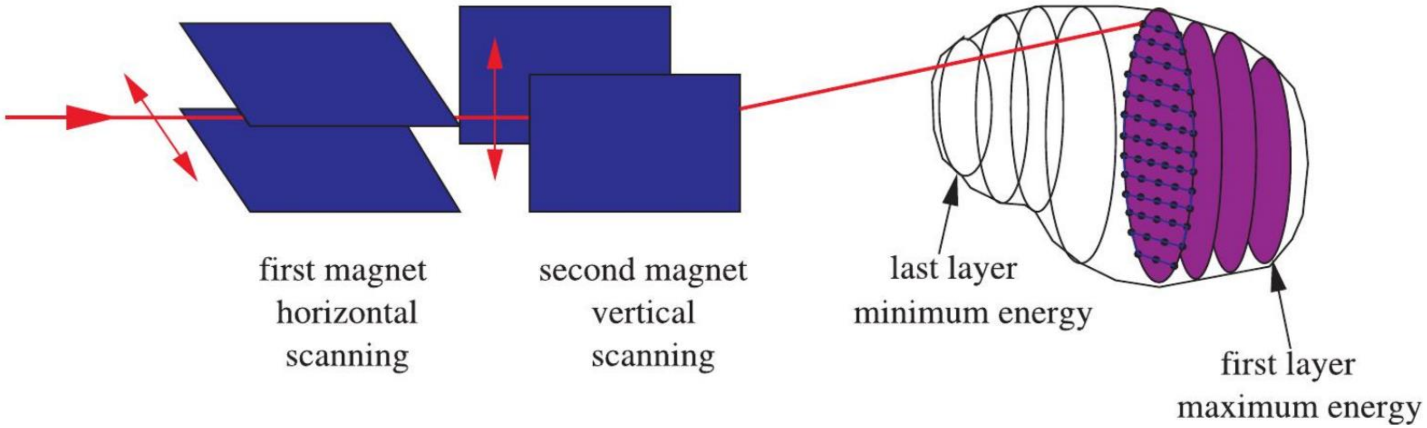
- Introduction to hadrontherapy
- Challenges for magnets in hadrontherapy
- Activity on power losses for LTS CCT (I.FAST 8.2)
- Activity on power losses for HTS CCT (I.FAST 8.3)
- Knowledge transfer to other projects (PNRR-IRIS)

Images reprinted from: Grevillot, Loïc. *Monte Carlo simulation of active scanning proton therapy system with Gate/Geant4*. Diss. Lyon, INSA, 2011.

Hadrontherapy

- Hadrontherapy is a form of radiotherapy that, unlike traditional radiotherapy, based on X-rays or electrons, involves the use of protons and carbon ions.
- Among charged particles, the main difference between protons and carbon ions regards the radiobiological effectiveness (RBE).

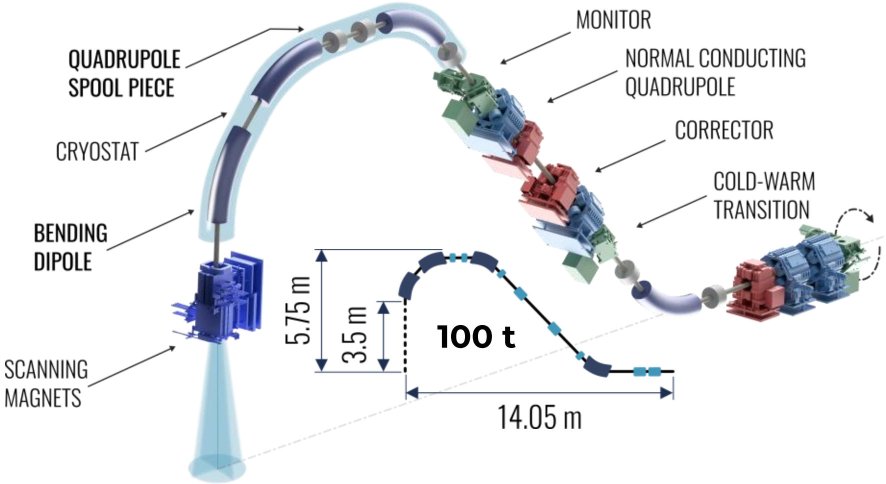




Hadrontherapy

- More specifically, we focus on “pencil scanning” with a rotating structure (**gantry**).
- Rotation allows for desired medical angle without moving the patient (up to 360°).
- Depending on the depth and on the particle, different beam rigidity: $E[\text{GeV}] = 0.3\,\rho[\text{m}]B[\text{T}]$
  Protons: 220 MeV for 30 cm, $\text{B}\rho = 2.3\ \text{T m}$
  Carbon Ions: 4.8 GeV for 30 cm, $\text{B}\rho = 6.6\ \text{T m}$
- The gantry in CHIBA (Japan), made by Toshiba, is the only working superconducting ion gantry in the world. That’s due to serious challenges.

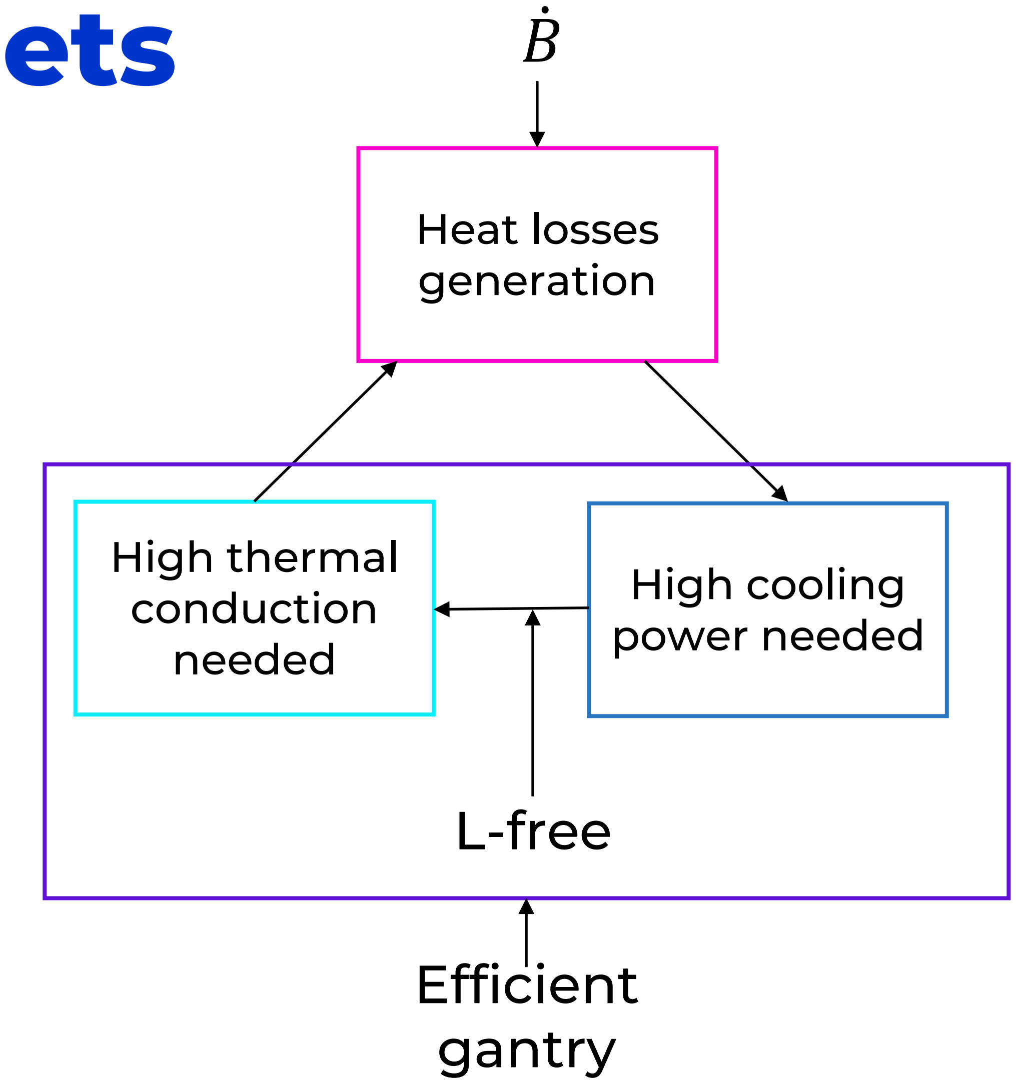
Toshiba ion gantry (5.5 m × 13 m, D: 2.3 m × 2.88 T, 350 t)



SIG ion gantry (running project)

Challenges for magnets in Hadrontherapy

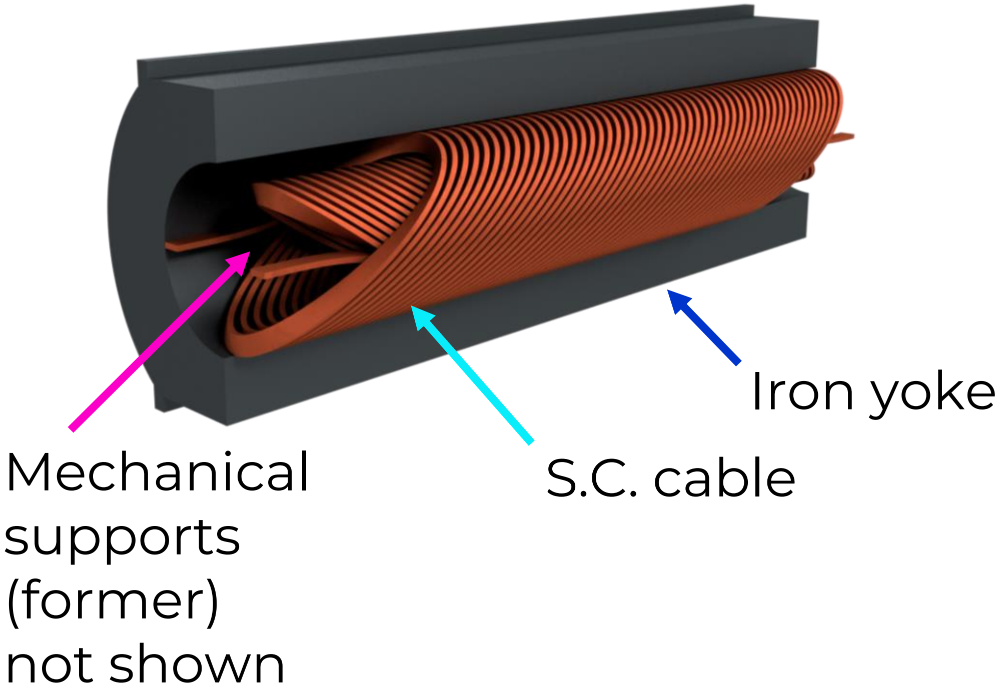
- Higher B means lower ρ, thus smaller gantry.
  → Need for **superconductivity** (so, **cryogeny**).
- Performance = operating temperatures where cryocoolers are inefficient
  → Need for **High-T_c Superconductivity**
- Scanning at different depth = different particle energies. → Need for **>100 mT/s ramp-rate**
- Rotating structure is better operated if no liquid is flowing in the structure
  → Need for **liquid-free cooling**



Note: Challenges above motivate other research paths, such as high-momentum acceptance magnets [1], or novel concepts as GaToroid [2].

Losses in Superconducting Magnets

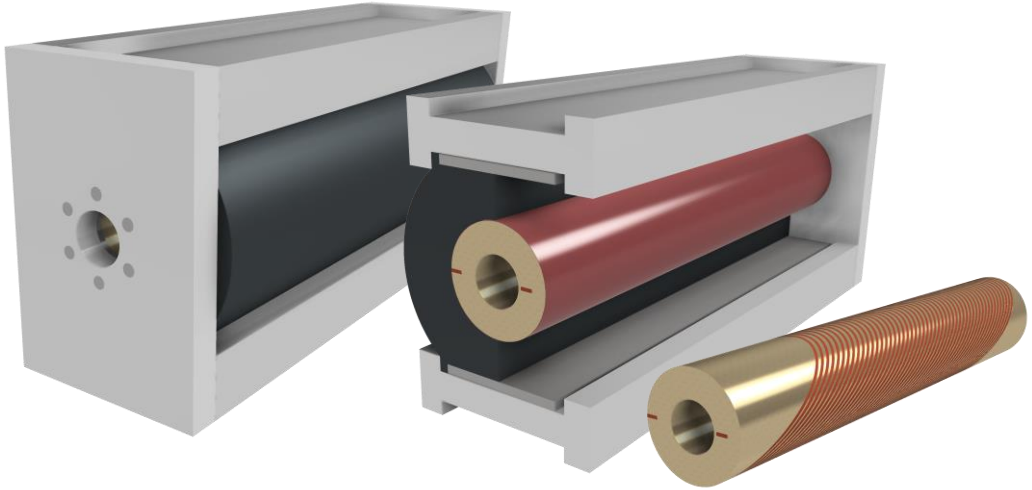
Typical layout of CCT in WP8:

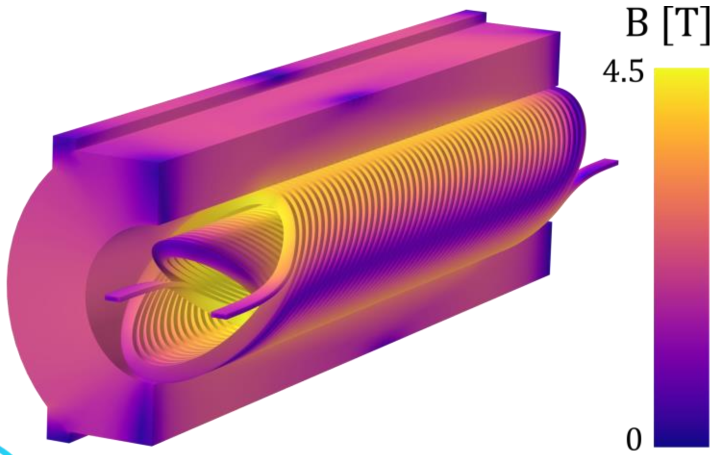


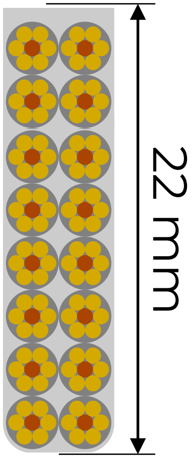
1. Losses also in resistive magnets: **eddy currents** in conductive materials (Faraday's law) and **yoke magnetization** (iron hysteresis), <u>if any</u>
2. Losses **from warm ambient** (conduction trough supports, radiation even in vacuum)
3. Losses from **resistive current leads**
4. Losses in **superconductors** (magnetization, inter-filament, etc..)

Losses in LTS CCT of I.FAST 8.2

- Main reference is D8.2: LTC CCT employs a Nb-Ti **low-losses** 6+1 rope, with an Aluminium-Bronze support.
- **T_{op} = 4.7 K** means ~**2 W per cryocooler**. Magnet cannot go above **6.3 K**





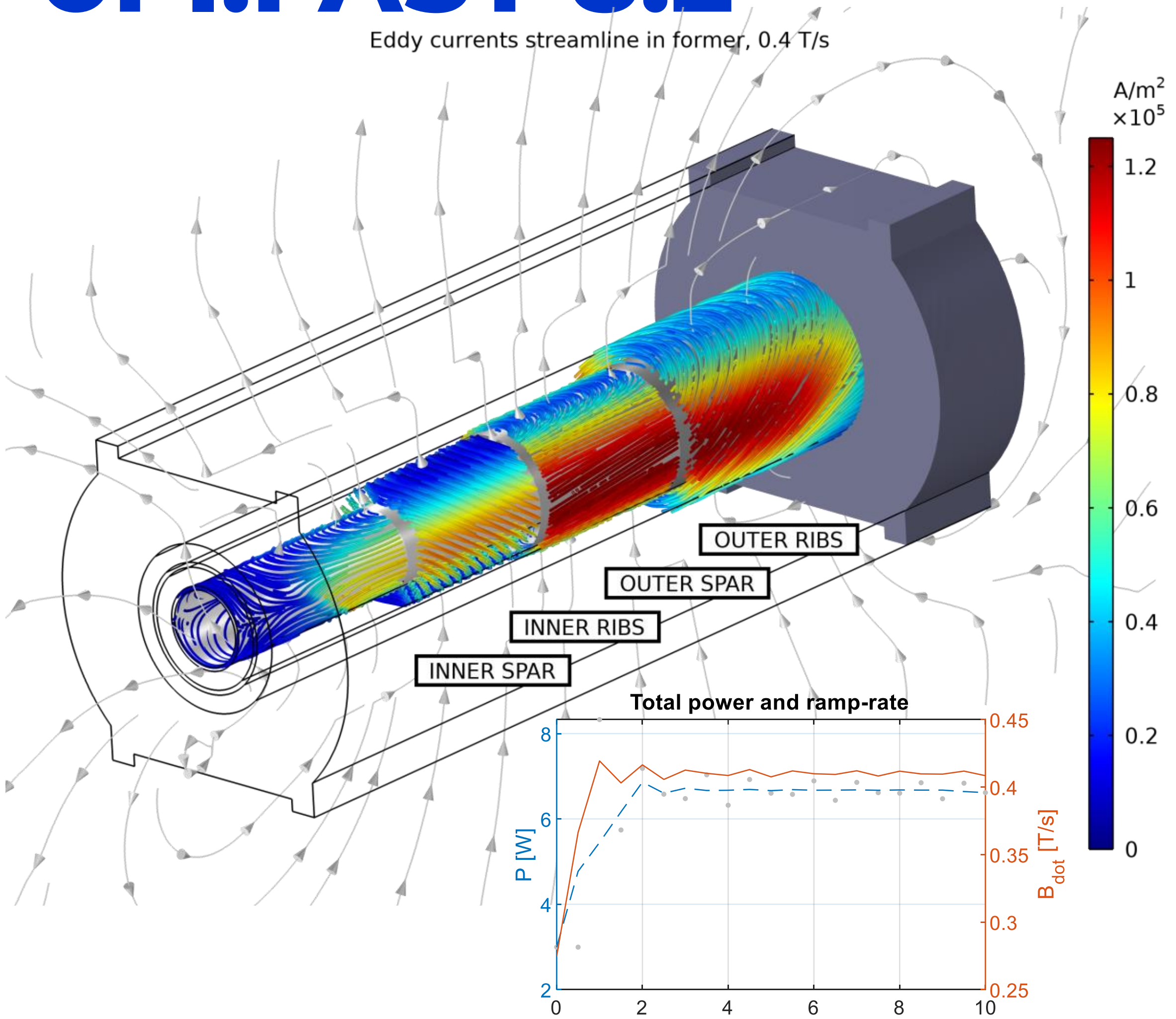


Magnet Parameters	Values	unit
Dipole field B_o	4	T
dB/dt	0.4	T/s
Magnetic and physical length	0.8, 1	m
Bore diameter	80	mm
Operation temperature	4.7	K
Current in rope cable	1.3	kA

Losses in LTS CCT of I.FAST 8.2

- **Eddy Currents in former**: metallic material employed for the sake of thermal conduction. Aluminium-Bronze is in between stainless steel and aluminium.
- 4-mm-spar design simulated in 3D time-domain simulation with nonlinear (non-conductive) yoke. Total power 6 W.
- Magnet in D8.2 (8-mm former) has around 14 W.

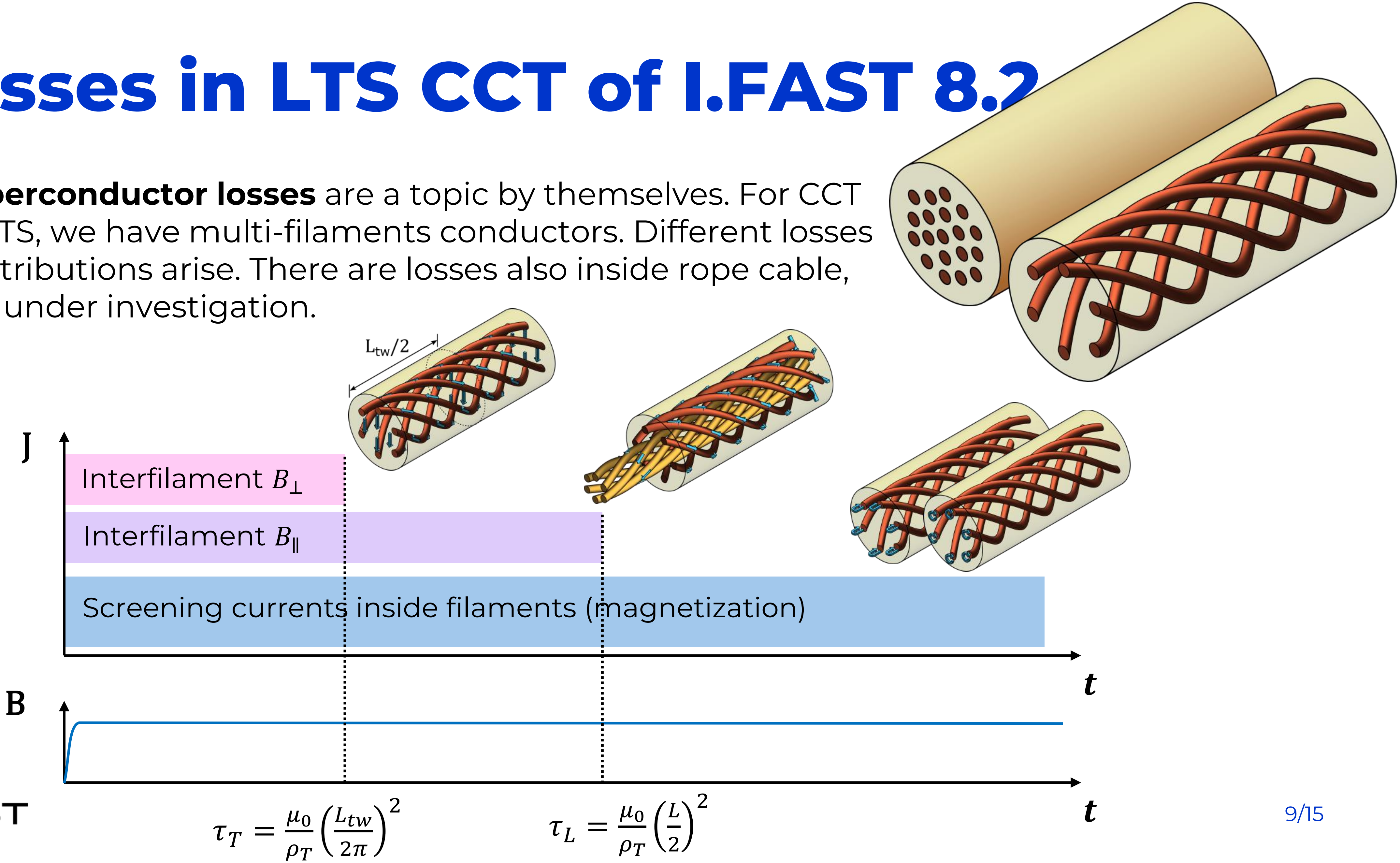
→ solutions under investigation to reduce eddy currents


Eddy currents streamline in former, 0.4 T/s

Total power and ramp-rate

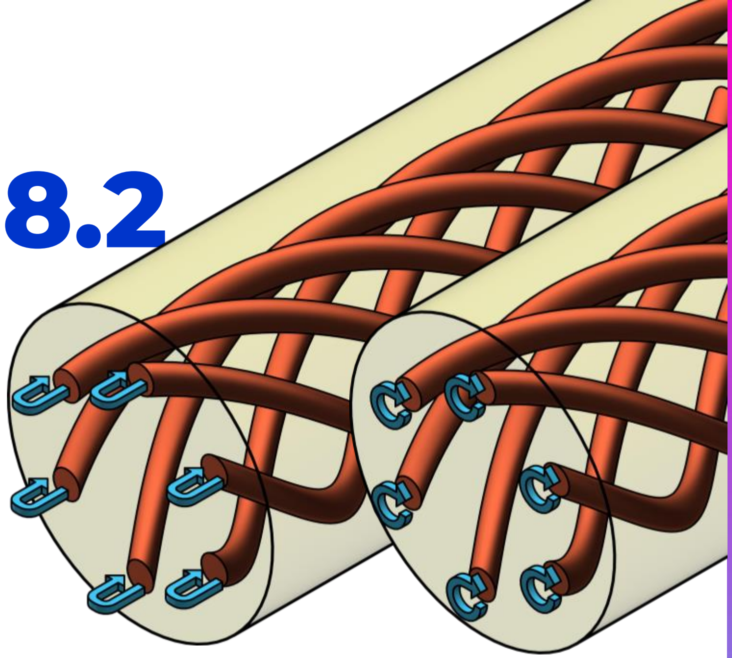
Losses in LTS CCT of I.FAST 8.2

- **Superconductor losses** are a topic by themselves. For CCT in LTS, we have multi-filaments conductors. Different losses contributions arise. There are losses also inside rope cable, still under investigation.

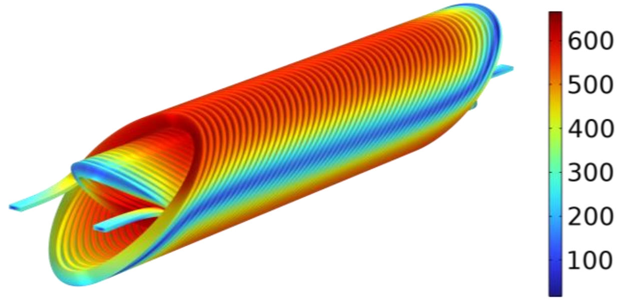


$$\tau_T = \frac{\mu_0}{\rho_T}\left(\frac{L_{tw}}{2\pi}\right)^2 \qquad \tau_L = \frac{\mu_0}{\rho_T}\left(\frac{L}{2}\right)^2$$

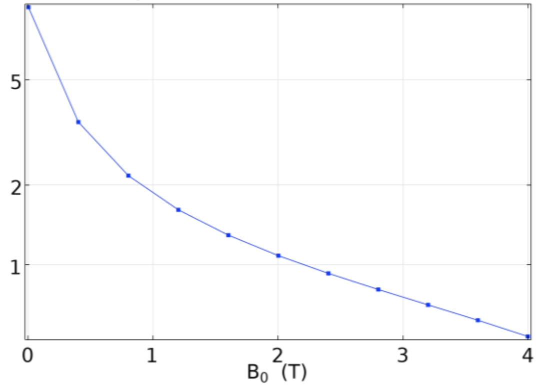
Losses in LTS CCT of I.FAST 8.2



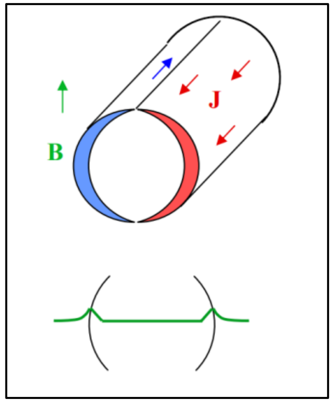
- We profit from INFN Discorap project and employ the same low-losses conductor (2.5 μm filaments, resistive CuMn barriers in between filaments).
- Estimated major contribution is **magnetization**. Analytical formulas (Wilson) are employed on top of a 3D simulation:

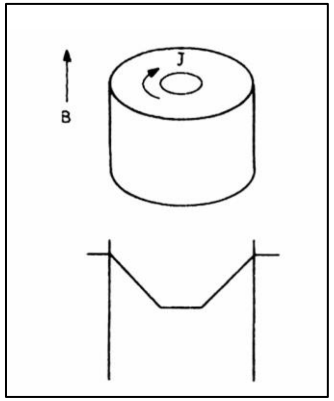


Magnetization P at 9 s of ramp-down (W/m^3)



Magnetization Losses in CCT, P (W)



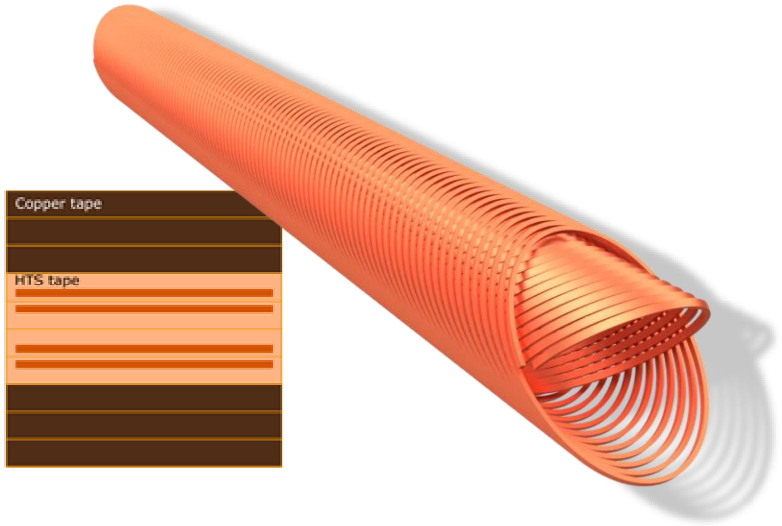


$$M_\perp = \frac{4}{3\pi} J_c \qquad M_\parallel = -\frac{1}{3} J_c$$

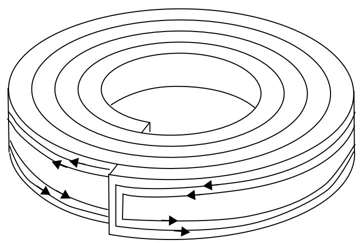
- Total power during ramp is on average 2 W.
  WIP magnetization effects on field quality

Losses in HTS CCT of I.FAST 8.3

- The same loss components ideally hold for HTS magnet, also. Iron yoke is not included.
- Main difference is that superconductor is in the shape of tapes → **higher s.c. losses**.
- Main solution for HTS magnet is the higher operation temperature, set at **20 K (T_{max} = 30 K)**. Cryocoolers at this level can absorb around 40 W.
- Main reference is D8.3. Collaboration with Jeroen van Nugteren (Little Beast Engineering). Both coupling and screening currents are included in a 3D numerical model. Estimated 50 W cycle-av.
- Magnet can sustain 1 cycle w/out cooling (ΔT = 8 K)

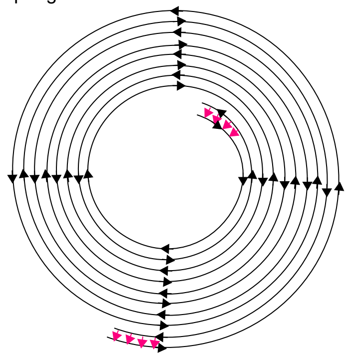


Screening Current



Tries to screen radial magnetic field
limited by the critical current of the tapes
therefore closely related to flux pinning

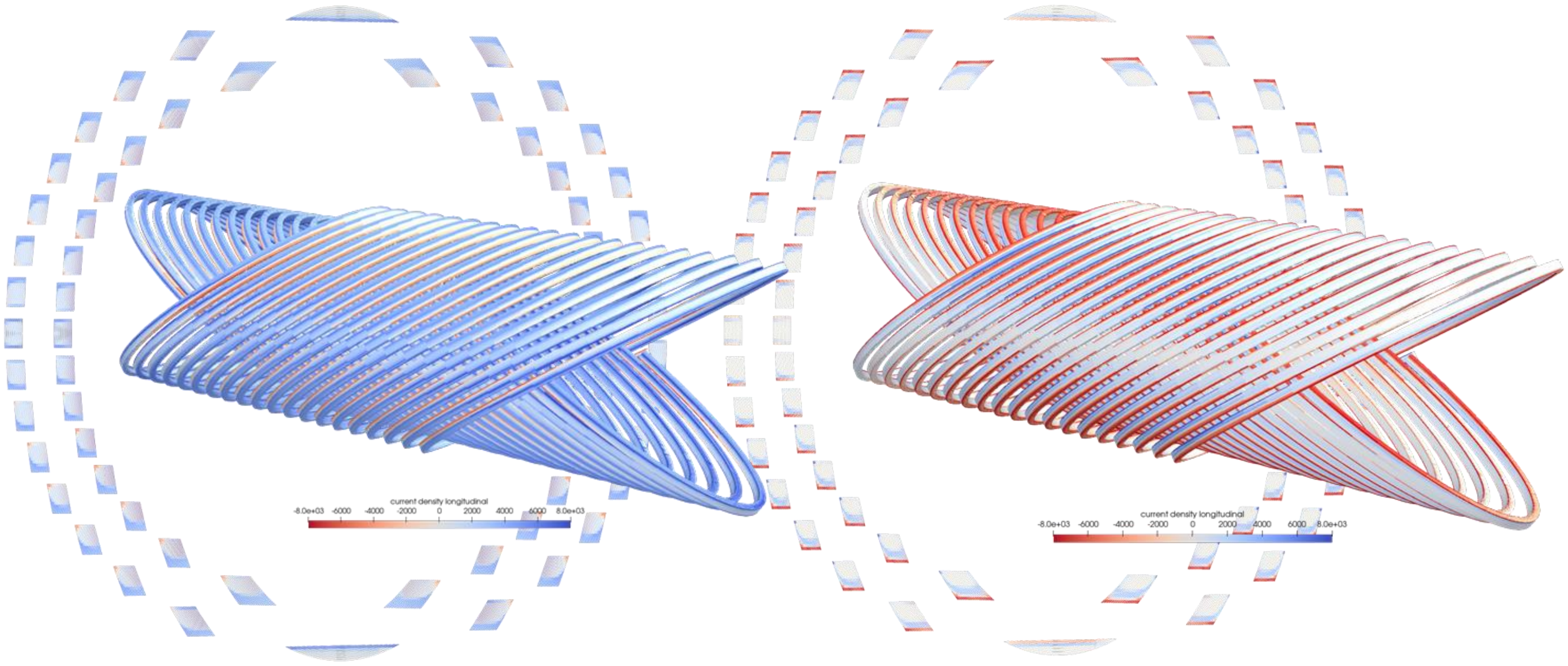
Coupling Current



Tries to screen axial field
Only in multi strand cables
Beware: also limited by critical current of tape!

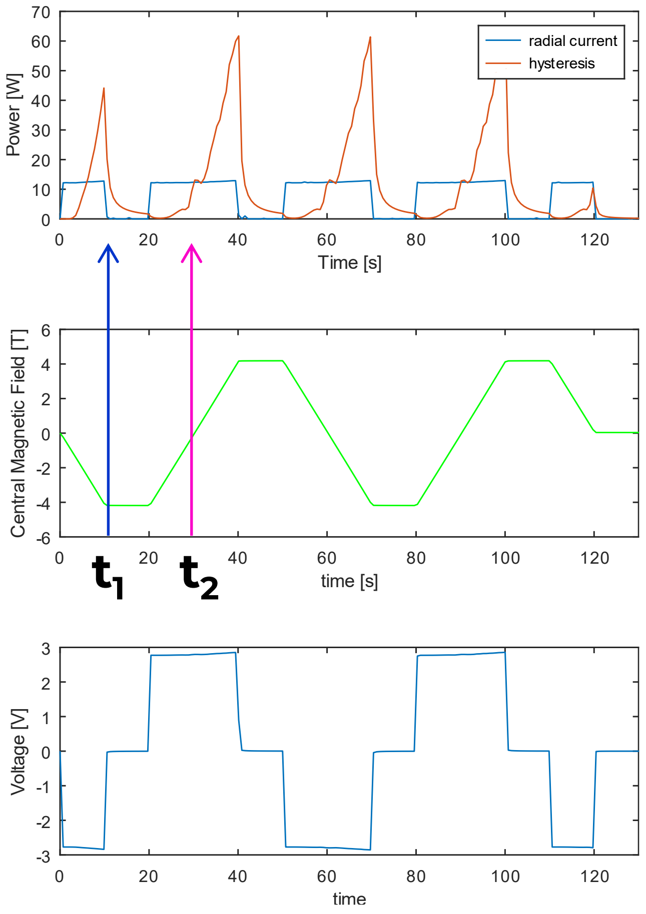
IFAST WP8: AC losses calculation for HTS Magnet, pt. II

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



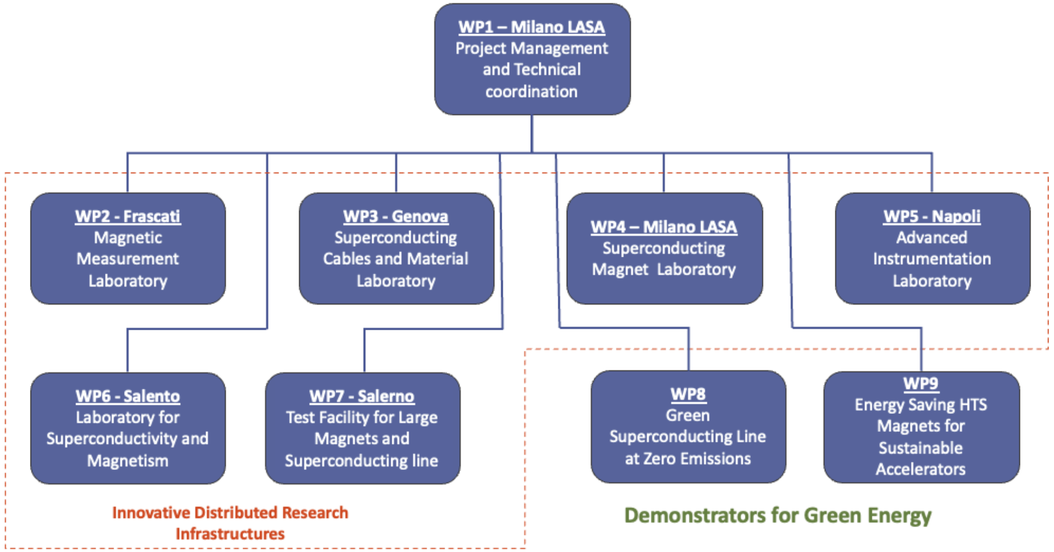
End of 1° ramp (t_1)

Passing at 0 A (t_2)



IRIS project

A distributed research infrastructure



WP1 – Milano LASA
Project Management and Technical coordination

WP2 - Frascati
Magnetic Measurement Laboratory

WP3 - Genova
Superconducting Cables and Material Laboratory

WP4 – Milano LASA
Superconducting Magnet Laboratory

WP5 - Napoli
Advanced Instrumentation Laboratory

WP6 - Salento
Laboratory for Superconductivity and Magnetism

WP7 - Salerno
Test Facility for Large Magnets and Superconducting line

WP8
Green Superconducting Line at Zero Emissions

WP9
Energy Saving HTS Magnets for Sustainable Accelerators

Innovative Distributed Research Infrastructures

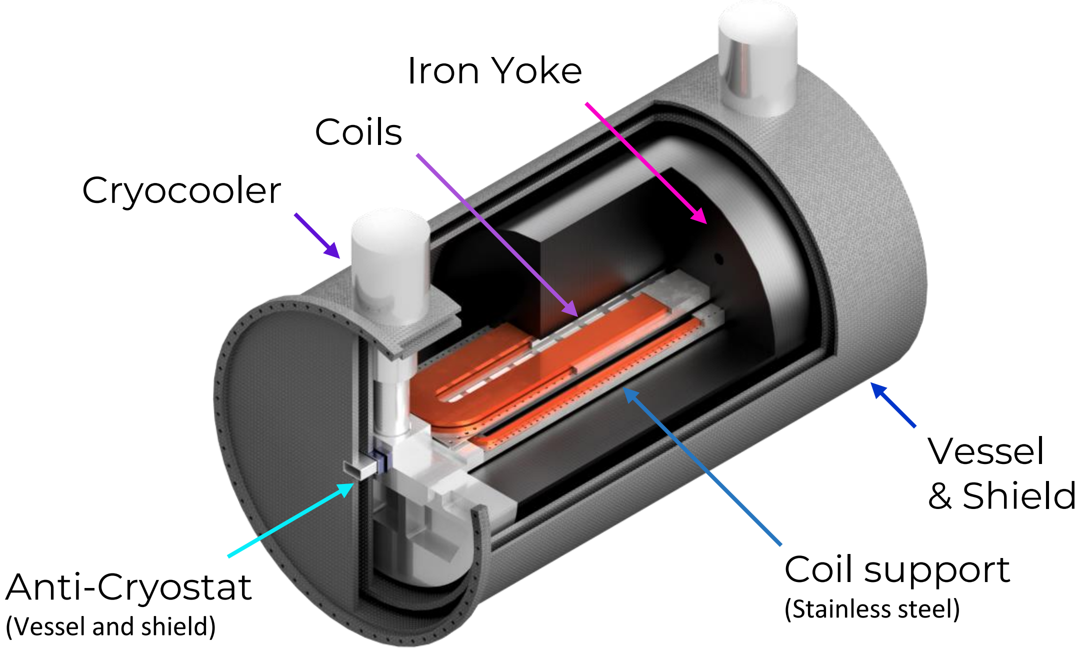
Demonstrators for Green Energy

A wide range of objectives

1. Fundamental Physics instrumentation
2. Societal Applications
   - Green: energy transport at zero emission and energy saving magnets;
   - Medical: Superconductivity could play a key role in heavy ion therapy by enabling a rotatable gantry;
3. Two full-scale demonstrators.
4. Final deadline is 30 October 2025.

HTS demonstrator in IRIS

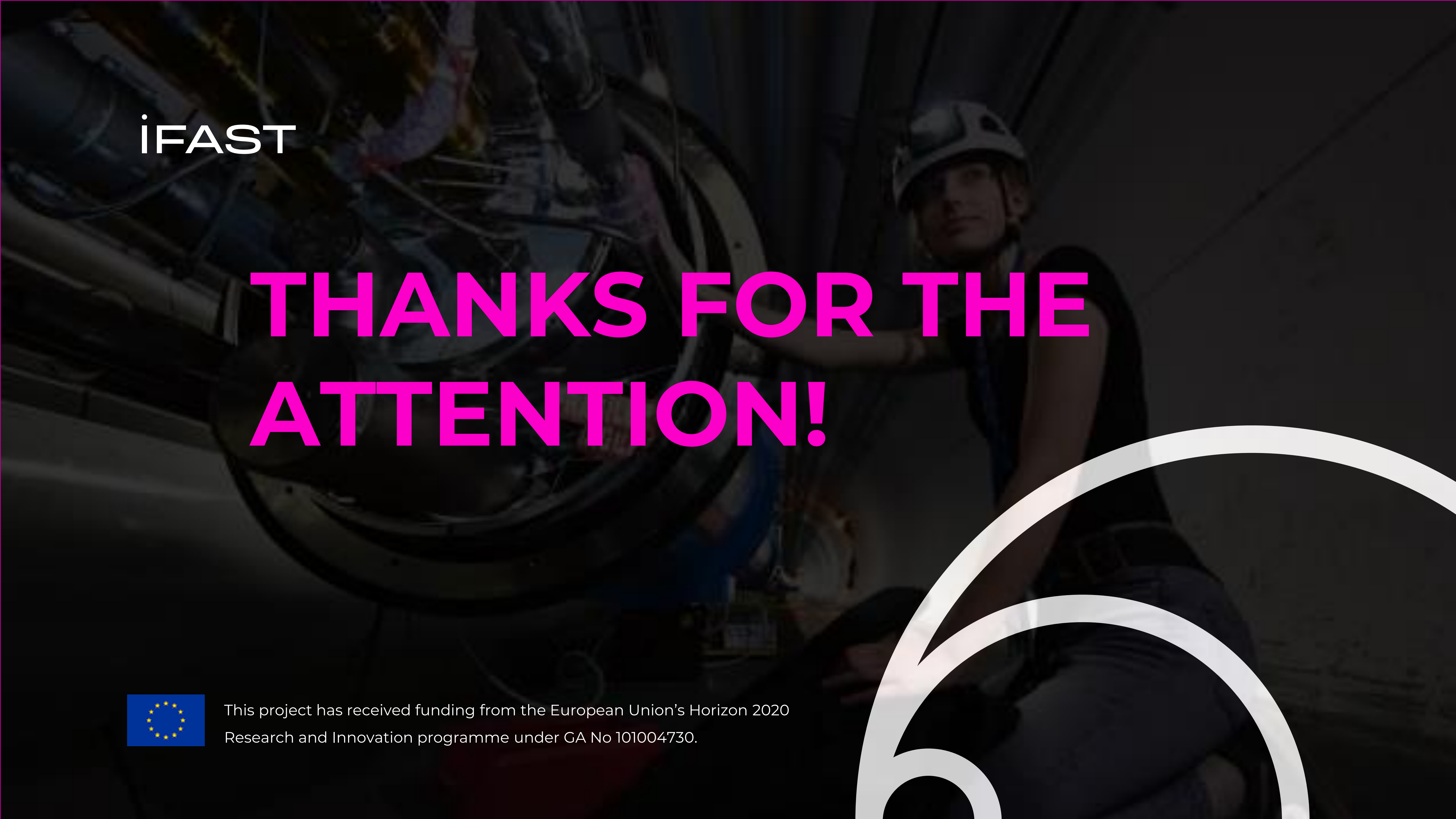
- This wide-purposes demonstrator wants to address some of the main challenges for future-accelerators magnets.
- Despite it expects a slow ramp-rate (a few mT/s), superconductor behavior still needing accurate evaluation.
- Expected cooling by cryocoolers, same challenges as I.FAST 8.3.



Q [W]	At 60 K	At 20 K
Mechanical supports	12	1
Radiation between layers	9	0.1
Current-Leads	80	0.5
Joints inside HTS tapes	0	0.5
TOTAL	**101**	**2.1**
But S.C. losses not considered here!		

Summary and conclusions

- **Hadrontherapy** poses serious challenges due to the need for tumor scanning through a hundreds-tons rotating gantry (fast-ramping, liquid-free magnets)
- **Losses in LTS** are critical with respect to the limited cooling budget available. IFAST 8.2 CCT is operated at 4.7 K, where 4 W + P_{fomer} are to be taken by 2W cryocoolers
- **Losses in HTS** are easier to manage on paper, thanks to the higher operation temperature (20 K), so that even >50 W can be taken away with a pair of cryocoolers. Nevertheless, HTS pose other challenges (such as protection, not discussed here)
- Challenges addressed in hadrontherapy magnets can be of interest also for accelerators in other fields, fostering accelerator science and technology.



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THANKS FOR THE ATTENTION!

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[1] Alessandria et al., Technical Design Report Of The Superconducting Dipole For Fair SIS300

A: Losses in LTS CCT of I.FAST 8.2

- We can go through the list at slide 7 to discuss each contribution:

1. The **eddy currents** in former are evaluated numerically (next slide), **yoke magnetization** is conservatively estimated by results of INFN Discorap project [1] in up to 0.72 W for the magnet (laminated, low-losses iron).
2. The **losses from warm ambient** are to be computed after gantry integration (still, room for optimization).
3. Losses from **resistive current leads** come from analytical solution for optimal current leads (46 W/kA), leading to 120 W (but can be intercepted at 60 K by thermal shield employing mixed Cu-HTS leads)
4. Losses in **superconductors** are computed with a mixed analytical-numerical approach (following slides)