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Progress in SC magnets for a European ion therapy gantry

I.FAST – 1st Annual Meeting
05 .May.2022

Ernesto De Matteis, Lucio Rossi – INFN-MILANO-LASA
On behalf of my IFAST, HITRIplus and SIG colleagues

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Summary

- Introduction to Ion Therapy Gantry
- Superconducting magnets progress:
  - IFAST WP8 – Innovative Superconducting Magnets;
  - HITRIplus WP8 - Superconducting Magnet Design ;
  - SIG WP2– INFN project
- Conclusions and next steps

Hadron Therapy

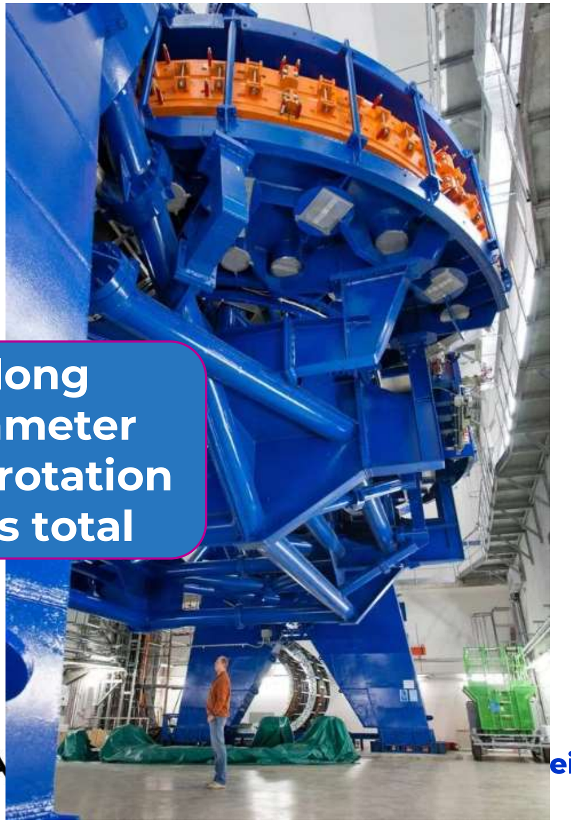
- Hadron therapy is a medical treatment that uses carbon ions and protons to cure cancer.
- Carbon ions are more effective for tumours resistant to traditional therapy and protons, but their use is limited by the size and cost of the needed infrastructure.

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

E. Benedetto – Tuesday talk

Ion Therapy Gantries in the world

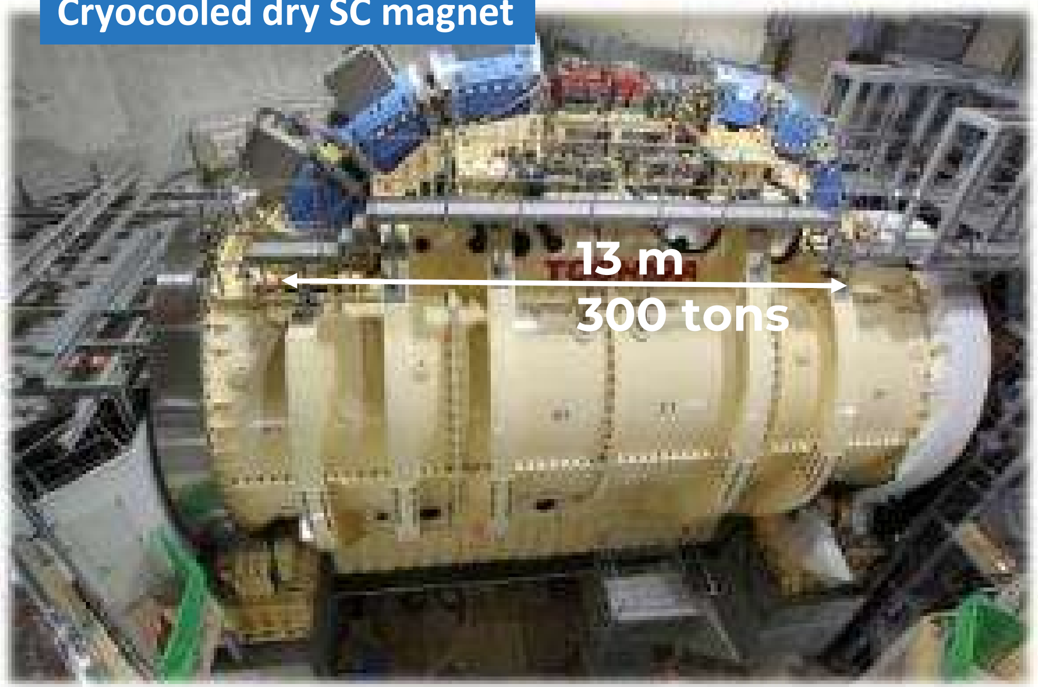
HIT - Heidelberg Ion Beam Therapy Center
(first in EU) – normal conducting magnets (B<2 T)



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)

Cryocooled dry SC magnet



Superconducting Ion Therapy Gantry

Main advantages:

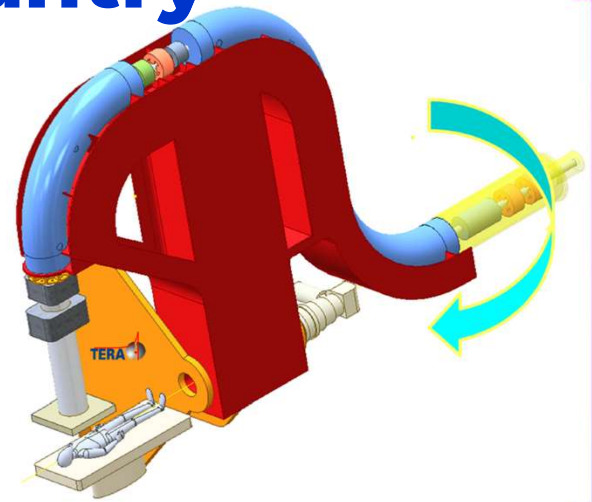
- Reduction of weight (300 → 50 ÷100 tons)
  - Reduce the number of magnets (B = 3→4 T)
- Footprint and cost reduction
  - Gantry cost is about 25% of facility cost;
  - Total cost of facility is about 200-250 Meuro (50 Meuro for the gantry);
- Power consumption (SC vs NC magnets);
- Reduction of size: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

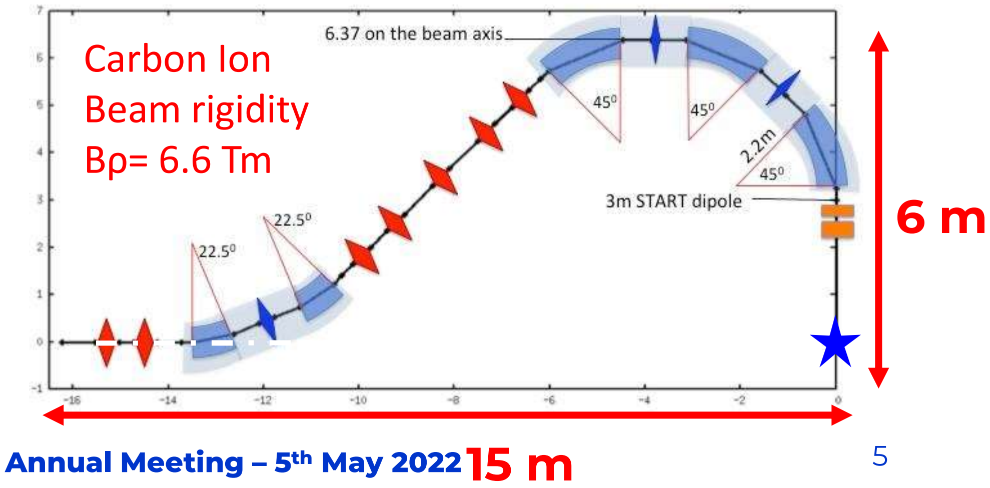
Main disadvantage:

- Need of cryogenic system (Top =4.7 K, no liquid helium);
- Higher initial costs.

Rotating Gantry

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





Projects on SC magnet design for Gantry & Co

European projects

I.FAST — **WP8 - Innovative Superconducting magnets**

L. Rossi – Wednesday talk

HITRIplus (Heavy Ion Therapy Research Integration) — **WP8 - Superconducting magnet design**

INFN project

Superconducting Ion Gantry — **WP2 - Superconducting Magnet Design**

HITRIplus & I.FAST: CEA, CERN, Ciemat, Wigner, INFN, Paul Scherrer Institut (PSI), Uppsala Universitet

I.FAST: Bilfinger Noell GmbH, Université de Genève, Elytt Energy, Scanditronix

HITRIplus: SEEIIST, CNAO, Sentronis

SIG: INFN, CERN, CNAO

IFAST WP8 – Innovative Superconducting Magnets

Aim of the WP about SC magnets:

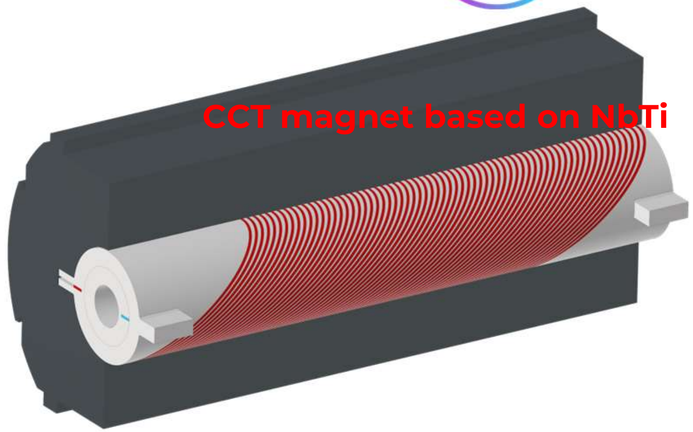
- Manufacture of a **straight HTS Canted Cosine Tetha (CCT) demonstrator** of about 4 T preceded by a **straight LTS CCT demonstrator** magnet in collaboration with different institutes and **industries**;

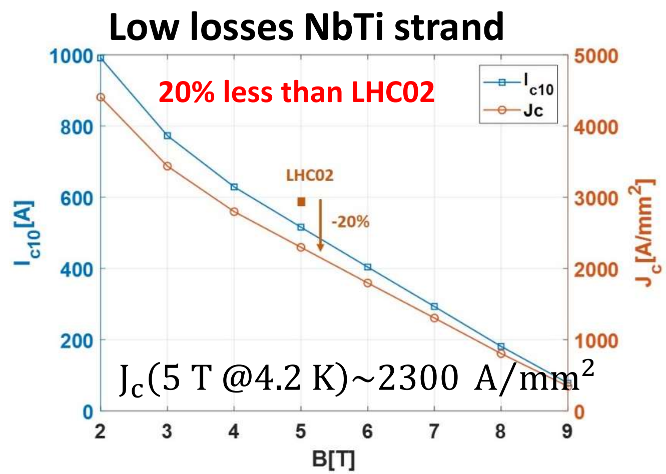
Specification and Design parameters:

- Common baseline between the two CCTs (with HITRIplus and SIG);
- 4T of bore field, 0.4 T/s of ramp rate, 80 mm of bore diameter, 1 m of maximum physical length;
- LTS CCT based on **NbTi,** HTS conductor under decision;

Characterization of the strand in NbTi (INFN, UNIGE, CERN):

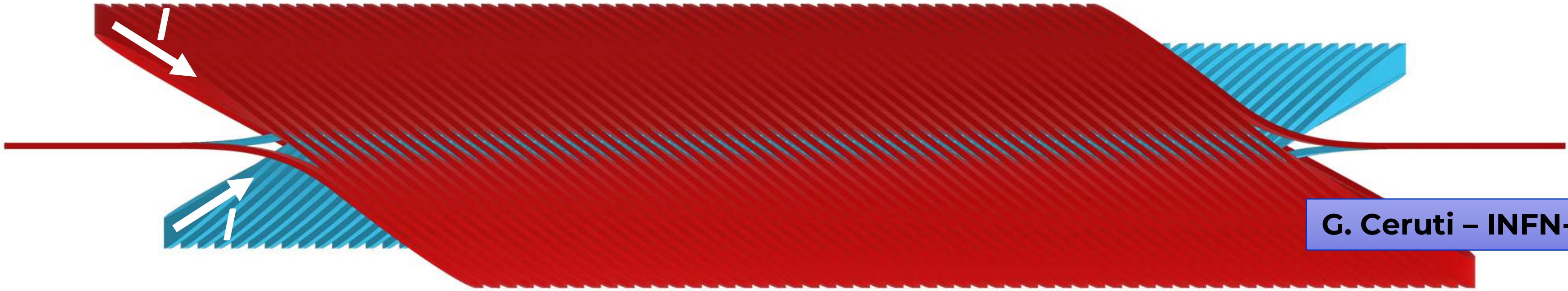
- Low losses NbTi strand (0.8 mm diam, 3 um fil. diam., 20% less Ic wrt LHC outer layer) , critical current, magnetization and RRR.
- **Milestone MS32**: https://zenodo.org/record/5901601#.YmrIvNpByUl





Canted-Cosine-Theta (CCT) Magnet

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



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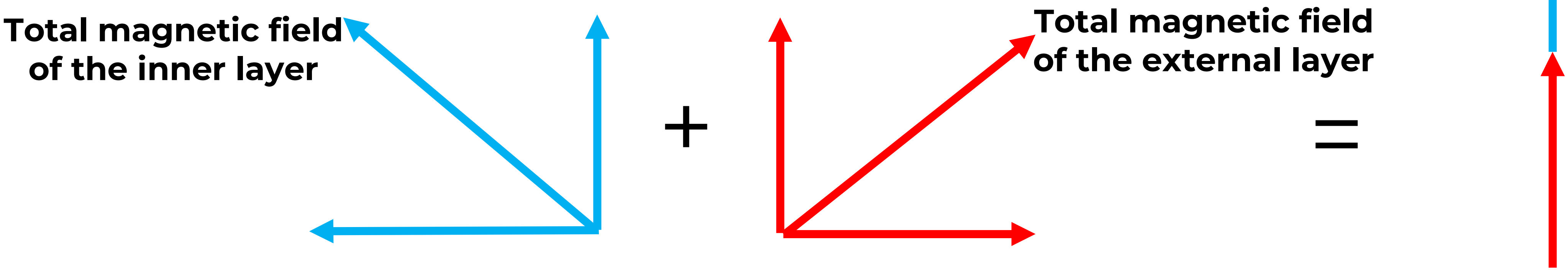
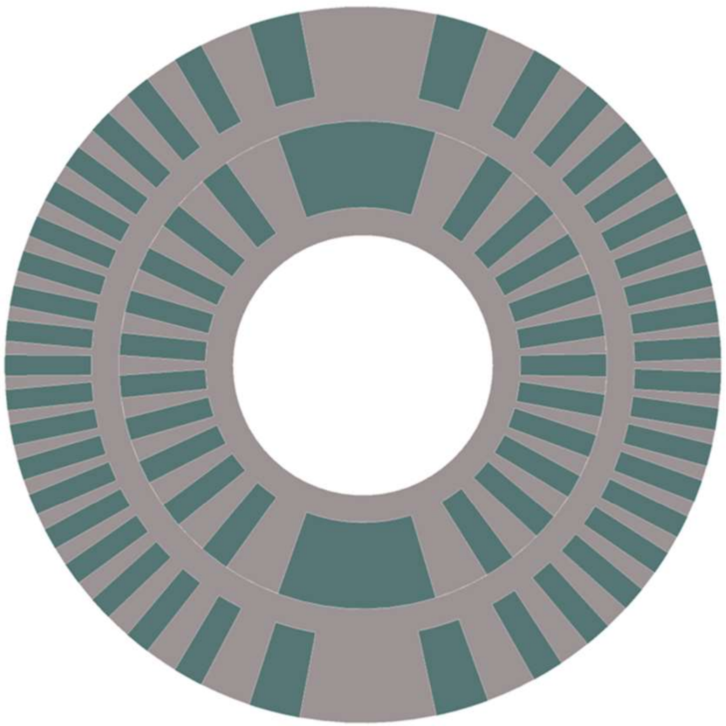
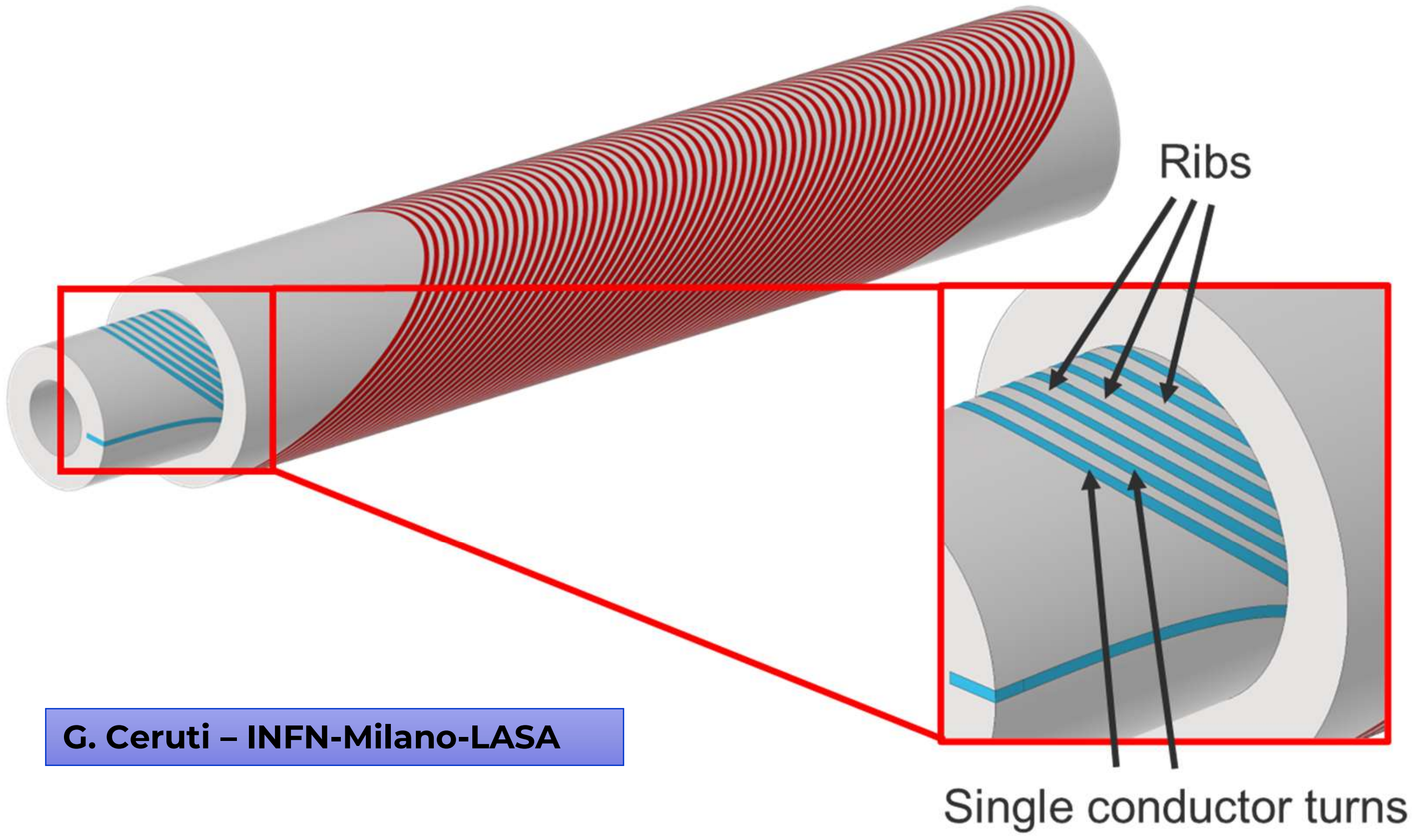
- **Current *I* flows in the two conductors so that the transverse magnetic field components add up and axial field components cancel each other out.**



CCT schematics





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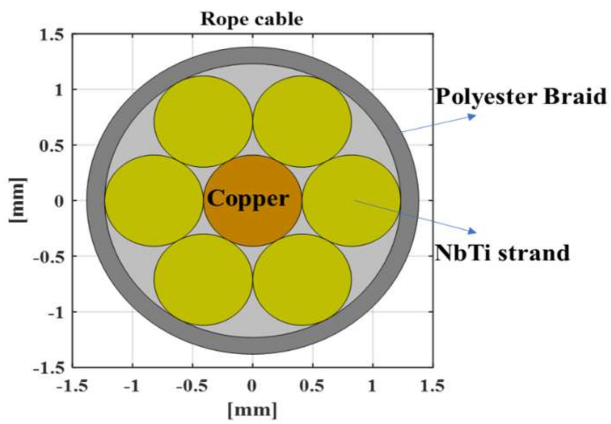
IFAST WP8 – Combined CCT magnet based on NbTi

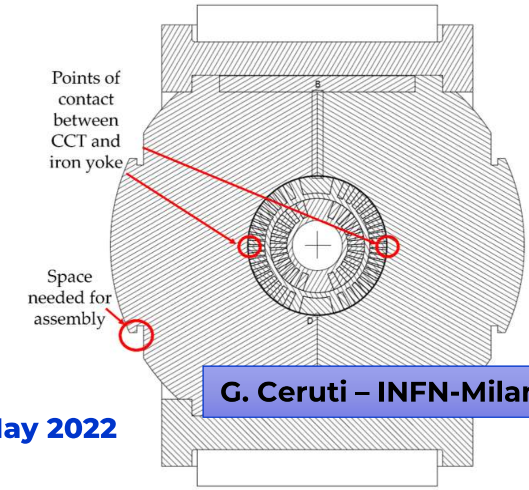
Conceptual design of the **Combined CCT magnet based on NbTi**:

- **Magnetic design:**
  - Combined fields (**4 T dipole + 5 T/m of quad. @4.7 K,** 28.7% LL margin, magnetic length of 0.73 m;
  - **Conductor: 2 x 8 ropes** (1300 A each) – low current, less costs and heat
- **Mechanical design**:
  - **Full mechanical structure** (Former+ Iron yoke+ Assembly);
  - Materials for the former (Al Br and **PEEK**);
- **Stability and Protection**:
  - Large time margin of **0.325** s for a rope 6 NbTi+1 copper strands.
- **Power Losses:**
  - Conductor Losses and eddy current losses for metal formers (0.4 T/s of ramped field) → St Steel good but difficult to machine, AlBronze good but sufficient for 0.25-0.3 T/s and difficult to procure
  - → solution **PEEK (or polymer former);**

Deliverable 8.2 https://zenodo.org/record/6389851#.YmwhA9pByUl



Iron yoke as shield and collar



G. Ceruti – INFN-Milano-LASA

IFAST WP8 – Conceptual Design of HTS CCT magnet

The main goal of the WP8

- Baseline (**4 T dipole @ 10 K**, > 15 K of margin);
- Superconductor **ReBCo** (Tapes);

Two preliminary designs implemented (No iron):

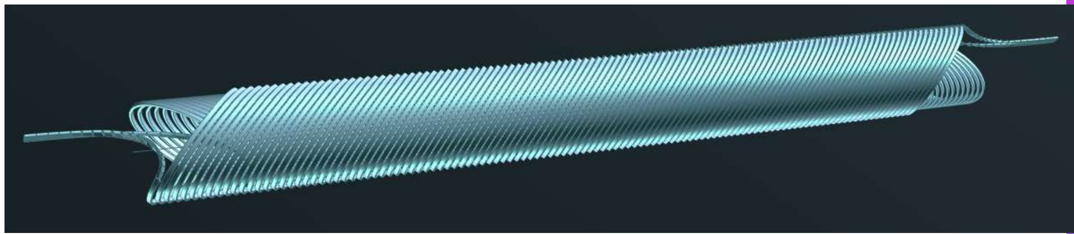
- "**Metal-as-Insulation-like**" design with 2 layers cable (780 A x 2 tapes x 14 cables)
- "**Insulated-like**" design (added copper to conductor);

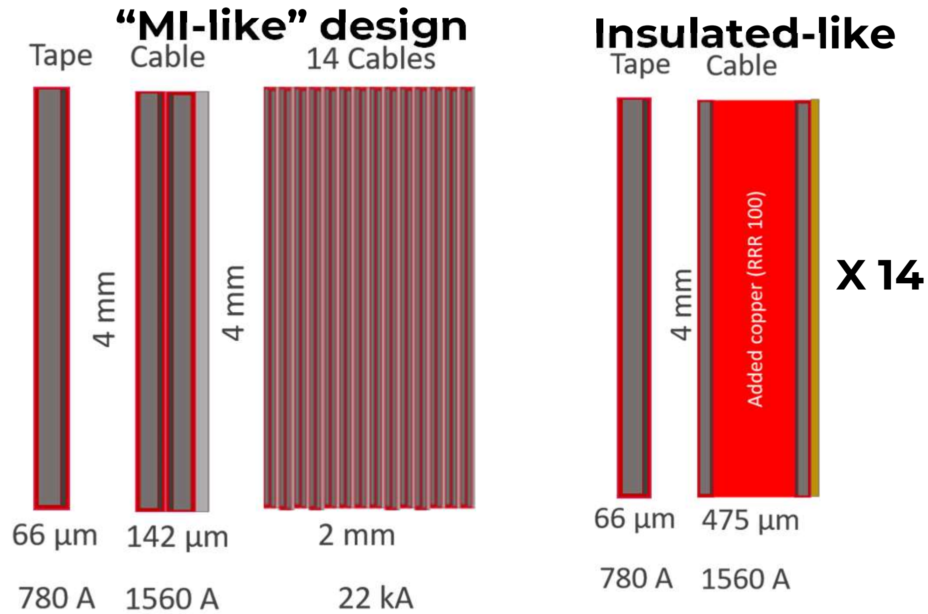
Protection aspect is the critical point for both:

- No classical protection for the MI-like;
- 10-50 μV threshold and 10 ms delay (Insulated-like) adding more than 320 μm of copper;

<u>Work in progress (Milestone Report in preparation)</u>

T. Lecrevisse (CEA) – Task leader





HITRIplus WP8 – Superconducting magnet design

HITRI plus
Heavy Ion Therapy Research Integration

Aims of the WP:

- Technical and financial **assessment** of various magnet designs for a novel type of carbon ion synchrotron and gantry complex;
- Manufacture and test of a **curved demonstrator magnet** for accelerator and gantry (beam rigidity Bρ = 6.6 Tm).

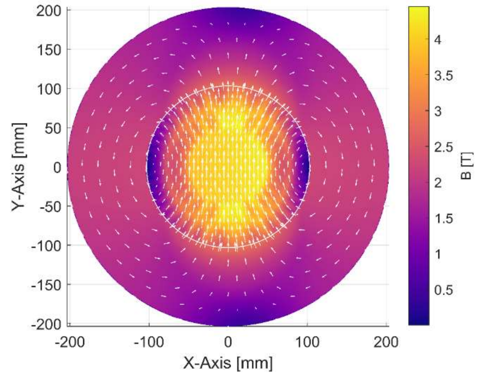
Specification and demonstrator parameters:

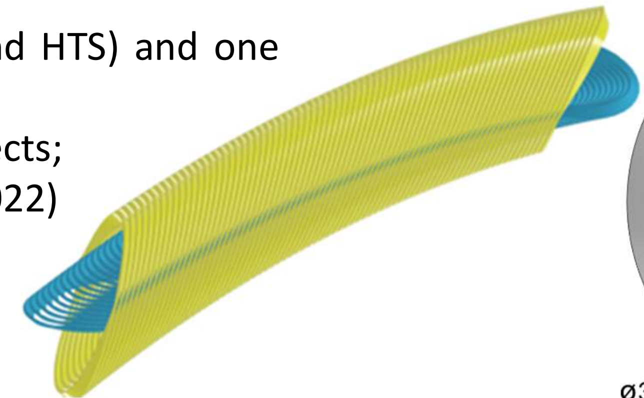
- Baseline - **curved CCT based on NbTi** (**4 T dipole** field, 80 mm of bore, **30 deg., 1.65 m of curvature radius,** 1 m of length, 4.7 K of Top, 0.4 T/s of ramped field) – matching with the goals of IFAST and SIG WPs;
- **Low losses NbTi strand** and decision for **Rope cable** (as IFAST program);

Magnet Assessment of various designs:

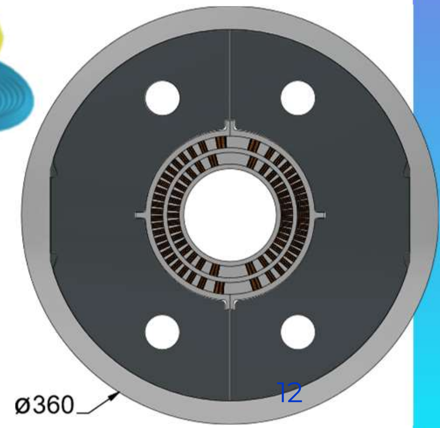
- **Four CCTS** based on different SC (NbTi, Nb3Sn, MgB2 and HTS) and one **CosTetha** based on NbTi;
- Highlights on magnetic, losses, SC costs and electrical aspects;
- **Deliverable 8.1 report** under submission (deadline May 2022)

CCT NbTi – 4 T





CCT Nb3Sn



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HITRIplus WP8 – Preliminary design

Mechanical design with iron, curved, 75 mm of bore, 30 degree: design complete of cold mass (mechanical structure) – MME CERN group

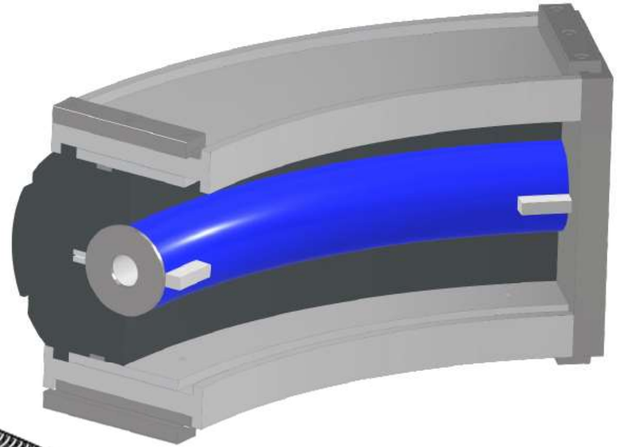
- Definition of structure, former machining and assembly procedure;

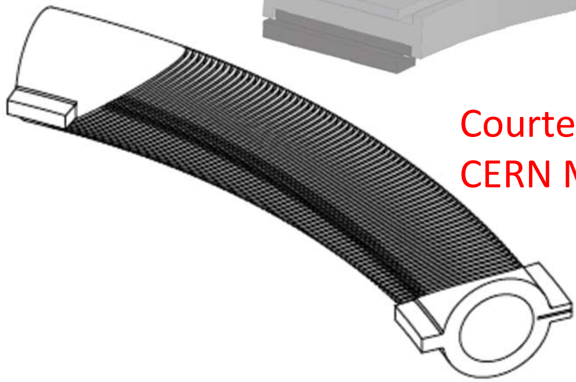
Heat losses for various formers' materials and superconductor (0.4 T/s):

- Al, AlBr, StSt former (Bulk and long. Cut) – **solution Polymer (PEEK)**;

Engineering Design (Task 8.3 – D. Barna, task leader):

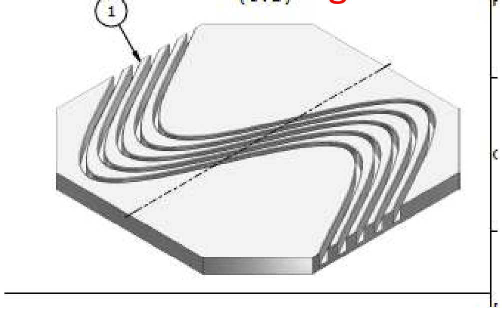
- Former materials (metals, polymer);
- Alternative technology investigation (3D printing);
- Roping and Winding tests: dummy cable, definition of the tools;
- Mechanical test (INFN and CERN): test groove (Al and PEEK), and formers (ongoing).



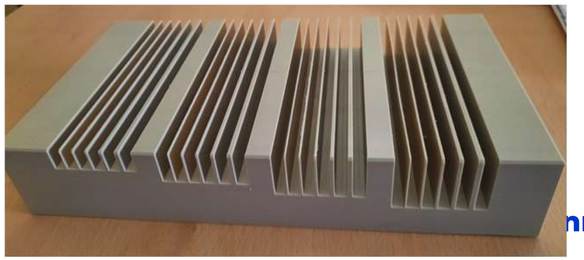


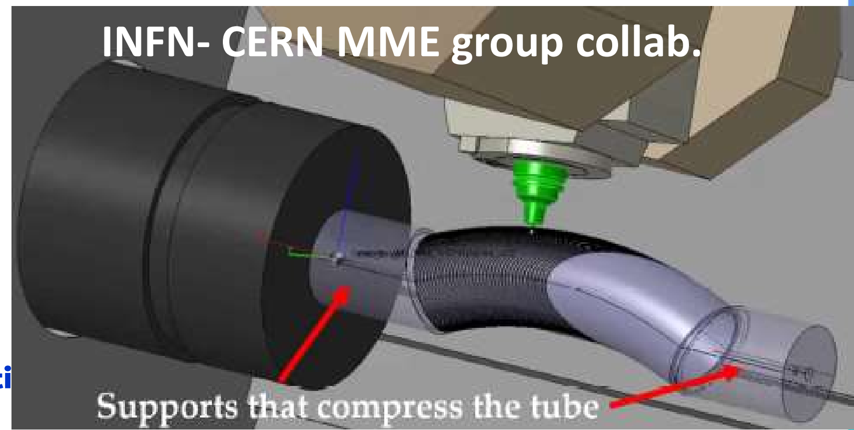
Courtesy of K. Scibor
CERN MME group

Plate for winding test



PEEK – test groove – Tosti s.r.l.
Castel del Piano, Grosseto, Italy.

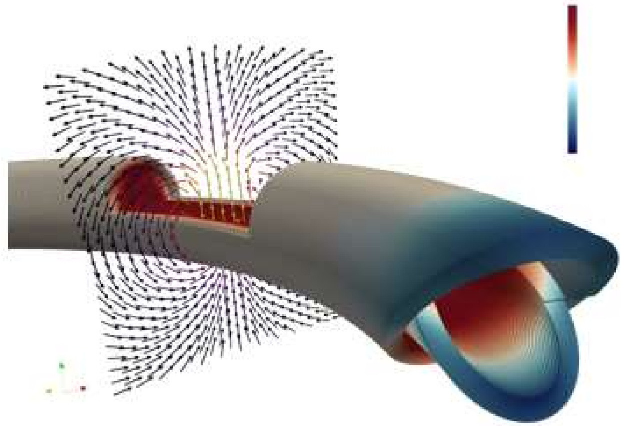




HITRIplus WP8 – Linked activities

Working Group on Field Quality for Curved magnets (D. Barna and E. Benedetto):

- dedicated meetings on the topic
- Algorithm to link the CCT conductor path with field derivatives (optics) (D. Veres, D. Barna et al.)https://doi.org/10.1109/TASC.2022.3162389.



CCT Computation and Design Workshop (Chair L. Rossi)

Scope: the strong interest of Canted Cosine Theta (CCT) magnet design according to the, pursued in both European H2020-HITRIPlus and H2020-I.FAST programs, HITRIPlus-WP8 (Superconducting Magnet Design) and H2020-I.FAST-WP8 (Innovative Superconducting Magnet)

The workshop was held in remote and on 21 and 22 September afternoon (3.00 pm - 7.00 pm)

Attendees: I-FAST and HITRIplus partners but also other groups, as LBNL and CERN

HITRI plus
Heavy Ion Therapy Research Integration

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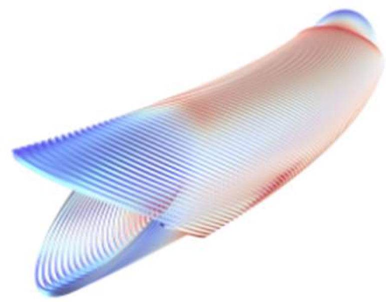

CCT-CDW - 1

https://indico.cern.ch/event/1065779/

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SIG WP2 – Superconducting magnet design

Superconducting
Ion
Gantry

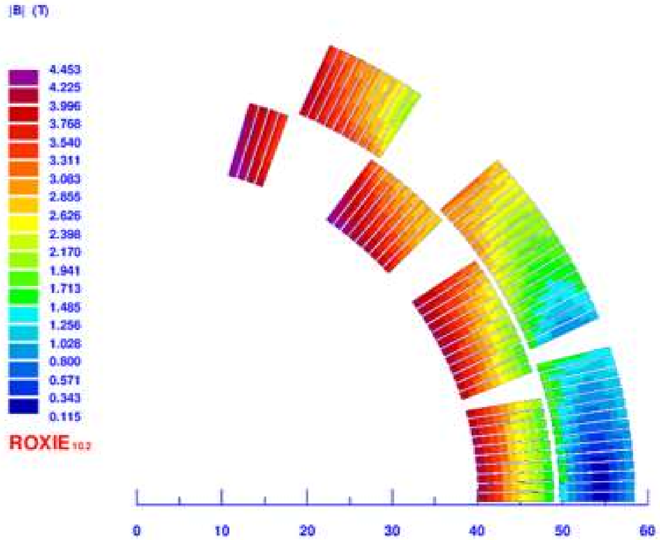
Aim of the WP:

L. Rossi and M. Prioli – WP responsibles

- Realize a magnet demonstrator for SC Ion Gantry;

Baseline is a **curved CosTetha magnet based on NbTi**

- Building on the CERN **SIGRUM** design (M. Karppinen)
- SIG is the result of a three-party agreement: INFN – CERN – CNAO



Dipole magnet main params.	
Coil type	Cos-θ
Superconductor	NbTi
Bore field	0.4 - 4 T
Bore diameter	80 mm
Curvature radius	1.65 m
Magnetic length	1.3 m (45°)
Ramp-rate	0.4 T/s
Operating Temperature	4.7 K
Cooling	Indirect

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SIG WP2 – main technical challenges

<u>Windability</u> with high curvature (ρ=1.65 m)

- Baseline: **cos-θ coil type** with convex-concave winding with many posts (extension of DISCORAP)
- Alternative: **block-coil type** with fully convex winding (**<u>S. Farinon</u>** et al., IEEE-TAS, 14, No. 2, p. 585, 2004)

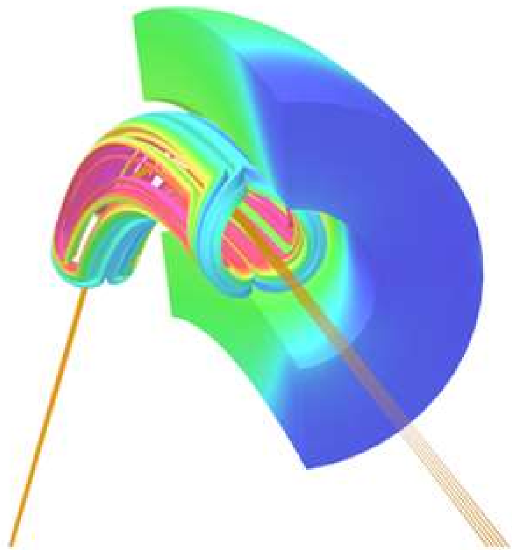
<u>Indirect cooling</u> due to the incompatibility with LHe

- Baseline: coil engineered with **<u>heat extraction by a cryocooler</u>**
- Alternative: forced convection with GHe

<u>Fast ramped magnet (0.4 T/s)</u> to reduce the treatment time

- Optimized **low-loss conductor** with small filaments and CuMn matrix
- **Rutherford cable with stainless-steel core**
- Proper selection of the materials for the cross-section

→**<u>Not all the features in the (first) demonstrator!</u>**



Conclusions and Future steps

IFAST WP8 - first year activities (05/2021-05/2022) presented:

- Conceptual Design of the **Combined CCT based on NbTi** →Engineering Design: winding (**ropes**) and former tests, thermal design, with growing involvement of companies;
- **CCT based on HTS** → Finalize the conceptual design (Define the conductor and solve the protection aspect) → Engineering design complete of a mechanical structure (+Iron yoke), former and winding tests, thermal design;

HITRIplus WP8 - first year activities (04/2021-05/2022):

- **Curved CCT based on NbTi** → Complete and optimize the preliminary design (Conceptual design)→ Engineering design: winding (**ropes**) and former tests, thermal design…

SIG WP2 (started the 01/2022) – few months activities:

- **Curved CosTetha based on NbTi** → define the layout and conductor (curved costetha or block coil)→ winding tests are needed.

Papers on the WPs activities

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. **(HITRIplus and IFAST WP8)**

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, doi: 10.1109/TASC.2022.3162389.**(HITRIplus)**

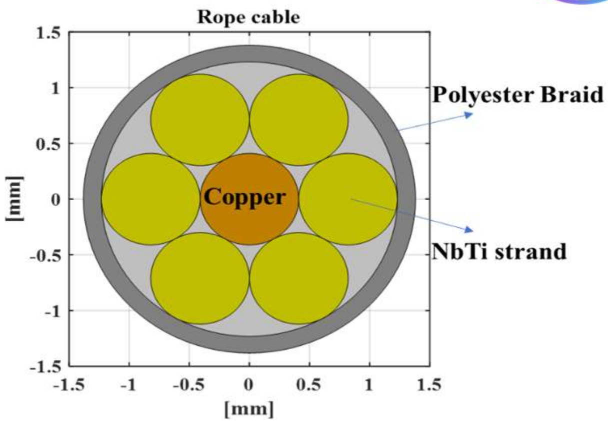
L. Rossi *et al.*, "Preliminary Study of 4 T Superconducting Dipole for a Light Rotating Gantry for Ion-Therapy," in *IEEE Transactions on Applied Superconductivity*, vol. 32, no. 6, pp. 1-6, Sept. 2022, Art no. 4400506, doi: 10.1109/TASC.2022.3157663. **(SIG)**

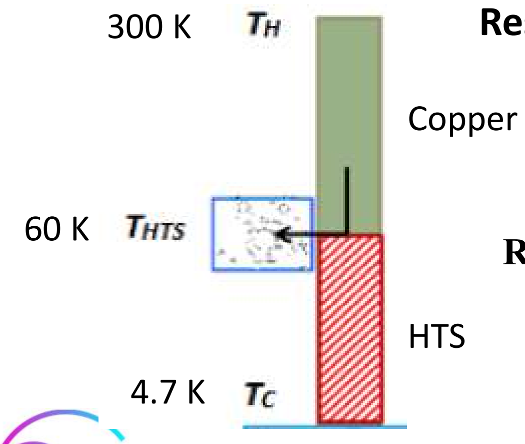
Thanks for the attention!!!

IFAST WP8 – Cable decision : Rope 6 + 1 NbTi + copper

Definition of the conductor:

- Comparison between Rutherford & Rope (6+1) of NbTi strands;
- Computation heat losses Current Leads (conduction cooled by **cryocooler**);
- Decision for **Rope cable NbTi** (as for **HITRIplus**) : less expensive, cheaper power converter (2 kA, 150 A/s), winding is easier (?).





Resistive part between 300 K and 60 K:

$$\frac{Q_{c,min}}{I} = 46\left[\frac{W}{kA}\right]$$

For each CL

Rutherford cable(I ~10 kA)	$Q_{c,min} \sim 460\ W$
Ropes (I ~1.5 kA)	$Q_{c,min} \sim 70\ W$

Test rope made of 7 NbTi strands and a single **polyester braid**