27th International Conference on Magnet Technology (MT27)
Fukuoka, Japan / 2021

Preliminary study of 4 T superconducting dipoles for a light rotating gantry for ion-therapy

L. Rossi[1], on behalf of the SIG collaboration

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CNAO Centro Nazionale di Adroterapia Oncologica

CERN

INFN

MT27

Oral talk at THU-OR4-401-05 session on

Magnets for Medical, Biological, and Analytical Applications

Superconducting Ion Gantry

Summary

A collaboration between CERN, CNAO, INFN and MedAustron has been formed with the aim at designing a light rotating gan-try suitable for hadron therapy based on 450 MeV carbon ion beams.

After a preliminary design based on 3 T dipole field, see related paper in this session by M. Karppinen, now the collaboration **is engaging to improve the design to 4 T dipole field, or possibly more.** The magnets are designed according to cosθ layout to be wound with Nb-Ti conductor, most probably a Rutherford cable.

The main challenge of this magnet is the very small curvature radius of 1.65 m with a relatively large aperture, 70 to 90 mm. Another considerable challenge is the use of indirect cooling (most probably cryogen-free) despite the cycling operation with 0.3-0.4 T/s. The design of these 4 T dipoles, to which will be superimposed a further 0.3 T of quadrupole field, is therefore very challenging. The paper will report the preliminary computations on various configuration aiming at 4 T with typically 20% margin in operative conditions. A 1 m long demonstrator will be manufactured at INFN-LASA in three years. A candidate conductor has been measured, with 3 micron Nb-Ti filaments embedded in a Cu-Mn alloy matrix. The resulting gantry is very compact: with proper integration between gantry structure and magnets the rotating weight maybe less than 50 tons, a factor five gain on the pre-sent state-of-the art.

SEEIIST

South East European International Institute for Sustainable Technologies

Fighting against cancer

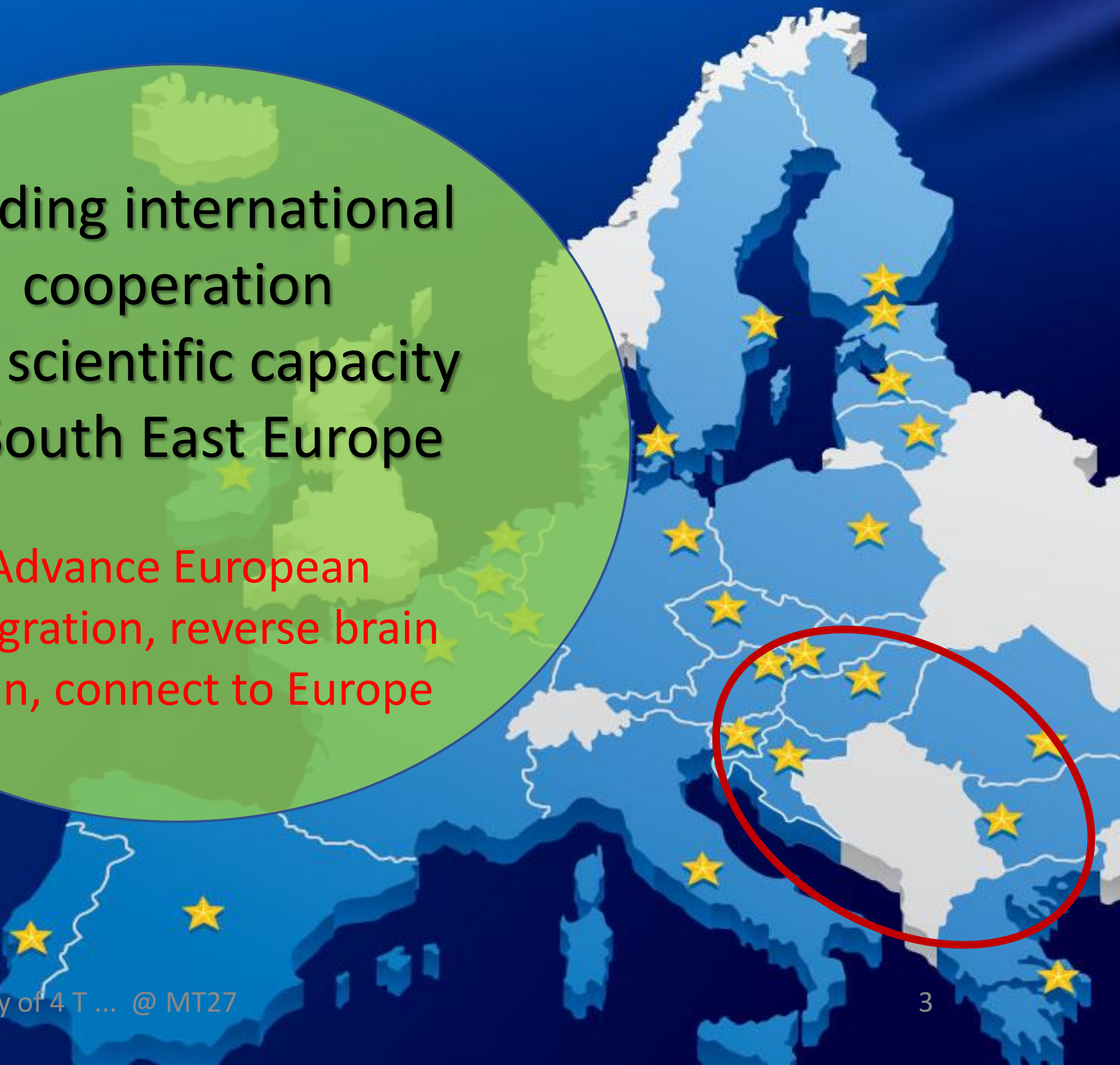
Nuclear medicine as crucial component of future personalised cancer care

Develop advanced cancer therapy with ion beams and isotopes

Two Strategic Objectives – One initiative

Building international cooperation and scientific capacity in South East Europe

Advance European integration, reverse brain drain, connect to Europe

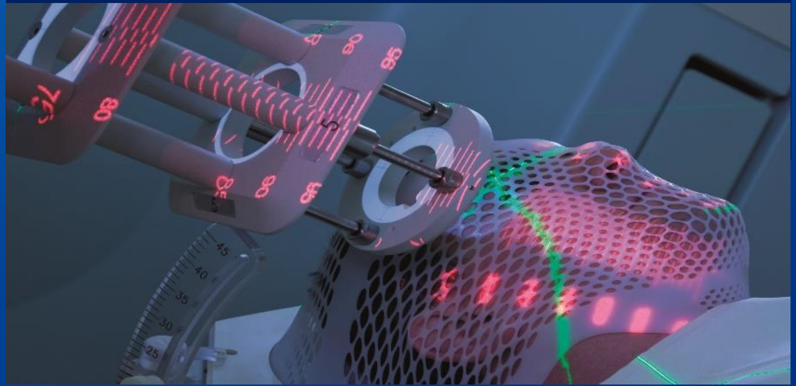


SEE IIST
South East European International Institute for Sustainable Technologies

<u>Comprehensive Dimension:</u> both Cancer Therapy and Research Center with 50% of the beam time dedicated to research – other Unique Selling Points

MULTI-DISCIPLINARY RESEARCH WITH HEAVY IONS

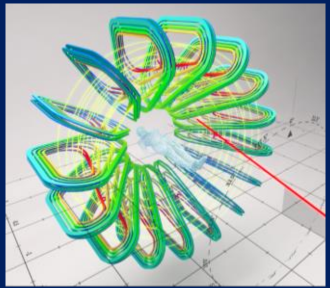
- Pre-clinical (medical, radiobiology)
- Clinical, including clinical trials
- Industrial research (microelectronics)
- Material research
- Ultra-high dose rates (FLASH)

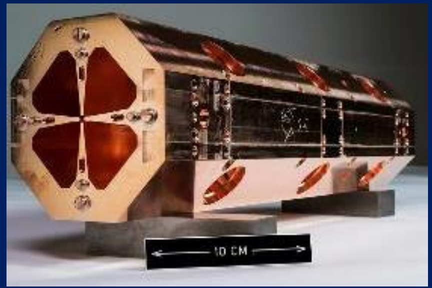


Cutting-edge innovative and novel research in any of these topics driven by novel technological opportunities
Complementary to all existing facilities

BREAKTHROUGH IN TECHNOLOGY

- Multi-ion synchrotron (beyond presently used p and C-ions)
- More compact and much cheaper Superconducting synchrotron
- Superconducting gantry
- Higher beam intensity, faster extraction; Real time imaging





Will make cancer treatment with ions accessible to a large fraction of the European population and bring back Europe the lead position in this field

SCIENCE DIPLOMACY

- Declaration of Intent signed at CERN in October 2017 by 8 SEE countries
- MoC signed by 6 Prime Ministers of the SEE Region in July 2019, at the Summit of Berlin Process, Poznan
- Political support by the Swiss Government to establish SD roadmap

With the strong supporting consortium of 18 European research centers and clinics the SEE region is trying to revive its technological tradition

SEE IIST
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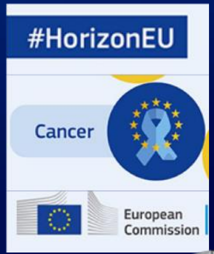
for Sustainable Technologies

SEEIIST – First Green Infrastructure in line with Horizon Europe Cancer Mission



Gantries are a key tool for particle (hadron) therapy
However, for ions they are bulky and expensive
Compact superconducting magnets are changing the scene

Heidelberg (De)HIT
First ion gantry ever
Resistive magnets
600 tons rotating
25 m long (2012)

HIMAC- QST NIRS (Jp)
First SC gantry ever
2.3-2.9 T from 2018
Ca. 300 tons

Cryocooled dry SC magnet

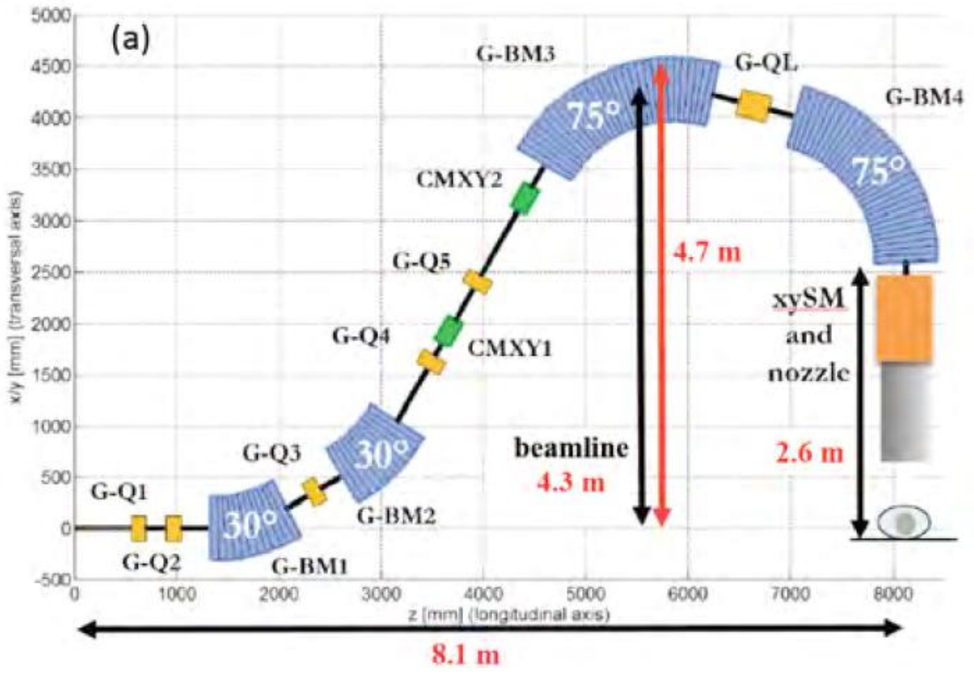
Pursuing an idea from TERA and CERN (collaboration with LBNL) for a **light gantry**…

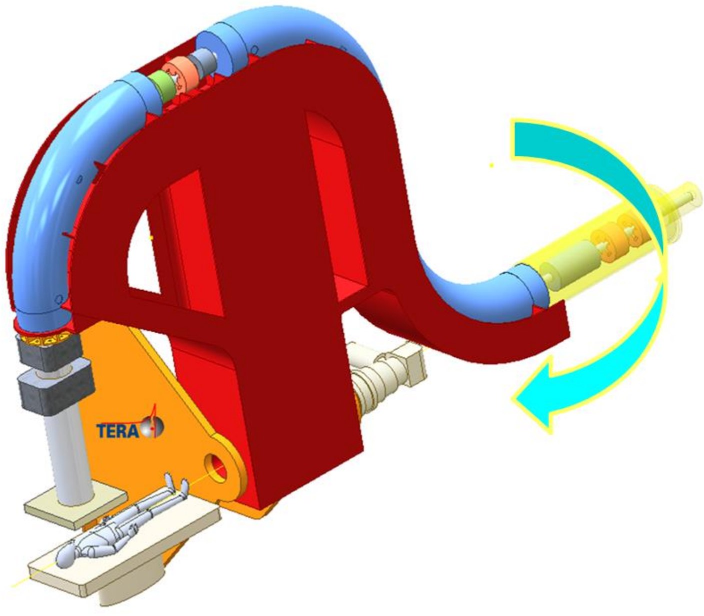
Design based on CCT magnets

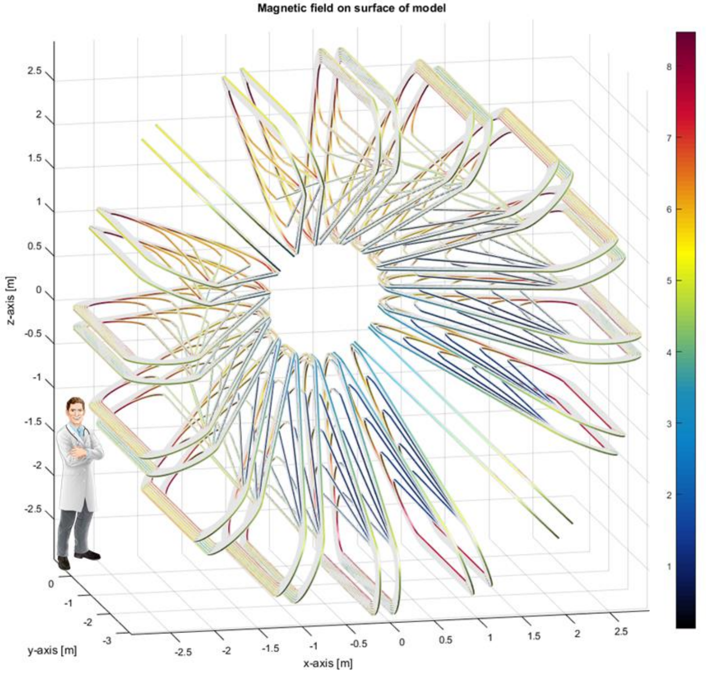
Conceptual sketch

Alternative: Toroidal gantry pursued by CERN as R&D (mainly for protons)

L. Bottura, E. Felcini, A. Haziot





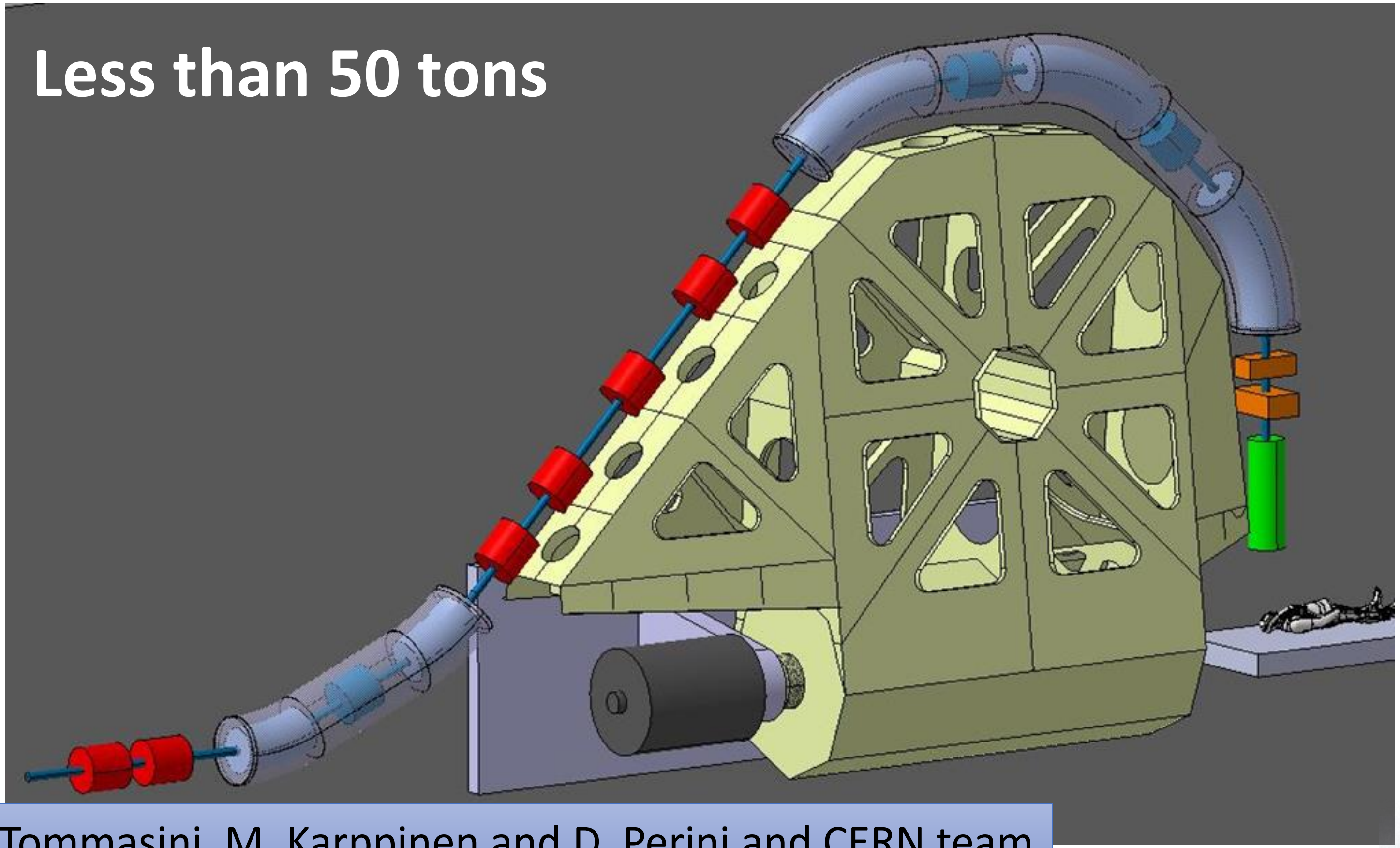


collaboration
CERN-CNAO-MedAustron-INFN on C-ion GANTRY:
4-Party Agreement

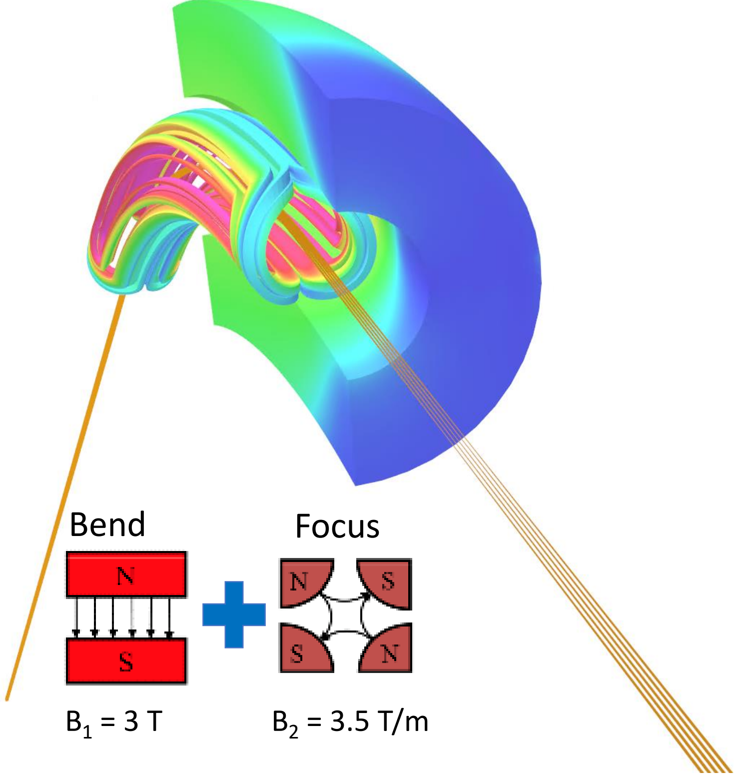
- Improve the efficiency (medical effectiveness and treatment time) of the present facilities
  - CNAO (Pavia, IT)
  - MedAustron (Vienna, AT)
- Design a gantry compatible with the present layout without large civil engineering and infrastructure investment
- Leveraging the design capability and technology infrastructure of HEP community (CERN) to strenghten the medical technology in EU.
  → **NIMMS program at CERN** led by M. Vretenar

TERA → CERN → 4-Party Agreement Gantry SIGRUM_v1.0

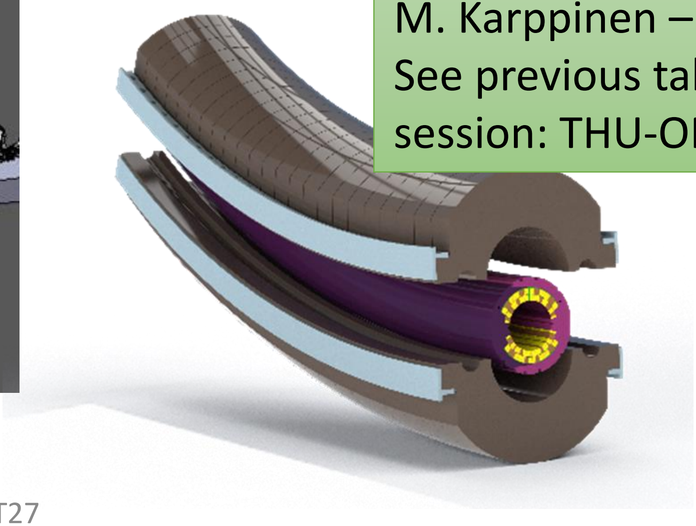
Present design based on $\cos\vartheta$: 3 T dipole (+= 0.3 T gradient field)



D. Tommasini, M. Karppinen and D. Perini and CERN team



Defocussing configuration



M. Karppinen – CERN
See previous talk In this session: THU-OR4-401-03

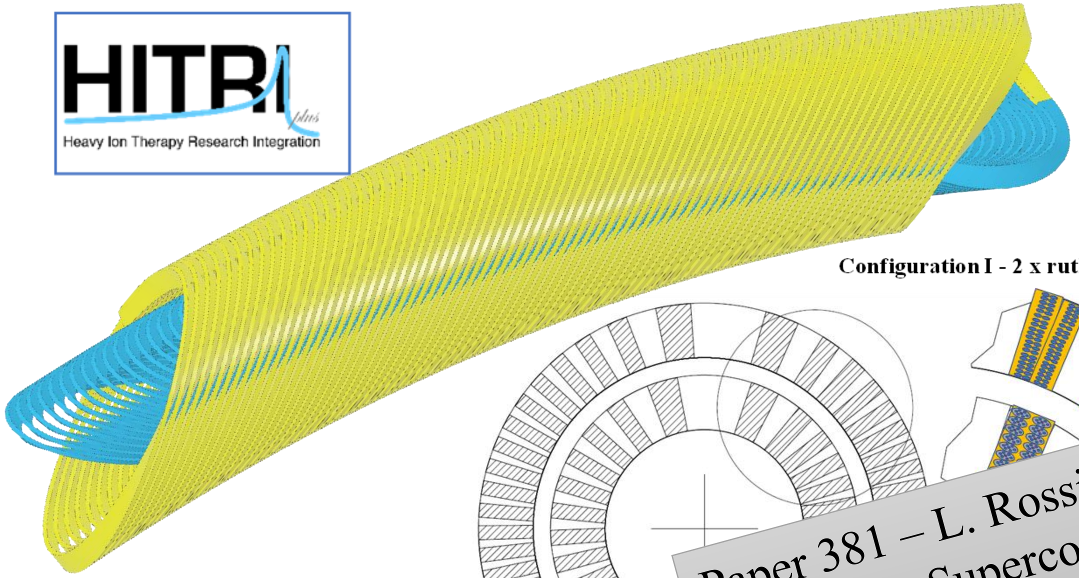
HITRI*plus* and I.FAST EU initiatives on CCT magnets for ion therapy: large collaborations for magnet R&D

These initiatives are parallel to the 4-Party Agreement, devoted mainly to advancing magnet technology in EU

The EU programs HITRIplus and I.FAST will explore CCT design for 4-5 T, 60-90 mm aperture, dB/dt =0.1-0.5 T/s

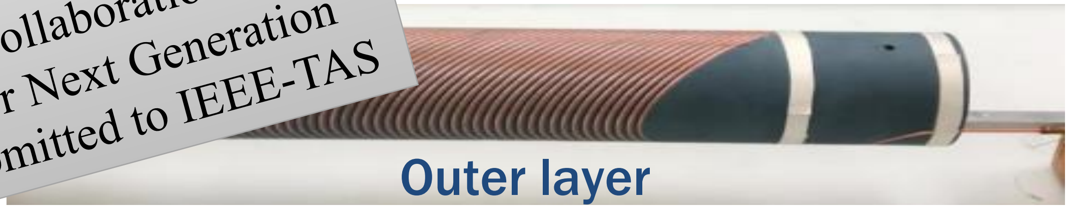
HITRIPlus (activity mainly in the Labs)

- **We want check how to make CURVED CCT with R = 1.5 – 2.5 m !!**



Paper 381 – L. Rossi et al., A European collaboration to investigate Superconducting Magnets for Next Generation Heavy Ion Therapy, EUCAS2021 – submitted to IEEE-TAS

I.FAST: exploring CCT with HTS and combined function!. Labs → Industry

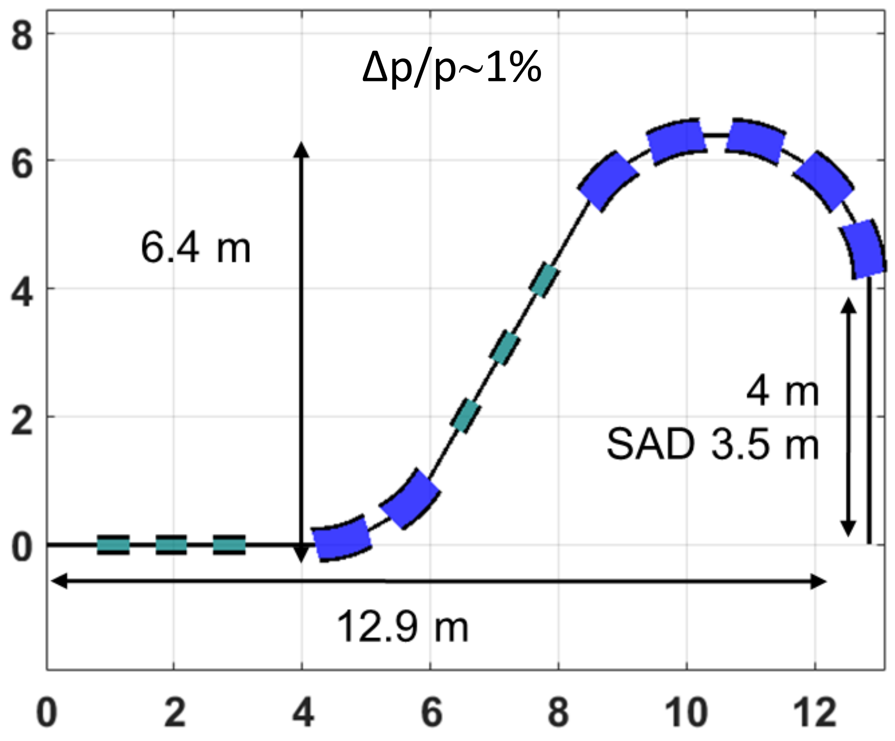


Outer layer

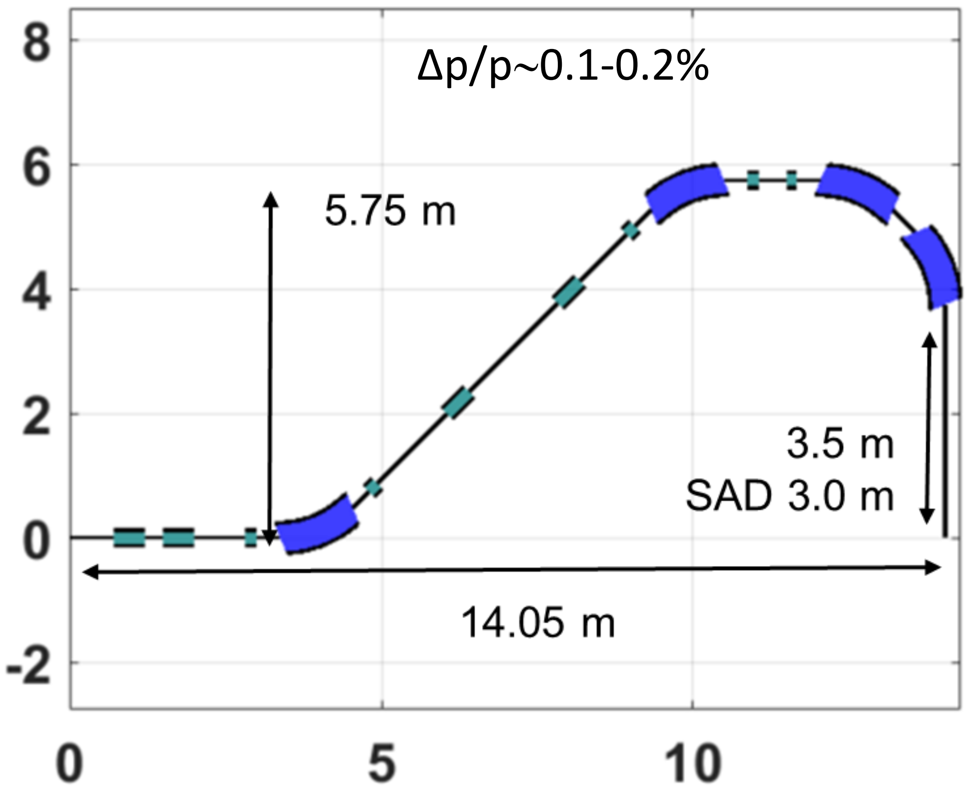
CCT coil wound wiht CORC
Courtesy of Xiaorong Wang (LBNL)

International review called by 4-Party Agr., Dec. ‘20 → explore field B_{dip} ~ 4 T (dB/dt ~ 0.3-0.4 T/s)

New solution: DT1; 6×30°dipoles B=4 T Nested quadrupole inside each dipole



New solution: EF6; 4×45°dipoles with combined quad. $B_{peak}=B_d+B_q$= (4+0.2) T

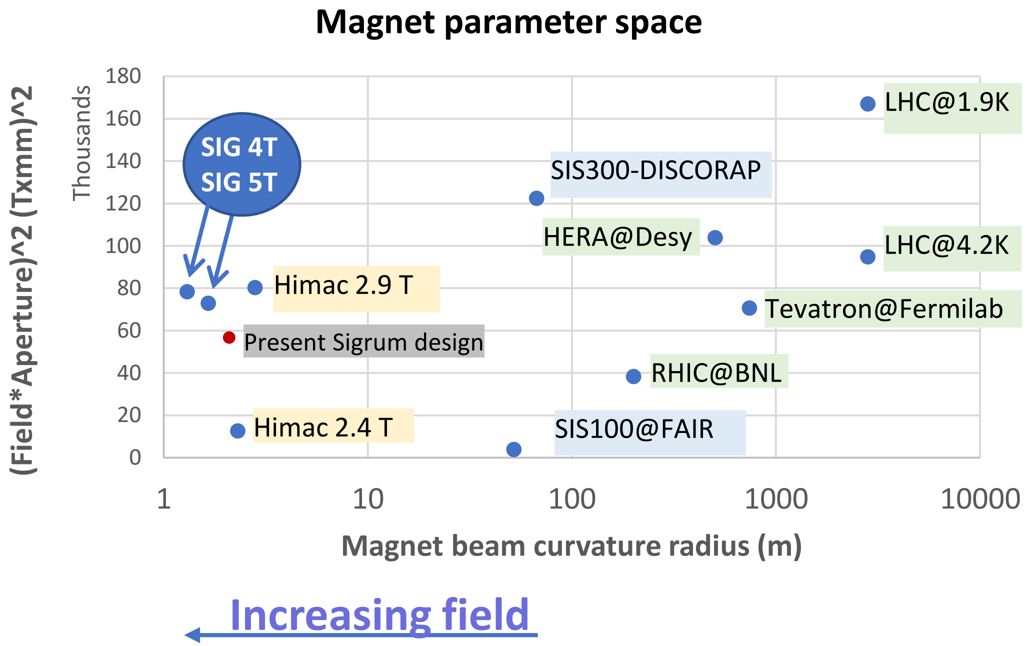


SIG – Superconduting Ion Gantry

Superconducting Ion Gantry

- Our team (INFN-Mi-LASA and INFN-Genova) has has applied to a competitive call by CSN5, and got a grant of 1 M€. The heart of the program (2022-2024) is the:
  - Design and construction of a cosϑ demonstrator for the SIGRUM gantry, 4-5 T, Ø = 70-90 mm
    - Bρ=6.6Tm; 4 T → R_{bend}= 1.65 m
    - 30° wide → L ~ 1 m
    - dB/dt .3÷.4 T/s (cryocooled)
      - →Nb-Ti low loss, 2÷3 μm filam, CuMn matrix (low J_c, too…)
  - Test in LHe and then indirect cooling
- The program SIG includes also
  - Study of fast scanning magnets
  - Study of a novel Dose Delivery + Range Verification system → adaptive treatment (+ possibly MRI imaging)
- Budget for the SC magnet demo:
  - 1260 k€ (Material incl. touch labour + temporary personnel for 8 FTE-y)
    - 660 k€ INFN grant
    - 600 k€ Contribution CNAO and CERN
  - 12 FTE-y Personnel INFN
  - Support from staff CNAO and CERN

Synoptic view of all main project of cosϑ (plus HIMAC) with «Energy» vs. beam radius (curvature)

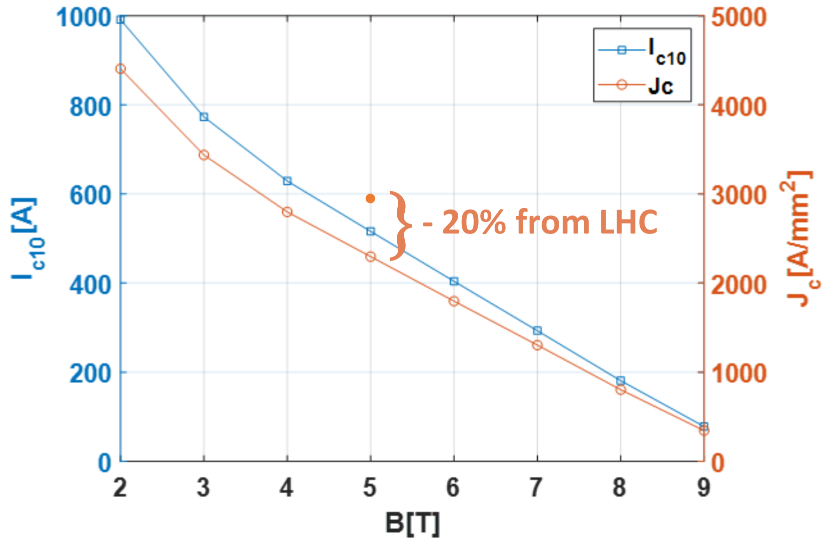


- Used Field (without iron) × Aperture to grade the difficultly of the magnet
- Plotted vs the magnet curvature (beam path radius)
- HEP dipoles are almost straight…
- GSI-FAIR SIS100 and SIS300 have noticeable curvature (however > 65 m, still)
- HIMAC SC gantry: 30 times less!!

Conductor first:
Nb-Ti for first demo

- Nb-Ti from DISCORAP project INFN with GSI for FAIR SIS300 dipole – 4.5 T 0.6 T/s in LHe
- 0.82 mm dia. Coated Sn(5%Ag)
- ~3 µm filament size (2.6 µm measured: microgr. and magnet.)
- In CuMn matrix
- 1:1.36 Cu/nonCu
- Left over both from Luvata and Bruker production

Features	Value	Meas. unit
Diameter	0.821	mm
Cu/NoCu	1.36	-
Twist length	6.6	mm
Jc (5T @ 4.2 K)	2296	A/mm^2
Ic (5T @ 4.2 K)	516	A
RRR	135	-
n	>30	-

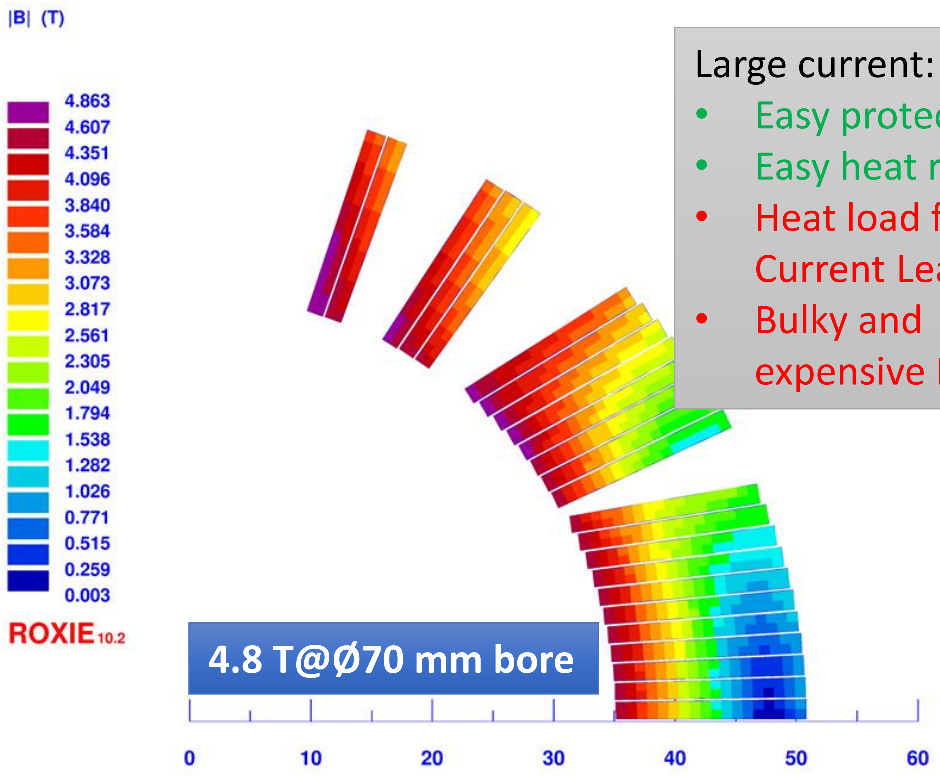


E. De Matteis and M. Prioli
INFN-Milano-LASA

Exploring the parameter space: T_{op} = 4.7 K
5 T@20% margin on load line; 70-90 mm bore; 1-2 layers

1 layer : Ø.825mm x 36 strands Ruther. cable (LHC02)

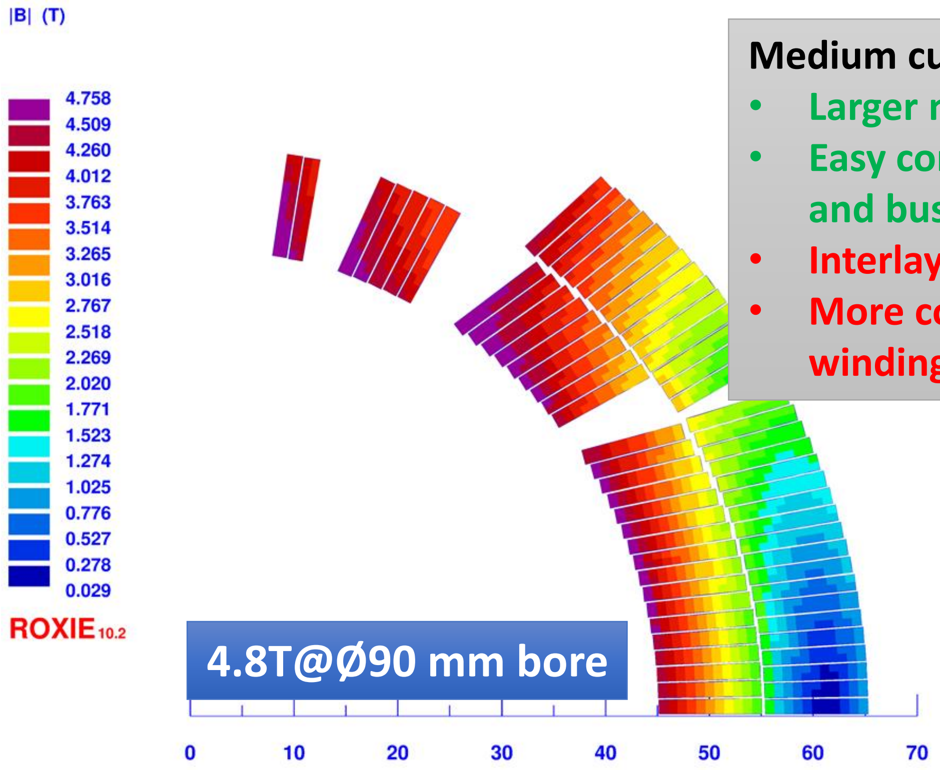
I_{op} = 9.8 - 8.5 kA (iron far-near coils); I_{op}/I_{ss}= 85%-80%



Large current:
- Easy protection
- Easy heat removal
- Heat load from Current Leads
- Bulky and expensive P.C.

2 layers : Ø.825mm x 22 strands Ruther. cable

I_{op} = 4.6 – 4.0 kA (iron far-near coils); I_{op}/I_{ss}= 76%-72%



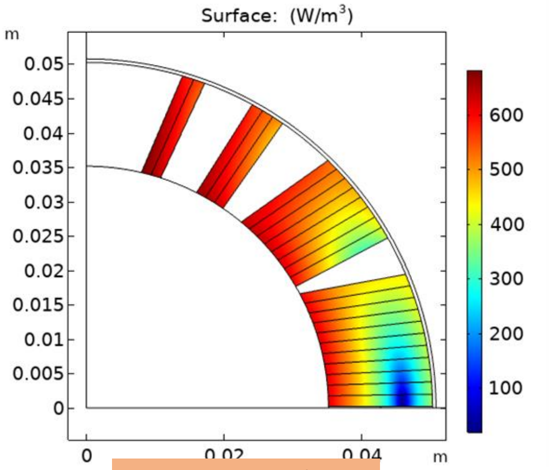
Medium current:
- **Larger margin**
- **Easy connections and buses**
- **Interlayer barrier**
- **More complex winding**

Thermal studies: conductor losses only (no iron)
Persitent, interfilament, interstrand (cored cable)

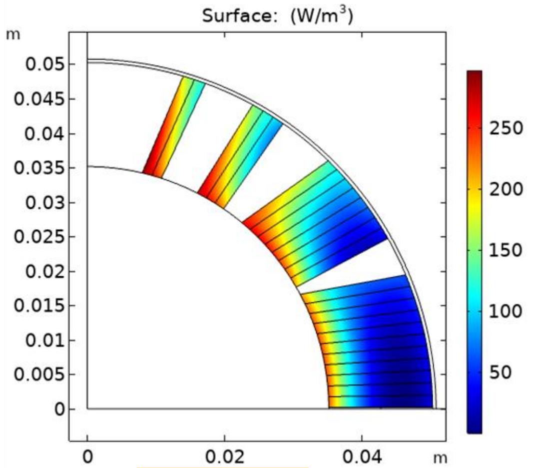
70 mm
Cable 36 Strands

dB/dt = 0.4 T/s
B_0=0.45 T→ 4.5 T

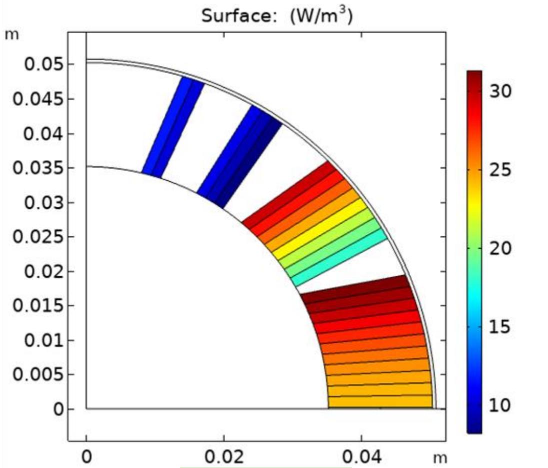
70 mm
Cable 22 Strands



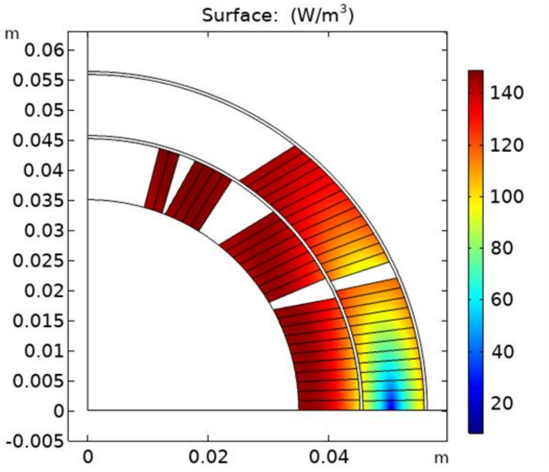
Persistent loss

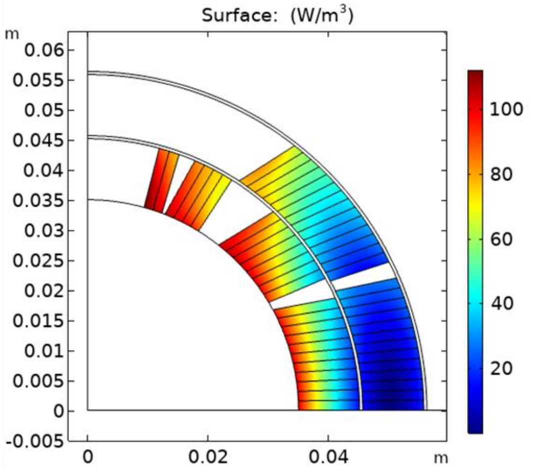


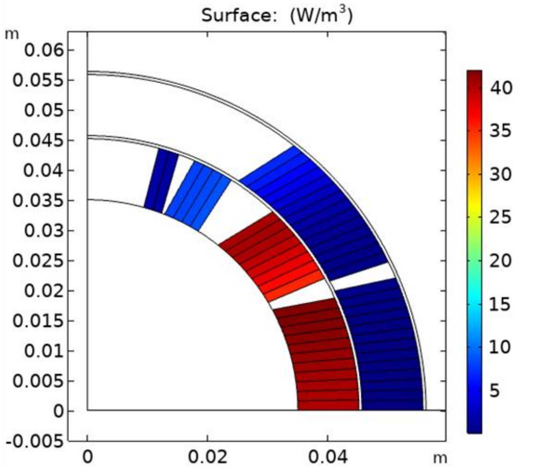
IFCC loss



ISCC loss

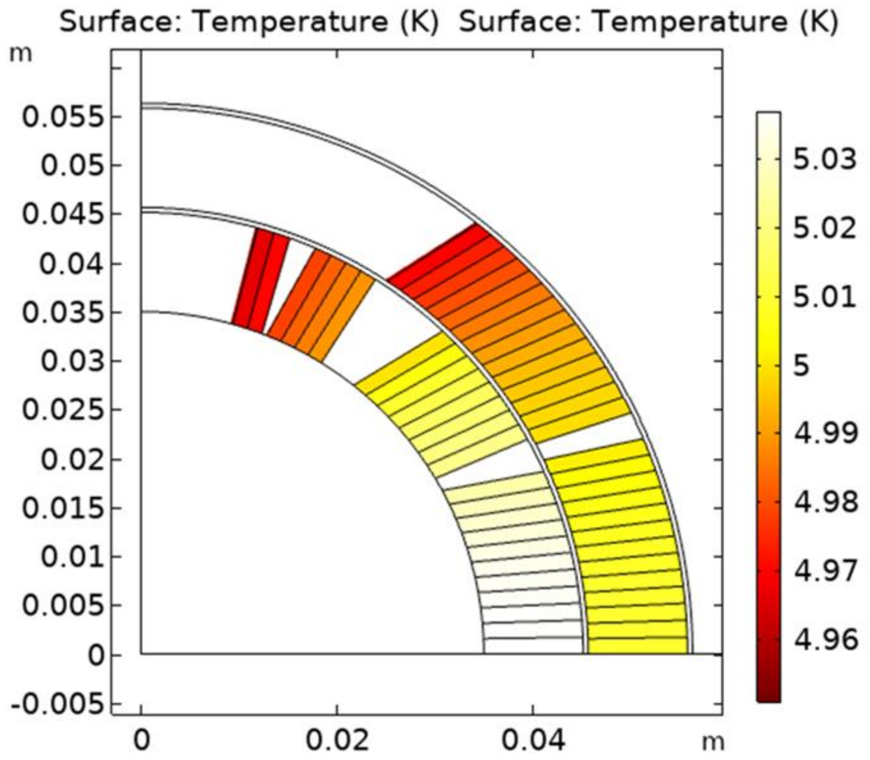




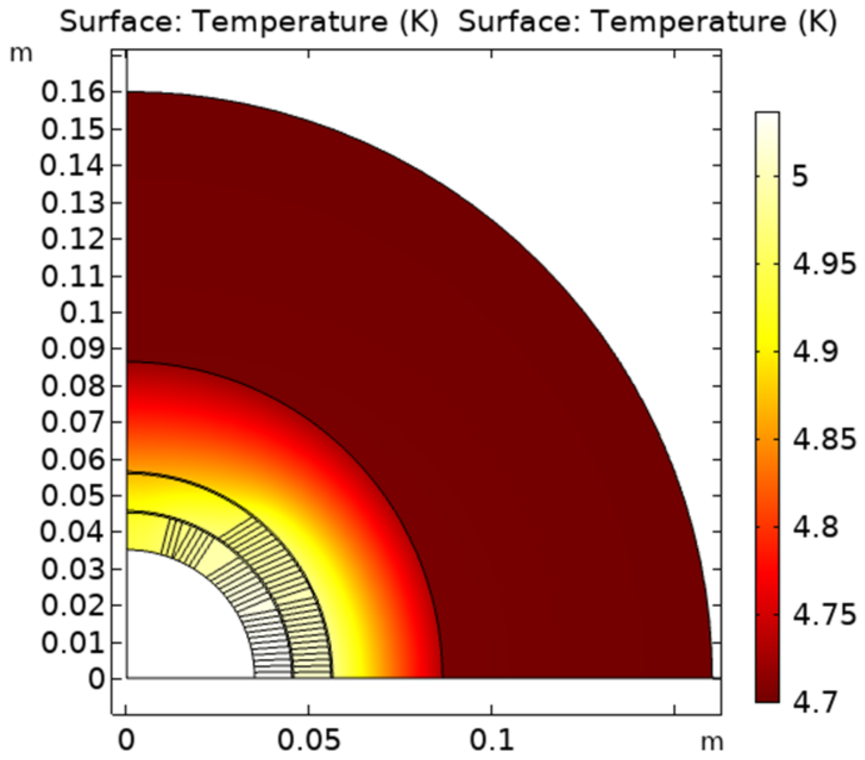


Thermal analysis, with far iron (30 mm collars) bottom line: 2 layers good!!

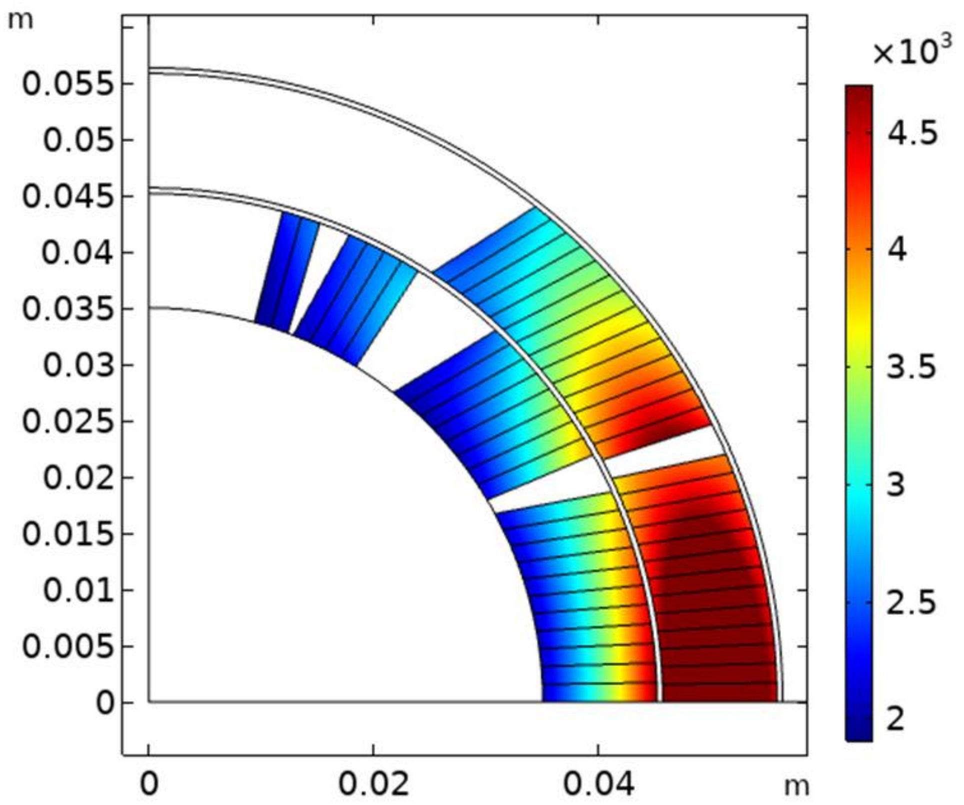
Max coil temp is 5.04 K, ΔT=340 mK (+70 mK w.r.t. the single layer)



Highest thermal gradient in the thick stainless steel collar



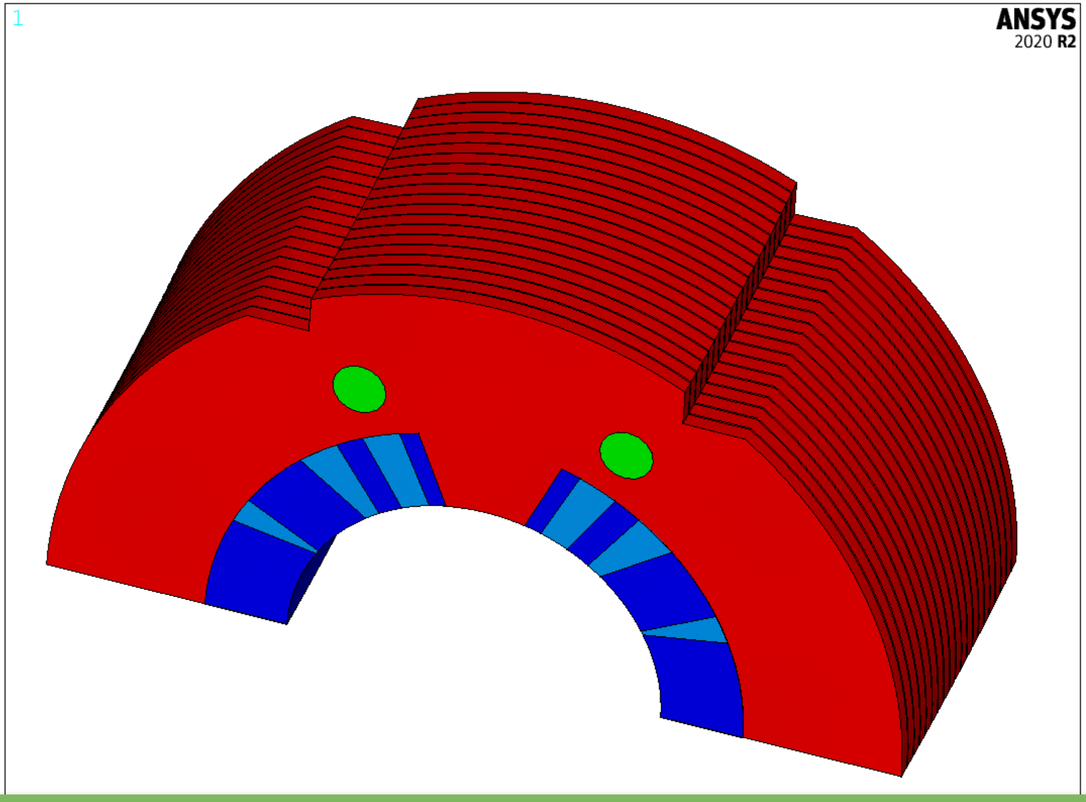
Thermal analysis: reduction due to temperature increase of the Critical current density in the SC

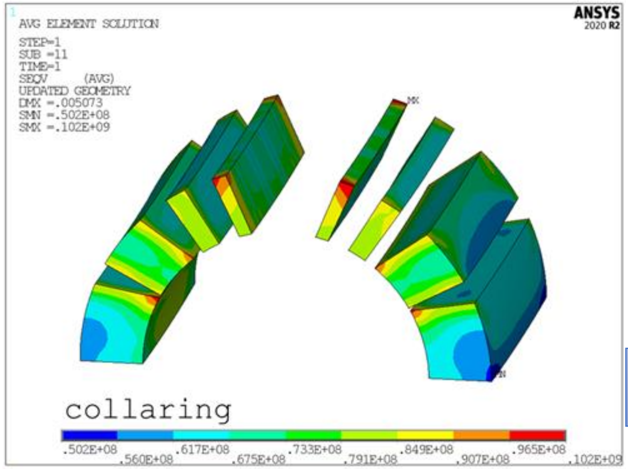


dB/dt = 0.4 T/s
B_0=0.45 T→ 4.5 T

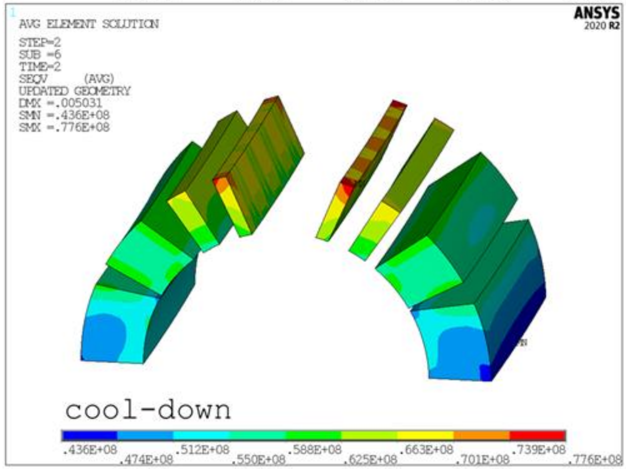
- Min. value 1911 A/mm^2 reached in the pole turn:
- compared to 2088 A/mm^2 @ 4.7 K
- - 8% reduction of margin
- Despite the much higher losses in low field region, the limitation remains in the high-field zone
- **But very much acceptable!**

Structural analysis:
1st collars as only force restrain – first done
2nd : explore yoke support (like 3 T SIGRUM

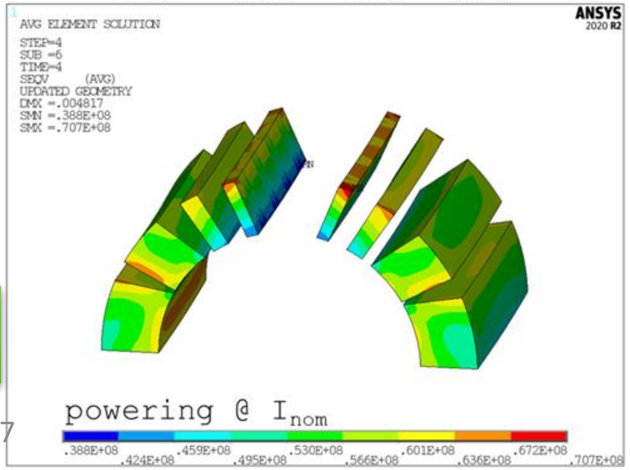




100 MPa



80 MPa

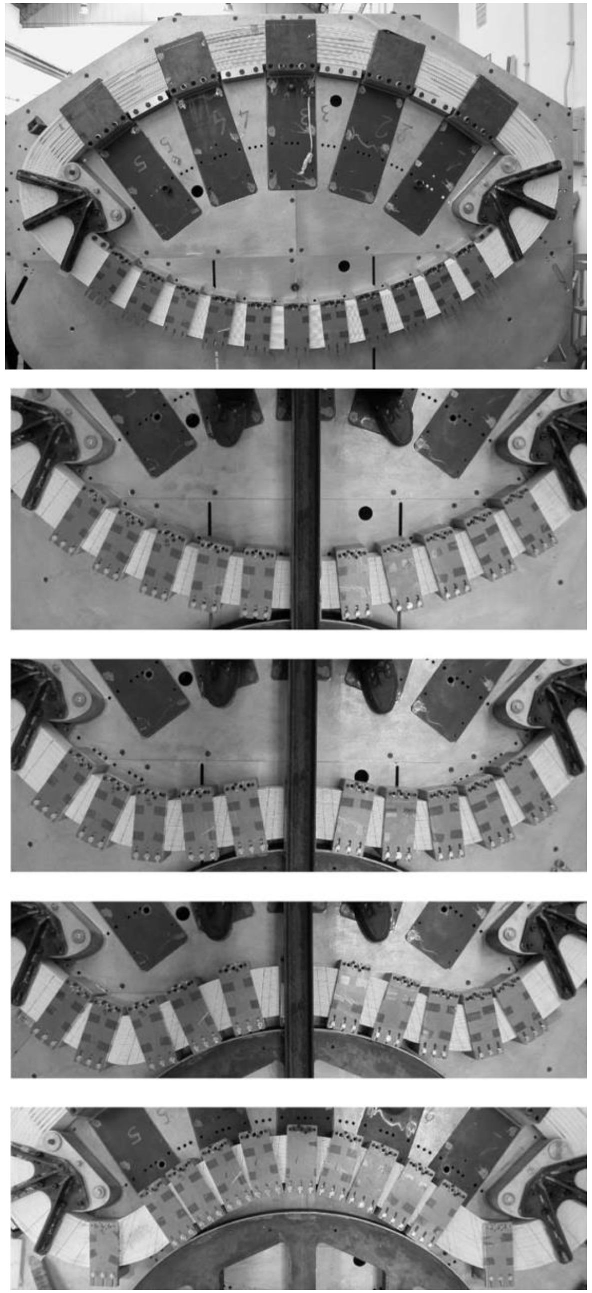


70 MPa

Much more to be done but it looks we are in business …

Curved winding: the main issue for these “tubular magnets”

- We think this is the main issue in using accelerator magnet, tube-shaped, with strong curvature
- Exploring three methods
  - Convex-concave winding: proposed and tested by INFN-Ge for solid conductor (S. Farinon et al., IEEE-TAS, **14**, No. 2, p. 585, 2004
  - Concave direct winding with many winding posts (extension of DISCORAP)
  - A mixture of the two…



Conclusion

- SIG project of INFN (Milano-LASA and Genova units) in collaboration with CNAO and CERN: 2022-mid 2025.
  - aim at a demonstrator dipole
    - **R_{bend} = 1.65 m**
    - 30 deg with (about 1 m long)
    - **4-5 T dipole field**
    - 75 mm (70-90 mm)
    - **0.3-0.4 T/s** ramp rate
  - Final decision if to use the small cable-low amperage of first SIGRUM design or these new one s will be soon taken
- The design of SIGRUM gantry is under revision in view of the 4 T magnets
- Decision on the focussing system (nested quad, alternating combined function, etc…, is kept separated from the dipole demonstrator that will be a simple dipole maybe with a modest combined gradient. **Proof of curvature is essential!!**