Innovative gantry designs, continued

Projects at CERN's magnet group: GaToroid and Fusillo

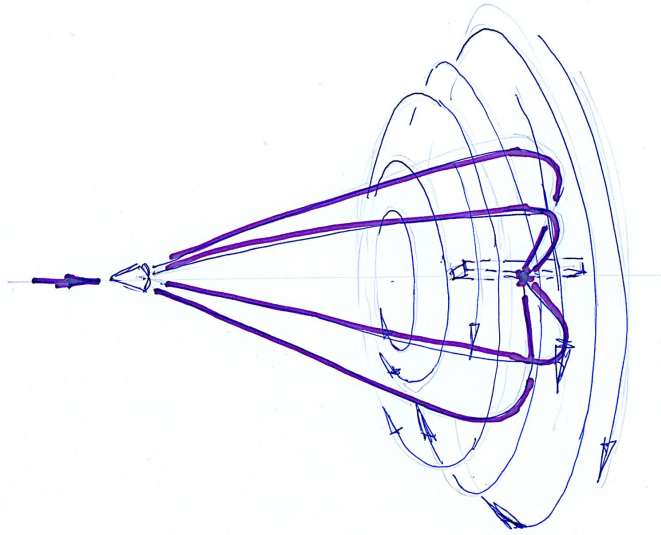
Presented by A. Haziot

IAEA Regional Workshop on Hadron Therapy

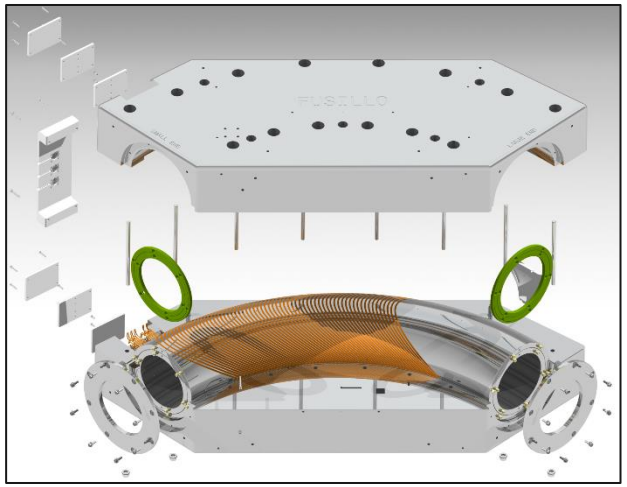
Friday 18th of October 2024

Outline

- GaToroid
  A novel Magnet Configuration for Hadron Therapy Gantry



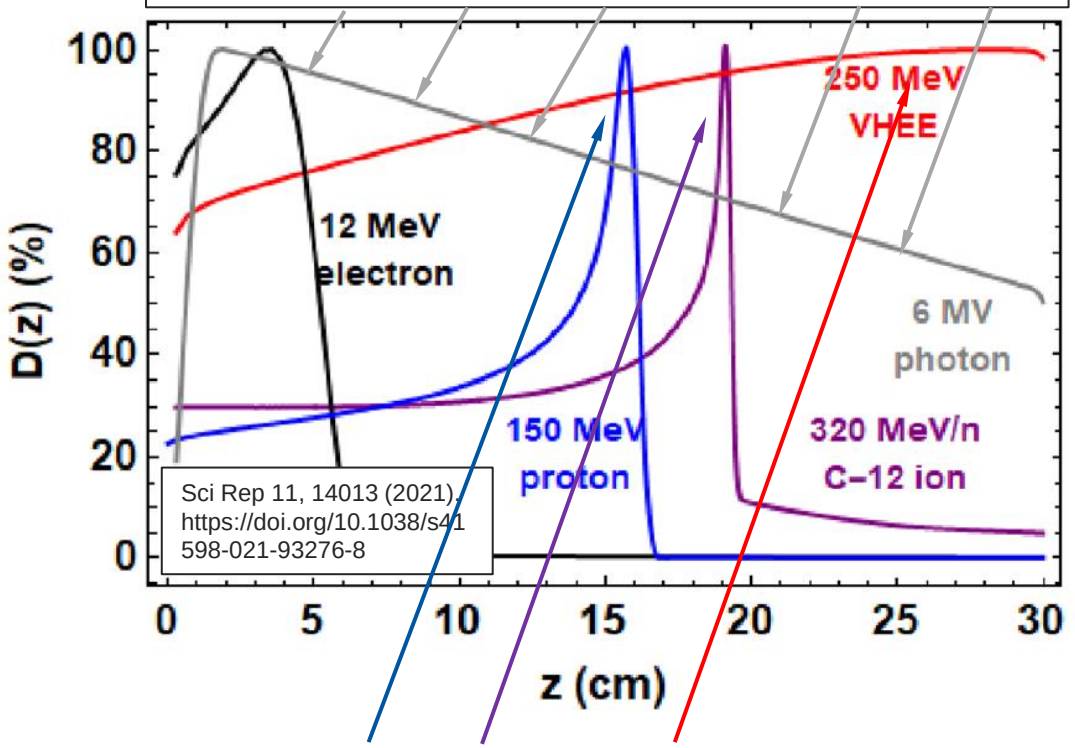
- Fusillo
  A compact, curved, and large acceptance dipole magnet



Radiation therapy

Choice of radiation type

Photons have large unwanted dose

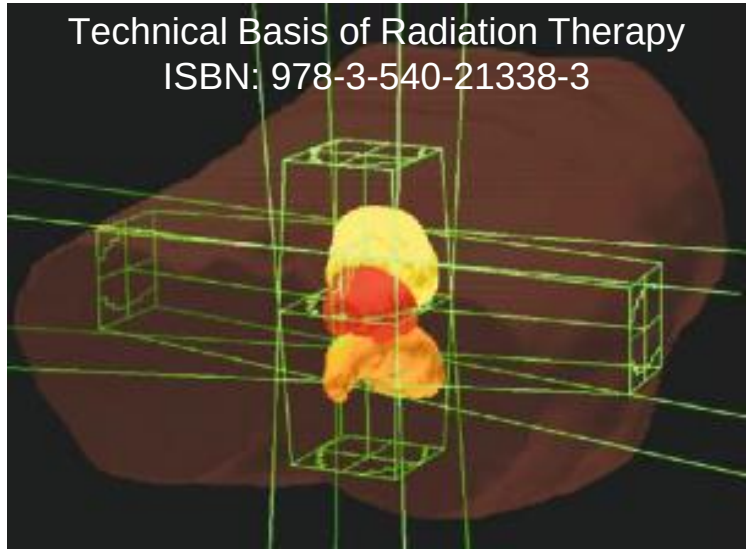


Charged particles (e^-, p^+, C^{6+}, He^{2+}) have peaked dose distribution which can spare healthy tissues

Conformality

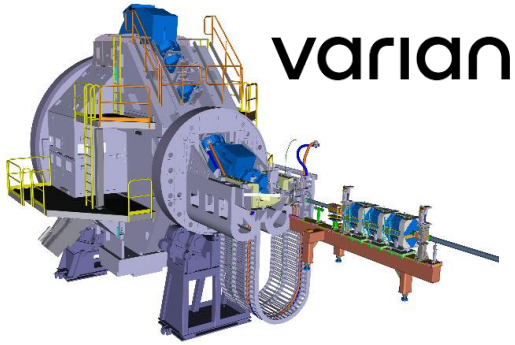
Charged particle beams can be directed by magnetic fields.

The area treated is mapped by multiple beams. This requires the ability to deliver beams from multiple directions ⇒ **Gantries**

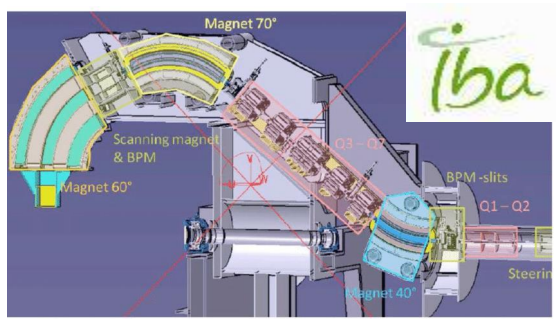


Gantries – bulky precision objects

protons



Length = 10.5 m
Diameter = 10 m
Weight = 270 tons

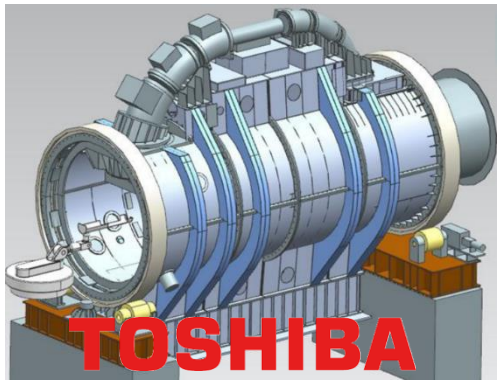


Length = 9.5 m
Diameter = 7.2 m
Weight = 110 tons

Length = 10 m
Diameter = 8 m
Weight = 17 tons(*)

ions

Length = 25 m
Diameter = 13 m
Weight = 670 tons



Length = 13 m
Diameter = 10 m
Weight = 350 tons

Length ≈ 9 m
Diameter ≈ 9 m
Weight ≈ 240 tons

What is GaToroid ?

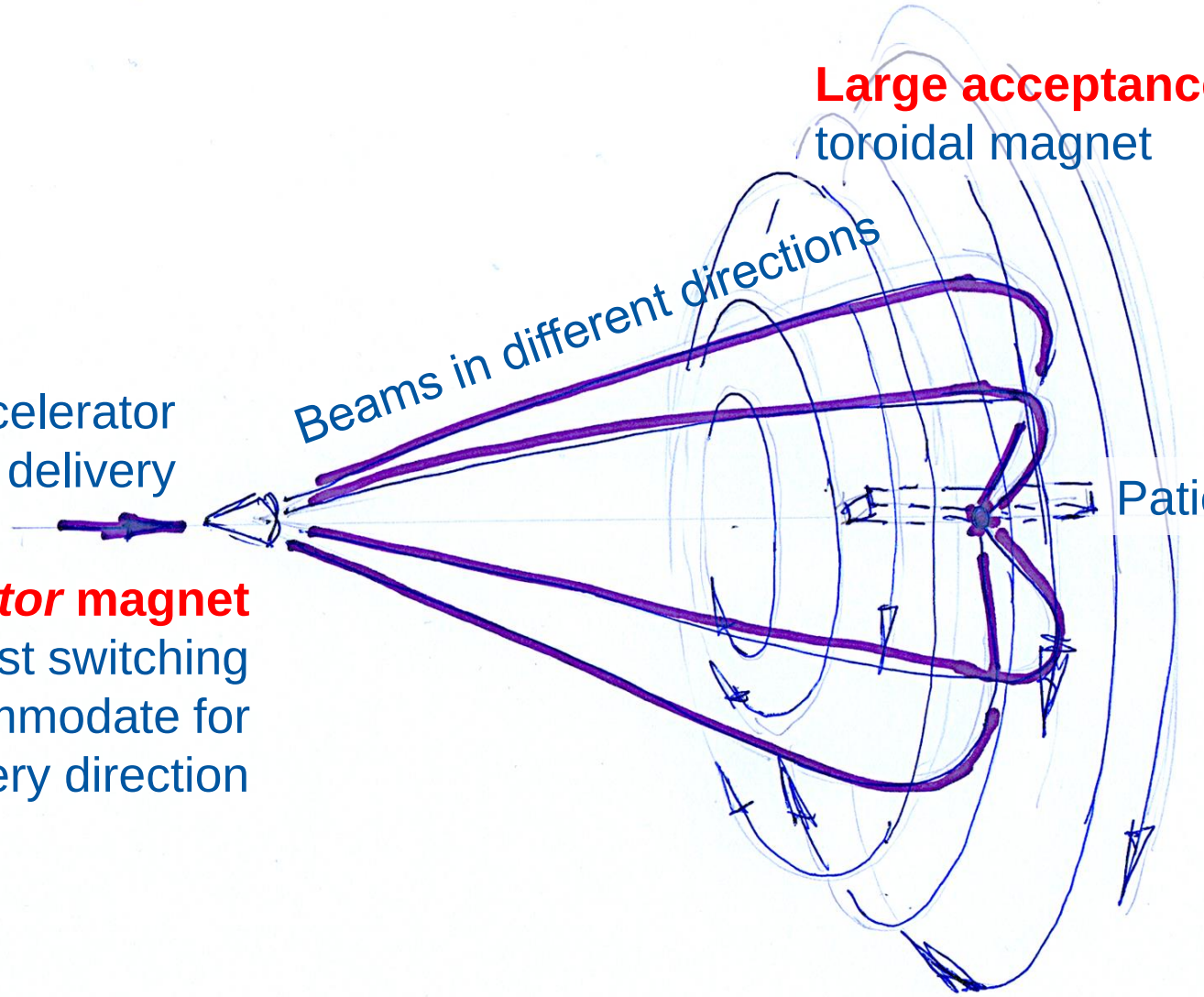
Large acceptance, steady-state
toroidal magnet

Beams in different directions

Accelerator
beam delivery

Patient location

***Vector* magnet**
X-Y kicker with fast switching capability to accommodate for change of delivery direction



What is GaToroid ?

Large acceptance, steady-state
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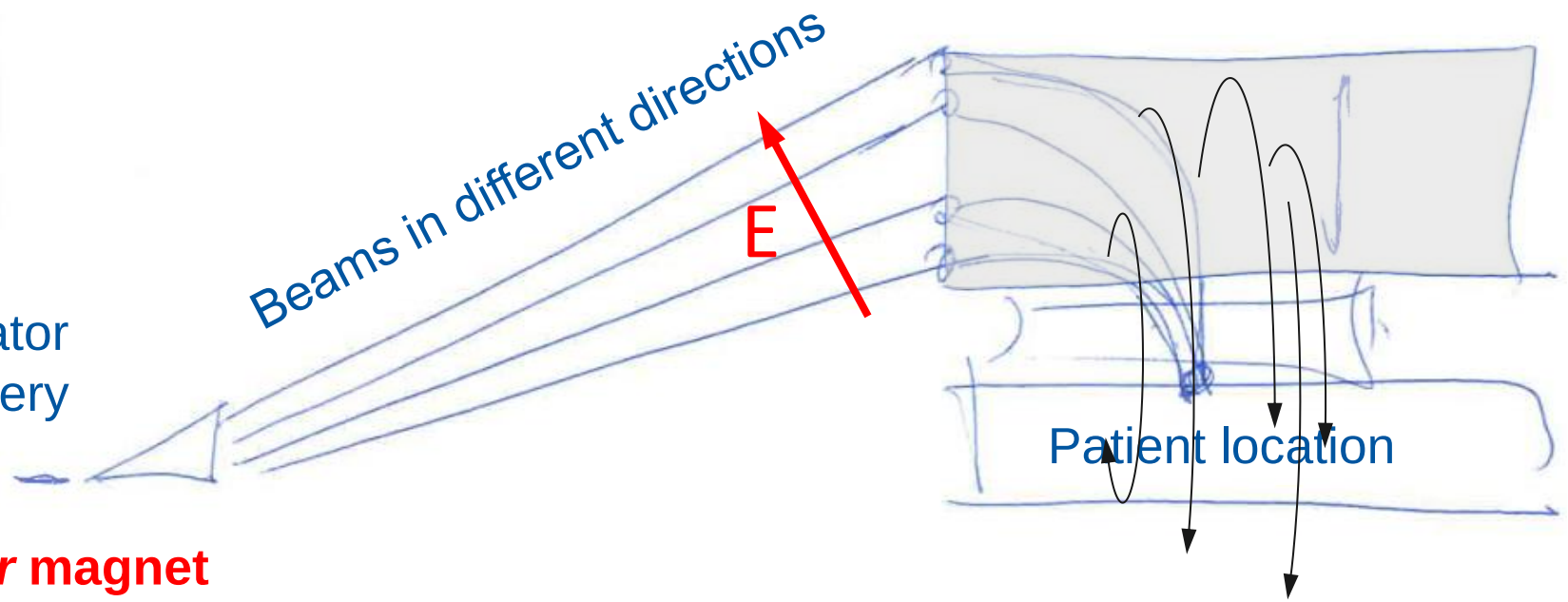
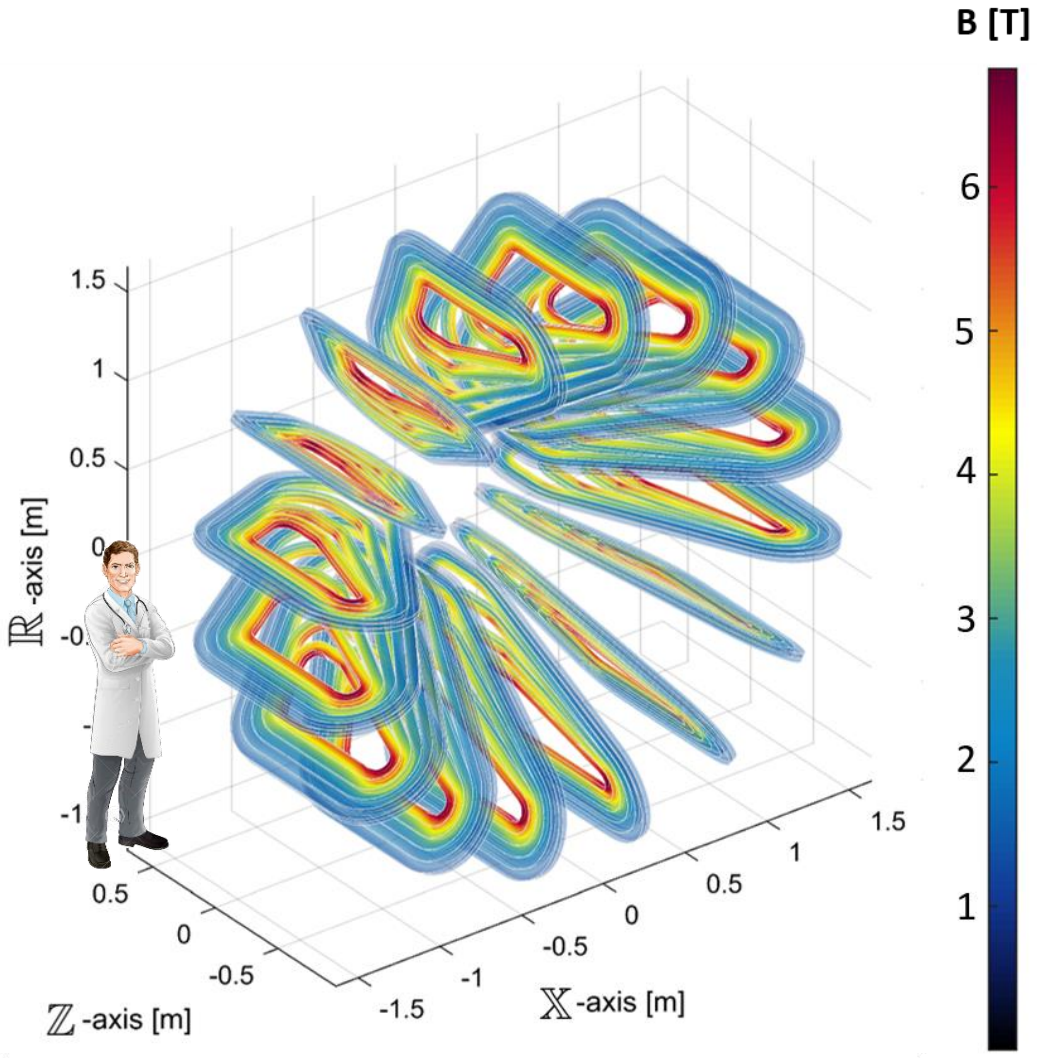


Accelerator
beam delivery

***Vector* magnet**
X-Y kicker with fast switching capability to accommodate for energy change

Fast direction and energy switching is possible because of the steady state toroidal field and large magnet acceptance
GaToroid would provide FLASH capability with multi-directional treatment and multiples energies.

GaToroid for protons



Number of angles	16
Peak magnetic field	6.8 T
Eng current density	100 A/mm2
Stored Energy	31 MJ

Coil dimension	1.7 m x 1.2 m
Torus dimension	1.7 m x 3.3 m
Bore size	0.8 m
Vector Magnet position	3.6 m

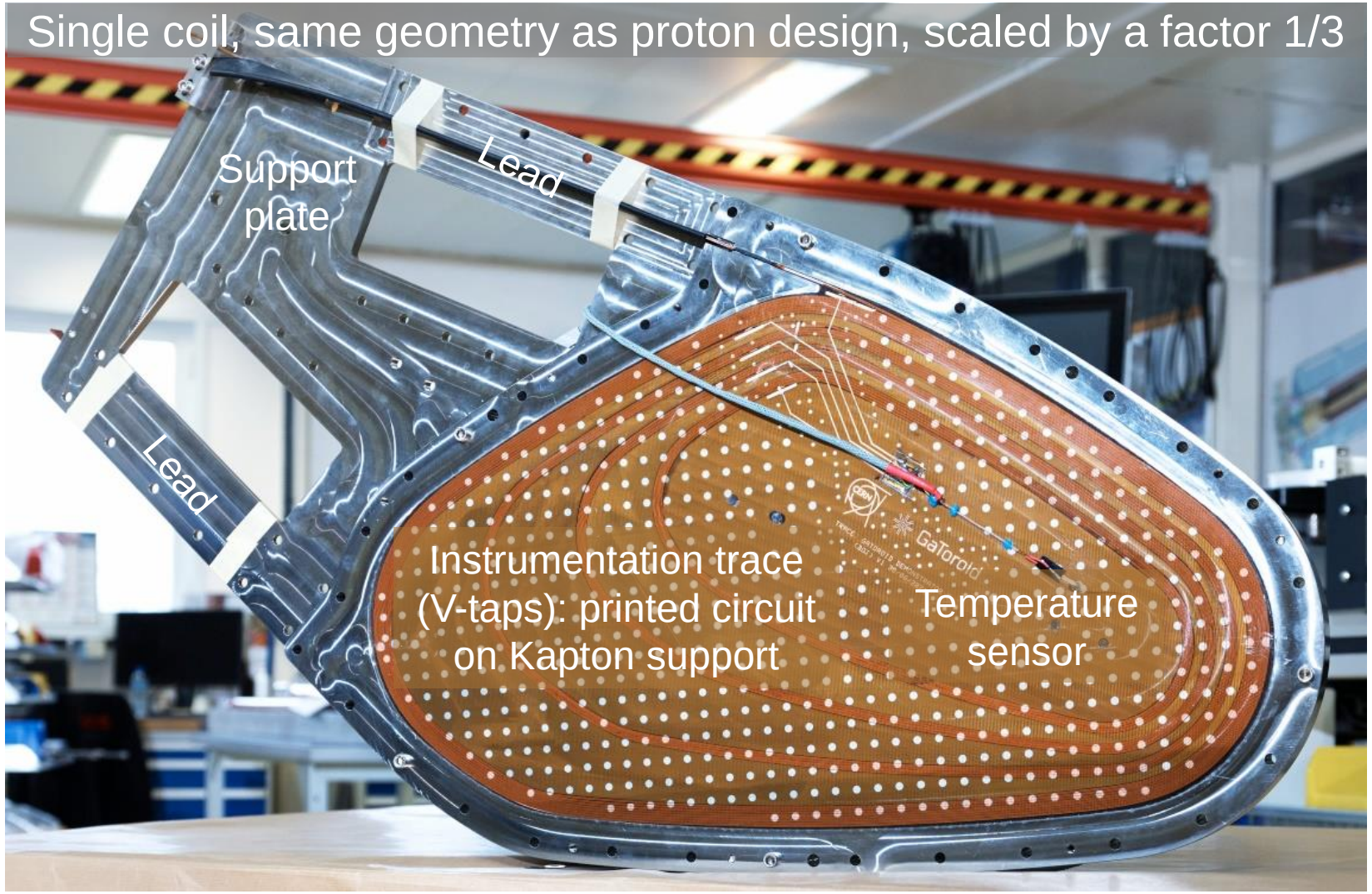
Operating temperature	4.5 K - 20 K
Operating current	1800 A

Estimated total mass	12 tons

Courtesy of E. Felcini, CNAO

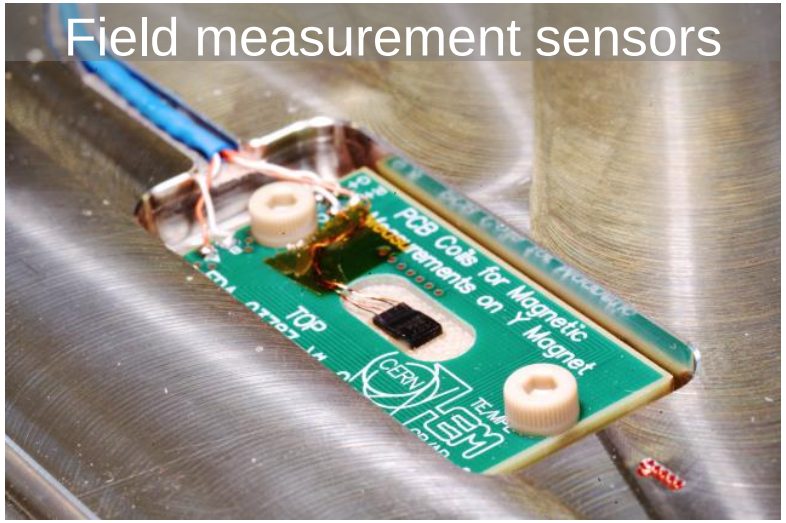
GaToroid demonstrator

Single coil, same geometry as proton design, scaled by a factor 1/3



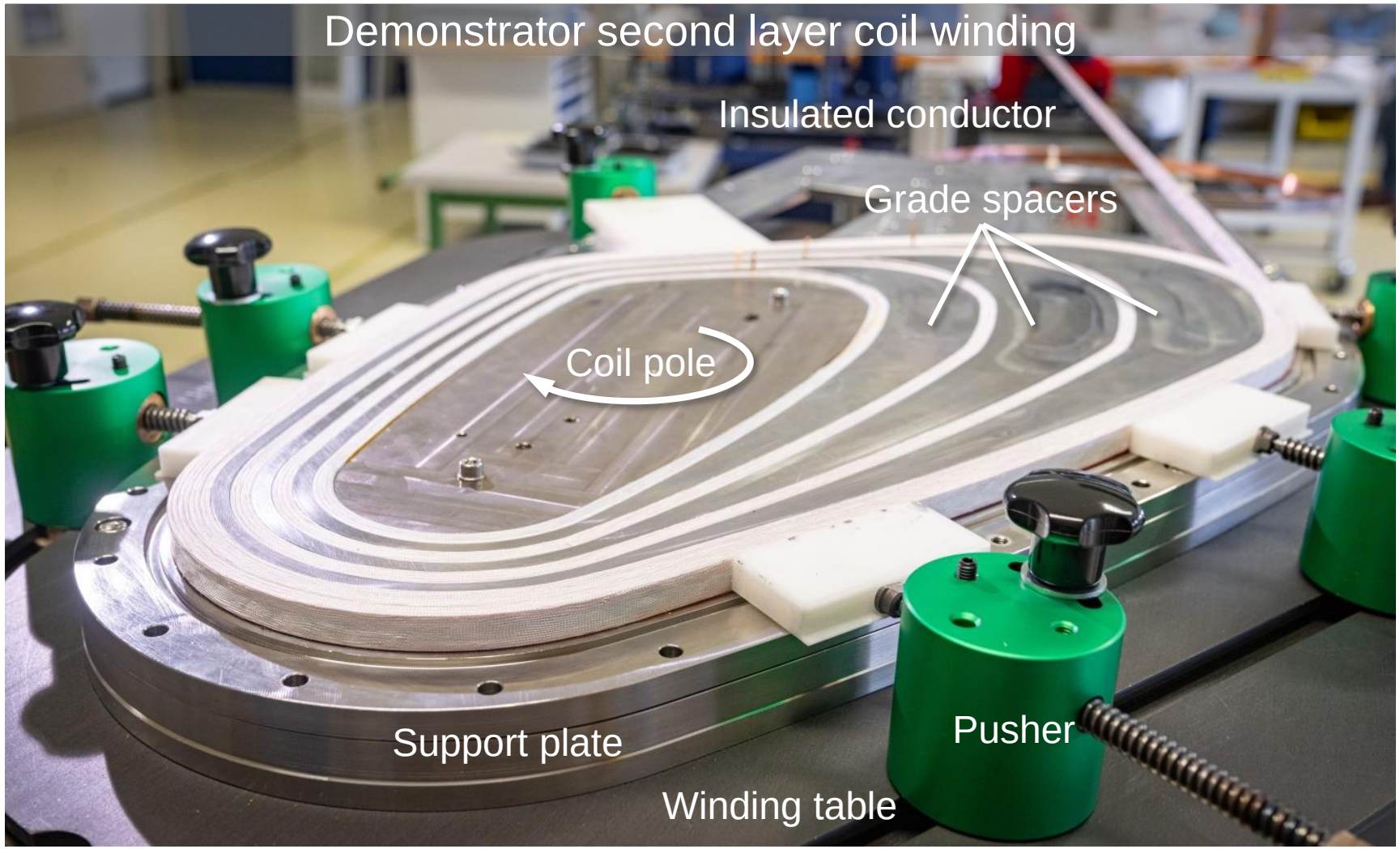
Cover plates placing

Field measurement sensors

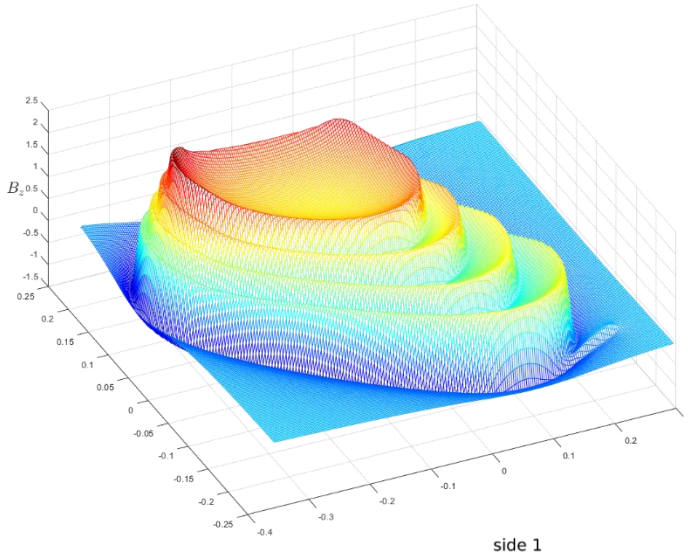


Demonstrator winding

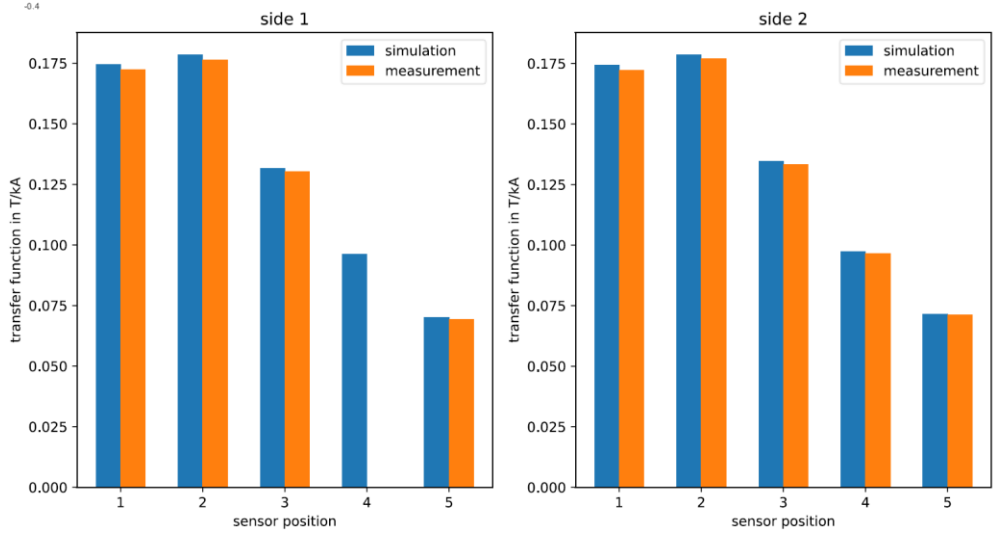
Coils were designed and fabricated in the short model laboratory at CERN.

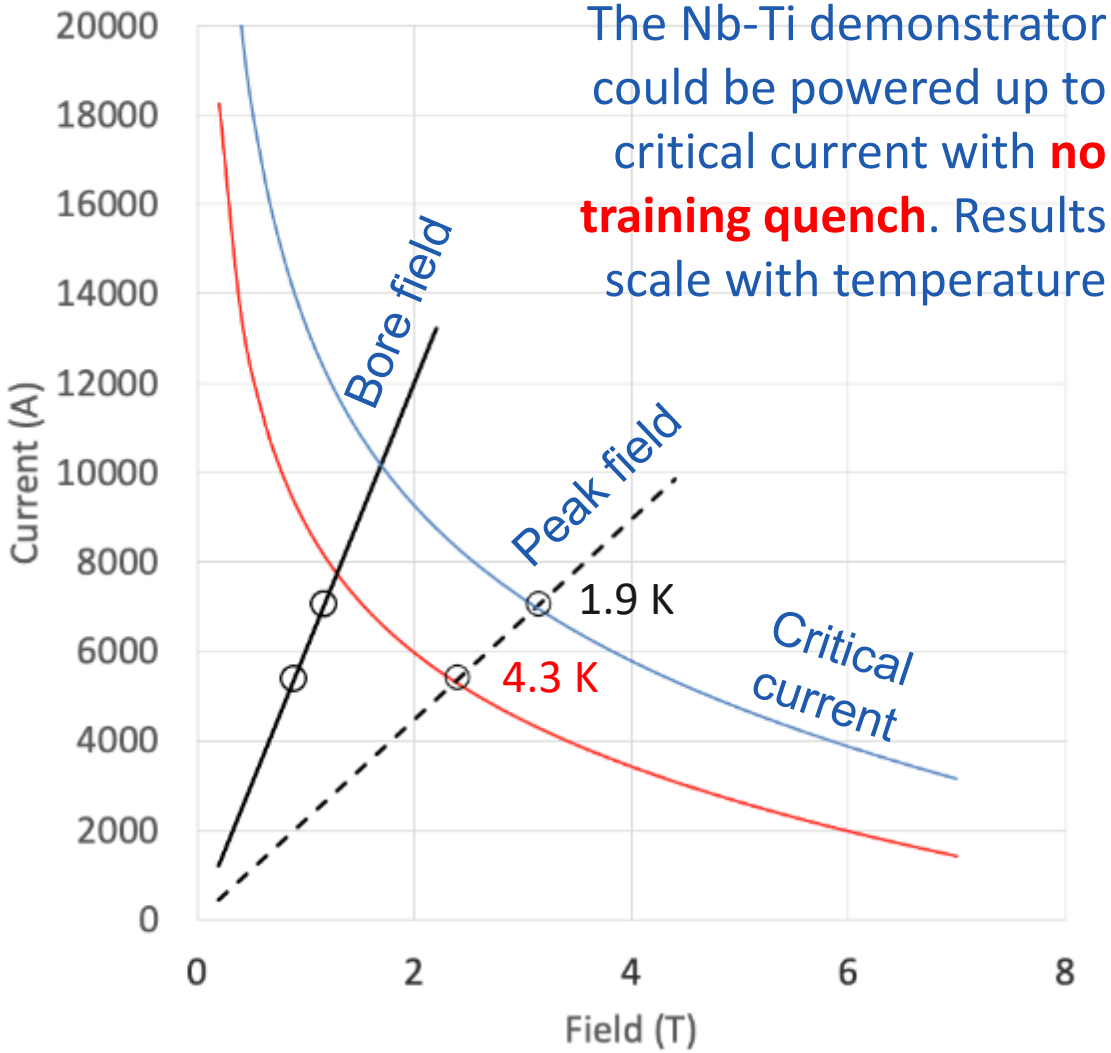


GaToroid demonstrator test



The measured field profile matched the simulations performed using nominal geometry to **better than 1 %**

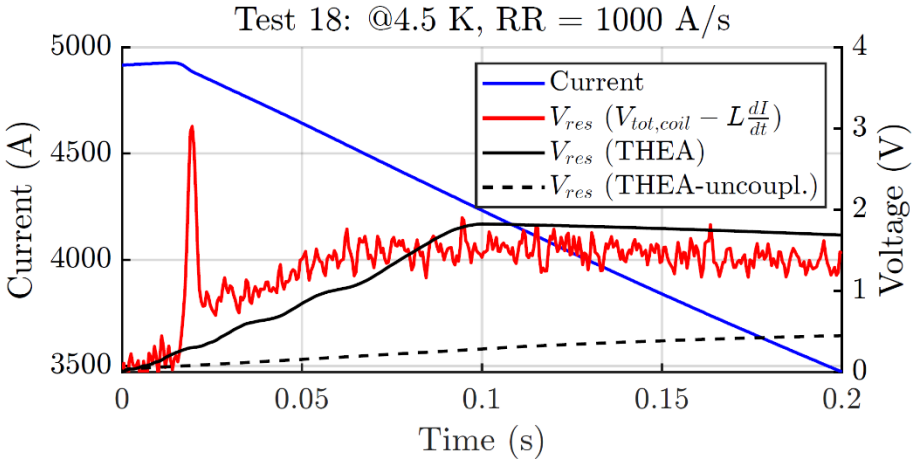


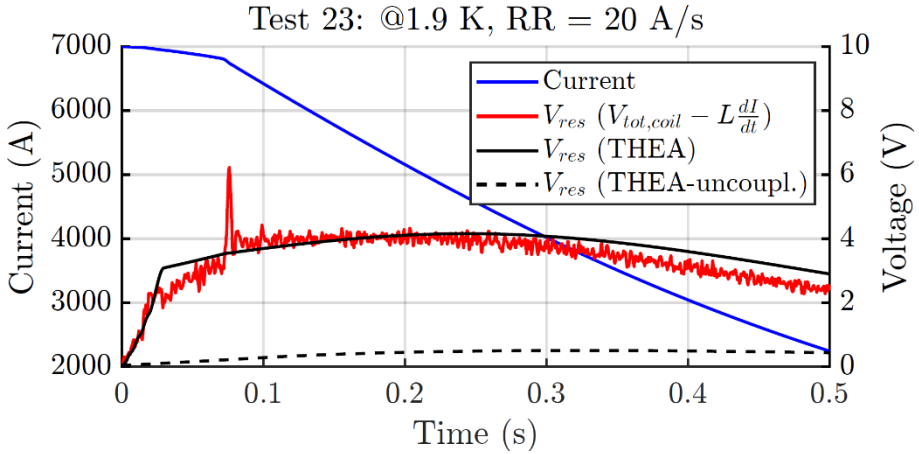


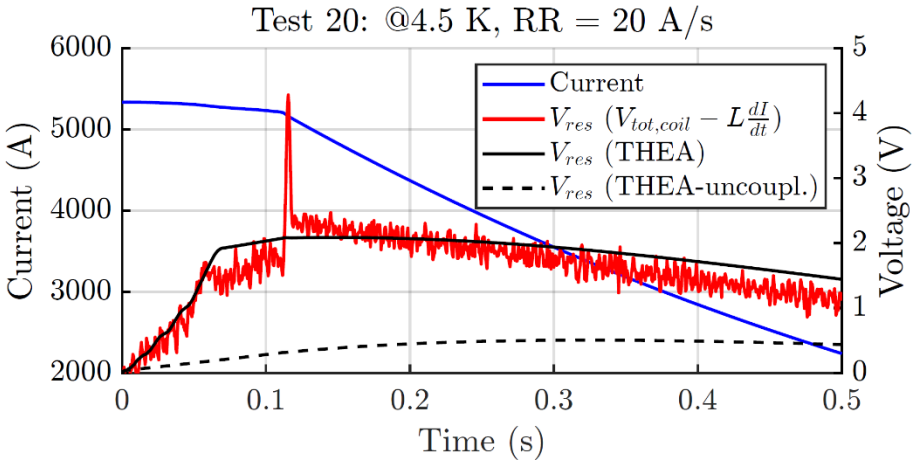
The Nb-Ti demonstrator could be powered up to critical current with **no training quench**. Results scale with temperature

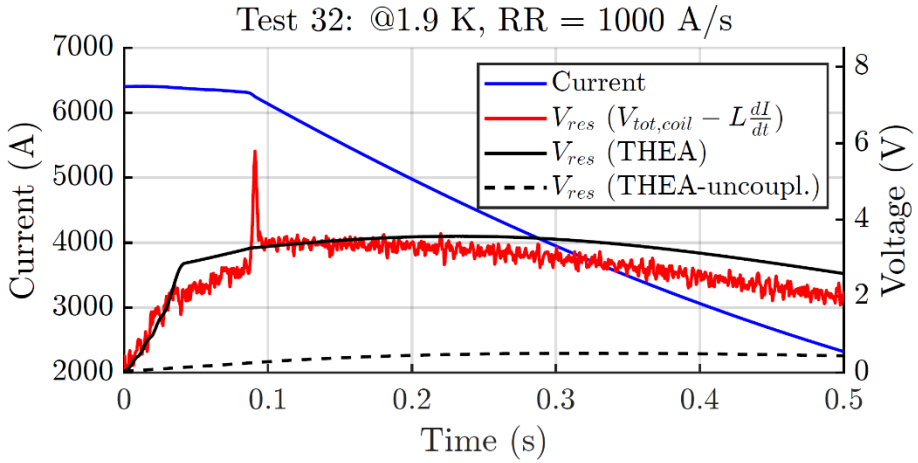
Tests performed at the CERN cryogenic test facility

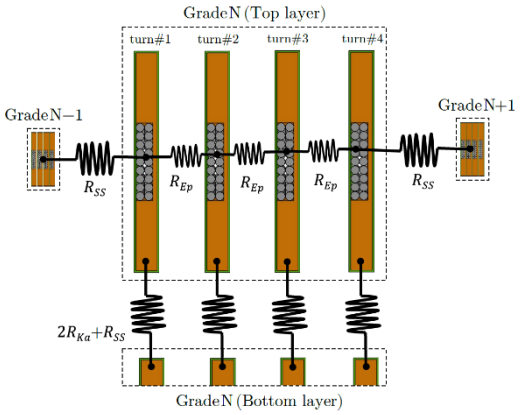
GaToroid demonstrator test









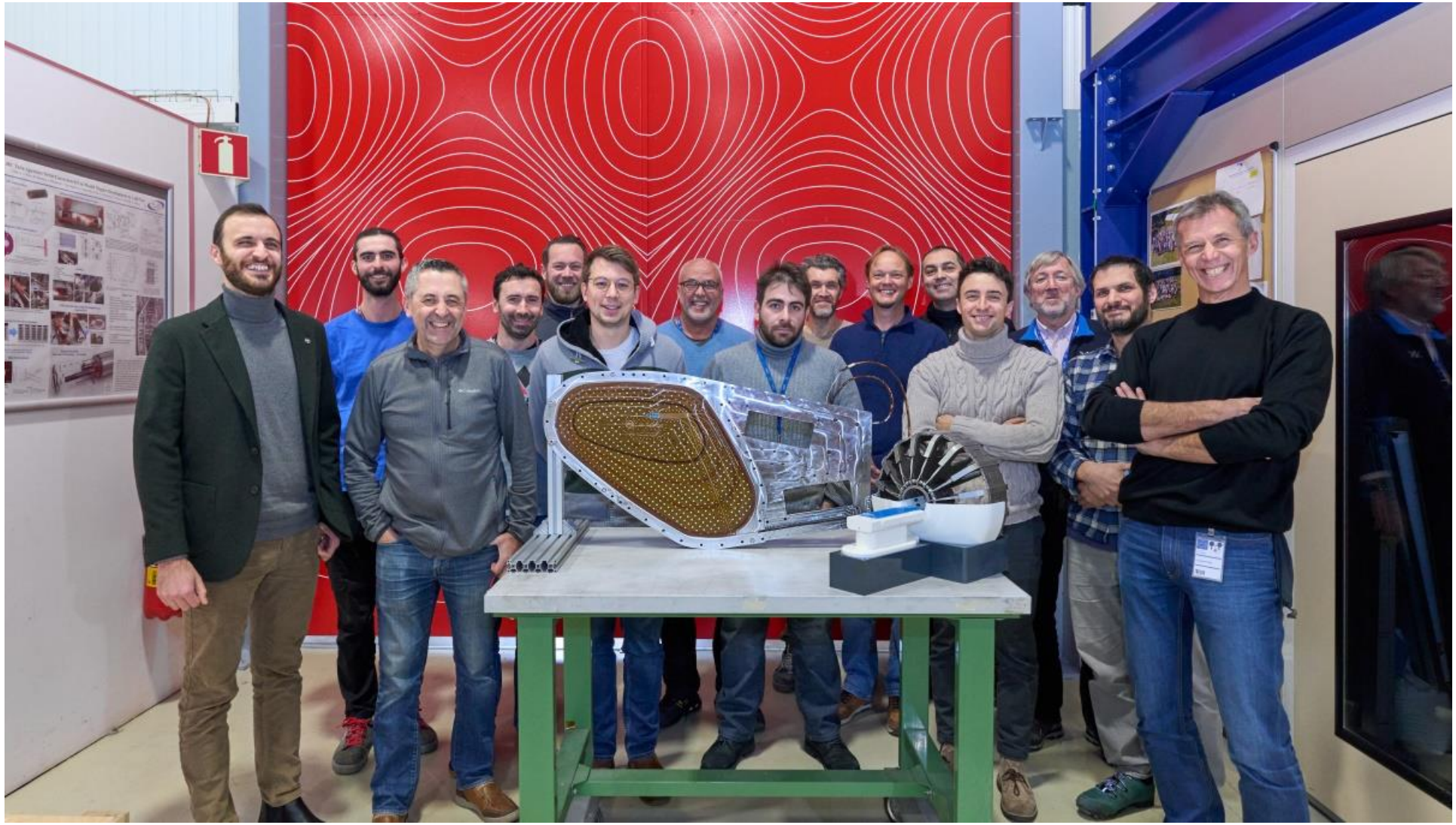


Thermal network used to simulate the transverse quench propagation

Quench propagation and protection well understood, including 3D effects. We have confidence in the extrapolation to the full-size toroidal magnet

Work performed in collaboration with University of Bologna, presented at 2024 Applied Superconductivity Conference, paper 1LPo1D-07: L. Soldati, et al., *Quench Analysis of the GaToroid Demonstrator Magnet for Hadron Therapy*

Many thanks to a great team !



VHEE for the future

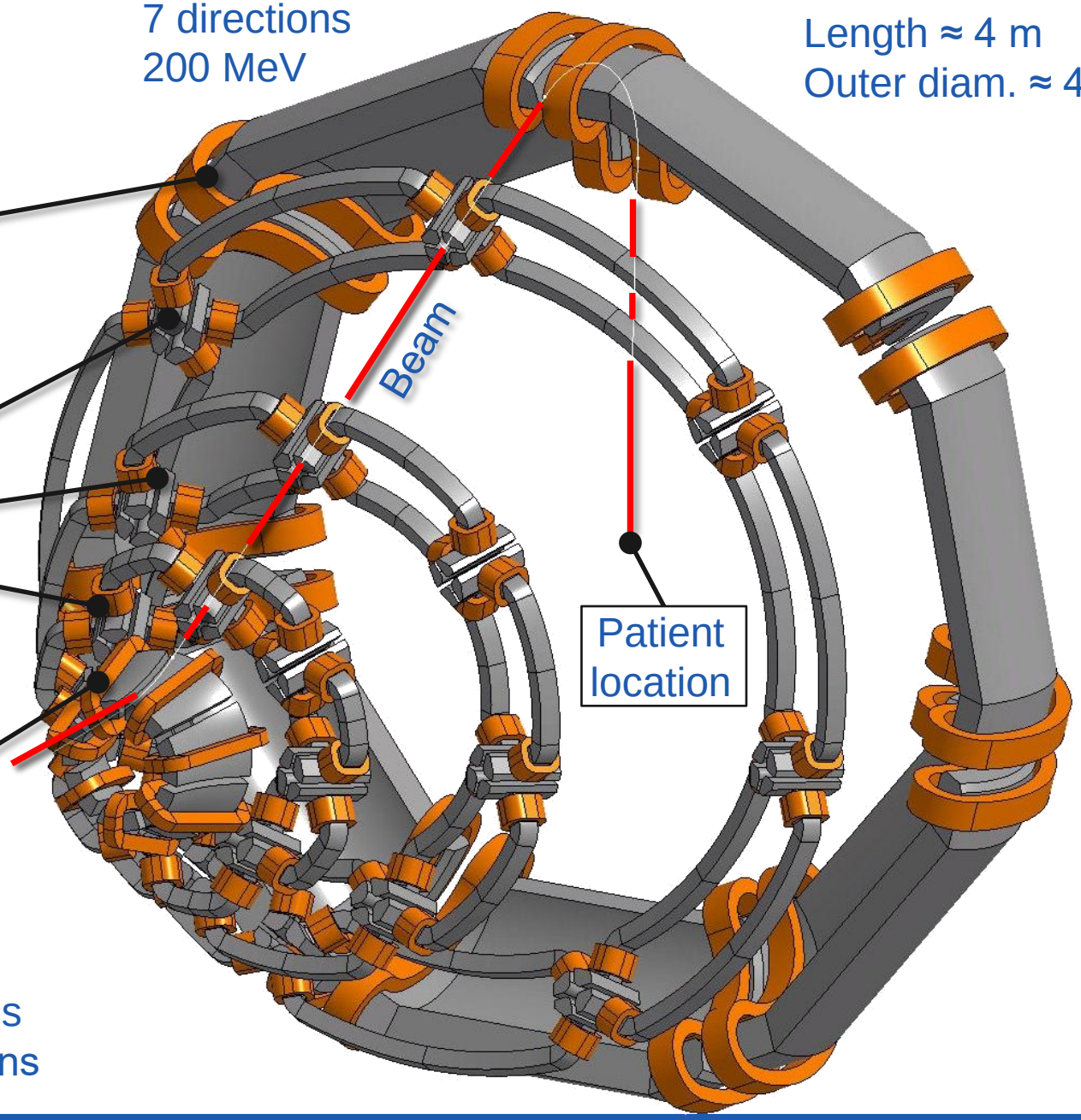
7 directions
200 MeV

Length ≈ 4 m
Outer diam. ≈ 4 m

Toroidal dipole (final bend)
Bore field: 1.5 T
Current: 665 kA-turns
Aperture: 80 mm x 200 mm

Toroidal quadrupoles
Gradient: 16.7 T/m
Current: 150 kA-turns
Aperture: 58 mm

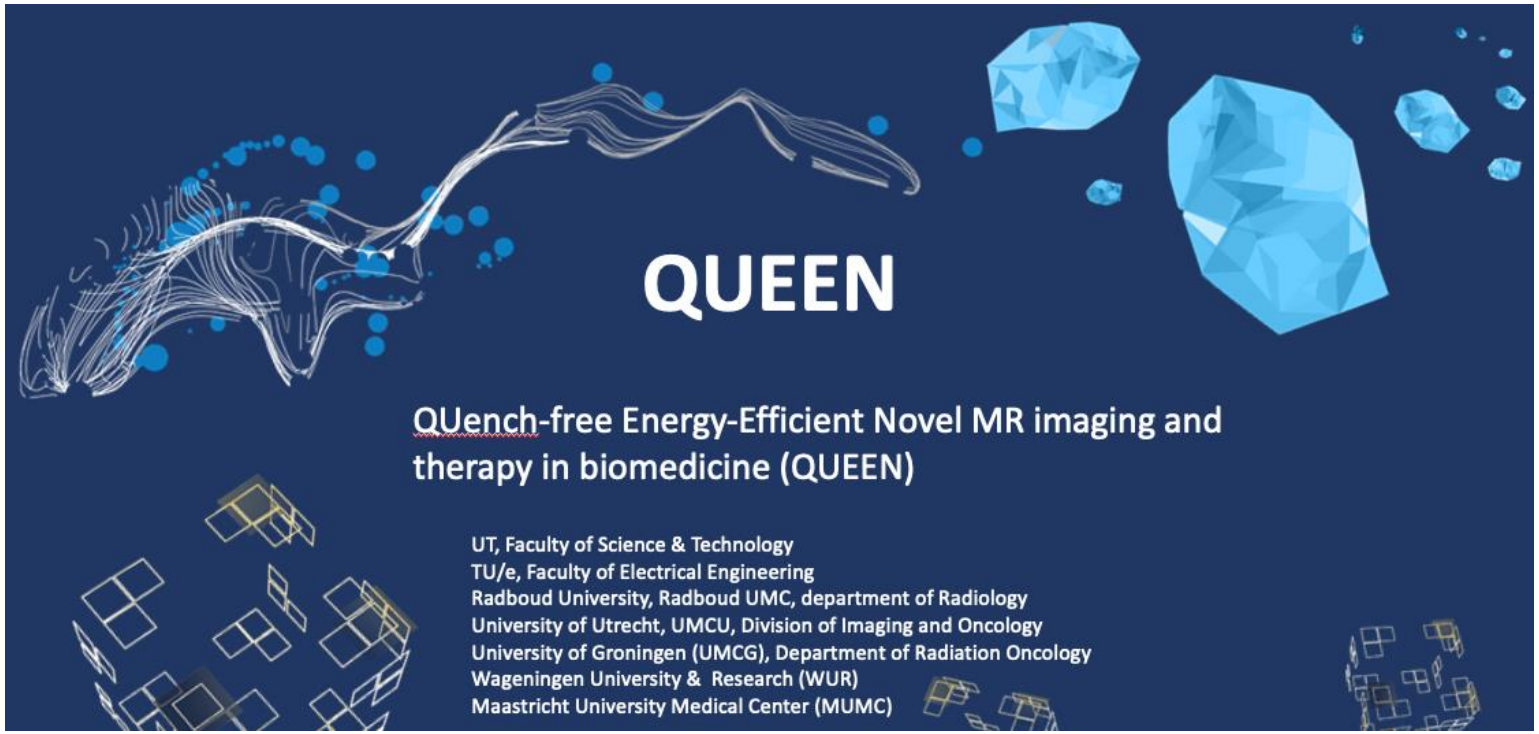
Toroidal septum
Bore field: 0.15 T
Current: 100 kA-turns
Aperture: 50 mm x 100 mm



Iron weight: 17 tons
Coils weight: 3.7 tons
Total weight: ≈ 21 tons

L. Bottura, et al., Magnetic Design of a Compact GaToroid for Very High Energy Electron and Pre-clinical Hadron Beams, IEEE TAS, 34(5), 2024, 4403005

GaToroid in QUEEN



Large-Scale Research Infrastructure (LSRI), National Roadmap consortia 2024
QUEEN proposal sent on 23.9.2024 (Budget 26.7 MEUR)
Coordinator: Prof. H. Von Oort, University of Twente
WP5 Leader: Prof. A. Gerbershagen, University of Groningen

- WP1 – Expansion of Superconductor Applications: 20T modular HTS Solenoid
- WP2 – Healthy Imaging: A compact open 3T system
- WP3 – Precision Imaging: A 7T HTS insert inside an existing 7T system
- WP4 – Precision Theranostics: A field-cycling MRI scanner
- **WP5 – Novel Treatment: A Superconducting gantry at PARTREC**

A unique research infrastructure

Reduced setup for animal irradiation (E_{kin} ≤ 150 MeV)

Two beam directions with switching time of ~1ms

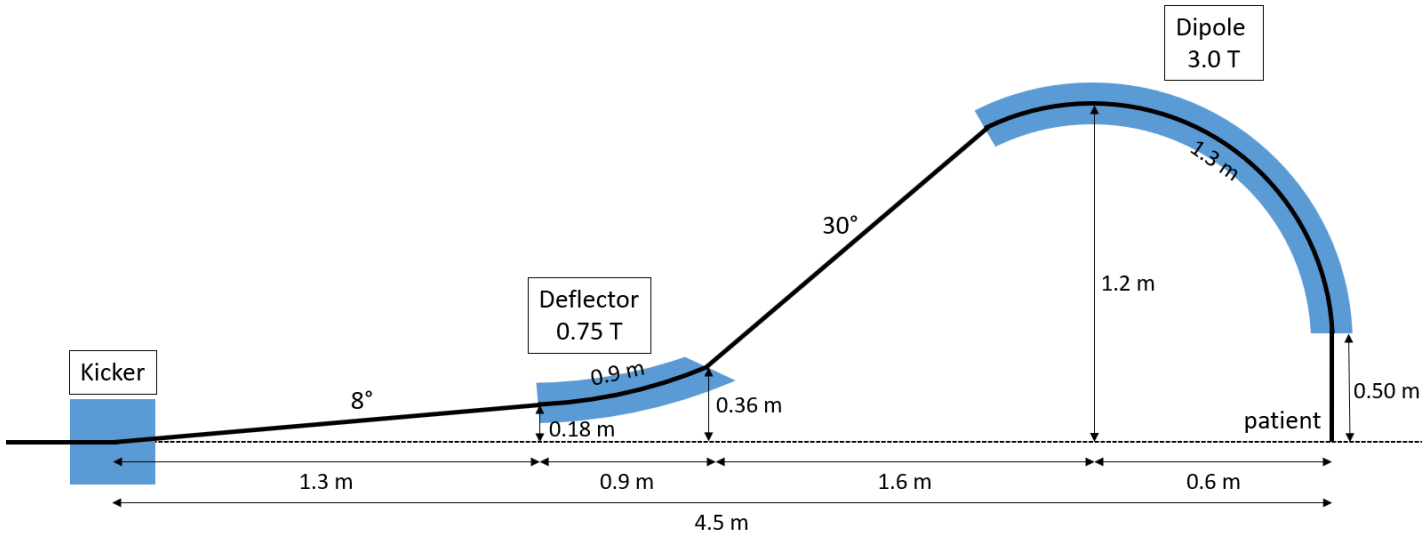
Ultra-fast (tens of ms) scanning and energy modulation

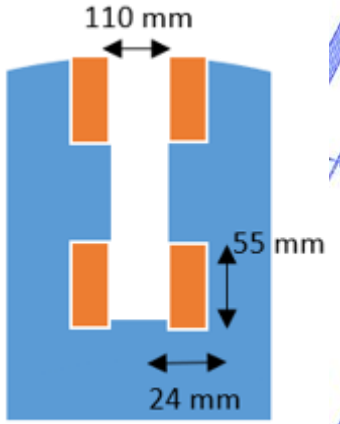
Superconducting final bend, B=3T

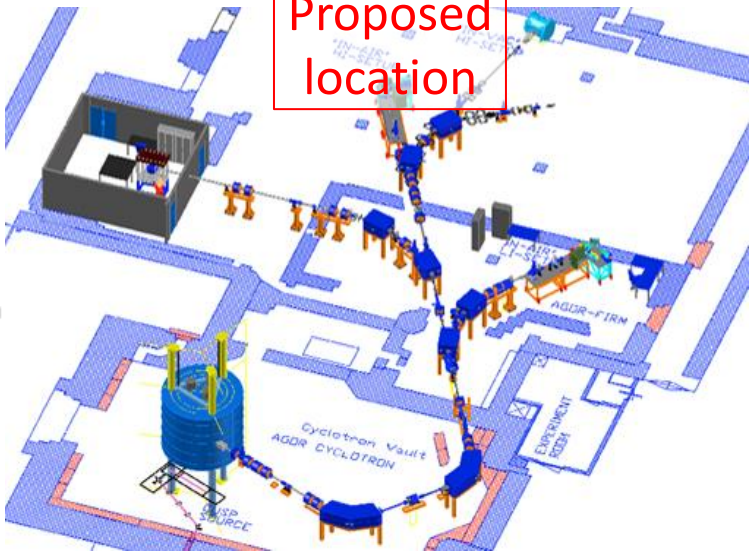
} Conformal hadron FLASH possible !!!

Cost of construction, installation and commissioning: ~4.2 MEUR

Integrated with CT, PET and proton radiography







PARTREC at University of Groningen

In conclusion

The demonstrator test has shown that the magnet concept of GaToroid in its original materialization (compact protons) is feasible and matches well the design expectations. **This is no longer a technology issue**

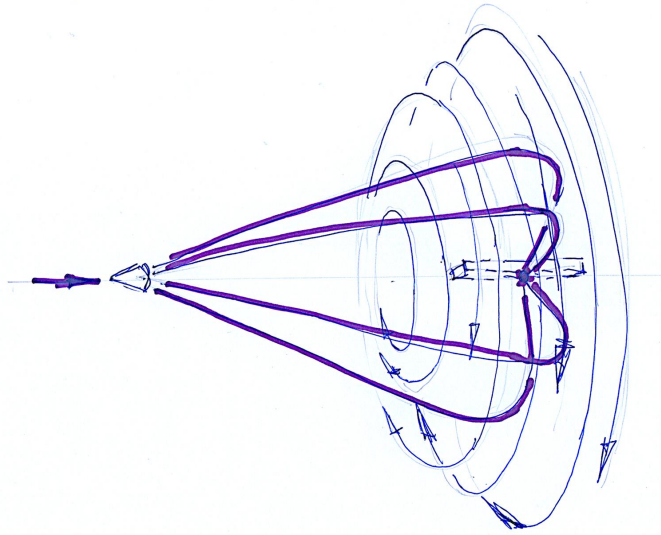
The main obstacle to a first prototype for therapy is **acceptance by the medical community**.

- GaToroid is a paradigm change in treatment planning, not easy to accept…
- … but it has an unfair competitive advantage offering FLASH capabilities that standard gantries do not have

QUEEN offers the possibility to realize a reduced-scope but full-size prototype, and test it in research conditions relevant to particle therapy, thus **bridging the gap towards the first medical realization**

Outline

- GaToroid
  A novel Magnet Configuration for Hadron Therapy Gantry



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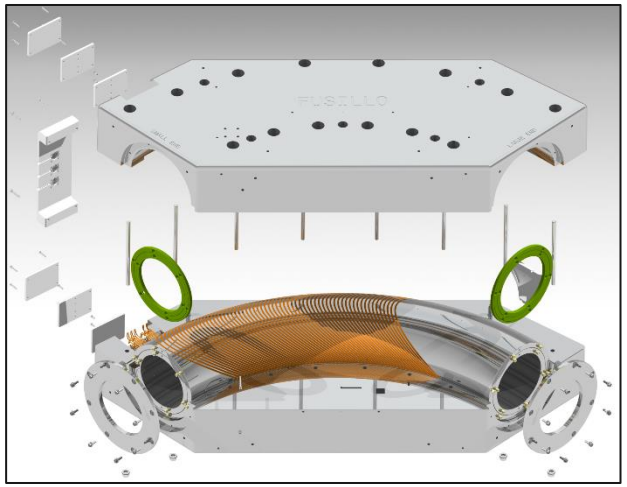
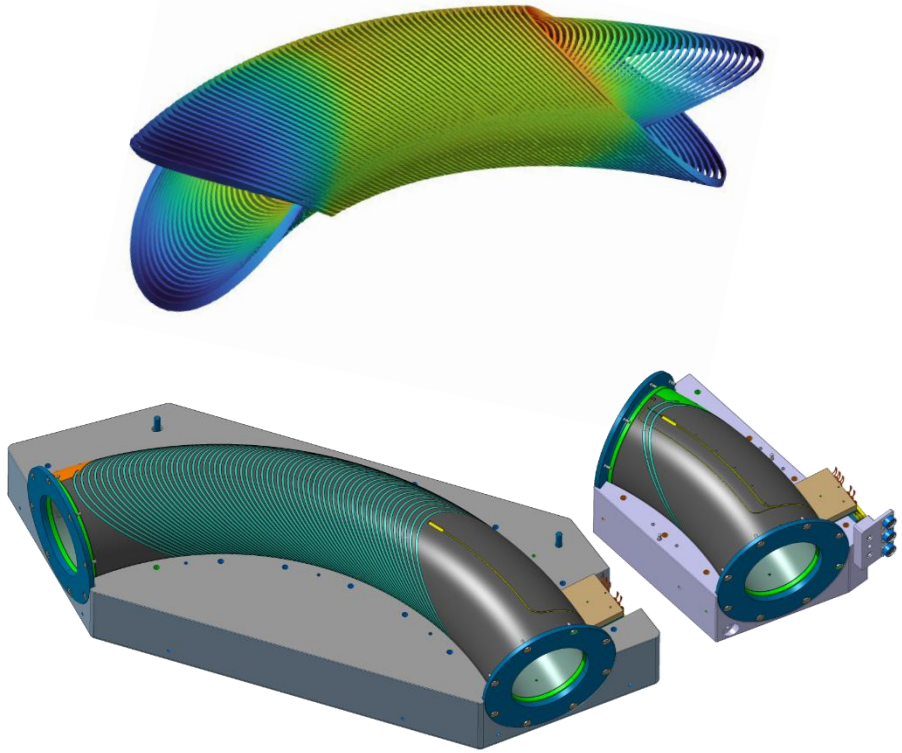


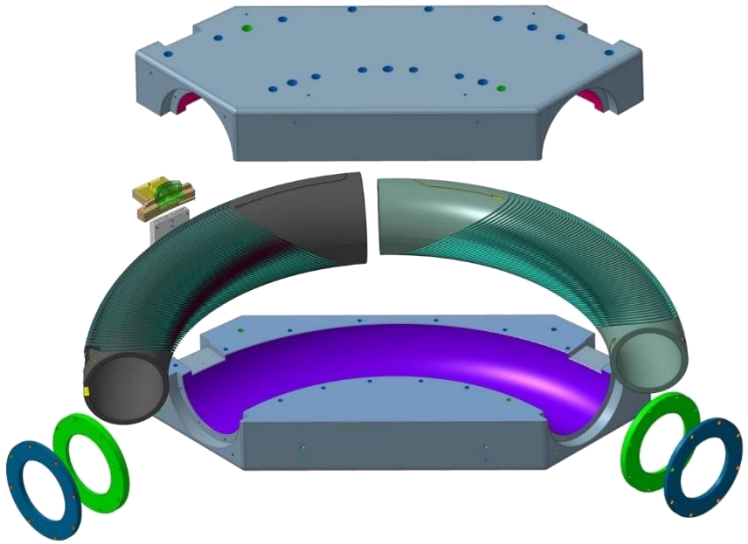
Fusillo: a CCCT technology demonstrator

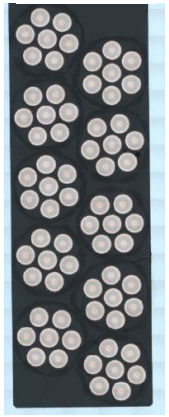
Design, manufacture and test of:
3 T central field CCT dipole, bent over 90° with 1.0 m radius, 236 mm aperture



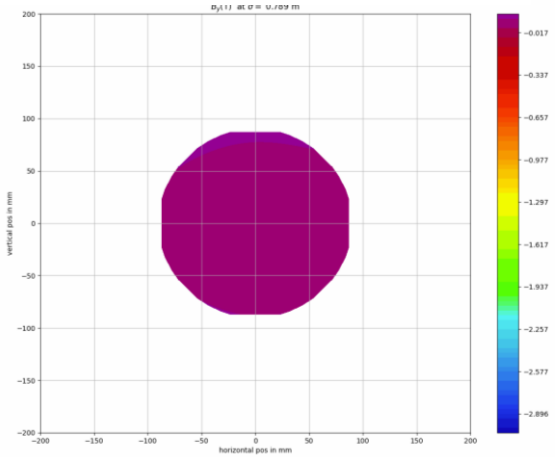
- The project includes a final demonstrator and 2-3 subscales.
- It capitalizes on the CCT technology developed at CERN since 2016 and used to produce HL-LHC orbit corrector magnets MCBRD.
- Possible applications are bending magnets in compact particle accelerator (ISRS at CERN) or for compact radiotherapy gantry systems.

Fusillo design

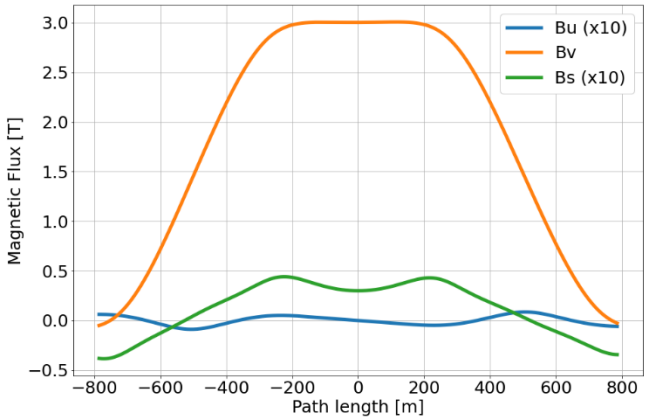




Dipolar field cross sections over 90°

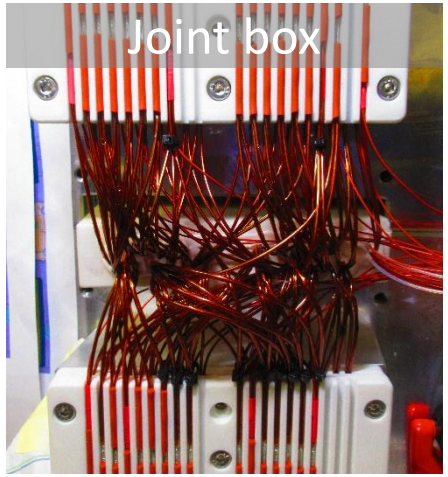


Field profile along aperture in the centre



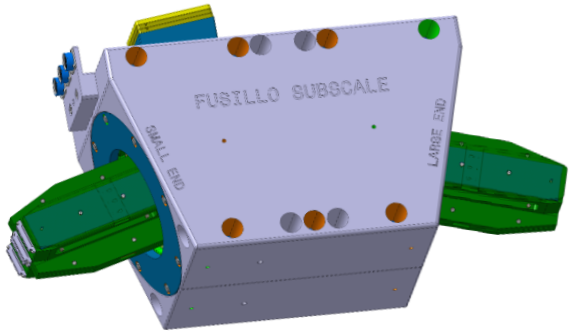
- A conductor design with 70 insulated wires allows powering at low current (290 A). Simple power converters can be used, compatible with clinical installations
- Multipole corrections in winding provides a very tuneable and homogenous field over the whole large aperture and over the full length
- Simple mechanical design (very few parts) and compatible with dry-cooling systems.

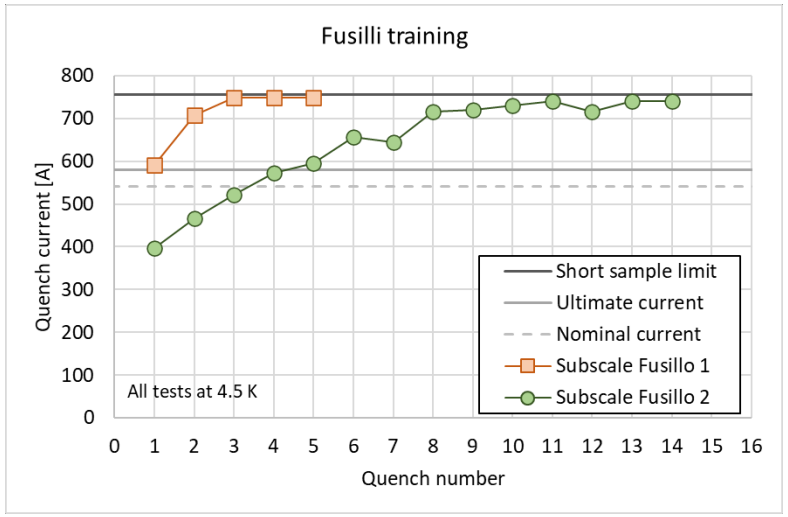
Subscale fabrication

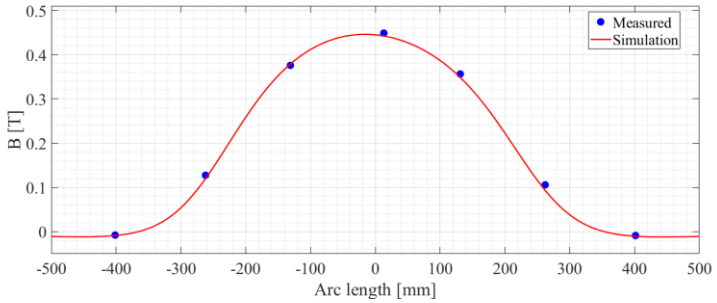


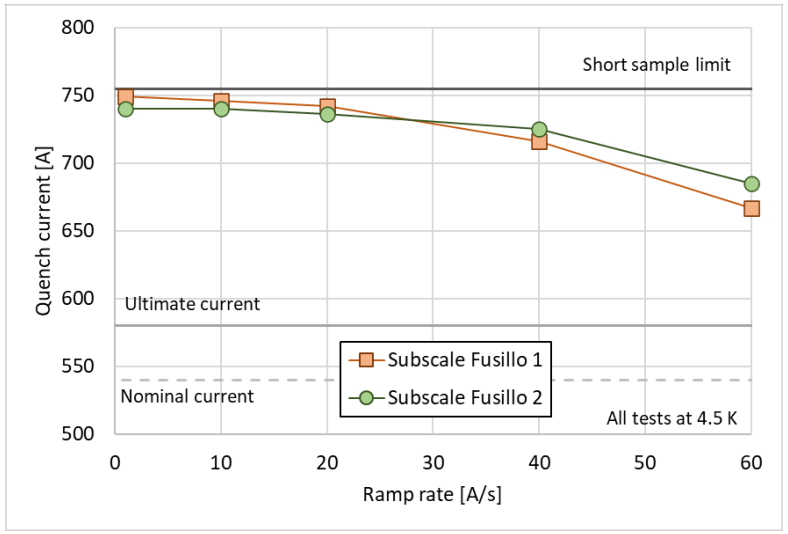
Subscale tests results

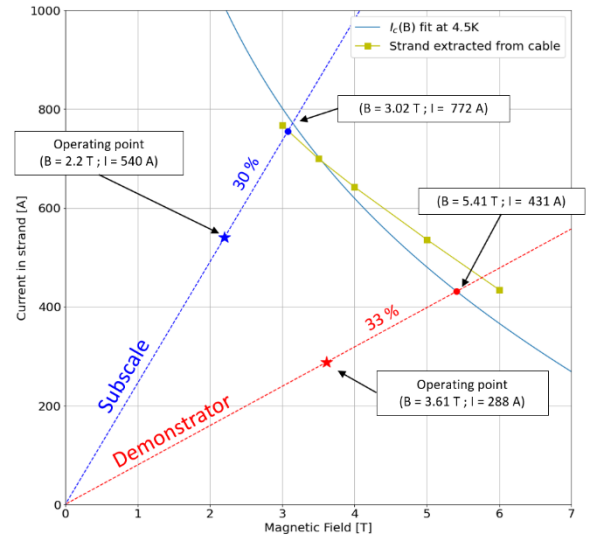
- Subscales were powered at higher current to fit the demonstrator working conditions.
- Both subscales reached nominal operation (580 A) and limit conditions (750 A) after training
- Good performances even at high ramp rates.
- The magnetic field was measured within 1% compared to simulation.





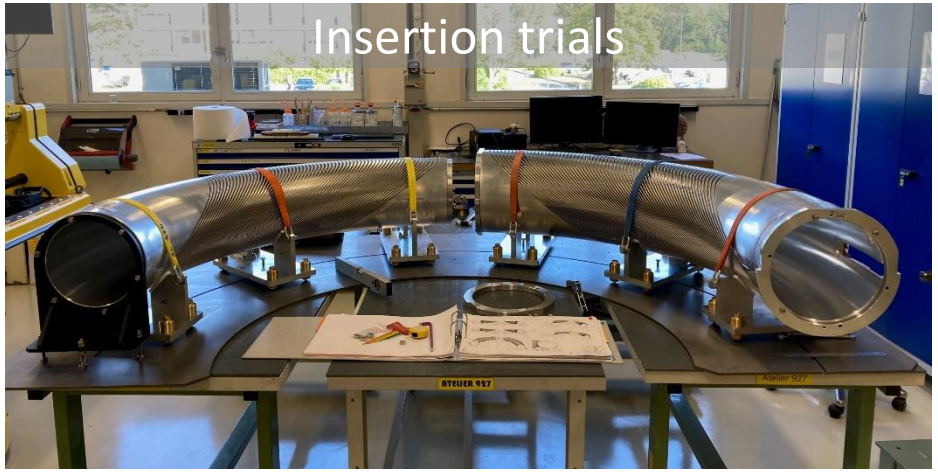




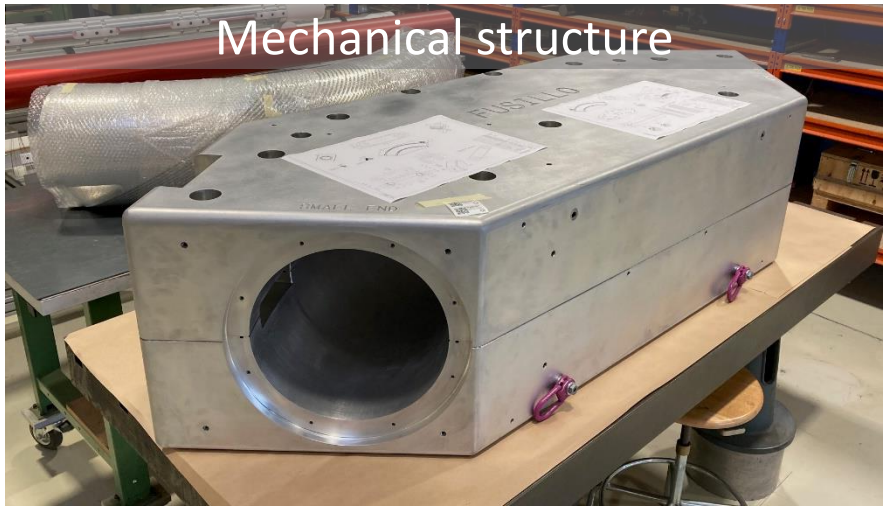


Demonstrator fabrication


Winding inner layer


Insertion trials

Magnetometer


Mechanical structure

- All parts for the demonstrators are ready including the full-length magnetometer
- Powering test are planned for early 2025.
- If successful, a beam test can be proposed as a spectrometer.

Thank you
for your attention !

GaToroid references

1. L. Bottura, Patent No. EP 3 573 075 A1 (2019)
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3. L. Bottura, E. Felcini, V. Ferrero, V. Monaco, F. Pennazio, M. Rafecas, P. Cerello, Hybrid High-precision In-vivo Imaging in Particle Therapy, *ATTRACT Report* (2020)
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13. S. Leadley, Magnet Design for an Innovative Particle Therapy Gantry, *Master Thesis at University of Oxford* (2023)
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