Istituto Nazionale di Fisica Nucleare
Laboratorio Acceleratori e Superconduttività Applicata

Superconducting Ion Gantry

SIG:
A Technology Development Program Toward A Compact Superconducting Ion Gantry

Marco Prioli on behalf of INFN-Milano, UniMi, INFN-Genova, UniGe, INFN-LNF, INFN-Torino, UniTo, CNAO

Seconda Giornata Acceleratori, INFN-LNS Catania, Marzo 2023 – M. Prioli

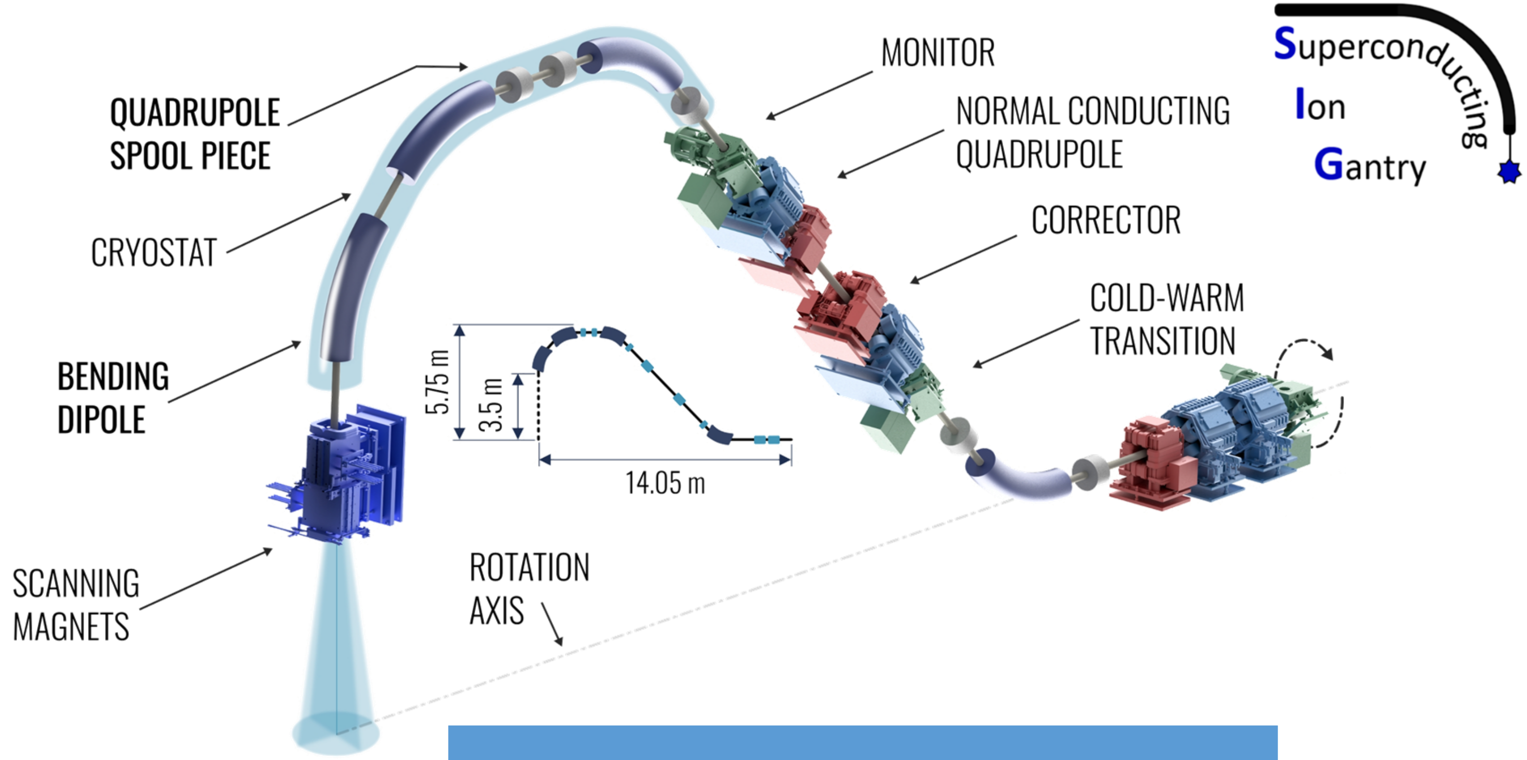
What is SIG

- SIG = Superconducting Ion Gantry
- Scope: study and development in 3.5 years of the key technologies for the next generation ion gantry of “only” 50 tons. This R&D of SIG will enable non-coplanar ion irradiation, greatly increasing the quality of the cancer treatment.
- Competitive 2021 call to INFN-CSN5
- Time span: ~3.5 years 2022 – mid 2025
- Budget: 1 M€ (+ 600 k€ Ext. Funds: CNAO+CERN)
- Personnel: 50 FTE-y (12 FTE-y Fellows included in the budget)

From: https://web.infn.it/csn5

Gantry key features

- Particles up to a rigidity of 6.6 Tm (430 MeV/u carbon ions)
- 14 m long, ~50 tons weight
- 4 T curved superconducting dipoles
- Superconducting spool piece quadrupoles
- Downstream scanning magnet system
- Dose Delivery and Range Verification Systems for adaptive cancer treatments



Ion gantry @ Himac (Jp) by TOSHIBA

~300 tons, 11m diameter, 13m length

Project structure

- WP1: Project coordination – Principal Investigator: L. Rossi (INFN-MI)
  - WP2: Superconducting dipole magnet demonstrator – Technical coordinator: M. Prioli (INFN-MI). Group: INFN-MI, INFN-GE, CERN, CNAO
  - WP3: Scanning magnet system – Technical coordinator: L. Sabbatini (INFN-LNF). Group: INFN-LNF, CNAO
  - WP4: Dose Delivery System (DDS) – Technical coordinator: S. Giordanengo (INFN-TO)
  - WP5: Range Verification System (RVS) – Technical coordinator: E. Fiorina (INFN-TO)

WP2: scope

Superconducting Ion Gantry

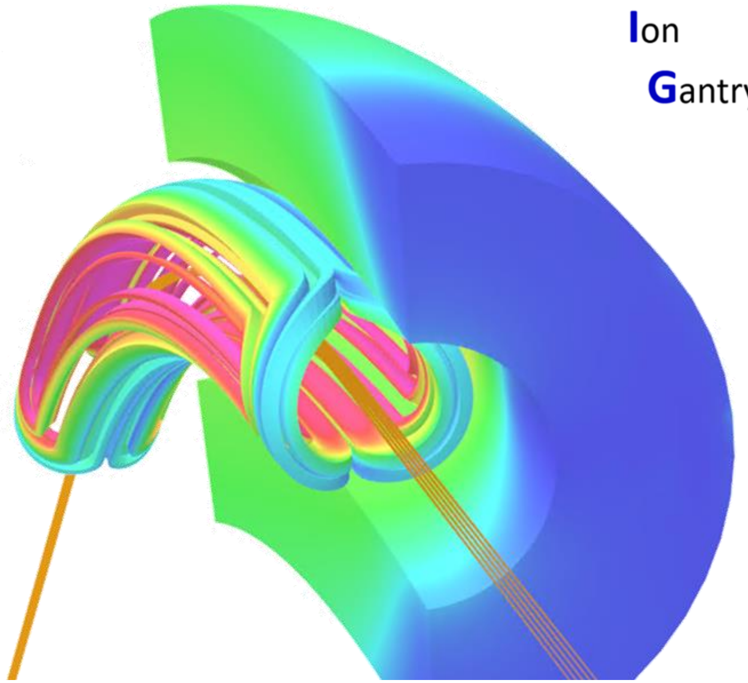
WP2 scope: design, construction and test of a curved superconducting demonstrator magnet (SDM) for ion gantries

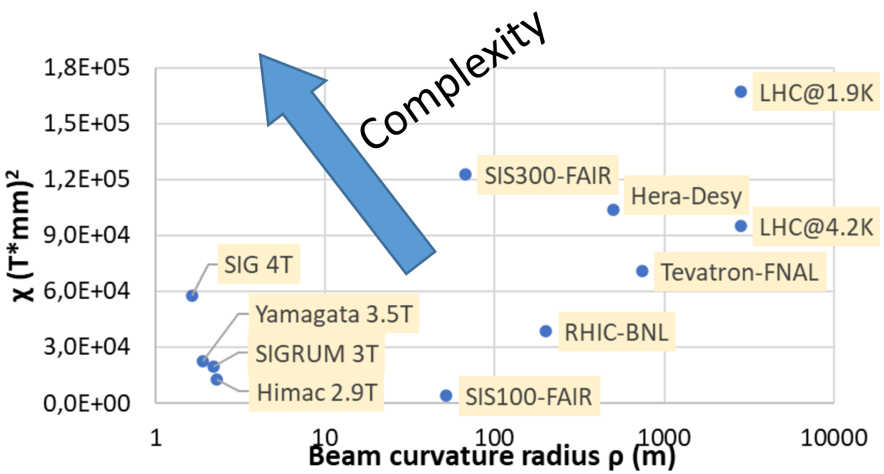
- SIG is the successor of SIGRUM by CERN and Tera Foundation ([link]()) with updated params:

  present SIG (previous SIGRUM)

  - Cos-θ coils
  - Pure dipolar field: 4 T (3 T with gradient)
  - Bore diameter: 80 mm (70 mm)
  - Small curvature radius: 1.65 m (2.2 m)
  - Angular sector: 30°
  - High field ramp-rate: 0.4 T/s (0.1 T/s)
  - Compatible with conduction cooling (no LHe) but no optimization

- A parallel program at CERN is devoted to the construction of a straight thermal demonstrator





European Projects on SC magnet design for Gantry[1]

Superconducting Ion Gantry

WP8 - Innovative Superconducting magnets

exploring **CCT with HTS and combined function**!

Labs → Industry (two demonstrators)

Outer layer

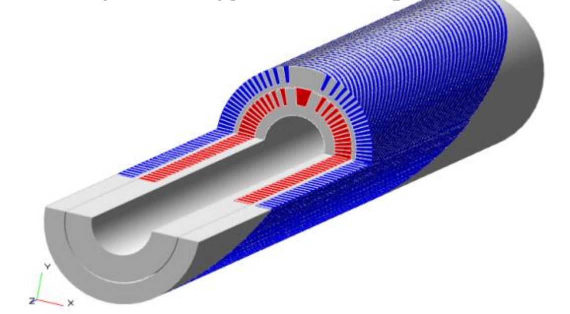
Courtesy of Xiaorong Wang

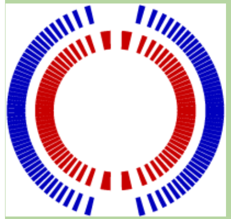
HITRIplus

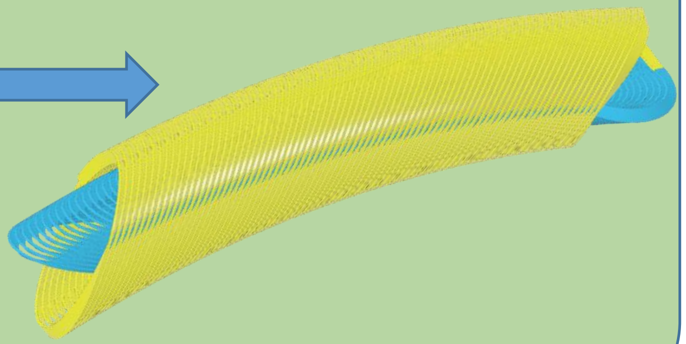
Heavy Ion Therapy Research Integration

WP8 - Superconducting magnet design

CURVED CCT with R = 1.65 m (Ion gantry-oriented)







Courtesy of Tengming Shen

Institutes/Companies Partners

cea, CERN, Ciemat, Wigner, INFN – Istituto Nazionale di Fisica Nucleare, Paul Scherrer Institut PSI, Uppsala Universitet

HITRIplus & I.FAST

I.FAST

Bilfinger – Bilfinger Noell GmbH, Université de Genève, Elytt Energy, Scanditronix

HITRIplus

SEEIIST – South East European International Institute for Sustainable Technologies, CNAO – Centro Nazionale di Adroterapia Oncologica, Sentronis – a Senis company

[1]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.

Courtesy of E. De Matteis

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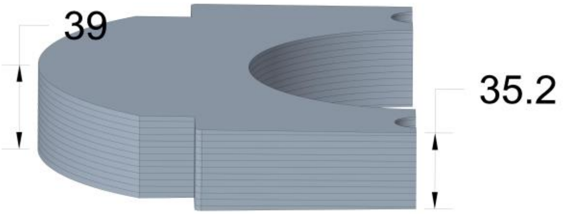
WP2: magnet curvature

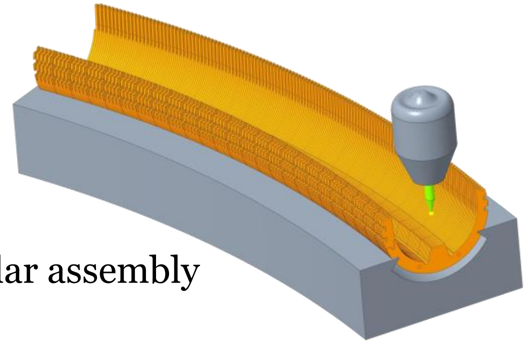
WP2 accent is on the magnet curvature, why it is so demanding?

- Modelling
  - Mathematical (e.g., definition of harmonics, together with HITRIplus W.G..)
  - Software tools for optimization consider straight geometry
- Some design steps become iterative (e.g., ends design & integrated field)
- Winding and manufacturing strongly concave coils → dedicated tooling
- Mechanical
  - Selection of materials and manufacturing techniques
  - Structural concept

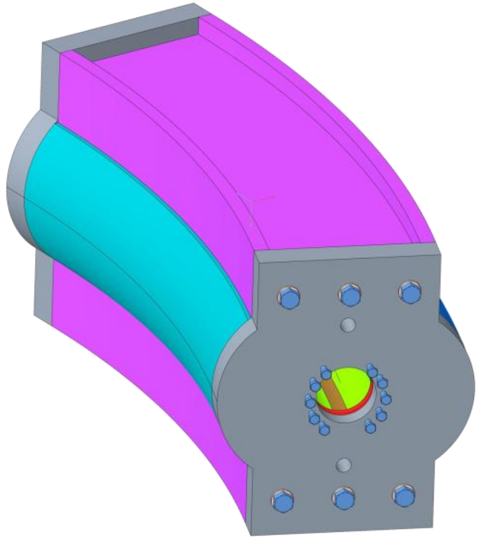
Curved magnet assembly (preliminary!)



Tapered yoke laminations



Curved collar assembly



Courtesy of S. Farinon, R. Cereseto

INFN-MI/GE, UniMi/Ge

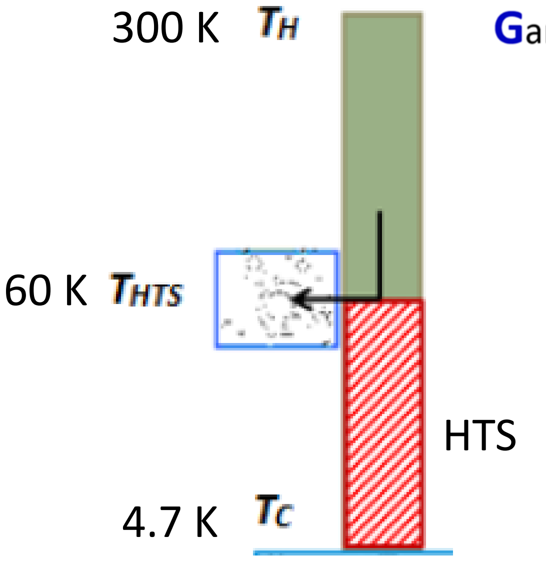
WP2: main findings (1)

A possible showstopper was identified: conduction cooling of current leads requires a high power. For the resistive part between 300 K and 60 K:

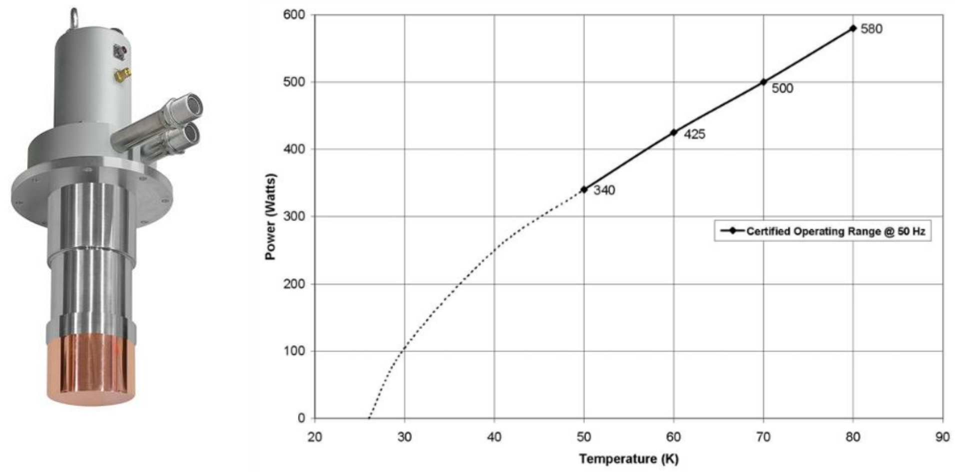
$$\frac{Q_{c,min}}{I} = 46 \left[\frac{W}{kA}\right]$$

→ The operational current must be minimized

Cable	Discorap III gen. →	CERN LHC05
Strand diameter [mm]	0.821	0.48
Operational Temperature [K]	5	5
Operational Current [A]	4195	2790
$Q_{c,min}$ [W]	2 x 193	2 x 128
Margin on Load Line [%]	28.1	21.9
Temperature Margin [K]	1.49	1
Inner Layer Turns	24	35
Outer Layer Turns	29	43



Example: Cryomech GM AL600: 425 W @ 60 K



INFN-MI/GE, UniMi/Ge

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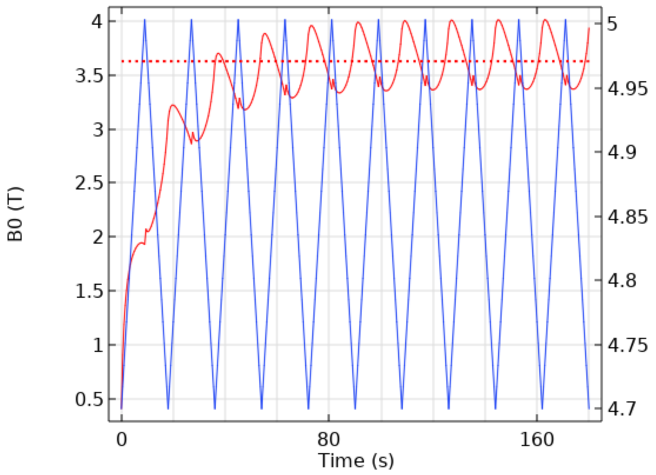
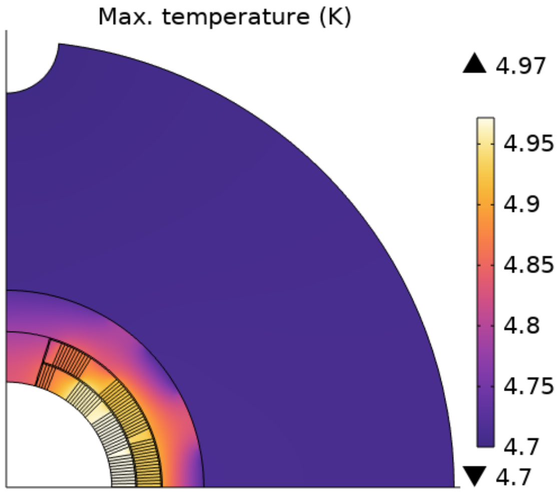
WP2: main findings (2)

B’ = 0.4 T/s seems within reach for the final prototype

- Coil loss ~ 1 W/m with a low-loss cable design (DISCORAP experience)
- For the demonstrator, too long lead-time for such a dedicated cable → LHC05 with reduced ramp-rate
- The final prototype will inherit DISCORAP and LHC05 beast features

Cable	Operational current (kA)	Max. dB/dt (T/s)	Coil loss (W/m)
Discorap III gen.	4.2 ✗	0.4 ✓	1
CERN LHC05	2.8 ✓	0.15 ✗	0.98
Future ad-hoc	2.8 ✓	0.4 ✓	1





	Straight part	Int. l = 1.1 m (45°)	Ends
Conductor loss	1 W/m	1.1 W	0.18 W
Iron hyst	0.32 W/m	0.35 W	0.14 W
Eddy current	0.37 W/m	0.41 W	0.41 W
Total		**1.9 W**	**0.7 W**

2.6 W * 1.5 = 4 W @ 4.7 K

INFN-MI/GE, UniMi/Ge

Superconducting Ion Gantry

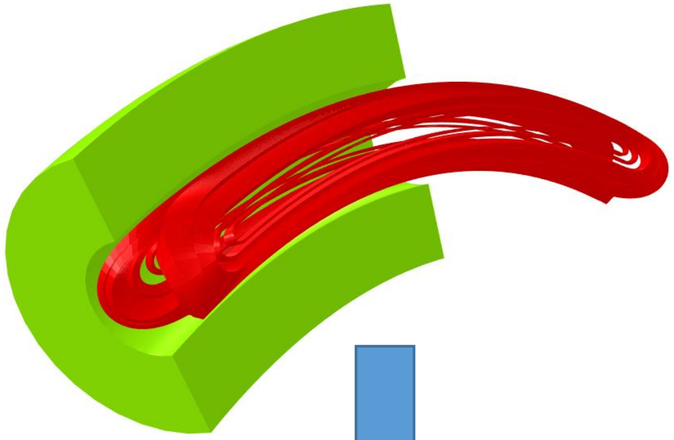
WP2: electromagnetic design

MAIN PARAMETERS OF THE ELECTROMAGNETIC DESIGN.

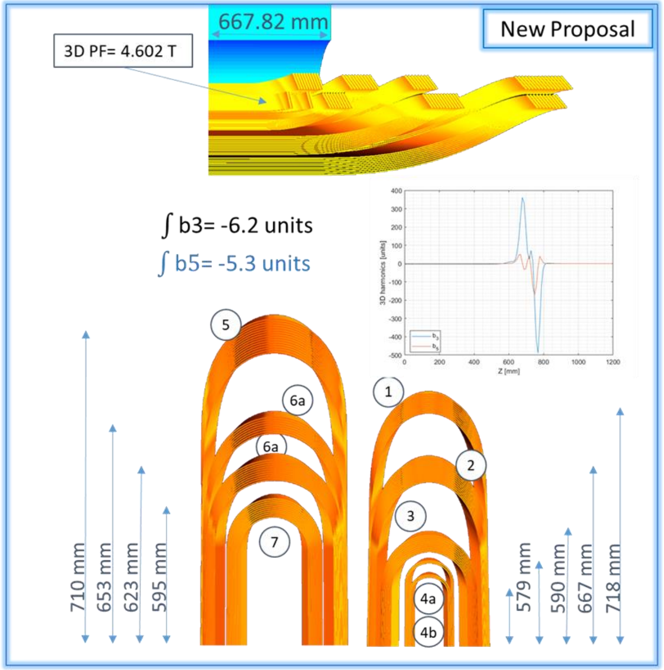
Operational temperature (K)	5
Operational current (kA)	2.79
B_0-B_{peak} (T)	4-4.46
Yoke inner-outer diameter (mm)	75-170
Margin on load-line (%)	21.9
Temperature margin (K)	1
Inner layer turns	35
Outer layer turns	43
2D field harmonics ($\cdot 10^{-4} B_0$)	$b_{3,5,7}=0$ $b_9=1$

Electromagnetic design loop closed!

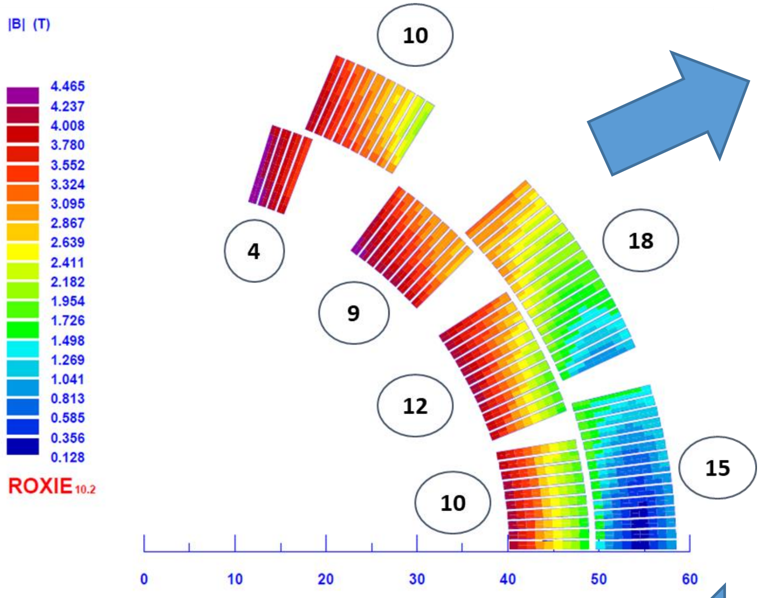
OPERA 3D curved



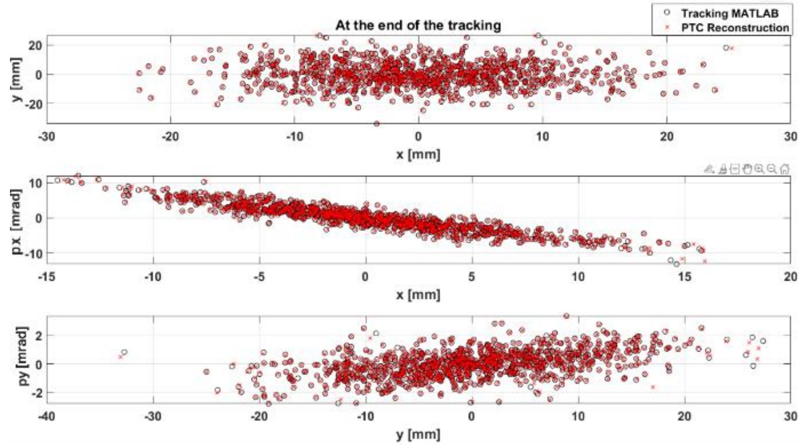
ROXIE 3D straight



ROXIE 2D



Beam optics simulations (CNAO)



Courtesy of E. Felcini

Superconducting Ion Gantry

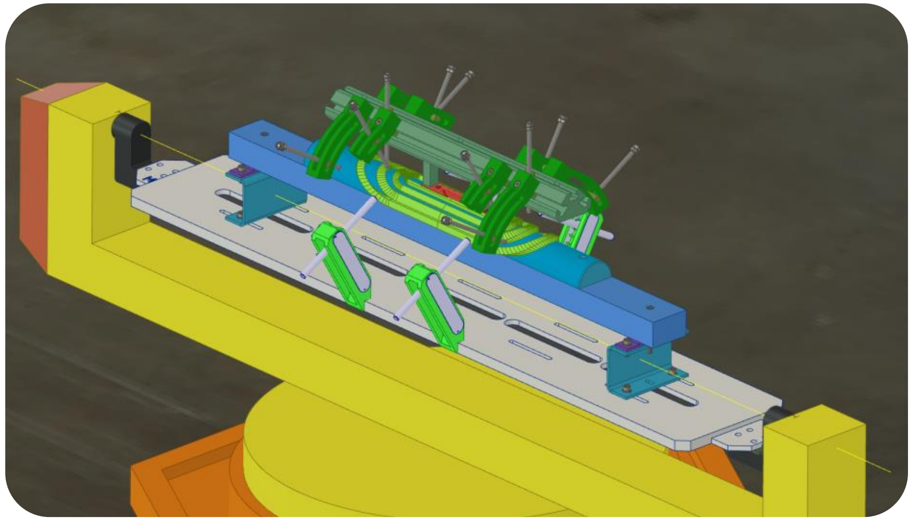
WP2: present efforts

We are now concentrated on the preparation of the winding trials, fundamental to have design iterations

- CERN winding table installed
- Cable tensioner foreseen in March
- Design of winding tooling and components ongoing

Winding table

Straight practice coil



Courtesy of A. Palmisano

End-spacer

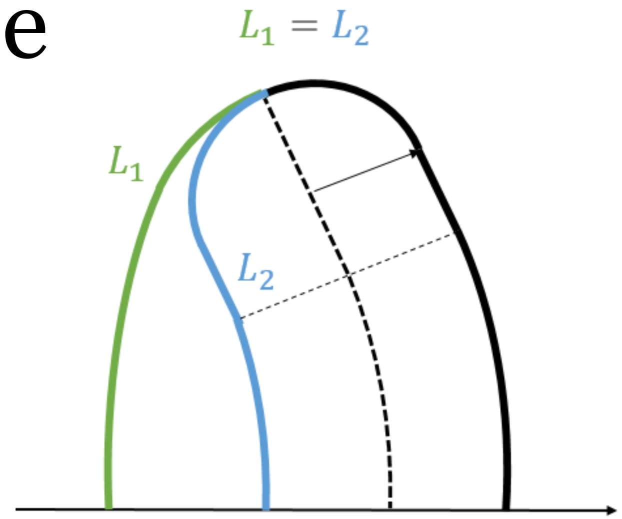
Plan: 2x50 m Cu cable from CERN on May, first straight practice coil by July

INFN-GE, UniGe

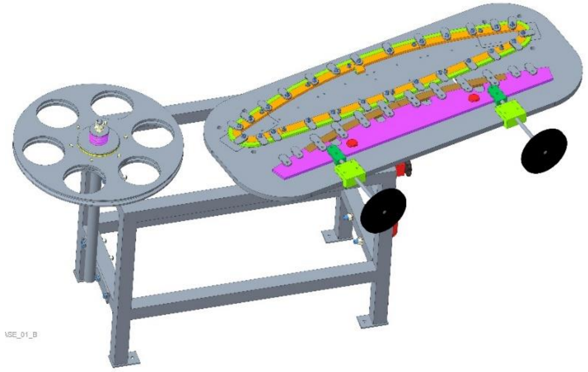
WP2: alternative winding technique

Alternative winding technique developed for a coil block magnet

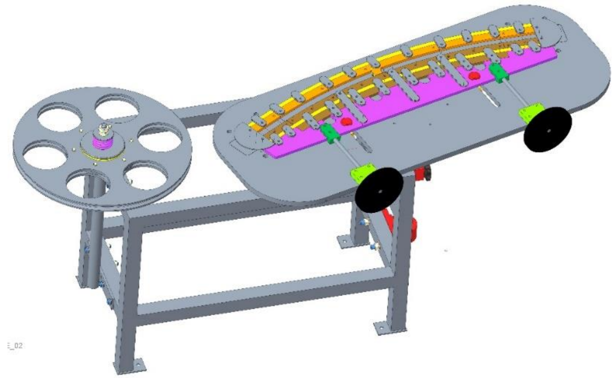
At first the coil is wound in a convex shape (L_1) and then it is pushed to obtain the final concave form (L_2)



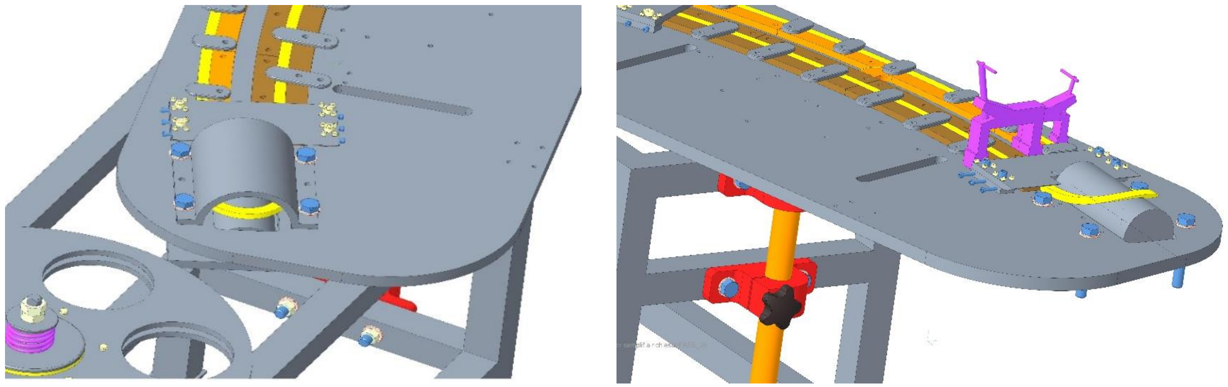
Courtesy of A. Gagno, R. Cereseto



1. The coil is wound on a manual rotating table



2. A template pushes one side of the coil in order to obtain the final shape



3. The table is equipped with a support that inclines the heads

INFN-MI, UniMi

WP2: quadrupole spool pieces

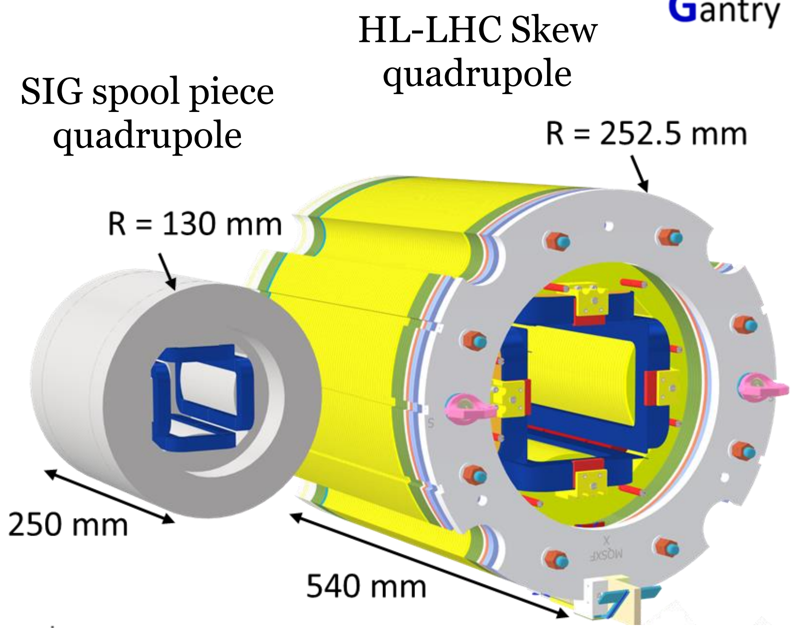
The gantry optical layout requires spool piece quadrupoles at each end of the dipole magnets

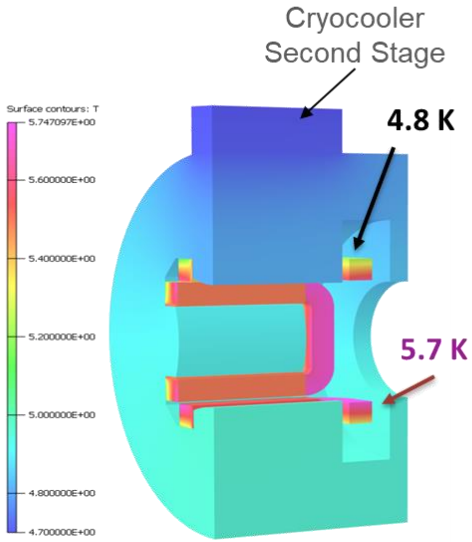
One possibility is to leverage on the INFN-MI LASA experience on the superferric HOC magnets for HL-LHC

First design:

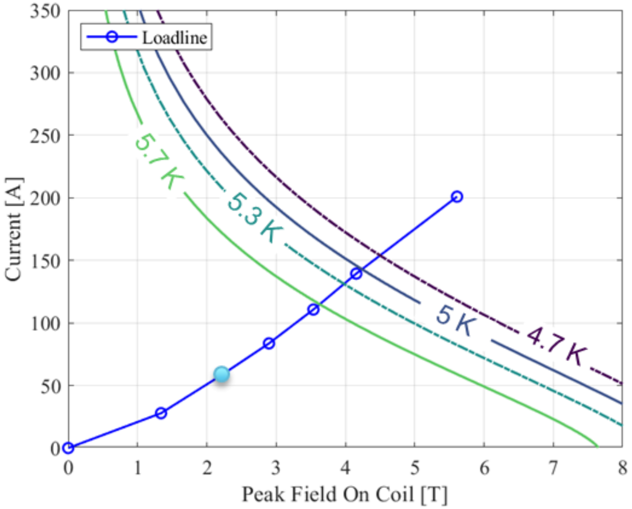
- 40 T/m @ R_{ref} =26.7 mm of magnet field gradient
- 175 mm of magnetic length
- 60% margin on the loadline @ T = 5.5 K.
- Indirect Cooling (gas vs cryocooler)

The thermal design is more demanding!





Courtesy of S. Mariotto, F. Mariani



WP3: scanning magnet system

Coordinated by CNAO in SIGRUM

Superconducting Ion Gantry

Parameter	Boundaries	Optimal Value
B_{0x} [T]	[0.3 - 1]	1
B_{0y} [T]	[0.3 - 1]	0.85
α_x [rad]	[0 - 1]	0.042
α_y [rad]	[0 - 1]	0.064
I_x [A]	[500 - 800]	800
I_y [A]	[500 - 1500]	1500

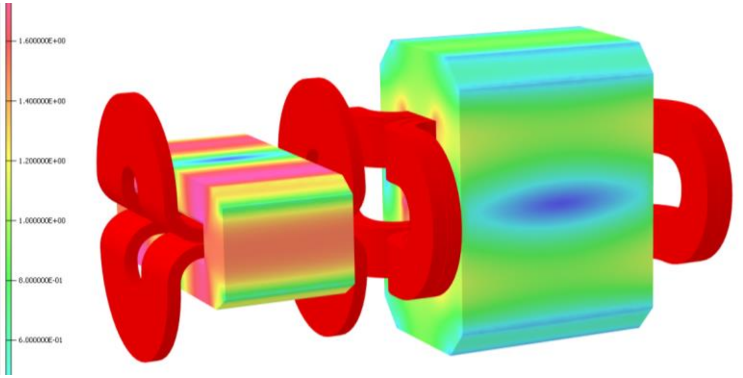
Table 2: The set of free parameters used for the optimization

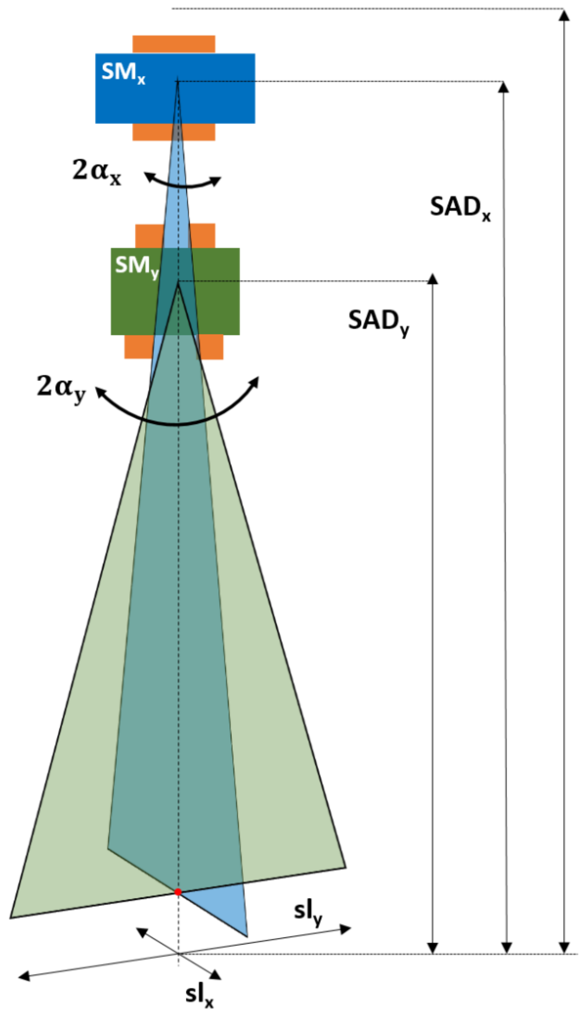
Parameter	Value
Gap SMx [mm]	53
Gap SMy [mm]	113
Yoke length SMx [m]	0.221
Yoke length SMy [m]	0.380
Stored energy SMx [kJ]	0.64
Stored energy SMy [kJ]	3.21
Ampere-turs SMx [kA turns]	42.18
Ampere-turs SMy [kA turns]	77.00
Inductance SMx [mH]	2.00
Inductance SMy [mH]	2.86
dI/dt SMx [kA/s]	200.0
dI/dt SMy [kA/s]	300.0
Current density Cu SMx [A/mm2]	6.91
Current density Cu SMy [A/mm2]	12.96
Total voltage V_{tot} SMx [V]	409.0
Total voltage V_{tot} SMy [V]	880.9

Table 3: The set of parameters resulting from optimization

Design targets:
- Wide area 240 x 300 mm²
- Scanning speed: 20 m/s
- Beam accuracy better than 0.5 mm

Technical implications:
- Demanding power supply (MedAustron)
  → Possibility of including a complete system demonstrator
- Field repeatability 0.3 % in transient



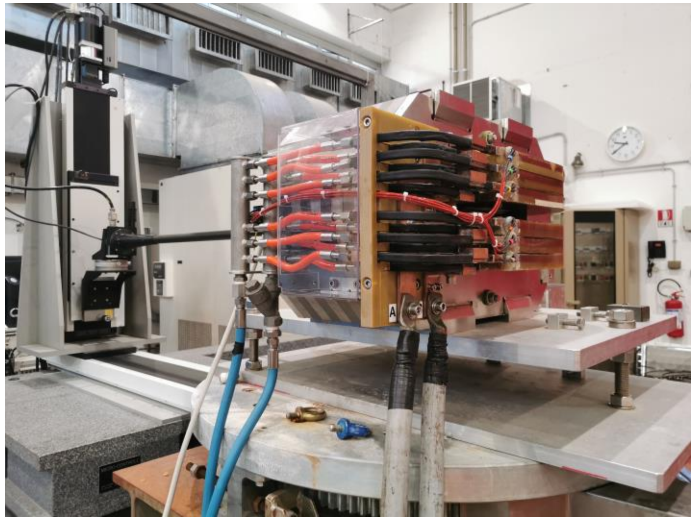


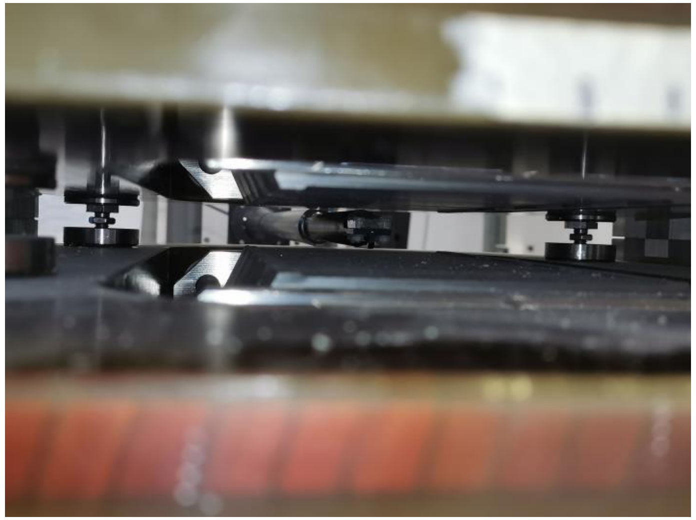
Courtesy of E. Felcini

WP3: scanning magnet system

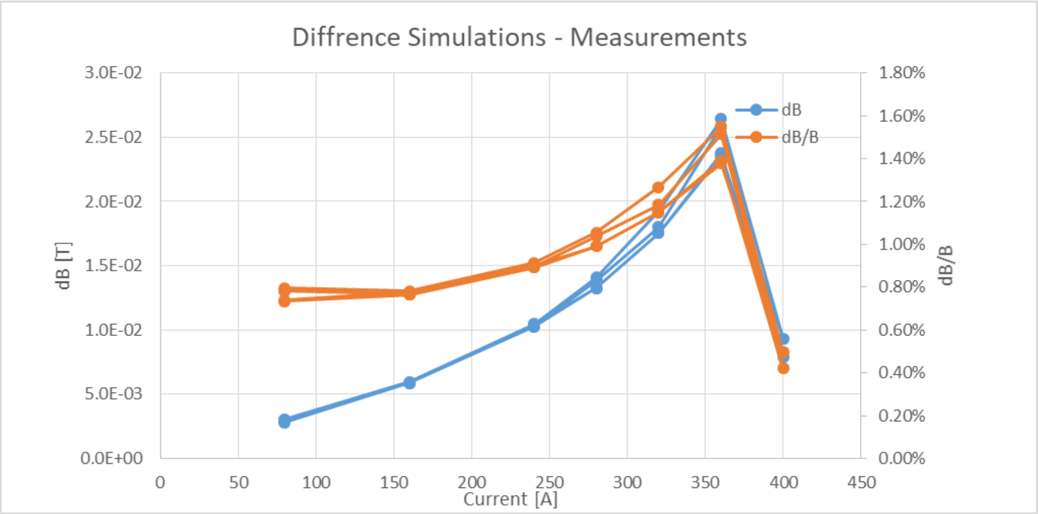
Present efforts:

- 3D numerical models for the optimization of the magnet design
- Study of the magnet's crosstalk, hysteretic and dynamic effects
- Characterization of the FeCo properties at INFN-LNF
  - Option: real time modelling of the dynamic effects for field feedback?





Courtesy of L. Sabbatini, A. Vannozzi



Courtesy of E. Felcini

WP4 & WP5: integrated DDS & RVS

INFN-TO, UniTo

Courtesy of S. Giordanengo, E. Fiorina, R. Sacchi

Superconducting Ion Gantry

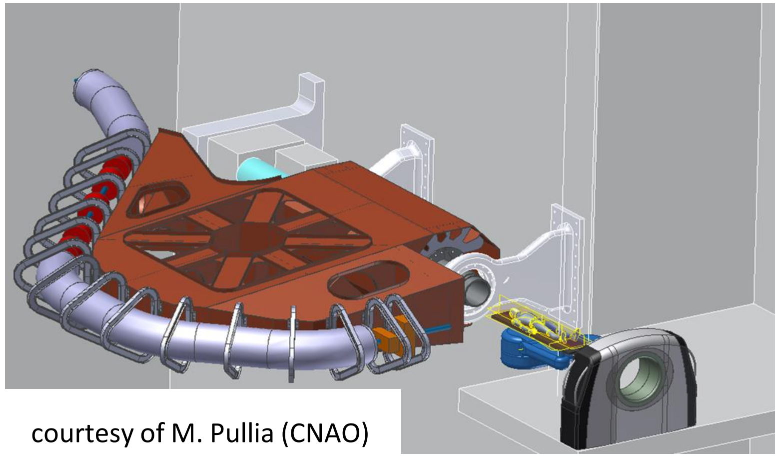
General scope: accurately and safely delivering the prescribed radiation dose by monitoring and controlling, <u>in real-time</u>:

- Parameters of the scanned particle beam (DDS)
- Its effect on the patient (RVS)

  Paves the way to adaptive treatments!

Design features:

- Mechanical integration in the ion gantry
- First integrated system optimized for ions:
  - Accurate and fast beam monitoring system for ions
  - Accurate RVS signals analysis with DDS signal synchronization
  - Online dose quality feedback with integrated GPU-based calculations



courtesy of M. Pullia (CNAO)

robotic arm in use at MedAustron for patient positioning
→ possible solution for RVS mechanics?

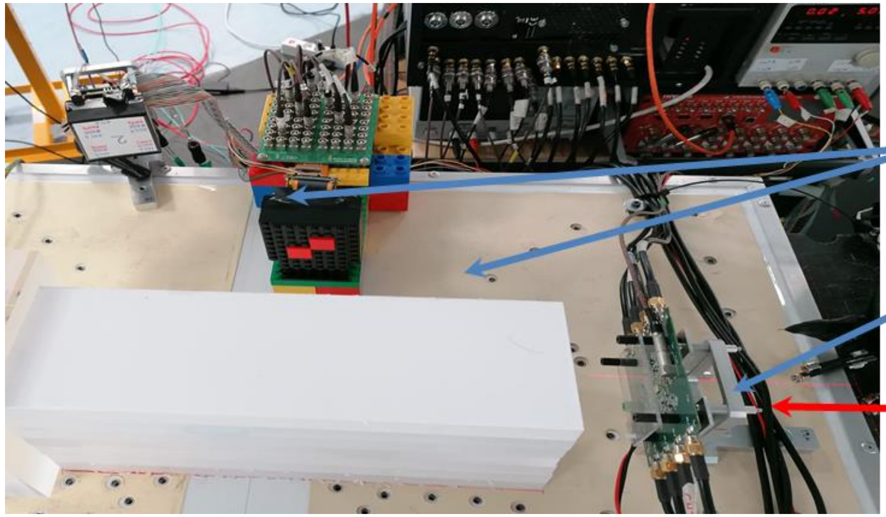
WP4 & WP5: starting point

INFN-TO, UniTo

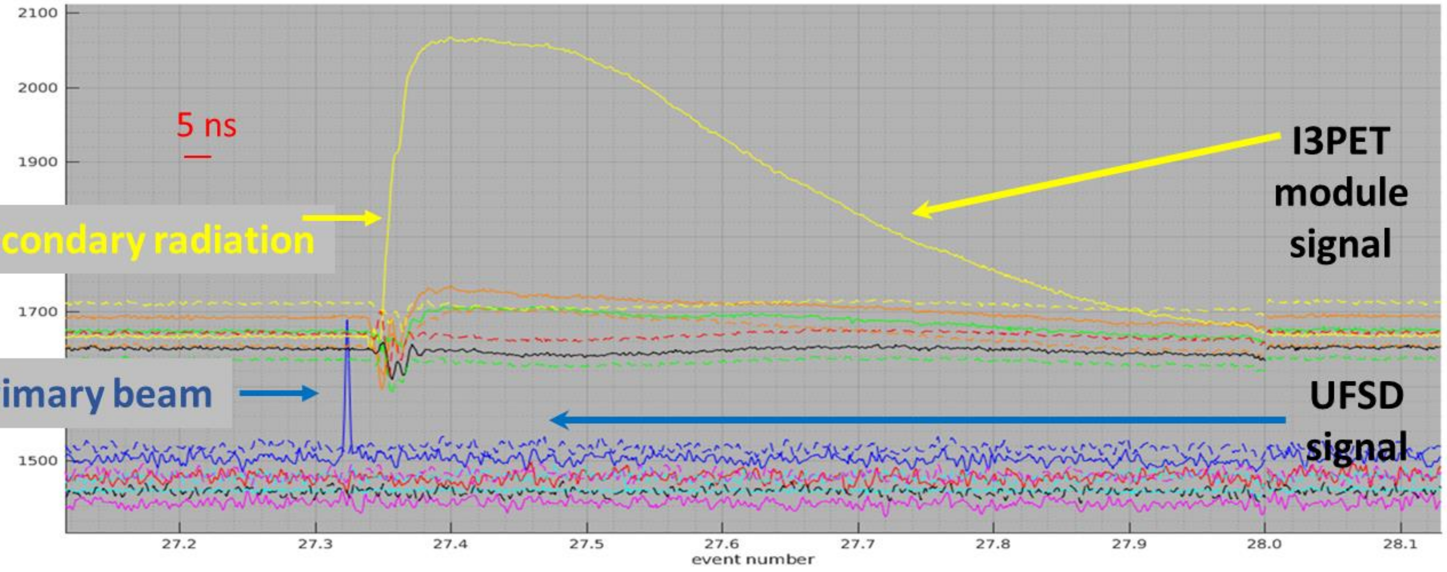
Courtesy of S. Giordanengo, E. Fiorina, R. Sacchi

Superconducting Ion Gantry

Results with protons
DDS: • MoVeIT detectors for protons • RIDOS GPU-based dose calculation RVS: • I3PET modules • Algorithm for secondary radiation data analysis



First I3PET proton beam test (June 2021):
primary-secondary radiation coincidences identified!!!



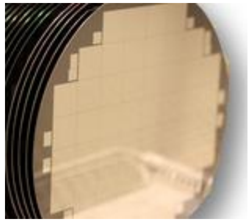
INFN-TO, UniTo

Courtesy of S. Giordanengo, E. Fiorina, R. Sacchi

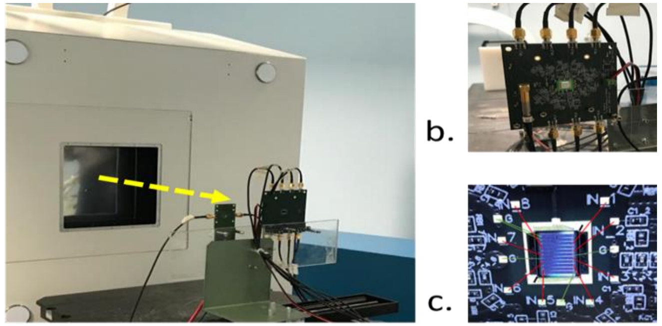
Superconducting Ion Gantry

WP4: DDS tasks

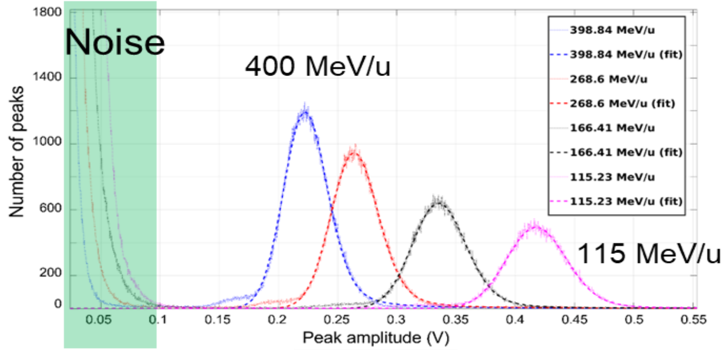
T4.1 – Thin planar silicon sensors for Carbon ion counter



- Single ion signal
- Ionization density effects
- Radiation resistance

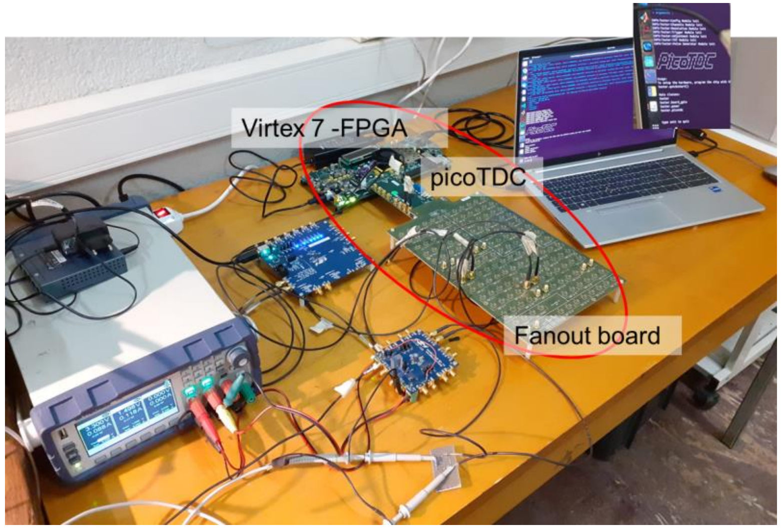


First characterization at CNAO with carbon ions



T4.2 - Single ion crossing time measurement

- **Proof of Concept** to provide the time stamps for ions with high efficiency.
- **Start counter** for range verification system.



pico-TDC ASIC for precise time-tagging of up to 64 inputs channels, 3ps or 12ps binning very low jitter (<1ps)
Virtex 7 FPGA

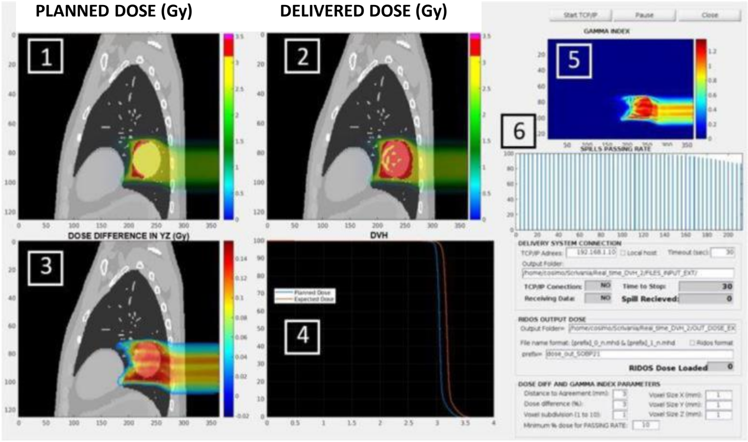
T4.3 – GPU-based data analysis for online dose verification

New GPU-based algorithms to exploit ion treatments (ADAPTIVE PT) with a very fast data analysis for online feedback on the dose delivered.

GSI

→ Collaboration with GSI within the **RAPTOR** project (ETN – H2020)

Real-Time Adaptive Particle Therapy Of Cancer



ONLINE results: (1) planned and (2) delivered doses, (3) dose difference, (4) DVH, (5,6) gamma index

INFN-TO, UniTo

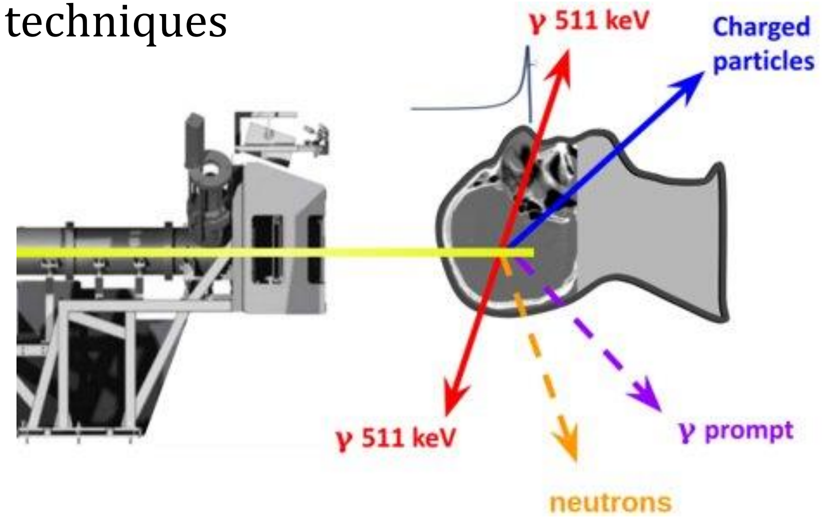
Courtesy of S. Giordanengo, E. Fiorina, R. Sacchi

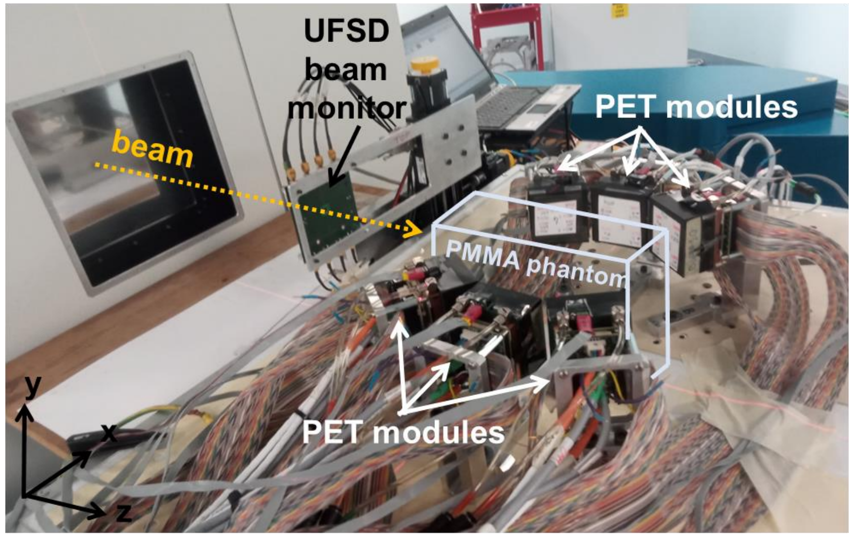
Superconducting Ion Gantry

WP5: RVS tasks

Effective RVS for ion gantry based on PET and/or PGT (Prompt Gamma Timing) techniques

OPEN ISSUES	R&D WP5 TASKS
Production of secondary radiation (prompt photons and positron emitters) by ions (from He to O) dramatically reduced wrt to proton beams. Extensive study not performed yet. Feasibility of a hybrid approach PGT-PET **for ions** to be demonstrated	**5.1 Detector development** PG detector (LaBr3 + SiPM) PGT-PET detector (from I3PET project, LFS + SiPM) DDS-RVS integrated DAQ (ASIC-based, collaboration with WP4) **5.2 Detector optimization study** beam test at CNAO and GSI
Standard data analysis methods not available for online ion range verification	**5.3 PET-PGT reconstruction algorithms** Maximum A Posteriori (MAP) based algorithm for PET Maximum Likelihood Expectation Maximization (MLEM) based for PGT *Algorithms developed in collaboration with University of Lubeck*
Feasibility of a **full-size RVS** for an ion gantry	**5.4 MC simulations** evaluation of the final RVS performance





Conclusion & acknowledgement

- The SIG project brought together a motivated community for a substantial contribution to the technology development of ion gantries
- 2.5 years to deliver effective technology demonstrators!
- I would like to thank all the (direct and indirect) collaborators

INFN Milano & UniMi	INFN-Genova & UniGe	CERN	CNAO	MedAustron	INFN-LNF	INFN-Torino & UniTo
L. Rossi M. Prioli A. G. Carloni G. Ceruti E. De Matteis F. Mariani S. Mariotto A. Palmisano M. Sorbi S. Sorti M. Statera R. U. Valente	R. Musenich S. Farinon E. Bianchi R. Cereseto A. Gagno F. Levi	E. Gautheron M. Karppinen D. Tommasini L. Gentini	M. Pullia E. Felcini S. Savazzi A. Mereghetti M. Donetti G. Frisella	C. Kurfuerst M. Pivi	L. Sabbatini A. Vannozzi L. Pellegrino A. Trigilio	S. Giordanengo E. Fiorina R. Sacchi R. Cirio F. Mas Milian S. Garbolino C. Galeone E. Data A. Fadavi F. Pennazio P. Cerello V. Ferrero R.J. Wheadon S. Ranjbar