Numerical Design of an Innovative Superconducting Magnetic Trap for Probing β-decay in ECR Plasmas

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On behalf of the PANDORA collaboration

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Outline

- Introduction
- Magnetic system: required performances and geometry
- OPERA numerical design and simulation results
- CST Studio Suite validation
- Magnetic system procurement status
- Technical design from first ranked company
- Conclusion and perspectives

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Introduction

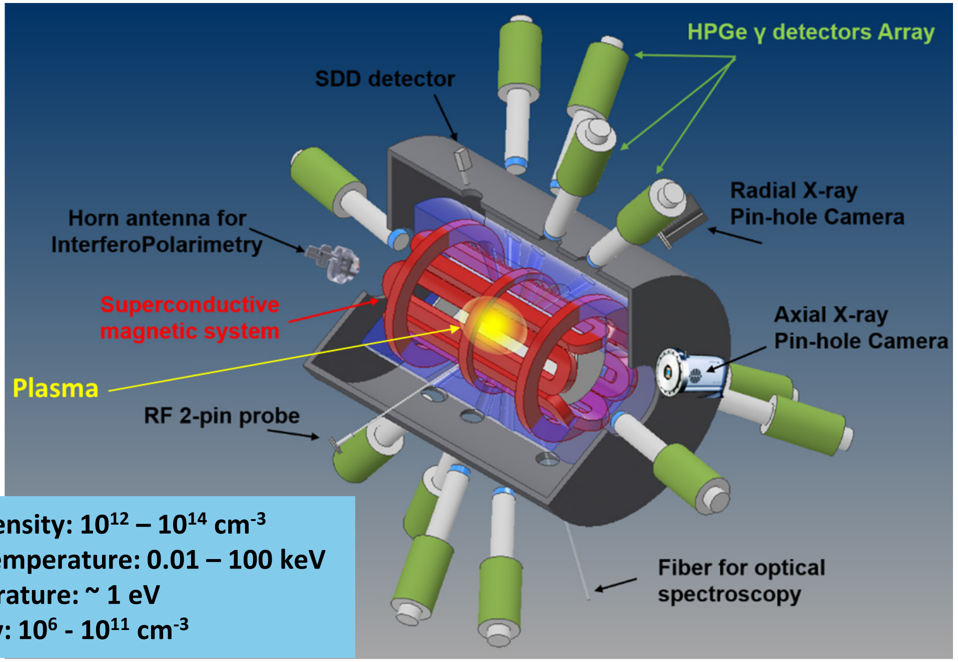
- **PANDORA goal: study β-decays in laboratory magneto-plasmas**
- **Theoretical models predict modifications of β-decaying isotopes lifetimes in strongly ionised atoms (even order of magnitudes);**
- **Strongly affects nuclear astrophysics scenario: the main important branching points in s-processes**
- **There are only very few experimental evidences performed in storage rings.**
- **GOAL: to study if and how the lifetimes is affected by the atomic charge state and by the plasma "*environment*"**

> **<u>A NEW CHALLENGE</u>: Reproduce in laboratory some stellar-like conditions and measure the expected variations of nuclear lifetime in β–decaying nuclei.**

> **Necessity of a plasma-confining magnetic system that allows to have long plasma lifetime and sufficient flexibility and accessibility for several diagnostics.**

Mascali et. al, *Universe* **2022**, *8*, 80

See talk *by* D. Mascali



- **Electron Density: $10^{12} – 10^{14}$ cm^{-3}**
- **Electron Temperature: 0.01 – 100 keV**
- **Ion Temperature: ~ 1 eV**
- **Ion Density: 10^{6} - 10^{11} cm^{-3}**

Introduction

- Two crytical points to take into account:

➢ **plasma confinement time;**

➢ **magnetic system feasibility.**

1. The total ion confinement time inside the trap can be written as:

Mascali et. al, Review of Scientific Instruments 85, 02A511 (2014)

- $\tau_i^q \cong 7.1 \times 10^{-20} \left(\frac{l}{2}\right)^2 ln\Lambda_{ij} \frac{q^2}{T_i^{5/2}} n_e \sum_j \sqrt{A_j} \langle q \rangle_j$

  ($ln\Lambda_{ij}$ denotes the Coulomb logarithm ($ln\Lambda_{ij}$ = 10 - 15), A_j the atomic mass number)

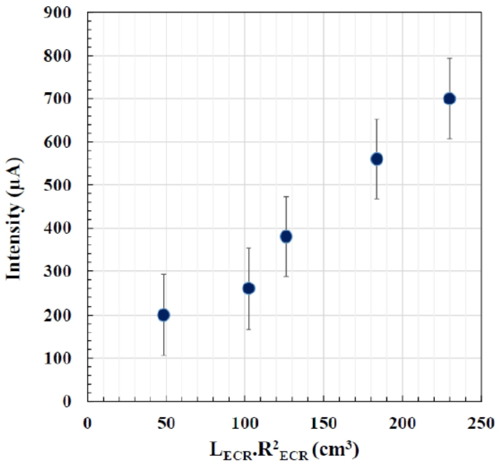
- τ_i^q ~ B_{max}/B_{min}

- Both plasma chamber length and magnetic field mirror ratio play a fundamental role for reaching high charge states.

- **PANDORA plasma trap: optimal compromise between performances and feasibility.**

- **INFN-LNS, Catania (IT) ECRIT – PANDORA:** 18 GHz, 5 kW, B-min, $L_{ECR}*R^2_{ECR}$ ~ 1400 cm^3

	VENUS	ASTERICS	unit
L	500	600	mm
R	72	91	mm
V	8.1	15.6	liters
B_{wall}	1.85	1.97	T
L_{ECR}	178	205	mm
R_{ECR}	50	58	mm



T. Thuillier et al 2024 J. Phys.: Conf. Ser. 2743 012059

Figure 1. Best Ar^{12+} beam intensity produced in various ion sources as a function of $L_{ECR}.R^2_{ECR}$. From left to rigt: PHOENIX V2, PHOENIX V3, GTS [6], HI-ISI [7],SUSI [8].

See talk *by* A. Pidatella

Introduction

Design Parameters	**VENUS**	**SECRAL**	**SECRAL II**	**RIKEN**	**FECR**	**PANDORA**
Superconductor	NbTi	NbTi	NbTi	NbTi	Nb_3Sn	Nb_3Sn
B_{inj} [T]	4	3.7	3.7	4	≥ 6.4	1.7 - 3
B_{ext} [T]	2 - 3	2.2	2.2	2.2	≥ 3.4	1.7 - 3
B_{hex} [T]	2	1.7	2	2.1	≥ 3.4	1.6
B_{peak} [T]	7	7.8	7.8	7.4	11.8	8.5
Mirror length [mm]	500	420	420	500	500	**700**
Pl. chamber ID [mm]	150	116	125	150	150	**280**
f_{rf} primary [GHz]	28	24	28	28	45	18
kW primary	10	7	10	10	20	4.8
f_{rf} secondary [GHz]	18	18	18	18	45 - TBD	21
kW secondary	2.4	3	2.4	2.4	TBD	1.5

D. Leitner, 10th Int. Particle Accelerator Conf. (IPAC'19), doi:10.18429/JACoW-IPAC2019-WEXPLS1

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Magnetic system: required performances and geometry

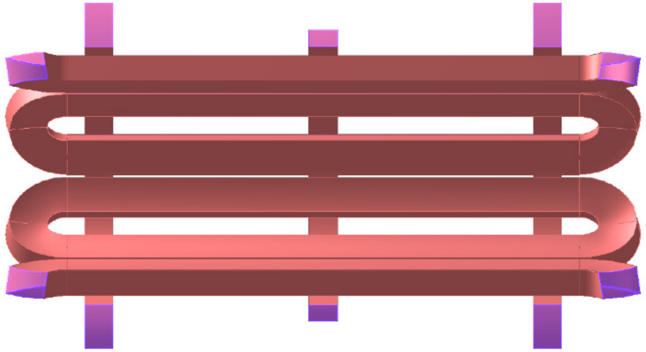
The PANDORA's trap has been designed to operate at 18 + 21 GHz.

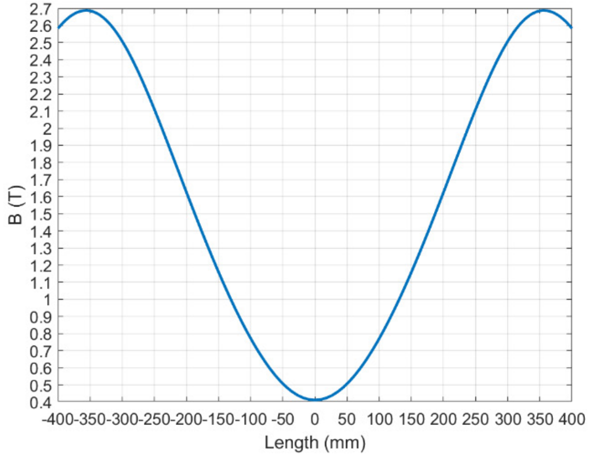
- The magnetic system, fully superconductive, consists of:

1. #3 axial coils that generates the axial magnetic field;
2. #6 hexapole coils that generates the radial magnetic field.

- It will enclose a plasma chamber with inner radius $\mathbf{R_{CH\_IN} = 140\ mm}$ and length **L = 700 mm**.

MAGNETIC FIELD REQUIREMENTS	
B_{inj} max @ z = - 350 mm	3 T
B_{inj} operative range	1.7 T – 3 T
B_{ext} max @ z = 350 mm	3 T
B_{ext} operative range	1.7 T – 3 T
B_{min} @ z = 0 mm	0.4 T
B_{hex} @ R_{CH_IN} = 140 mm	1.6 T
Lhe	Free
Warm Bore radius	150.5 mm
Distance between mirrors	700 mm
Stray field (as above specified)	Less than 0.2 T





Mauro et. Al, Front. Phys., Sec. Nuclear Physics, Volume 10 - 2022

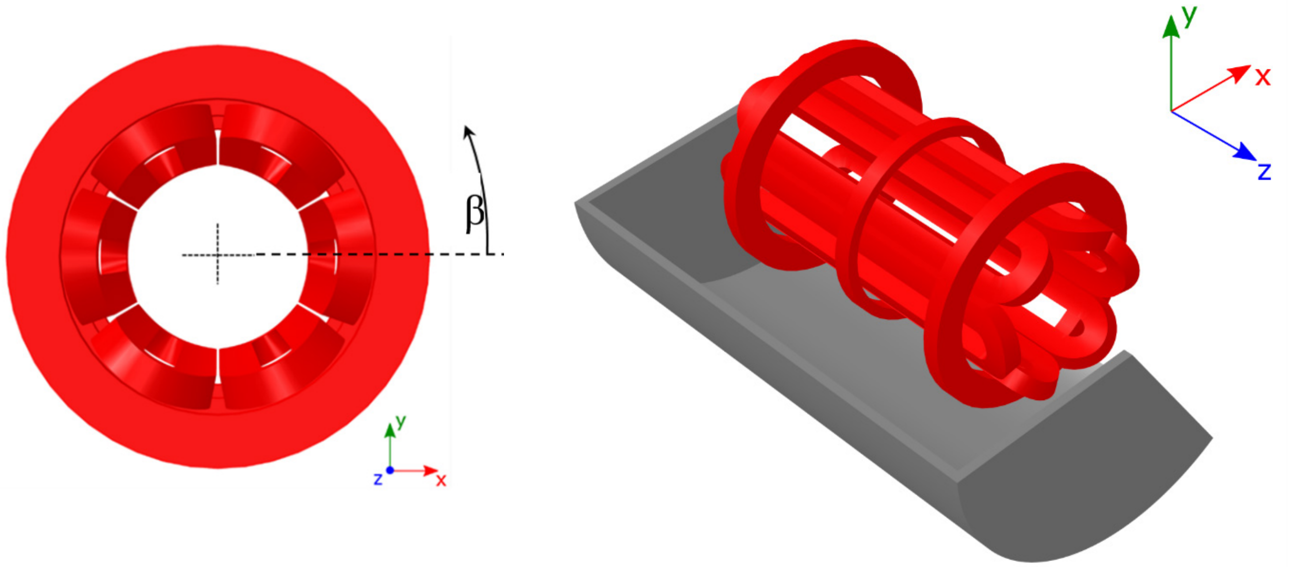
Magnetic system: required performances and geometry

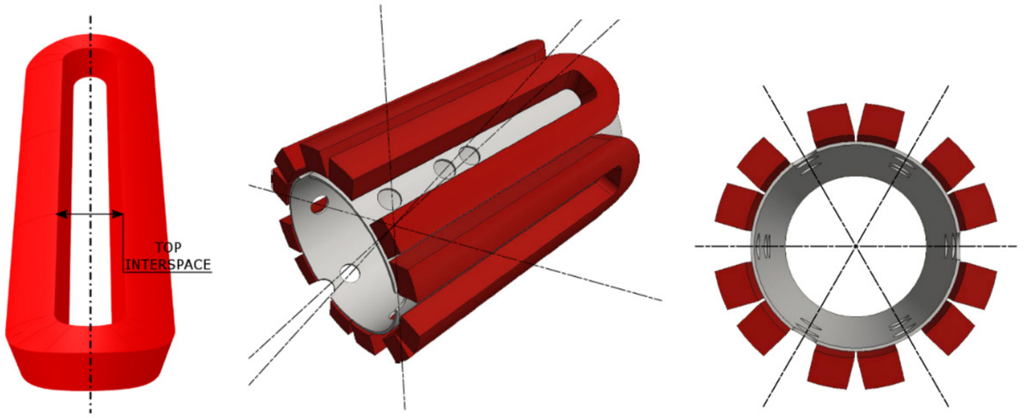
- SEXT-IN-SOL configuration. The hexapole conductors (**racetracks**) will be azimuthally placed, with poles at β = 0, 60, 120, 180, 240, 300-deg.

- **For diagnostics purposes**, it is needed to **keep up to 18 lines of sight between the warm bore radius and the external iron yoke,** through the cryostat and the cold mass.

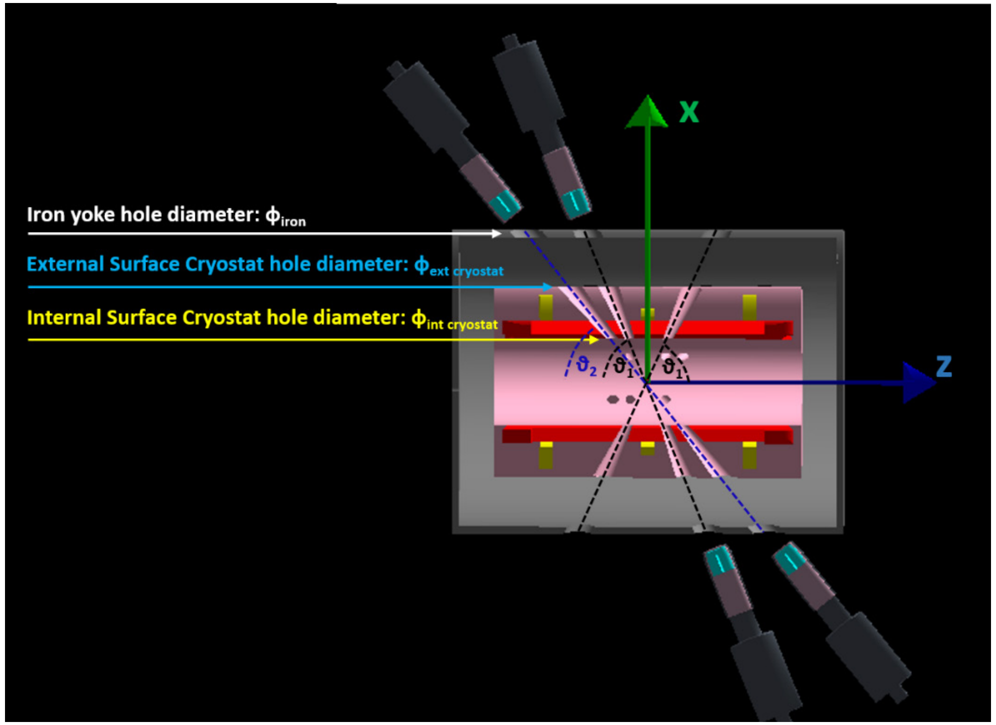
- **Solution**: placing the **holes along the axis of each hexapole conductor**.

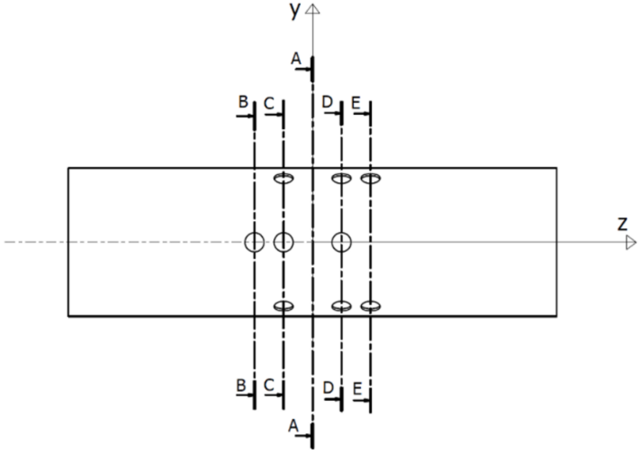
- Each line of sight shall pass through the center of the magnetic system (z=0).

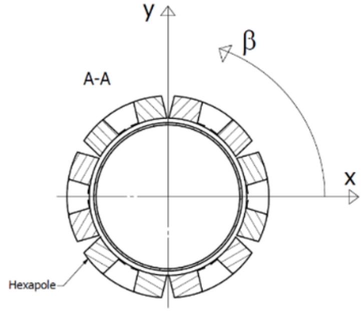




Magnetic system: required performances and geometry







- 18 detectors (12 HPGe) will surround the magnetic system.
- Each triplet of holes has been placed, along the magnetic system axis, in order not to intercept the magnetic branches.
- **The magnetic trap will employ a single, bulk cryostat that will enclose both the three axial coils and the hexapole.**
- The **cryostat plays also the role of multi-collimator** for the HPGe array, **suppressing the sources of background arising from photons coming from the walls** and not directly from the plasma core, thus **improving the signal-to-noise ratio**.

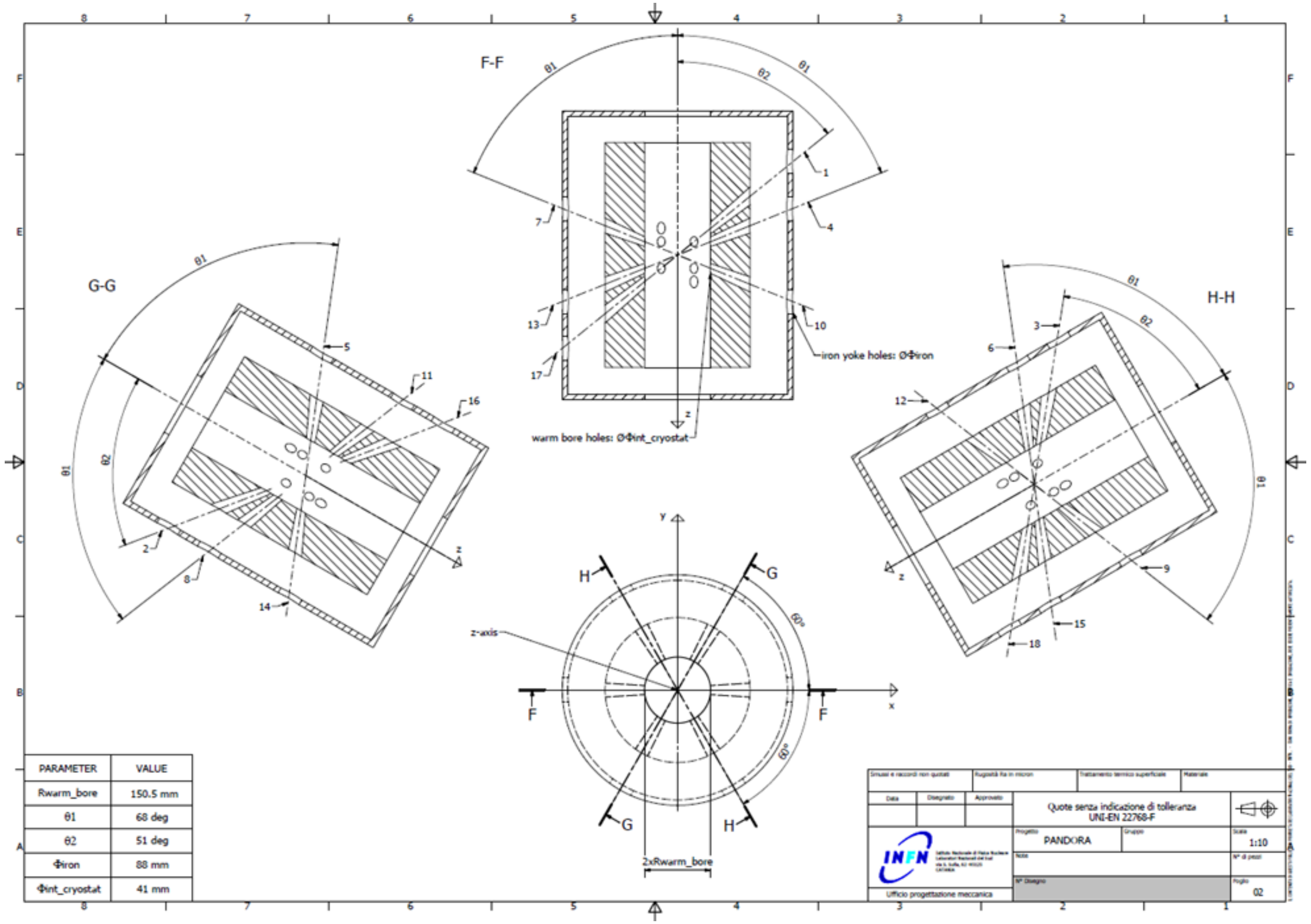
PARAMETER	DESCRIPTION	VALUE	RANGE
Φ_{iron}	Iron yoke holes diameter	88 [mm]	86-90 [mm]
$\Phi_{int\_cryostat}$	Warm bore radius diameter	41 [mm]	40.5-41.5 [mm]
θ_1	1st inclination angle (2 holes)	68 [deg]	67-69 [deg]
θ_2	2nd inclination angle (1 hole)	51 [deg]	50-52 [deg]

Naselli et. al, Front. Phys., Sec. Nuclear Physics, Volume 10 - 2022

See talk *by* D. Mascali

Magnetic system: required performances and geometry

- **A number of detailed magnetic system conceptual drawings have been created**.
- In particular, the actual (simulated) geometries of the cryostat and iron yoke are depicted.
- Conceptual drawings show the detector holes required inclination angles and collinearity along specified magnetic system cut planes.



PARAMETER	VALUE
Rwarm_bore	150.5 mm
θ1	68 deg
θ2	51 deg
Φiron	88 mm
Φint_cryostat	41 mm

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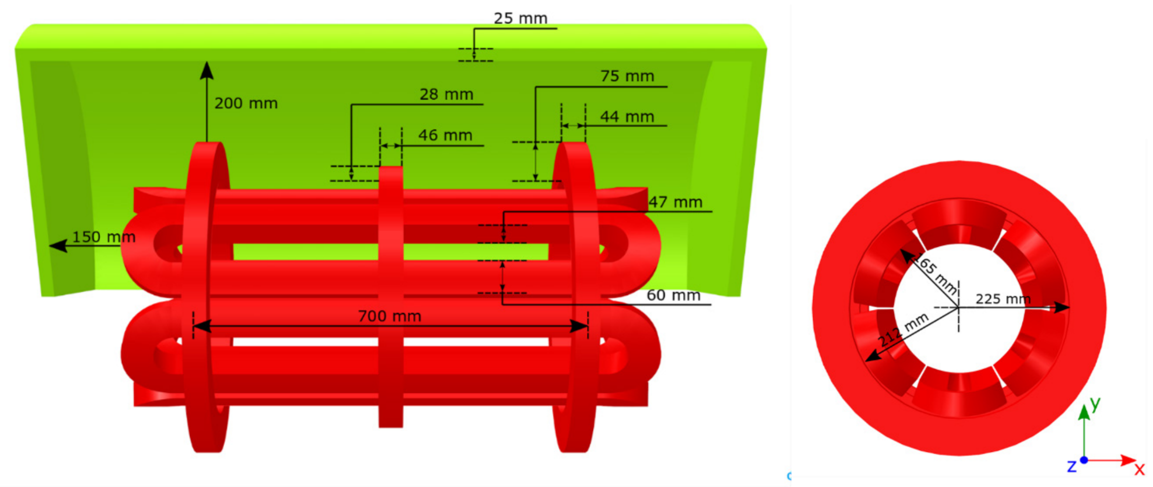
OPERA numerical design and simulation results

- The magnetic system has been simulated with the commercial software OPERA.
- **The geometry and current densities employed for the simulations have been chosen in order to reach the magnetic field profile needed.**
- Two magnetic field profiles have been simulated, named case 1 (18 GHz) and case 2 (21 GHz).

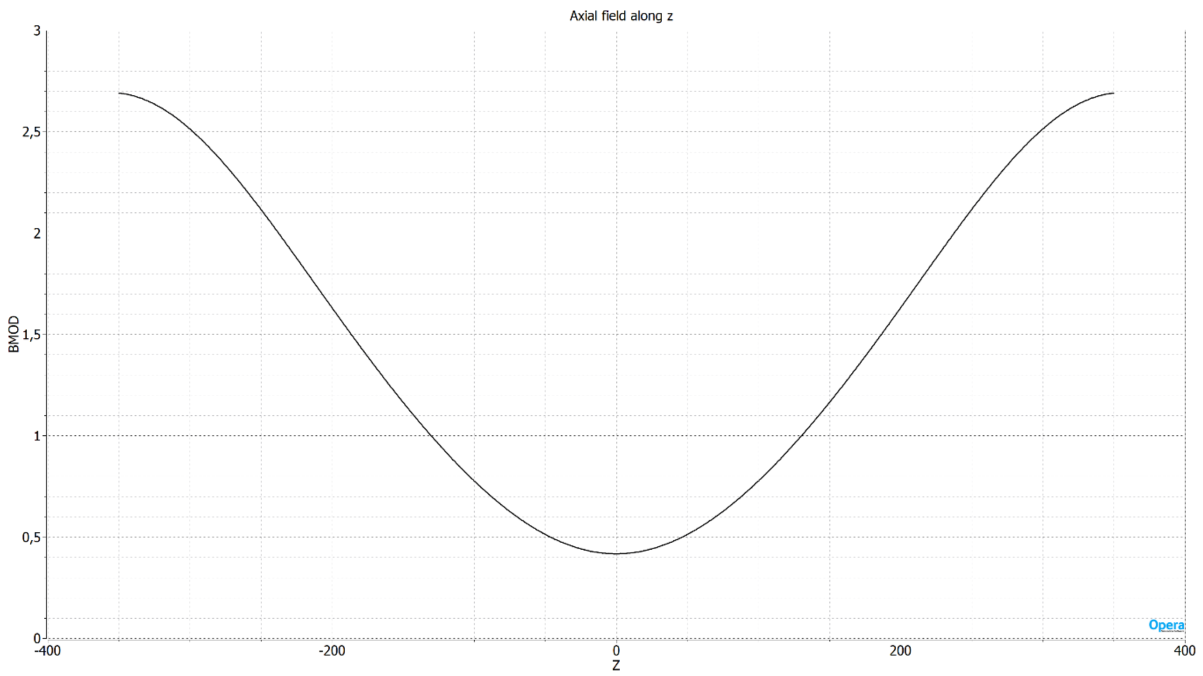
AXIAL COILS	
Coil inner radius (INJ, MED, EXT)	225 / 225 / 225mm
Coil outer radius (INJ, MED, EXT)	300 / 253 / 300 mm
Center of coil (INJ, MED, EXT)	-350 / 0 / 350 mm
Coil width (INJ, MED, EXT)	44 / 46 / 44 mm
HEXAPOLE	
Hexapole inner radius	165 mm
Hexapole outer radius	212 mm

AXIAL COILS	
Case 1 (INJ, MED, EXT)	-330 / 220 / -330 [A/mm^2]
Case 2 (INJ, MED, EXT)	-365 / 235 / -365 [A/mm^2]
HEXAPOLE	
Case 1 and 2	± 95 [A/mm^2]

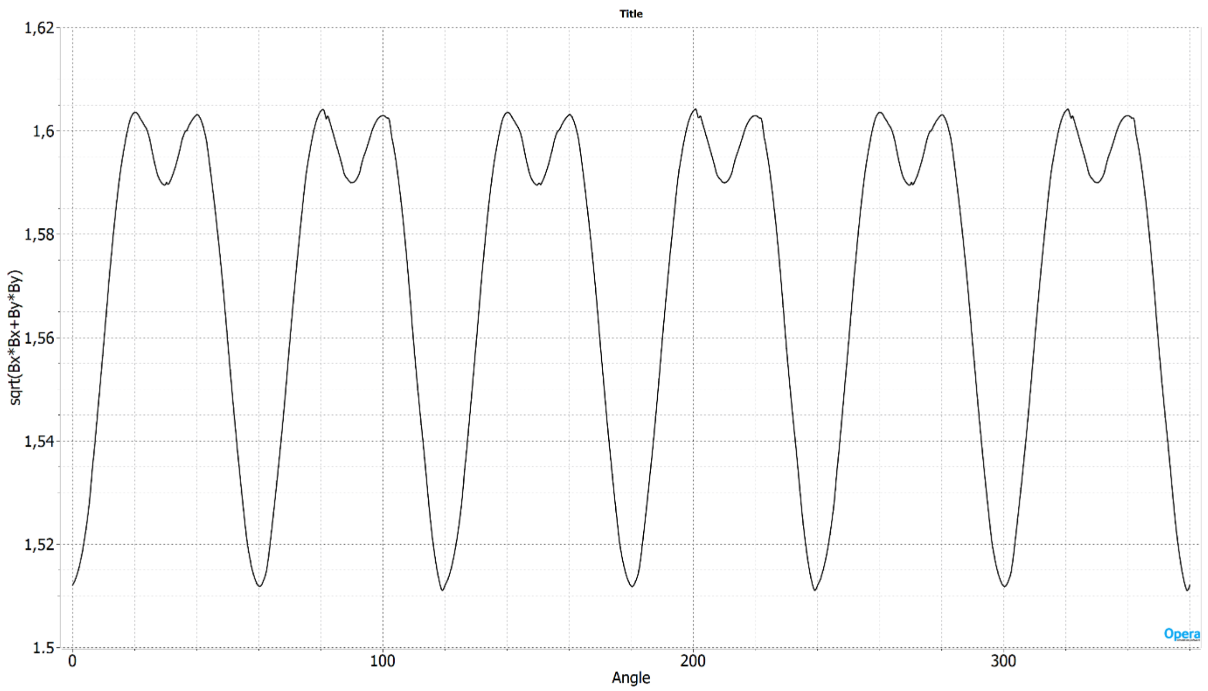


The magnetic trap is surrounded by an ARMCO iron yoke (green object).

OPERA numerical design and simulation results

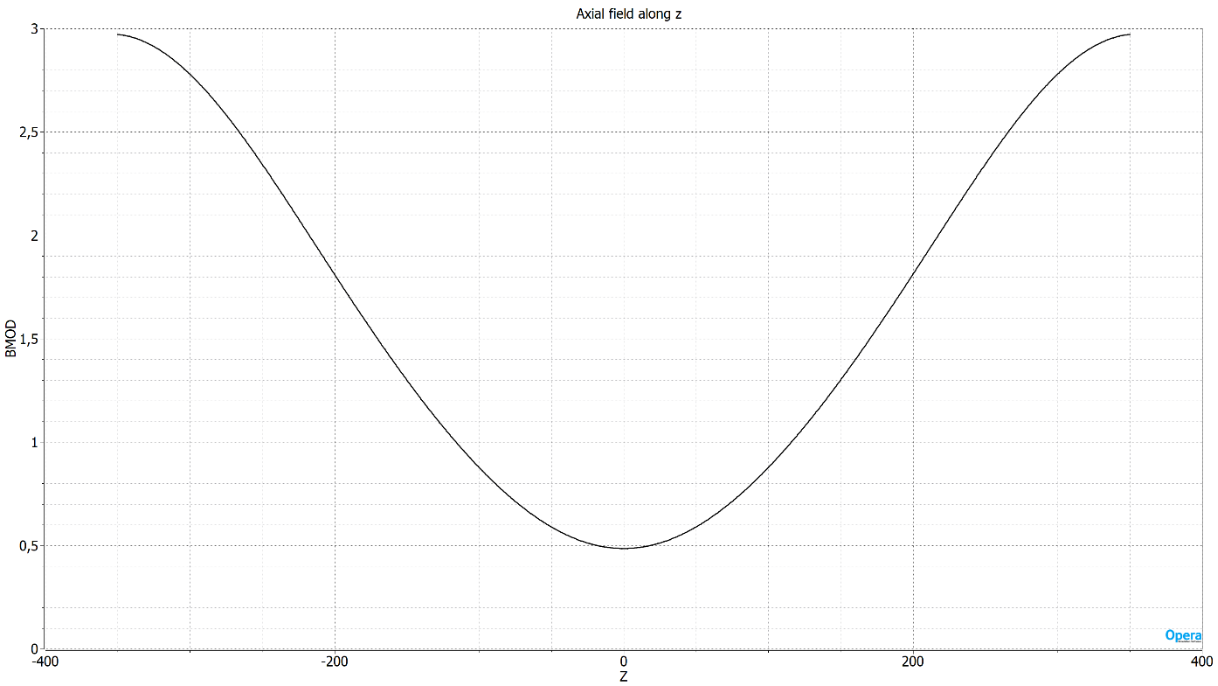


Magnetic field module |B| along plasma chamber z-axis.

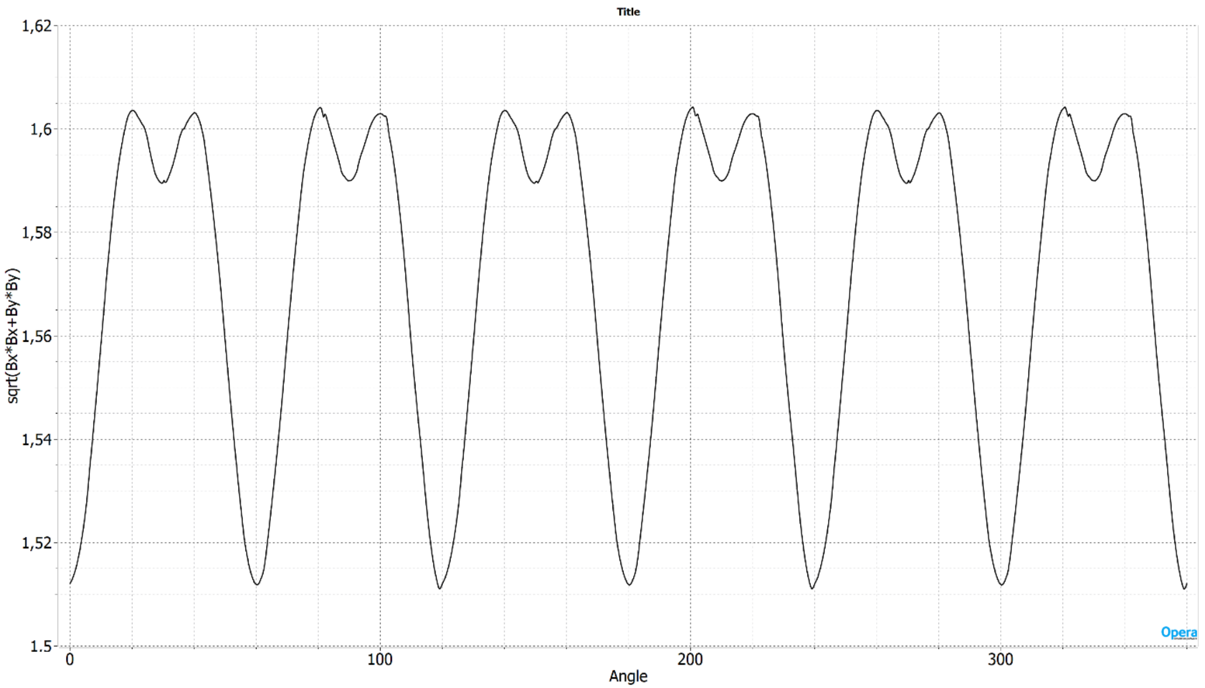


Radial field component module ($|B_{rad}| = \sqrt{B_x^2 + B_y^2}$) of the ***hexapolar stand-alone structure*** *on a circumference of radius R_{CH_IN} = 140 mm (chamber inner radius) and axial position z = 0 mm.*

OPERA numerical design and simulation results



Magnetic field module |B| along plasma chamber z-axis.



Radial field component module ($|B_{rad}| = \sqrt{B_x^2 + B_y^2}$ *) of the* ***hexapolar stand-alone structure*** *on a circumference of radius* R_{CH_IN} *= 140 mm (chamber inner radius) and axial position z = 0 mm.*

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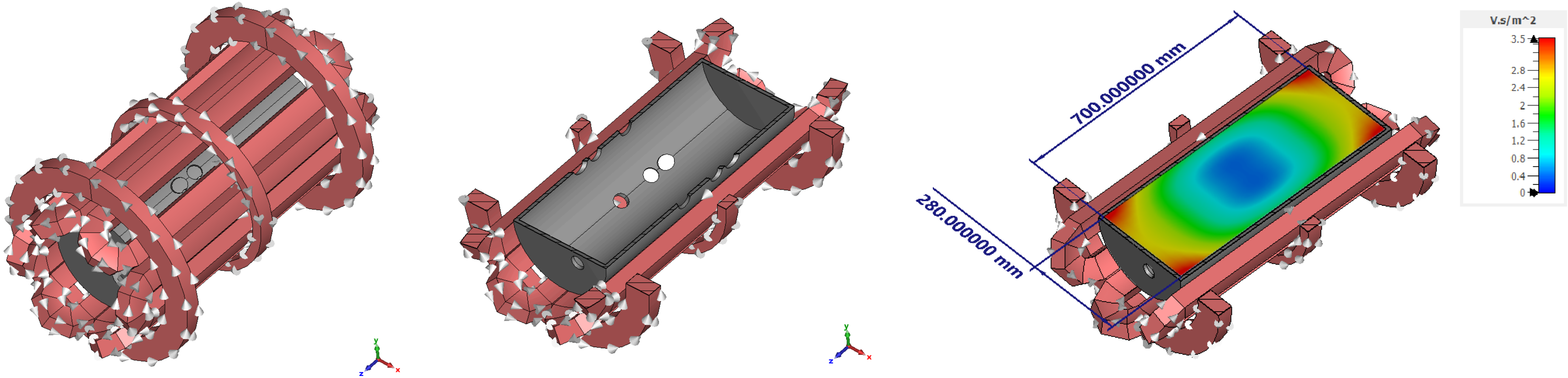
CST Studio Suite validation

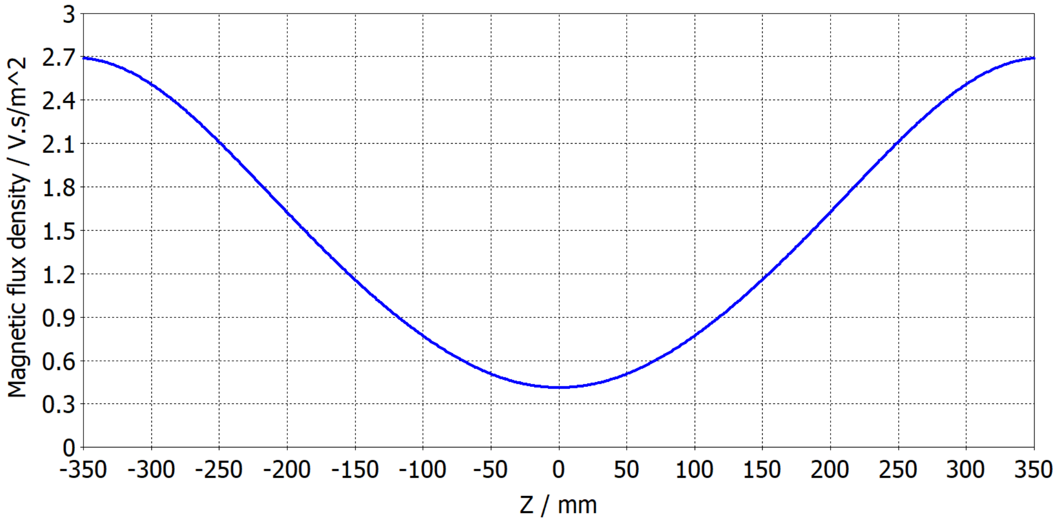
- OPERA magnetic system design validated with **CST Studio Suite** commercial simulator;

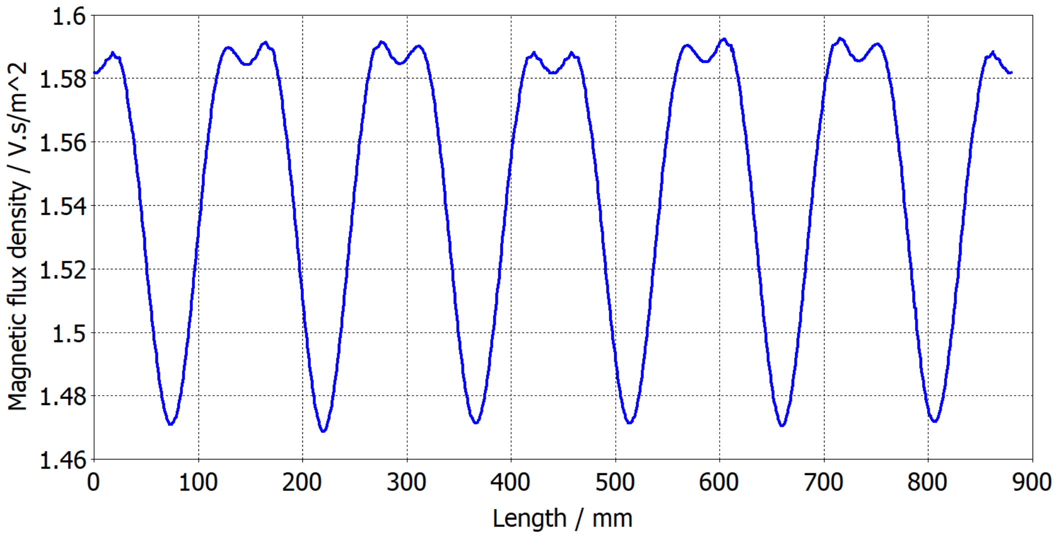
- Identify the **positions of the magnetic branches, where B-field is intense, for the correct gamma ray detectors placement**.

- In fact, in these positions a rather strong Bremsstrahlung radiation generated in the plasma is present due to the intense flux of electrons escaping the magnetic trap.

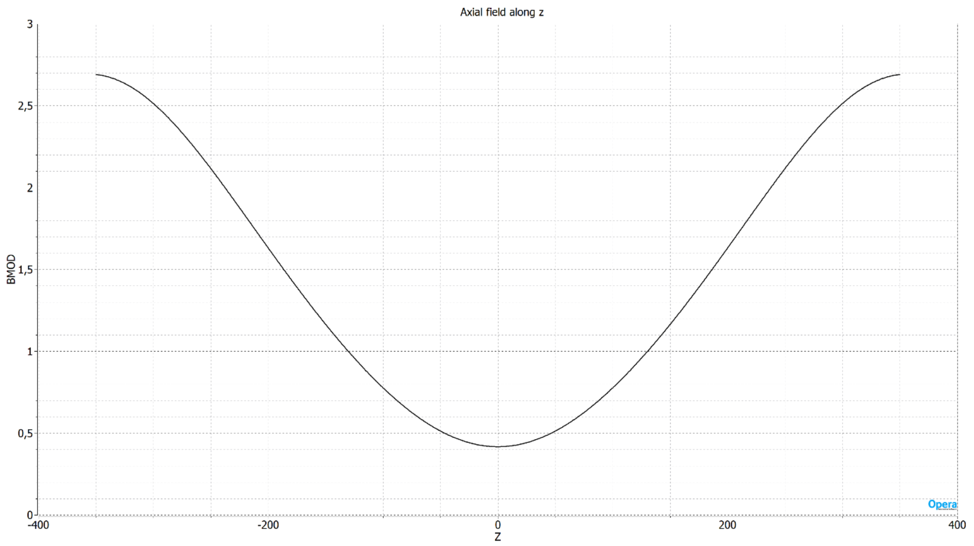


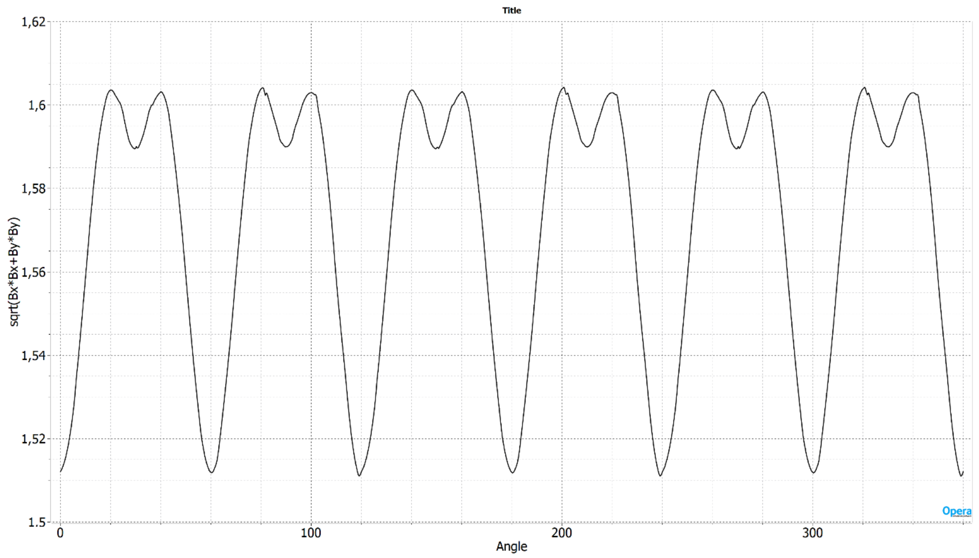
CST Studio Suite validation





Simulation results almost equivalent to those obtained with Opera.

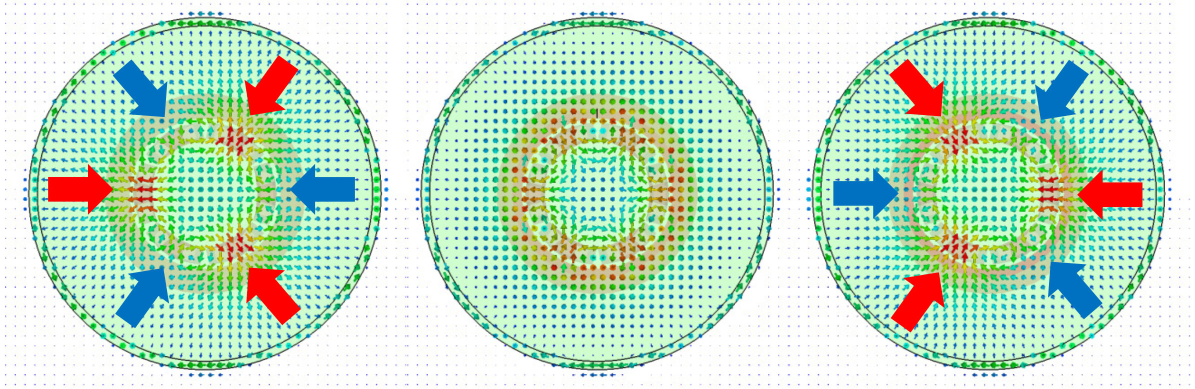




CST Studio Suite validation

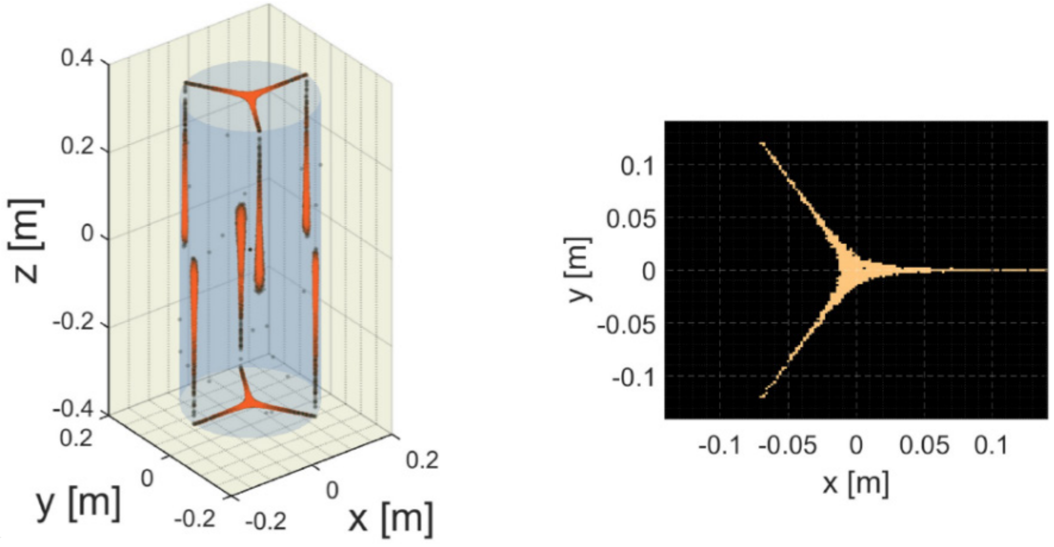
- Numerical simulations have also been performed to **identify the positions of the magnetic branches that need to be avoided** when placing the array of gamma ray detectors.

- **In these positions a rather strong Bremsstrahlung radiation generated on the plasma chamber wall is present** due to the intense flux of electrons escaping the magnetic trap, that decreases the detectors performance.



- The **distribution of lost electrons on chamber walls due to the magnetic branches** has been calculated through the use of a MATLAB particle mover code, using the magnetic field results from simulations.

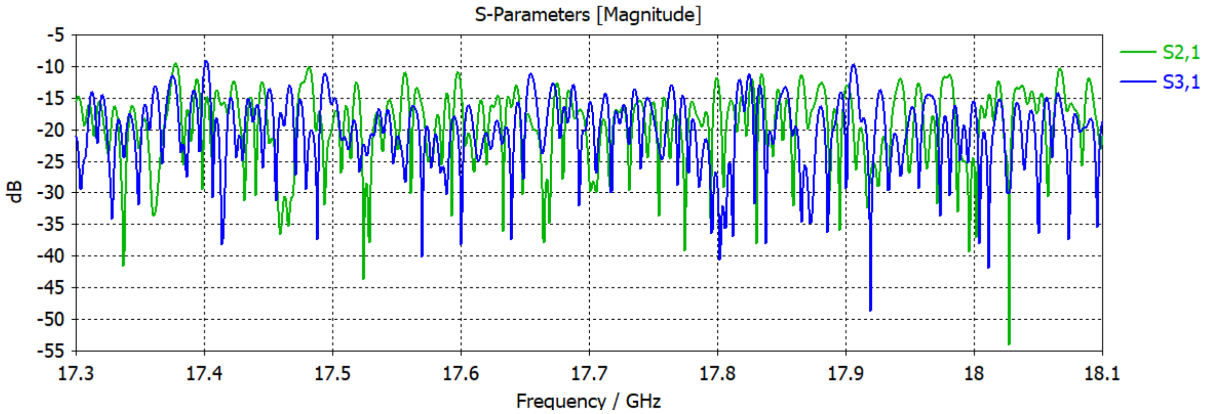
- Informations relevant for: **dimensioning of the bias disk, plasma diagnostics, MW injection waveguides and isotope injection system optimal placement.**

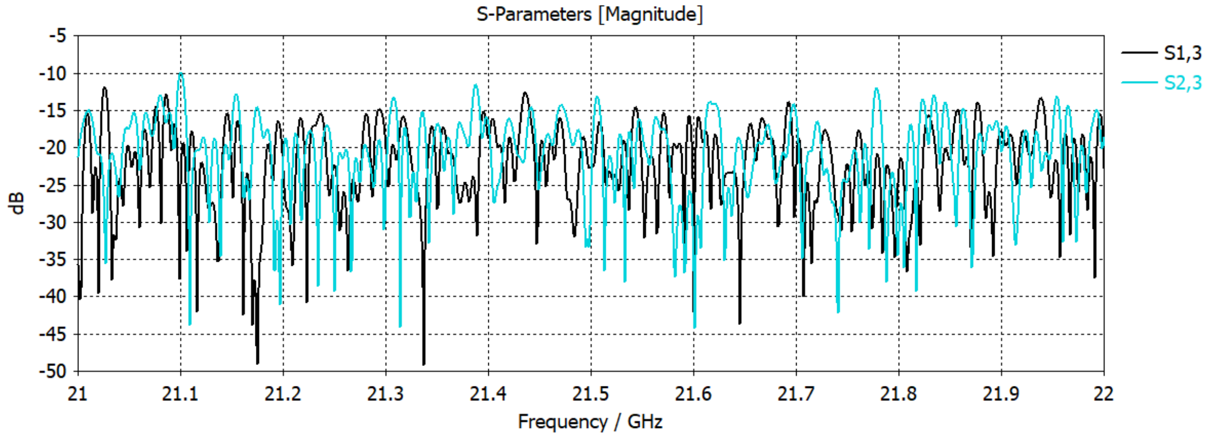


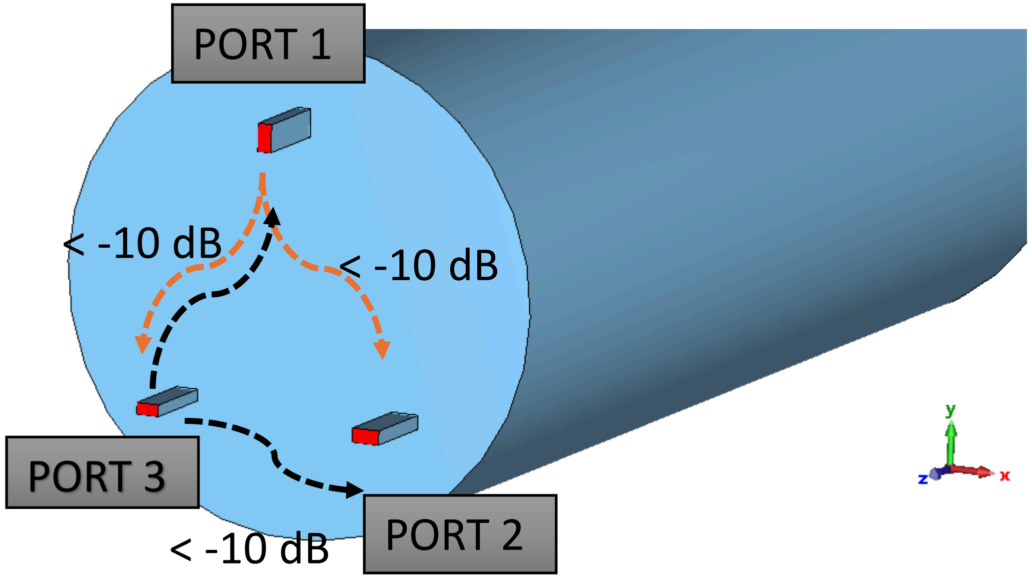
See talk by A. Pidatella

CST Studio Suite validation

The position (**off-axis microwave injection position**) and **reciprocal orientation** angle between the three waveguides ports shall be chosen so that: **power “crosstalk” is minimized.**







Simulated “Transmission”/”**Cross-Coupling coefficient** $S_{2,1}$ $S_{3,1}$, $S_{1,3}$, $S_{2,3}$ < -10 dB

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Magnetic system procurement status

- The **procurement strategy** was **discussed and elaborated with the PANDORA collaboration group**.

- The magnetic system is a complex component of the project, whose technical specifications could change during the realization.

- It has been decided that the **most proficient way to obtain the magnetic system design is to adopt a *competitive dialogue* procedure between the partecipating companies**.

- The procedure consisted of a **continous exchange of informations between the suppliers and INFN**, that allowed the latter to chose the best solution the market had to offer.

Total magnetic system cost: about 1.6M€

DocID	Rev.	Validità
INFN-CSN3-QA -PANDORA_Gr3-300.00	5.9	Final

ANNEX A - DoR Magnetic System

Technical requirements for the

PANDORA_Gr3 MAGNETIC SYSTEM

Prepared by	*Checked by*	*Approved by*
G. S. Mauro	L. Celona	L. Celona
G. Torrisi	D. Mascali	D. Mascali
E. Naselli	D. Santonocito	D. Santonocito
F. Russo	M. S. Musumeci	M. S. Musumeci
V. Bonanno		

Magnetic system procurement status

The procurement procedure consisted of **three phases**:

1. Pre-qualification: the Contracting Authority (INFN-LNS) publish the DoR, the Evaluation Criteria and the Pre-qualifications requirements. The suppliers able to accomplish the pre-qualification requirements partecipated at the Competitive Dialogue.

2. Competitive dialogue: the selected suppliers elaborated their proposal (Technical Documentation) basing on the DoR. During this phase, the best technical solutions were identified (**two companies emerged from the procedure**).

3. Tender Phase: the Contracting Authority putted on to tender the best technical solutions emerged in the previous phase.

- **The tender has been finalized in June 2024.**

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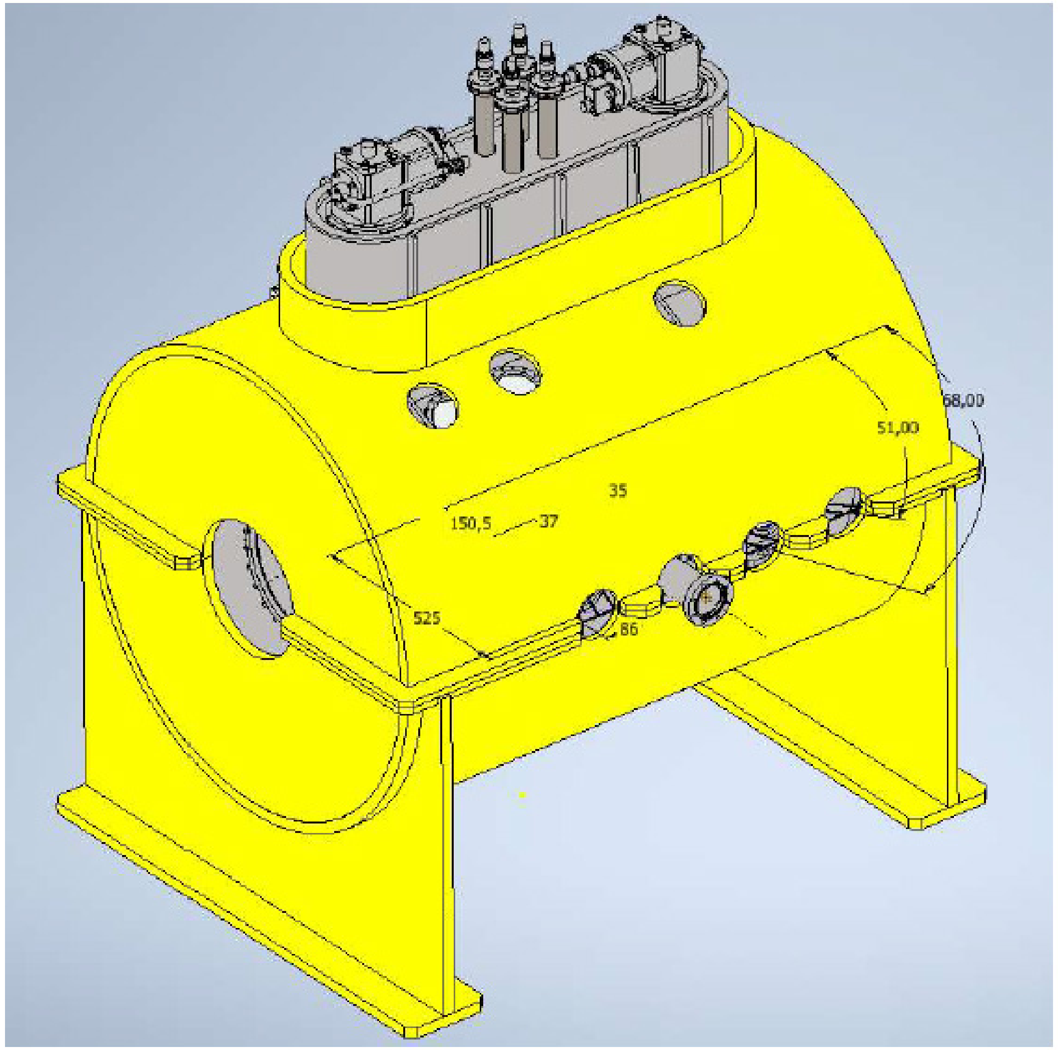
Technical design from the first ranked company

- **A magnetic trap layout has been developed by the first ranked company, reproducing the magnetic field of the specification.**

- Because of the combination of high field and current on the injection solenoids, a standard Western Superconducting **Nb3Sn/bronze** wire has been selected.

- Solenoids have been arranged so that they could be supplied with the same current. A current of 186.4 A will circulate in the solenoids, while a current of 108 A will circulate in the hexapoles.

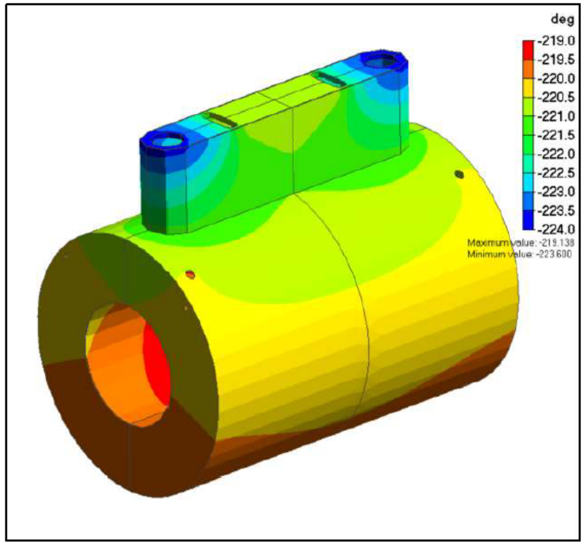
NOTE: full layout structural analysis is in progress.

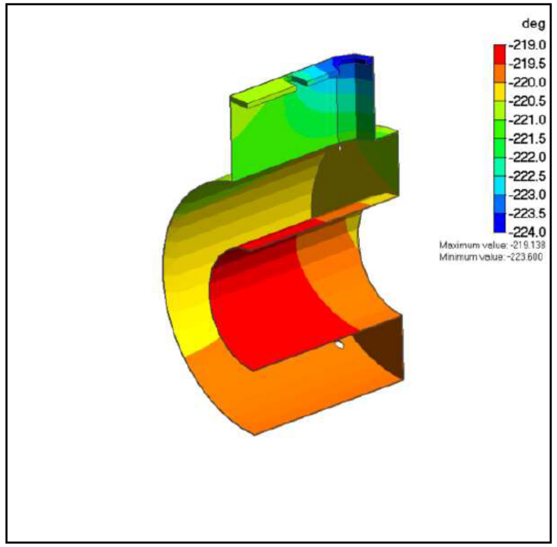


Technical design from the first ranked company

- Finite element simulations have been done to assess the soundness of the **thermal design** and check that temperature distributions are consistent with the correct operation of the magnet.
- Shield walls and central bore have been considered as made out of aluminium alloy.

- **Heat loads have been set on a simplified model of the thermal shield**, where a 15 mm thick OFHC plate is connected to a 3 mm-thick aluminum shield.
- Interfaces of the cryocoolers with the top OFHC plate have been set to 48.4 K (-224.6°C).
- Temperature on the top plate, where the heat leak from the current leads is directed, is around 51 K (-222°C).
- **The calculated temperature distribution evidences a temperature gradient of 5 K, with a peak of 54 K (-219°C) that is compatible with the maximum (64 K) allowed by the CryoSaver Current Leads.**





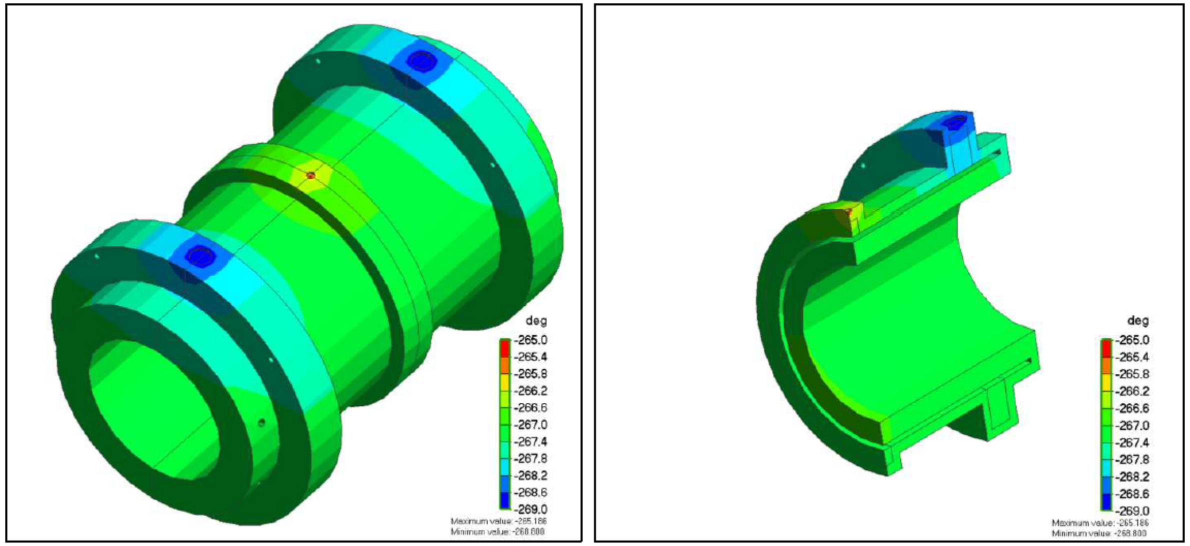
Thermal shield temperature distribution

Technical design from the first ranked company

- Inner cylinder has been considered as a full aluminum element, while the solenoid coils have been assumed as made out of an isotropic material with a thermal conductivity of 3 W/m K @ 4.2 K.

- Interface with the 2nd stage crycoolers cold finger has been set to -268.8°C (4.2K), while the input coming from solenoid current leads has been applied at the center of the magnet.

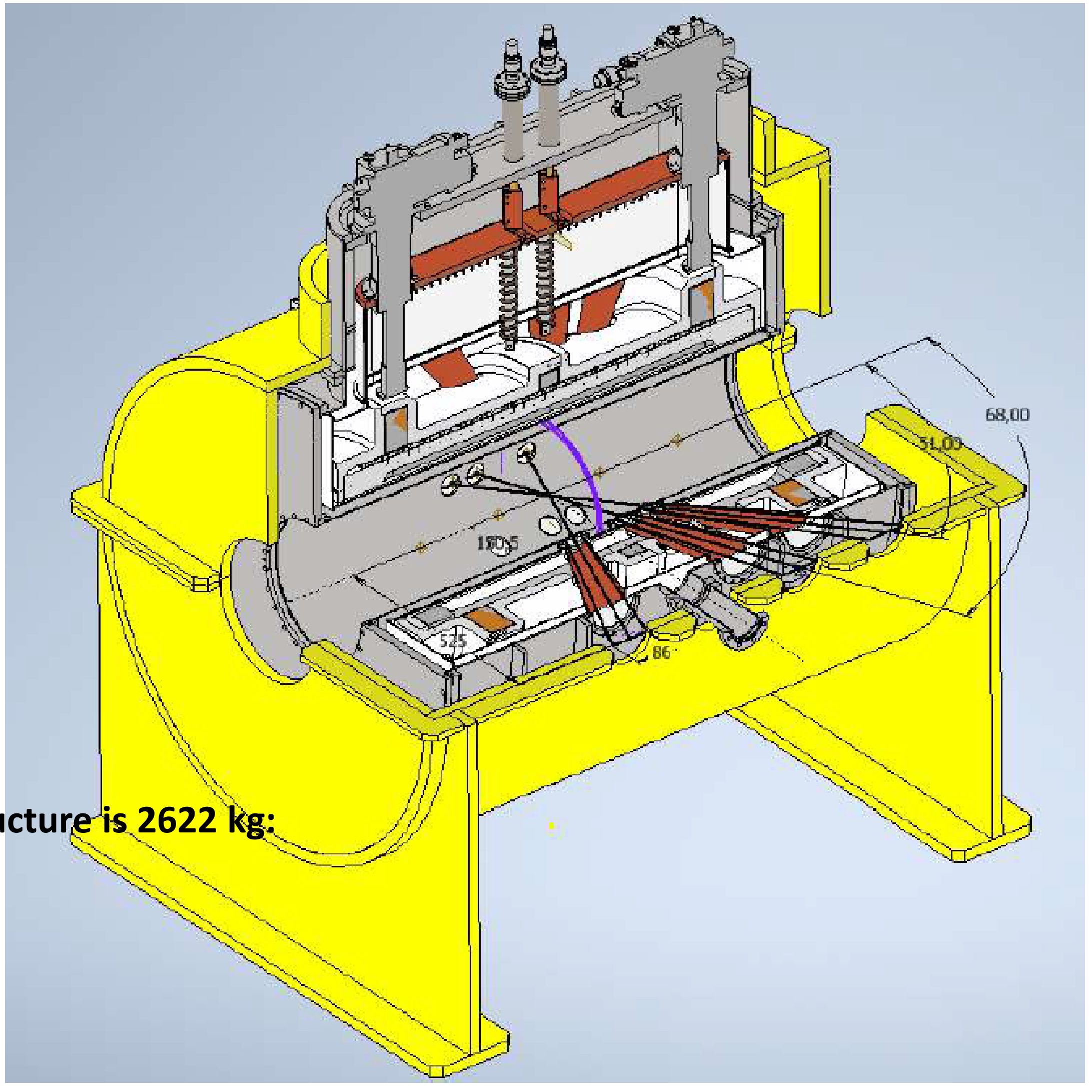
- **Results indicate a reasonable operating temperature peak below 7 K on the central solenoid and below 6 K on the injection solenoids.**

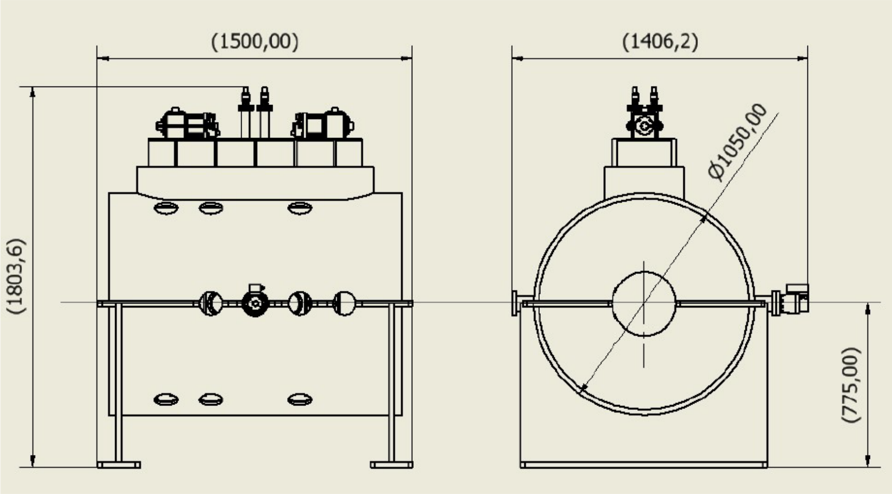


Cold mass temperature distribution

Technical design from the first ranked company

- The general arrangement of the magnet features a cold mass vacuum-isolated inside a cryostat that, on its turn, is housed inside a magnetic yoke.
- The magnet will be equipped with 4 current leads: a couple to bring current to the solenoids, another couple to bring the current to the hexapoles.
- Cryocoolers are vertically arranged, in a service turret positioned on top of the vacuum vessel, that houses also the current leads.





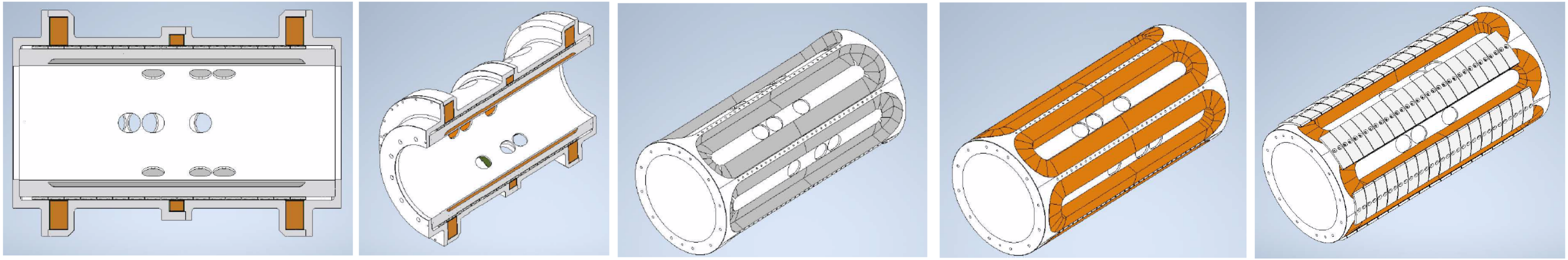
Estimate mass of the full structure is 2622 kg:
- **Magnetic yoke: 1457 kg;**
- **Cryostat: 441 kg;**
- **Thermal shield: 68 kg;**
- **Cold mass: 586 kg;**
- **Cryocoolers: 70 kg.**

Technical design from the first ranked company

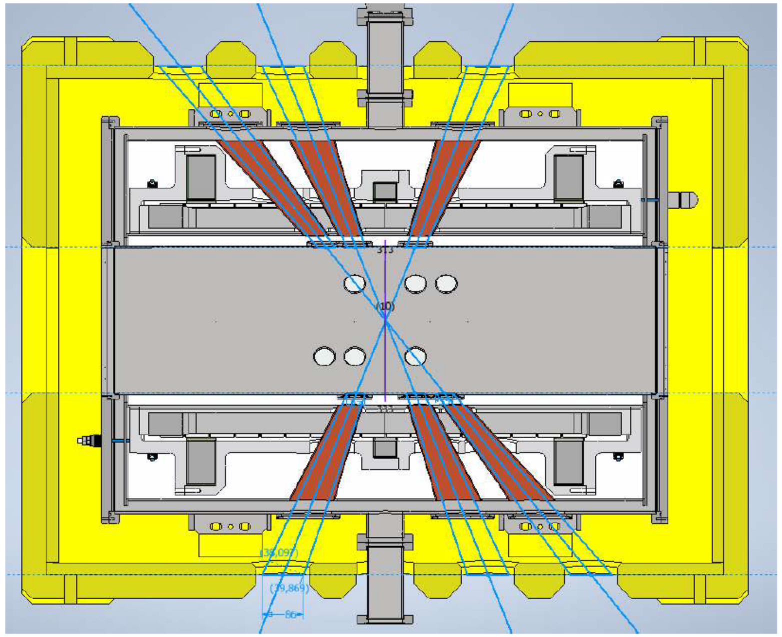
- Coils are housed in a mechanical structure made of several components machined out of forged aluminium alloy cylinders.

- Hexapoles are housed in appropriate recesses machined on the central cylinder, where they are finally embedded.

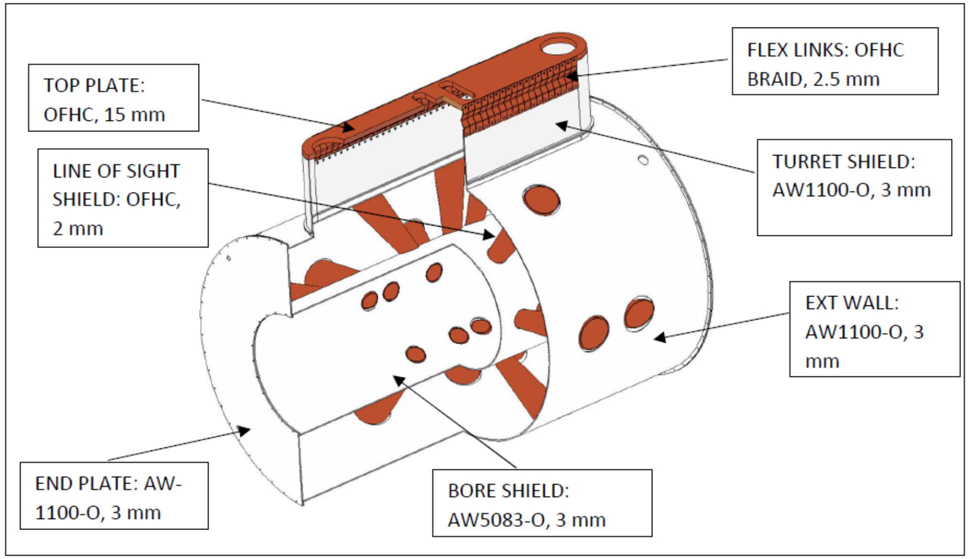
- Hexapoles are kept in position against radial forces by means of brackets.



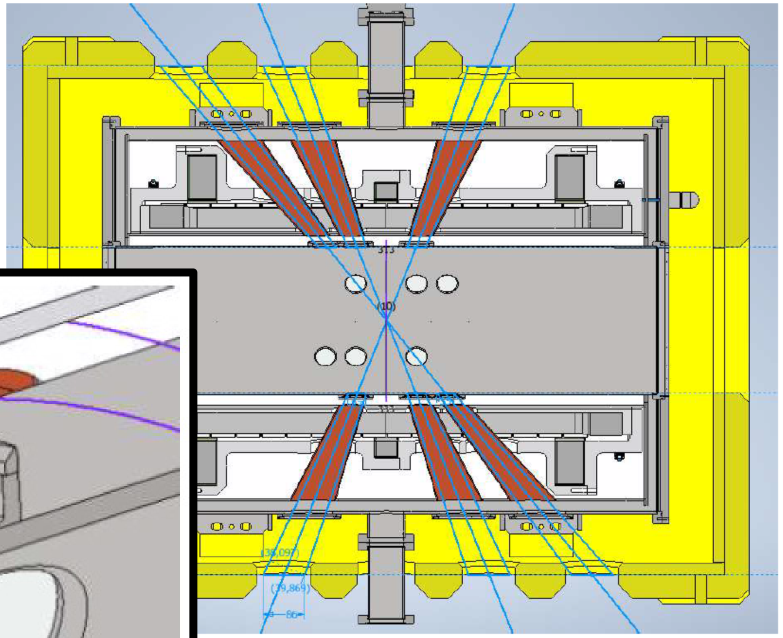
Technical design from the first ranked company



- **Detailed Geant4 simulations have been performed at INFN-LNS to obtain the optimal dimensions of the cryostat tapered holes that will act as collimators for the HPGe detectors.**
- The arrangement of the 18 lines of sight as required in the technical specification showed to be rather challenging.
- Most of the difficulties are concentrated at the level of the vacuum vessel warm bore, where windows will be clamped against it by means of a screwed frame.
- **Copper conical shielding elements** will be employed around the lines of sight to protect the cold mass against radiation from the quartz/aluminum windows.
- **The design requires rather accurate manufacturing and assembling.**



Technical design from the first ranked company



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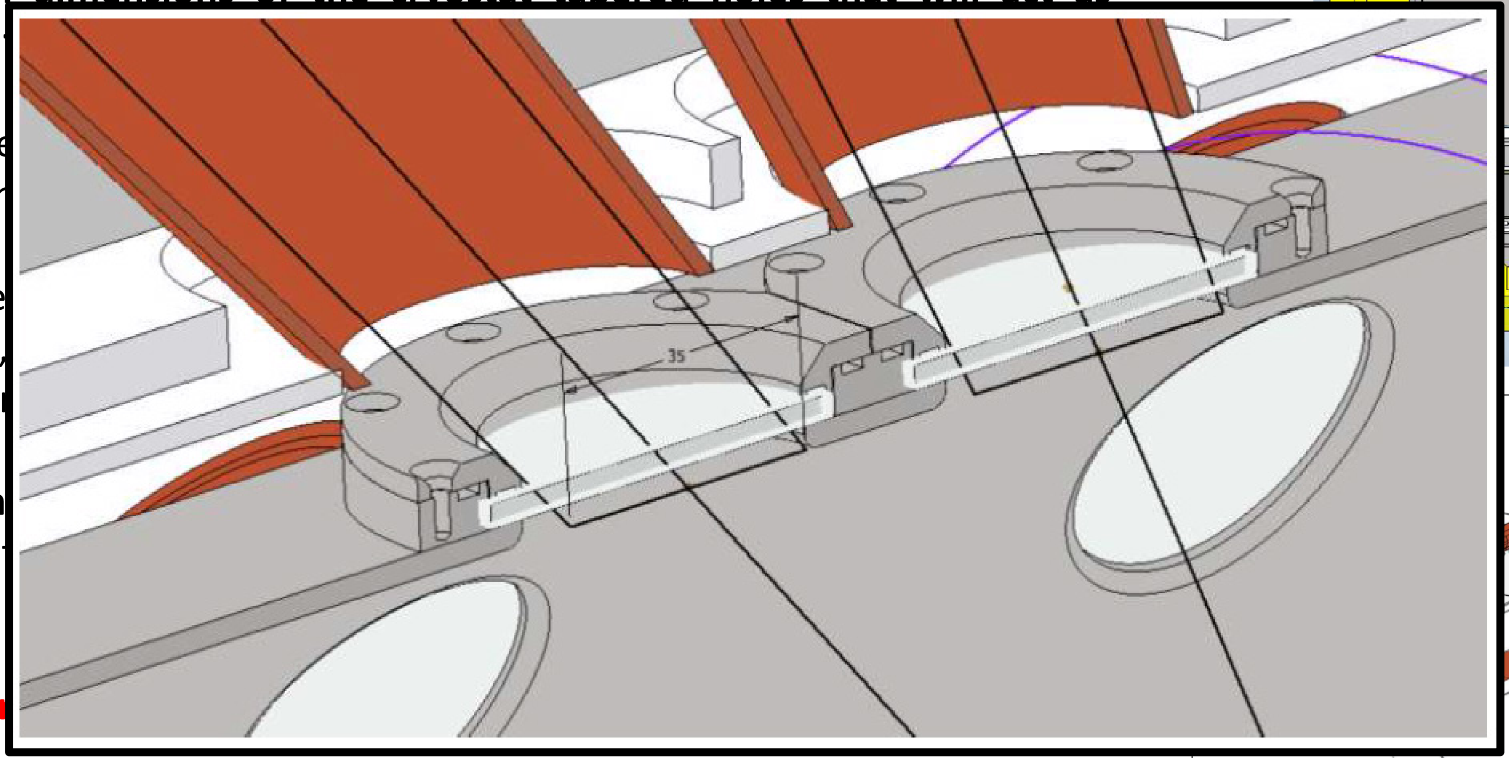
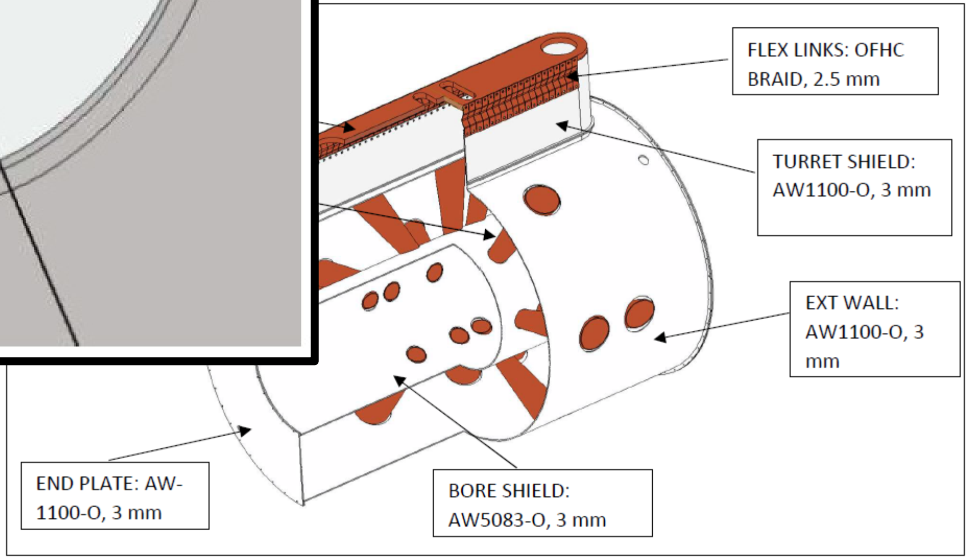
- **The design**





Outline

- Introduction
- Magnetic system: required performances and geometry
- OPERA numerical design and simulation results
- CST Studio Suite validation
- Magnetic system procurement status
- Technical design from first ranked company
- **Conclusion and perspectives**

Conclusion and perspectives

- PANDORA magnetic trap will operate at the frequencies of 18 and 21 GHz.
- According to these operating frequencies, a minimum-B magnetic system design has been carried out.
- The PANDORA magnetic system has then been validated with commercial simulation softwares OPERA and CST, showing excellent agreement with each other in terms of field profiles.
- A detailed Document of Requirements, containing all the magnetic field and geometry requirements and specifications, has been compiled.
- Tender procedure for the PANDORA magnetic system ended in June 2024.

➢ **First studies and mechanical drawings from the first ranked company are available. A detailed interaction between supplier and INFN will begin during next months.**

Numerical Design of an Innovative Superconducting Magnetic Trap for Probing β-decay in ECR Plasmas

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On behalf of the PANDORA collaboration

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Thank you!