Study of the magnets used in a mobile isocenter gantry

ESR

Jhonnatan Osorio Moreno

Supervisor

Marco Pullia

fondazioneCNAO

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General overview

1. Introduction
2. Why a mobile isocenter gantry
3. Magnetic line for a mobile isocenter gantry
4. Conclusions

Introduction

The aim of the WP21 was to participate in the research line already pursued at CNAO concerning the carbon ion gantry design

It means to work *together* with the *ULICE* WP-6 researchers

in *developing a conceptual design of a carbon ion gantry*

ULICE
Union of Light Ion Centres in Europe

PARTNER
Particle Training Network for European Radiotherapy

The job was distributed in:

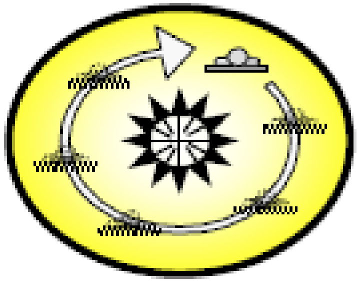
PARTNER
Particle Training Network for European Radiotherapy

+

ULICE
Union of Light Ion Centres in Europe

=

Mobile isocenter gantry



WP-21

WP-6

- **Magnet simulations**

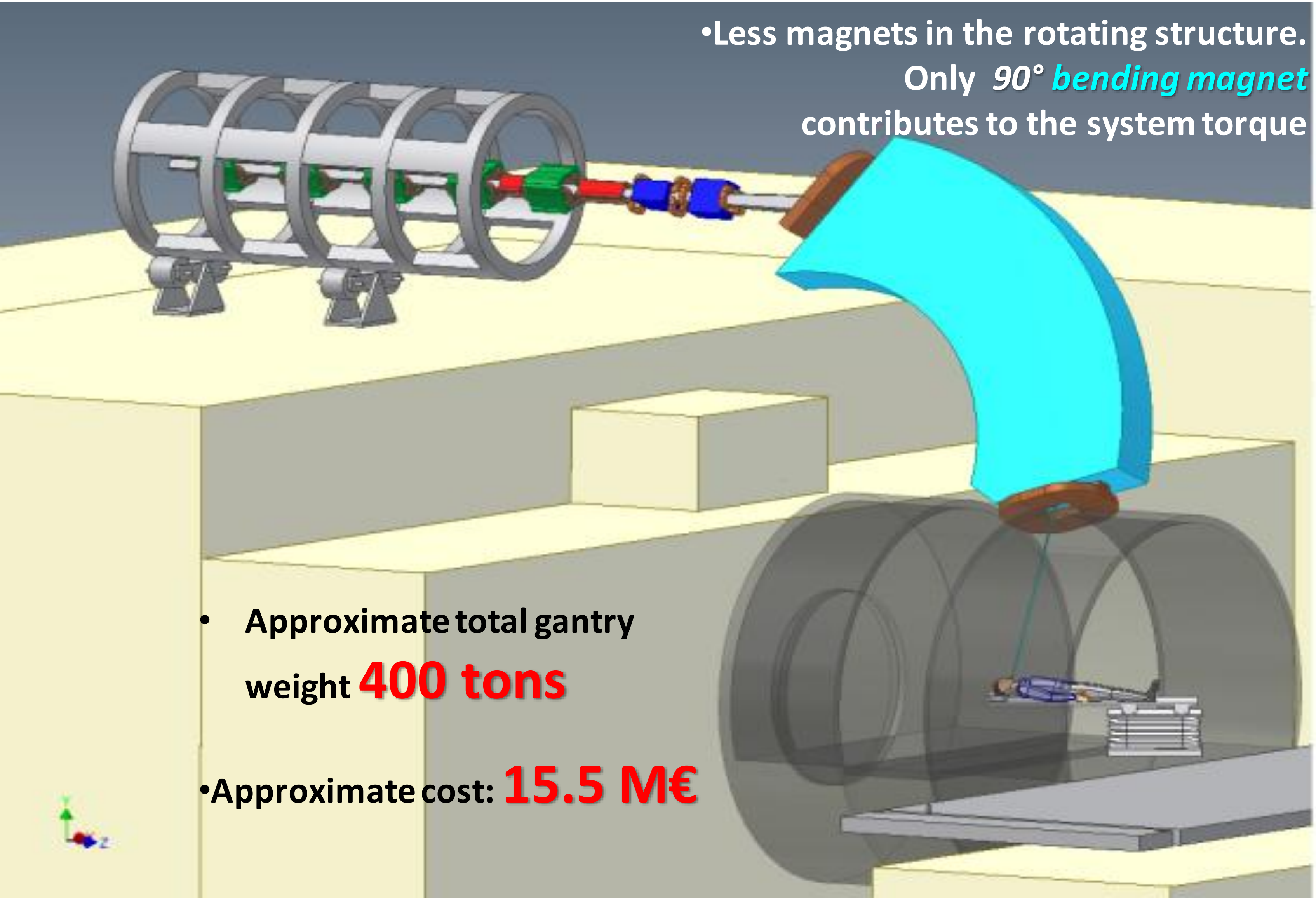
+

- **Beam line simulations (beam optics)**
- **Shielding aspects**
- **Mechanical structure**
- **....**

= **Conceptual design**

Why a mobile isocenter gantry

The layout shows:



- Less magnets in the rotating structure. Only *90° **bending magnet*** contributes to the system torque

- **Approximate total gantry weight 400 tons**

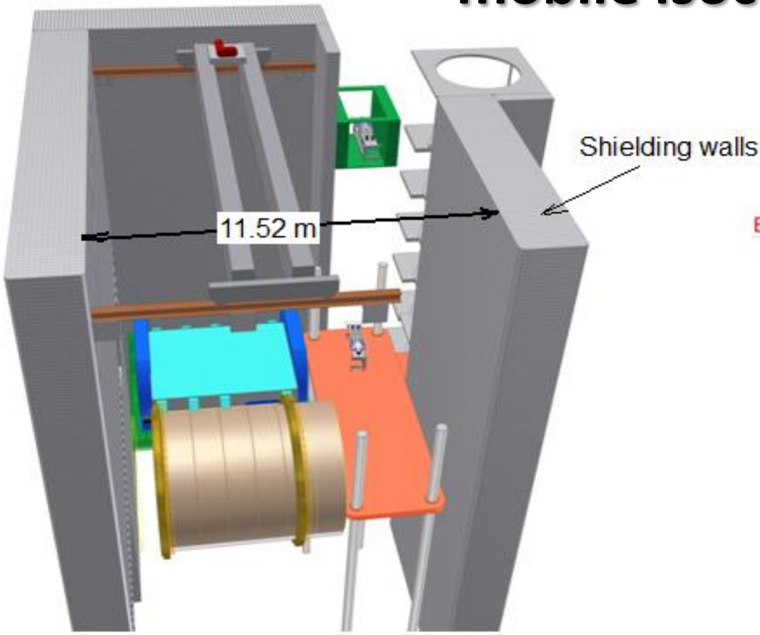
- **Approximate cost: 15.5 M€**

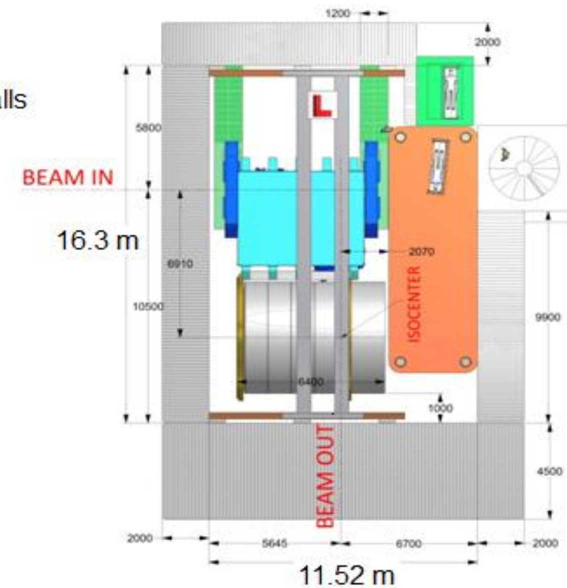
90° bending magnet

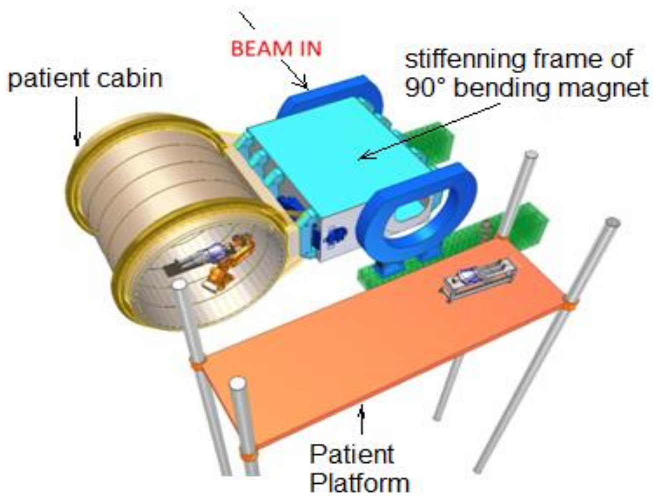
Quadrupoles

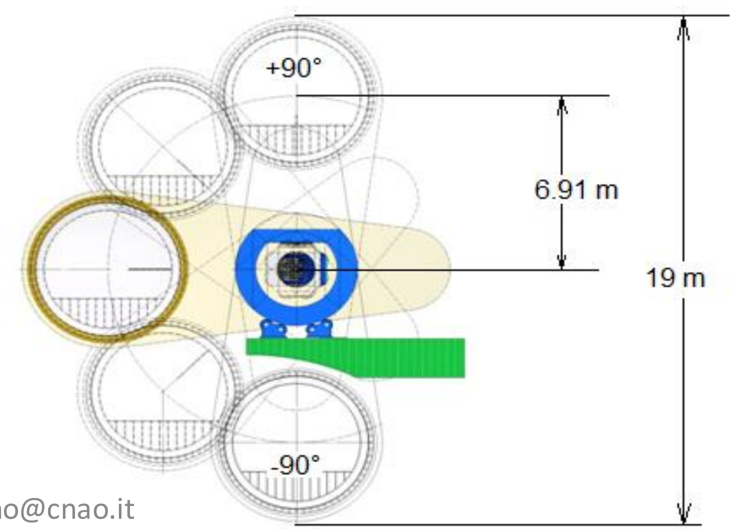
Corrector magnets

Preliminary conceptual layout for a mobile isocenter gantry



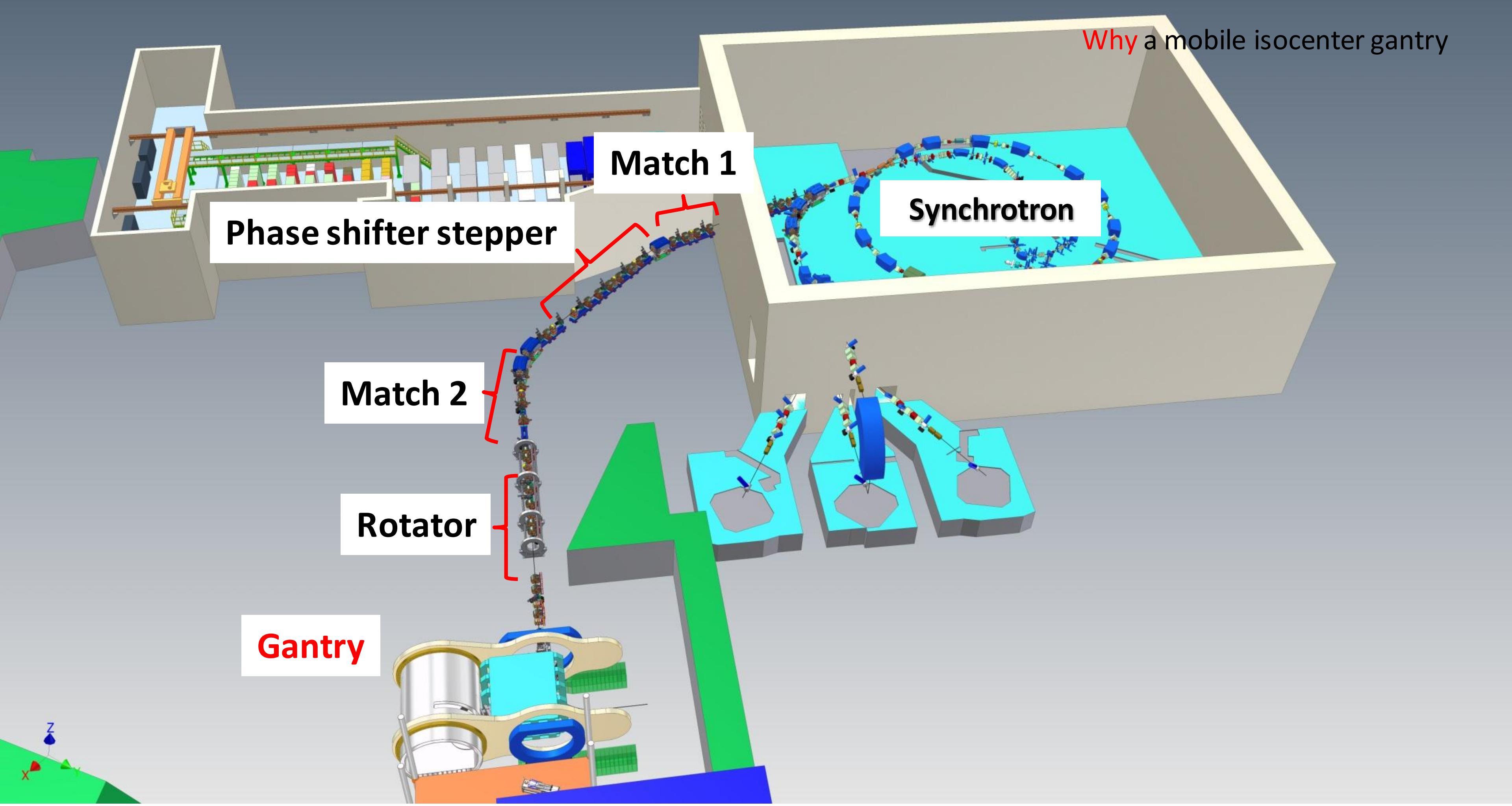






jhonnatan.moreno@cnao.it

Why a mobile isocenter gantry



Synchrotron
- particle Beam source
- Initial beam conditions

→

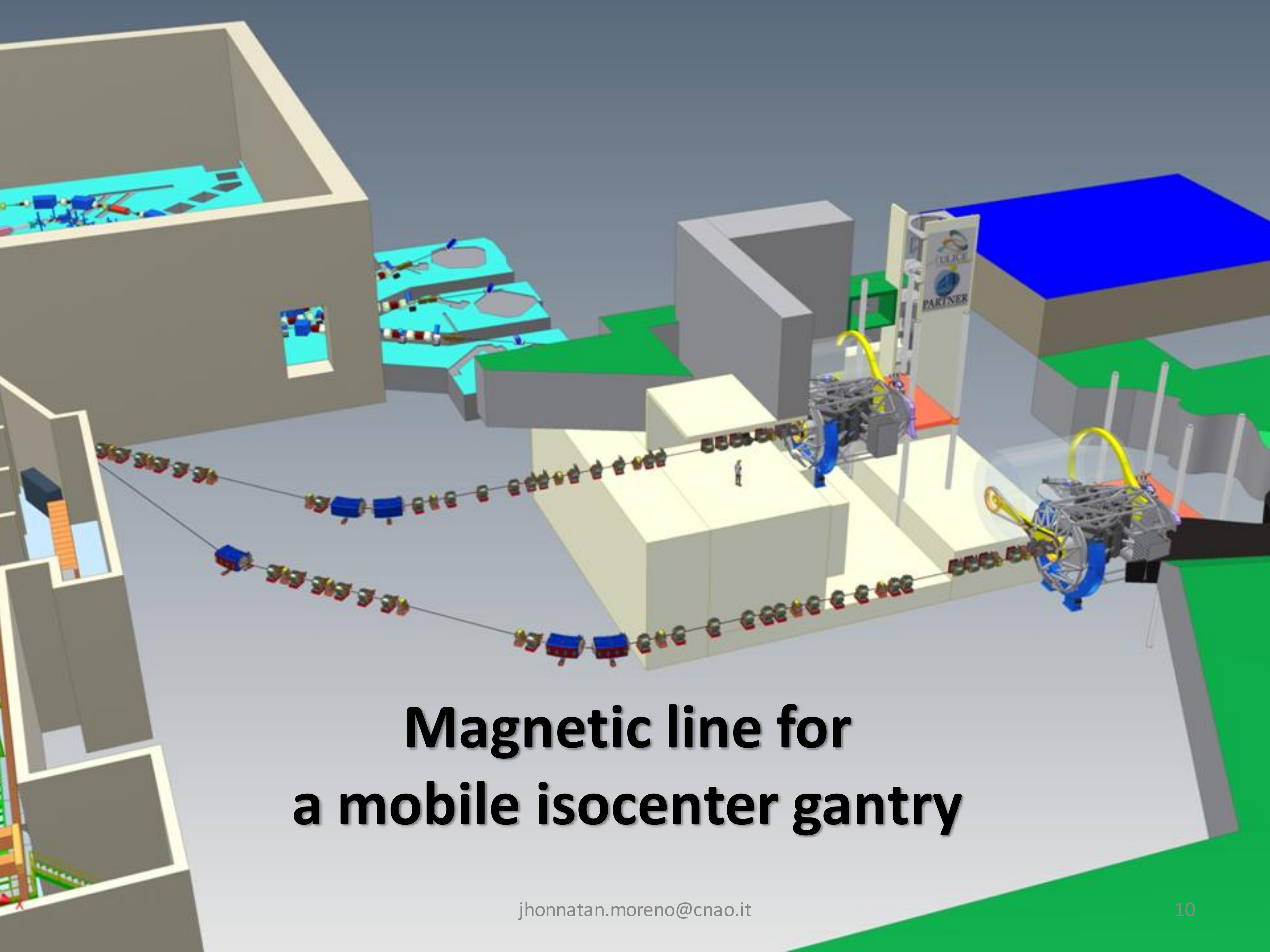
Match
- Adjust the beam parameters to the following elemets

→

Phase shifter stepper
- Adjust the beam dimensions at the isocenter

→

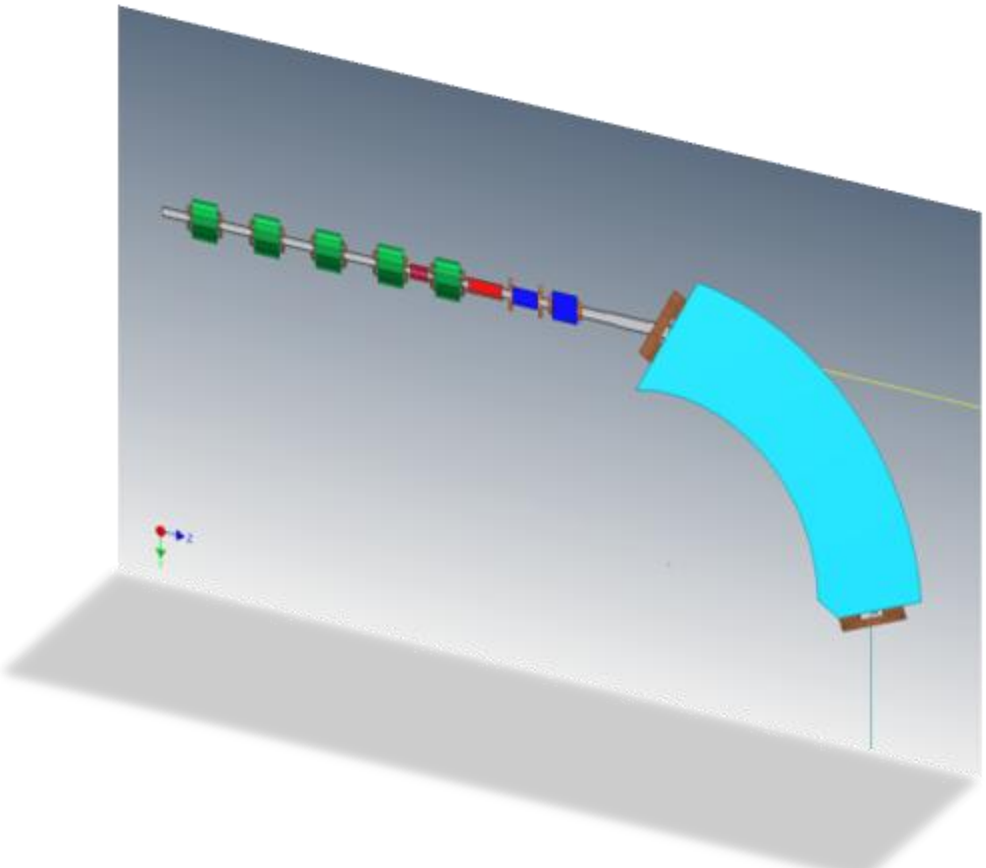
Telescope
- Final Match
- Rotator
- Gantry



Magnetic line for a mobile isocenter gantry

Development of technical aspects of magnets

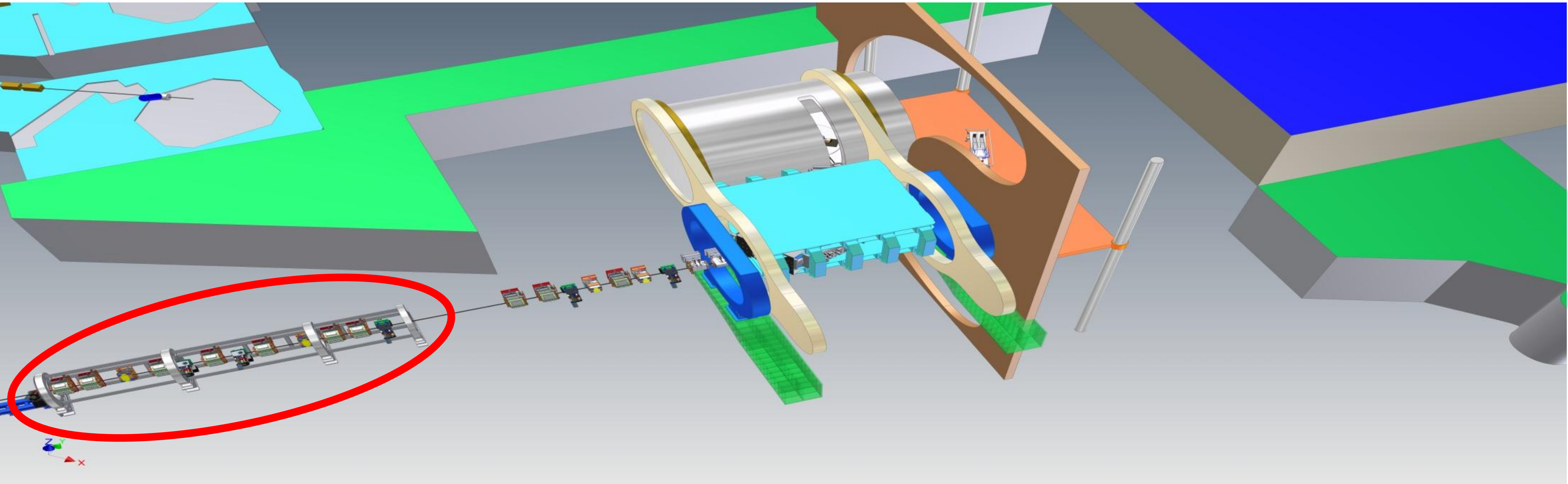
to be used in the conceptual gantry design



These magnets are:

- **Bending dipole ($\pi/8$)**
- **90° last bending magnet**
- **Quadrupoles**
- **Correctors**

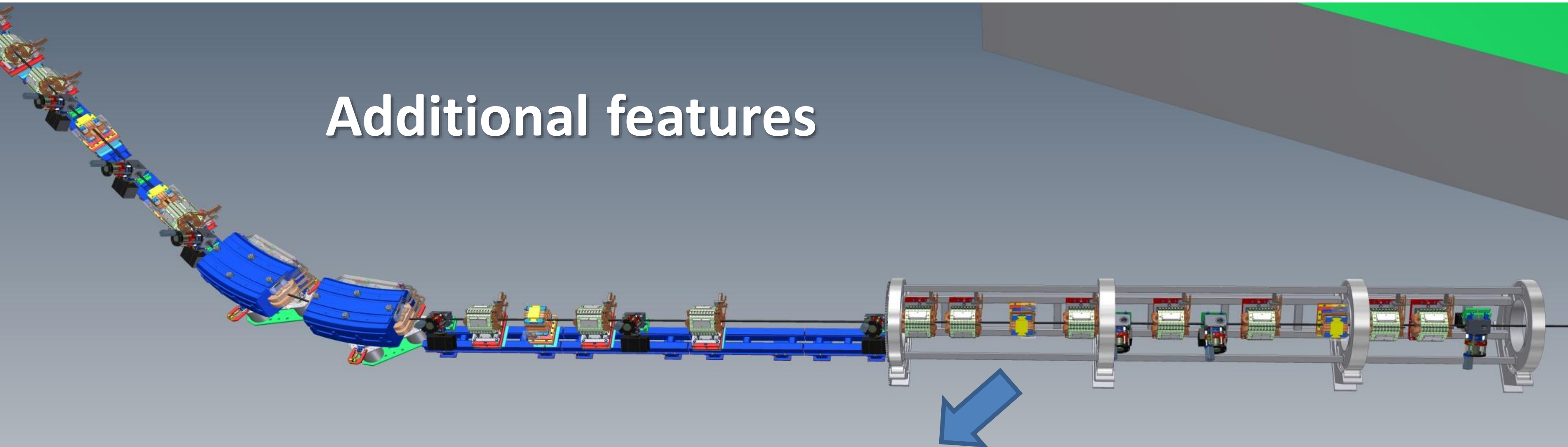
Additional features:
the rotator

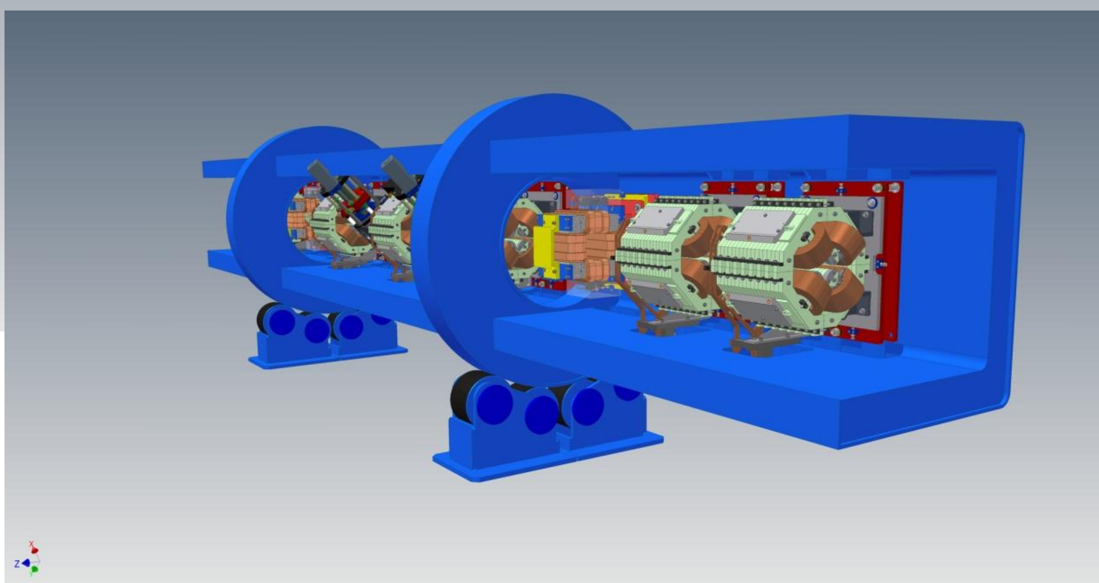


What is the rotator?

It is a set of quadrupoles placed in a rotating structure which allows to match the fix part of the line with the rotating part (gantry)

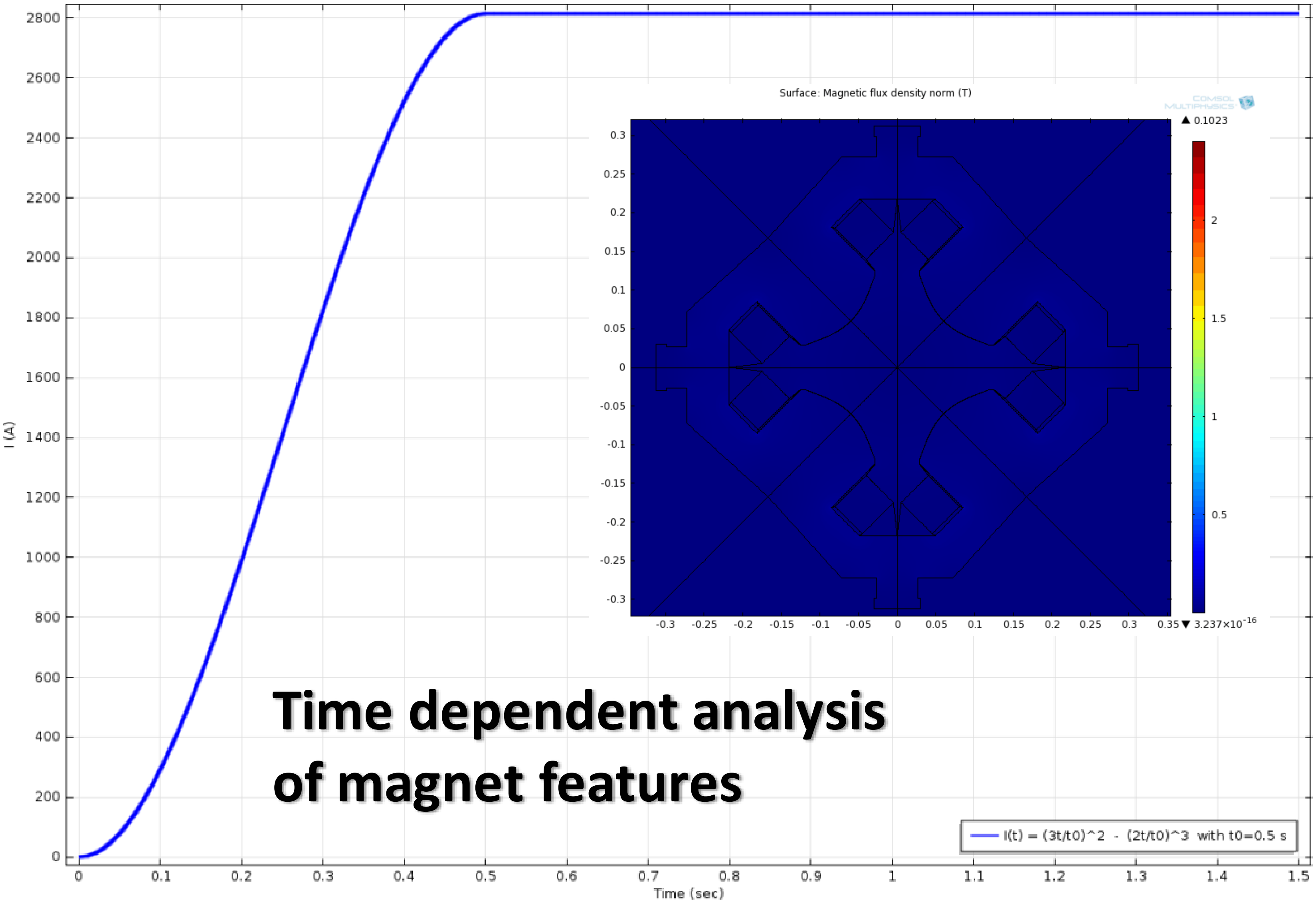
Additional features





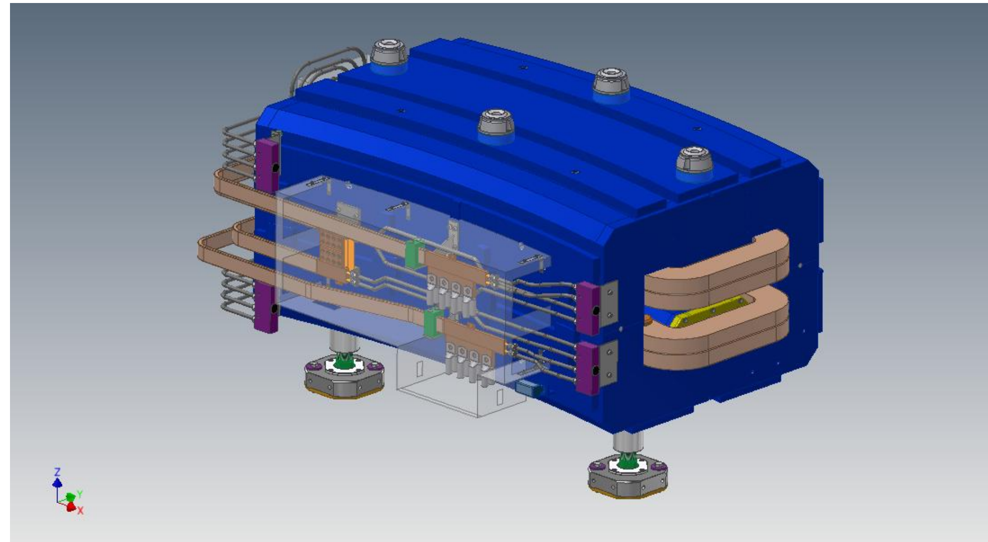
To characterize the influence of the rotator structure on the magnetic field of quadrupoles and correctors

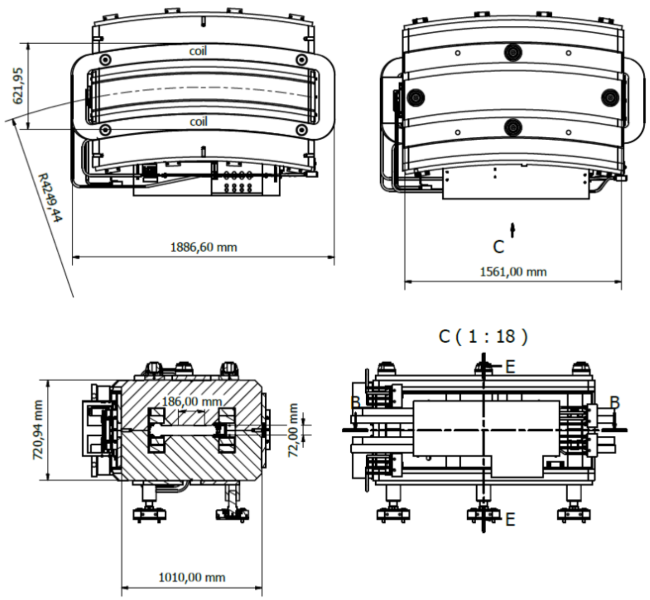
Additional studies

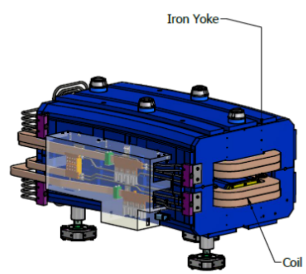


Time dependent analysis of magnet features

Bending dipole (π/8)



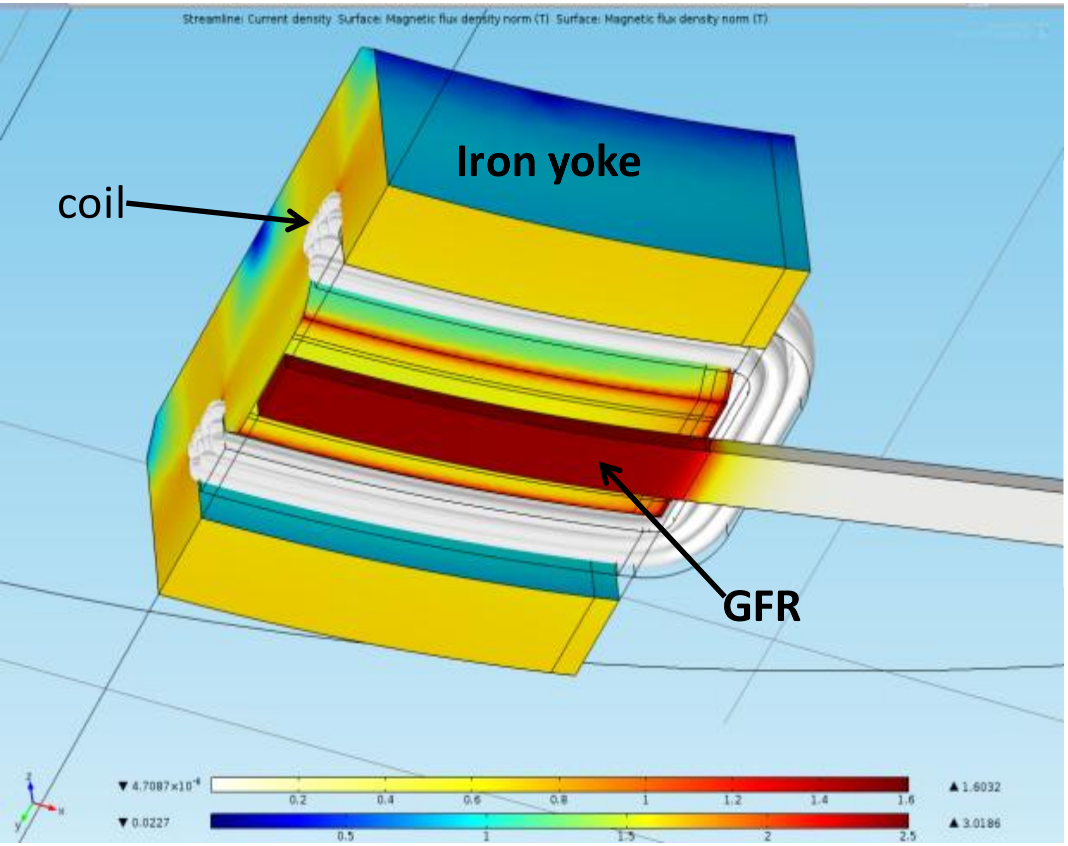




In the gantry line there are three bending dipoles (π/8)

They are used to control and match the beam dispersion along the line.

Bending dipole (π/8)



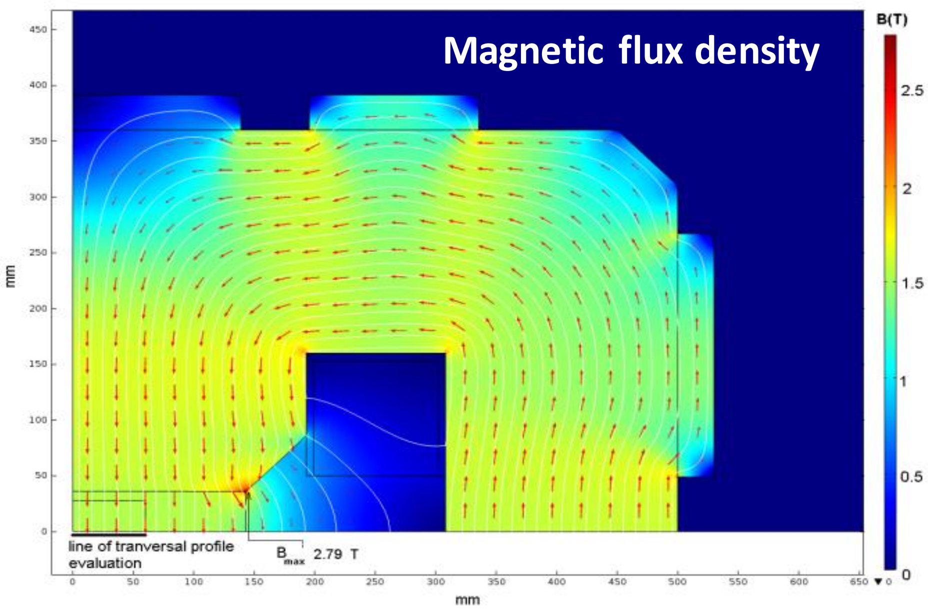
The static simulations are useful to verify:

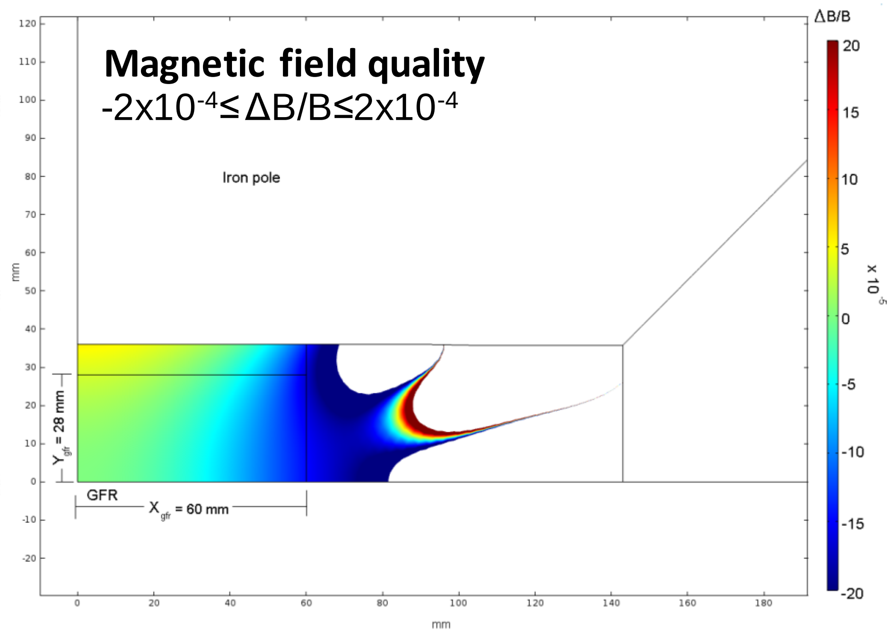
1. The iron field saturation level
2. The magnetic field intensity in the **Good Field Region** (**GFR**)
3. The magnetic field homogeneity

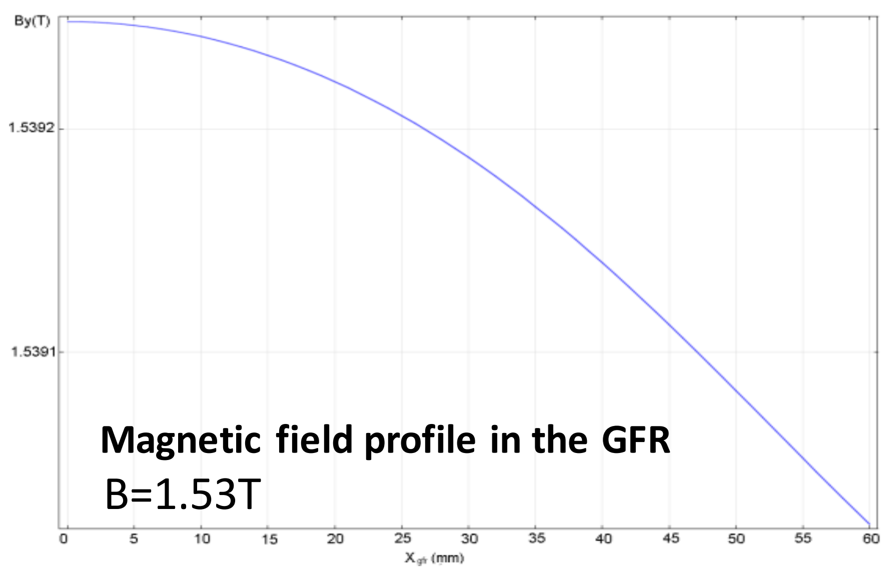
Static Simulations

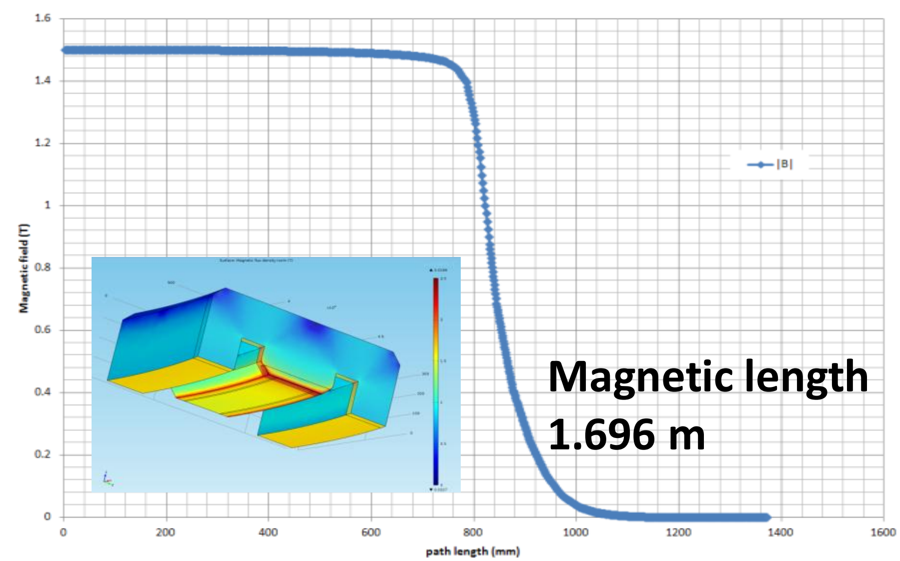
Bending dipole (π/8)

Static Simulations



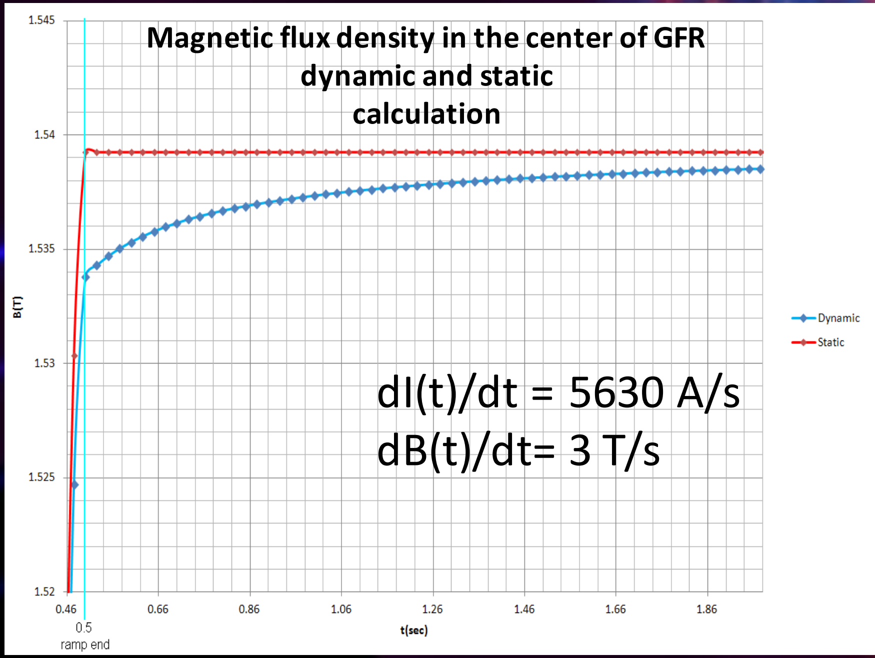


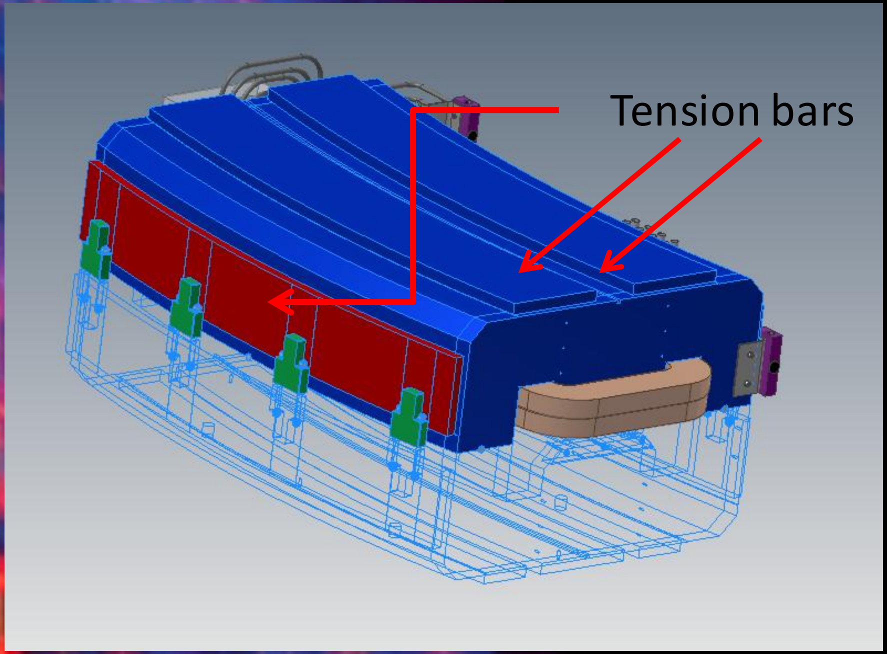




Time dependent calculations

The energy beam variations during the treatment requires variations in the magnetic field strength of every magnetic element in the gantry line.

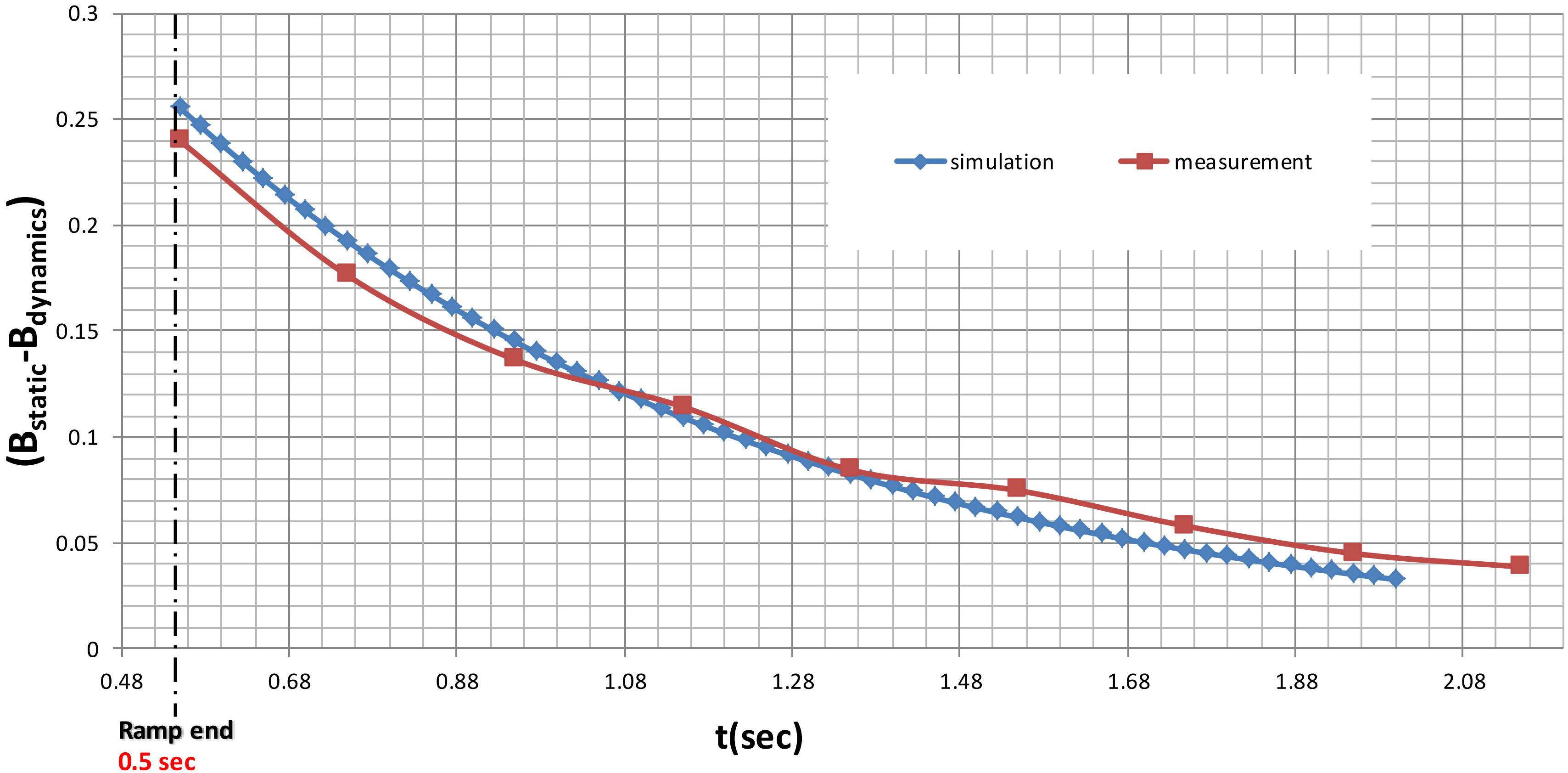




To validate the Finite Element Method calculations, a comparison between dynamic measurements and simulations has been done

Bending dipole (π/8)

Time dependent calculations



The results show a good agreement between the calculated and the measured data

Remarks about bending dipole (π/8)

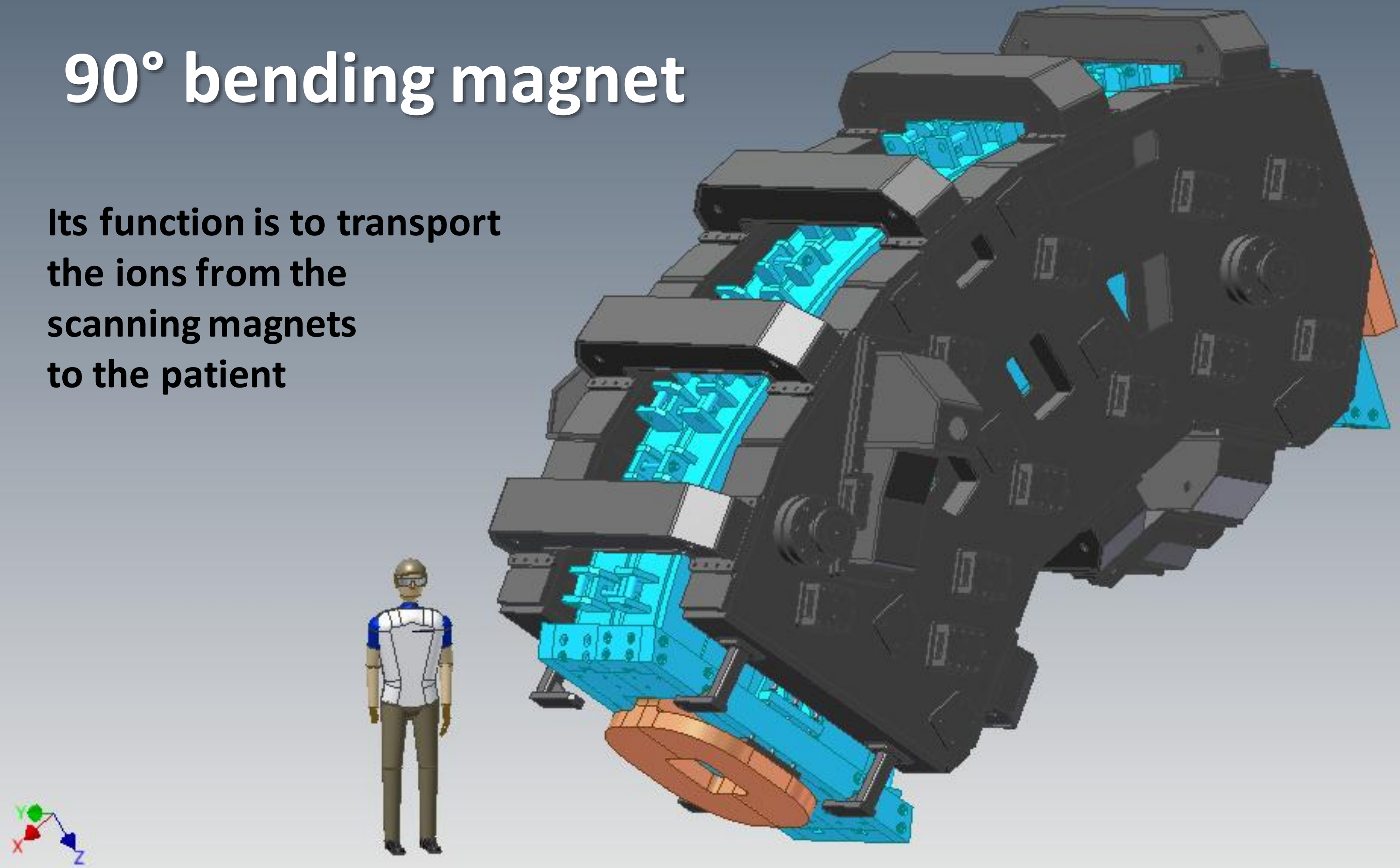
- This magnet model has been used as validation model in the dynamic regime

Magnetic field[T]	1.539
$(Bx-B_0)/B_0$ at GFR	$[-0.03x10^{-4}, 1.67\ x10^{-4}]$
Stored Energy[J]	48418.4
Inductance[mH]	12.22
Dissipated DC power[kW]	36.88
DC voltage in the coil[V]	13.10
Total dipole resistance[mΩ]	4.65
Integrated Magnetic field[T*m]	2.5461
Magnetic length[m]	1.696

Main features calculated for π/8 bending dipole

90° bending magnet

Its function is to transport the ions from the scanning magnets to the patient

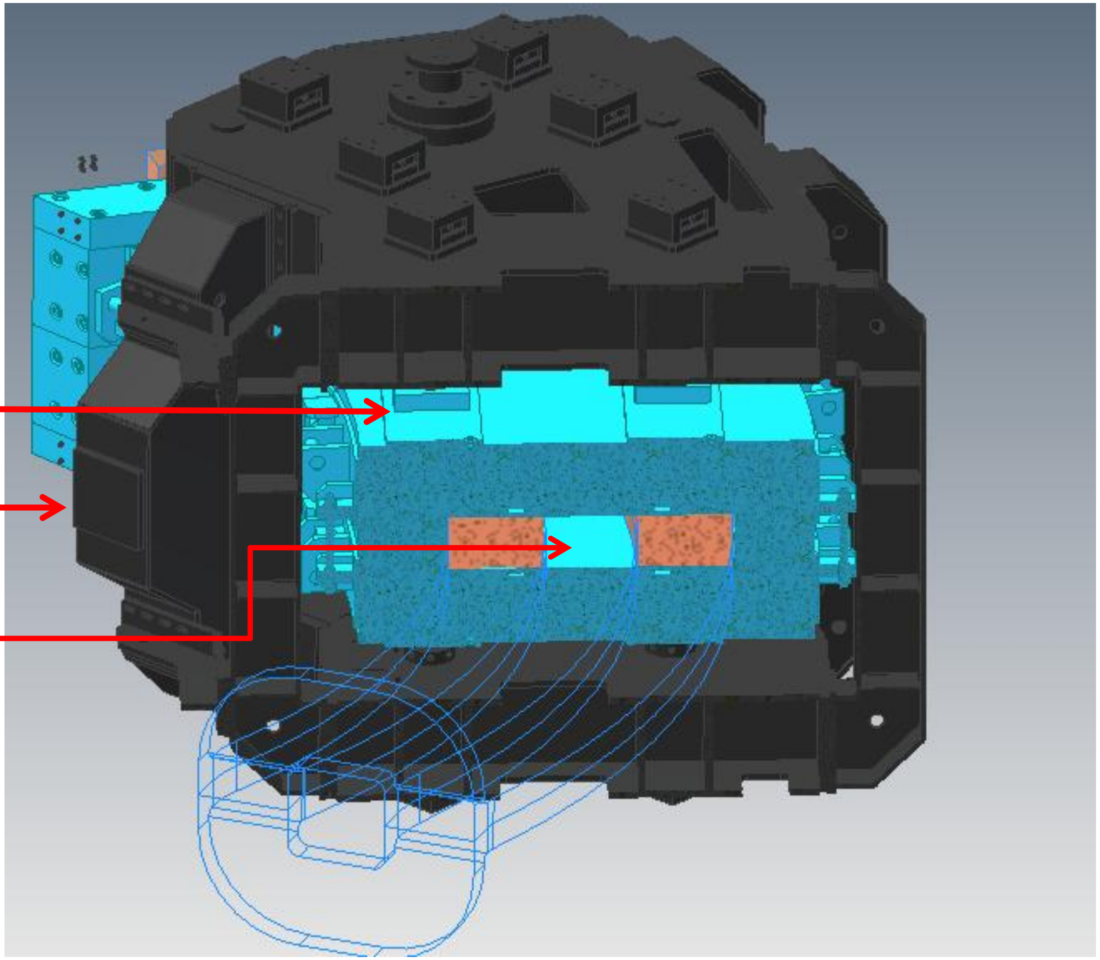


jhonnatan.moreno@cnao.it

Static Simulations

This magnet have particular features:

- Tension bars
- Ferromagnetic stiffening frame
- Magnet weight: 82 tons
- GFR: 20 x 20 cm^2



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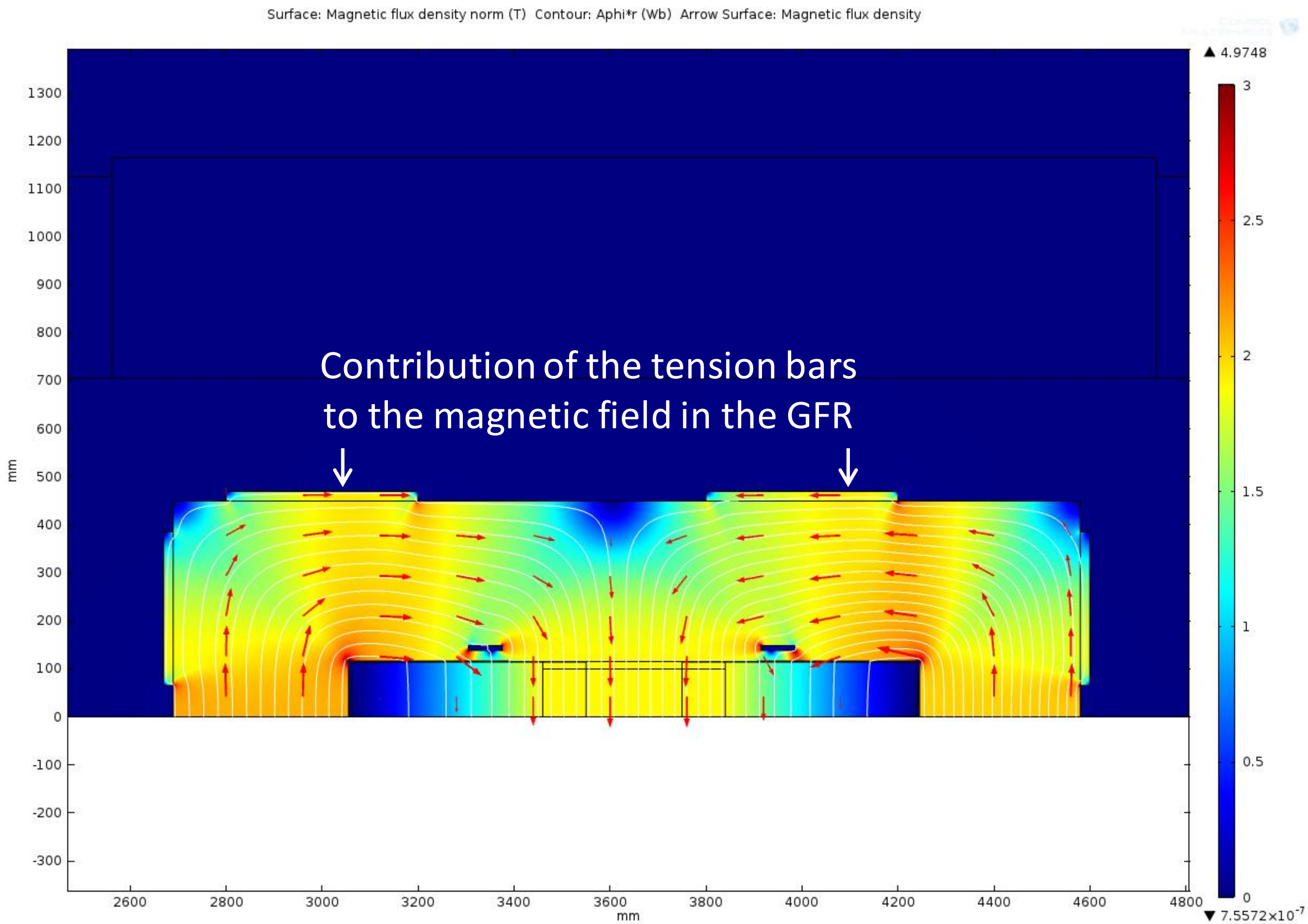
Static Simulations



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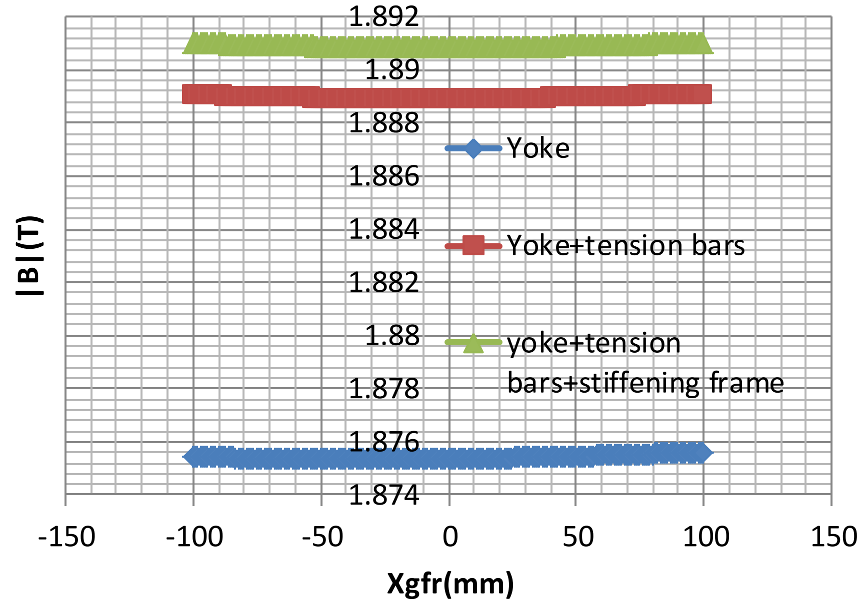
Static Simulations

	B in the center of the magnet [T]	Delta (%)
Only iron yoke	1.8753	0
Yoke+tension bars	1.888	0.67
Yoke+ tension bars + stiffening frame	1.890	0.78

Values of the magnetic
field strength in the middle of the GFR



Magnetic Field profile in the GFR

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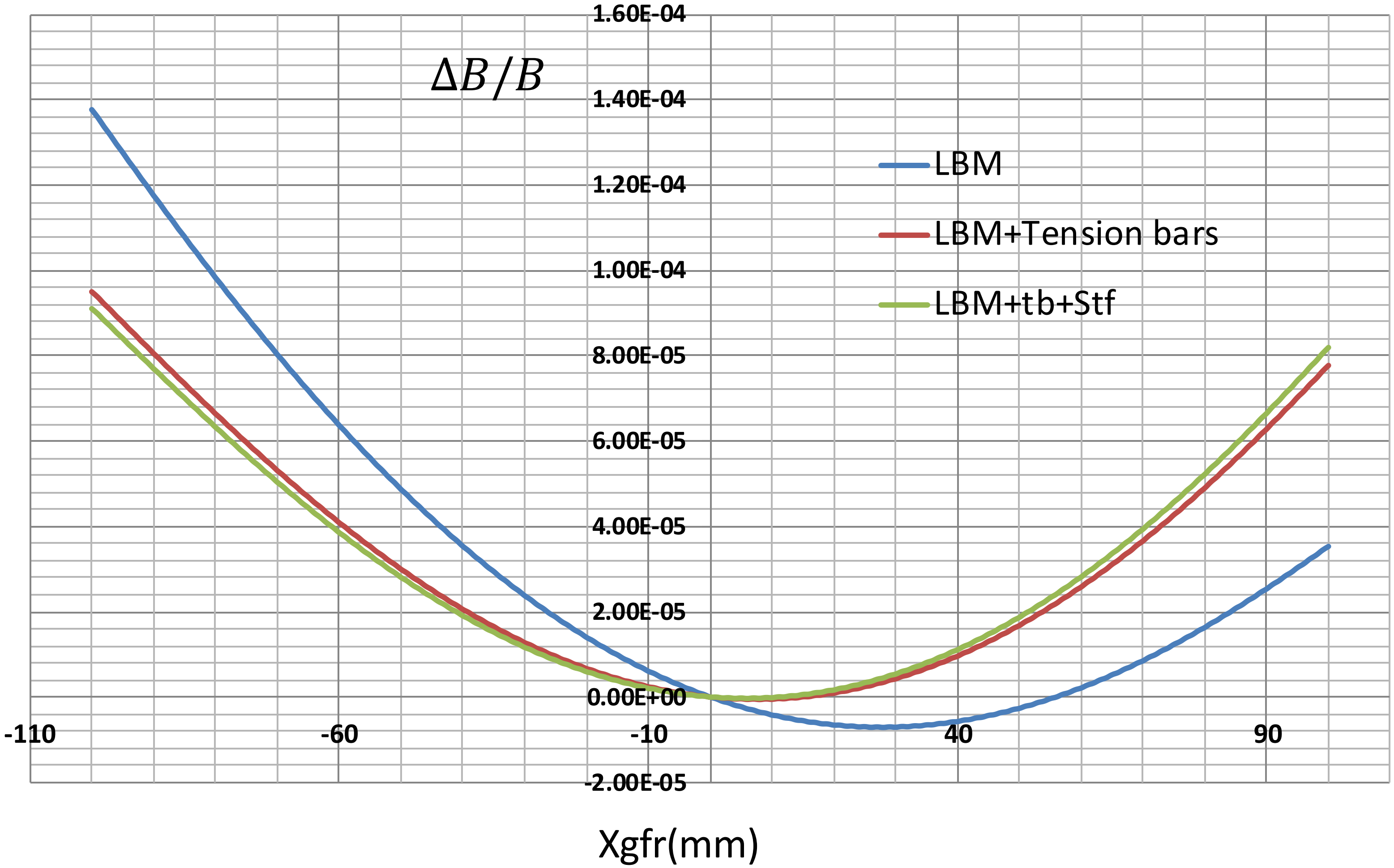
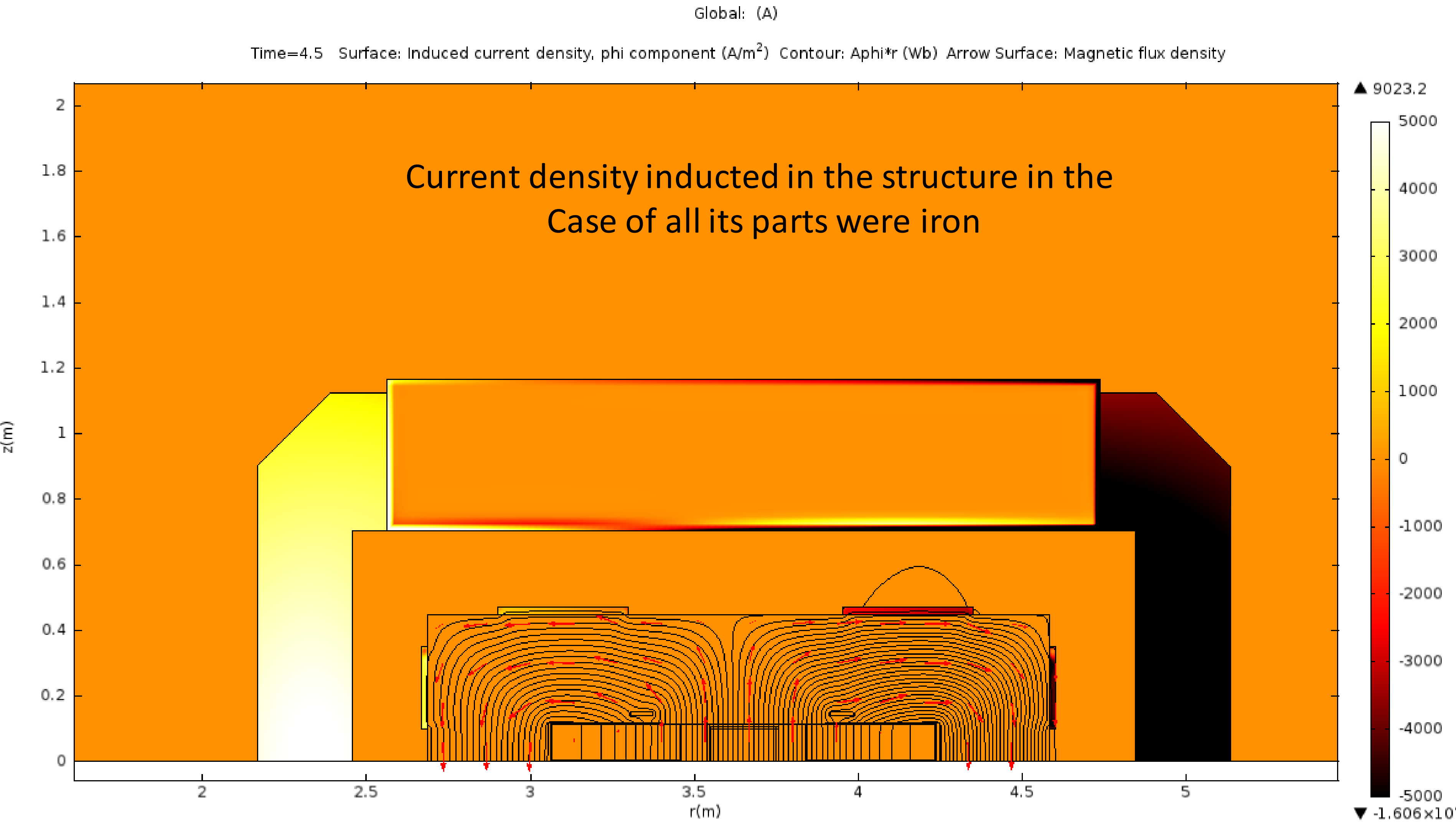
Static Simulations



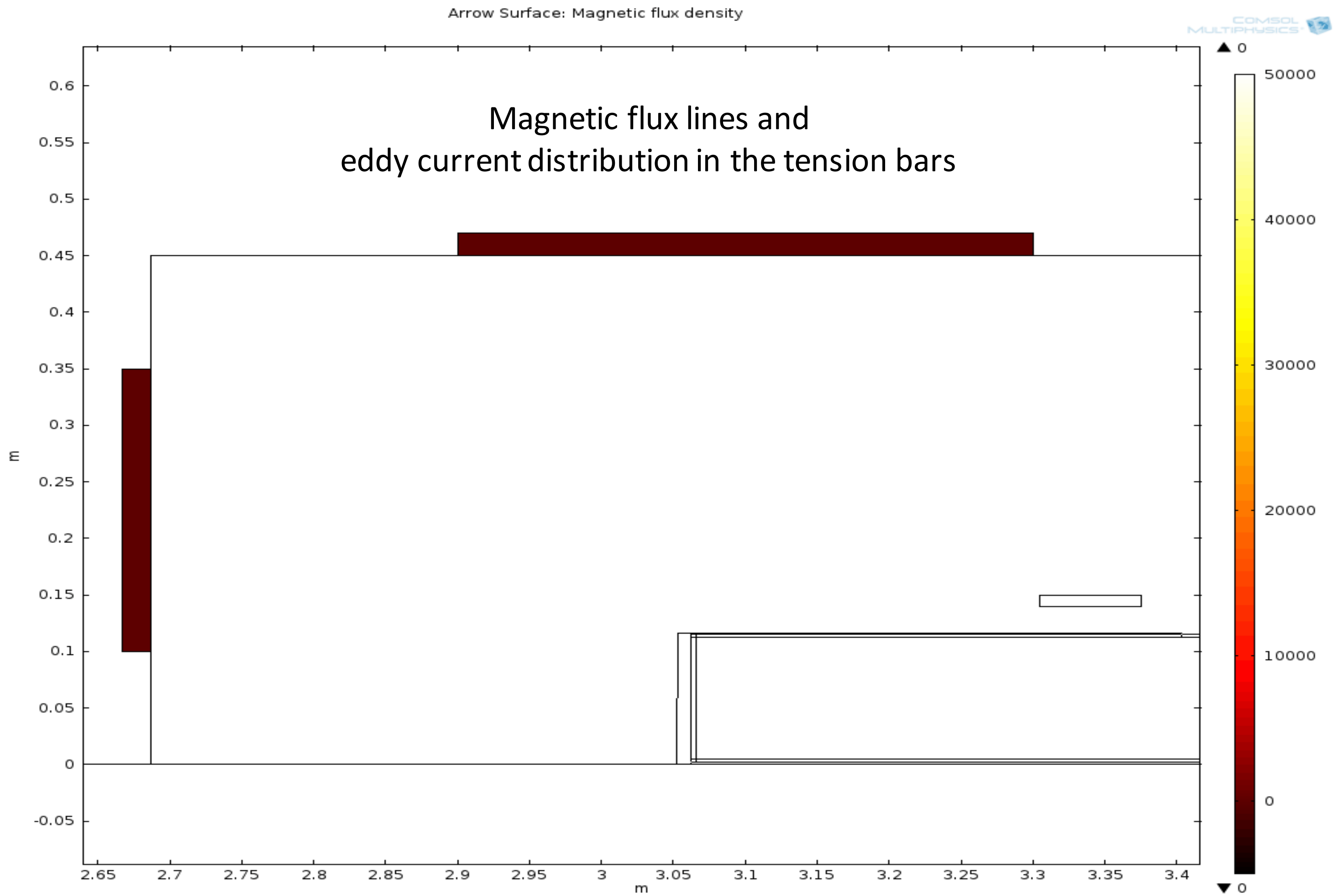
Magnetic field homogeneity contribution of the tension bars and of the tension bars + the stiffening frame, respectively

jhonnatan.moreno@cnao.it

Dynamic simulations



Dynamic simulations



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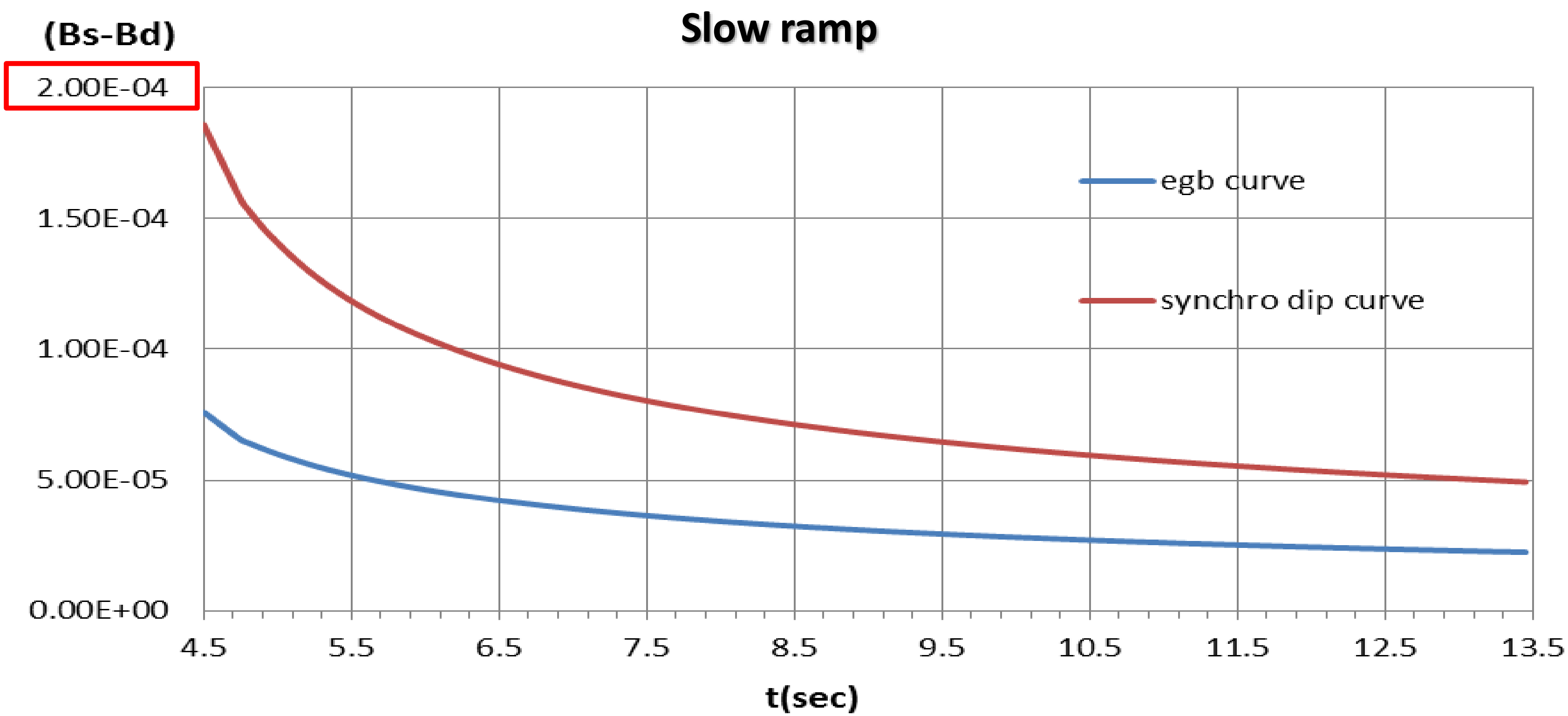
Dynamic simulations



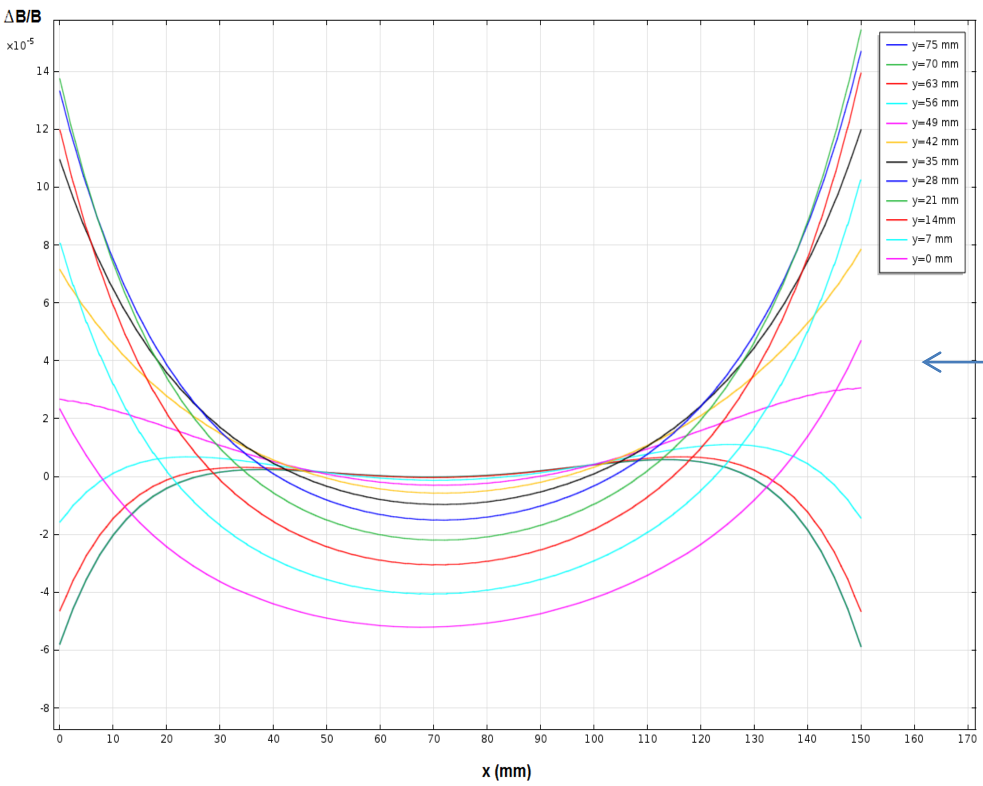
Difference between static field (Bs) and dynamic field (Bd) at the end of the feeding current ramp t = 4.5 s

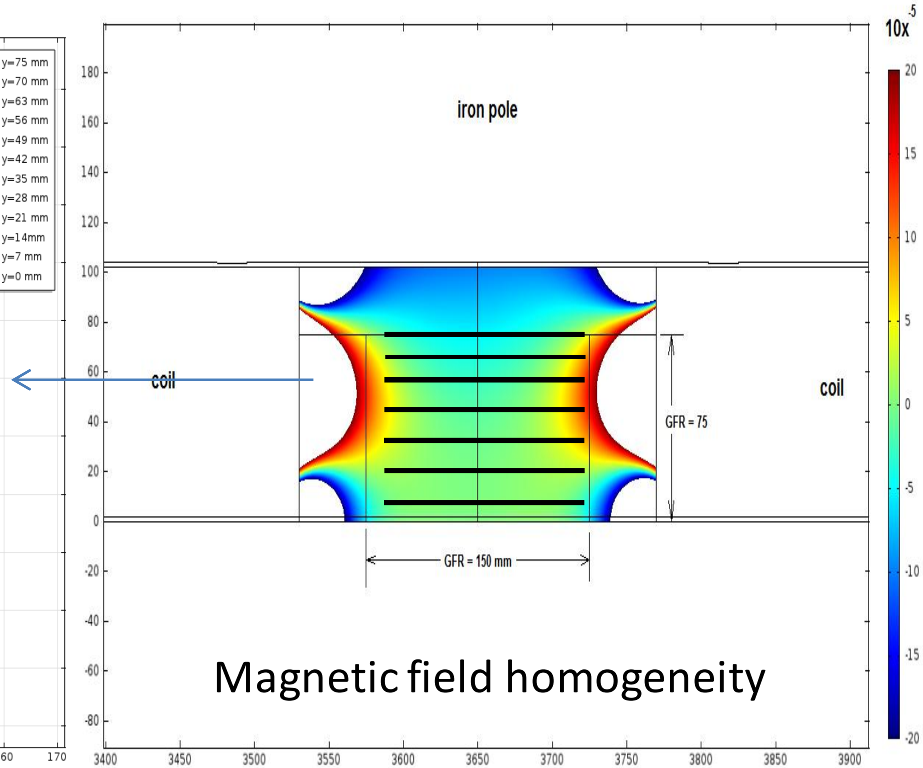
$$(B_s - B_d) \sim e^{-(t/\tau)}$$

The eddy currents generated in the tension bars give a time constat (τ) of **1.13 s**

An alternative: reducing the GFR

A similar magnet with a reduced GFR (15 x 15 cm²) was also studied in order to evaluate the possibility to minimize weight and/or power consumption





Magnetic field homogeneity

jhonnatan.moreno@cnao.it

An alternative: reducing the GFR

The magnet with 15 x 15 cm^2 reduced GFR gap allows to save approximately **10 tons** in weight and to save **30%** of power consumption

	GFR (15 x 15 cm^2)	GFR (20 x 20 cm^2)
Magnetic field [T]	**1.814**	**1.87**
$\Delta B/B_0$ at GFR	[-0.58×10^{-4}, 1.375×10^{-4}]	[-0.8×10^{-4}, 1.03×10^{-4}]
Stored Energy [J]	882227.24	1213924.48
Inductance [H]	0.26	0.47
Dissipated DC power [kW]	**426.64**	**613.65**
DC voltage [V]	164.1	269.16
Inducted Voltage [V]	150.6	236.8
Excitation current[A]	2600	2800
Ampere-turns	156000	182400
Magnet Weight [tons]	**70**	**82**

Comparison table between the reduced 90° bending magnet (GRF 15 x 15 cm^2) and the reference 90° CNAO bending magnet (GFR 20 x 20 cm^2)

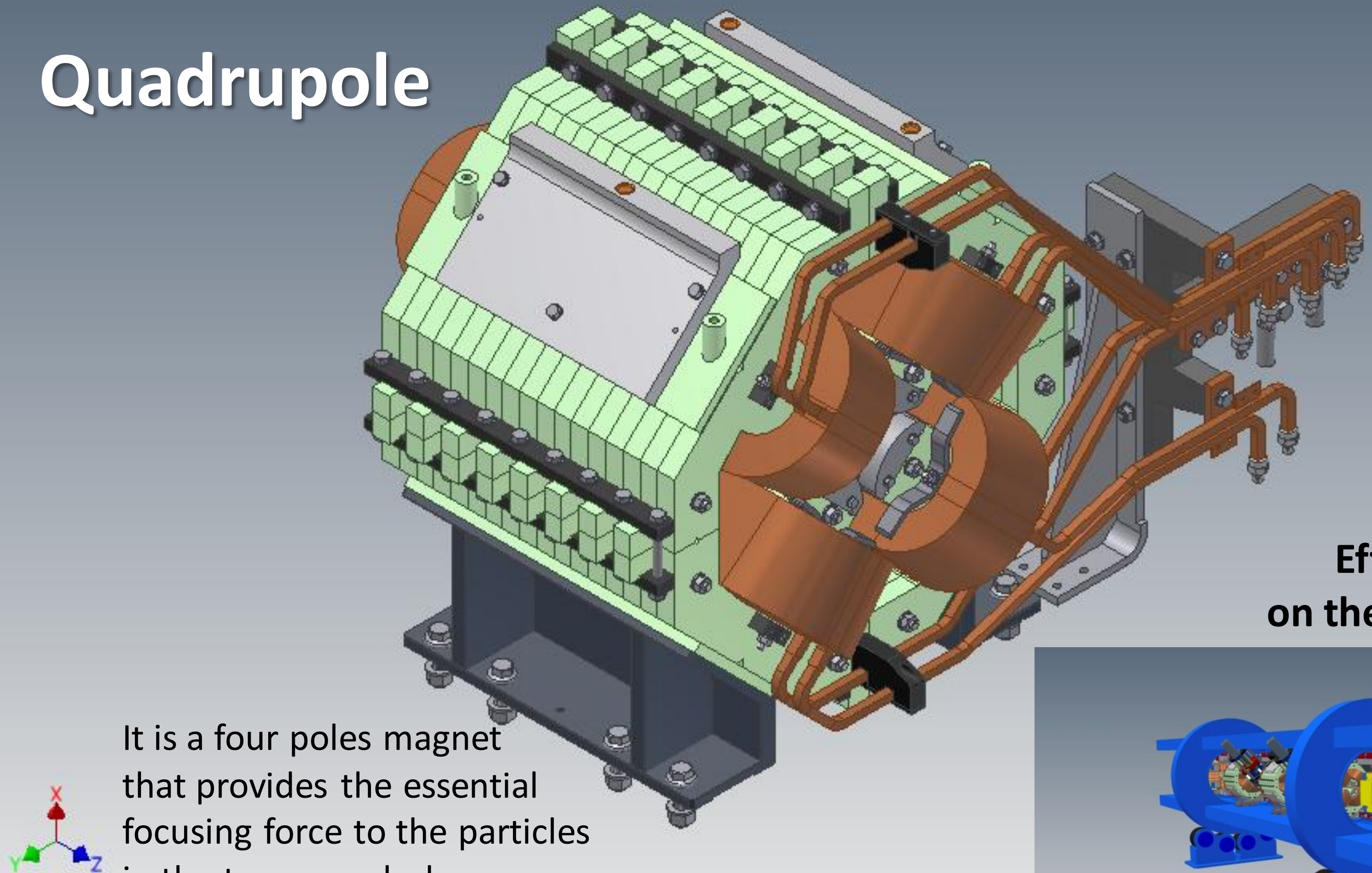
Remarks about 90° bending magnet

- Static simulations of the CNAO 90° large gap dipole have shown that the 2D field homogeneity is acceptable and that the influence of the stiffening frame structure and of the tension bars cannot be neglected

- The variation in the absolute value of the field in the gap is not significant for the requirement on the excitation current and the effect on the field homogeneity is unimportant

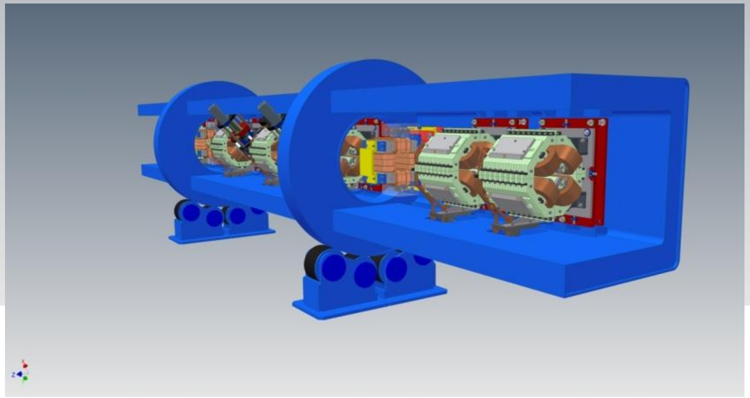
- A reduced GFR 90° bending magnet has been evaluated. The corresponding layout allows saving about the **30%** of power consumption and **10 tons** on the overall weight

Quadrupole

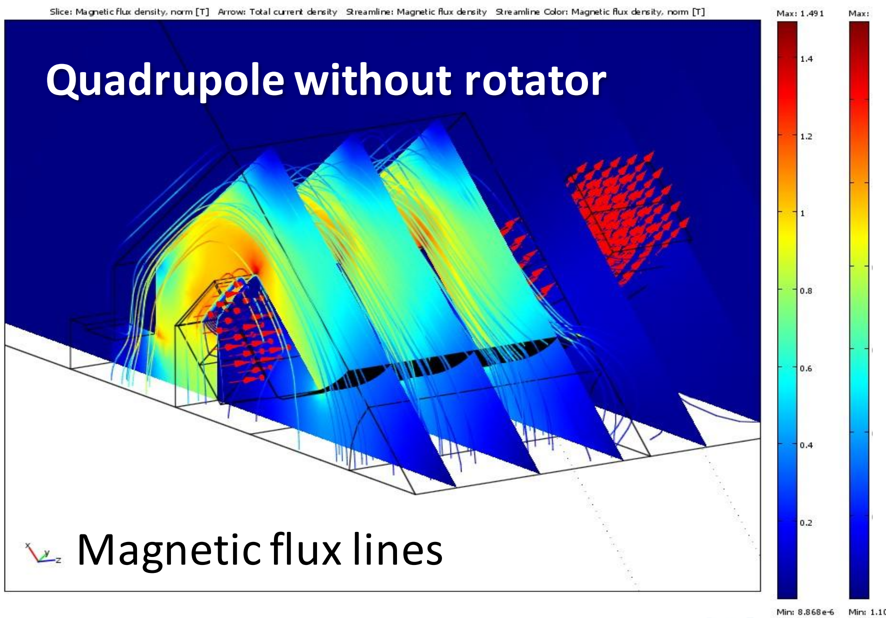


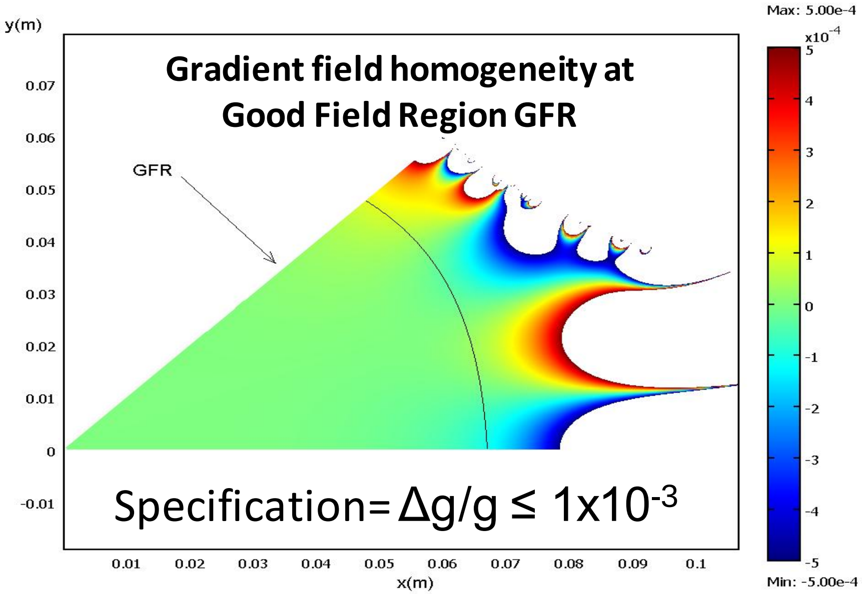
It is a four poles magnet that provides the essential focusing force to the particles in the transversal plane.

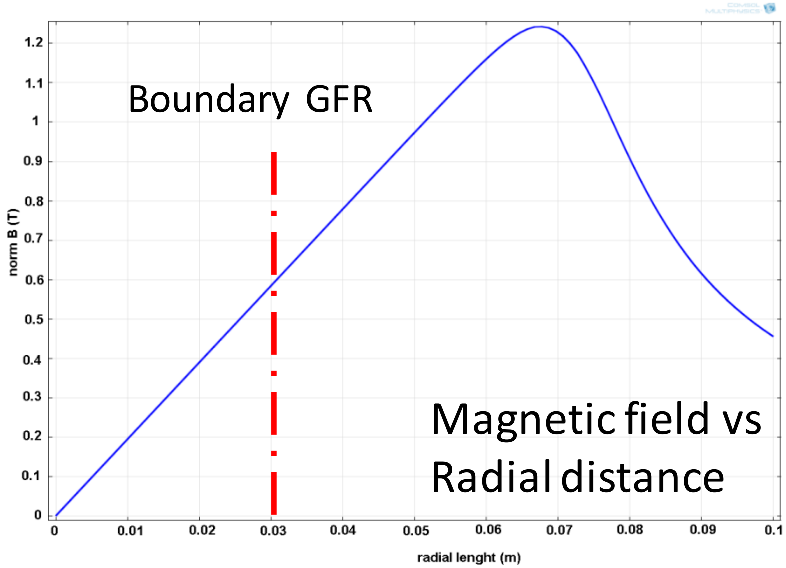
Effect of the rotator on the quadrupole field

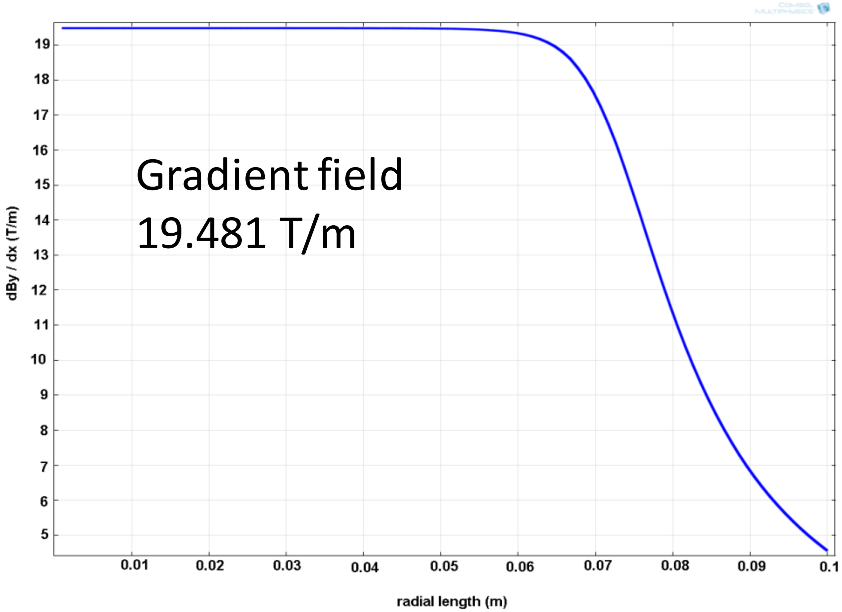


Static Simulations



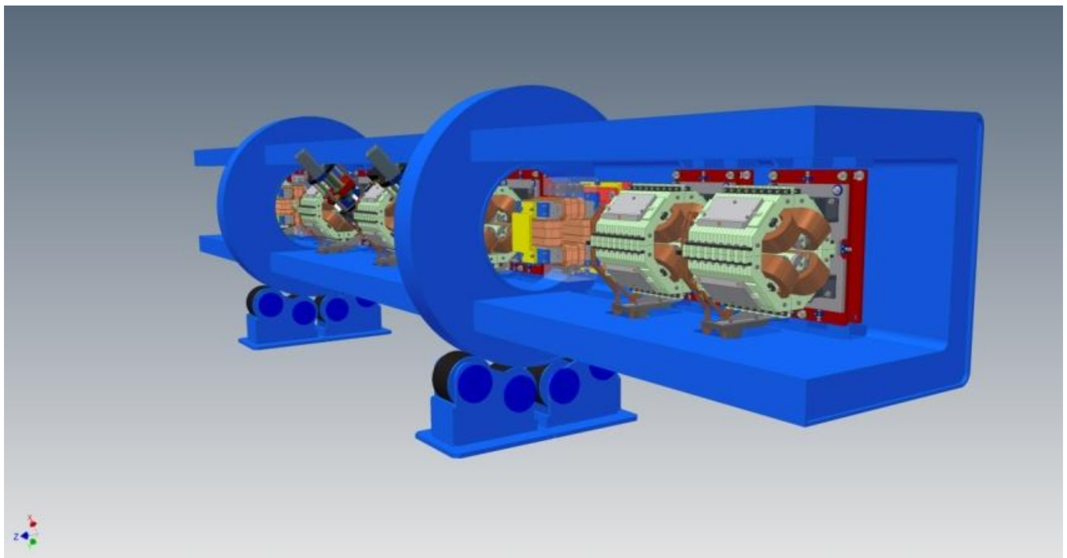




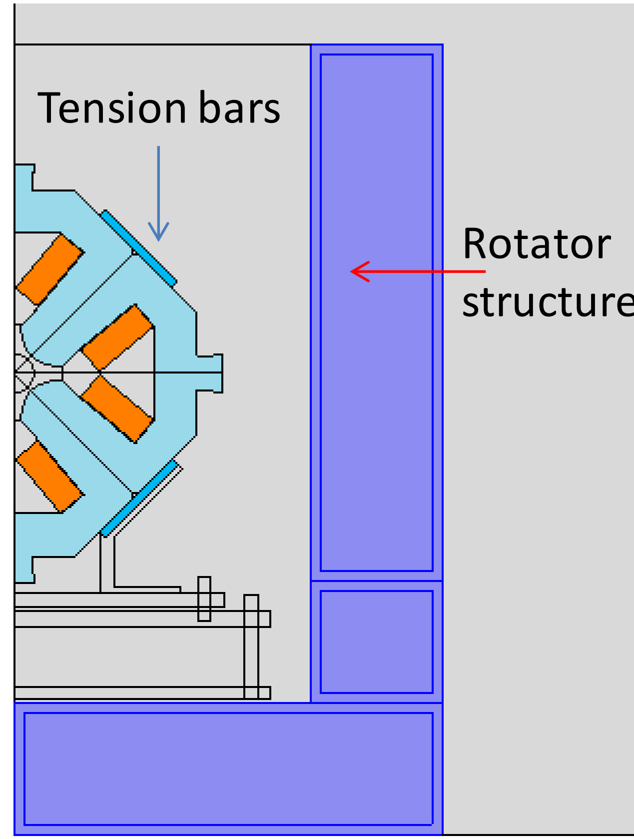


Static Simulations

Rotator



CAD design of the rotator structure

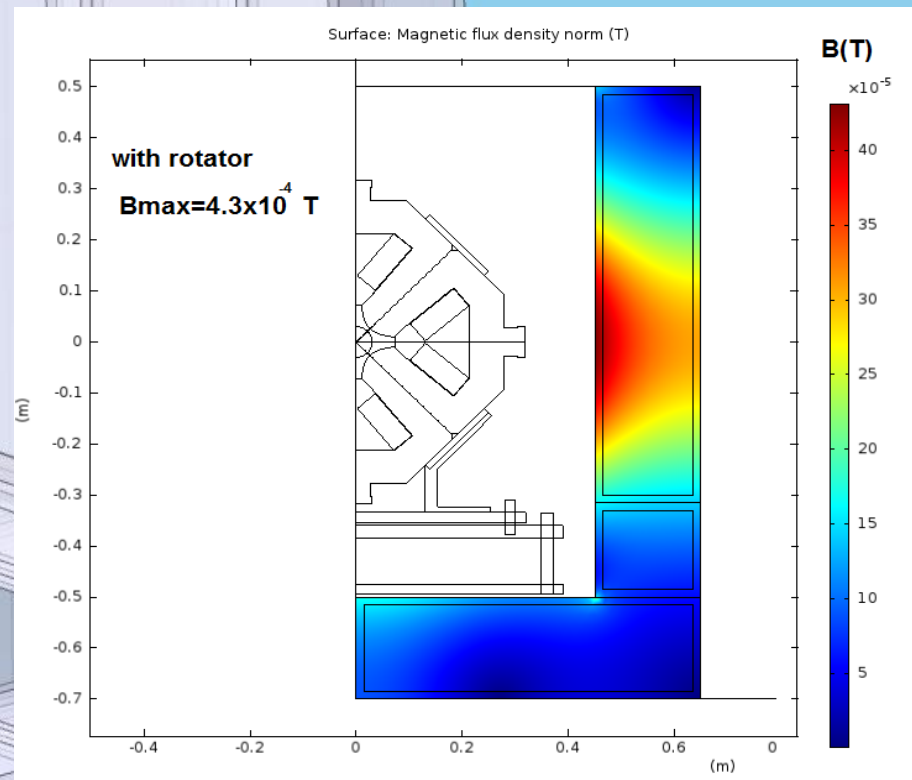


2D geometry implemented in the FEM code

Static Simulations

Rotator

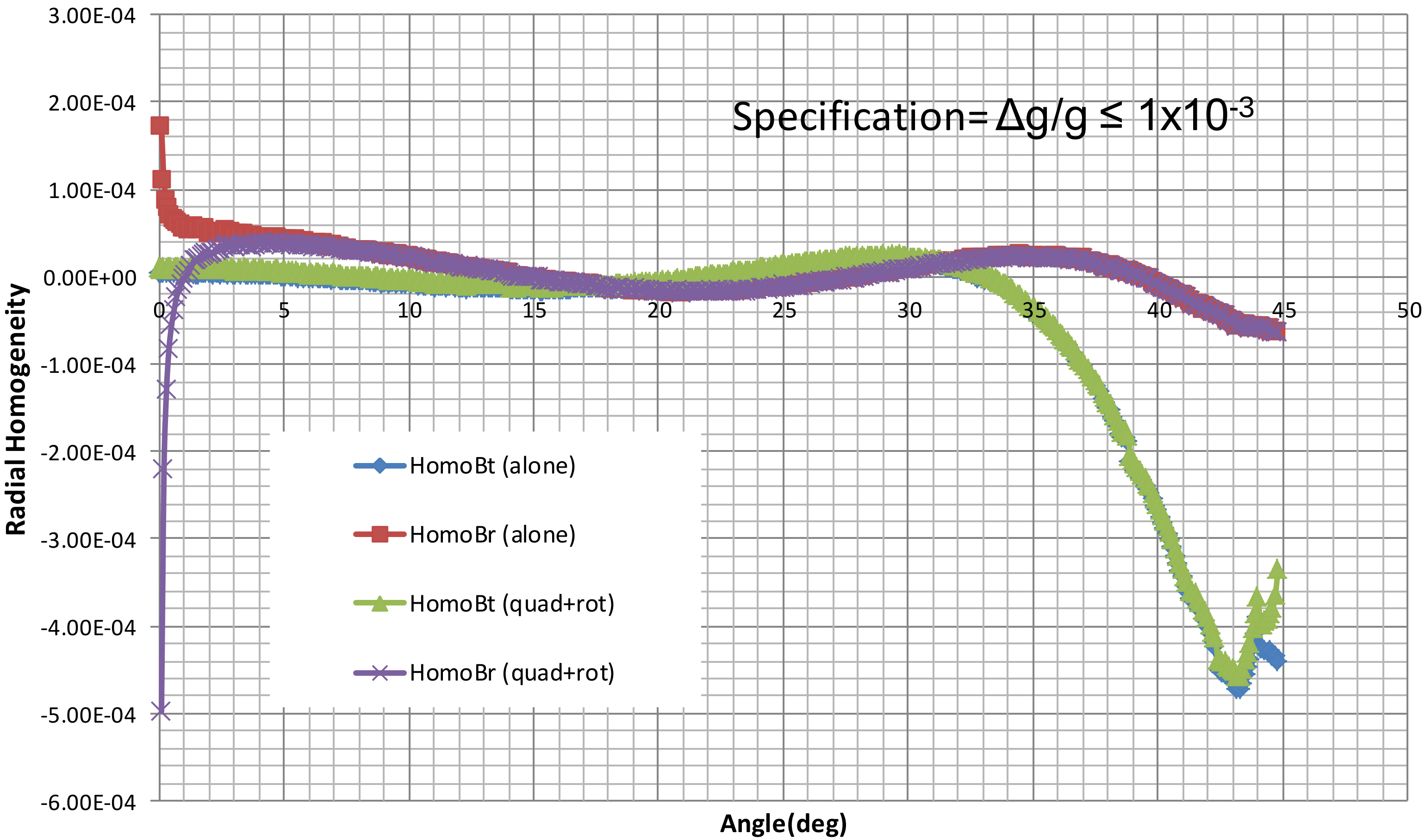
2D	Gradient in the center of the magnet [T/m]	Delta (%)
Only iron yoke	19.481	0
Yoke + tension bars	19.503	0.11
Yoke + tension bars + rotator structure	19.505	0.12



Values of the magnetic field gradient
in the GFR boundary
(r = 30 mm)

Static Simulations

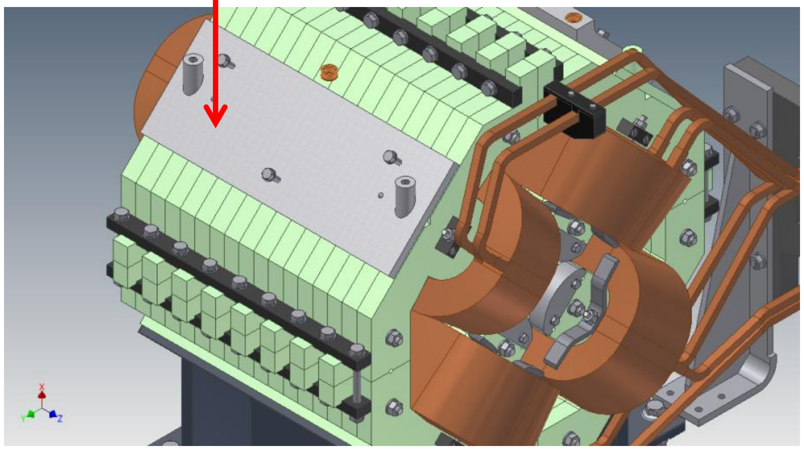
Quadrupole+Rotator



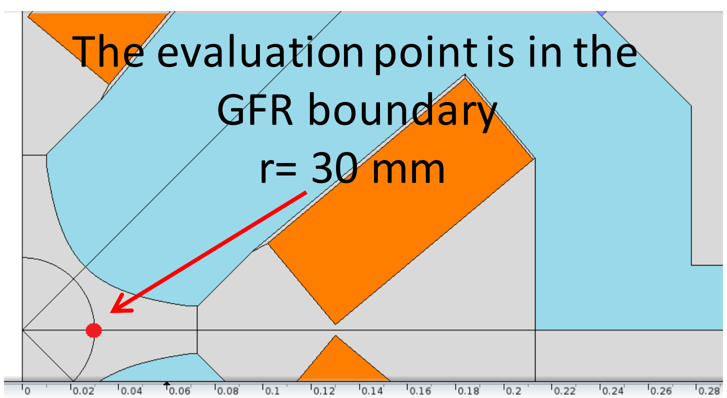
Values of the magnetic field gradient homogeneity in the GFR boundary
(r = 30 mm)

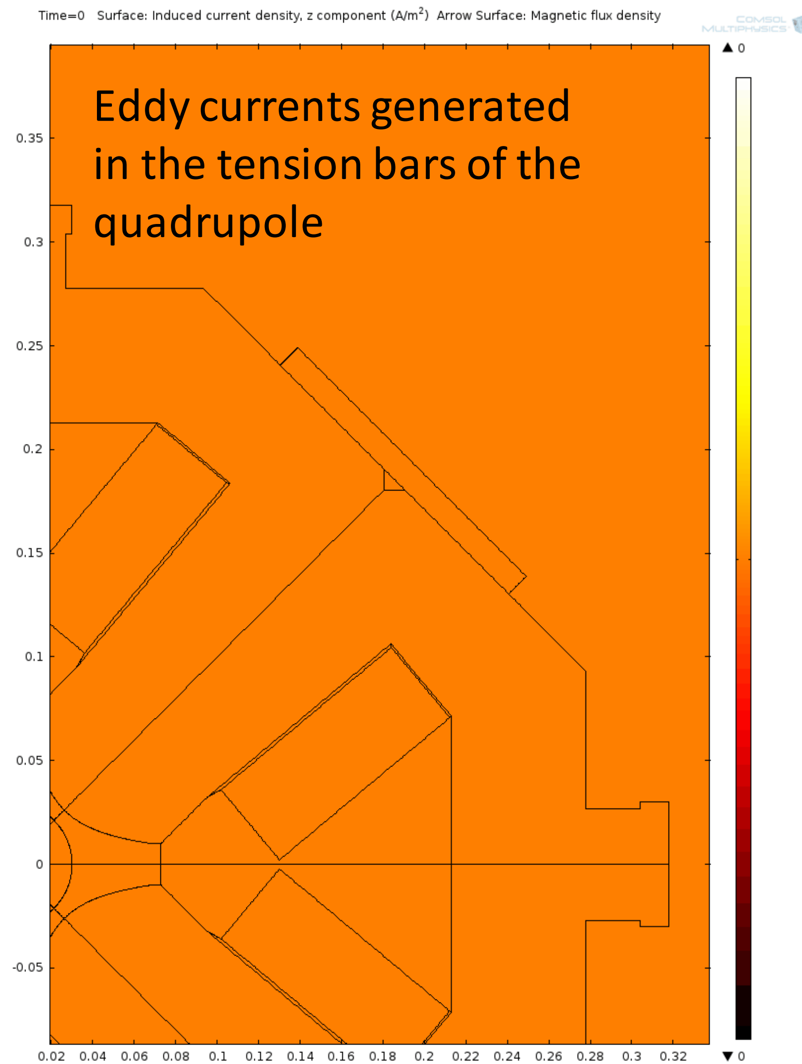
Dynamic simulations

Tension bar

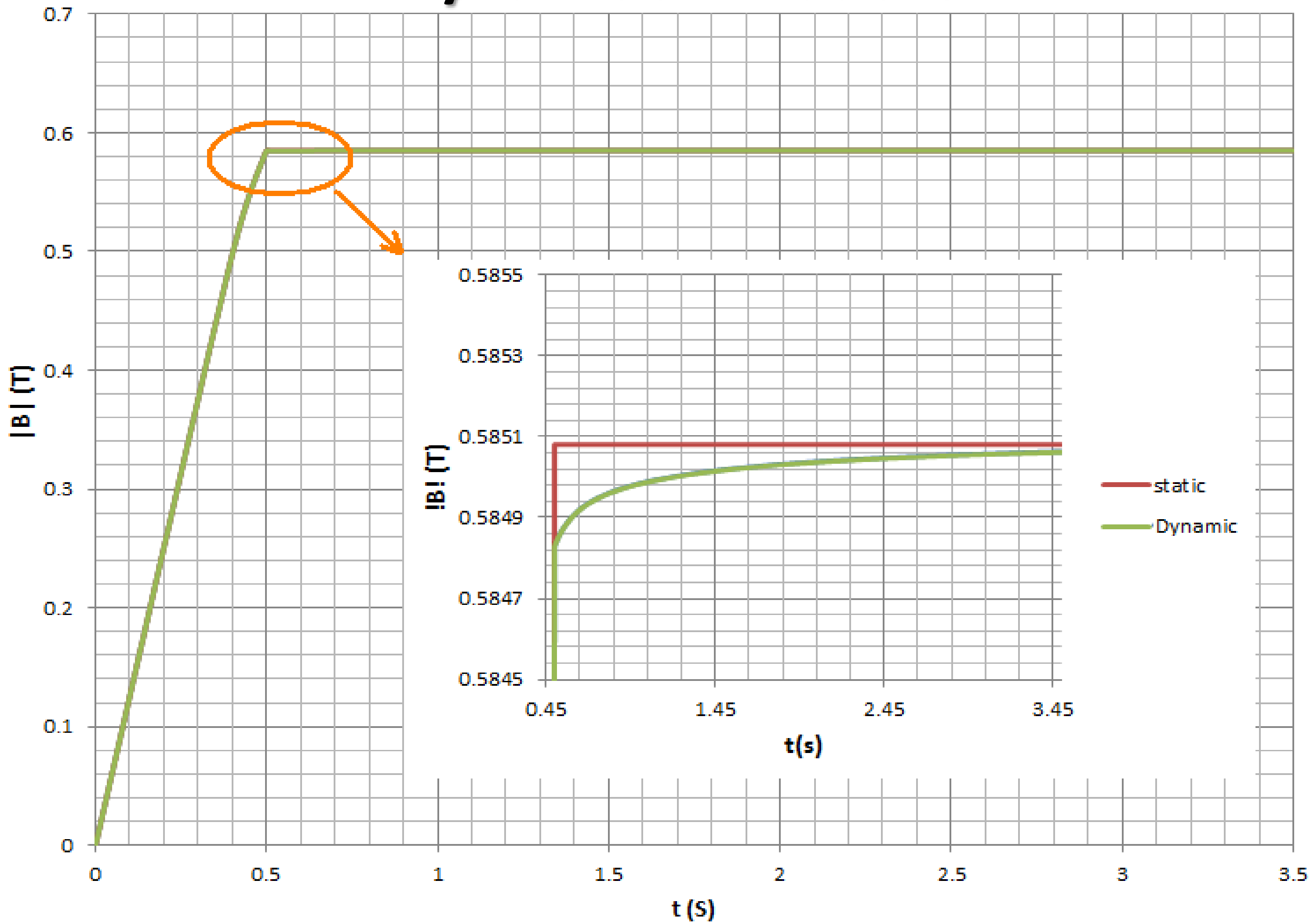


Sketch of quadrupoles lamination with the tension bars welded in the external part of the yoke





Dynamic simulations

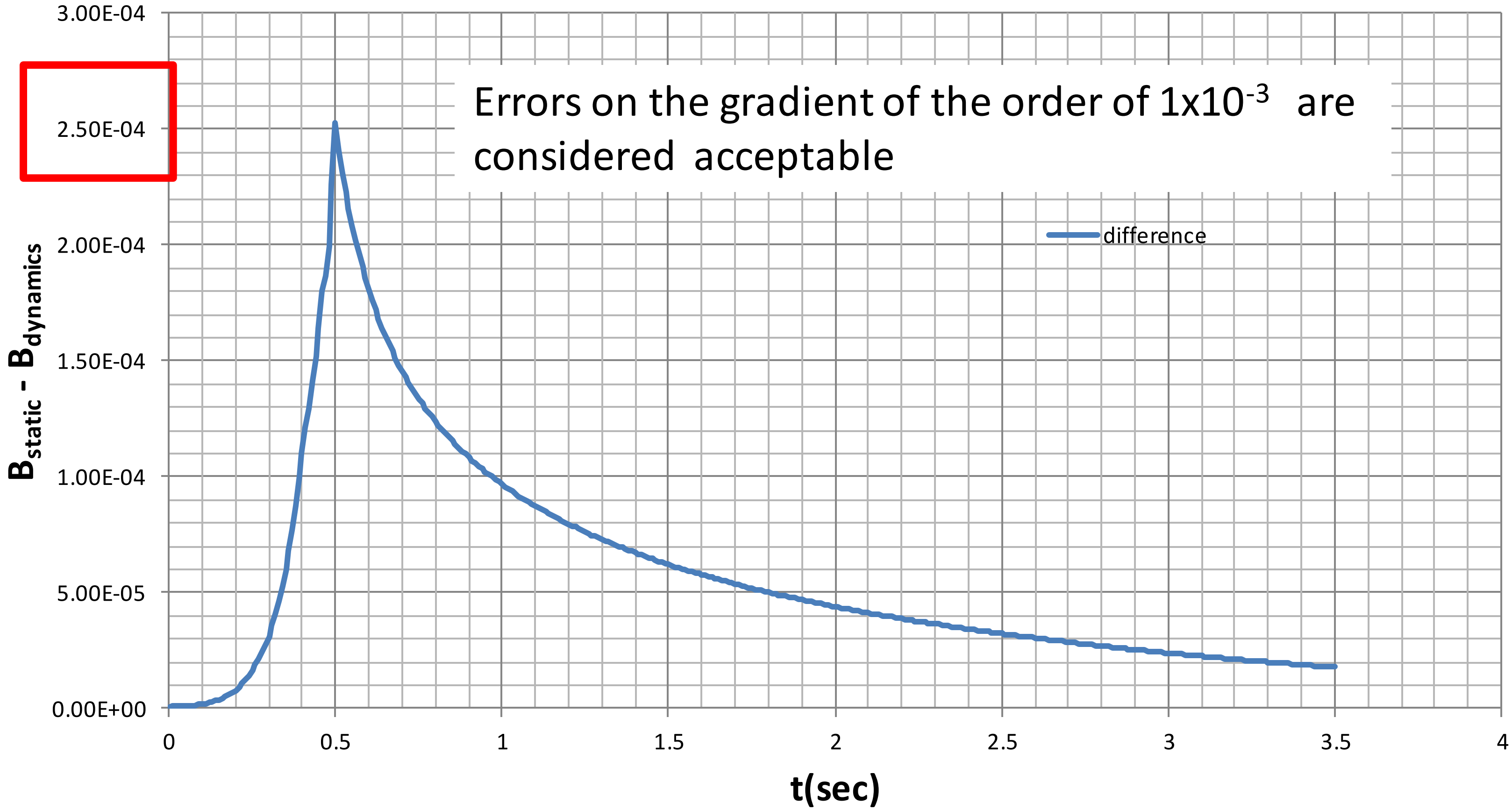


NO rotator

B(t) using a linear current ramp of $dI/dt = (2xI_{max})/t = 572.5$ A/s

jhonnatan.moreno@cnao.it

Dynamic simulations

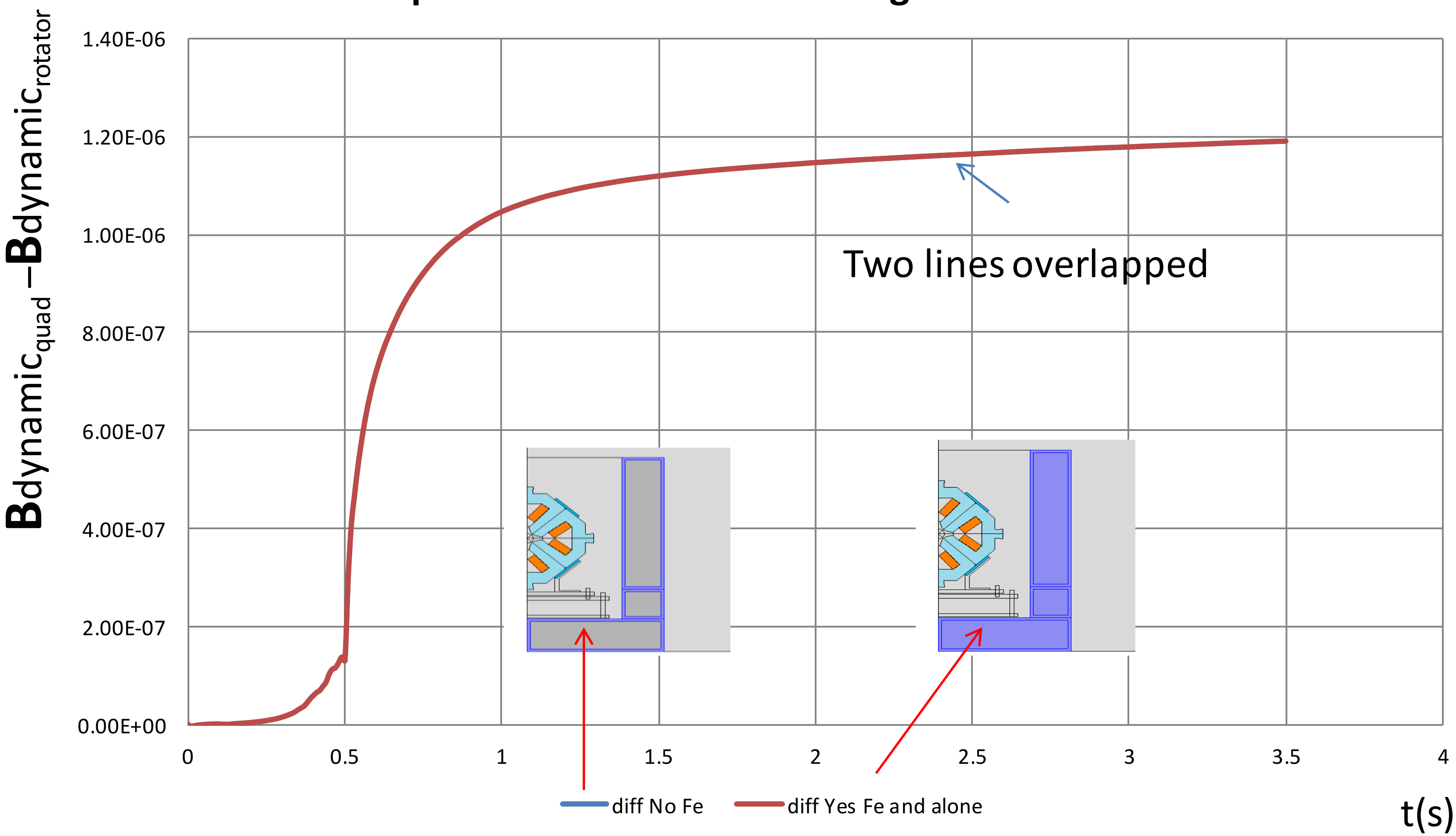


The eddy currents generated in the tension bars give a time (τ) of **0.48 s**

jhonnatan.moreno@cnao.it

Dynamic simulations

Difference between quadrupole+ tension bars and the quad+tension bars+ferromagnetic rotator sructure



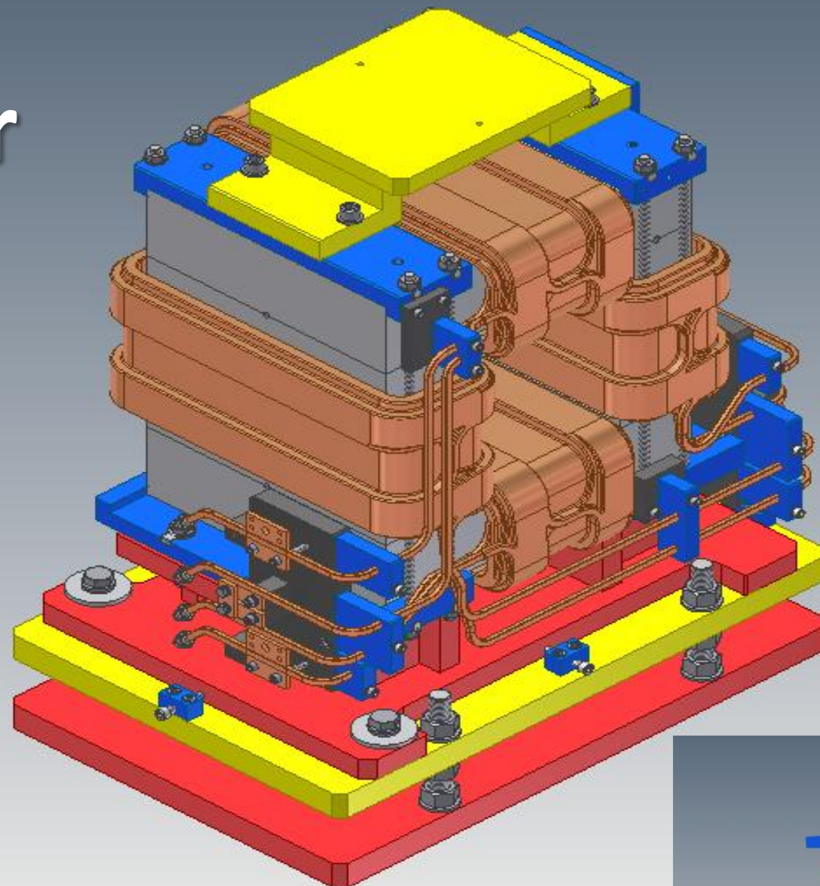
Remarks about the quadrupole magnet

- Differently from the 90° bending magnet, the dynamic effects introduced by additional elements, like the tension bars and rotator structure, can be neglected

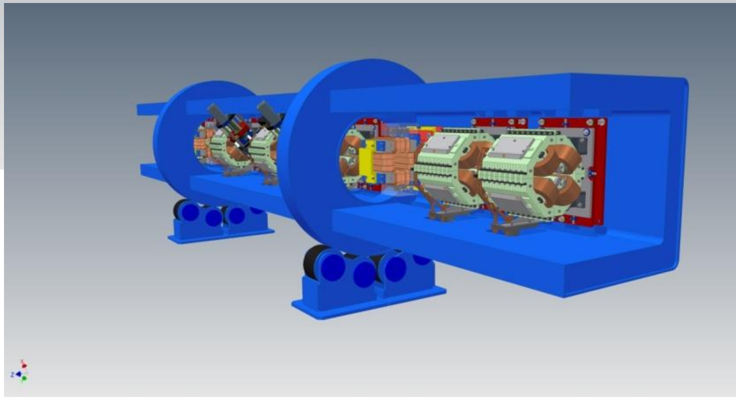
- The static field contribution of the previously mentioned structures is almost negligible; it amounts to approximately 0.1% and it is mainly due to the ferromagnetic tension bars welded to the iron

Corrector

Its main function is to correct the orbit distortions.

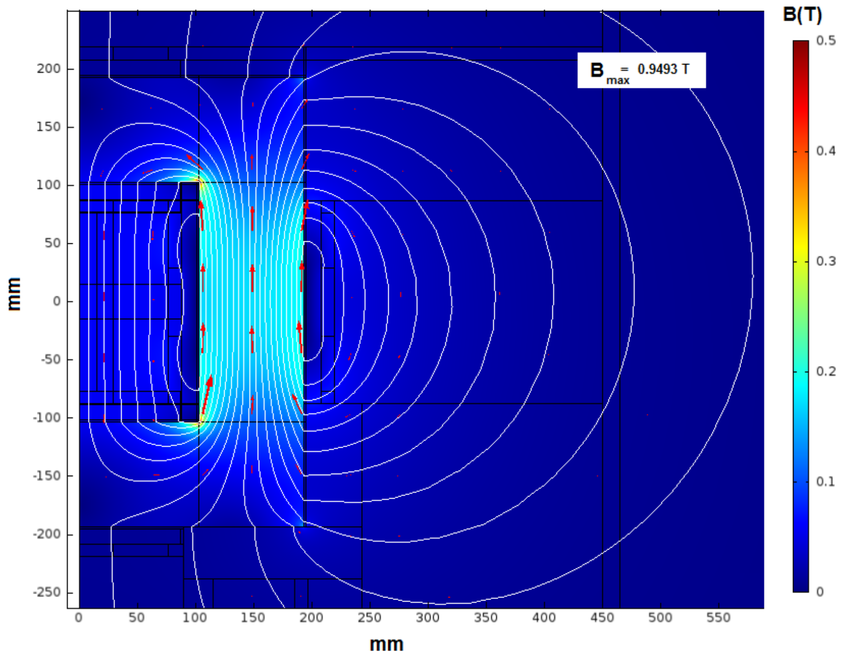


Effect of the rotator on the corrector B field

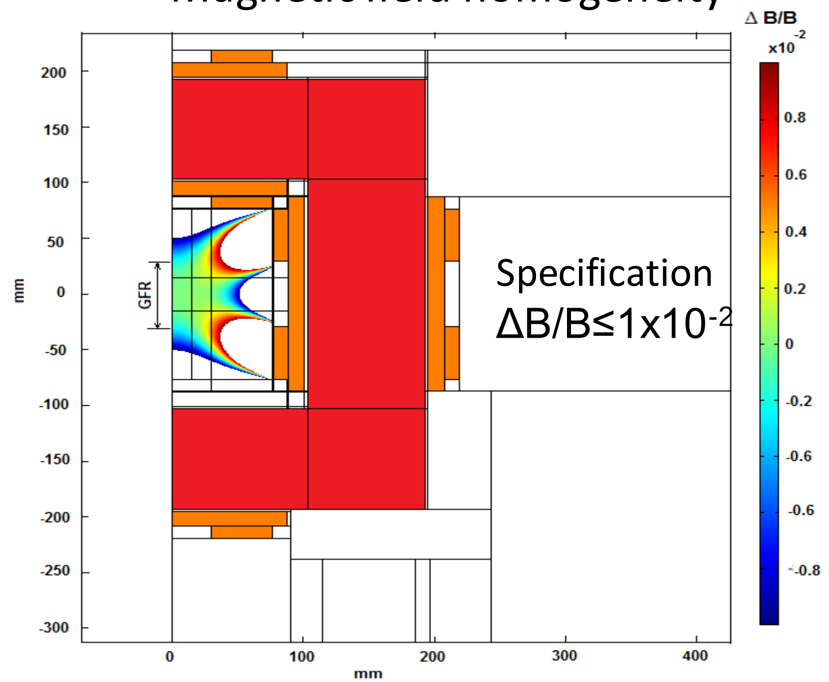


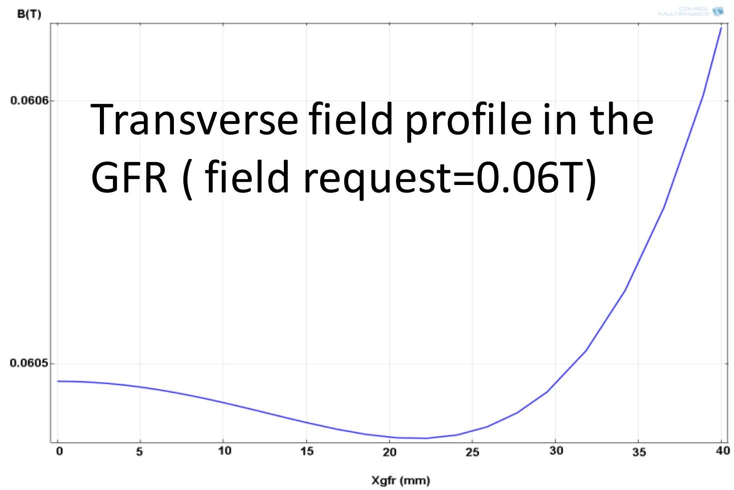
Static Simulations

Magnetic flux lines



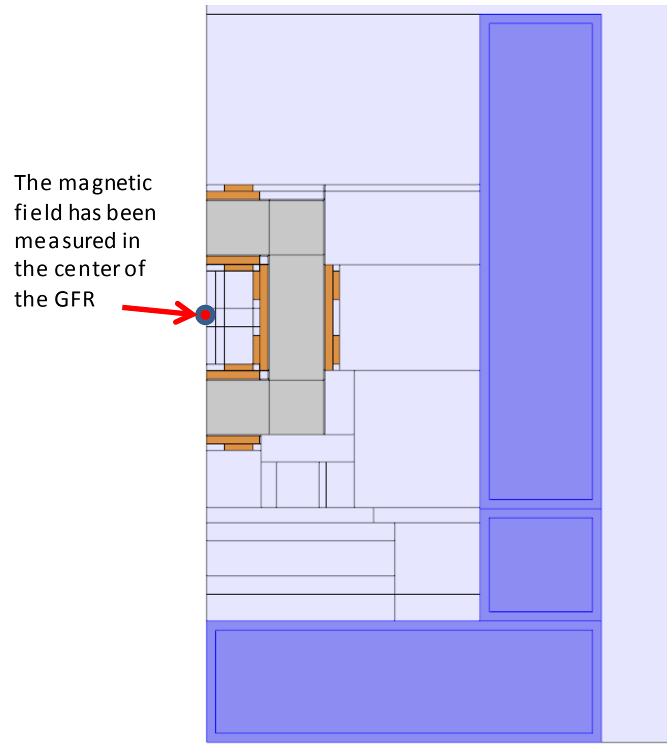
Magnetic field homogeneity

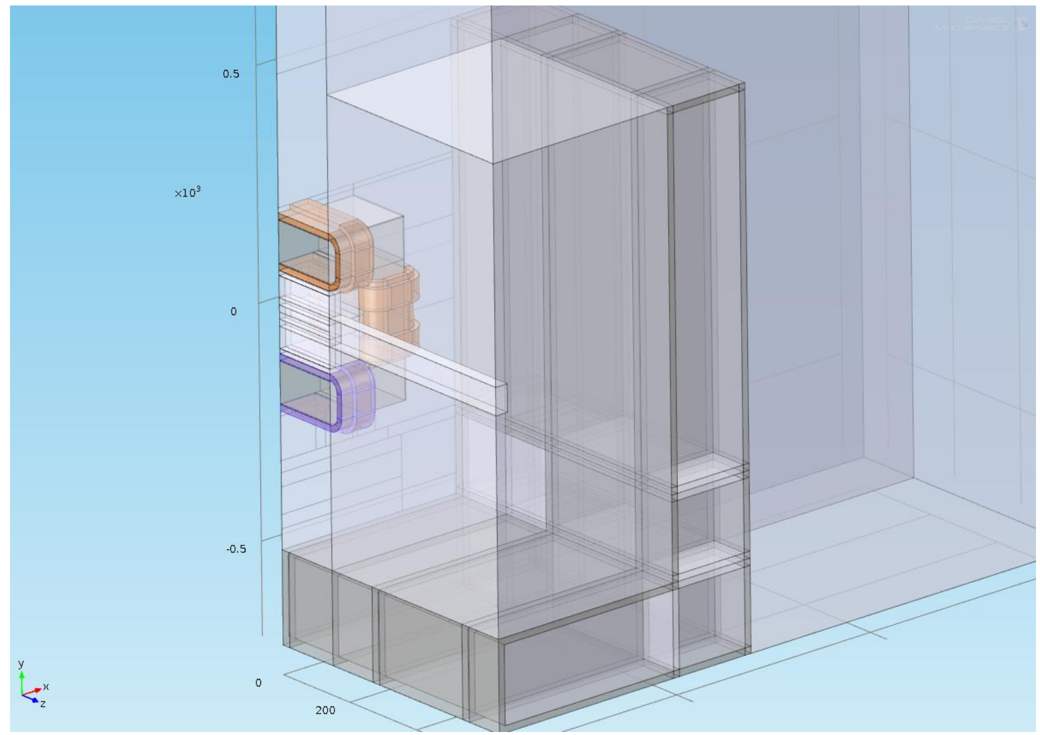




Static Simulations

rotator

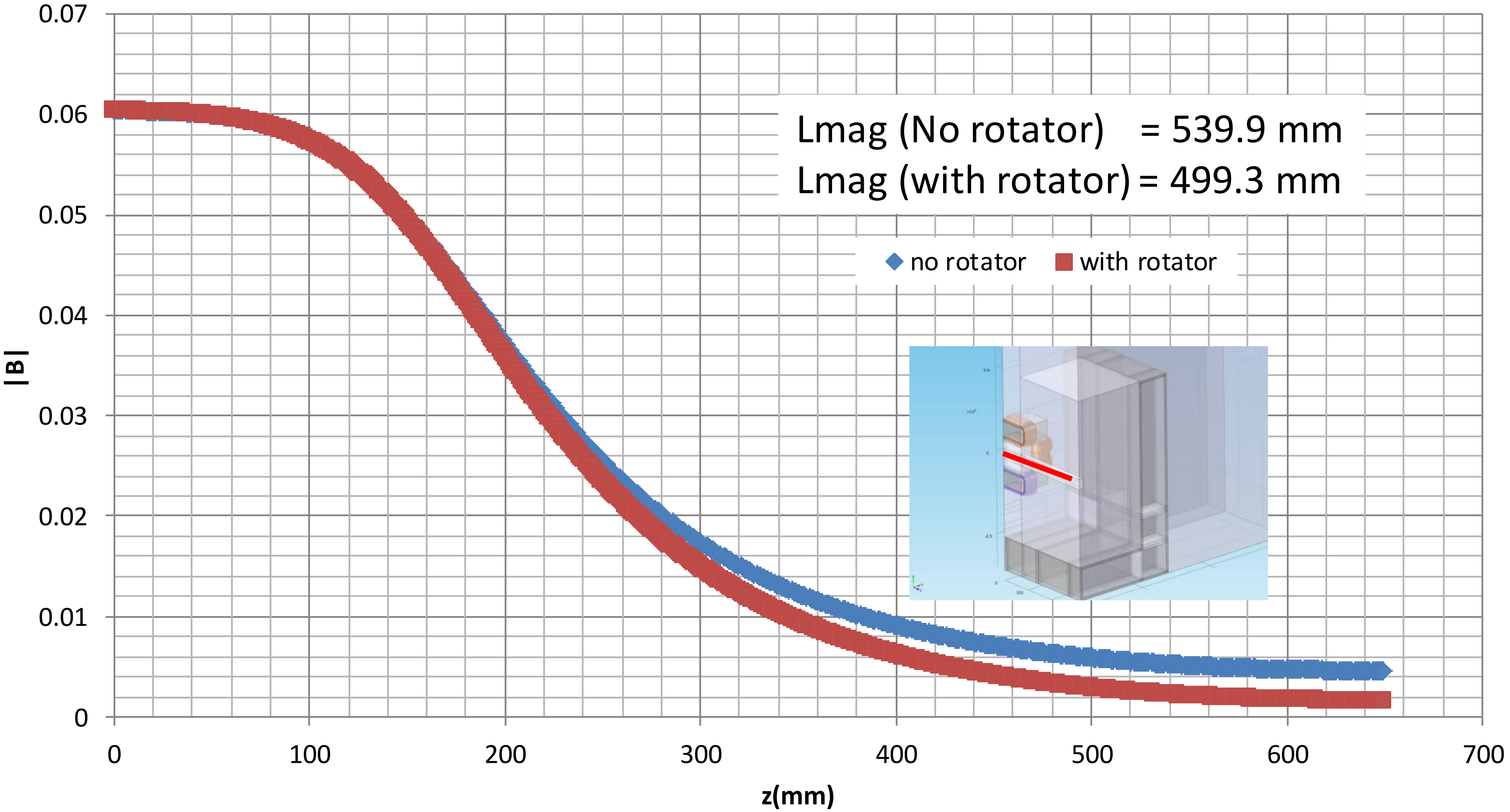




2D geometry implementation In the FEM code

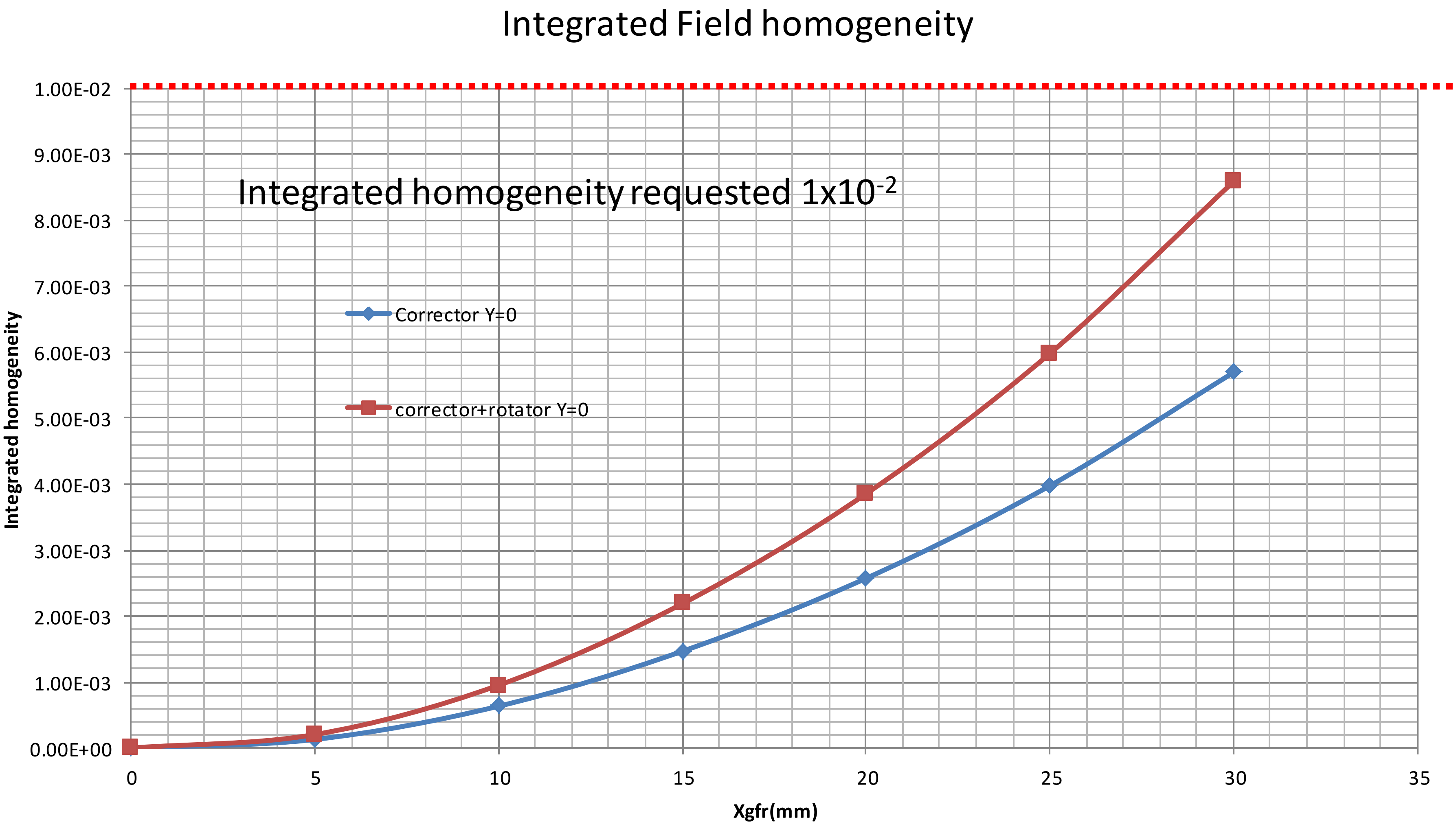
3D geometry implementation in the FEM Code

Static simulations



Longitudinal magnetic field profile in the center of the GFR. Blue line corrector without rotator
Red line corrector inside the rotator

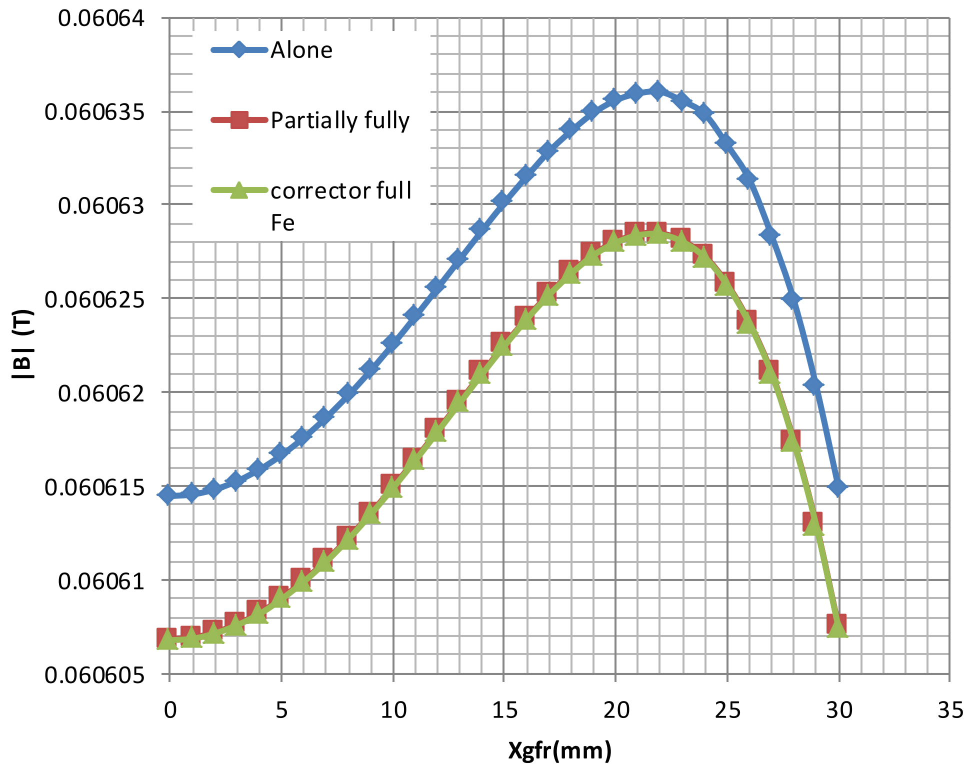
Static simulations



Static simulations

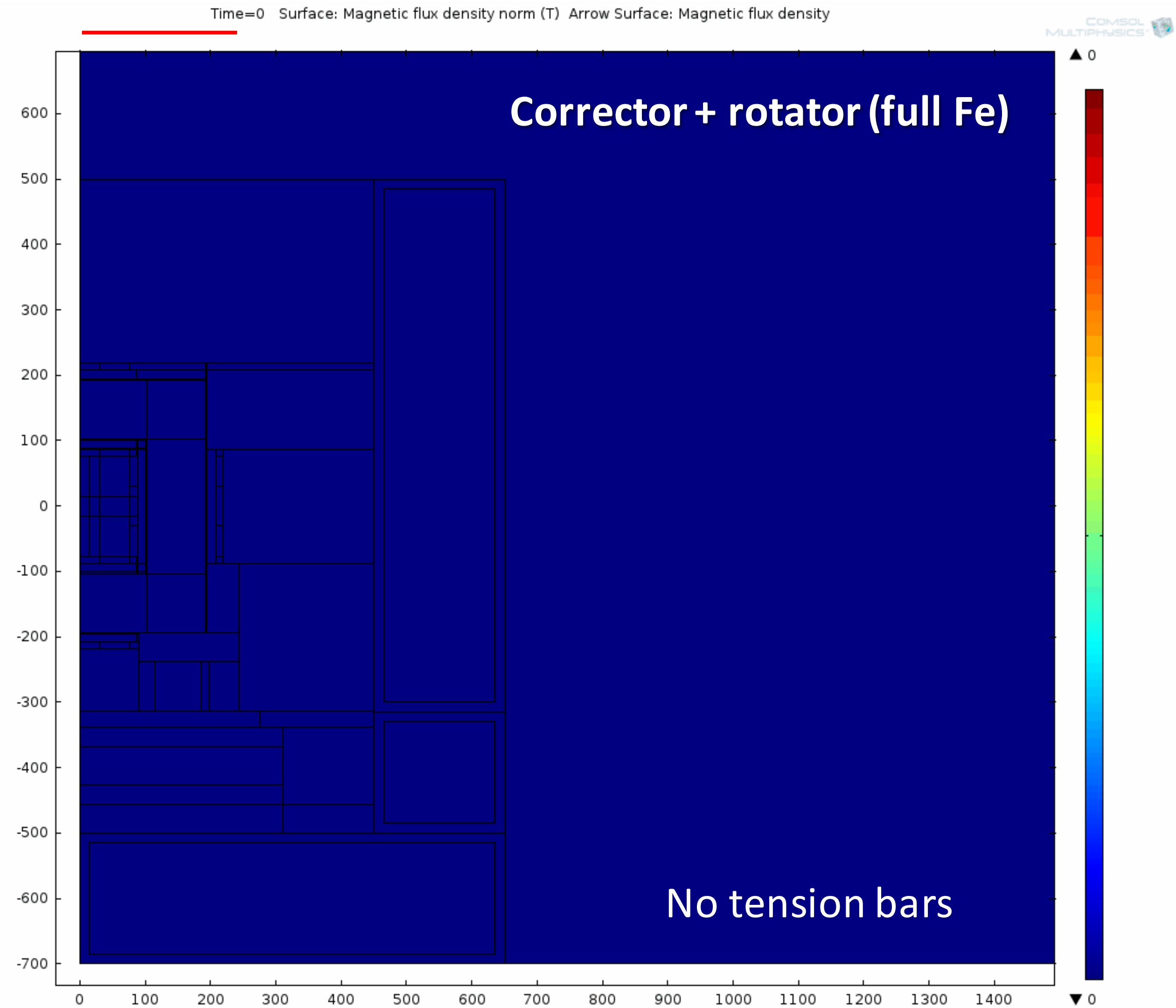
2D	B field in the center of the magnet [T]	Delta (%)
Only iron yoke	0.060614	0
Corrector + partially full of Fe	0.060606	0.012
Corrector+ Totally full of Fe	0.060606	0.012

Values of the magnetic field in the center of the GFR



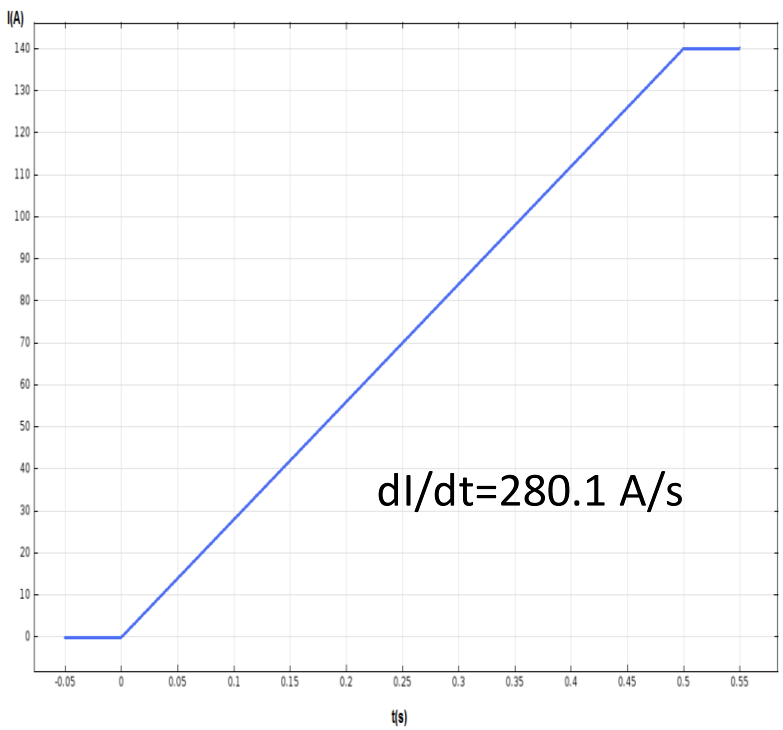
Magnetic field profile different contributions

Dynamic simulations

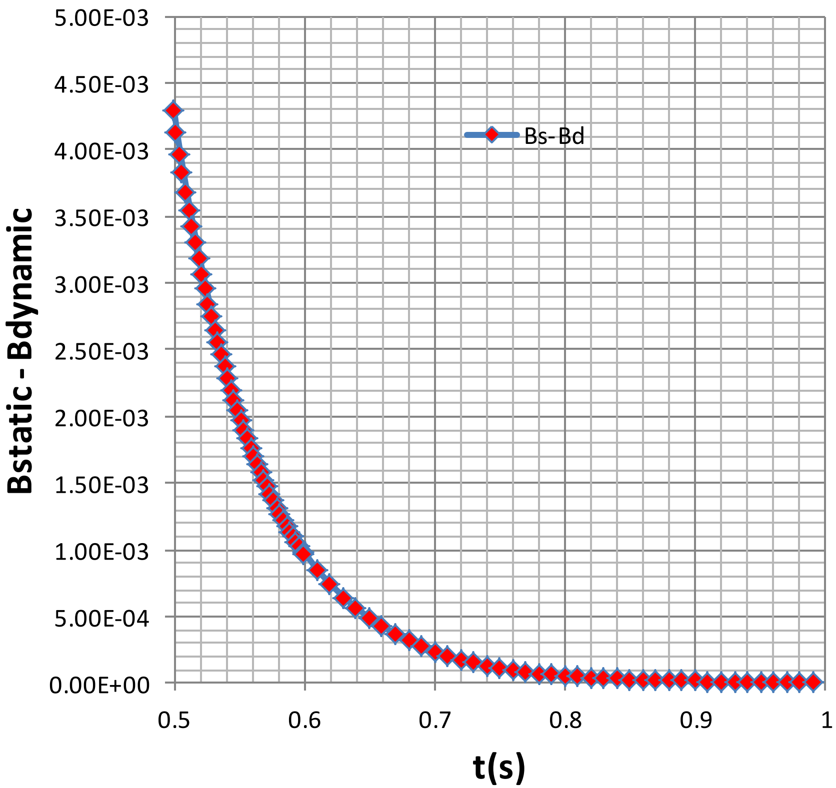


Dynamic simulations

Corrector



Linear current ramp used



The eddy currents generated in the coils and rotator structure provides a time (τ) of **0.068 s**

Remarks about the corrector magnet

- The effect of the rotator on the corrector field strength is very low (0.012%) and it can be neglected.

- 3D and dynamic simulations of the magnet in the rotator are in progress

Conclusions

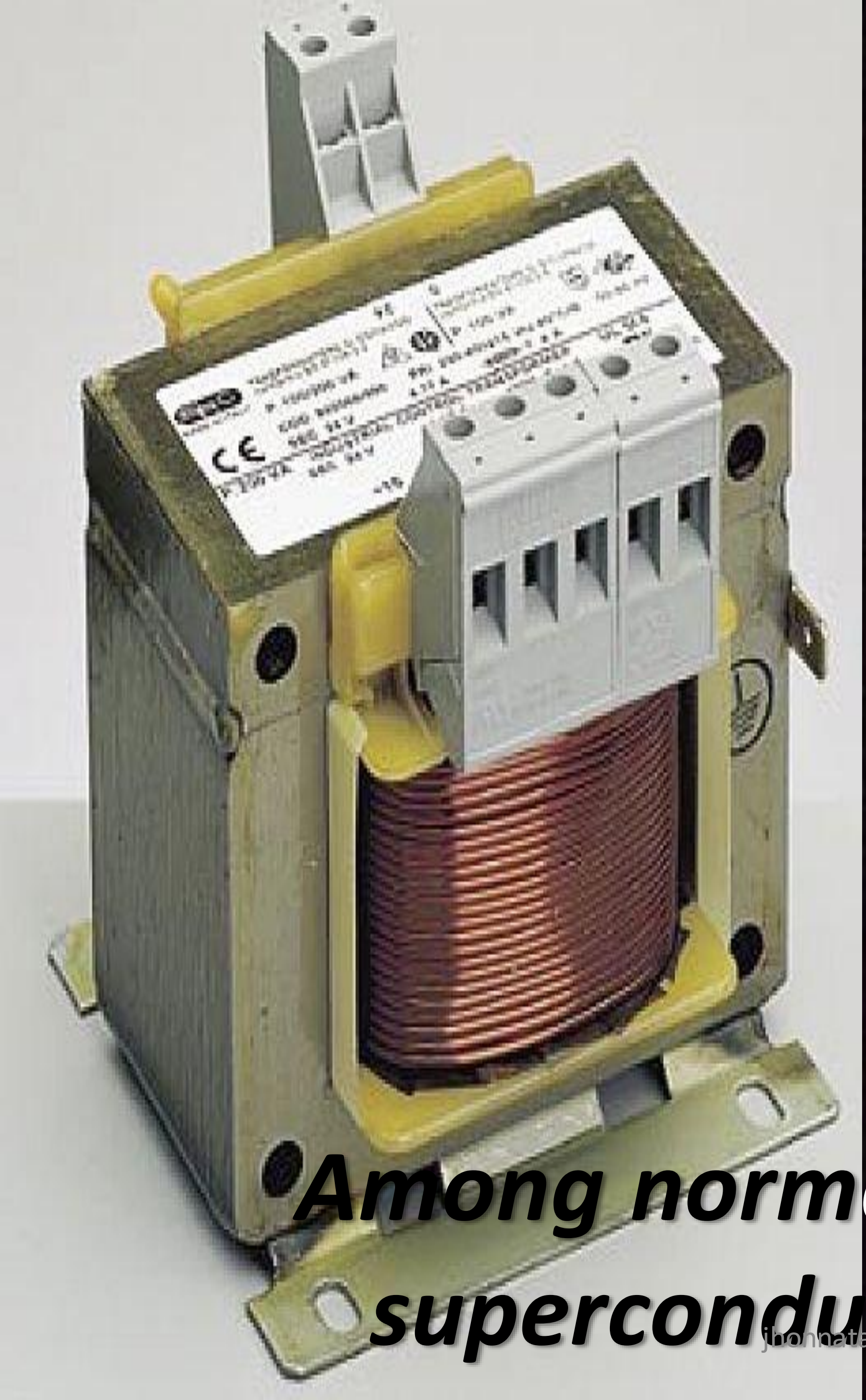
- The magnets of the gantry line have been characterized.

- In general, the dynamic effects in the transfer line magnets can be neglected because of the low ramp rate needed to follow the energy change.

- Although there is no strong impact in the dynamics of quadrupoles and correctors due to rotator structure, the magneto static 3D simulations suggest an optimization phase of magnet and rotator design to compensate the (small) effect on the field homogeneity.

Thank you for your attention

Additional slides

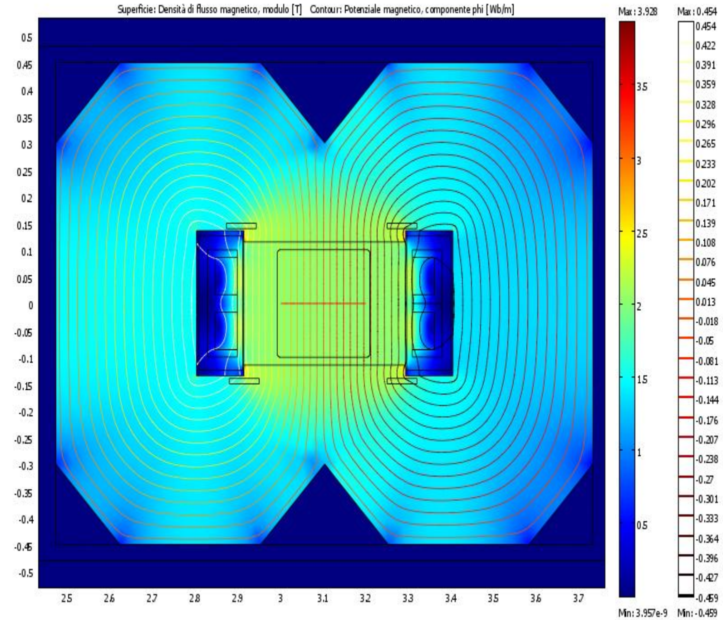


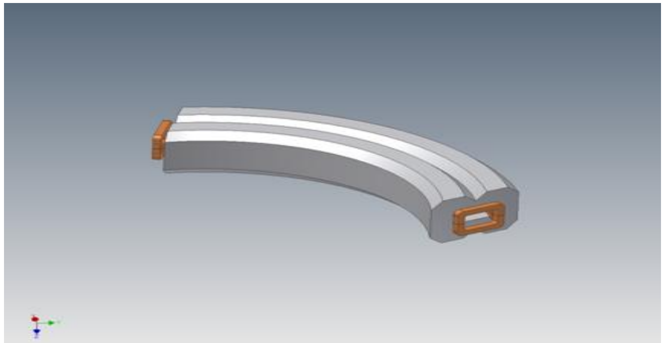
Among normal conducting or superconducting magnets

Superferric iron dominated 90° dipole

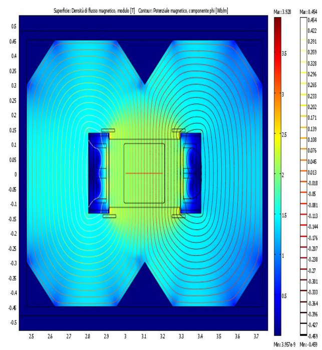
This magnet is the superconducting version of the conventional 90° dipole presently employed in the CNAO vertical line. The use of a superconducting cable allows reducing the dimension by a factor two.

The superconducting coil is placed in the cryostat, which is included into the ferromagnetic yoke





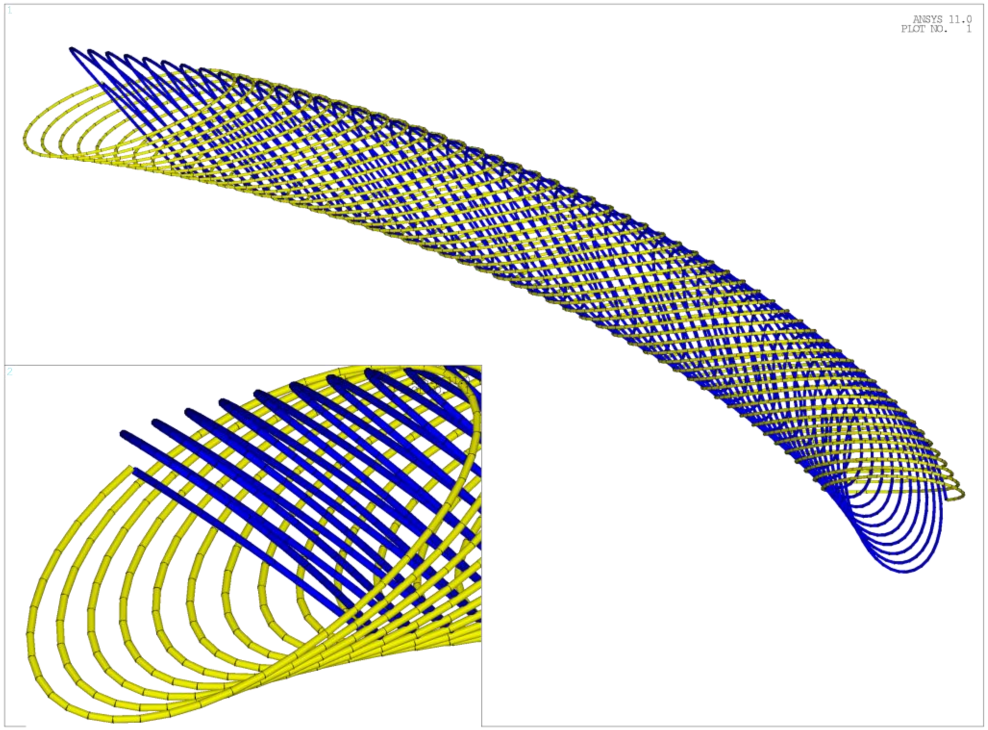
weight = 40 tons
curvture radius = 3.31 m



Superferric iron dominated 90° dipole

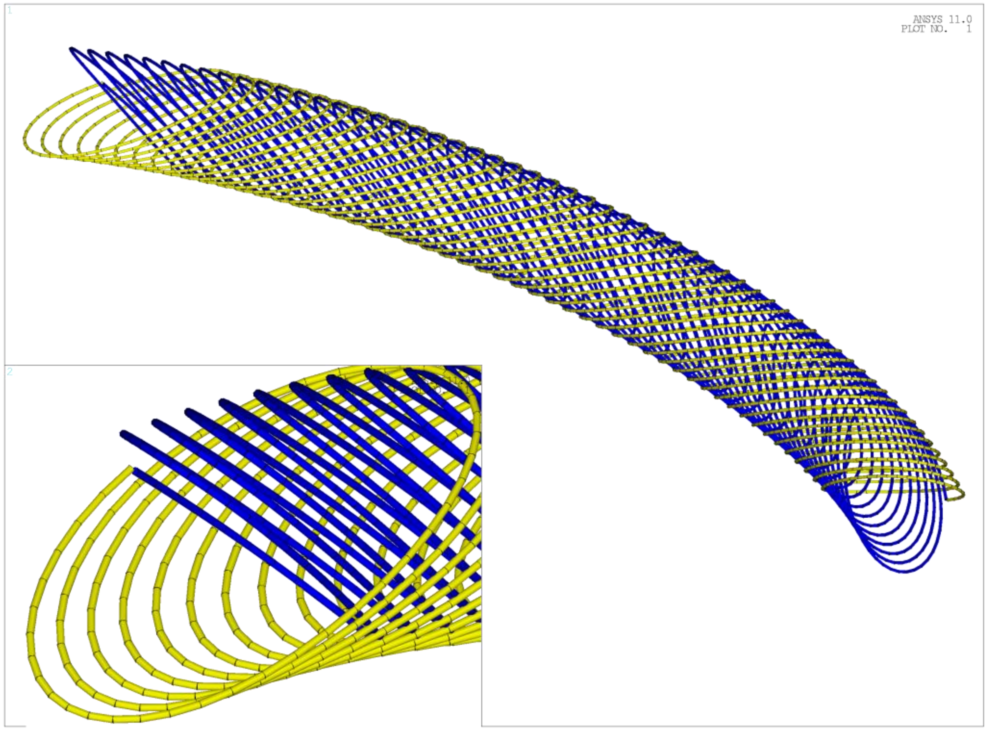
Pros	Cons
Low weight wrt normal conducting magnet	Complex winding and cryostat
Low required power at 300K wrt normal conducting magnet	AC losses at 4.2K limiting ramp rate at 0.1 T/s (0.2 T/s)
The winding is a limited part of the magnet wrt full SC magnet	Low temperature margin using NbTi (but much higher than full SC magnet)
Low AC losses wrt full SC magnet	Very difficult coil using Nb_3Sn
	Magnetic forces curbing/withstanding

Double helical coil 90° dipole



number of double layers	**1**
dipole field	3 T
bending radius	2.2 m
current	6112 A
turns per layer	838
good field region diameter	120 mm
inductance	0.12 H
stored energy	2.23 MJ

Double helical coil 90° dipole



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Detailed mechanical analyses showed that in order to hold the magnetic forces, a massive structure is required. The difficulties in finding a reasonable overall technical solution led to abandon this option in favor of a standard normal conducting 90 degree magnet