COMSOL CONFERENCE EUROPE 2012

Electromagnetic characterization of big aperture magnet used in particle beam cancer therapy

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COMSOL

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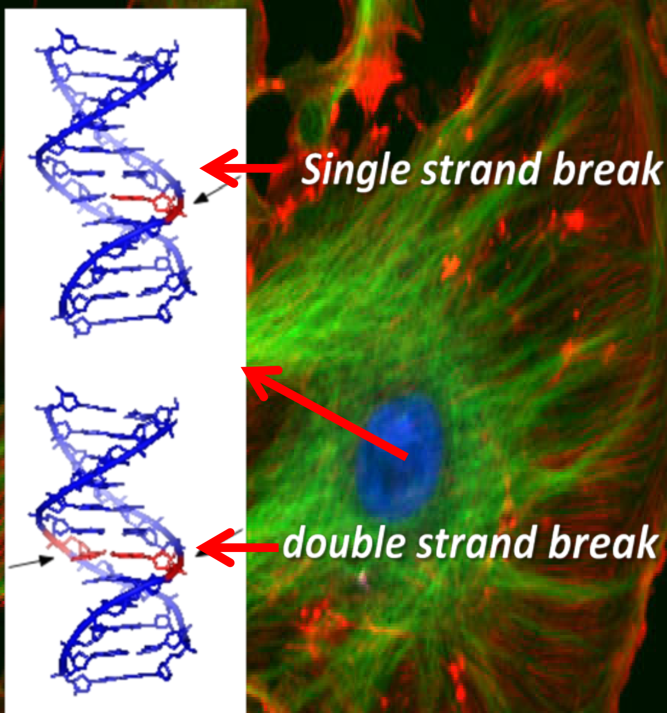
General overview

1. Introduction
2. Validation of COMSOL simulations
3. Big aperture magnet characterization
4. conclusions

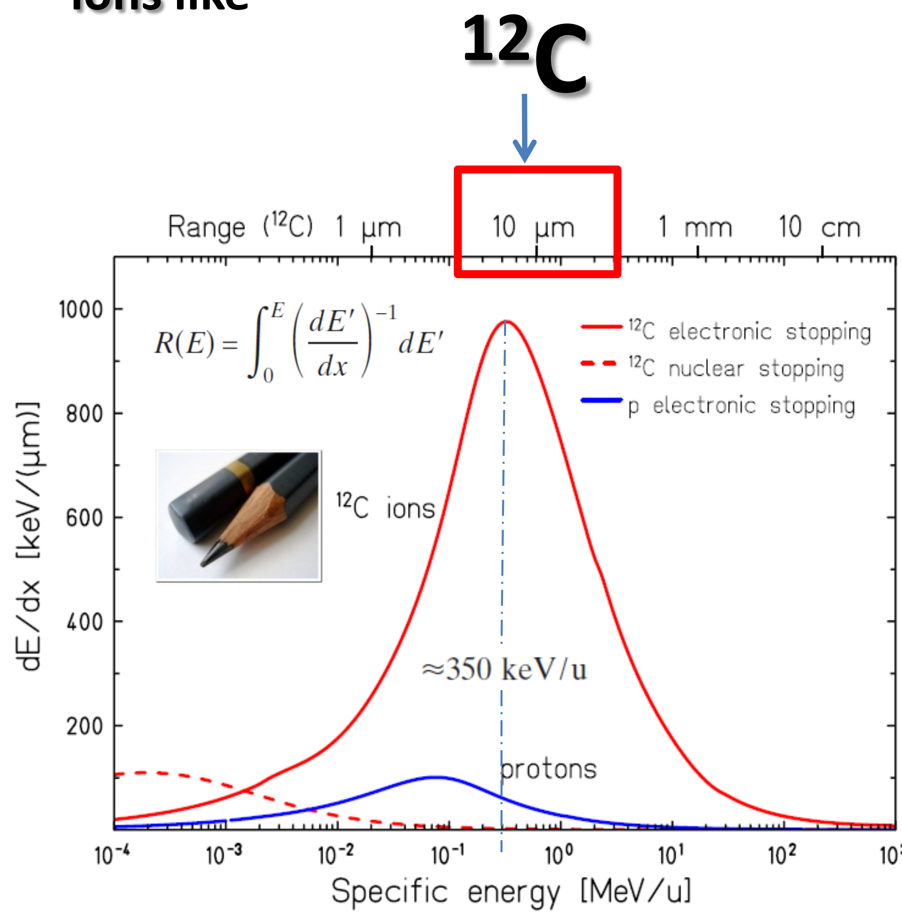
Particle beam cancer therapy is:

The external proton, ion or neutron beam irradiation to tumor cancer cells

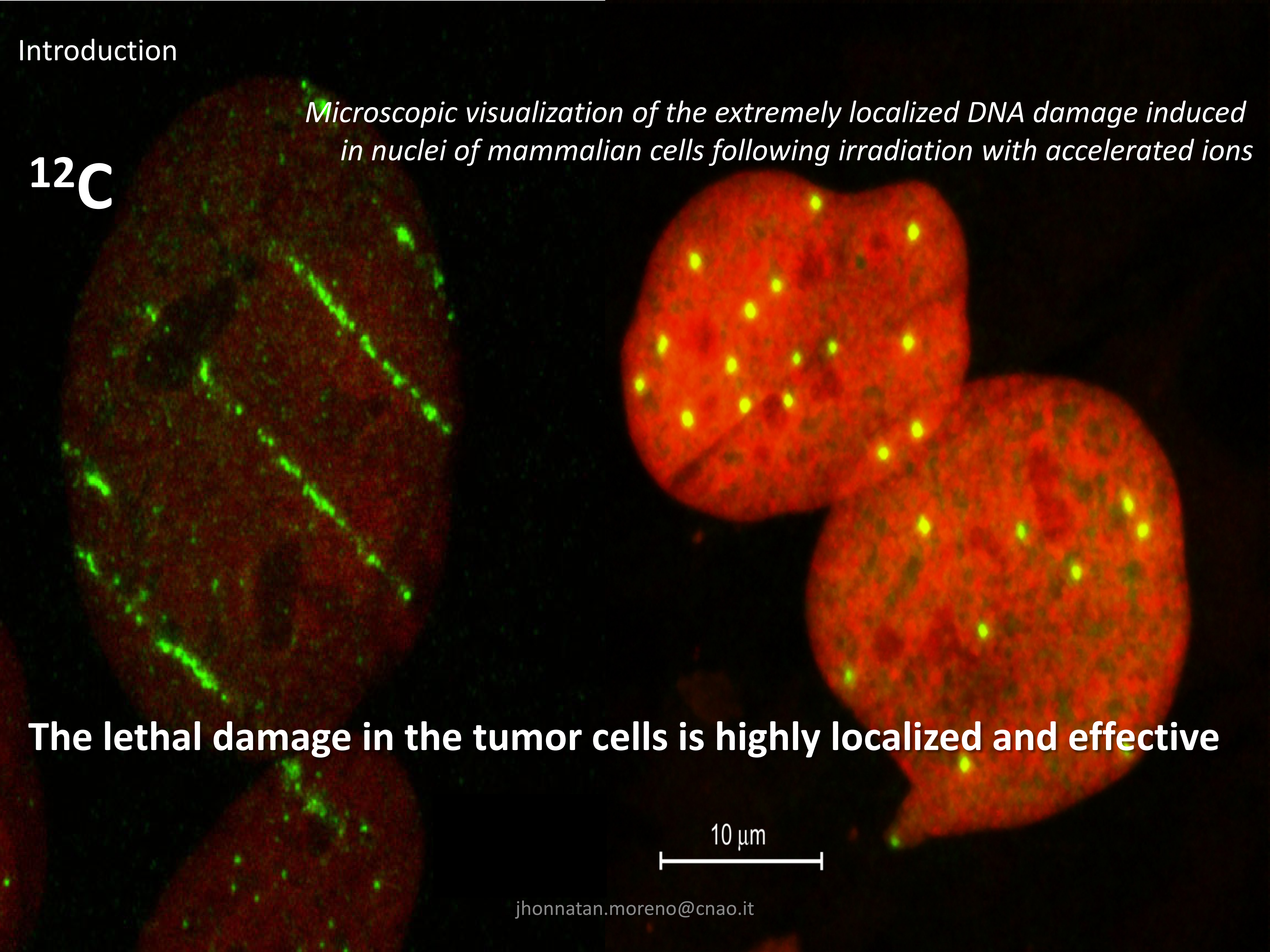
The tumor cell damage depends on the number of single and double strand breaks in DNA structure.



If the tumor tissue is irradiated with ions like

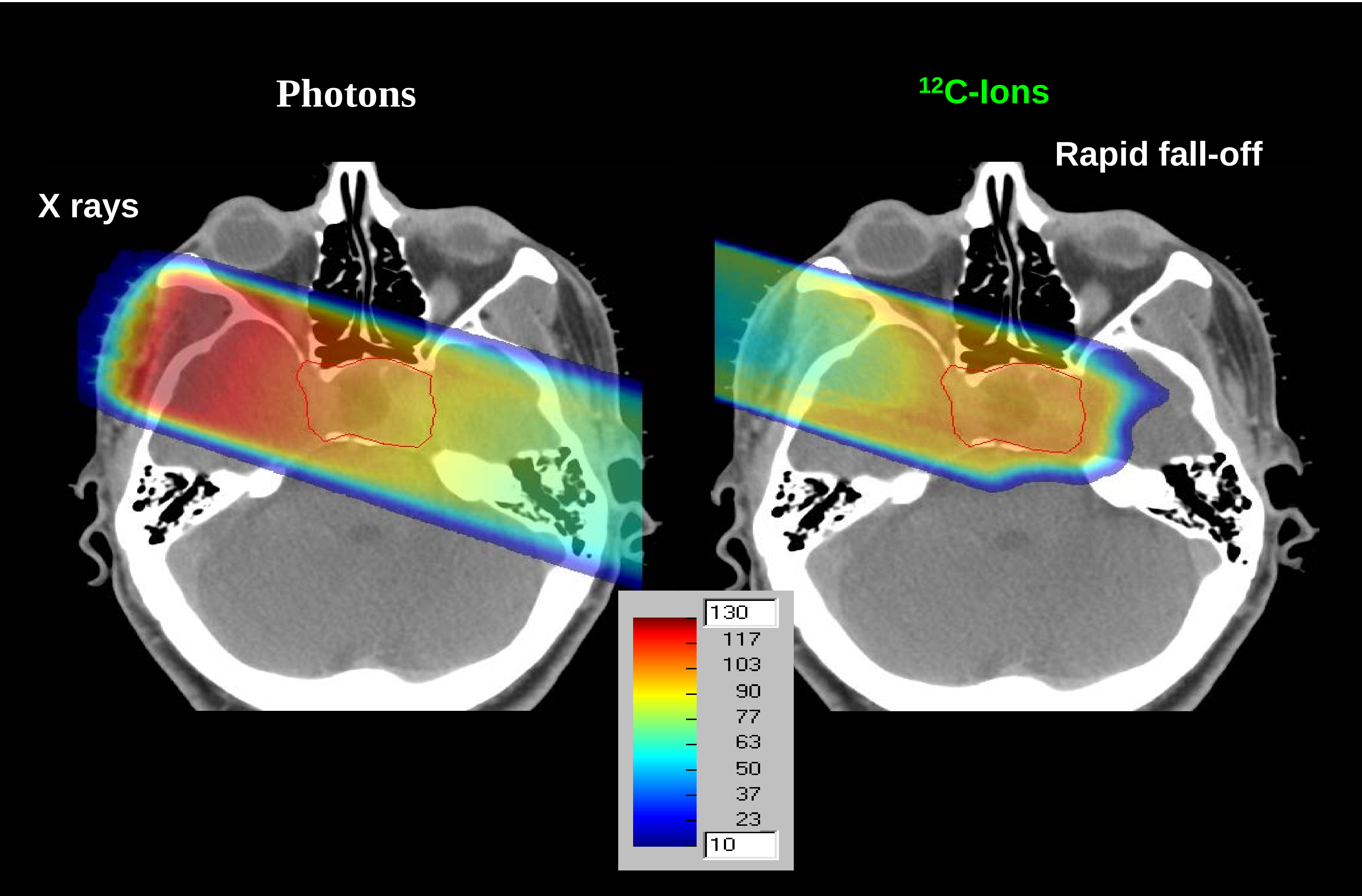


Microscopic visualization of the extremely localized DNA damage induced in nuclei of mammalian cells following irradiation with accelerated ions

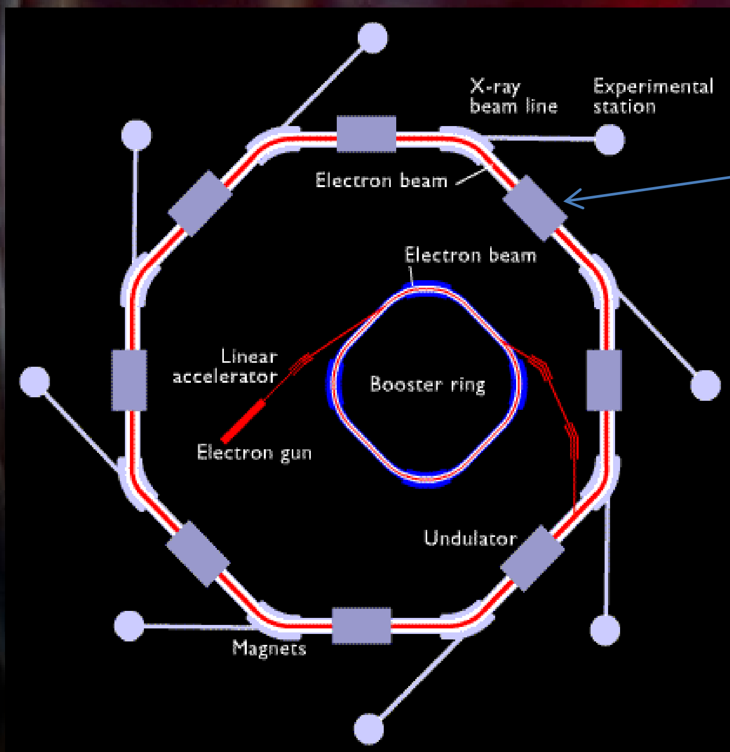


The lethal damage in the tumor cells is highly localized and effective

The particles irradiation fields have a favorable depth dose profile



Highly homogeneous magnetic fields are used to control and direct the ion beam towards the patient

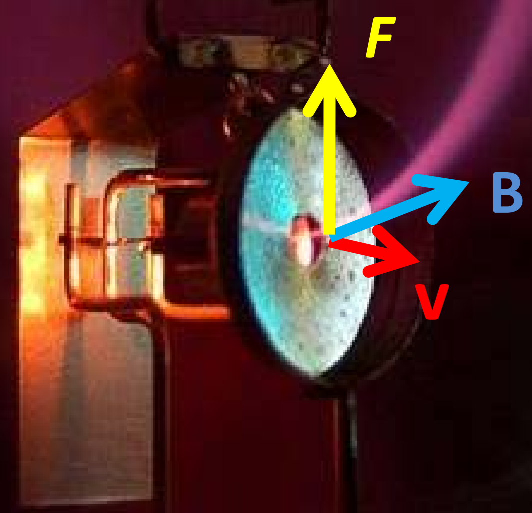


Bending magnets

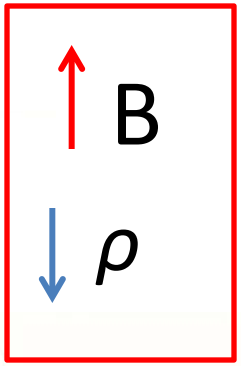
Synchrotron

Lorentz Force

$$\vec{F} = q\vec{v} \times \vec{B}$$



Bending radius (ρ) and magnetic rigidity



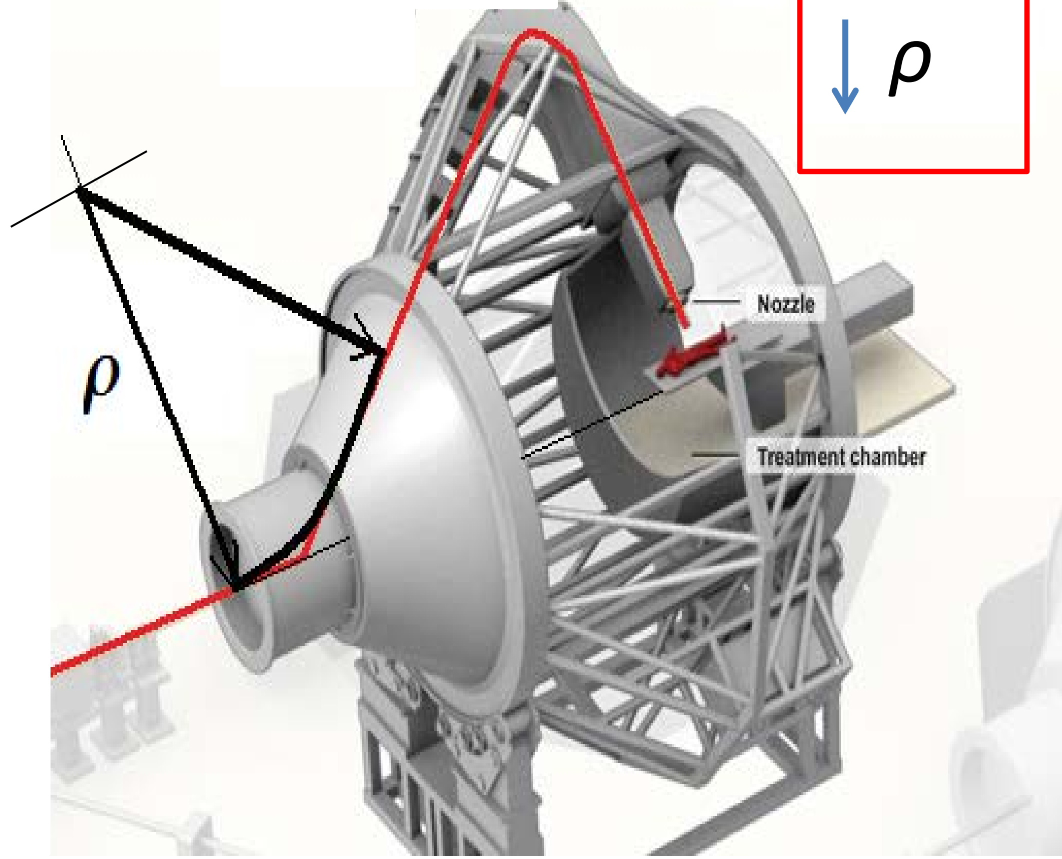
Lorentz Force

$$\vec{F} = q\vec{v} \times \vec{B}$$

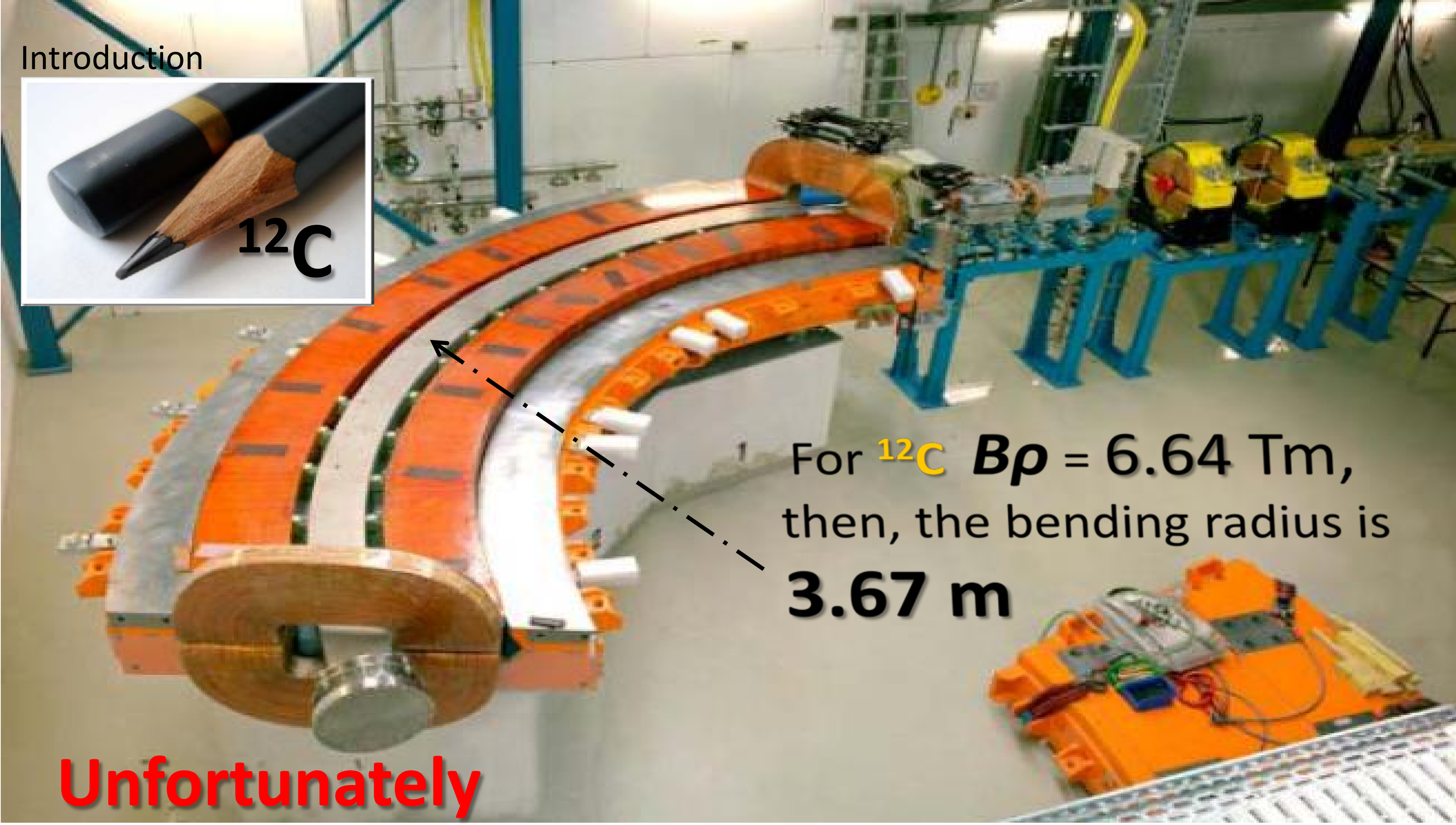
$$evB = m\frac{v^2}{\rho} \rightarrow \boxed{B\rho(Tm)} = \frac{pc}{ec}$$

Magnetic rigidity

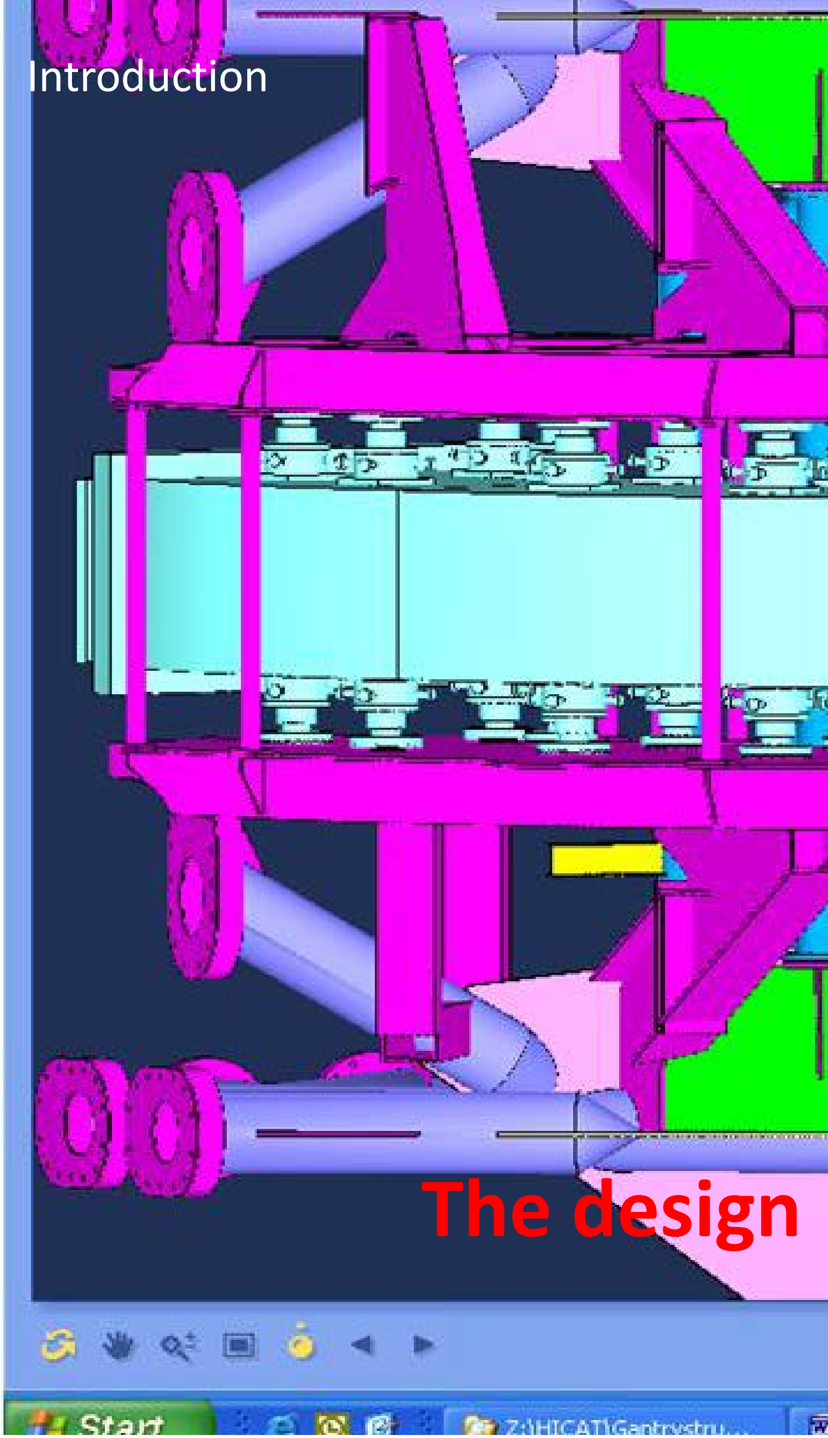
$$B\rho(Tm) = \frac{\sqrt{2E_0E_{kin} + E_{kin}^2}}{ec}$$

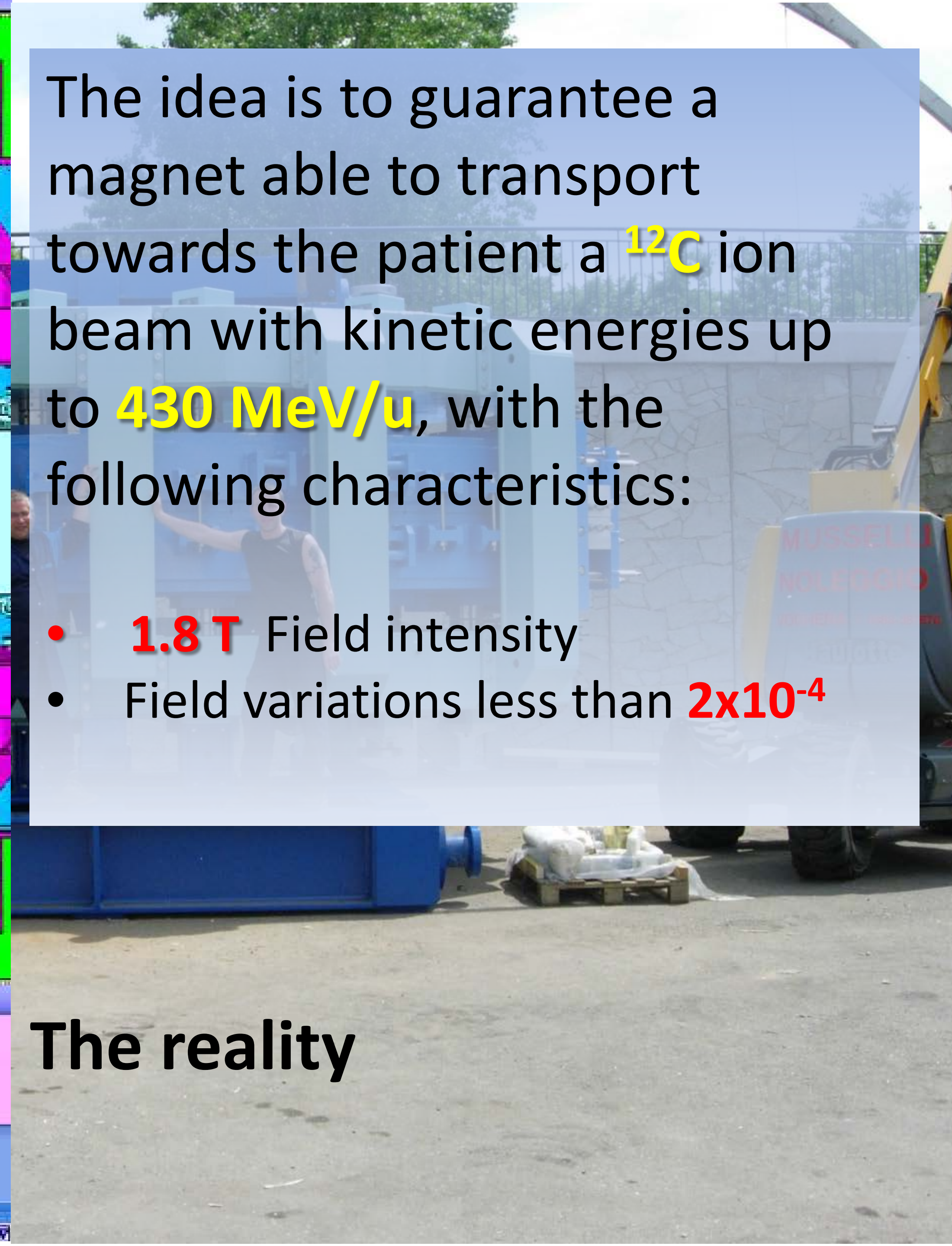


Carbon ion treatments require
430 MeV/u (~27 cm in depth)
to be clinically useful



The iron-dominated magnets only reach about B=1.8T of maximum magnetic field (B) without loosing the optimal conditions for ion beam transport.



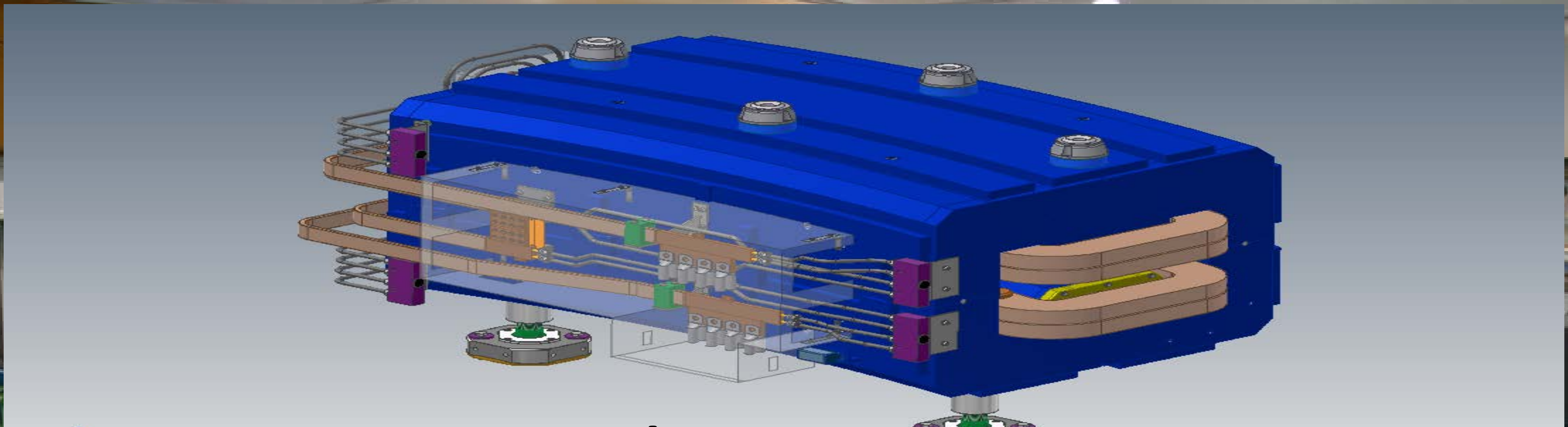


The idea is to guarantee a magnet able to transport towards the patient a **^{12}C** ion beam with kinetic energies up to **430 MeV/u**, with the following characteristics:

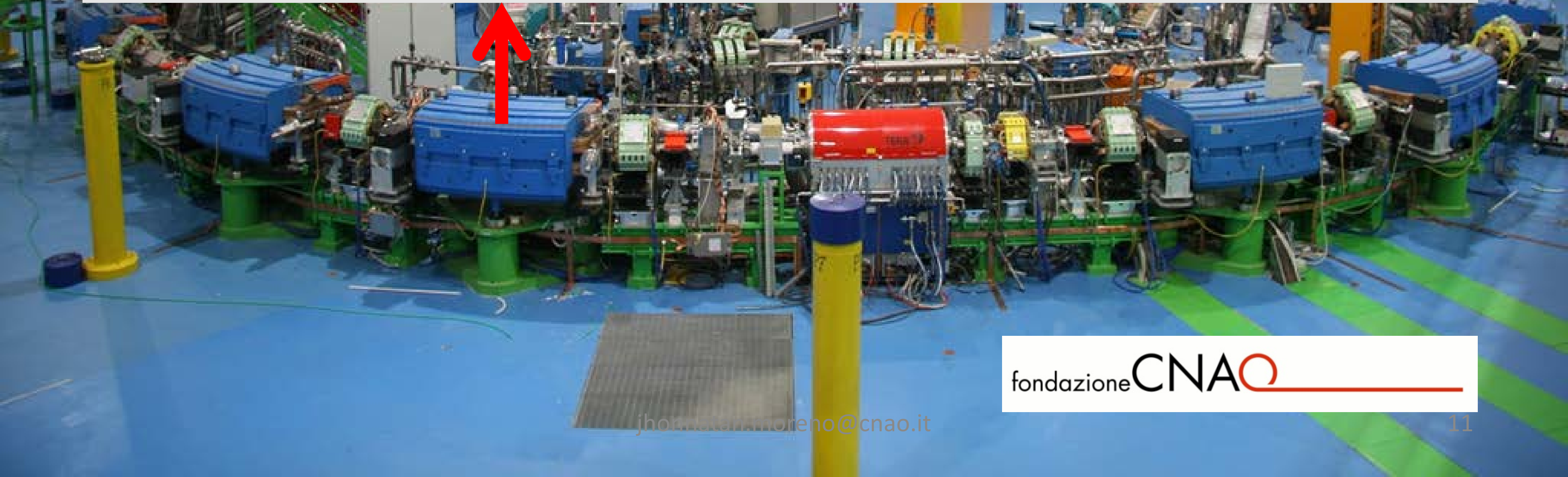
- **1.8 T** Field intensity
- Field variations less than **2×10^{-4}**

The design **The reality**

Validation of COMSOL simulations

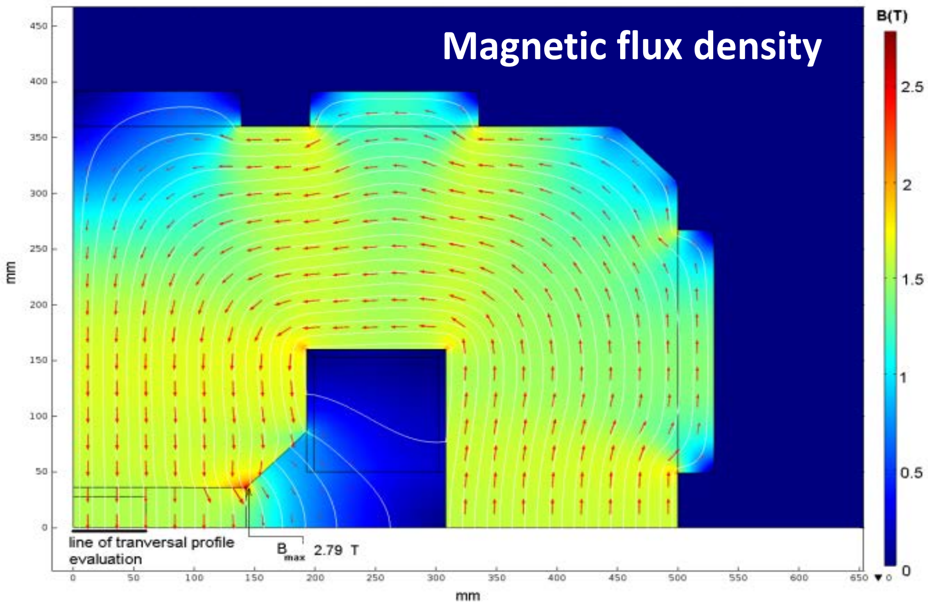


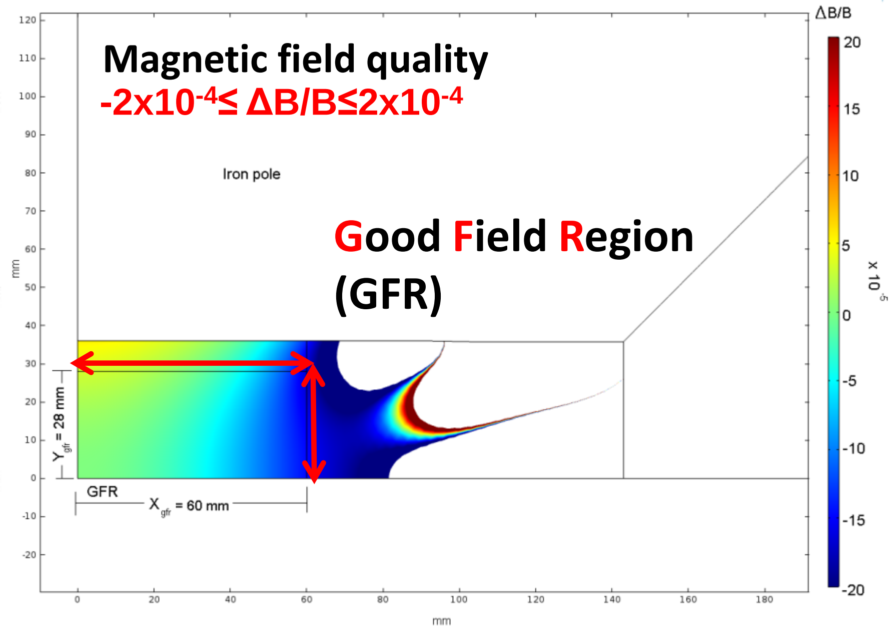
Bending dipole (π/8)

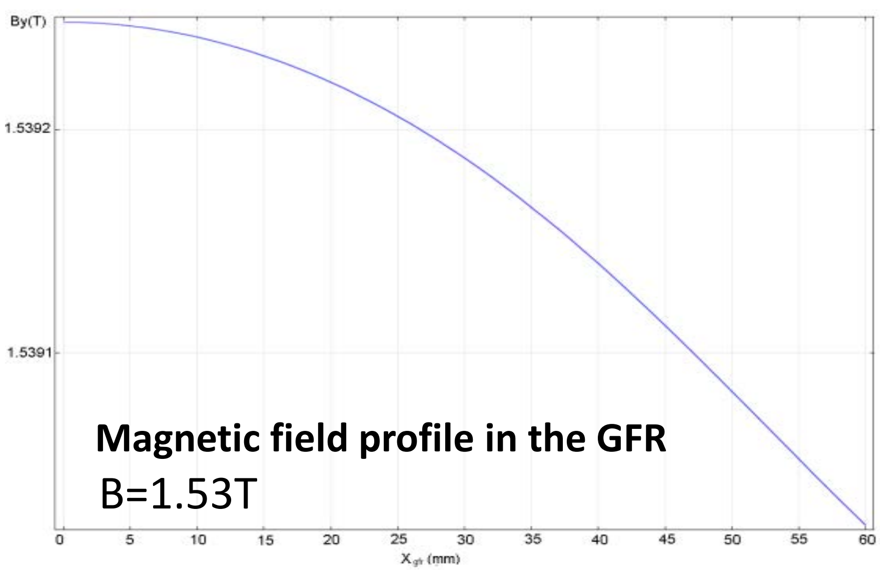


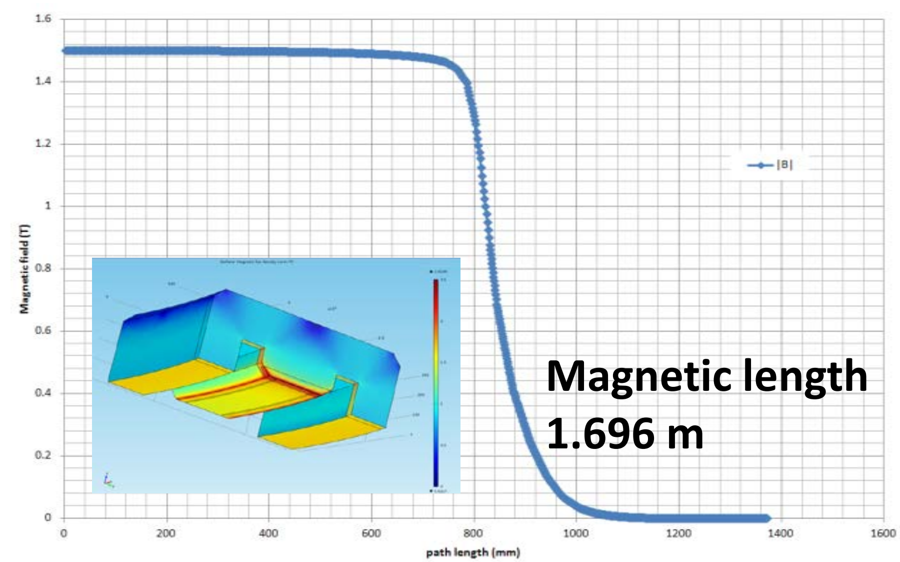
Validation of the simulations

Static Simulations



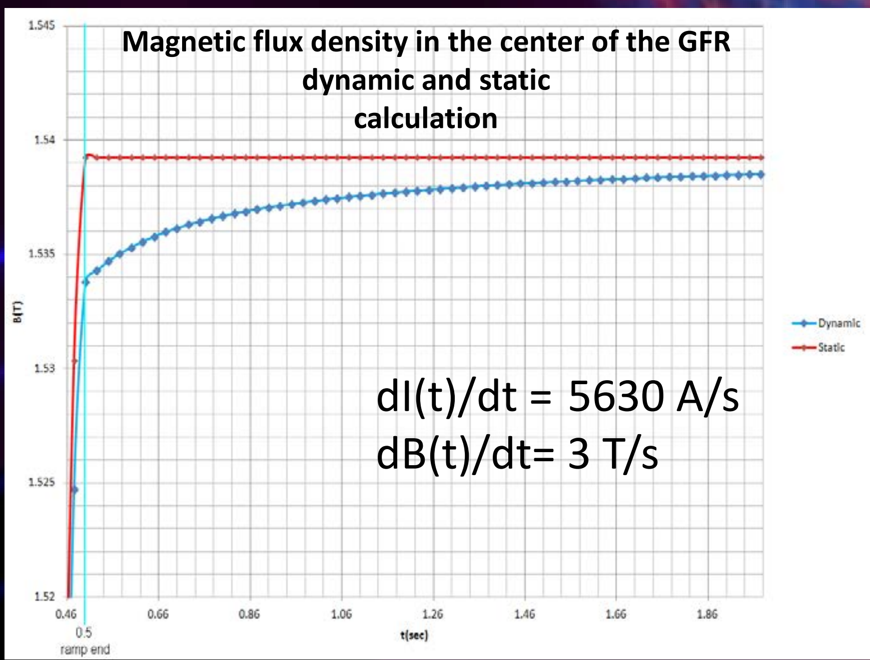


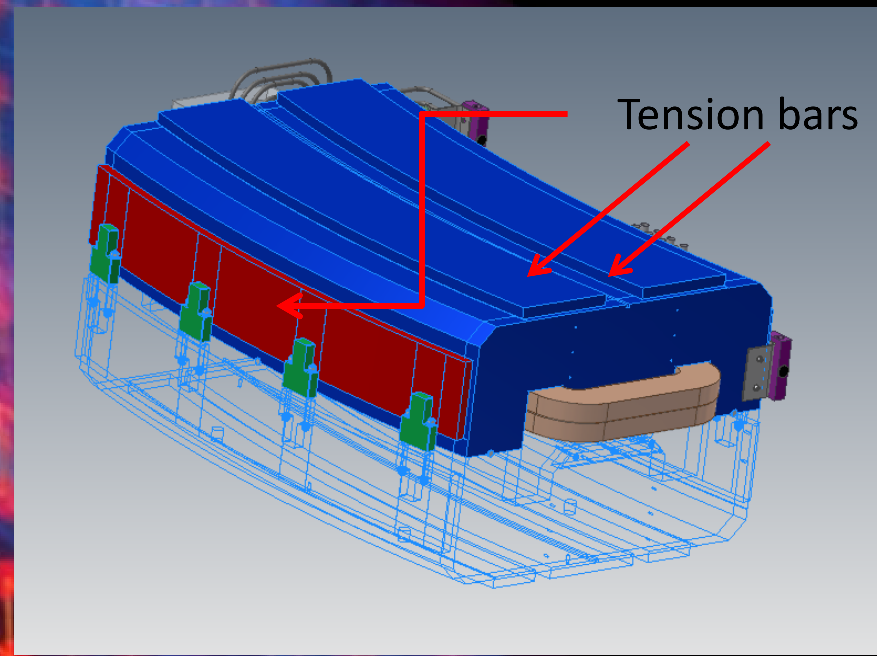




Time dependent calculations

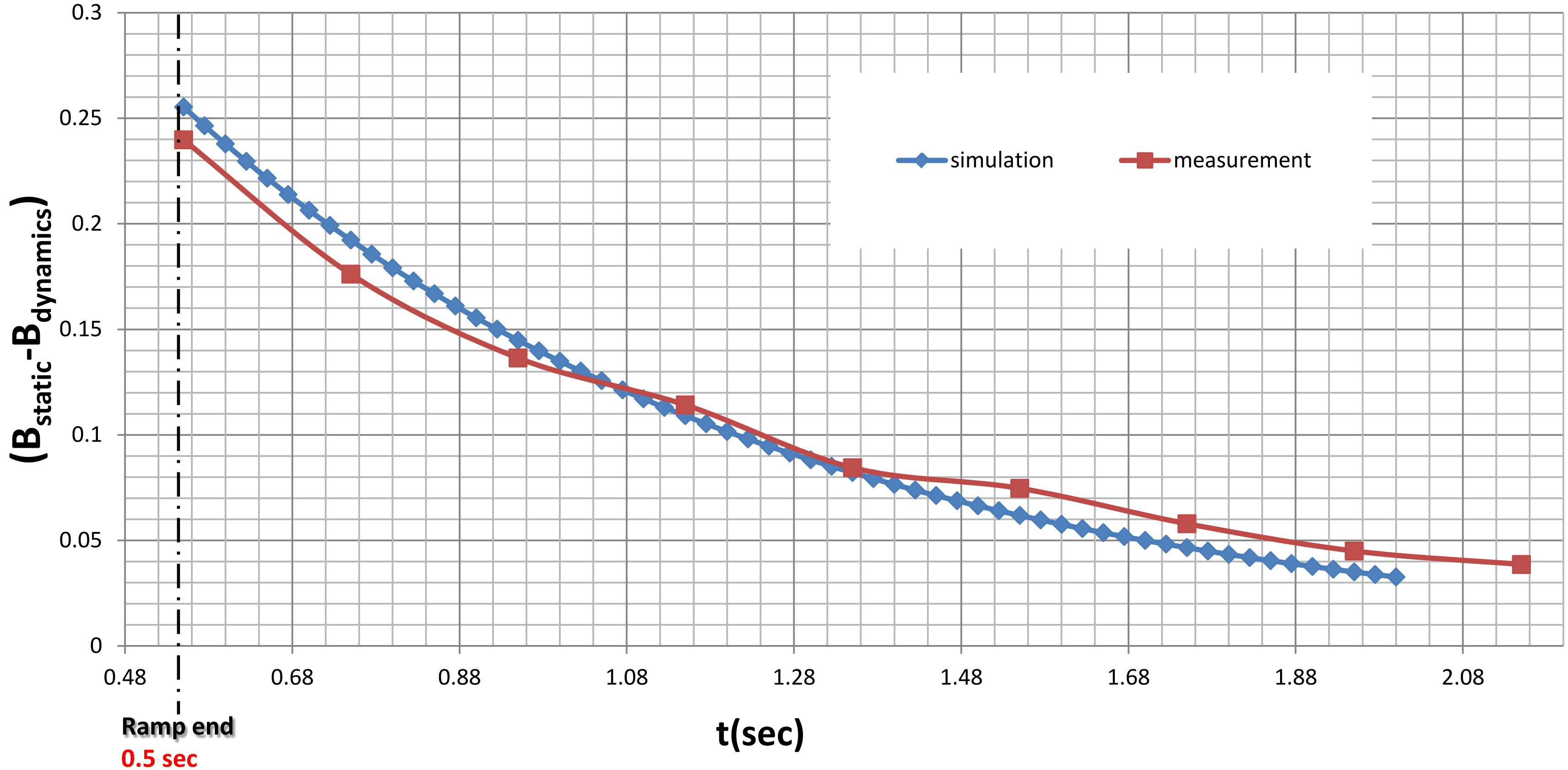
The energy beam variations during the treatment require variations in the magnetic field strength of every magnetic element in the gantry line.





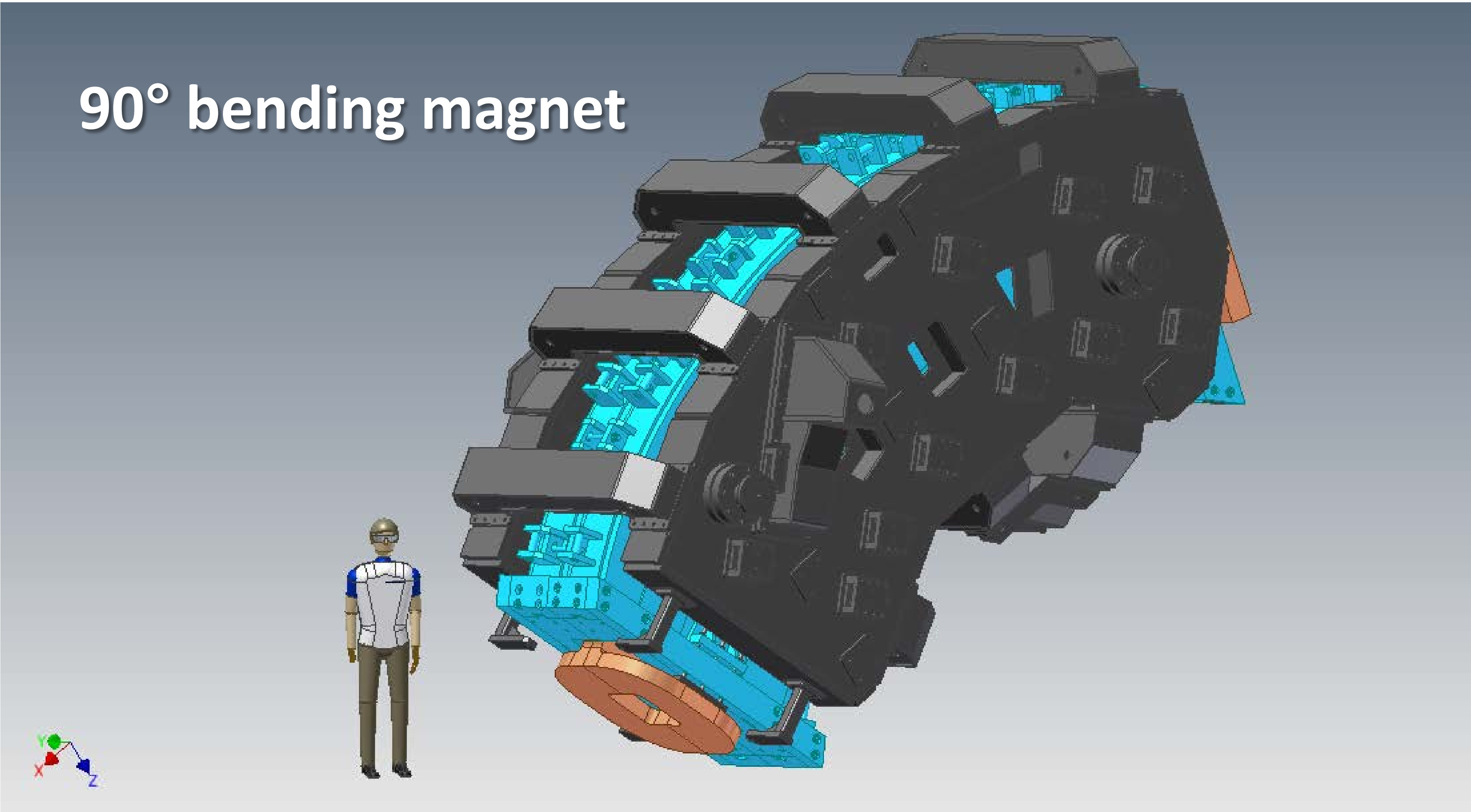
To validate the COMSOL calculations a comparison between dynamic measurements and simulations has been done

Time dependent calculations



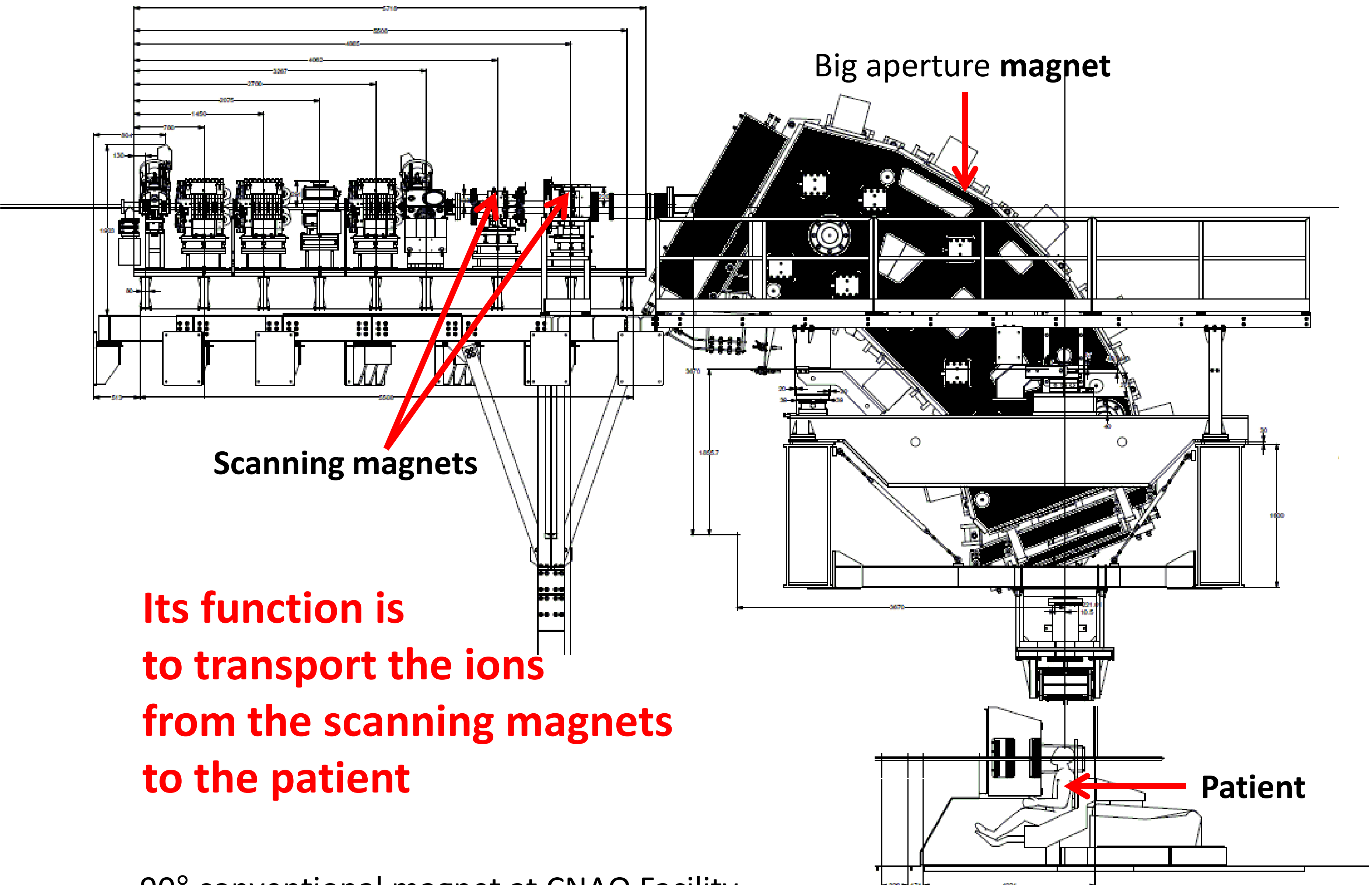
The results show a good agreement between the calculated and the measured data

90° bending magnet



Big aperture magnet characterization

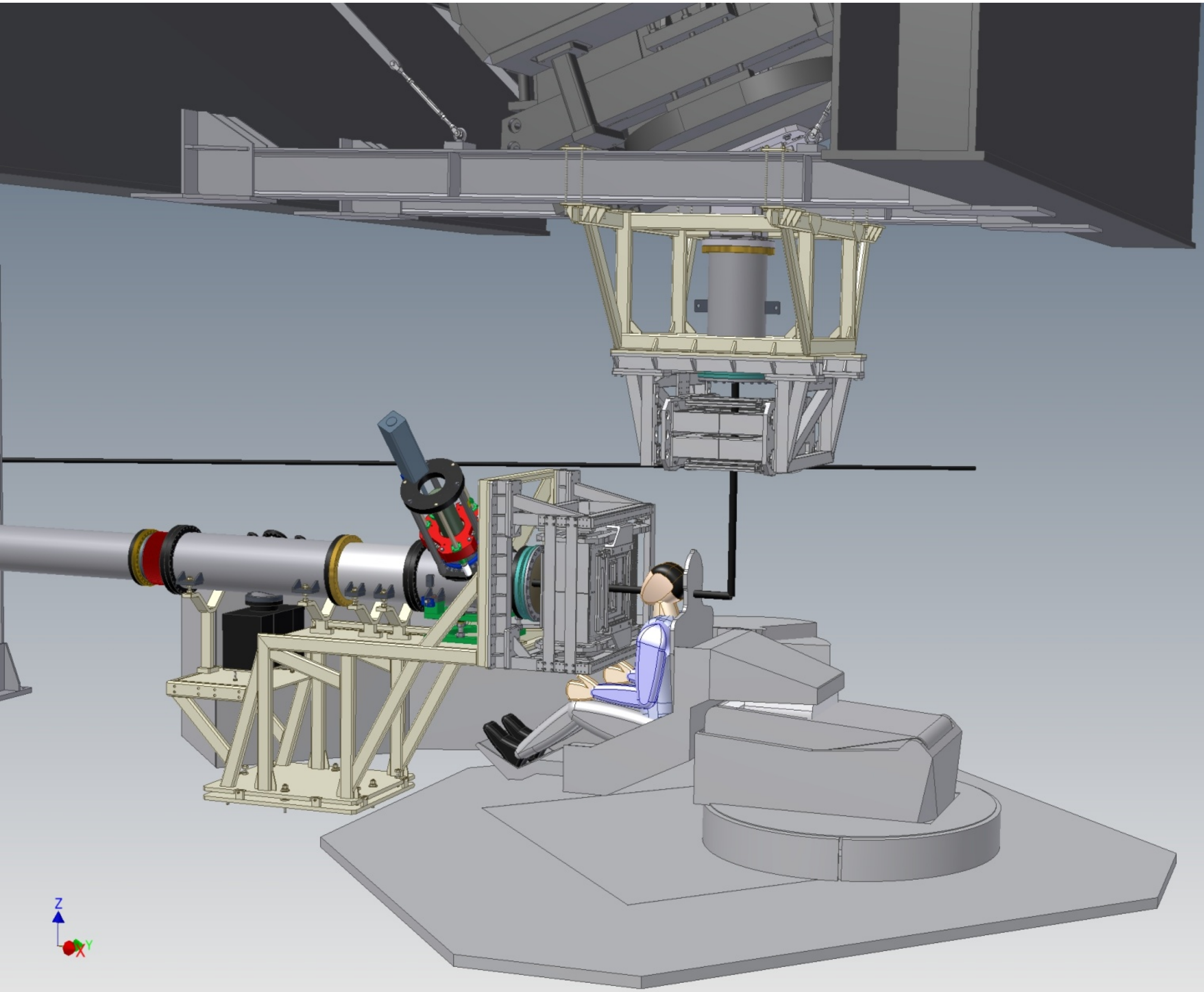
90° bending magnet



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

90° conventional magnet at CNAO Facility

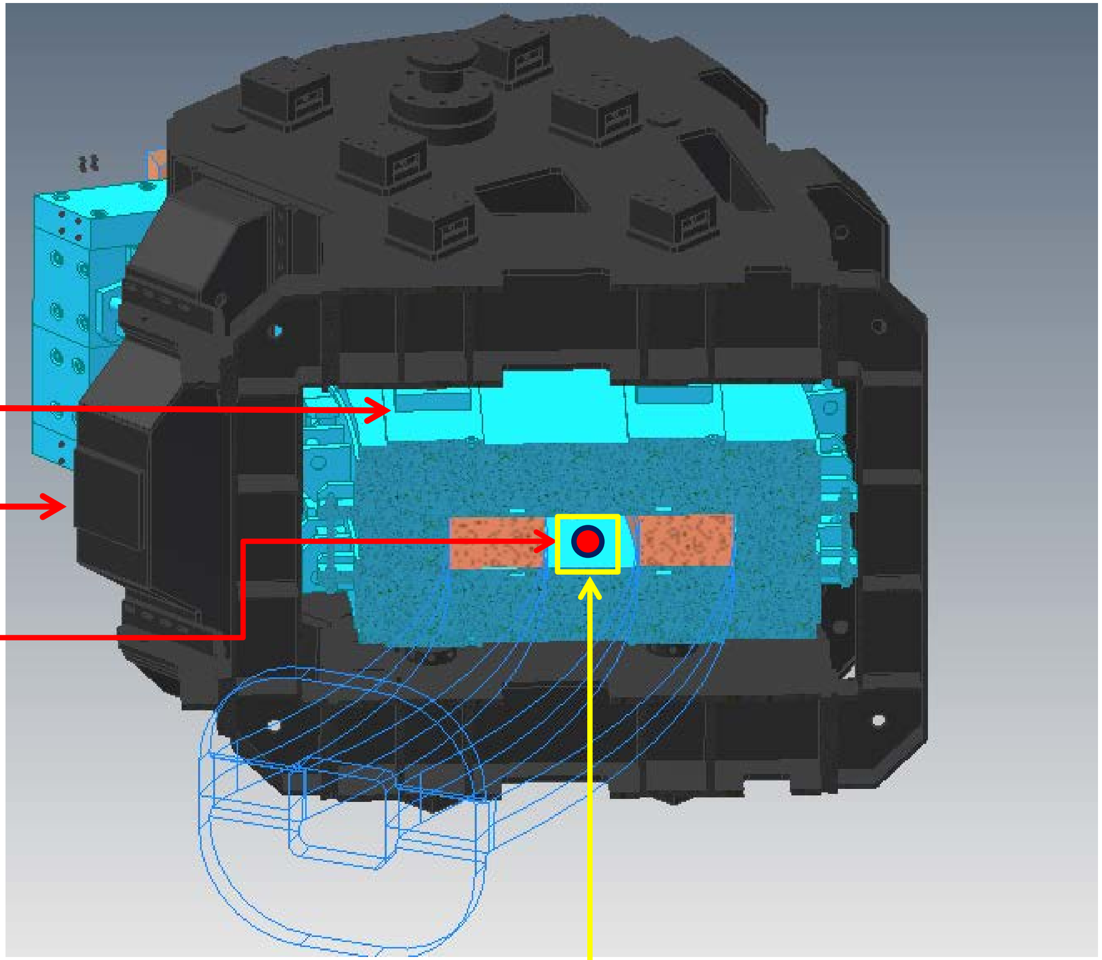
90° bending magnet



Schematic view of the treatment room

Static Simulations

This magnet has some particular features:



- Tension bars
- Ferromagnetic stiffening frame
- Magnet weight: 82 tons
- GFR: 20 x 20 cm^2
- Magnetic field quality requested in the **GFR** is **$\Delta B/B \leq 2\times10^{-4}$**

Magnetic field quality definition:

$$\frac{\Delta B}{B} = \frac{B(x,y) - B_0(0,0)}{B_0(0,0)} \quad \forall \quad x,y \in \; GFR$$

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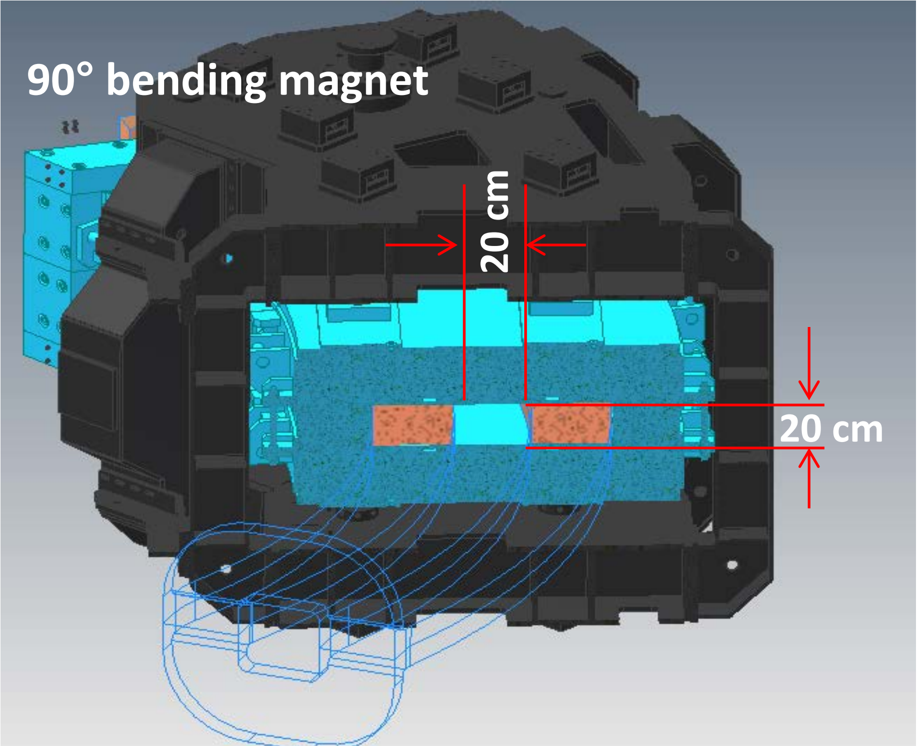
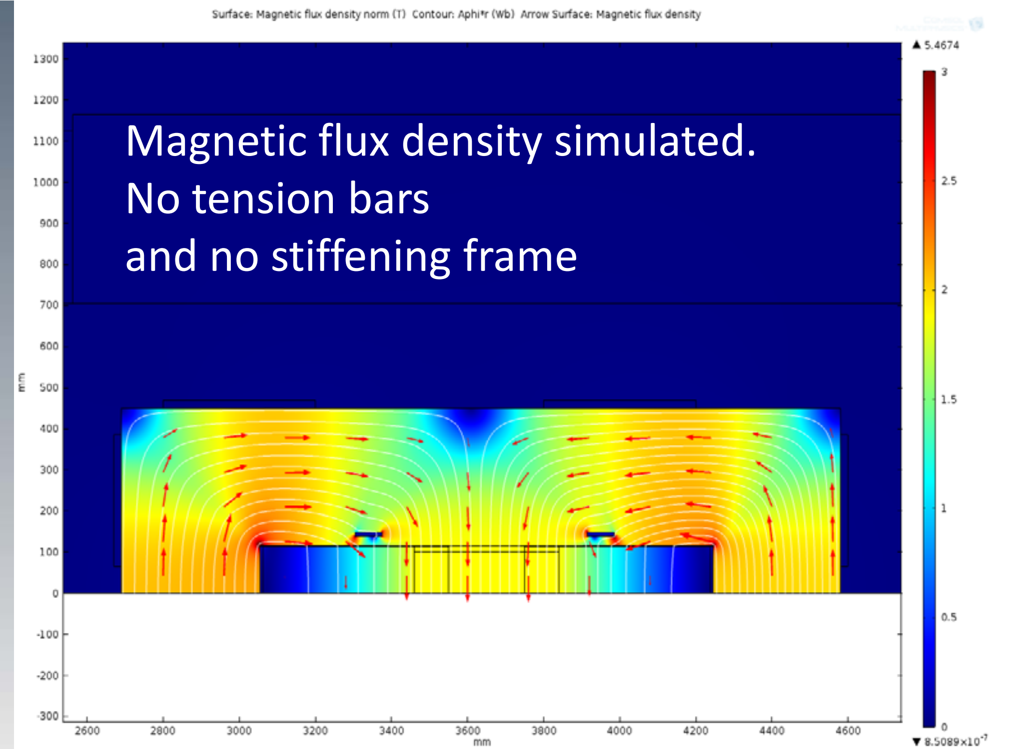
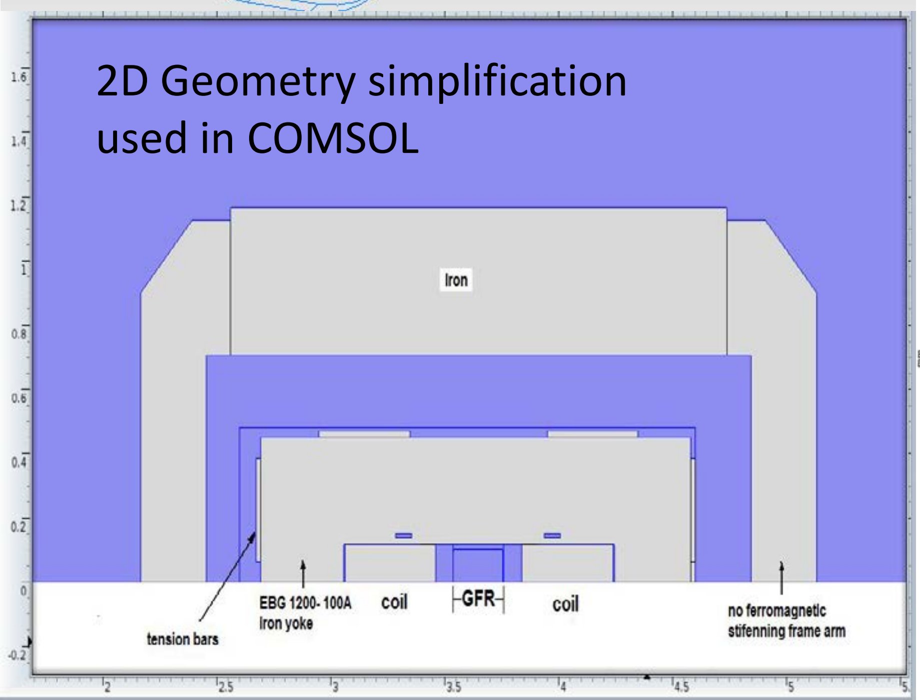
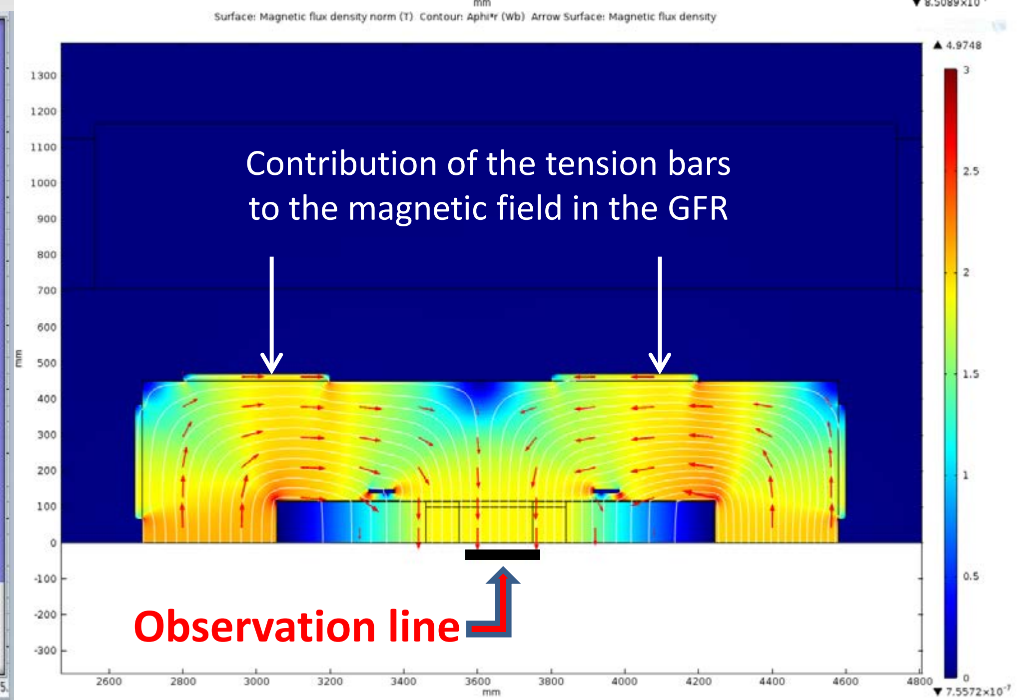

90° bending magnet
20 cm
20 cm


Surface: Magnetic flux density norm (T) Contour: Aphi*r (Wb) Arrow Surface: Magnetic flux density
Magnetic flux density simulated.
No tension bars
and no stiffening frame
mm
▲ 5.4674
▼ 8.5089×10⁻⁷


2D Geometry simplification
used in COMSOL
Iron
tension bars
EBG 1200- 100A
Iron yoke
coil
GFR
coil
no ferromagnetic
stifenning frame arm

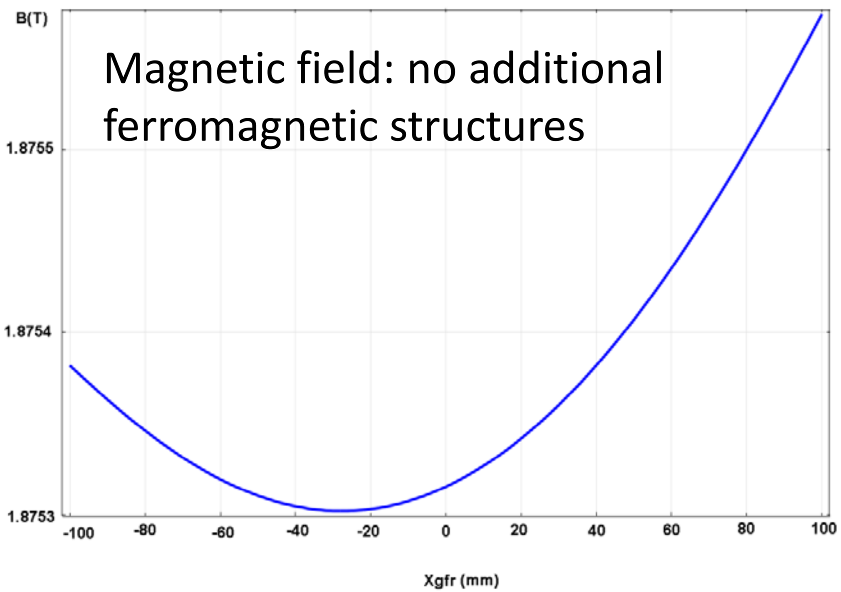

Surface: Magnetic flux density norm (T) Contour: Aphi*r (Wb) Arrow Surface: Magnetic flux density
Contribution of the tension bars
to the magnetic field in the GFR
Observation line
mm
▲ 4.9748
▼ 7.5572×10⁻⁷

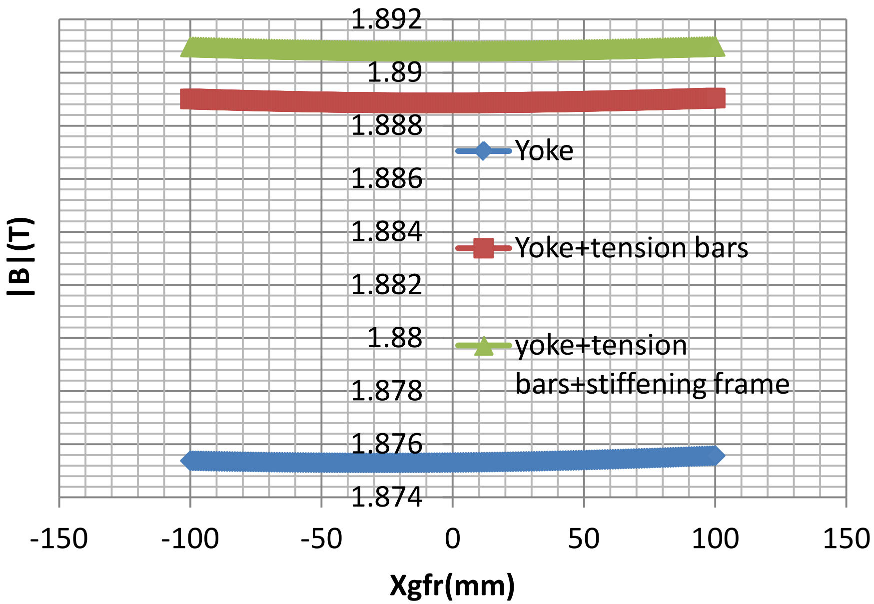
90° bending magnet

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 profiles in the center of the magnet

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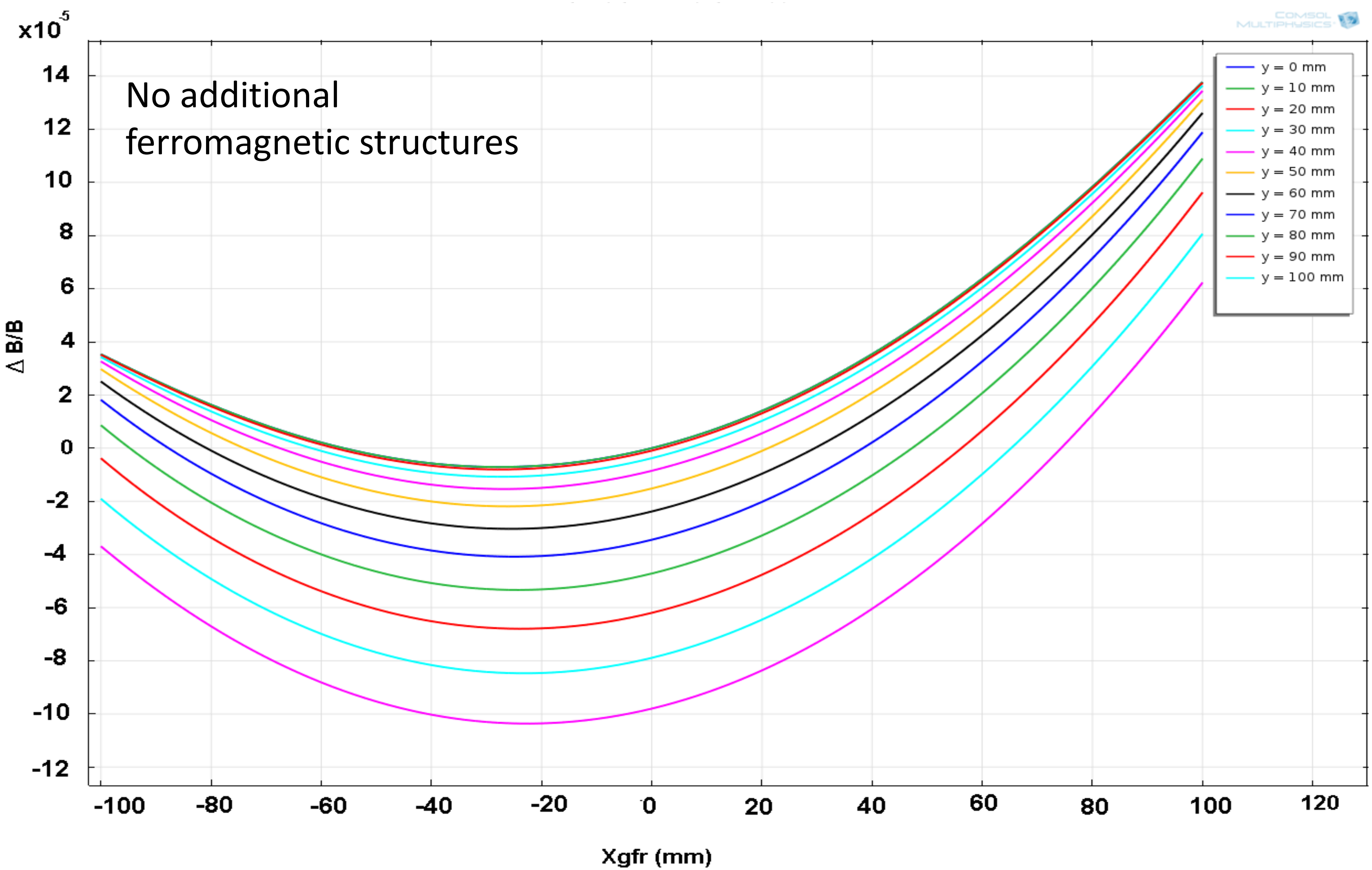
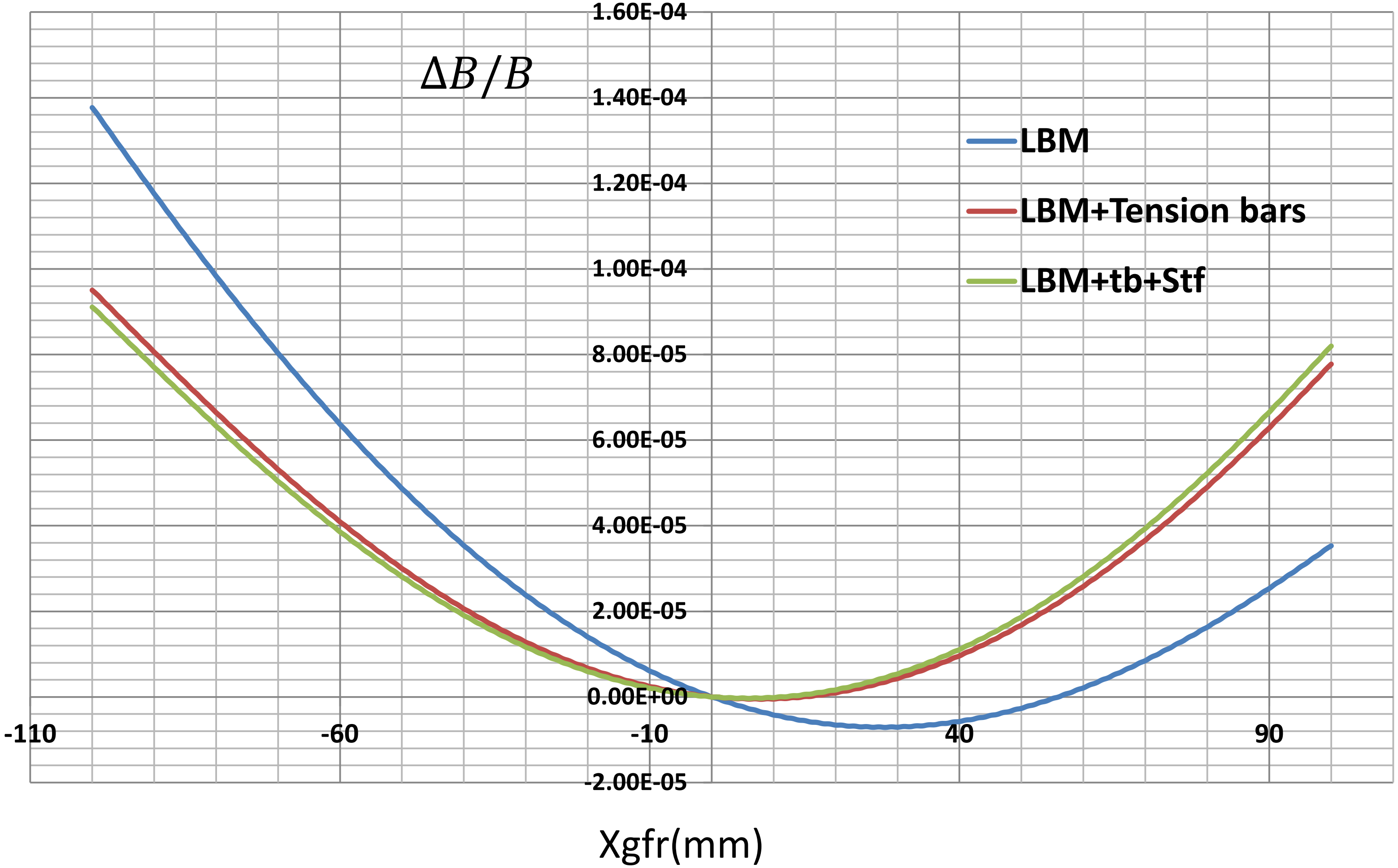
Static Simulations

No additional ferromagnetic structures



90° bending magnet

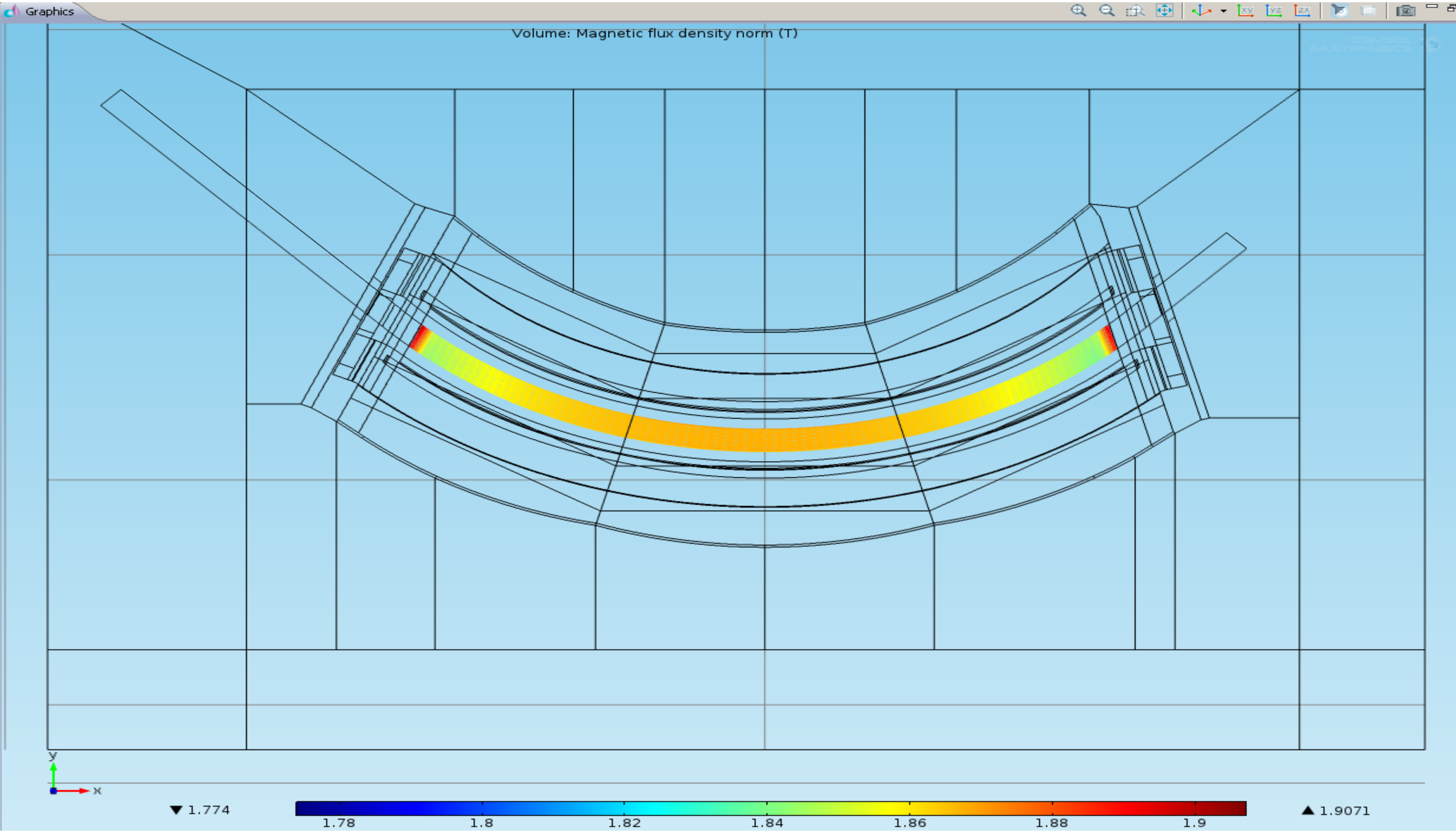
Static Simulations



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

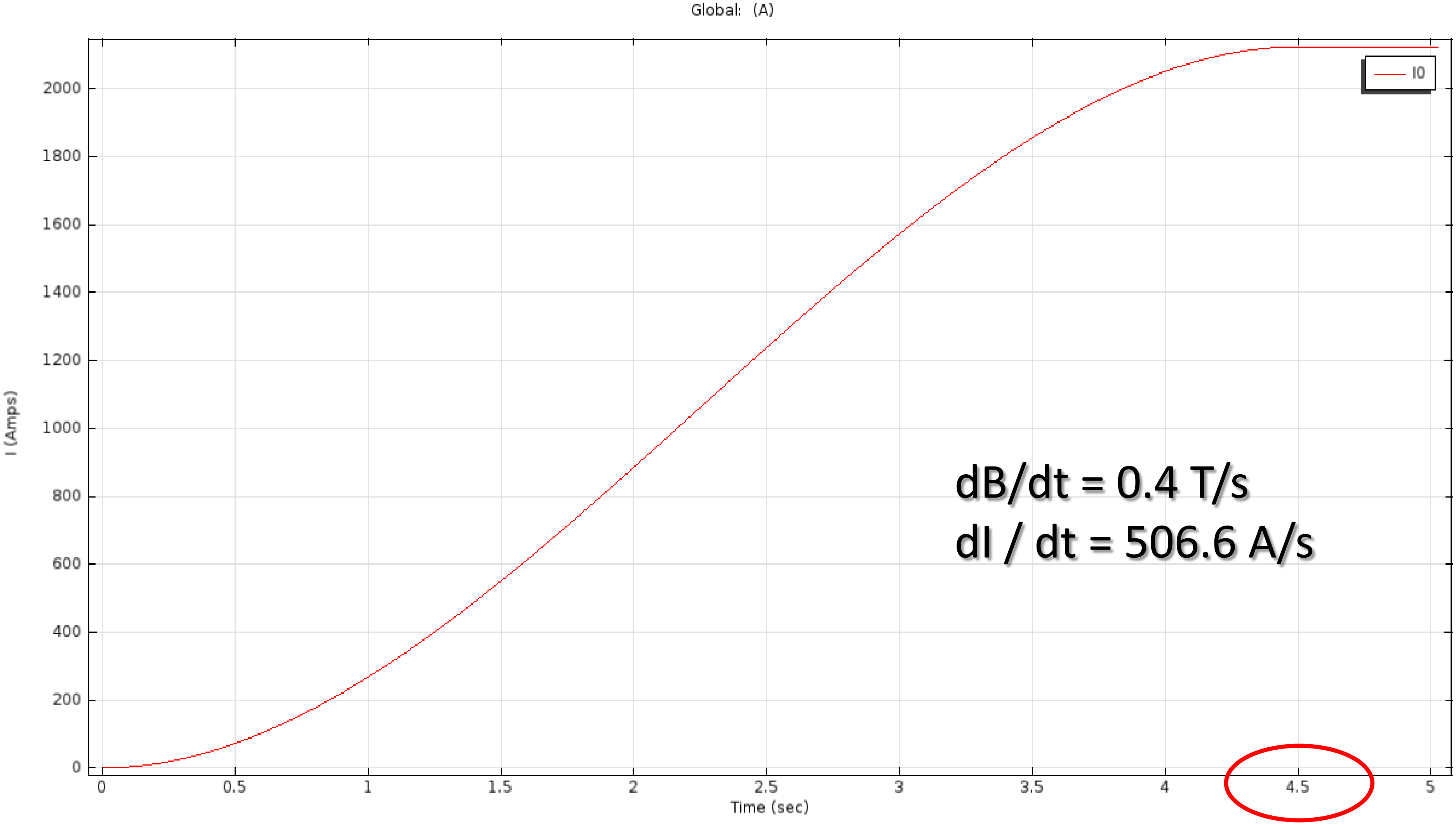
90° bending magnet

Static Simulations



90° bending magnet

Dynamic Simulations



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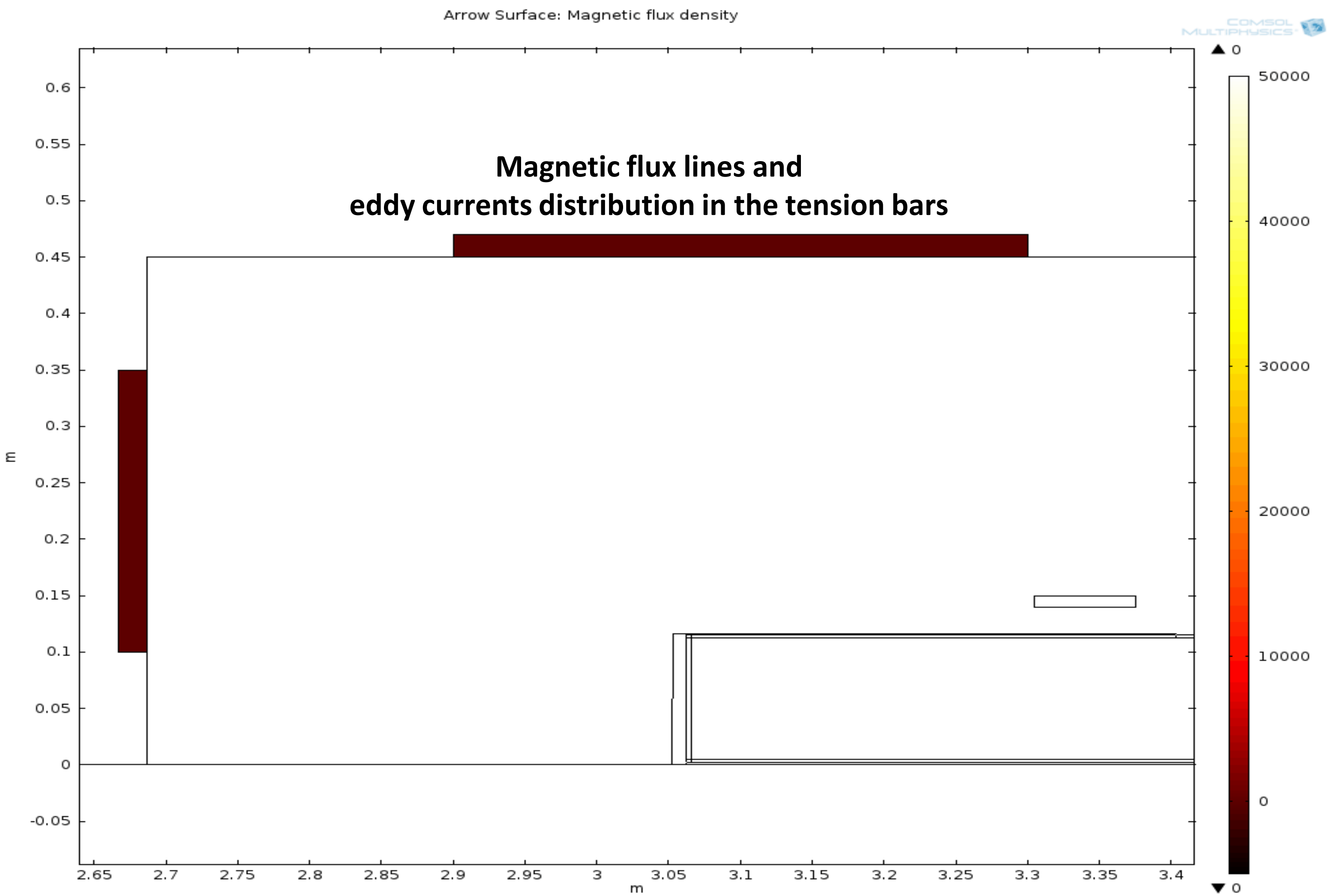
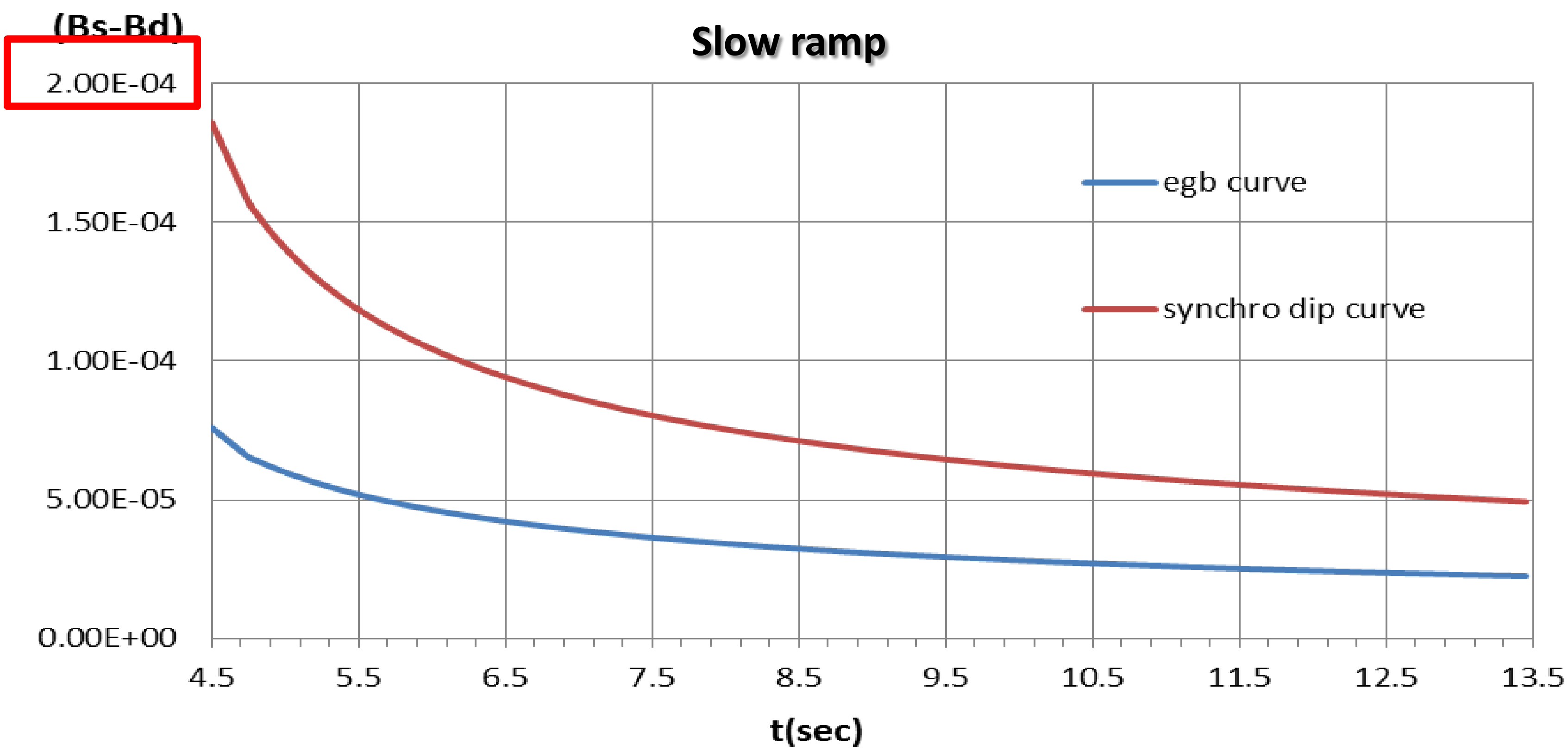
90° bending magnet

Dynamic Simulations



90° bending magnet

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**

Conclusions

- 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

Thank you for your attention

Additional slides

Hadron

From Wikipedia, the free encyclopedia

In particle physics, a **hadron** is a composite particle made of quarks held together by the strong force.

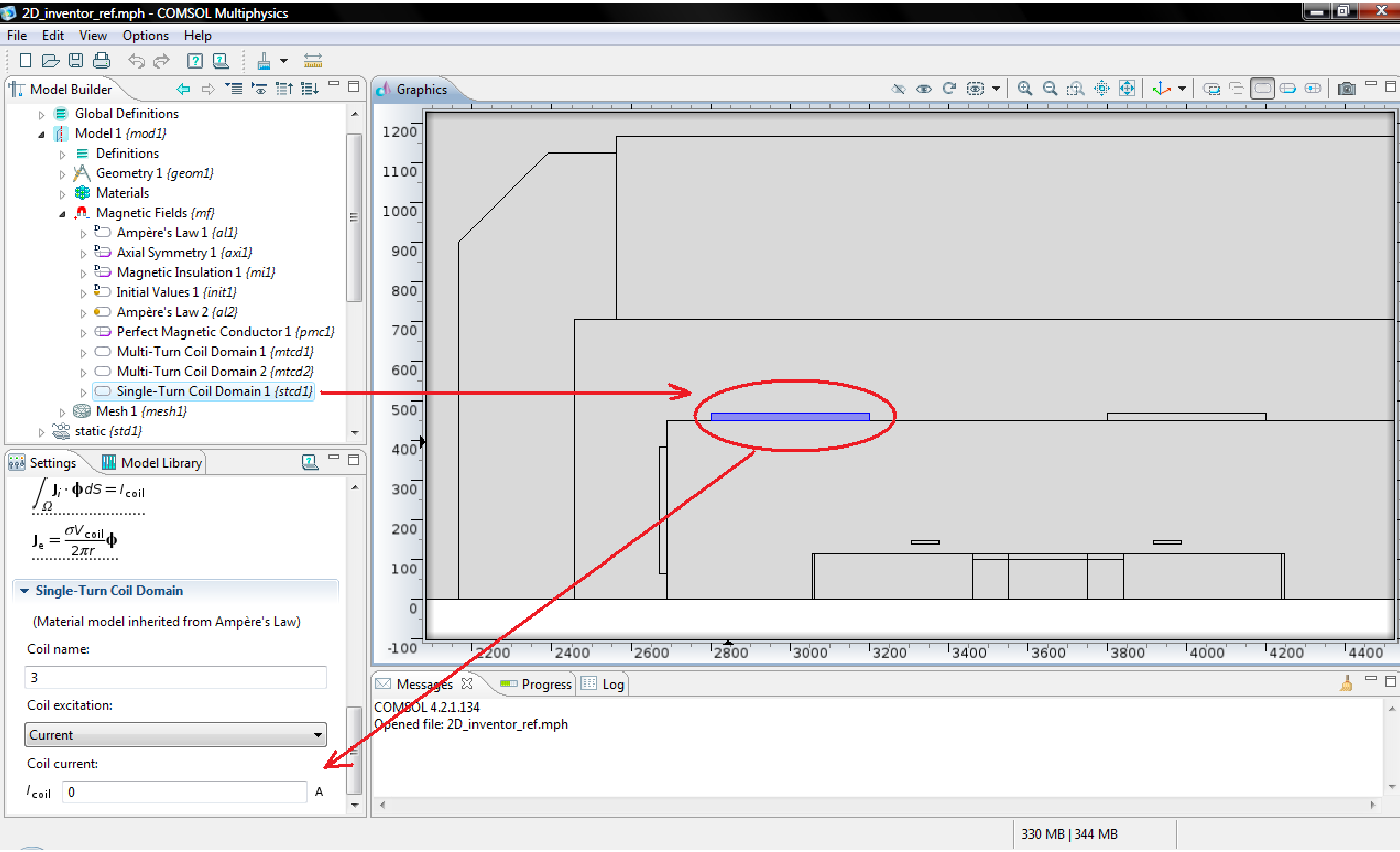
Hadrons are categorized into two families: baryons (made of three quarks) and mesons (made of one quark and one antiquark).

Summary of big aperture magnet simulated characteristics

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

To simulate the eddy currents in the tie dependent calculations , the tension bars Have to be simulated as a single turn coil domain.



Comsol Model

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