Characterization of a big aperture magnet used in particle beam cancer treatment

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Introduction: The transport of carbon ions used in cancer treatment techniques is a reality and it is actually being used. Due to the irradiation technique and the particle beam rigidity, the last bending magnet should guarantee a high field homogeneity in 20x20 cm^2 of the Good Field Region (GFR) .

Parameter	Value
Nominal field [T]	1.81
Ramp rate [T/s]	0.4
Bending radius [mm]	3650
Edge angle (upstream) [deg]	30
Edge angle (downstream) [deg]	21
Good Field Region (GFR) around ref trajectory [mm x mm]	±100 x ±100
Turns per pole	80
Nominal current [A]	2280
Yoke weight [t]	68
Conductor weight [t]	6.3
Maximum magnet weight [t]	75
Integrated field quality [ΔBL/BL]	$\leq \pm 2 \times 10^{-4}$

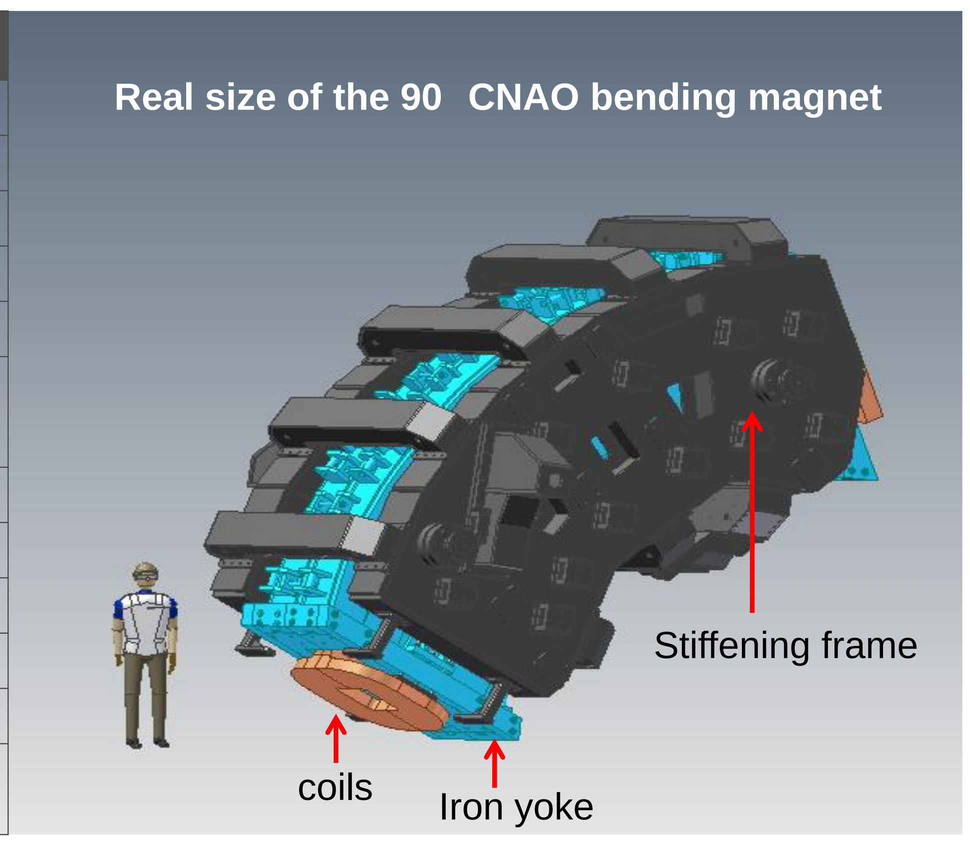

Figure 1. The CAD model of the CNAO 90 bending magnet and its main technical specifications [1].

Objective and Computational Methods: This magnet has been modeled to calculate:

1. The influence of external ferromagnetic elements in the center of the magnet
2. The effect of the eddy currents generated by the tension bars and to estimate the stabilization time of the magnet

$$\nabla \times \mathbf{H} = \mathbf{J} \qquad (1)$$

$$\mu \mathbf{H} = \nabla \times \mathbf{A} \qquad (2)$$

$$\frac{\Delta B}{B} = \frac{B(x,y) - B_0(0,0)}{B_0(0,0)} \quad \forall \ x,y \in \ GFR \qquad (3)$$

The model consists in solving the Ampere s law (eq 1) in a not linear material (iron yoke) and in air i.e. in the (GFR). The field homogeneity is evaluated in the GFR and it should be less than 2×10^{-4} (eq 3).

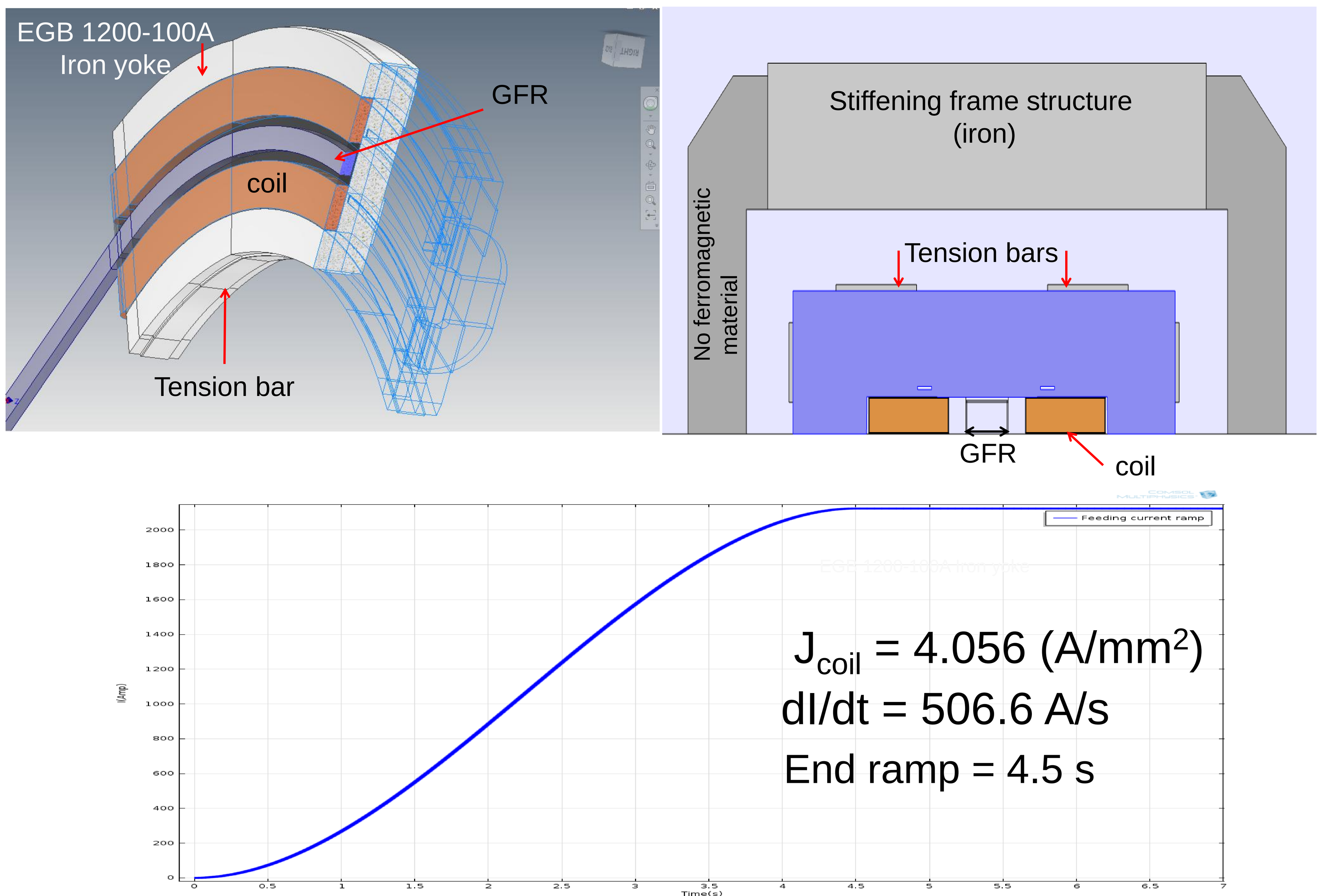

Figure 2. 3D simplify geometry and its representation in 2D (up) Feeding current ramp used in time dependent model (down)

Results: The tension bars and the stiffening frame have an influence on the field in the GFR. This is more evident for the tension bars, which are directly welded on the iron yoke. The results are in table 1: the field quality is slightly higher than the reference value (Fig 1), the main calculation parameters are reported in table 1.

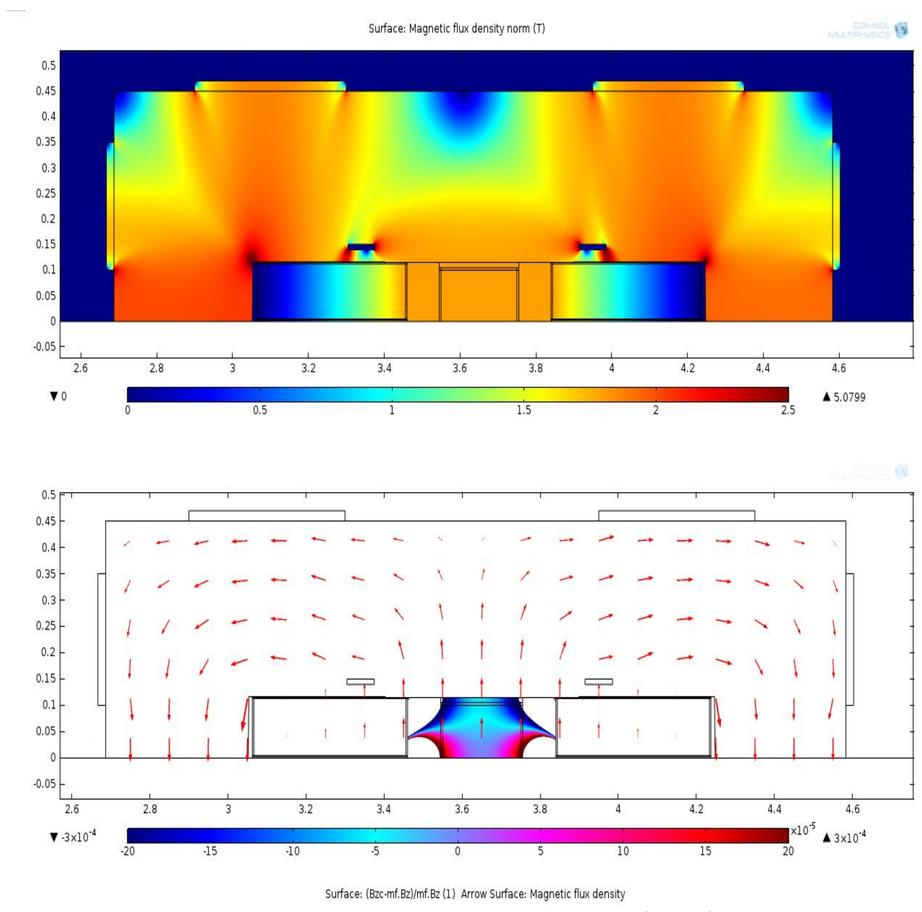

Figure 3. magnetic field (up) and Field quality in the air gap (down)

	B in the center of the magnet [T]	Delta (%)
Only iron yoke	1.8759	0
Yoke+tension bars	1.8913	0.82
Yoke+ tension bars + stiffening frame	1.8932	0.92

Table 1. Influence of different structural elements

The time delay calculated is 1.13 sec; the delay time effect can be neglected, because the differences between the magnetic field strength (B_{static}-$B_{dynamic}$) are below 10^{-4} T (fig 4) and, thus, it is within the acceptance range of variation [1].

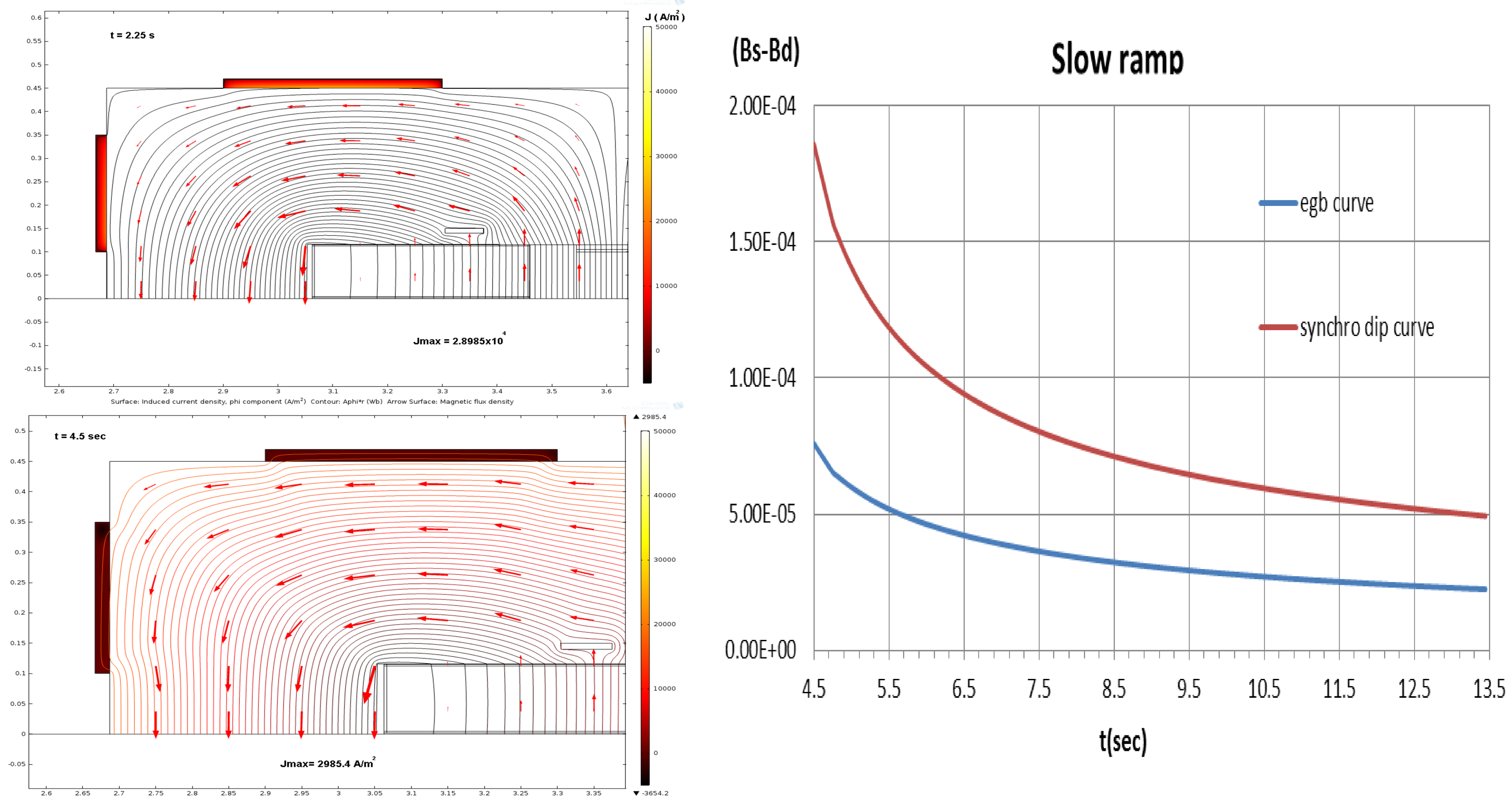

Figure 4. Magnetic flux lines and eddy current distribution in the tension bars at 2.25 s and at the end of the ramp 4.5 s (left). Difference between static field (Bs) and dynamic field (Bd) at the end of the feeding current ramp (t=4.5 s. in figure 2) for two different yoke materials (right).

Conclusions: The static and the dynamic regime simulations give results within the expected design values, with a particular low contribution of eddy currents in the dynamic magnet regime. The slow feeding current ramp rate could explain the low impact on the magnetic field strength.

The relevance of high quality FEM calculations is related to the possibility of employing a similar magnet, with eventually an improved stiffening frame, to be included in the design of a carbon ion gantry. For a sake of completeness, a gantry is a rotating transfer line that allows patient irradiation from any directions.

References:

1. C.Priano, M.Pullia, P.Fabricattore , *Magnetic design improvement and construction of the large 90 bending magnet of the vertical beam delivery line of CNAO*, 1782-1784. Proceedings of EPAC, Genova (2008)