MAGNETIC DESIGN IMPROVEMENT AND CONSTRUCTION OF THE LARGE 90° BENDING MAGNET OF THE VERTICAL BEAM DELIVERY LINE OF CNAO

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Abstract

The CNAO (Centro Nazionale di Adroterapia Oncologica) is the medical centre dedicated to the cancer therapy, under construction in Italy. Protons with energy ranging from 60 to 250 MeV and carbon ions with energy 120 to 400 MeV/u will be delivered to patients in three different treatment rooms, of which one is served with both horizontal and vertical beams. The vertical line requires a 70 tons 90° bending magnet providing 1.81 T in a good field region of x = ± 100 by y = ± 100 mm^2 with an integrated field quality (ΔBL/BL) at all field levels ≤ ± 2×10^{-4}. Starting from the experience matured when constructing the large bending magnet for HICAT gantry, we have developed a design able to meet these more stringent requirements in both 2D and 3D and special attention was paid to the study of manufacturing tolerances.

INTRODUCTION

The Italian hadron-therapy centre CNAO (Centro Nazionale di Adroterapia Oncologica) [1][2] is presently under construction in Pavia.. It is based on an evolution of the Proton-Ion Medical Machine Study (PIMMS) synchrotron capable to accelerate carbon ions up to 400 MeV/u and protons up to 250 MeV. Four treatment lines, in three treatment rooms, and a dedicated facility for clinical and radiobiological researches are foreseen in a first stage (fig.1).

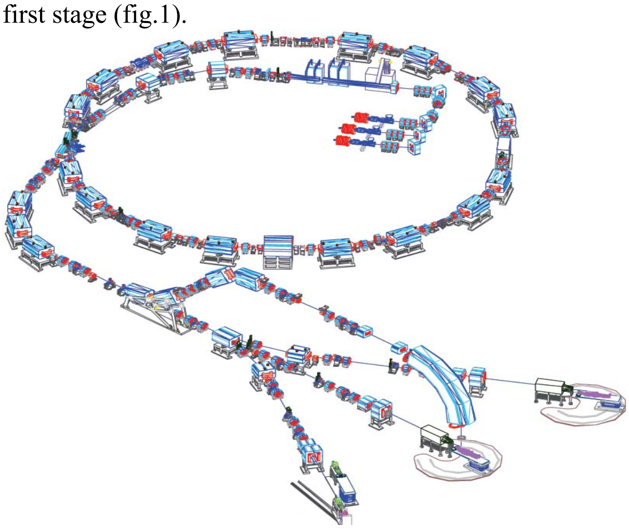

Figure 1: The CNAO facility layout

The vertical line features a large aperture 90° bending magnet, with field homogeneity characteristics fit for scanning beam delivery. It is based on the design made by GSI for the HICAT (Heavy Ion Cancer Therapy) facility in Heidelberg [3][4] but with much stringent demands on homogeneity and a good field region that is twice the size required for the Heidelberg magnet, in both directions.

This paper describes the design study and improvements to achieve these goals. The magnetic measurements are described elsewhere [5].

MAGNET SPECIFICATIONS

The Heidelberg magnet was built in 2001 by Sigmaphi according to GSI blueprints. A 0/+4×10^{-4} homogeneity specification on the integral field was aimed at, in a ±100 mm in-plane and ±48 mm out-of-plane volume. Measurements were performed in GSI and are reported in [6][7].

On the other hand, the CNAO magnet was ordered in 2006 according to much stringent magnetic specifications, the axial dimensions of the homogeneity volume being increased from. ±48 mm to ±100 mm. Sigmaphi was responsible for performances, design, construction and magnetic measurements. The requirements on both HICAT and CNAO are summarized in figure 2.

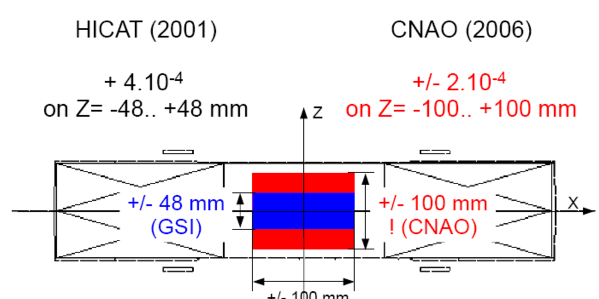

Figure 2: Specifications on integral field homogeneity

Field integrals are calculated along trajectories that simulate the use of a search coil. The circular part of this virtual coil has a radius of 3650 mm, with an angular dimension of 90°. Straight sections, 500 mm long, are added on each end of the circular part.

The homogeneity of the field integral versus the radial offset with respect to the central trajectory is better viewed if a linear component is removed. However, different choices are possible, subtracting either the same linear trend for all axial planes or a plane-dependent linear function (or its “light version”, a plane-dependant constant value). We use the first method since it compares all values to a single reference while the latter compares the values plane by plane. The difference in the method of analysis explains the difference in the homogeneity graphs presented in [7] and in the present paper. In both methods, the central integral (reference trajectory in the median plane) is the reference value to compute the homogeneity.

MAGNET DESIGN

Magnetic modelling

The 3D model is carefully designed to enable accurate calculations. The orientation of the laminations in the yoke and a 98% packing factor are taken into account. Mesh properties are adjusted to the accuracy needed, with a very fine mesh in the air gap and in fringe field regions. The body is subdivided into small units to allow a thorough control of the mesh (fig 3). The mesh size is decreased until the field is invariant with respect to mesh size. Precisely meshed, total potential quadratic elements air regions are used in the whole volume where accurate fields needs to be computed. The Opera default BH curve is very close to that for the EBG 1200-100A steel and is used for all calculations.

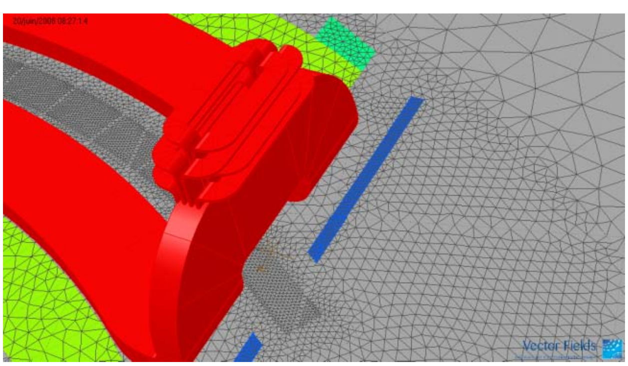

Figure 3: Bedstead end showing mesh density, subsections for mesh control and cooling busbars

2D and 3D models compare very well in the magnet centre and the 3D model is in very good agreement with the measurements performed by GSI.

Improvements of initial design

- No change was made to the already very well optimized 2D section
- The Rogowski profile was found almost optimal and was not modified
- The integral homogeneity was improved by changing the field clamps size and shape (fig 4)
- Changing the iron collar size slightly improved (20%) the independence of the edge angle on coil current

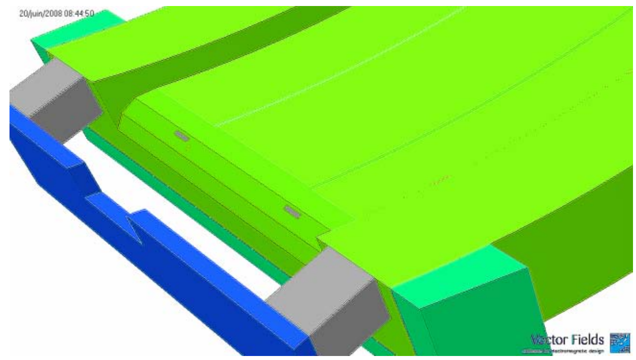

Figure 4: Detail of one of the edges showing the pole profile, the triple Rogowski, the pole slots (gray), the field clamp (blue) and the iron collar (water green).

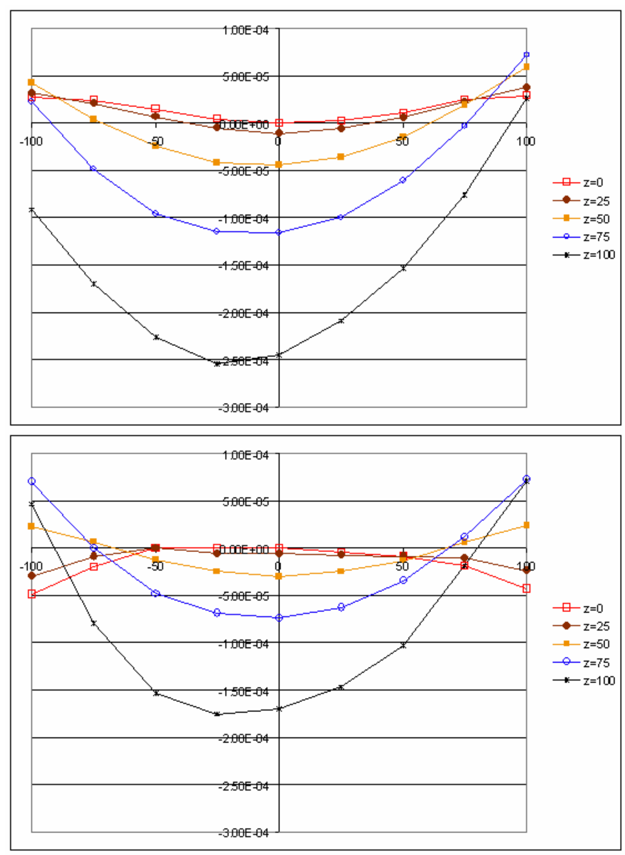

Figure 5: Comparison between the Integral field homogeneity versus radial offset in the original HICAT (top) and revised (bottom) designs in different axial planes at B_0=1.86 T (nominal current).

Fabrication Tolerances

The model was found rather sensitive on coil positioning, especially with median plane symmetry breaking but less on iron defects.

- A 0.1 mm parallelism defect across the pole makes almost no difference in the homogeneity
- A 5 mm horizontal displacement of both coils slightly changes the homogeneity ($5x10^{-5}$)
- The same displacement of 1 coil only makes the homogeneity drop from $2x10^{-4}$ to $2x10^{-3}$

We also found the position, size and orientation of the coil bedstead ends, a very touchy parameter.

Post-construction remodelling

Measurements performed on the magnet were found in very good agreement with the model on the exit side but, much less on the entrance side. This difference was attributed to the special geometry of the coil.

One electrical circuit is too long for cooling and is split in its middle. The 2 ends are output to the outside of the coil, fed separately for cooling and reconnected through busbars to ensure electrical continuity. This induces not only an awkward geometry on the top of the bedstead end (fig 6) but also a thicker bedstead to allow the wires out, both in disagreement with the modelled coil.

These 2 features were taken into account in a new opera-3d model (fig 3 and 7) and this allowed reaching an agreement between measurement and model comparable to the one we had on the exit side.

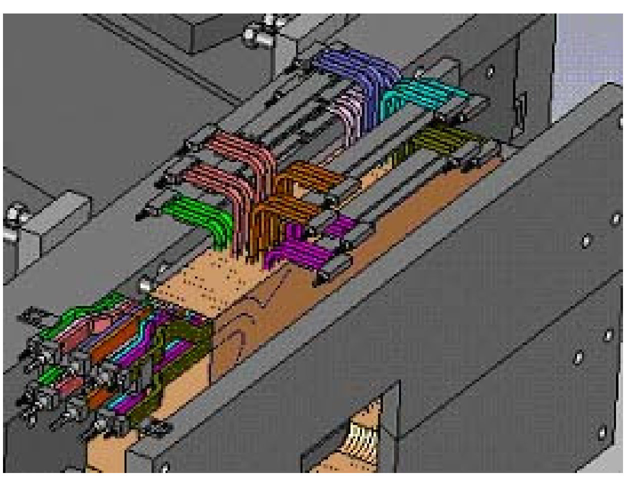

Figure 6: Bedstead end of the coil on the entrance side with current leads and cooling circuit busbars

Figure 7: Detail of the modelling of the busbars

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