ISBN: 978-3-95450-232-5 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2022-TUPA30

DEVELOPMENT OF A COMPACT 2D CARBON BEAM SCANNER FOR CANCER THERAPHY*

B. Mustapha†, J. Nolen, A. Barcikowski, Argonne National Laboratory, Lemont, IL, USA
N. Tsoupas, Brookhaven National Laboratory, Upton, NY, USA
V. Derenchuk, P. Osucha, ProNova Solutions, LLC, Maryville, TN, USA

Abstract

A novel trapezoidal coil 2D carbon beam scanner has been designed, and a prototype has been successfully developed and tested. The field performance of the magnet has been characterized and it is in excellent agreement with the simulations. A better than 1% field uniformity in both planes has been achieved within the useful aperture of the magnet. This represents a significant improvement over the prior art of the elephant-ear scanner design. A comparison of the two designs and the test results from the new trapezoidal-coil design will be presented and discussed. High power and online beam testing are planned in the future.

INTRODUCTION

In existing carbon ion and most proton beam gantries, the scanning magnets are placed prior to the last bend of the beam delivery system [1]. This requires the last gantry magnets to have a large aperture diameter of ~20 cm which greatly increases their mass and cost. Placing the scanning magnets in the final drift, as is presently implemented in the ProNova superconducting (SC) proton gantry [2], a next-generation carbon beam gantry can be much more cost effective. By demonstrating this technology with a working distance of ~3 m, it becomes feasible to implement SC carbon ion beam gantries with a footprint comparable to present day proton beam gantries [3]. For protons, this same scanner can double the field size or allow SC proton gantries and fixed beam delivery systems to be even more compact with a ~1 m working distance.

The scanners must have as short as possible working distance so that they can be placed after the last gantry bending magnet to enable the use of small aperture magnets. The concept of a 3D scan, in x-y, and energy is shown in Fig. 1 [4]. For compactness, the x-y scanners can be combined into a single combined function 2D scanner magnet. Combined with programmed intensity variation during the 3D scan, this method is known as Intensity Modulated Particle Therapy (IMPT).

SPECIFICATIONS AND DESIGN CHOICE

The general specifications for a carbon beam scanner magnet satisfying the requirements are shown schematically in Fig. 2 with more details listed in Table 1. While in most cases a 40 cm scanning field is not needed, some spine tumors require a wide field at least in one dimension.

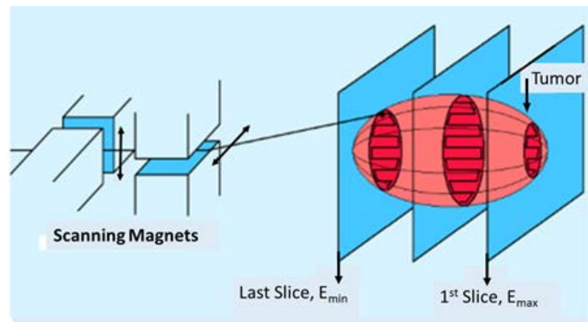

Figure 1: Concept of a 3D, x-y and depth scan of a tumor.

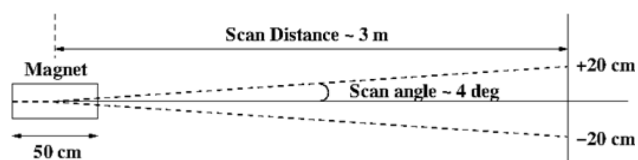

Figure 2: Schematic layout of 1D beam scanning using a 0.5 m long magnet with a working distance of ~ 3 m covering a +/- 20 cm field.

Table 1: Design specifications for a 2D carbon beam scanner magnet with ~3 m working distance and 40 cm scanning field.

Parameter	Value
Beam rigidity, T·m	6.6 (430 MeV/u C^{6+})
x-y deflection angle, °	4.2 (40×40 cm at 3 m)
Bend radius, m	6.6
Peak field, T	1
Effective length, m	0.5
Good field area, cm	6
Scanning frequency, Hz	100

Based on these specifications, we have developed different design options for a compact 2D carbon beam scanner; the most promising were an elephant-ear design and a trapezoidal-coil design and selected the trapezoidal coil design for prototyping. The main criterion was the field uniformity in both planes, to avoid beam distortions due to non-linearity, which could affect the delivered dose conformity to the tumor during spot scanning. The trapezoidal coil design provides a better than 1% transverse field uniformity in both planes, while an equivalent elephant-ear design with rectangular coils [5] has asymmetric field uniformity of ~1% in one plane and ~9% in the other. We can clearly see this effect in Fig. 3, comparing both designs and

*This work was supported by the U.S. Department of Energy, under Contract No. DE-AC02-06CH11357. This research was supported through the DOE's Accelerator Stewardship program.
† brahim@anl.gov

5th North American Particle Accel. Conf. NAPAC2022, Albuquerque, NM, USA JACoW Publishing
ISBN: 978-3-95450-232-5 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2022-TUPA30

the corresponding simulated transverse field uniformities. It is important to note that this effect was observed for the original elephant-ear scanner design for protons [5].

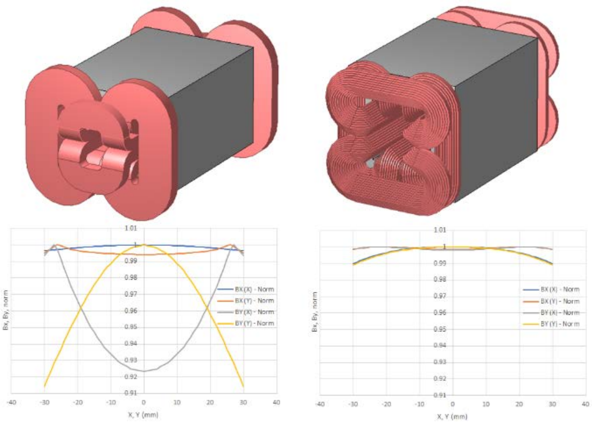

Figure 3: 2D Elephant-ear (left) and trapezoidal-coil (right) scanner magnet designs. The corresponding transverse field uniformity is shown under each design over the useful magnet aperture of ~60 mm.

PROTOTYPE AND TEST RESULTS

In collaboration with ProNova we have developed a prototype scanner based on the trapezoidal-coil design. Figure 4 shows pictures of the trapezoidal-coil scanner fully assembled and being mapped using a 3D field measurement system. The measured field profiles and excitation curves (B vs. I) are shown in Fig. 5 in very good agreement with the simulation results. The magnet full current design is 550 A; however, it was tested only up to 225 A due to power supply limitations. High power testing is planned in future using a newly purchased power supply. Figure 6 shows the measured results for transverse field uniformity or flatness, which is better than 0.5% for the transverse scans of the vertical field and better than 0.7% for the horizontal field over the useful magnet aperture of 6 cm.

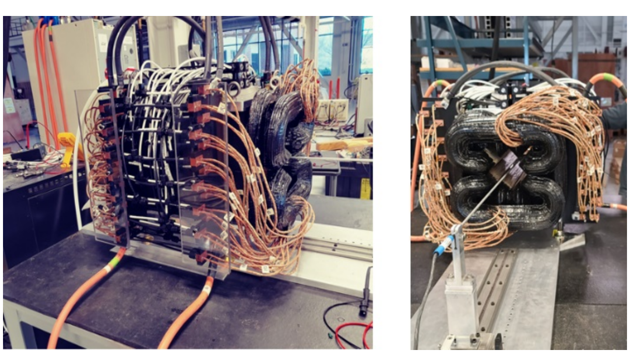

Figure 4: 2D Trapezoidal-coil scanner magnet prototype, fully assembled (left) and its field being mapped (right).

Finally, the magnet bandwidth was checked by varying the field scanning frequency and measuring field variation, see Fig. 7. The results demonstrate the desired operating frequency of 100 Hz in both planes without field degradation due to eddy current effects. Due to power supply limitations, these tests were performed only at 50 A and 100 A. More tests at higher power are planned in the future with a new power supply. In addition to high power testing, online beam tests are also planned using proton beam.

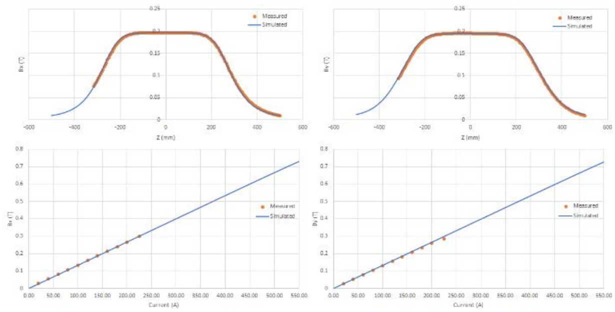

Figure 5: Field measurements vs. simulation results. Horizontal (left) and vertical (right) field profile along the magnet axis measured at 150 A. The corresponding excitation (B vs. I) curves are shown below the field profiles up to a current of 225 A, not yet reaching the full magnet design current of 550 A.

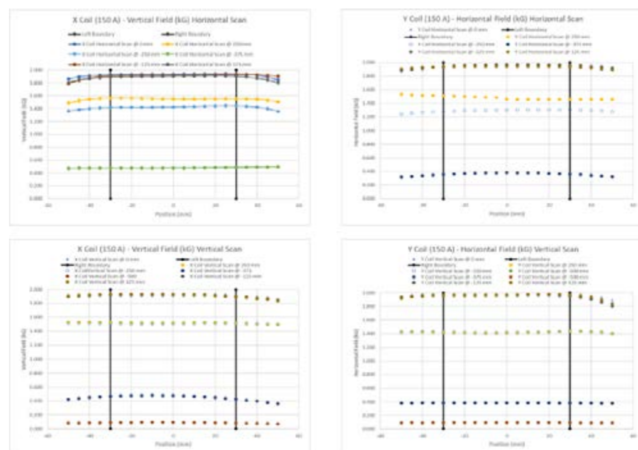

Figure 6: Field uniformity measurements at different locations on the magnet axis. The 4 plots correspond to both components of the field; vertical and horizontal, each scanned in the horizontal and vertical directions within the magnet aperture. Different curves correspond to different longitudinal (z) locations. The plots show better than 1% field flatness within the magnet, it's larger at the magnet ends.

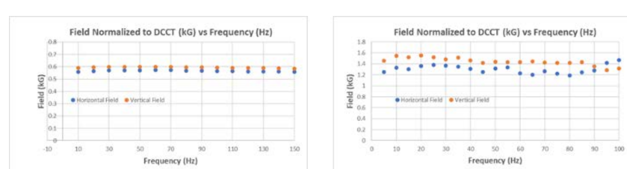

Figure 7: Fields vs. scanning frequency up to 150 Hz at 50 A (left), and up to 100 Hz at 100 A (right).

SUMMARY

In summary, a novel trapezoidal-coil compact 2D carbon beam scanner prototype has been successfully developed. The field performance of the magnet has been characterized and it is in excellent agreement with the simulations. A better than 1% field uniformity in both planes has been achieved within the useful aperture of the magnet. This

ISBN: 978-3-95450-232-5 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2022-TUPA30

represents a significant improvement over the prior art of the elephant-ear design. Higher power testing and online beam testing are expected soon following the receipt of a new more powerful power supply.

REFERENCES

[1] R. Fuchs *et al.,* "Assembly of the Carbon Beam Gantry at the Heidelberg Ion Therapy (HIT) Accelerator", in *Proc. EPAC'08*, Genoa, Italy, 2008, paper TUPP133, pp. 18329-1841. https://jacow.org/e08/papers/tupp133.pdf

[2] V. Derenchuk *et al.*, "Application of Superconducting Technology for Proton Therapy", talk at the North American Particle Accelerator Conference NAPAC'16, Chicago, IL, USA, Oct. 2016, slides FRB2IO01.

[3] S. Ishmael *et al.*, "Actively-Shielded, Bent Gantry System for Ion Beam Therapy Based on Round YBCO Wire", Presentation at the Applied Superconductivity Conference ASC-2016, Denver, Co, USA.

[4] H. Eickhoff, "HICAT- The German Hospital-Based Light Ion Cancer Therapy Project", in *Proc. EPAC'04*, Lucerne, Switzerland, Jul. 2004, paper FRYACH01, pp. 290-294

[5] V. Anferov, "Combined X-Y scanning magnet for conformal proton radiation therapy", *Med. Phys.*, vol. 32, pp.815-818, 2005. doi:10.1118/1.1862801