A COMPACT 2D CARBON BEAM SCANNER WITH INTERLEAVED SADDLE COILS*

B. Mustapha†, A. Ravichandran, J. Nolen, Argonne National Laboratory, Lemont, IL, USA

R. Meinke, E. Soiman, 3D Magnetics, LLC, Concord, MA, USA

Abstract

Scanning magnets are used in proton and ion beam therapy to produce a radiation dose conforming to the cancerous tumor. In most existing beam delivery systems, two separate magnets are used to scan the beam in the transverse planes. To enable more compact beam delivery systems and gantries, a combined function 2D scanner magnet with a short working distance to place at the end of the system is highly desirable. Earlier designs suffer from field non-uniformity in at least one plane. A compact 2D scanner magnet has been designed to produce high-field uniformity in both planes. The scanner was designed for carbon ions and could be easily scaled down for protons and other light ions. The design is based on saddle coils where the coils of the two magnets are interleaved to balance both field properties and power losses when scanning in both planes. The simulated field performance shows better than 0.5% field uniformity in both planes within the useful aperture of the magnet. This represents a significant improvement over the prior art of the elephant-ear scanner design. The proposed implementation using a ceramic support bobbin and a novel cooling approach is presented.

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

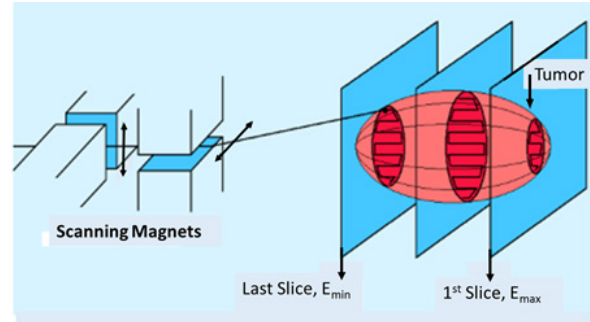3D scan, this method is known as Intensity Modulated Particle Therapy (IMPT).

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

SPECIFICATIONS AND DESIGN OPTIONS

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.
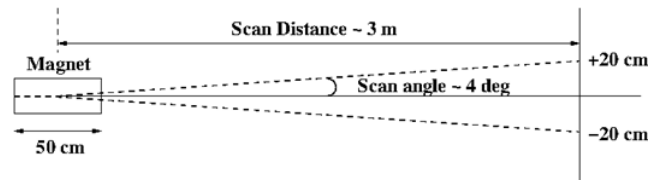

Figure 2: Schematic layout of 1D beam scanning using a 0.5 m long magnet with a working distance of ∼ 3 m covering a +/- 20 cm field.

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, deg	4.2 (40x40 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. In addition to the already known elephant-ear design [5], we developed a novel 2D interleaved saddle coil design,
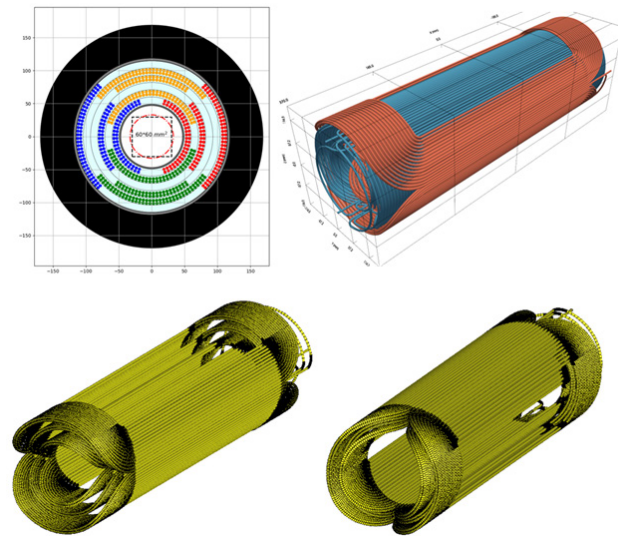
Figure 3: Novel 2D interleaved saddle coil scanner magnet design. Different views are shown: magnet cross section including iron yoke and combined/interleaved coil windings in the top, separate coil windings in the bottom.

shown in Fig. 3. The main design 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 interleaved coil design provides a better than 0.5% transverse field uniformity in both planes, while an equivalent elephant-ear design with rectangular coils [6] has asymmetric field uniformity of ~1% in one plane and ~9% in the other. We can clearly see this effect in Fig. 4, comparing both designs and the corresponding simulated transverse field uniformities. It is important to note that this effect was observed in the original elephant-ear scanner design for protons [5].
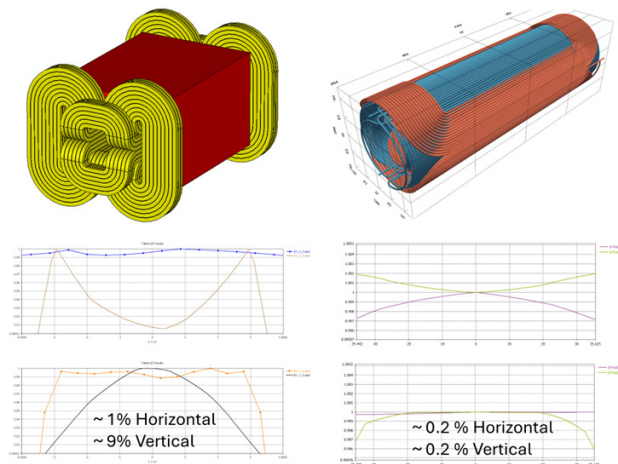

Figure 4: 2D Elephant-ear (left) and Interleaved-coil (right) scanner magnet designs. The corresponding transverse field uniformity is shown under each design over the useful magnet aperture of ~ 60 mm.

ELECTROMAGNETIC SIMULATIONS OF INTERLEAVED SADDLE COIL DESIGN

Following the coil winding design using a specialty software, the model was successfully imported into CST Design Studio [7] and simulated using EM Studio. The coil is wound out of 4 mm diameter filamented copper conductor. Figure 5 shows the design for one coil imported to CST along with the simulations results in terms of 3D fields and 1D profile. Simulations were also performed in DC mode for both coils with and without an iron yoke. The results presented in Fig. 6 show a significant field enhancement from the yoke, of ~ 40%. Finally, AC simulations were performed using a new Monte-Carlo method [8] for individual coils and for the interleaved coils system while powering a single coil at a time. The conditions and results of these simulations are shown in Fig. 7. The results show that DC losses are dominating the power losses which suggests that a thicker copper conductor, of 5 mm diameter or larger, would better balance the AC and DC losses.
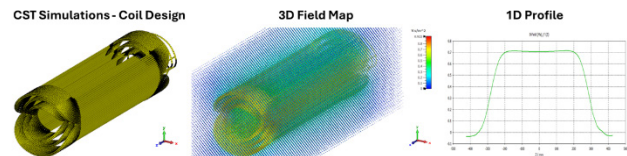

Figure 5: Coil design, 3D field map and 1D field profile as simulated in CST EM Studio.
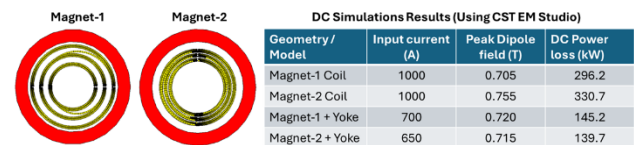

DC Simulations Results (Using CST EM Studio)			
Geometry / Model	Input current (A)	Peak Dipole field (T)	DC Power loss (kW)
Magnet-1 Coil	1000	0.705	296.2
Magnet-2 Coil	1000	0.755	330.7
Magnet-1 + Yoke	700	0.720	145.2
Magnet-2 + Yoke	650	0.715	139.7

Figure 6: DC simulations results for both magnets with and without an iron yoke.

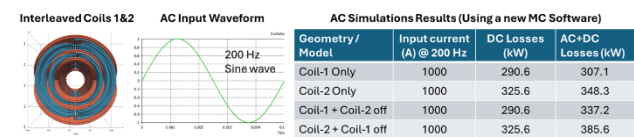| AC Simulations Results (Using a new MC Software)			
Geometry / Model	Input current (A) @ 200 Hz	DC Losses (kW)	AC+DC Losses (kW)
Coil-1 Only	1000	290.6	307.1
Coil-2 Only	1000	325.6	348.3
Coil-1 + Coil-2 off	1000	290.6	337.2
Coil-2 + Coil-1 off	1000	325.6	385.6

Figure 7: AC simulations results for individual coils and both interleaved coils when a single coil is powered at a time.

PROPOSED IMPLEMENTATION – WINDING SUPPORT AND COOLING

Concerning how to build such an interleaved coil scanner magnet, we propose to use support bobbins made of ceramic with grooves for the conductor as shown in Fig. 8. We are currently developing a 3D printing method for ceramic which would make this process much easier. Considering the fragility of ceramic, machining the grooves onto ceramic cylinders would be near impossible. Different layers of ceramic bobbins are needed where each cylinder could support two coil layers, one from each side, inner and outer. Finally, for cooling, we propose to submerge the

magnet, coils and support bobbins into a cylindrical tank with special cooling fluid as being used for cooling circuits in modern-day data centers [9, 10] and shown in Fig. 9. The need for coolant circulation will be evaluated, and if necessary, an appropriate cooling circuit will be included.
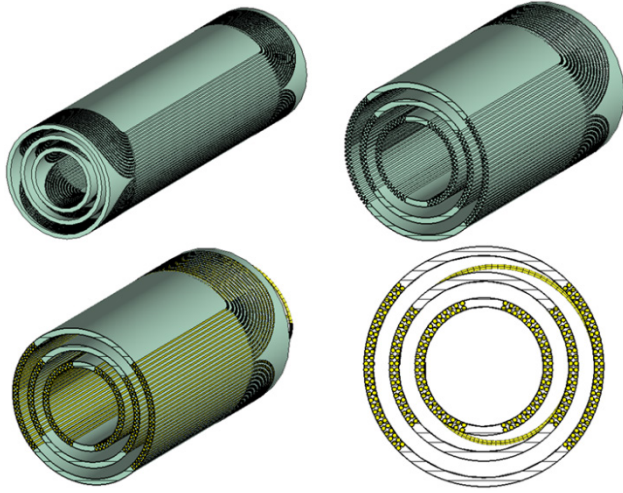

Figure 8: Bobbins made of ceramic to support the coils. Multiple layers are required with grooves to hold the copper wire. Different views and cross sections are shown.

Figure 9: Electronic circuit boards submerged in tanks filled with special cooling fluid used in modern-day data centers. A similar approach is being proposed here to cool the scanner magnet.

SUMMARY

In summary, A novel interleaved saddle coil 2D carbon beam scanner design has been developed. The expected field uniformity is better than 0.5% in both planes, which represents a significant improvement over the prior art of the elephant-ear design. Prototyping is underway. It is based on novel 3D-printed ceramic support bobbins and efficient cooling with special fluid as used in modern-day data centers.

REFERENCES

[1] U. Weinrich, R. Fuchs, and E. Sust, "Assembly of the Carbon Beam Gantry at the Heidelberg Ion Therapy (HIT) Accelerator", in *Proc. EPAC'08*, Genoa, Italy, Jun. 2008, paper TUPP133, pp. 1839-1841.

[2] V. Derenchuk *et al.*, "Application of Superconducting Technology for Proton Therapy", presented at NAPAC'16, Chicago, IL, USA, Oct. 2016, paper FRB2IO01, unpublished.

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

[4] H. Eickhoff, T. Haberer, B. Schlitt, and U. Weinrich, "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 V. Anferov, "Combined X–Y scanning magnet for conformal proton radiation therapy," *Biol. Med. Phys. Biomed. Eng.*, vol. 32, no. 3, pp. 815–818, Mar. 2005. `doi:10.1118/1.1862801`

[6] B. Mustapha, A. Barcikowski, V. P. Derenchuk, J. A. Nolen, P. Osucha, and N. Tsoupas, "Development of a Compact 2D Carbon Beam Scanner for Cancer Therapy", in *Proc. NAPAC'22*, Albuquerque, NM, USA, Aug. 2022, pp. 417-419.

     `doi:10.18429/JACoW-NAPAC2022-TUPA30`

[7] CST Studio Suite, `https://www.3ds.com/products/simulia/cst-studio-suite`

[8] A. Ravichandran, R. Meinke, and H. Gutierrez, "Monte Carlo model to determine eddy currents in 3D winding configurations with and without ferromagnetic materials," *Comput. Mech.*, May 2025. `doi:10.1007/s00466-025-02625-1`

[9] Electrical circuits encased in fluid may reshape data-center design, `https://www.sandia.gov/lab-news/2024/05/30/hpc-cooling/`.

[10] Immersion Cooling - Everything you need to know, `https://submer.com/immersion-cooling/`.