The Fast Ramped Bending Magnets for the Gantry 2 at PSI

Marco Negrazus, Alexander Gabard, David George, and Vjeran Vrankovic

***Abstract*—The PROSCAN project at the Paul Scherrer Institute (PSI/Switzerland) involves a number of innovative elements in tumor treatment. Apart from the compact superconducting dedicated proton cyclotron COMET, a fast energy degrader and laminated magnets in the beam lines, including the newly conceived Gantry 2, will enable rapid energy changes of the proton beam to modulate the range of the scanning pencil beam in three dimensions over the tumor volume. The last multifunctional 90° bending magnet of the Gantry 2 transport system is not only the largest of the three gantry bending magnets, but also the most challenging element because of its dynamical eddy current effects during ramping and the reduction of these effects with a special arrangement of laminated parts in the pole of the magnet. The design of the three Gantry 2 bending magnets and measurements of the magnet field and the dynamic behavior of the two 58° bending magnets are presented.**

***Index Terms*—eddy currents, magnetic variables measurement, magnets.**

I. INTRODUCTION

At the Paul Scherrer Institute PSI in Switzerland, the new proton cyclotron COMET [1] has finished the commissioning phase in 2006 and started routine operation. The tumor treatment program started in February 2007 with the existing Gantry 1. A new Gantry 2 with sophisticated spot scanning capabilities [2] is now under construction.

The spot scanning technique requires a relatively fast change of the beam energy in the range of 70 – 230 MeV for tumor treatment in various depths of tissue. Energy steps of 1 – 2% of the maximum energy within 50 ms are foreseen and all beam line and gantry magnets have to switch to the new energy on time. This energy switching generates eddy currents which would disturb the beam until they decay. To avoid eddy currents, all magnets are built in laminated technique with 1 mm lamination thickness coated with organic bonding lacquer (Stabolit 70). However, laminated magnets are not completely free of eddy current effects and they can still have a distorting influence on the beam [3]. This limits the quickest possible energy switching and causes longer medical treatment time.

II. DESIGN OF THE GANTRY 2 BENDING MAGNETS

In an ideal laminated iron magnet, the return magnetic flux stays inside one lamination and never moves to the neighboring lamination. There are no magnetic field components perpendicular to the lamination and therefore no eddy currents occur in the lamination when the magnet field is ramped.

In a real bending magnet, there is magnetic flux with a component perpendicular to the lamination, especially at the entrance and exit regions of the poles. Fig. 1 shows qualitatively the current density of the eddy currents during ramping, which are driven by the perpendicular field components at the entrance or exit region of the pole [3]. The simulated H-type bending magnet was laminated and driven by a linearly increasing current ramp to the maximum current. The simulated effect corresponds to the local heating effect of laminated AC magnets.

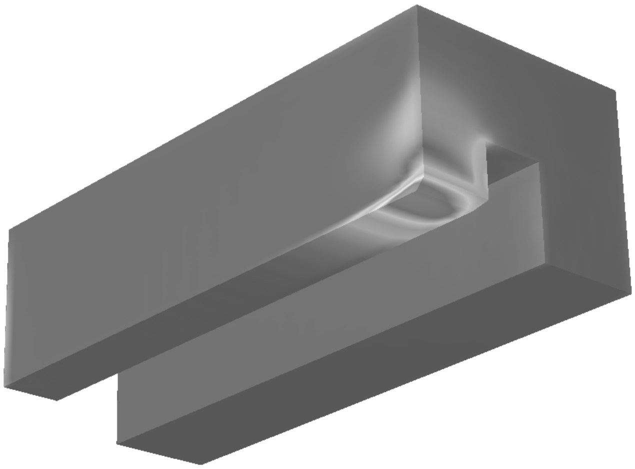

Fig. 1. One eighth of a simulated laminated H-type bending magnet (the coil is not shown). The current density of the eddy currents in the entrance or exit region of the pole are shown during ramping [3].

With a test laminated H-type bending magnet, we investigated this eddy current effect by making time dependent measurements of the magnetic field at the entrance or exit region and the center of the pole with a Hall probe based measuring system. The measured test magnet is a straight standard laminated bending magnet (1 mm lamination thickness) with a magnet field of 1.4 T at I = 220 A, a gap height of 60 mm and a magnetic length of 1.8 m. The current was ramped linearly from 0 A to 220 A in 4.5 s and held

---

Manuscript received August 23, 2007.

M. Negrazus, A. Gabard, D. George, and V. Vrankovic are with the Paul-Scherrer Institute PSI, WMHA, 5253 Villigen PSI, Switzerland. (e-mail: marco.negrazus@psi.ch; alexander.gabard@psi.ch, david.george@psi.ch, vjeran.vrankovic@psi.ch)

constant at this maximum value. Figs. 2 and 3 show the characteristic of the magnetic field from the end of the linear ramp up to 10 s. Fig. 2 shows the field in the longitudinal center of the magnet. The field values are divided by the static field value at this position. The normalized field value at the end of the current ramp is roughly 0.996 and increased asymptotically to 1 over some seconds.

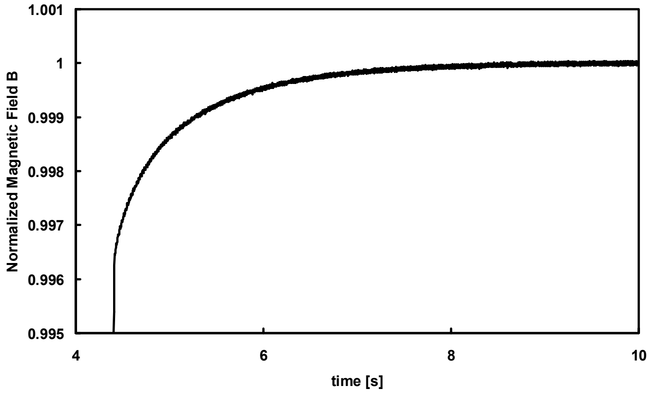

Fig. 2. Magnetic field measured by a Hall probe in the center of the test magnet after a linear current ramp from 0 A to the maximum current of 220A.

Fig. 3 shows the field at the entrance (or exit) area of the magnet. At the end of the current ramp, the field value is roughly 1.004 and decreases asymptotically to 1 over some seconds.

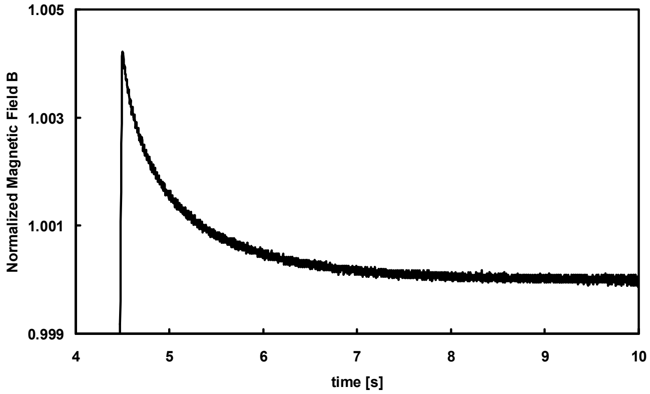

Fig. 3. Magnetic field measured by a Hall probe at the entrance/exit of the test magnet after the current ramp.

The eddy currents at the magnet entrance and exit excite a characteristic overshoot behavior of the magnet field after ramping and would disturb the proton beam and yield to mis-steering and displacement of the beam. The tumor treatment would be delayed until the eddy currents decayed to an acceptable level. An acceptable level of the field integral is estimated to 0.01%.

To get rid of the eddy current effects at the magnet entrance, we decided to use a special lamination scheme in the bending magnets for the Gantry 2. Fig. 4 shows a cross section of one half of a Gantry 2 bending magnet. The whole magnet yoke is conventionally laminated parallel to the figure face except for a channel in the center of the pole. In this region, we use a curved vertical lamination parallel to the beam orbit along the whole pole. This lamination scheme suppresses eddy currents in the entrance/exit region of the pole because the magnetic field is no longer perpendicular to the lamination at the new channel lamination.

Technically, the channel in the pole was machined out of a conventionally produced laminated magnet yoke. The longitudinal laminated channel part was produced separately and glued in the channel of the pole. The final machining of the pole surface was done afterwards.

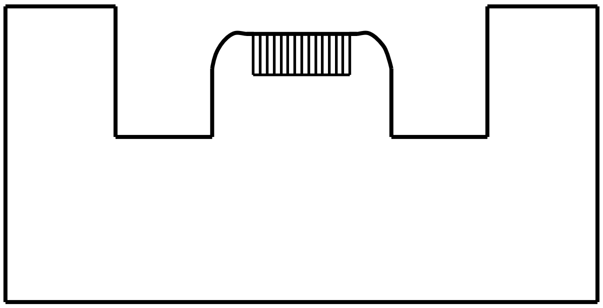

Fig. 4. Sketch of the cross section of the lower half of a Gantry 2 bending magnet. The vertical lamination in the channel along the longitudinal axis can be seen in the center of the pole. The lamination in the other yoke parts is in plane of the drawing.

III. MEASUREMENT RESULTS OF THE GANTRY 2 BENDING MAGNETS

The bending magnets of the Gantry 2 have been built with the new lamination scheme. The Gantry 2 beam line consists of three curved bending Magnets, two with a bending angle of 58° (AMF1+2) and one with a bending angle of 90° (AMF3). Table 1 shows the specifications of the magnets.

TABLE 1 GANTRY 2 BENDING MAGNET SPECIFICATIONS

Gantry2 bends	**AMF1+2**	**AMF3**
Quantity	2	1
B [T]	1.53	1.53
Gap [mm]	60	150
Good field reg.	90 mm x 60 mm	260 mm x 150 mm
Length [m]	1.54	2.36
Weight [t]	7.8	45
Bend angle [°]	58	90

The high weight of 45 t of the 90° bending magnet results from the relatively large dimensions of the good field region. Two sweeper magnets for the horizontal and vertical spot scanning are placed in front of the 90° magnet and this leads to the large gap height and pole width.

All magnets have been delivered to PSI (see Fig. 5). Until now, measurements of the dynamic behavior have only been made with the 58° bending magnets AMF1+2.

Figs. 6 and 7 show the Hall probe measured magnetic field after a linear current ramp from 0 A to the maximum current value of 220 A with the same ramping time as with the test magnet measurements. Fig. 6 shows the magnetic field in the center of the magnet and Fig. 7 the field at the entrance/exit of the magnet. The relatively high 50 Hz noise in Figs. 6 and 7 comes from the magnified scale and the lower inductivity of the AMF2 magnet (1 H) in comparison with the test magnet (1.8 H). The eddy current distortions of the AMF1+2 magnets with the new lamination scheme are roughly 10 times smaller than the distortions measured with the test magnet. The normalized magnetic field values at the end of the current ramp have a value of 0.9994 at both positions in the magnet and the values increases asymptotically to the value 1.

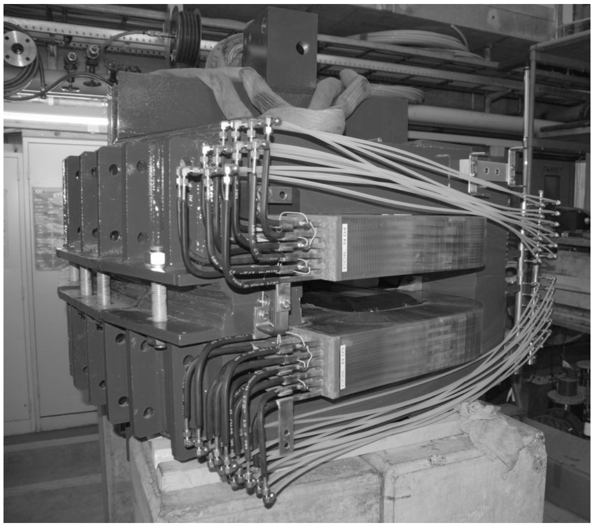

Fig. 5. The AMF2 magnet in the workshop.

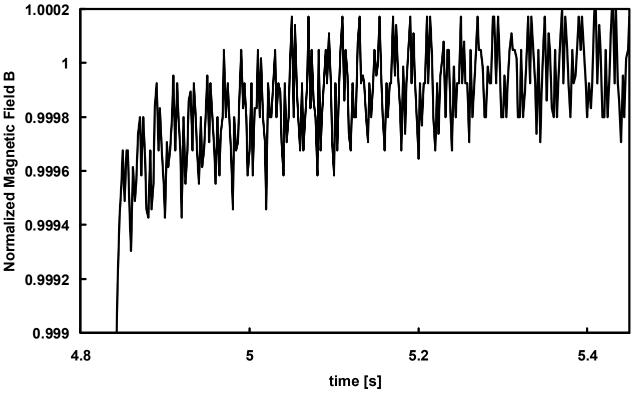

Fig. 6. Magnetic field measured by a Hall probe at the center of the AMF2 magnet after the current ramp.

A comparison of Figs. 2 and 5 and especially Figs. 3 and 7 confirms the success of the new lamination scheme. The different behavior of the eddy current effects at the entrance/exit of the two magnets shows that the local distortion in this region has vanished in the AMF1+2 magnets with the new lamination scheme. The residual distortion which can be seen in Figs. 5 and 7 is not localized at the pole entrance/exit but distributed over the whole yoke.

Fig. 8 shows the field integral measurement results of a small linear current ramp from 215 A to 220 A with a long measuring coil in the gap of the AMF2 bending magnet.

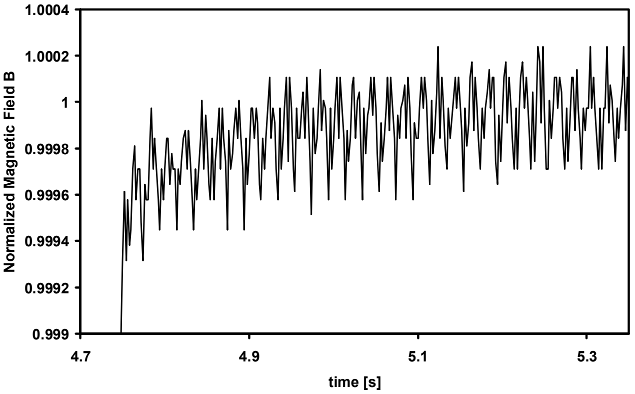

Fig. 7. Magnetic field measured by a Hall probe at the entrance/exit of the AMF2 magnet after the current ramp.

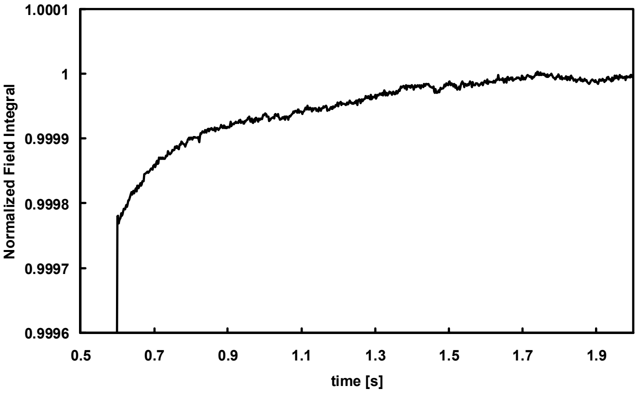

Fig. 8. Magnetic field integral measured by a long coil in the gap of the AMF2 magnet after a current ramp from 215 A to 220 A.

IV. CONCLUSION

A new lamination scheme for fast ramped bending magnets was presented. Measurements show that the new scheme suppresses eddy current effects in the pole entrance/exit region of bending magnets. We expect that the duration of the tumor treatment with the Gantry 2 will be speeded up due to the new lamination scheme. This lamination scheme could also be used in AC bending or quadrupole magnets to avoid heating problems at the poles. A disadvantage of the new lamination scheme is the mechanical accuracy of the magnet pole because of the non tolerated space between the longitudinal laminated channel part and the channel floor in the pole.

REFERENCES

[1] J.M. Schippers, “Overview of the PROSCAN Facility”, Proceedings of 17th International Conference on Cyclotrons and Their Applications 2004, Tokyo, October 2004.

[2] E. Pedroni et al., The PSI Gantry 2: A second generation proton scanning gantry, Zeitschrift für Medizinische Physik, Z. Med. Phys. 14 (2004) 25-34.

[3] M. Negrazus, D. George, V. Vrankovic, M. Werner, Eddy Current Reduction in Fast Ramped Bending Magnets, Proceedings of the 19th International Conference on Magnet Technology, MT-19, IEEE Transactions on Applied Superconductivity, Vol. 16, No. 2, pp. 228-230, June 2006.