Magnetic Measurements and Commissioning of the Fast Ramped 90° Bending Magnet in the PROSCAN Gantry 2 Project at PSI

A. Gabard, M. Negrazus, V. Vrankovic, D. George

Abstract – **The Paul Scherrer Institute (PSI/Switzerland) is developing, within the PROSCAN project, a new method of proton radiotherapy for treating cancers using a gantry based spot scanning technique for irradiating deep-seated tumors. Among the innovative elements are the laminated magnets in the beam lines, including the newly conceived Gantry 2, that will enable rapid energy changes (<150 ms) to modulate the range of the scanning pencil beam in three dimensions over the tumor volume. The last and multifunctional 90° bending magnet in the Gantry 2 transport system is not only the largest, but also the most challenging element. The dynamic eddy current effects during ramping were reduced with a special arrangement of laminated parts in the central pole region of the magnet. The construction of the Gantry 2 is finished and the first proton beam reached the treatment area in May 2008. The start of the patient treatment program is planned for the near future. In this paper, the 90° bending magnet construction and the results of the magnetic measurements (both static and dynamic) are presented, together with the commissioning experiences of the Gantry 2 magnet system. The results of the magnetic measurements validated the design, showing a very successful reduction of the eddy current effects so that the fast switching between two treatment energy steps (1 to 2% of the total energy) can be realized in less than 80 ms.**

Index Terms—eddy currents, magnetic measurements, magnets

I. Introduction

FOR the last 50 years, extensive research has been invested into proton therapy for cancer treatment. To date, more than 50,000 patients have been treated worldwide, and this broad experience has shown that proton therapy has many advantages over classic X-Ray therapy [1].

The Paul Scherrer Institut (PSI) in Villigen, Switzerland, started treating eye tumors in 1984 with a success rate of more than 98% of killed tumors. This success was the motivation for PSI specialists to develop new techniques for the treatment of deep seated tumors. By using the so-called "Spot Scanning" technique, a computer controlled pencil beam of protons (7 mm in diameter) delivers high dose spots within the tumor, allowing for extremely precise and homogeneous irradiation ideally adapted to the shape of the tumor [2].

The facility required for this kind of treatment, called the Gantry 1, has been in operation since 1996. To date, more than 350 patients have been treated. The treatment is specially indicated for children since the damage to the healthy tissue surrounding the tumor is minimized. The success speaks for itself, since in more than 80% of the cases the tumor is successfully killed.

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With the project PROSCAN, the success of the proton treatment at PSI was consolidated. It consisted of the installation of a new superconducting cyclotron exclusively dedicated to proton therapy and the construction of a new Gantry 2. Initially, the proton beam was delivered by the 590 MeV main proton accelerator in operation at PSI; the installation of the new cyclotron now allows the treatment program to be independent of the operating schedule of the main accelerator. Another purpose of this new project is to provide new scanning features to open new possibilities in tumor irradiation. So far, with Gantry 1, it was only possible to treat immobile tumors. With the newly installed Gantry 2, the goal is to allow for a dynamic adjustment of beam position and penetration depth to be able to apply the therapy to moving tumors as well. To allow for these dynamic adjustments, it is required to tune the beamline in a time scale of less than 150 ms. As a consequence, the dynamic behavior of the whole beamline is crucial to the achievement of this goal.

The first beam in the isocenter of Gantry 2 was achieved on May 9, 2008. The Gantry 2 area is currently being finished, and patient treatment is planned to start in the near future. This article will describe the last element of the Gantry 2 beamline, the 90 degree bending magnet sitting directly above the patient. The first part will explain the encountered design constraints and their consequences, while the second part will detail the results of the static and dynamic measurements of the magnet. The remaining part will report the experiences gained during installation and commissioning of the magnet.

II. Design of the 90° Bending Magnet

A. Magnet Shape and Parameters

Numerous constraints limited the choices which could be taken to design the 90 degree H type bending magnet. First of all, Gantry 2 is designed for a parallel beam at the magnet exit, which means that the position of the beam is modulated with sweepers prior to the entrance of the magnet. The magnetic gap was set to 150 mm since for the treatment window of 120 mm × 200 mm, a good field region of 150 mm × 260 mm inside the magnet is required.

Due to the dynamic requirements for the beamline, saturation in the iron yoke should be low. A value of 1.3 T would be ideal [3] to avoid eddy current effects in the yoke, but the specified bending radius and space and weight limits leads to a field of up to 1.9 T in the yoke. The mass of the magnet could not be chosen at will since the cranes in both the assembly area and the Gantry 2 hall have a maximum capacity of 20 tons. Stretching this limit by including a reserve of 10 to

15%, the maximum weight of one half yoke including coils could not exceed 23 tons.

All these constraints required fine tuning regarding magnet mass vs. performance. Since many large machining facilities are also limited to 20 tons, the right manufacturing procedures had to be established as well. In the end, packs of plain rectangular sheets were assembled and cut to an angle, which were then welded together into four pieces, and welded again after machining the pole contour, to form the two half yokes.

Table I shows the final data of the fabricated 90 degree bending magnet.

TABLE I. MAIN PARAMETERS OF THE 90 DEGREE DIPOLE

B [T]	1.53
Gap [mm]	150
Good Field Region	260 mm x 150 mm
Bending Radius [m]	1.5
Beam Path Length [m]	2.36
Weight [t]	46
Bending Angle [°]	90
Max. Energy [MeV]	230
Max. Current [A]	500

B. *Vacuum chamber*

One notable feature of the 90 degree dipole is the integrated vacuum chamber. Since increasing the magnetic gap would have required increasing the iron mass beyond the technical limits described above, there was no possibility to achieve a gap larger than 150 mm. This in turn meant that there was no space for a standard vacuum chamber between the pole surfaces, since any kind of chamber in this region would have reduced the useable aperture. Therefore, an alternate design was chosen. The vacuum chamber consists of a fiberglass wall that follows the pole contour; a rectangular rubber seal between the chamber and the pole surface ensures vacuum tightness. Fig. 1 shows a view of the vacuum chamber.

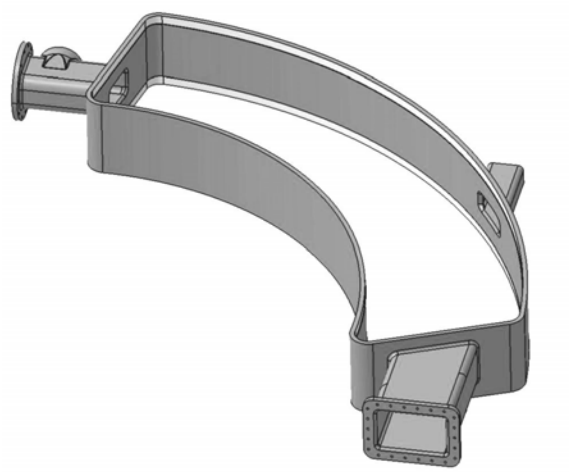

Fig. 1. 3D View of the vacuum chamber for the 90 degree bending magnet.

Since this design required vacuum tightness for the pole surfaces, an attempt was made to achieve this vacuum tightness by vacuum impregnation. Subsequent testing proved that the viscosity of the epoxy resin is too high for it to penetrate between the yoke laminations and provide a tight seal of the laminated iron. Ultimately, the pole surfaces were sealed vacuum tight with a 2 mm layer of epoxy/glass fiber composite. The performance of this sealing technique was proven beforehand by performing a pressure test on a sample.

C. *Eddy currents*

To avoid the eddy currents resulting from ramping the magnet to achieve fast energy changes, based on previous experience [3][4], special attention was paid to the entrance and exit regions. These eddy currents origin in the fact that in these regions, the magnetic field has a component that is perpendicular to the lamination. This would result in a time delay for the tumor treatment until the eddy currents decayed to an acceptable level, which 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. 2 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 in the new channel lamination. The longitudinal lamination package also leads to a flat longitudinal field profile due to the potential equalization.

Technically, the channel in the pole was machined out of the 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. This design was also applied to the two 58 degree bending magnets of Gantry 2 which are upstream of the 90 degree bending magnet. The eddy current reduction could be demonstrated successfully with the 58 degree bending magnets. The entrance and exit distortions due to eddy currents were completely suppressed [4].

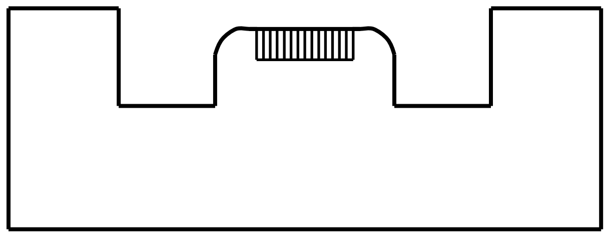

Fig. 2. Sketch of the cross section of the lower half of the 90 degree Gantry 2 bending magnet.

III. MAGNET MEASUREMENTS

A. *Measurement equipment and setup*

The magnetic measurements were done with a 5 axis Hall probe measuring machine [5]. To cover the whole pole area with the measuring arm, it was necessary to measure the field from both sides of the magnet with overlapping field maps. Magnetic marks on the pole surface gave the reference for combining the field maps from both sides. The static measurements were made in an on the fly measuring mode.

The dynamic measurements were made with the Hall probe located at a fixed position while the current of the magnet was ramped.

B. Static measurements

Only the main field component B_y was measured and the other two components were derived mathematically. The measurements were taken on the magnet mid plane y=0 (Fig. 3), on two planes above (y=+30 and +45 mm) and on two planes below the mid plane (y=-30 and -45 mm).

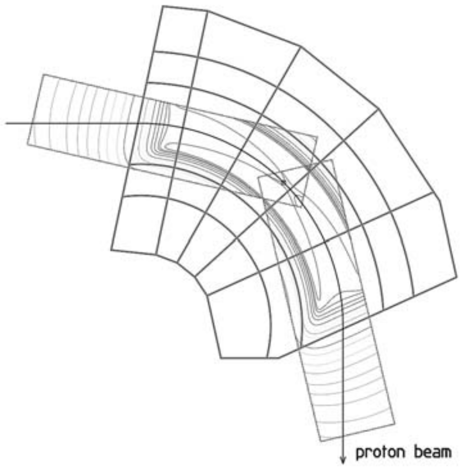

Fig. 3. Top view of the 90 degree magnet with field maps of mid-plane at 250 A measured from both magnet ends and merged together. The field maps show contour plots of the field.

A possible small angle error of the Hall probe with respect to the main field component causes incorrect measurement readings. On one hand the main field component reading gets reduced with the cosine of the angle error (a negligible effect for small angles), on the other hand, with the sine of the angle error (and therefore much more problematic), the reading includes also the side field components. This unwanted contribution can be cancelled out by averaging the measurements in the planes above and below the mid plane because of the opposite signs of the side field components.

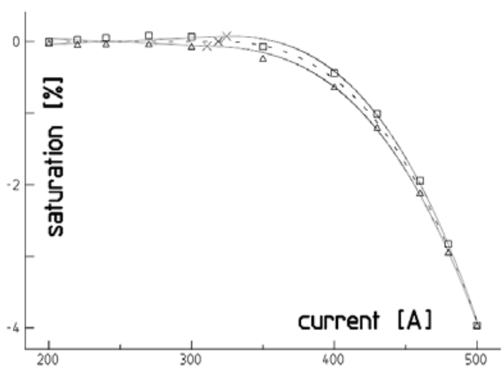

Fig. 4. Excitation curve showing ca. 4% saturation at the maximal current of 500 A.

The main field component can be approximated with a symmetric polynomial function B_y=f(y) of the 4th order, and the coefficients are calculated from the measurements in the mid-plane and from two other averaged planes as described above. Integration of the main field component gives the magnetic potential V, from which the other field components are calculated by differentiations in the corresponding direction, $B_x=\partial V/\partial x$ and $B_z=\partial V/\partial z$.

The complete 3D field maps were used for particle ray tracing analysis to calculate the beam vertex, position, shape and size at different beam energies. All field maps and the excitation curve (Fig. 4) were measured after pre-cycling the magnet with 0→500A→200A→500A→200A→500A prior to the setting of a current.

The field homogeneity of integrated fields in the horizontal plane of ±150 mm along the beam is better than 0.07%. The variations of the main magnet parameters with the current (or beam energy) are found to be:

- entrance edge angle = -11.9° ±0.3°
- exit edge angle =-23.0° -0.5° +0.2°
- bending radius =1539.7 mm -1.2 mm +0.6 mm

C. Dynamic measurements

The dynamic measurements were made with programmed current curves. 10 A Current steps were measured from 250 to 260 A, 380 to 390 A and 490 to 500 A with a speed of 100 A/s. After the step the current is constant. The measured 10 A steps are higher than the steps required for the medical treatment of 3.5 A and therefore a longer time of 0.8 s is needed to reach the 0.01% accuracy after a 10 A step shown in Fig. 5.

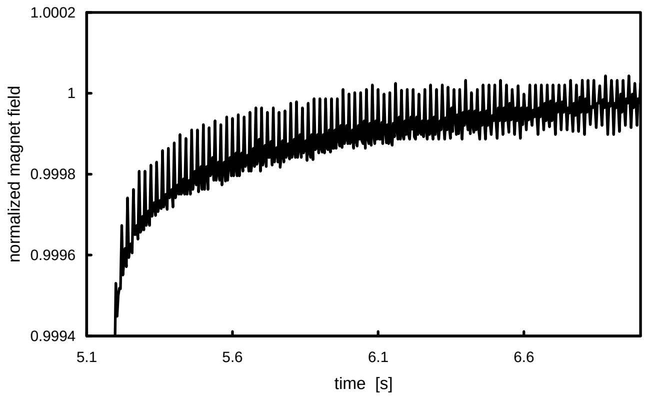

Fig. 5. Asymptotic behavior of the normalized magnet field after a current step from 250 to 260 A. The 50 Hz noise arises from the Hall probe power supply.

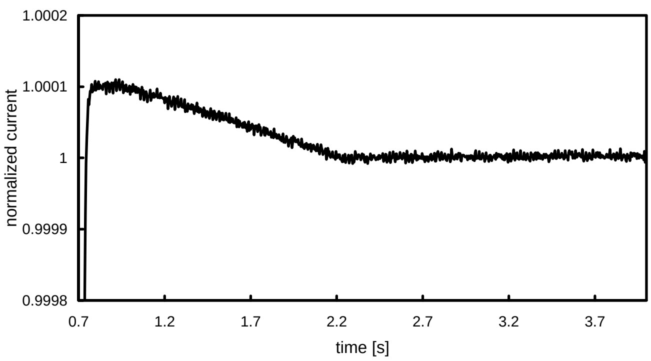

Fig. 6. Normalized overshoot current ramp after a current step form 250 to 260 A. The overshoot is 25 mA.

With a special current overshoot ramp shown in Fig. 6, an improvement of the time reaching the 0.01% accuracy to 30 ms was achieved (Fig. 7). The overshoot option is not used in the commissioning phase because the magnets are fast enough without it.

IV. Installation and Commissioning

A. Installation

Since it was impossible to carry the assembled magnet with the available cranes, it had to be assembled and disassembled several times during the assembly and installation process. Numerous problems had to be solved; the most problematic issue turned out to be the final assembly of the magnet with the vacuum chamber in place. Extreme precision was required to avoid damage to the fiberglass chamber.

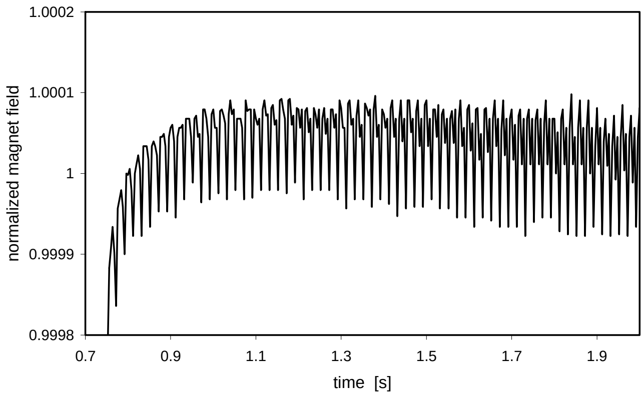

Fig. 7. Improved behavior of the normalized magnet field after a current step from 250 to 260 A with overshoot (Fig. 6).

To install the magnet, the Gantry 2 was rotated to the horizontal position. Using mobile hydraulic cylinders, a girder was built to support the magnet. The cylinders were adjustable in height and moving horizontally on an arrangement of rails. On top of the cylinders, a welded frame was set up that would adapt to the magnet geometry. The magnet was then assembled on site, its vacuum tightness confirmed, and slid in place. After installation of the counterweights compensating for the magnet weight, the insertion girder could be removed and the Gantry rotated normally.

B. Commissioning

1) Vacuum tightness and performance

Even though the vacuum tightness had been confirmed twice beforehand, questions remained about the tightness after installation and about the long term performance of the combined vacuum system consisting of the vacuum chamber, the sealing of the pole surface and the rectangular rubber seal. So far, this concept has proven very successful. No problems were encountered immediately after the final installation of the magnet, and the long term performance so far has shown to be very satisfying, going far beyond any expectation. Immediately after the installation in spring 2008, the vacuum reached a value of 2×10^{-5} mbar; in November of the same year, the vacuum dropped below 10^{-5} mbar, and after one year of continuous operation it has stabilized around 6.5×10^{-6} mbar. The initial design requirement having been 10^{-3} mbar or better, this is certainly a great success.

2) Magnet performance

The first beam in the iso-center of the Gantry 2 was achieved on May 9, 2008. The initial experimental phase was used to demonstrate the performance of the new concepts of the system: the very fast changes of the beam energy and the parallelism of the scanned beam [6].

A fast degrader system placed immediately after the superconducting cyclotron is used to set the correct beam energy. Within the beamline, the 90 degree bending magnet represents the most crucial element. Owing to the novel design of the lamination orientations described in Chapter II, an energy change corresponding to a penetration depth of Δs = 5 mm in water, namely a ΔE = 2.5 MeV or ΔI = 3.5 A in current, can be reached in 80 ms. This value, again, is far better than the initial design requirement of 150 ms.

The achieved parallelism of the beam is very satisfying as well; both the sophisticated design of the 90 degree dipole and the upstream scanning contribute. However, the spot form changes along the x-scan axis, which corresponds to the horizontal plane inside the dipole. This was expected beforehand, and a corrector quadrupole was placed between the two quadrupoles of the first doublet on the Gantry 2. To achieve an invariant spot shape in the complete scan region, this corrector quadrupole must be changed dynamically and linearly with the x-sweeper magnet; therefore, both magnets are connected in series.

V. Conclusions

The results of the measurements and the first experiences with the Gantry 2 operation have confirmed the excellent performance of the 90 degree dipole and the whole beamline. The innovative arrangement of longitudinal laminations in the central region of the pole suppresses eddy currents and allows for fast beam energy changes. Both static and dynamic performances of the magnet are beyond expectations. The 90 degree bending magnet will contribute substantially to the future success of the Gantry 2 cancer treatment program.

Acknowledgments

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