The Winding Method and Model of a Superconducting Bending Dipole for Hadrontherapy

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Abstract—The cancer therapy (hadrontherapy) with accelerated particle beams is an innovative method that allows an accurate and effective treatment of several kinds of tumors minimizing the irradiation of the surrounding tissues and avoiding intercepting vital organs. The deep tumors are usually treated with proton or ion beams by using a rotating gantry that allows the 360° irradiation of the patient. For the carbon ion hadrontherapy, being the energy in the order of 400 MeV, huge gantry structures are required if resistive magnets are used. An alternative solution was studied, involving the use of a cryogenic free superconducting magnet. The magnet consists of ten 90° bent superconducting dipoles wound with an aluminum stabilized Cu/NbTi conductor and mechanically supported by an aluminum alloy structure. In order to validate the feasibility of such a magnet, an accurate study of the winding technique was carried out, together with a winding test of a coil prototype.

Index Terms—Gantry, hadrontherapy, superconducting dipole.

I. INTRODUCTION

T HE construction of an ion gantry puts serious technical difficulties if considering the conventional technology. The high magnetic rigidity of ion therapy beams (over 6 Tm), dictated by the desirable penetration range of ions in the patient body (around 25 cm), requires carbon ions of 4.5 GeV energy. In order to fulfill this requirement the resulting gantry weight and dimensions exceed some practical limits, especially when considering a dedicated installation in a common hospital environment [1], [2]. This consideration suggested the idea of a more compact gantry equipped with a superconducting magnet.

In Fig. 1, a perspective view of the superconducting dipole we designed is shown [3], [4]: it is made by ten superconducting bent racetracks, indirectly cooled through the aluminum alloy mechanical structure by means of cryocoolers, so that the use of cryogenic fluids can be avoided. It is able to generate a magnetic field of 4 T along a circular path, 1.6 m in radius and 90° angularly. The conductor for winding the bending dipoles is a Rutherford cable made by 6 multifilamentary NbTi/Cu wires 0.8 mm in diameter and embedded in a pure aluminum stabilizer $5 \times 3 \text{ mm}^2$ through a co-extrusion or conform process.

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Fig. 1. Perspective 3D view of the superconducting dipole.



Fig. 2. Equivalence of the lengths of the convex and the concave profiles.

In order to demonstrate the mechanical feasibility of such a magnet, it is fundamental to set up and test a winding technique of one bent racetrack coil. In general a racetrack coil, for its two parallel straight legs, imposes a particular care during winding to avoid creating gaps among turns. For the compaction of windings, the racetrack coil cannot take advantage from the hoop stress present in conventional circular solenoids. Here, the situation is even worse, because the coils are curved, and this implies that one of the two legs is concave, highlighting the need of a totally new winding method.

II. THE WINDING PRINCIPLE

A particularity of the bent racetrack geometry suggested and made possible an alternative approach for the winding. As shown in Fig. 2, the concave profile of the coil, included half of the development of each coil head, is exactly identical to the convex profile of the other leg of the coil. This means the



Fig. 3. Main parameters of the model coil.

concave profile can be replaced with an equivalent convex one, without affecting the overall turn length. Since this is true for any profile, it is applicable to all the coil turns. This geometric property allows the winding to be made with a simpler and different approach: the coil is wound with the two legs convex and symmetrical, mirrored with respect to the coil longitudinal axis. Once all the turns have been wound, the convex leg is pushed and moved gradually toward its final concave profile. This procedure is much more simpler from the mere winding point of view, but we had to analyze how pushing safely the leg in the concave position. This definitely imposes to test the whole procedure on a mock-up, to verify that the turn matrix is not loosed and damaged during the transferring. Indeed, turns are deformed and consequently submitted to a large mutual slipping. This has to be well controlled in order to avoid creating gaps among turns, that could cause some turns lose irremediably their original design shape.

In order to maximize the information obtainable from the test, we decided the winding of one full scale mock-up, whose dimensions, number of turns and coil cross section are those of the smallest coil of the gantry magnetic system (see Fig. 3). Obviously, it was used a dummy conductor, having the correct $5 \times 3 \text{ mm}^2$ section, but made of pure aluminum, fully annealed and insulated with a half overlapped dry glass tape.

III. FINITE ELEMENTS ANALYSIS

Before performing the test, finite element analyses have been carried out in order to define the clamping configuration of the bending leg, to estimate the force needed to push the convex leg in its final position, to understand the influence of the friction on the bending operation, and finally to evaluate the intermediate configuration of the bending leg.

The finite element analyses were performed using the code ANSYS [5] and 2D modeling the pure aluminum conductor, with its stress-strain curve, as a flexible-to-rigid contact to the pushing template and to the final concave profile.

The first problem we approached was if keeping or not in its position the semi-head which, after the winding, is already in the final location. In Fig. 4, the deforming sequence of one turn with the conductor, in the head region, completely free to move is shown. As it comes from the third frame, the conductor, during its natural deformation, assumes a very dangerous configuration: a sort of closed loop, which has a curvature radius smaller than designed and completely out of control. For this reason we decided to tightly contain that semi-head by mean of a certain number of retainers, as it can be deduced by Fig. 9.



Fig. 4. Deforming sequence as calculated by ANSYS in case of a winding completely free to move in the head region. It is half the model of one turn.



Fig. 5. Intermediate configuration of a two turn bending; the inset shows the detachment between the two adjacent turns.

The next important task is to evaluate the order of magnitude of the force necessary to bend the convex leg, but without modeling the whole winding pack. From the finite element calculation of the bending of one single turn, we found that the force needed is about 2 N for most bending path. Then, it is trivial to understand that the force is linearly proportional to the number of turns per layer (14), due to the problem geometry. Less obvious is the fact that the linear proportionality is maintained also on the number of layers (41), which we demonstrated up to 15 layers. This can be easily understood looking at Fig. 5, in which an intermediate configuration of a two turn bending is shown. Actually, during the deformation the turns slightly detach one from each other making negligible the effect of the friction, so that the needed force is nearly the same for all the turns, leading to a total force obtainable simply by multiplying the force necessary to bend one turn by the total number of turns. That total force was then calculated to be about 1.2 kN, a value



Fig. 6. Intermediate positions of the bending of one turn.



Fig. 7. The completed winding pack.

which was totally confirmed by the test on the mock-up. A fundamental consequence is that in order to allow the necessary slipping among turns, but without any friction, the winding pack has to be clamped tight enough not to let different layers to penetrate one each other, but not so tight to prevent the possibility of relative movements between neighboring layers.

The final interesting aspect that can be gathered from the finite element analysis is a prediction of the intermediate configurations assumed by the winding pack during the bending. Actually, due to the extremely high plasticity of the conductor, this task is not intuitive at all, and can greatly influence the success of the operation. Particularly, we have to take care that the conductor, in the head region, does not take any curvature higher in radius than designed, since its recovery would be very risky for the winding itself. As shown in Fig. 6, the choice to keep fixed the semi-head already in the final position directly implies that winding portion corresponding to the other semi-head remains substantially flat during most bending path, getting the right curvature only in the final stage. This was qualitatively confirmed by the test on the mock-up (see Fig. 8).

IV. THE WINDING METHOD

Basing on the above considerations, the manufacturing sequence is the following:

- all turns are wound on a special winding form that replaces the concave coil leg with its homologue convex shape (see Fig. 7);
- once the winding is completed, all turns are tighten together by suitable clamps;



Fig. 8. Four intermediate positions during the bending test.

- the semi-heads which are already in their final positions are tightly contained by suitable retainers (see Fig. 9);
- the part of the winding form, relative to the temporary convex leg, is then removed;
- the winding pack is now free to slide on the winding table;
- turns are slowly and gradually pushed toward the concave portion on the winding form (see Fig. 8);
- in order to allow slipping among turns, the compaction given by the clamps is suitably graded and adjusted;
- the clamps used to guide the winding arm during its transition are not disengaged, they reach their final design position and lock and maintain the coil shape (see Fig. 9).

V. THE WINDING TEST

The winding test of the mock-up, carried out at Ansaldo Superconduttori premises as described in the previous paragraph, was completely successful. Indeed, we obtained a very good quality winding pack and we were able to lock the bended leg in the foreseen position on the winding table, obtaining the shape we designed, shown in Fig. 3, with a satisfying precision (see Fig. 9).

Next, but of less importance than the bending test, we planned to verify the possibility to wrap the mass insulation around the completed winding pack. Also this test was successfully performed (see Fig. 10), giving useful information on how much



Fig. 9. The winding ready to be removed from the winding table.



Fig. 10. The mass insulation wrapping in the head region.

the exact shape of the winding could be maintained by subsequently dismounting and remounting the containments one at a time.

Finally, the conclusion of our activity was the attempt to impregnate the winding. This was performed in air by gradually immersing the winding in a resin bath. The result is shown in Fig. 11. Obviously, the real dipole would be impregnated by a completely different technique, more complicated but much better qualitatively, a vacuum impregnation using an epoxydic



Fig. 11. The winding after the impregnation.

resin. Anyway, this impregnation test had the only aim to entirely free the dipole from any mechanical containment, in order to better control the accuracy of the shape. The result was that the winding did not show any significant difference from the original dimensions.

VI. CONCLUSION

We designed and tested a mock-up allowing to verify the feasibility of a new winding technique for bent racetrack coils. The results we obtained were very encouraging: actually, we wound, bent, wrapped and impregnated the dipole with a relative easiness of execution. This allows the possibility of constructing a superconducting bending dipole for a gantry structure, opening the way to the imaginable advantages in terms of weight, dimensions and costs.

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