THE C235 IBA-SHI PROTONTHERAPY CYCLOTRON FOR THE NPTC PROJECT MAGNETIC SYSTEM DESIGN AND CONSTRUCTION

W. BEECKMAN, A. LAISNÉ, Y. JONGEN, D. VANDEPLASSCHE, S. ZAREMBA, J.C. AMÉLIA, G. LANNOYE

Ion Beam Applications, rue J. Lenoir 6, B–1348 Louvain-la-Neuve, Belgium

T. SATOH, T. TACHIKAWA, M. SANO

Sumitomo Heavy Industries, Niihama-City, Japan

This paper presents the design and construction of the magnetic system of the C235 isochronous cyclotron for the NPTC Project in Boston, MA, USA. This includes the overall magnet design, the foundry and machining of the magnet steel and finally the coil manufacturing.

1 Introduction

At the beginning of 1994, the Massachusetts General Hospital (MGH) of the Harvard Medical School in Boston, MA, USA, selected a team led by IBA to supply the proton therapy equipment of its new Northeast Proton Therapy Centre, (NPTC). The IBA integrated system includes a compact 235 MeV isochronous cyclotron, a short energy selection system transforming the fixed energy beam extracted from the cyclotron into a variable energy beam, one or more isocentric gantries fitted with a nozzle, one or more horizontal beam lines, a global system including an accelerator control unit and several independent but networked therapy control stations, a global safety management system and a robotic patient positioning system. A general presentation of this facility can be found in these proceedings [1]

In the present document, we focus on the design and construction of the magnetic circuit.

First, the clinical specifications of the proton beam are translated into physical specifications of the accelerator and to subsequent physical and geometrical characteristics of the magnet and of the main coils. This gives a first estimate of the machine parameters.

More detailed 2-D and 3-D magnetostatic calculations are then outlined.

Finally, the foundry and machining of the magnet steel and the manufacturing of the coils are described.

2 Basic design parameters

The magnetic system main dimensions and characteristics can be inferred from the clinical specifications. For instance, the "Range in patient" clinical specification dictates the maximum proton energy. A value of 32 g/cm^2 is achieved with a proton energy of 235 MeV. The corresponding magnetic rigidity together with the maximum mean field values which can be achieved with non superconducting coils, enables the determination of approximate magnet poles dimensions. Coil position and dimensions are then determined according to the required field values and taking into account possible winding techniques and cooling requirements. Finally, the return yoke dimensions are a compromise between low power losses in non-saturated iron and reduced overall dimensions of the accelerator.

Designing the magnetic circuit to get the proper mean field versus radius is sufficient to ensure isochronism. However, the beam stability also depends on the detailed shape of the magnetic field. Proper radial and axial focusing through the whole acceleration process are obtained by the correct dimensioning of high and low field regions and by the special shape of the magnetic poles. Special attention is also given to the crossing of resonances which could deteriorate beam quality.

One of the main difference with most classical cyclotrons is the respective contribution of the iron and of the coil. In most classical cyclotron magnets, coil dimensions are obtained from the required median plane field values and from power consumption and engineering considerations. In these magnets, saturation is generally avoided because it increases the magnetic power. Engineering issues aside, there is very little dependence of the field on coil dimensions and position.

In the C235 magnet, the situation is different. Here, compactness is aimed at which requires high field values. This is achieved with a special gap shape and a different distribution of the iron and coil contributions to the total field, more in the spirit of superconducting magnets. The iron is saturated and the field values depend more upon the coil dimensions and position than in classical cyclotron magnets. It is worthwhile mentioning that, though having a significant contribution to the total field produced by room temperature coils is rather unconventional, the power consumption is kept within very reasonable limits, amounting to less than 200 kW.

3 Magnetic field calculations

3.1 Introduction

Detailed magnet calculations using two-dimensional and three-dimensional computer codes are used to confirm and improve the initial design.

The execution time of 3-D programs is proportional to n^3 where n is the number of created node points. There is thus in 3-D models a balance between the accuracy one can achieve (the density of mesh points) and the computation time. In this respect, less time- and memory-consuming 2-D calculations are preferred whenever possible.

Both 2-D and 3-D calculations were performed using the OPERA code from Vector Fields Ltd.

3.2 2-D calculations

Though, the magnet geometry must in principle be handled as a full 3-D problem, it is possible to simulate the 3-D structure in a 2-D code using the so-called stacking factors method in order to take into account the regions where the magnet structure differs from axisymmetry (sectors and valleys, holes in the yoke, ...).

The stacking factor SF is defined as the fraction of the circle occupied by the real ferromagnetic material. The magnetic properties of the pseudo-material are described by the following B-H curve:

$$B_{pseudo} = \mu_0 \cdot H + (B - \mu_0 \cdot H) * SF$$

where B and H are related by the B-H curve for the real ferromagnetic material.

Two-dimensional programs are also useful to study details or local modifications which produce local effects. This avoids the burden of 3-D models, saves computation time and allows much more refined meshing of the region of interest. This can be done either on a full model or on a zoomed model. In this latter technique, a zoom is made of the area of interest in the large model and is driven by imposing vector potential values calculated from the full scale model, on its boundaries. This is especially important close to the outer pole edge of the C235 cyclotron where the magnet behaves as if it were rotationally symmetrical.

Finally, 2-D codes are used during the mapping procedure to shape the radial pole edge, as explained in [2].

3.3 3-D calculations

In 3-D modelling, one tries to take into account as many features as possible of the actual magnet in order to meet the reality at best. It was observed in previous IBA cyclotrons that absolute results of calculations and measurements differ up to $2 - 3\%$, which can be explained mainly by differences in the actual and modelled properties of the steel (B-H curves) and also by some geometrical differences due to details which are not taken into account in the model. Also sometimes small discontinuities of the magnetic fields are observed due to the limited number of node points in the model mesh.

Whereas absolute calculated values are within a few percent of the measured values, relative calculated and observed values are in much better agreement. In the C235, the agreement between calculated and measured value is better than 2

A small number of 3-D calculations, say 5 to 10, were used to correct or improve the design, mainly the return yoke size and shape, the position and dimension of pumping holes and the valley steps. Most of the 3-D calculations were used to obtain the proper hill shape for isochronism. This implies not only the hill to valley ratio but also the lateral steps dimensions and the spiral angle. Eventually, a satisfactory field map was obtained from both isochronism and focusing standpoints.

Another important result from 3-D calculation was an algorithm for pole edge machining during the mapping/shimming process. Such an algorithm is extremely useful in order to make the process converge as quickly as possible (3 -4 iterations expected).

4 Magnet Construction

4.1 Engineering issues

The magnet is split in the median plane. Both halves consist of 3 parts, the pole, the yoke and the plug. The magnet partition is sketched in figure 1.

As the main contribution to the magnetic induction comes from the steel magnetization, it is of the utmost importance to get the best magnetic properties. This can be achieved with very low carbon content foundry steels.

A single block cast pole is stiffer than a structure made from assembled parts and thus minimizes the deformation. Finally, in a cast structure the final accuracy is only given by the machining accuracy of the poles because they are machined out of one block and are not assembled parts so that there is no additional tolerance for positioning.

4.2 Foundry

The selected foundry, Creusot-Loire Industries (CLI), Le Creusot, France, already cast the AGOR parts. The required steel chemical composition was based on this experience. A chemical analysis was performed by the foundry on each steel batch. The results are shown in figure 2 together with the requested composition.

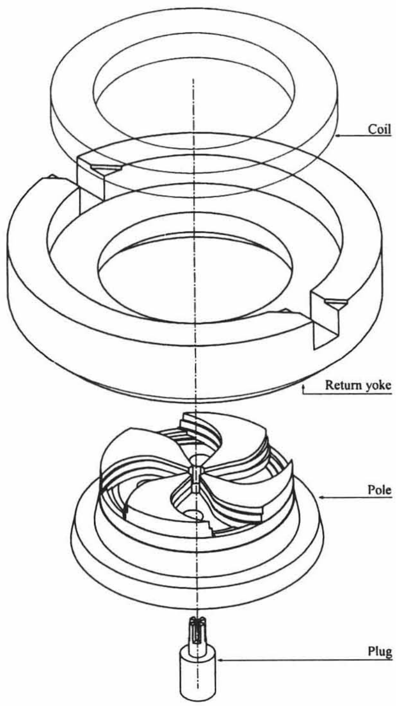

Figure 1: Exploded view of the C235 magnetic circuit

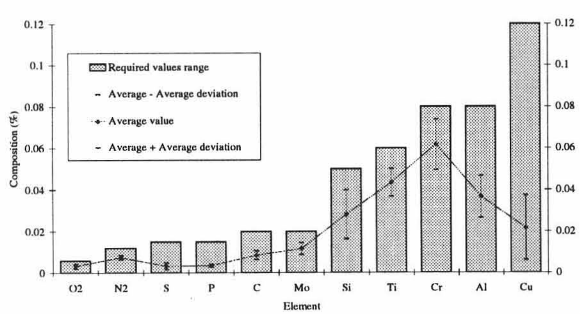

Figure 2: Requested and achieved chemical composition of the foundry steel (main impurities)

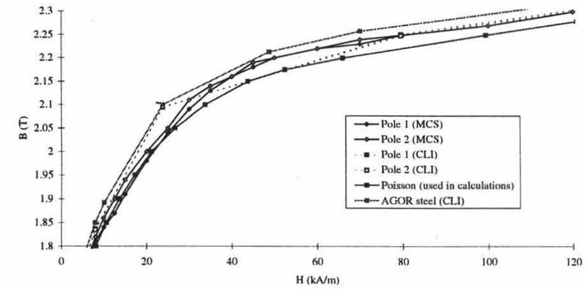

Figure 3: Magnetic characteristics of 2 different steel batches of the foundry steel (two independent measurements)

The magnetic properties were measured by the foundry and by the Magnet Centre of the University of Sunderland (MCS), Sunderland, UK. The results are shown in figure 3 together with the Armco steel (lower curve) used in calculations and with the AGOR steel (upper curve).

4.3 Machining

The parts were machined by Cockerill Mechanical Industries (CMI), Seraing, Belgium. Most of the machining was conducted separately on each part. The elliptic pole surface and the yoke-to-yoke contact surfaces were machined with the pole plug and return yoke assembled. Very tight tolerances were required especially for the elliptical pole surface, for the contact surfaces between the pole plug and the corresponding return yoke and for the contact surface between the two yokes. As a typical example of this, the accuracy on the most outer diameter of the pole plug and the corresponding diameter in the return yoke (Φ=3060 mm), is 0.2 mm.

In addition to the 6 main parts mentioned above, 2 sets of 16 removable pole edges were machined and assembled with very tight accuracies.

4.4 Quality control and schedule

Concerning the quality follow-up, very little defects, mistakes or non-conformities were recorded during the magnet construction phase and the whole process was conducted smoothly by both subcontractors.

Though tight, the schedule was also very well respected by both subcontractors as shown in the below schedule table.

	Foundry CLI	Machining CMI	Coils ΣΦ	PS Danfysik
Order	19-05-94	17-11-94	30-06-94	03-11-94
Scheduled	28-10-94	16-05-95	25-01-95	07-03-95
Delivery	24-11-94	17-05-95	30-12-95	01-02-95

5 Main Coil Manufacturing

For handling purposes, each coil is divided in 2 packs which consist of 4 double pancakes winding each. This design is the result of an extensive study where a series of different winding patterns have been investigated regarding their cooling merits. The study of the temperature distribution in a coil made as a stack of double pancakes shows that, a "...-in-in-out-out-..." sequence of water connections for successive double pancakes, gives a better temperature distribution than an "...-in-out-in-out-..." scheme.

The coils were manufactured by ΣΦ, Vannes, France. The required and achieved dimensions and accuracies in mm are indicated below.

Inner diameter	Required	2357 ±	3.0
	All packs	2357.0 ±	0.0
Outer diameter	Required	3320 ±	6.0
	Packs 1 & 4	3319.7 ±	0.5
	Packs 2 & 3	3320.7 ±	0.5
Height	Required	176 ±	0.75
	Pack 1	176.04 ±	0.17
	Pack 2	176.00 ±	0.16
	Pack 3	176.05 ±	0.11
	Pack 4	175.90 ±	0.20

Extensive mechanical, electrical and hydraulic testing was conducted on all 4 packs. No non-conformity was found. The coil flatness measurement was considered irrelevant due to plasticity. Again, the whole process was conducted very smoothly and within the schedule (see schedule table above).

6 Overall Magnetic Circuit Quality - On Site Testing

The different parts of the magnetic systems were assembled in IBA factory and tested.

In addition to the above mentioned parts, a yoke lifting system supplied by Hydrobel, Houtain-Saint-Siméon, Belgium and a 800 A, high-stability power supply from Danfysik, Copenhagen, Denmark, were installed. Here again, both suppliers did very well and in due schedule (see table above). For example, a long term current stability of ± 1.5 10^{-6} was achieved in the power supply though the specification was "only" ± 1.0 10^{-5}.

Besides extensive magnetic field measurements still in progress [2], a series of parameters of the magnetic circuit were recorded. Regarding the steel foundry and machining and the coil and power supply fabrication, it was found that all the specifications were met, especially about symmetry considerations.

References

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