THE C235 IBA-SHI PROTONTHERAPY CYCLOTRON FOR THE NPTC PROJECT PROGRESS REPORT OF THE MAGNETIC FIELD MAPPING AND SHIMMING

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This paper presents a status report of the magnetic field mapping and pole shimming process of the C235 isochronous cyclotron for the NPTC Project in Boston, MA, USA. First, some operating characteristics of the mapping system are presented. Then, the overall mapping and shimming process is outlined. Finally, the present status of the process is presented with special emphasis on the very good agreement between 2-D magnetostatic calculations and measurements.

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 this document, we present the status (November 95) of magnetic field mapping and pole edge shimming for the cyclotron isochronization.

2 Parameters of the field mapping system

The field mapping system can be equipped with three different probes. Two probes are used the most frequently: the Hall probe and the search coil. The magnetic field resolution is better than 1 G. Both probes have been calibrated with a relative precision of 10^{-4}.

A radial grid of measurements along a chosen azimuth is defined by the user and covers the radii between -80 and 1220 mm with respect to the cyclotron center. The radial position of the probe is measured using an optical encoder. The minimum radial step length and the precision of the radial position is 0.05 mm.

Azimuthal measurements cover a full turn and can be performed in both directions. The azimuthal step is half a degree. The precision of the azimuthal positioning of probes is 0.1 mrad.

Several regions of interest with different radial and azimuthal steps can be defined during one cyclotron mapping.

The mapping system is centered with respect to the cyclotron geometrical center with a precision of 0.05 mm. The precision of the probe positioning with respect to the cyclotron median plane is 0.5 mm. The maximum probe tilt with respect to the cyclotron median plane is 5 mrad. The arm tilt with respect to the cyclotron median plane is smaller than 2 mrad.

Measurements are fully automatic and their end can switch-off automatically the cyclotron main coil power supply (200kW).

3 The field mapping procedures

The final goal of the mapping and shimming process is to obtain an isochronous magnetic field together with suitable focusing in both planes and adequate optical characteristics ensuring the preservation of good beam quality throughout the acceleration (about 700 turns).

The whole process can be subdivided in a certain number of smaller serial processes, each of which has a limited purpose and is independent of its successors. This breakdown is listed below.

- Mapping system calibration
- Field reproducibility and stability checking
- 4-fold symmetry verification
- Initial mapping
- Radial edge correction
- Central bump correction
- Lateral edge correction

- Confirmation mapping

In this breakdown, we will focus more on the "Radial edge correction" which is presently completed. The next step, i.e. the "Lateral edge correction" procedure will be briefly outlined.

4 The radial edge correction procedure

4.1 Introduction

The magnetic field mapping and pole edge shimming is used in all IBA cyclotrons to achieve isochronism of the magnet. In this process, the so-called "lateral edges" are milled to decrease the angle spanned by high field regions (hills) at all radii. After some iterations, the isochronous $\langle B \rangle$ versus r law is achieved.

The C235 magnet not only features "lateral edges" but also "radial edges". These latter removable parts are used to shape the field close to the extraction radius. Indeed, as shown in figure 1, the C235 elliptic gap presents some unique field characteristics, among others

- A very sharp field decrease for radii above the pole radius
- The appearance of a strong field peak close to the pole radius if the ellipsoid is not closed. This peak moves inwards and flattens as the gap opening grows.

According to 2-D calculations, it is possible to find a specific shape of the radial edge which smoothens this peak through a flux redistribution to smaller radii. The radial edge is shaped accordingly during the initial machining process but large safety margins are allowed to cope for possible discrepancies between calculations and reality.

4.2 Rationale and description of 2-D modelling

The final radial edge shape is established using 2-D models only because:

- The dimensions of the features of interest are small as compared to possible mesh sizes in 3-D models.
- The strong saturation of the iron causes the magnet to behave like an axisymmetrical (2-D like) object, except very close to pure 3-D features i.e. mainly close to the lateral pole/valley limits.
- Finally, 2-D calculations are much less time-consuming than 3-D ones for such a trial-and-error process.

For "full hill" azimuths (between approx $-2°$ and $+12°$ in figure 2), the 2-D model represents a $360°$ hill magnet. The flux through the circuit is thus much larger than in the real magnet which, for the same return yoke dimensions (axial and radial), gives the circuit a much higher reluctance. This finally results in a decreased B value in the gap as compared to the real magnet.

We can partially correct this by increasing the return yoke dimensions in the 2-D model in order to decrease the return yoke saturation. The coil current, which in a non-saturated magnet could also be increased to solve the problem, cannot be modified here. Indeed, in the C235, the coil field is well above the required value to saturate the steel. The extra coil field so produced is used to shape the total $\langle B \rangle$ versus r law, more in the spirit of superconducting magnets.

Finally, it is found that the 2-D modelled fields show radial profiles identical to those of the real magnet plus an offset. This offset is independent of the radius but different for all azimuths. This situation reflects the "translation" of 3-D features of the real magnet in a 2-D model.

One of the most interesting aspects of this magnet is indeed its full 2-D behaviour. For "full hill" azimuths this is expected, but it is far more surprising for azimuths crossing the hill in the very end of its spiral shape. This is clearly shown in figure 1 where 4 very different azimuths are displayed (see figure 2, for the respective parts of hill and valley corresponding to those azimuths).

4.3 The procedure

The main lines of the "Radial edge correction" procedure are the following:

1. For the machine in its initial configuration, a series of 2-D models at different azimuths are compared with the corresponding field measurements.
2. The offsets between computed and measured data are found, one for each azimuth (every $2°$).
3. The radial edge (upper and lower) on one of the poles is milled and the corresponding model is computed.
4. The mapping is compared with the computed results, using the same offsets as previously.
5. No field change is found on the 3 unmodified poles compared to the previous configuration, showing their independence.
6. A very good agreement between the computed and the measured field for the modified pole is found, proving the validity of the 2-D models. Figure 1 shows the comparison between measured (full line)

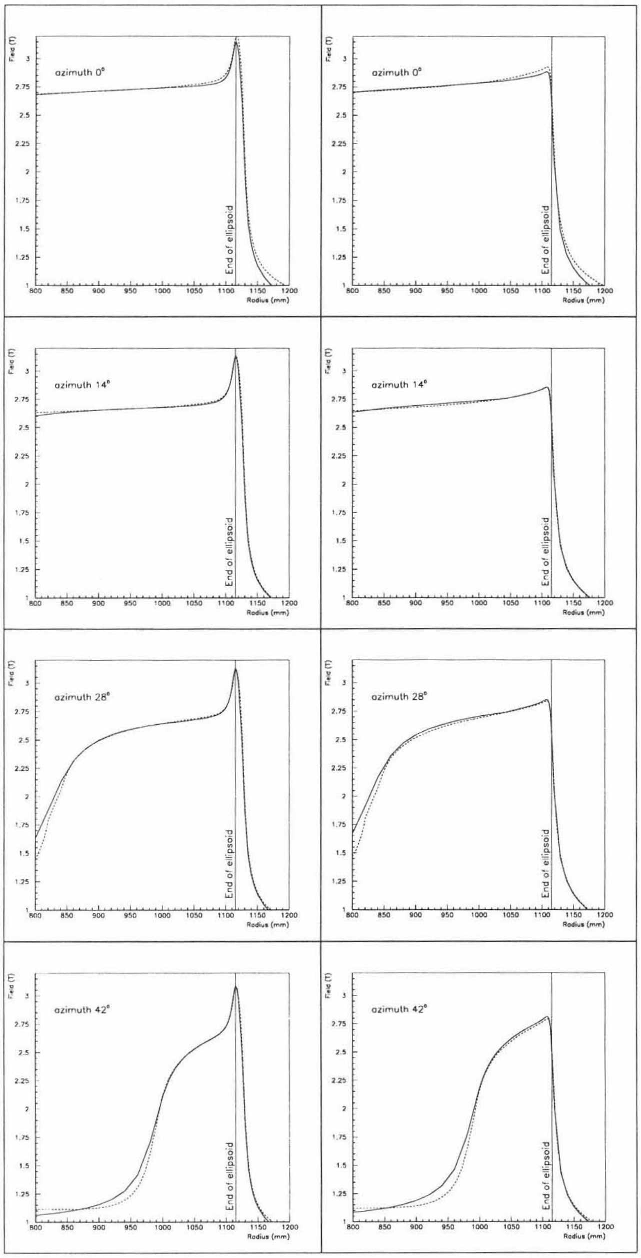

Figure 1: Comparison between measured (full) and 2-D model (dash) for the initial (left) and final (right) radial edge

and computed (dashed line) fields at different azimuths for the initial (left hand side) and final (right hand side) radial pole edge.

7. The pole edges are milled to their final shape according to the results of their initial 2-D model.

8. A special radial edge is modelled to take into account the gradient corrector[2]. Again, the geometry

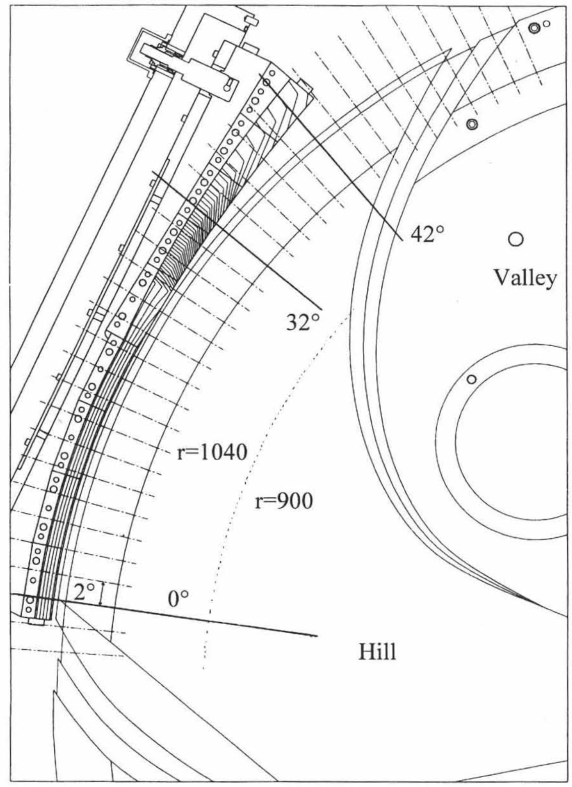

Figure 2: Top view of the pole featuring the gradient corrector

is fully computed by 2-D modelling at different azimuths every 2°. Figure 3 shows the comparison between measured and computed fields on the pole featuring the gradient corrector.

5 The lateral edge correction procedure

The lateral edge correction is performed as follows:

- A 360° mapping is recorded with a fixed azimuthal step of 2° (or smaller for the final field adjustment) and a variable radial step ranging from 2 cm in the low energy region down to 1 mm close to the extraction radius.

- Closed trajectories are computed for energies ranging from a few MeV up to the maximum energy for which a stable closed orbit still exist, with an energy step of 0.5 MeV. This approximately corresponds to the energy gain per turn. orbits approximately every turn.

- The phase shift of the particle motion with respect to the RF frequency is computed for every closed orbit.

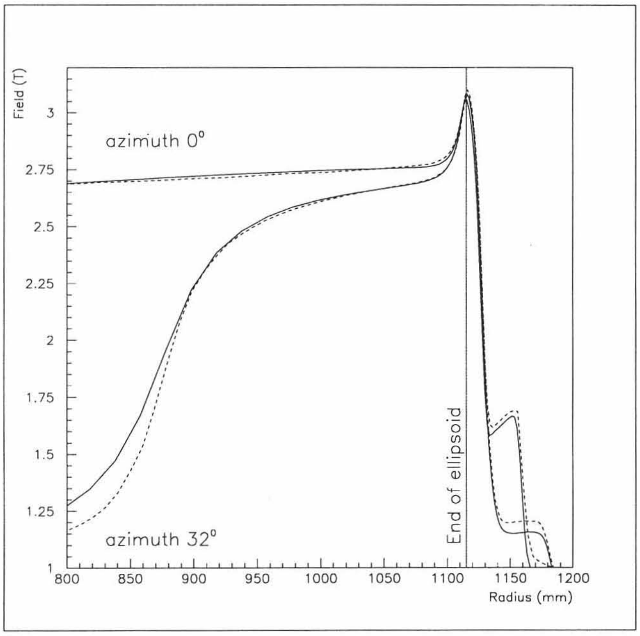

Figure 3: Comparison between measured (full) and 2-D model (dash) at 2 different azimuths on the pole featuring the gradient corrector for the initial radial edge

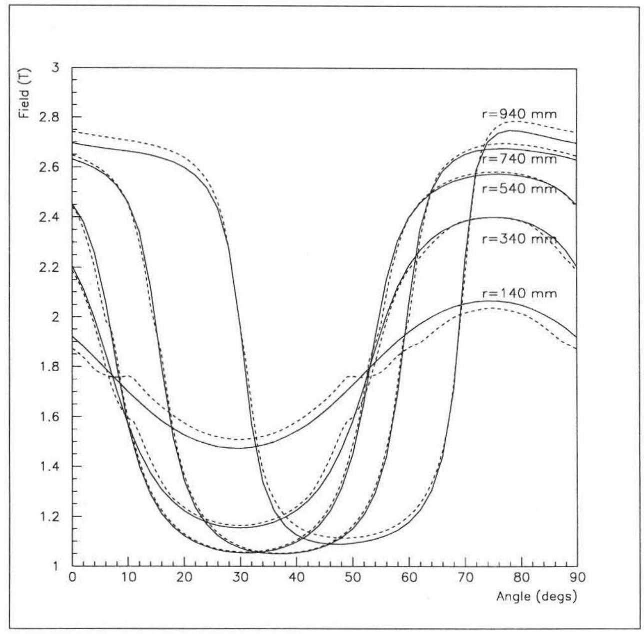

Figure 4: The measured (full) and 3-D modelled (dash) fields are in good agreement at all radii

- The reference RF frequency is always chosen so that the particle is in advance with respect to the RF. Reducing the angle spanned by high field regions will lengthen the path on which a particle with a given energy circulates, Its revolution frequency is thus reduced so as to finally match the chosen RF frequency.

- The central question is thus "How many mm of steel must be milled at a given radius to lower the integrated magnetic field experienced by a particle on its path at that radius ?"

- To answer this question, a series of 3-D models with different pole edges were compared in order to set-up an algorithm. The good agreement between measured and 3-D model fields are shown in figure 4.

- Due to the large number of turns, the phase shift at every turn must be kept within very small limits (integrated phase shift in the range $\pm 10°$) to ensure particle isochronism during the whole acceleration. This is a more stringent requirement as compared to the phase shift requirement in standard IBA cyclotrons.

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