

# EXTRACTED BEAMS FROM IBA'S C235

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## Abstract

IBA's proton therapy cyclotron (C235) has produced extracted 235 MeV proton beams and has fulfilled its factory tests. Model calculations have played an important role all along the course of this project: 2D and 3D magnetic fields, closed orbit analyses, particle trackings, beam transport layouts . . . These calculations and the corresponding tools are evaluated by a comparison to experiment.

## 1 INTRODUCTION

The purpose of this contribution is to describe the present status of IBA's C235 cyclotron as seen from an *a posteriori* viewpoint by the calculation team. Hence we will compare calculations and measurements of several subsystems of the cyclotron, and evaluate them.

## 2 MAGNETISM

Modelling of the magnetic circuit using Vector Fields Opera2d and Opera3d codes has been described in Ref. [1]. It must be stressed that, though a 3D approach is compulsory, the high mesh density offered by 2D models makes them much better suited for the description of mechanical details or of small variations. The *pseudo-2D* behaviour of C235 allowed us to fully exploit the complementarity of the 2 approaches: due to the full saturation of the magnet different radial slices are almost independent, and hence each slice may be adequately described by an appropriate 2D-like axisymmetrical model.

Using his technique allowed us to reach the final profile of the radial pole edge in just one iteration[1].

The gradient corrector (GC) was also designed that way. A series of models corresponding to several radial cuts and covering the azimuthal span of the GC have been built. They provided us with calculated shapes of the GC plates and quantified the strong influence the GC had on the inner adjacent pole field (closest approach  $\sim 4$  mm).

The calculated field map obtained in this way has been extensively used for the design of the extraction channel *before* the field was measured. The comparison with the experimental field map showed a very good agreement[2].

The permanent magnet quadrupoles (PMQ) were also designed from purely 2D models. The distance between these elements and the poles is large enough to avoid magnetic interaction, and the geometry of the quadrupoles fulfills the requirement for linear symmetry. Hence they have been described by a single 2D model with a simulated external field, and using a *BH*-curve provided by the manufacturer of the  $\text{Sm}_2\text{Co}_{17}$  material.

The real quadrupoles were mapped. The fitted field gradient is 19.1 T/m against a model value of 19.2 T/m and an almost identical deviation from linearity. The effective limit is found to be 3 mm outside the magnet.

3D models were also used to help shimming the pole edges in the process of isochronisation, in order to know the field redistribution caused by geometrical modifications (which is a fundamentally 3D process). This response function has thus been obtained via a series of 3D models, each one featuring a "unit cut" at a given radius. Here again the success of the method is undeniable.

## 3 BEAM OPTICS

The  $(Q_H, Q_V)$  diagram (Fig. 1) obtained from the closed orbit analysis of the circulating beam shows that a couple of potential resonance zones are crossed during acceleration.

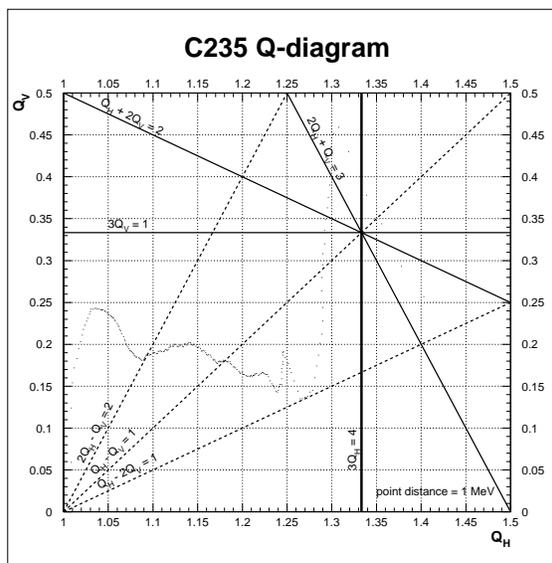


Figure 1: Working diagram throughout the acceleration in C235, as obtained from closed orbits in the final field map.

Coarse experimental betatron tunes are obtained from radial probe diagrams and are in good agreement with the computed values.

The  $Q_H - Q_V = 1$  resonance did actually show up during the initial beam tests. The calculations predicted this resonance not to occur since the skew quadrupole field components that drive it are neither present in the model nor in the measured median plane field map. The origin of the upper/lower asymmetry causing these skew components is still unknown. The experimental solution of slightly dif-

fering currents in the upper and the lower coil to cope with this problem has not yet received a calculated confirmation.

We also added a  $Q$ -corrector on the pole edge so as to cross the resonance as fast as possible by changing the shape of the working line. A realistic corrector is too small for a 3D simulation, but an upscaled version was calculated and has shown the correct properties (size and radial distribution of the  $Q$ -correction).

#### 4 EXTRACTION CHANNEL

Besides magnetic models, extensive particle tracking in the horizontal plane and beam optics computations have been carried out through the extraction channel, i.e., electrostatic deflector,  $GC$  and  $PMQ$  doublet (Fig. 2).

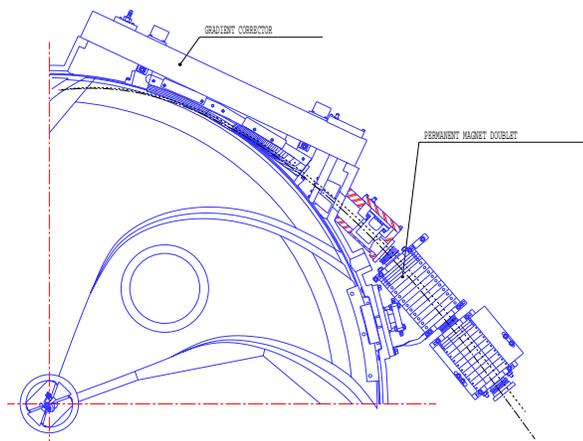


Figure 2: Comparison of the experimental (dash-dotted line) and the simulated (broken line) extraction paths.

Though the design of the channel was revised several times as new computational or experimental data were available, it must be stressed that the final design was good enough and the mechanical solution flexible enough for all the elements to be used as-built, giving a good practical measure of the quality and reliability of the calculations.

Particle tracking in the horizontal plane not only provides the extracted central path and the phase space diagram of the beam along its trajectory but also information about the non-linearities in the channel as well as hints to minimize them. It further allows to simulate radial current density plots and to compare them with experimental values obtained with the radial probe. Finally it permits a check of the accelerated beam optics through the effects of

- couplings between radial motion and acceleration
- hidden effects of the *large* first harmonic content
- energy spread

As initial conditions we always chose the central position and the Twiss parameters obtained from a closed orbit analysis, adding a known amount of off-centering if required. The assumed emittance comes from an early esti-

mate. However, since the extraction from C235 is a multi-turn process, the emittance of the extracted beam is in no direct relationship with that of the circulating beam.

The initial extracted beam tests have provided us with the geometrical path of the beam center and with beam profiles. It is found that the extracted beam is systematically at lower radial positions than in the simulations (Fig. 2), which in turn influences the optical properties. The circulating beam is intercepted at a slightly smaller radius because this position gives a better overall efficiency. The effect is partly corrected by shortening the  $GC$ . It is probable that the real beam suffers from optical imperfections which occur very close to the radial pole edge and which do not show up in the simulations. A  $Q$ -corrector has been added on a purely experimental basis, but a retrofit into the model has not been possible.

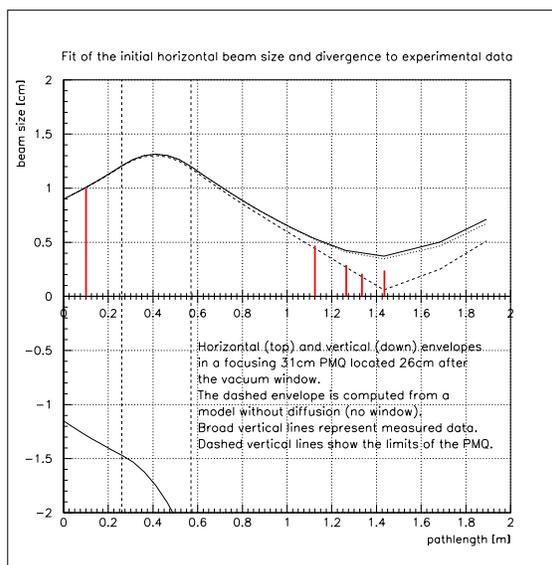


Figure 3: Beam envelopes with a focussing permanent magnet quadrupole, starting at the Al exit window.

During the design phase the extraction line optics were obtained according to the following recipe:

1. track particles (typ. 500) through the electrostatic deflector and the  $GC$  up to the entry of the first  $PMQ$ .
2. make the phase space plot at this position and fit the Twiss parameters and the emittance.
3. run  $MAD$  with the initial conditions of point 2 on the beam line made up by the quadrupole doublet, with end condition  $\alpha_H = \alpha_V = 0$ , and with the 2 quadrupole lengths as parameters.

Experimentally the following scenario was used:

1. visualize the beam spot on a quartz at several positions along the path with a *focussing*  $PMQ$  installed.
2. visualize the beam spots with a *defocussing* quad.

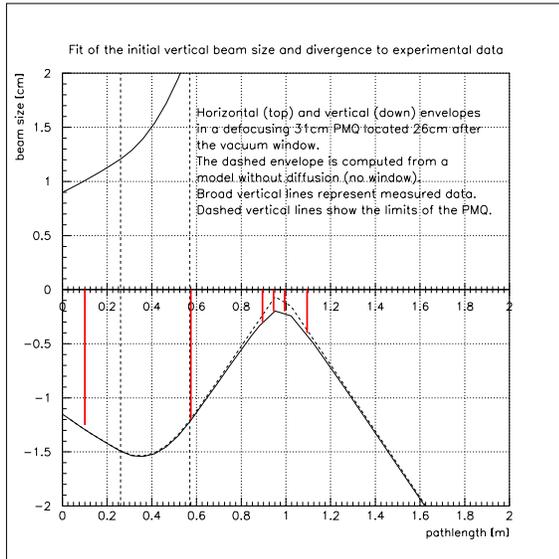


Figure 4: Beam envelopes with a defocussing permanent magnet quadrupole, starting at the Al exit window.

3. build realistic optical models of the 2 preceding set-ups, including measured *PMQ* (see Section 2), residual horizontally defocussing field gradient present between the main coils and multiple scattering caused by the Al exit window (1 mm) and the subsequent air layer (experimental conditions during the test).
4. using *TRANSPORT*, match the initial beam parameters to the observed beam spots.

The results of both fits are given in Figs. 3 and 4.

Starting from the initial values a new model of the line up to the Energy Selection System (incl. the 2 active quads at the exit of the cyclotron) has been made. Since 100% transmission cannot be obtained within the  $\varnothing$  56 mm vacuum pipes, the figure of merit for these calculations is the transport efficiency of the line, using as a constraint a double waist and a horizontal/vertical equivalence at the ESS. The resulting beam envelopes are shown in Fig. 5.

## 5 CONCLUSION

From its official start to the first extracted beams, the C235 project has taken three years. This performance is largely due to the successful calculations which have been performed beforehand and all along the course of the construction.

Knowing the reality now, we may state that magnetic field calculations generally give an excellent agreement, and the combination of 3D and 2D modelling may be a powerful tool for the description of even very small details. However, a full description of an isochronous field and of the tiny *Q*-correctors requires a finer meshing in the 3D models. Furthermore it is necessary to reduce the symmetry of the model from 8 down to 2 or even 1 if a realistic

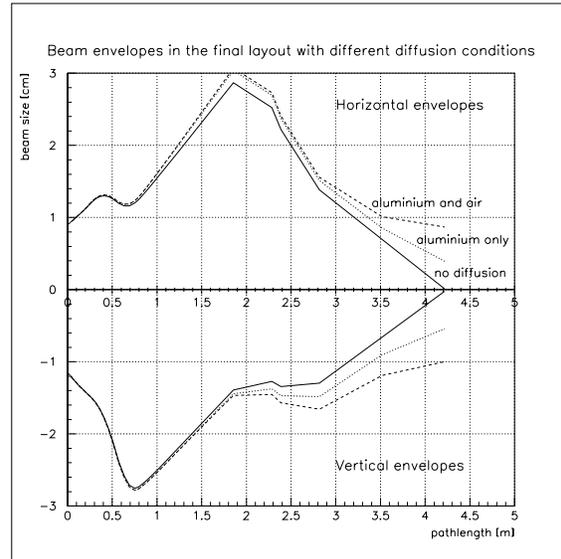


Figure 5: Beam envelopes in the extraction line for various multiple scattering conditions.

description of the machine is wanted. This makes us expect a 3D code capable of handling  $\sim 10^6$  nodes. There are discrepancies between the beam simulations and the real beam, and some experimental observations can not be reproduced. Some of these discrepancies can be explained, but some are inherent to our model. Particle tracking must include the vertical motion and the coupling between the 2 planes — however, we do not have a magnetic model giving rise to skew quadrupole components ... This being said, it remains that the tracking results have been extremely useful for the design of the extraction components.

## 6 REFERENCES

- [1] W. Beeckman, A. Laisné, Y. Jongen, D. Vandeplassche, S. Zaremba, J.C. Amélia, G. Lannoye, T. Satoh, T. Tachikawa, M. Sano, Proc. 14th Int. Conf. on Cyclotrons and their Applications, Cape Town (1995) 218–221.
- [2] W. Beeckman, M. Schuwer, D. Vandeplassche, S. Zaremba, J.C. Amélia, G. Lannoye, H. Miyazaki, *ibid* 222–225.