New Features in the Design of the IBA-SHI Proton Therapy Facility

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Abstract

The proton therapy facility developed by IBA and SHI has already been described in many papers. The present paper presents the status of the magnet and of the extraction system. In the magnet, the main changes compared to the previous design are an increase in energy from 230 MeV to 235 MeV and the study of an alternative extraction scheme featuring a small gap opening instead of the completely closed gap. Detailed extraction calculations using a combination of analytical and tracking approaches have been carried out and are presented here.

1 INTRODUCTION

Magnetic calculations on the IBA-SHI Proton Therapy Cyclotron were presented and updated elsewhere [1],[2]. The previous design was modified to accommodate an energy increase from 230 to 235 MeV. This mainly resulted in a 20 mm radius increase and in a slight modification in the lateral pole edges. Also, in the previous design, the elliptic gap was completely closed in order to keep a correct field up to the very last radius of the pole. Indeed, the field was too high close to the extraction radius and it was necessary to bypass some part of the flux through a "magnetic shunt". This implied that a channel had to be drilled in the shunt to let the beam out and also that the field mapping was complicated very close to the extraction radius where it is especially important. On the other hand all attempts to open the gap led to a smaller useful pole radius, at least if the radial hill profile was not modified. In this paper, we present an open gap solution which preserves the magnetic properties of the elliptical gap up to the radial edge. Such a solution is found if the radial hill profile is modified not only locally close to the median plane but to a much greater extent, from the median plane down to the foot of the hill.

The extraction from the C235 machine is studied through a combination of analytical and of tracking approaches. A phase space description is used to clarify the single turn extraction issues, and this view is confirmed by tracking results. Tracking is also used to determine the path of a central particle through the whole fringe field of the cyclotron. A *MAD* beam line description around this path allows to search for an adequate correction scheme.

Calculations are performed both on the circulating beam and on the extracted beam. The former aim at bringing the beam up to the entry of the deflector in an optimized way, whereas the latter study the behaviour of the beam throughout the extraction channel, i.e. starting at the deflector and up to the edge of the cyclotron field. These calculations can be performed using an analytical or a tracking approach. On the circulating beam both methods are applied. The extracted beam path is determined by tracking, but these results lead to an 'extraction beam line description' in terms of *MAD* beam line elements. This opens up the way for a convenient search of beam optical correction elements along the extraction channel.

2 MAGNET DESIGN

The magnetic characteristics due to the elliptical gap do show up in the real magnet exactly as in the theoretical infinitely long model, for all radii but the larger ones. At those radius, the field becomes too large and must be decreased to keep the correct mean value. Opening the gap seems the easiest solution but the field obtained that way is still too high. Moreover, the field maximum is displaced towards the interior, the larger the gap opening, the stronger the displacement. The only solution found up to now was to completely closed the gap in order to bypass the undesired flux. The shape and dimensions of this "magnetic shunt" allowed to get the correct field value. In all those solutions, the maximum hill radius was identical to the main ellipse axis i.e. 1120 mm for the 235 MeV version. All efforts were made to handle the extra flux at best, not to eliminate it

On the other hand, reshaping the hill not only locally close to the median plane but on its whole height helps to control the flux accepted in the hill. This in conjunction with a careful optimization of the hill shape close to the median plane allowed to get a correct solution. This is shown in figure 1 where the completely closed gap, the "simple" open gap and the "corrected" open gap fields are compared.

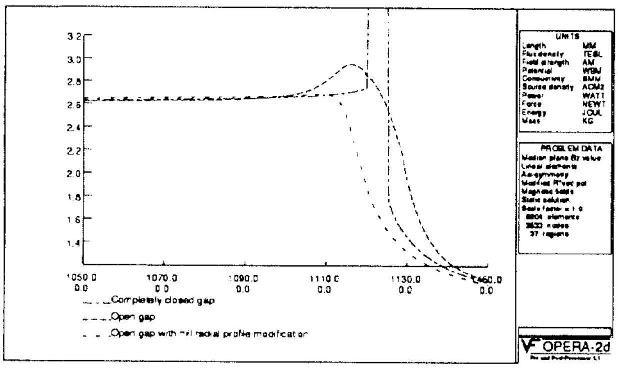

Figure 1: Comparison of median plane fields close to the extraction radius for three different shapes of the radial pole edges.

3 EXTRACTION STUDIES

Two fundamental characteristics of the C235 cyclotron are particularly relevant to its extraction :

- the machine has a hill/valley magnetic structure with a 4-fold symmetry, and with an azimuthal ratio $\sim \frac{55}{35}$.
- it has a virtually closed elliptical gap, leaving almost no vertical space at the extraction orbit.

As a consequence the 0.58 m long electrostatic septum must be located in a valley.

Table 1 lists numerical values at a few strategic points around the 235 MeV closed orbit. The tunes are : $Q_x = 1.31, Q_z = 0.45$.

From these data some important figures with respect to extraction are obtained.

The energy gain per turn at extraction is $\sim$ 500 keV. Hence

$$\frac{\Delta p}{p} = \frac{\gamma}{\gamma+1}\,\frac{\Delta T}{T} = \frac{1.25}{2.25}\,\frac{0.5}{235.} \approx 1.2\,10^{-3}$$

Since the dispersion at the entry of the deflector $D_x = 0.8$ m, it follows that the turn separation for a perfectly centered beam would be 1 mm. On the other hand, assuming a beam emittance of even as small as 1 π mm mrad, the total beam width is $2\sqrt{\varepsilon\beta_x} \approx 2.2$ mm. This clearly indicates that single turn extraction is impossible under these conditions.

The fact that the horizontal tune Q_x is very close to $\frac{4}{3}$ has 2 consequences :

First, the extraction kick given by the deflector must be such that the beam leaves the sectored region of the cyclotron just before the middle of the first encountered hill. Indeed, the phase advance from the deflector to the first mid-hill is 77° — which is a nearly ideal value — and no other mid-hill is as favourable. Due to the fact that all along the inflector both β_x and D_x decrease, a 5 mm high voltage gap is chosen. A voltage of 70 kV then yields an electric field $E = 14$ MV/m that produces a kick

$$k = \frac{E \cdot \ell}{(B\rho)\,\beta c} = 19.2 \text{ mrad}$$

With respect to the beam which would be unkicked the displacement at mid-hill becomes 17 mm, the angle 12.7 mrad. This figure of 17 mm is strongly reduced by different effects and a closest approach of circulating beam to the radial pole edge of $\sim$ 5–9 mm is realistic.

Another consequence is that by introducing a well-tuned off-centering, thus a closed orbit distortion, one can create a situation in which the orbit closest to the inside of the septum is separated by 3 turns from the extracted orbit. For that purpose, small transverse emittances not more than 2 π mm mrad in both planes are required. The theoretical feasibility of this single turn extraction scheme is studied with the optical function formalism and only considers particle distributions delimited by eigen-ellipses.

The optics (as obtained from *MAD*) are considered as constant during the whole extraction process, which typically lasts for 4 turns in this case. The beam is kicked with well-defined amplitude and phase in order to model its off-centering. It is considered that, in the real machine, this off-centering (created in the central region and causing the beam to perform significant betatron oscillations throughout its acceleration) does not cause any emittance increase due to dilution.

The situation regarding single turn extraction is viewed by plotting the phase space diagram at the entry of the deflector on successive turns, up to the septum jump. The septum itself is shown with its apparent thickness, considering that its curvature follows the path of the extracted beam. Fig. 2 shows an idealized situation clearly illustrating the concept of single turn extraction. The origin of the diagram corresponds to the position of the centered closed orbit of turn number 3 before extraction. The kicked beam ellipse is labeled '−3', and the kick is indicated by a dashed arrow. Then are drawn the beam ellipses '−2', '−1' and '0' (full ellipses) together with their unaccelerated partners (dashed ellipses). The family of dashed ellipses is simply obtained through 1-turn transformations, starting from the ellipse '−3' :

$$\begin{pmatrix} x \\ x' \end{pmatrix}_i = \mathbf{T} \begin{pmatrix} x \\ x' \end{pmatrix}_{i-1}$$

with $\mathbf{T}$ the transformation matrix over 1 turn in the machine. The accelerated partners are obtained by

$$\begin{pmatrix} x \\ x' \end{pmatrix}_{\text{acc}} = \begin{pmatrix} x \\ x' \end{pmatrix} + n \cdot \left(\frac{\Delta p}{p}\right)_{\text{turn}} \begin{pmatrix} D \\ D' \end{pmatrix}$$

Table 1: List of optical parameters at some special locations around the 235 MeV closed orbit.

	β_x [m]	α_x	μ_x [2π]	D_x [m]	D'_x	β_z [m]	α_z
entry pole edge	0.458	−0.406	0.126	0.566	0.202	3.842	1.276
mid hill	1.291	−0.729	0.233	0.755	0.309	2.143	0.946
exit pole edge	1.381	1.079	0.290	0.829	−0.344	1.802	−0.925
entry of deflector	1.241	1.389	0.297	0.803	−0.569	1.943	−1.547
mid valley	0.644	0.750	0.346	0.659	−0.458	2.915	−1.912

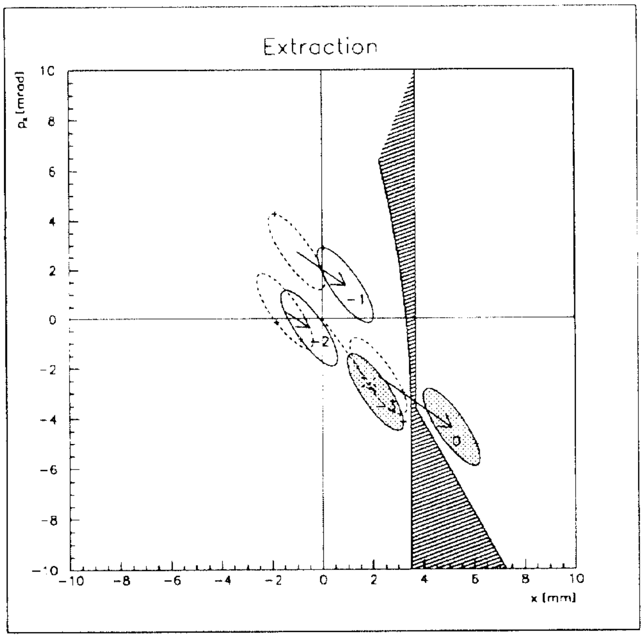

Figure 2: Phase space representation of the single turn extraction process at the entry of the septum. The beam ellipses have an area of 1 πmmmrad and are labeled by their turn number w.r.t. the extracted turn. The broken line arrow indicates the off-centering vector. The broken line ellipses and the full line ellipses are linked via the dispersion vectors (full arrows). Further explanations are given in the text. The septum itself (hatched area) is drawn with its apparent thickness.

and these displacements are indicated by full arrows.

Fig. 2 is obtained for a perfectly stable beam with an emittance of 1 πmmmrad and without momentum spread. A less clear-cut situation is obtained for a larger emittance and if momentum spread is taken into account. With a phase width $\sim \pm 3°$, a single turn the momentum spread at extraction is $\delta p/p < 1.8\ ^{\circ}/_{\circ\circ}$ giving beam sizes of about 4 mm in both planes at the entry of the deflector.

$$\text{size} = 2\sqrt{\varepsilon\beta + \left(D\frac{\delta p}{p}\right)^2}$$

However, though beam losses exist in this situation, they are still much lower if single turn is aimed at than with a pure "chaotic" extraction.

Tracking studies were performed to confirm and to refine the phase space description by including the effects of *changing* optics over the last turns, by including the acceleration and by checking the influence of non-linearities.

The results are very similar though the ellipse shapes are slightly changed from turn to turn, partly because of the changing optics, partly also due to the appearance of sextupolar distortions around $Q_x = 1.33$. This result confirms the value of the simple phase space model, which is much lighter to handle than the full tracking code.

Tracking is also used to obtain the beam path through the extraction channel, up to the edge of the cyclotron field. As soon as the extracted beam radially crosses the sector edge it experiences the very strong field gradient due to the steep radial field fall-off. In this region the beam sees gradients as high as −110 T/m. A quadrupole doublet located between the coils is used to keep the beam half-size below 3 cm in both planes.

4 REFERENCES

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