THE C235 IBA-SHI PROTONTHERAPY CYCLOTRON FOR THE NPTC PROJECT ON BEAM DYNAMICS ISSUES

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Some aspects of the C235 beam dynamics are presented, with emphasis on the central region and on the extraction system. Both these systems contain original solutions implied by the elliptical shape of the C235 pole gap. Recent simulation results are given in view of the presently ongoing magnetic field mapping.

1 Introduction

First it is important to situate the present status of the C235 project. At the time of writing this contribution the magnetic field of the C235 cyclotron is being measured. This means that the whole magnetic structure is assembled, including those components of the extraction system which have an influence on the internal field distribution. However, the field is not isochronous yet.

This contribution about beam dynamics aspects in C235 will mainly focus on injection and on extraction. Indeed, the high average field and the very small axial gap close to extraction require special and specific solutions to be implemented for these 2 topics. On the other hand, the beam dynamical parameters in the mid-field or circulating beam region are now fixed by the design of the magnet. The betatron tunes obtained from closed orbit calculations in the *measured* field are shown in fig. 1. They especially confirm the design goals of having $Q_V > 0.15$ for $T > 5$ MeV, and of having a very fast crossing of the $Q_H = \frac{4}{3}$ resonance near extraction.

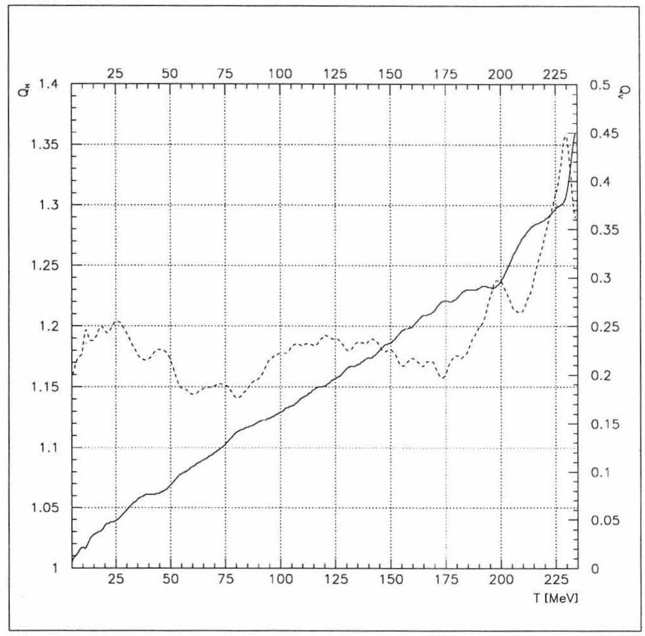

Figure 1: Horizontal (full line) and vertical (dashed line) betatron tunes obtained from closed orbit calculations in the measured field.

2 Injection system

A design of a central region of the cyclotron equipped with an internal ion source is usually a compromise between different factors that must be taken into account. The C235 cyclotron central region design tried to satisfy the requirements below.

The kinetic energy gain per turn has to be the greatest possible i.e. the dee voltage as high as possible. This is important due to the high magnetic field (about 1.74 T) in the C235 cyclotron center [1] and even more important for extraction of ions from the cyclotron. A radius of curvature of the first turn in the cyclotron has to be sufficiently large to avoid beam losses on the central region elements.

The dee voltage will be small enough to avoid the electric discharge between electrodes. Therefore a dee voltage variable along the dee is necessary. In the central region the dee voltage is 60 kV, and it increases up to 140 kV in the region prior to extraction.

The width of accelerating gaps will be small enough to avoid transit time problems and a possible deceleration of the ions for the cyclotron operating on the fourth harmonic mode. The first accelerating gap is the most important. The IBA experience proves that an electric field above 200 kV/cm can be easily kept in the central region of the cyclotron for very small ion source-puller gaps (1.5–2.5 mm). The gap width of 4 mm between the ion source and the puller has been chosen. Then the width of the next accelerating gaps increases up to a few centimeters for large radii. This width will be adapted taking into account not only the beam acceleration but also the dee capacitance which will be kept as small as possible.

The vertical beam dimensions have to be small. The axial gap between the poles diminishes from 96 mm in the center down to 9 mm in the extraction region.

The ion source is introduced axially in the cyclotron. Its diameter will be small to keep the axial hole in the magnet yoke as small as possible: such a hole produces a drop of the magnetic field which is axially defocusing. The central plug is used to obtain the required shape of the magnetic field close to the cyclotron center. The central plug shape, providing a second hole, symmetrical to the uncentered hole containing the ion source shaft, avoids the introduction of the first harmonic imperfection of the magnetic field and provides a space for necessary pipes supplying the ion source.

Electric axial focusing will be provided in the region where the magnetic axial focusing is not sufficient. This is done by a correct choice of accepted rf phases. A correct choice of the tilt angles of the first accelerating gaps which forces particles to go faster outwards minimizes the phase shift of the particles in this zone. Initial rf phases between -30 and -20 RF degrees have been chosen for the central region design. A further limitation of accepted rf phases will be provided by slits in the first turn.

Additional axial focusing will be provided by the correct shaping of the ion source emitting surface or by changes of the vertical aperture between the entrance and the exit of the accelerating gap.

Undesired rf phases are cut off by slits after the first half-turn. This also optimizes the orbit centering, and small harmonic coils installed on all sectors at $200 < r < 260$ are used to further reduce the beam off-centering.

To design the central region, calculations of particle trajectories were done in three dimensions. The magnetic field map in the median plane of the cyclotron was obtained from the program *Opera3d* [2]. The three-dimensional electric potential distribution has been calculated using *RELAX-3D* from TRIUMF and *Opera3d*. Particle trajectories were calculated up to $r = 200$ mm, where the kinetic energy of protons is about 6 MeV. Three potential maps have been used to describe more precisely the potential distribution. The first covered the region between the ion source and the puller, with a grid size of only 0.1 mm. The second map covered the square -50 mm $< x, y <$ 50 mm, and the third map the square -200 mm $< x, y <$ 200 mm. It was assumed that a variation of the dee voltage as a function of radius can be neglected up to 200 mm.

Figure 2 shows the central region used in the calculations, and some of the trajectories. This region corresponds to the second of the 3 potential distribution maps. The slit after half a turn is wide open, accepting initial rf phases between -50 and -20 degrees. In practice the phase acceptance will be reduced to less than 10 degrees.

The design of the central region ensures an excellent mechanical stiffness of the system in the axial direction,

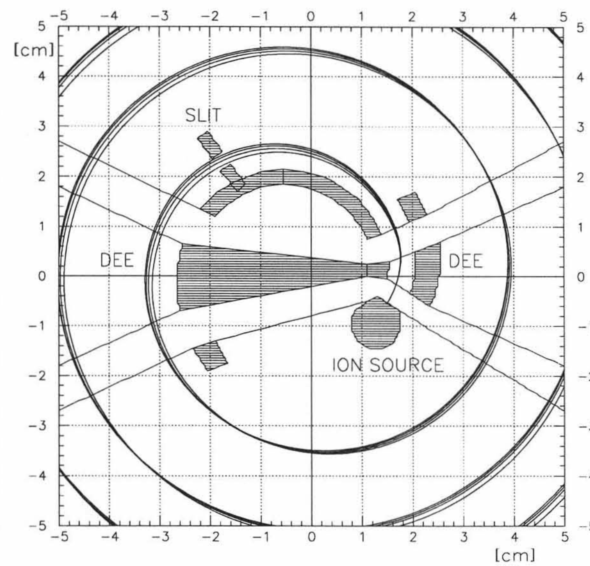

Figure 2: C235, the example of the medium plane section of the central region geometry and trajectories starting with same initial conditions but different initial rf phases.

but a smaller stiffness in the transverse direction.

The capacitance of the central region has been estimated as 8 pF using *Opera3d*.

3 Extraction system

The dominating feature of the C235 cyclotron with respect to the extraction system is the very small vertical gap (9 mm) at the radial pole edge. This has 2 main consequences:

- the electrostatic deflector can only be located in a magnetic valley, and is limited in length to the size of the valley.
- the field drop beyond the radial pole edge is extremely steep ($\partial B_z / \partial r > 100$ T/m).

Calculations for extraction comprise particle trackings over, typically, 20 turns, and beam optical calculations using *MAD* [3].

The extraction system will now be described through an enumeration of its components. The coherent outward kick on the last turn in the machine is given by an electrostatic deflector. Particle tracking in the measured magnetic field shows a most probable kick requirement of 17.8 mrad. The length of the deflector is limited to 0.58 m, hence a 235 MeV proton beam requires an electric deflecting field of 13 MV/m. The nominal values chosen for the design are shown in table 1.

Table 1: Nominal parameters of the electrostatic deflector.

azimuthal length	30°	
linear length	0.58	m
nominal gap	5	mm
voltage	70	kV
electric field	14	MV/m
angular kick	19.2	mrad
septum material	st. st.	
septum thickness	0.05	mm
HV electrode material	Cu	

After crossing the radial pole edge the beam enters a region of very steeply decreasing field. This gradient is horizontally defocussing. It is of the utmost importance to create a flat field channel along the beam path as close as possible to the pole edge, i.e. at less than 5 mm radial displacement. This very short distance cannot be achieved with a classical 3-bar-channel, and hence the gradient corrector is designed as a 2 parallel plate channel. It is located at 4 mm outside the radial pole edge. A 3D-view of the magnetic field measured in the region of the gradient corrector is presented in fig. 3. A radial field profile is shown on fig. 6. However, such a gradient corrector has a significant influence on the internal field, causing an important first harmonic component.

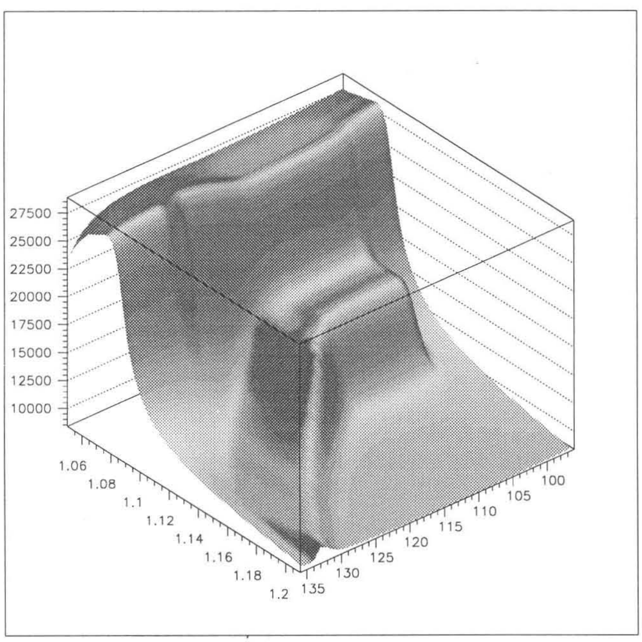

Figure 3: 3D-view of the magnetic field in the region of the gradient corrector.

At the exit of the gradient corrector the beam is diverging in both planes. It is then an obvious choice to

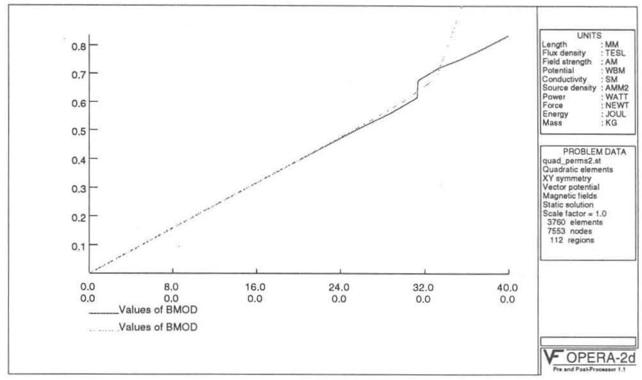

Figure 4: $||\mathbf{B}||(r)$ for 0° (full line) and for 22.5° (dashed line) in the geometry of fig. 5.

investigate the possibility of installing a quadrupole doublet in the space between the main coils (clearance = 100 mm). This is realistic if the quadrupoles are realized in carefully selected permanent magnet material — it has to withstand a significant radiation level and must have a high remanent field and a high resistance against demagnetizing fields. The only magnetic material which may satisfy these requirements is Sm_2Co_{17}. The quads have been designed using the *Opera2d* code [2] supplied with material data from commercial manufacturers. As is shown in fig. 4, a field gradient of 16 T/m is achievable in the geometry of fig. 5. The length of the quadrupoles is made adjustable by executing them as an assembly of slices.

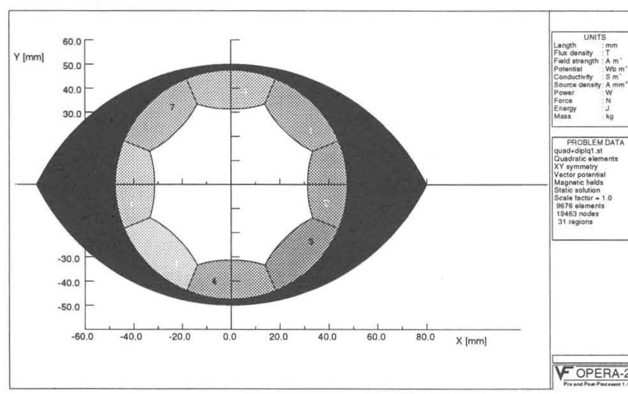

Figure 5: Geometry of the permanent magnet quadrupoles. The black collar is a soft iron shield.

The proton beam has to be transported to the energy degrader, where it will be focused in a small spot. A classical coil quadrupole doublet between the cyclotron exit flange and the energy degrader realizes these optical constraints.

The behaviour of the extracted beam has been studied by particle tracking. As initial conditions it has been chosen to fill a 2π mm mrad eigen-ellipse ~ 20 turns before extraction with a normally distributed particle population. The result of such a tracking is presented in fig. 6 as a sequence of particle density histograms along radial cuts through the gradient corrector.

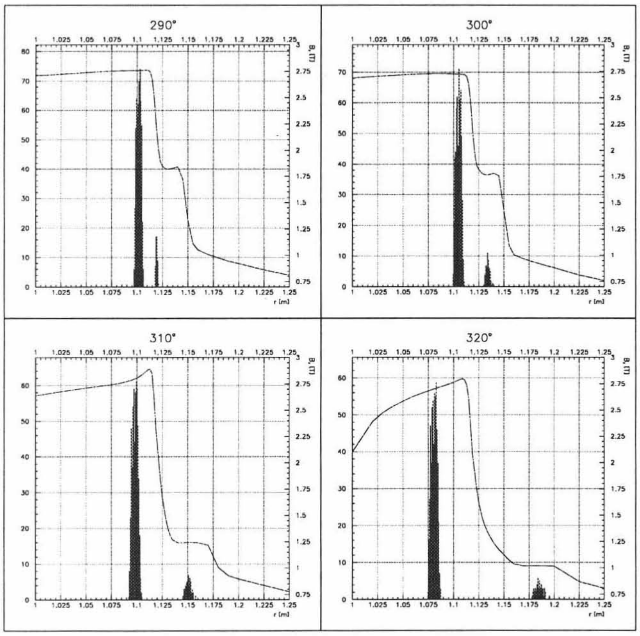

Figure 6: Radial beam density histograms superposed on the corresponding radial field profiles along subsequent cuts through the gradient corrector.

4 Present status

4.1 Ion source

A PIG ion source which will be used in C235 cyclotron has been constructed and tested. For medical purposes a short turn-on and turn-off time of a beam current is necessary. Measured turn-on and turn-off times are between 1 and 3μs. It was also tested that the beam current is proportional to the arc current. Required ion performances have been obtained with a gas flow-rate below 1 std.cc/min.

The ion source movement system has been designed, partially produced and tested. Since C235 is a fixed energy, one single ion species cyclotron, a mechanical adjustment of the ion source is not necessary during normal operation. However, initial beam tests do require the possibilities of a precise ion source positioning.

The introduction and the removal of the ion source will be done manually under vacuum. The coarse radial positioning of the ion source will be manual with the cyclotron open, but fine radial adjustments are possible under vacuum. The azimuthal position adjustment is most important for introducing and removing the ion source, and for reproducing a previous position. This movement is remotely controlled under vacuum. Finally, the axial positioning of the ion source is also manual under vacuum.

4.2 Central region

First measurements of the magnetic field have shown that the magnetic field bump in C235 cyclotron center is too high. First corrections of the central plug has been performed to obtain the shape of the magnetic field similar to the one used in the preliminary design. Performed corrections have been a fraction of necessary corrections to verify whether the model used to calculate them is correct.

4.3 Extraction system

The magnetic field mapping of both the cyclotron and of the gradient corrector show an excellent agreement with the calculations. This allows for a very fast convergence in the process of the pole edge corrections.

First mechanical tests in view of the construction of the electrostatic deflector have been undertaken. The main test issue is the tensioning of the stainless steel strips which constitute the septum.

The detailed design of the permanent magnet quadrupole doublet and a final choice of the supplier of the Sm_2Co_{17} material is now going on.

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