EXTRACTION SIMULATIONS FOR THE IBA C70 CYCLOTRON

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Abstract

In IBA's C70 cyclotron, 2 modes of extraction are implemented: (i) a variable energy extraction by charge exchange of negative ions, and (ii) a fixed energy extraction through an electrostatic deflector for positive ions. The stripping extraction will be implemented on two opposite poles allowing for a simultaneous dual beam extraction. At one side, the 2 extraction modes are linked by a strong geometric condition, i.e. they must converge in a common switching magnet. Basically this is obtained by having both extractions occurring from the same pole, where the length of the gradient correcting pole shim and the set of azimuthal positions of the stripper foil are adjustable parameters. The design of the extraction system is based on tracking studies in the deflection plane combined with beam optical calculations. Some constructional details of the extraction devices are given.

INTRODUCTION

The C70 cyclotron is a pseudo-fixed field multipurpose machine which will accelerate 4 different species: H^- up to 70 MeV, α up to 70 MeV, HH^+ up to 35 MeV, D^- up to 35 MeV. With "pseudo-fixed field" is meant that the maximum $B\rho$ is basically constant but that the radial field profile is adjustable by a set of correction coils. Since the cyclotron accelerates H^- up to 70 MeV, its peak field is limited to just over 1.6 T. The C70 has 4 magnetic sectors with a 30 mm gap and 4 deep valleys. A general overview of the machine is given in [1], the magnetic structure and the correction coils are described in detail in [2] and [3].

The study of the extraction will focus on H^- and on α. Obviously H^- is extracted by stripping, whereas the α's are to be extracted through an electrostatic deflector. However, both particles' paths should converge in a common switching magnet in order to be transported through a single versatile set of beam lines.

The need for an extraction by an electrostatic deflector has driven the design of the magnetic field. The 4 valleys are used as follows: 2 RF cavities, one for the deflector and one for diagnostics. Thus the deflector must fit within a single valley and drive the beam out of the guiding field on the next hill. The deflector is relatively short ($\ell = 471$ mm) and therefore produces a rather small transverse kick: 83 mrad for $E = 10^7$ V/m. So the beam has to circulate up to, say, 25 mm from the radial pole edge. This is only possible with a small value of the magnetic gap — we chose 30 mm. On the other hand, since our magnet

is rather unsaturated, we have the possibility to include a Gradient Correcting Extension (GCE) in the magnet pole itself, as a localised radial extension of the pole. This piece is repeated on the 4 poles in order to preserve the 4-fold symmetry.

With the α beam leaving the machine approximately tangentially from the middle of a magnetic sector, the stripper for the H^- beam shall be installed on the second angular half of the same sector. The proton beam will then leave the machine from the subsequent valley and cross the α path. At this crossing the switching magnet shall be placed. The schematics of the C70 extraction are shown in [1].

THE EXTRACTION BY THE ELECTROSTATIC DEFLECTOR

In the C70 the extraction process by electrostatic deflection is dominated by the fact that the extraction has to take place from a continuum of beam, i.e. without a separated turn structure. This is allowed by the fact that the contractual power of the extracted α beam is relatively limited: 35 pμA or 2450 W.

Extracted beam simulations

These simulations have been performed in a field map obtained from a 3D magnetostatic model calculation. The cyclotron was modelled using the Vector Fields software suite [4] (and in particular *TOSCA*), and an isochronous α-field was obtained. In this field map the last closed orbit is found around 68 MeV. The septum is positioned in such a way that the extracted beam energy is just above the energy of this last closed orbit.

Tracking simulations are performed in the deflection plane (the H plane) only. It is expected and assumed that the vertical motion is not or hardly affected by the extraction process, whereas the horizontal phase space is completely redefined by it. The vertical motion is therefore only handled by a beam optical code, *MAD* in our case.

Many multiparticle extraction simulations have led to the definition of the shape of the septum and of the required gap width. The voltage was chosen such that the central particle would leave the GCE on the pole just following the deflector in a centered way, so as to minimize the field non-linearities. The initial conditions for these simulations corresponded to the eigenellipse of the 60 MeV closed orbit with $\varepsilon_H = 6\pi$mmmrad (2σ value, corresponding to roughly $\frac{1}{2}$ the full acceptance from the central region [5]). The septum thickness at its entry is taken as 0.2 mm. Obviously,

without turn separation the minimization of this value is of crucial importance for obtaining a reasonable extraction efficiency. Note that the radial step per turn is estimated as 3.3 mm for an energy gain per turn of 0.4 MeV.

The simulations show an optimised extraction efficiency around 85%, with 10% of all losses on the high voltage electrode. The power loss on the septum would then be around 330 W, and 35 W on the HV electrode. The phase space plot right at the entry of the deflector together with the septum in an optimised position and showing its apparent thickness is given in Fig. 1.
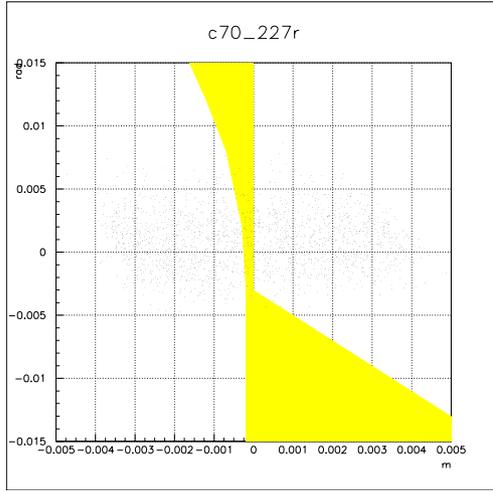
Figure 1: Horizontal phase space plot of 2 turns at the entry of the septum. The septum is shown with its apparent thickness as the yellow filled surface. The septum is angularly displaced in order to obtain an optimum extraction efficiency.

The extraction process redefines the phase space ellipse in the horizontal plane — it is assumed that the vertical emittance is preserved. At the exit of the GCE the horizontal beam characteristics are obtained by a fit of the tracking statistics, and an emittance of 14π mm mrad is found. The phase space is described by

	β [m]	α	ε [π mm mrad]
H	1.15	0.82	14
V	4.81	-5.15	8.5

In spite of the correcting effect of the GCE the phase space parameters are not suited for transporting the beam up to the switching magnet. Therefore a focusing element has to be inserted as soon as possible downstream of the GCE. In practice there will be a permanent magnet quadrupole singlet, horizontally focusing, installed 0.85 m from the GCE. The beam optics are calculated with *MAD*, showing that we typically need an integrated field gradient of 1.5 T — see Fig. 2.

The deflector — a few highlights

The deflector will create a nominal electric field of (on average) 10 MV/m in a gap varying between 5.5 (on entry)
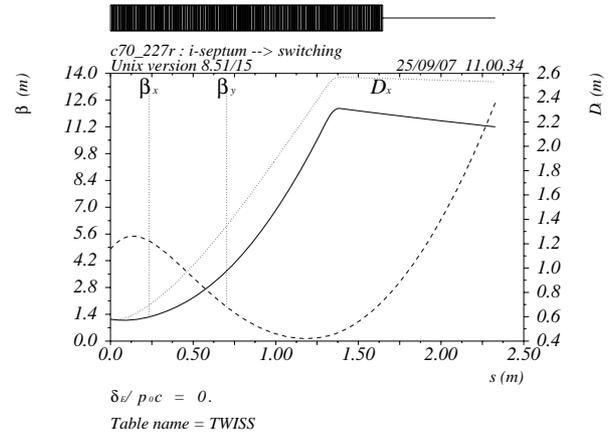
Figure 2: *MAD* plot of the optics between the septum entry and the switching magnet.

and 6.5 mm (on exit). For that its high voltage electrode will be at 58 kV, which is considered to be a comfortable value. Since the deflector is placed in a valley, there is ample space in the vertical direction for limiting the probability of discharge along the magnetic field lines.

The septum is 471 mm long. It will be machined from an OFHC copper plate. At entry its thickness should be 0.2 mm, rapidly rising along its length (1.3 mm thick at $\ell = 225$ mm). The septum plate is basically straight. It will have to be slightly bent over its first 200 mm by applying adequate spacers between it and its perfectly flat support structure. The septum plate is water cooled, but the 0.2 mm thick entry cannot dissipate the power corresponding to the beam loss, for which a maximum attainable value of 720 W is assumed. Therefore the septum is to be preceded by a "pre-septum" of the same thickness but heavily water cooled, V-shaped and split. If also this part is made out of copper, the temperature rise amounts to roughly 700 K.

The high voltage electrode will be thermally anchored to its water cooled supporting structure through 2 BeO pillars in horizontal mounting, 70 mm long and 20 mm in diameter. The thermal load onto the HV electrode is estimated as 50 W, and thereby its operational temperature rise is expected to be less than 30 K.

A general view of the deflector is presented in Fig. 3.

THE EXTRACTION BY STRIPPING

Like the α field, the H$^-$ isochronous field map was also obtained from a 3D magnetostatic model calculation by *TOSCA*. Single particle tracking studies have been used for determining the adequate stripper positions as a function of energy, in the range 35 – 70 MeV, in such a way that all paths cross in the center of the switching magnet.

The extraction process by stripping redefines the horizontal phase space parameters, whereas the vertical phase space is considered to be unchanged. These redefinitions
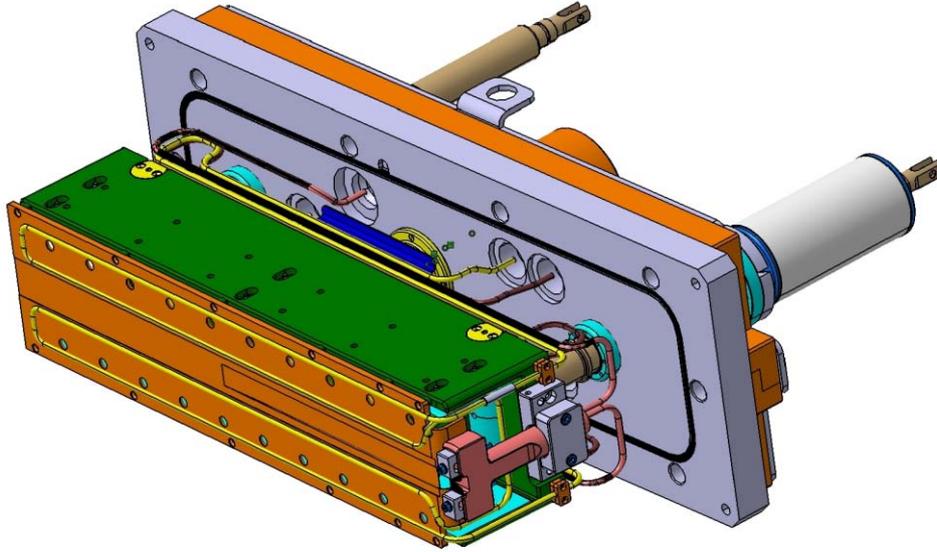
Figure 3: General view of the C70 deflector, the beam entry being in the foreground.

have been obtained by multiparticle tracking studies for the energies 70 MeV, 60 MeV and 35 MeV. Similarly to the α case, the initial Twiss parameters were obtained from the *MAD* analysis of a suitable closed orbit. The normalized emittance of the circulating beam is taken as $\varepsilon_{\mathrm{H}}^{N} = 6\pi$ mm mrad . The redefined horizontal emittances are significantly smaller than the circulating ones:

T [MeV]	70	60	35
ε_{H} [π mm mrad]	3.0	3.3	6.0

A correction of the optics on the path to the switching magnet is obviously not possible in this case. Even so, the envelope function β_x stays well below 20 m at the center of the switching. Figure 4 shows a tracking simulation of the 70 MeV proton beam from the stripper to the switching magnet.
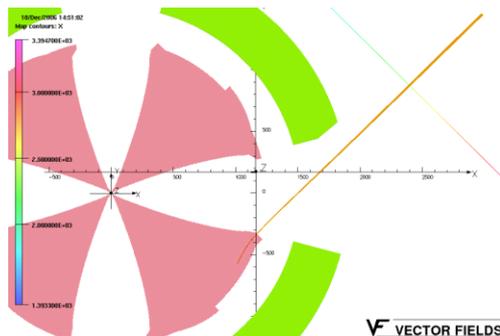
Figure 4: Tracking simulation in the *TOSCA* field for the 70 MeV extraction, stripper to switching.

CONCLUSION

At this point in time the study and the design of the extraction systems is entirely based on modelling data. Within the limitations generated by this situation, the double extraction, α's through an electrostatic deflector and H^{-} through stripping, into a common switching magnet is shown to be both possible and feasible. The use of an integrated gradient correcting tool ensures favourable optical properties of the deflector extracted beam.

The use of a preseptum allows to handle the power deposition caused by the beam loss in spite of the extraction scheme without separated turns. Nevertheless, a very good control of the accelerated beam quality, both in terms of emittance and of coherent oscillations, will be of prime importance.

Field measurements of the C70 cyclotron magnet are presently underway [6]. Initial analyses show that measurements and simulations compare very favourably, including in such sensitive zones like the gradient corrector.

REFERENCES

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