INJECTION AND CENTRAL REGION DESIGN FOR THE IBA C70 CYCLOTRON

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Abstract

The C70 cyclotron accelerates ions with $q/m = 1\ (H^-)$ as well as $q/m = 1/2\ (D^-,\ He^{2+},\ H_2^+)$. The beam is injected axially and bent onto the median plane with a spiral inflector. An electrostatic deflector placed at the exit of the spiral inflector, is used for centering both types of particles. An ECR ion source produces the He^{2+} and H_2^+ particles; a multicusp ion source produces the other two particles. A 90° dipole combination magnet bends both beams into the common vertical part of the injection line. The injection line further contains a quadrupole triplet that restores rotational beam symmetry and two solenoids that are used to match the beam to the cyclotron acceptance. A buncher is installed to increase the injection efficiency. The design approach for the central region is discussed. The design and optical properties of the injection line is discussed.

INTRODUCTION

There are several seperate contributions to this conference giving a general overview of the project [1], details of the magnet design [2], details of the magnetic field mapping [3], details of the extraction system [4] and details of the cyclotron magnet machining and assembly [5]. The main specifications of the C70 cyclotron are listed in Table 1. The negatively charged ions (H^-, D^-) are extracted by stripping; the positively charged ions (H_2^+, α) with an electrostatic deflector (ESD). After extraction, the H_2^+ molecule will be stripped to obtain a proton beam of 17.5 MeV that can be used for PET isotope production.

The C70 is a fixed field and fixed frequency machine; field isochronisation is done by correction coils wound around the poles [2]. The H^- is accelerated in harmonic mode $h = 2$; the other particles in harmonic mode $h = 4$. The magnetic field is reversed for particles with opposite charge. The dee voltage is 65 kVolt for all particles. There are two different orbit patterns in the machine: H^- makes about 540 turns (upto 70 MeV) and the other ions make about 155 turns upto their respective maximum energies. The two different orbit patterns are shown in Figure 1.

In order to well center both types of particles, an additional electrostatic deflection element is placed immediately at the exit of the inflector. By applying the correct deflector voltage, it places each of the two particle types on the cor-

Table 1: The four different particles that can be accelerated in the C70 cyclotron and the corresponding energy ranges and required maximum beam intensities.

ion	extraction	E_{min}	E_{max}	I_{max}
		MeV	MeV	$e\mu$A
H^-	stripping	30	70	750
D^-	stripping	15	35	50
H_2^+	ESD	–	35	50
α	ESD	–	70	70

Table 2: Summary of injection conditions: injection energy, ion source voltage, total inflector voltage, deflector voltage, magnetic field polarity, harmonic mode and the number of turns in the machine.

ion	E_i	V_{src}	V_{infl}	V_{defl}	B	h	turns
	keV	kV	kV	kV	–	–	–
H^-	40	-40	21.0	+5.5	$\Uparrow$	2	540
D^-	20	-20	10.5	-5.5	$\Uparrow$	4	155
H_2^+	20	-20	-10.5	+5.5	$\Downarrow$	4	155
α	40	+20	-10.5	+5.5	$\Downarrow$	4	155

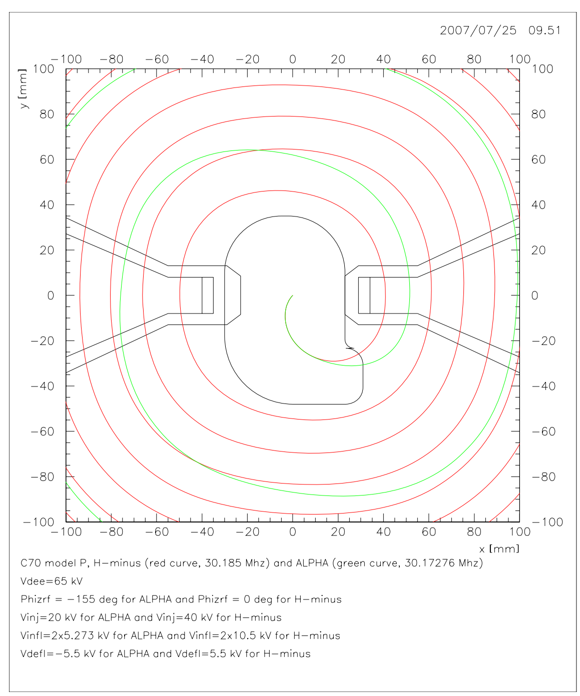

Figure 1: Turn patterns for particles accelerated on 2nd harmonic (red curve) and for particles accelerated on fourth harmonic (green curve).

rect equilibrium orbit. The main injection and acceleration conditions are listed in Table 2.

CENTRAL REGION DESIGN

The approach used can be divided in the following steps:

i) Construct an OPERA3D model of the cyclotron magnet and use it to create isochronous field maps for the two particle types and a detailed 3D field map in and around the inflector volume.

ii) Design the dee and dummy dee geometry by using the maximum available azimuthal space in between the two pole covers. The accelerating gap was chosen not smaller than 5 mm in order to avoid voltage breakdown. Solve the geometry with OPERA3D and obtain a 3D potential map around the median plane as needed by the tracking code.

iii) Determine the accelerated equilibrium orbit (AEO) for both particle types, by backtracking from high energy towards the center in the isochronous magnetic field and realistic dee-structure. The particles are started on a static equilibrium orbit (SEO) and have an RF phase that gives maximum energy gain. The energy of the SEO is optimized such that the final energy of the backtracked particle is exactly equal to the injection energy.

iv) Determine the crossing point of the two backtracked AEO's at injection just before entrance into the first accelerating gap. This is the point where the electrostatic deflector must be placed.

v) If necessary modify the geometry of the dee-tip in the center in such a way that the angle between the two AEO's at the crossing point, is not too large, such that reasonable deflector voltages will do the job.

vi) Obtain an initial estimate of the inflector central design orbit. This orbit must pass through the crossing point and divide the angle between the two AEO's in a convenient value. For this purpose a special mode of the tracking code is used in which the inflector is simulated by an electric field that is always perpendicular to the orbit. Within this mode the inflector is specified by its electric bend radius A, its tilt parameter k', its length L (measured along the orbit), entrance height above the median plane z_0, rotation angle α around the z-axis, and fringe field parameters. The code allows to automatically optimize the parameters L and z_0, so that the particle is injected exactly onto the median plane. The code also allows to automatically optimize the angle α so that the injected orbit passes through the crossing point. Since the electric rigidity of α is half of that of H^-, the injected orbit is placed at 2/3 from the α orbit. Optimization of the injected orbit angle at the crossing point is done by changing the tilt parameter k'.

vii) Construct the real 3D inflector electrodes around the estimated reference orbit using OPERA3D.

viii) Verify the design by orbit tracking in the real 3D electric and magnetic fields and make small modifications to the inflector if needed.

Figure 2 shows a 3D view of the final OPERA3D central region model that has been obtained. Figure 3 shows a photo of the C70 spiral inflector. The principle inflector parameters are listed in Table 3.

Table 3: Inflector parameters that have been used in the final OPERA3D model.

electric bend radius	A	mm	30
tilt parameter	k'	–	-0.55
electrode spacing	d	mm	8
electrode width	w	mm	20
orientation angle	α	deg	-141.8
height above median plane	z_0	mm	28.83

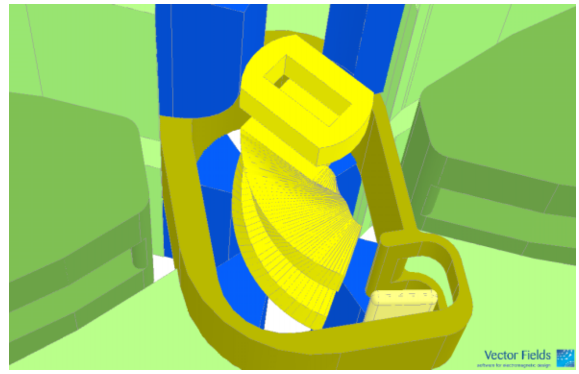

Figure 2: OPERA3D model of C70 central region. The inflector electrodes and collimator are shown in yellow. The tips of the dees and dummy dees are shown in dark and light coloured green. The deflector is shown in light yellow colour. The pole covers are shown in blue.

INJECTION LINE DESIGN

For optical design of the injection line, a good estimate was needed of both transverse phase space ellipses that would provide the best match to the cyclotron. Therefore

Figure 3: Photo of the C70 spiral inflector

Table 4: Transverse phase space 350 mm above the median plane giving a good match to the cyclotron. A round beam gives a good match. Values correspond with 3σ.

		H^-	α
half beam size	mm	20	21
beam divergence	mrad	60	56
correlation	–	-0.981	-0.9825
emittance	π mm-mrad	230	220
norm. emittance	π mm-mrad	2.1	1.0

a very large 4D transverse phase space containing 300000 particles was tracked through the cyclotron axial bore, the inflector and central region and the first 50 turns into the cyclotron (for H^- up to 7.5 MeV and for α upto 21 MeV). The particle was considered as accepted if it is within the horizontal and vertical eigenellipses of the cyclotron. The eigen-ellipses corresponding with a half beam size of 4 mm was used. For H^- this corresponds with horizontal and vertical emittances of 43 π mm-mrad and 23 π mm-mrad respectively. For α these values are 26 π mm-mrad and 14 π mm-mrad respectively. These emittances should be considered as 3σ values.

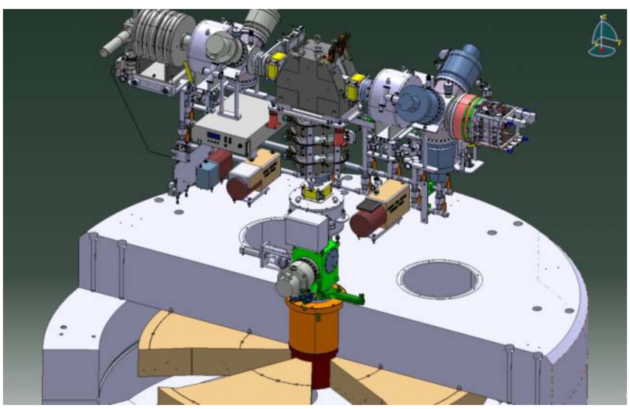

Figure 4: 3D view of the C70 injection line.

Particles that were not in those eigen-ellipses were removed from the initial injected beam and then the remaining injected phase space was analyzed. Since this is a full 4D phase space, it contains correlations between both transverse direction that can not be realized in practice. For that reason a subset of the full 4D phase space was extracted which would correspond to a beam without such correlations. It was found that this subset corresponded very well to a round beam. From this it was concluded that the best match to the cyclotron corresponds with a round beam at the cyclotron bore entrance. The properties of this matched round beam are given in Table 4. These conditions were used in TRANSPORT for fitting purposes. Comparing the emittances at injection and after 50 turns, we can estimate the emittance growth factors. These are 2.7 horizontally and 1.4 vertically for the H^- beam and 2.8 horizontally and 1.5 vertically for the α beam.

Figure 4 shows a 3D view of the injection line. On the right side is a cusp source producing H^- and D^-. On the left side is an ECR source (SUPERNANOGAN from PANTECHNIK) producing He^{2+} and H_2^+. Three turbos pump directly behind the ECR source and two turbos pump directly behind the cusp source. One turbo is installed in the vertical beamline just above the cyclotron. Both horizontal lines contain a solenoid for focusing and a small correction dipole for steering in both planes. The 90° combination magnet bends both beam into the vertical beam line. A quadrupole triplet is used to restore rotational symmetry of the beam (round beam) which was lost due to the asymmetric optics of the bend magnet. Further downstream are two solenoids that are used to match the beam to the cyclotron optics. The second solenoid is inserted in the cyclotron upper yoke. A buncher is placed behind the first solenoid. This solenoid is also used to create a small waist at the position of the buncher so that bunching efficiency may be better.

Figures 5 shows the H^- beam envelopes from the source to the inflector. It is seen that beyond the triplet the round beam is restored. Within the third solenoid the envelopes attain a maximum value and are then strongly focused to a size of a few millimeters corresponding with the calculated matching condition. Another minimum is just behind the second solenoid where the buncher is placed.

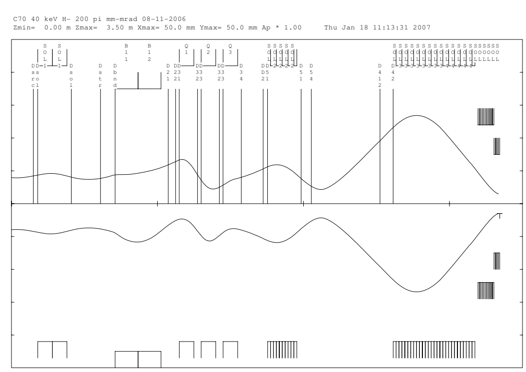

Figure 5: Beam envelopes for H^- in the injection line.

REFERENCES

[1] L. Medeiros-Romao et. al., "IBA C70 Cyclotron Development", These proceedings.

[2] S. Zaremba et. al., "Magnetic Field Design and Calculations for the IBA C70 Cyclotron", These proceedings.

[3] D. Vandeplassche et. al., "The magnetic Field Mapping System for the IBA C70 Cyclotron", These proceedings.

[4] D. Vandeplassche et. al., "Extraction Simulations for the IBA C70 Cyclotron", These proceedings.

[5] W. Beeckman et. al., "Machining and Assembly of the IBA C70 Cyclotron' Magnet', These proceedings.