ION OPTICS IN THE JYVÄSKYLÄ K130 CYCLOTRON

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ABSTRACT

Beam behavior in the K130 cyclotron and in the injection line has been studied numerically. Beam formation in the ECR ion source with space charge was calculated using a 3D code in order to re-design the puller electrode. The code TRANSPORT was used in the injection line. From the axial injection to extraction the code ION_TRACKER[1] was used.

In this paper, results from the ion optical studies from the ion source to extraction will be presented.

1. INTRODUCTION

The Jyväskylä K130 cyclotron[2] was built to accelerate mainly heavy ions from an ECR ion source for nuclear physics experiments. Part of the beam time will be used for radio isotope production. The assembly of the cyclotron started in May, 1990, and the first beam extraction took place in January 28, 1992.

2. INJECTION LINE

The injection line from the ECR ion source to the K130 cyclotron is based on solenoids. The beam line elements to the last Faraday cup before the axial part of the line are shown in Fig. 1. The solenoids S2–S5 between the two double focusing 90 degree dipoles were originally planned to be used as two telescopes. In the example shown in Fig. 1 solenoids S3 and S4 act as a telescope while S2 and S5 are stronger. This setup is a result of manual optimization of the beam current in the spiral inflector. The initial divergences in Fig. 1 roughly correspond to the acceptance of the line with the specific setup.

Numerical studies with a 3D tracking code of the beam formation in the ECR ion source with tranverse space charge forces predict larger divergences. The longitudinal space charge forces were not included. The treatment of space charge effects is similar to that by Xie at MSU.[3] Experiments also indicate that we lose beam before the first solenoid which is located 88 cm after the ECR extraction hole. We have therefore planned to add some extra focusing after the extraction electrodes – possibly an Einzel lens.

The original 45 degree puller electrode of the ECR ion source has been replaced with a Pierce puller in order to improve the beam quality from the source.

The quadrupoles Q1–Q4 are used for emittance matching.

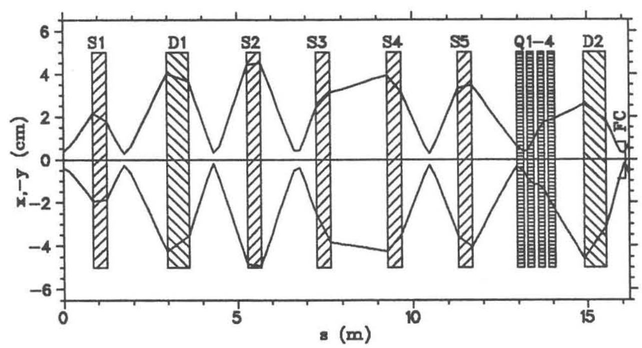

Fig. 1. The injection line elements and beam envelopes.

For the first couple of months of running the injection line we had severe problems with aligning the beam until we found out that the missing iron in the solenoid endplates (about 10 cm wide sector for current leads) caused a dipole component to the fringing field. Hence, changing the focusing strength of a solenoid resulted to a different dipole component in the field. The effect was also highly non-linear, and that disturbed the transverse phase space so that the beam had a crescent shape in the (x, y) space. Now the non-symmetric endplates of three solenoids have been removed, and the tuning of the injection line is much easier.

3. AXIAL INJECTION

There are two solenoids on the cyclotron axis, the first being outside the yoke and the second as close as possible to the median plane (23–63 cm from the median plane). The axial hole starts as a 474 mm × 474 mm rectangular hole, reducing to a 300 mm × 300 mm rectangular hole in the return yoke. In the pole piece (76 cm from the median plane) the hole is round with a diameter of 200 mm until the center plug which has a 40 mm diameter hole. The strengths of the solenoids are determined by tracking particles backwards from a 100 π mm mrad phase space ellipse that fits into the inflector acceptance to the Faraday cup which is located after the second dipole (D2). The optimum condition has been found to be such that the beam size is big between the last solenoids (almost parallel beam). A typical case of axial injection is shown in Fig. 2 where also the corresponding axial field has been plotted.

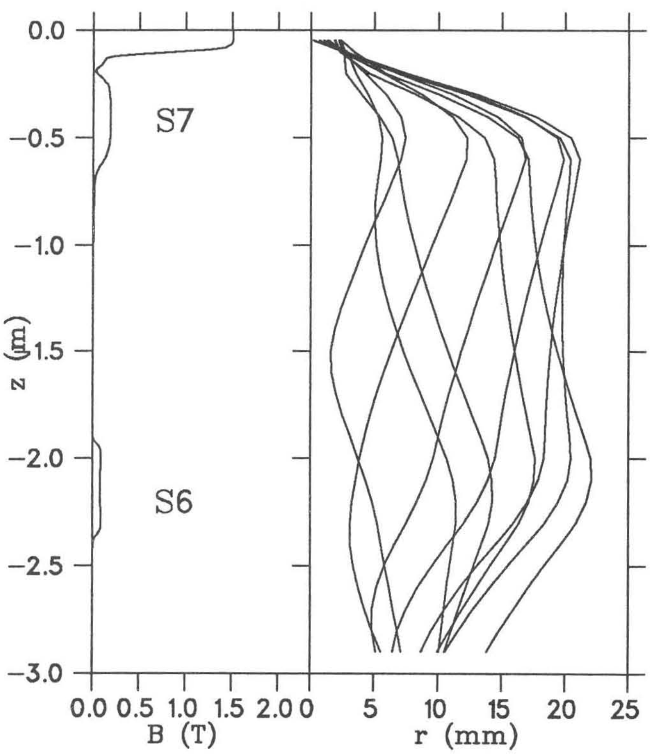

Fig. 2. Tracked beam in the axial hole of the K130 cyclotron and the corresponding axial magnetic field with solenoids S6 and S7.

3.1. Buncher

A buncher has been installed in the vertical hole of the cyclotron yoke, 145 cm from the median plane. It uses both first and second harmonic RF frequencies. The mechanical design has been adapted from MSU with minor modifications. Some parts of the electronics are still under construction. Numerical studies with ION_TRACKER have shown a beam intensity increase with a factor of 4 using only the first harmonic frequency. An example of such calculation is shown in Fig. 3 where only the first harmonic frequency has been used. The figures below show the effect of the spiral inflector to the longitudinal phase space.

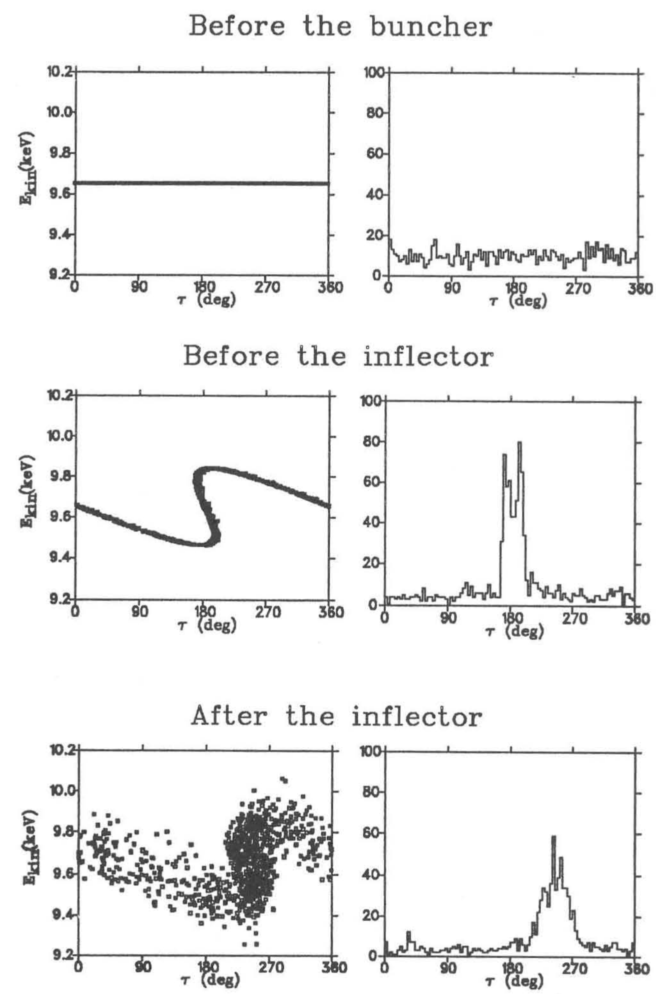

Fig. 3. Beam simulation with the buncher, before the buncher (above), before the inflector (middle) and after the inflector (below).

3.2. Spiral Inflector

The spiral inflectors for the three different harmonic modes were designed using analytic formulae and the electric fields for ION_TRACKER were calculated with RELAX3D.[4)] The acceptances of the inflectors have been determined both using linear transfer matrices and tracking particles using 3D fields. The transfer matrices were determined tracking four different particles through the inflector with moderate amplitudes (each component of the four dimensional phase space non-zero at the time). The results from these calculations for the second harmonic inflector are shown in Fig. 4. The acceptances correspond to non-correlated beams in the (h, u) space in the entrance of the spiral inflector. The horizontal phase space in the frame of the inflector gap is (h, hp) and the vertical one (u, up).

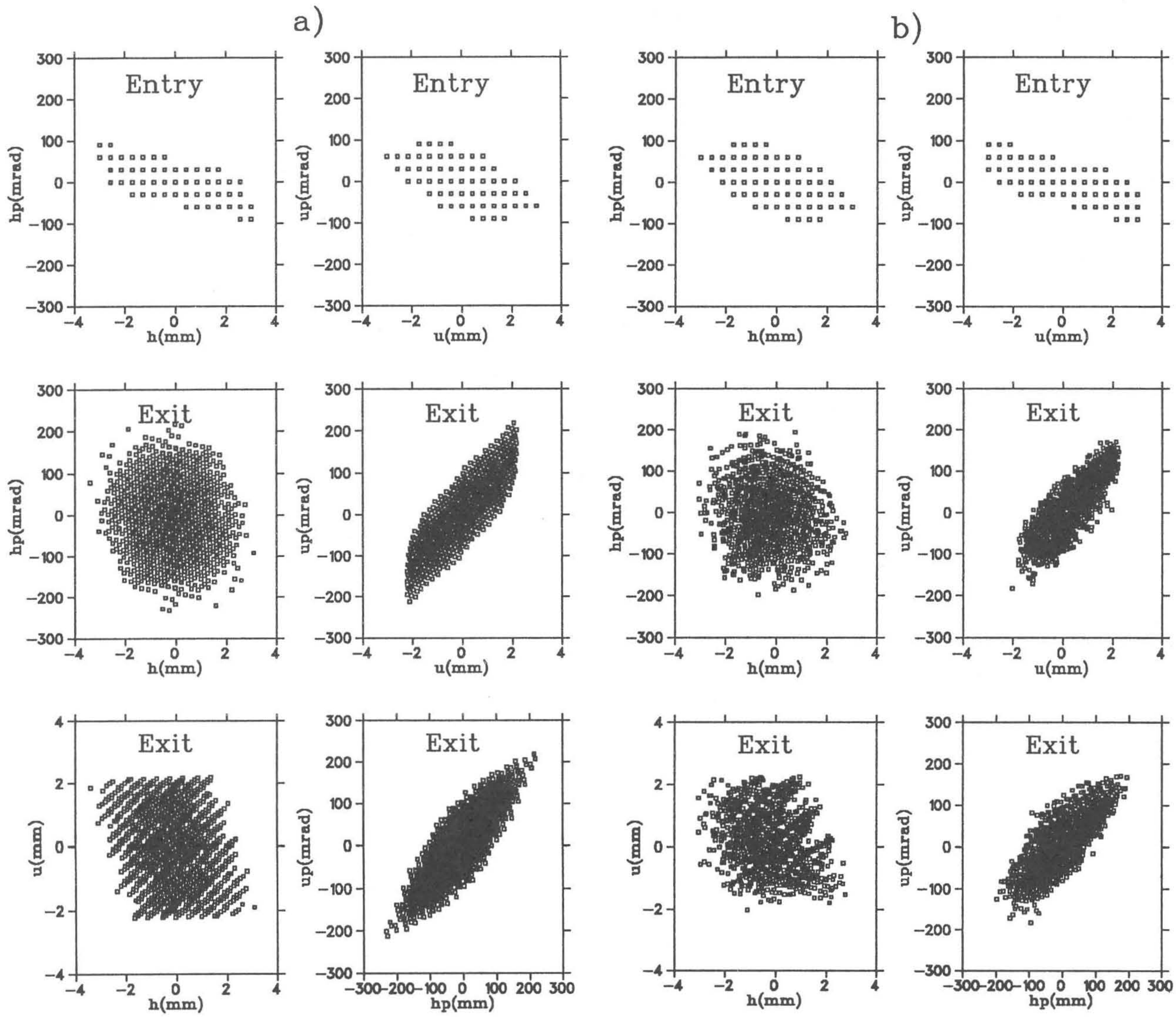

Fig. 4. The transverse acceptances (entry) of the second harmonic inflector using a) transfer matrices, and b) tracking particles with ION_TRACKER. Each point in the entry sub phase space contains several particles: same (h, hp) but different (u, up) and vice-versa.

The effective length of each spiral was determined with RELAX3D fields in ION_TRACKER so that the central ray leaves the inflector with zero axial velocity on the median plane. For example, the mechanical length of the second harmonic inflector is about 2 % shorter than that of a hard edged analytical spiral.

4. CENTRAL REGION

The central region has been designed so that only the inflector has to be changed when switching from one harmonic mode to another. This has lead to a tilted gap in the second harmonic inflector, the tilt parameter k' being 0.19 which corresponds to a final angle of 10.76 degrees. Also the maximum injection voltage must be limited in the first and third harmonic mode. The spiral inflector parameters are listed in Table 1.

Table 1. The spiral inflector parameters.

Harmonic mode	1	2	3
Max injection voltage (kV)	15.0	20.0	13.3
Spiral height (mm)	30.0	30.0	29.0
Gap height (mm)	5.0	5.0	5.0
Gap width (mm)	10.0	10.0	10.0
k'	0.00	0.19	0.00
Injection radius (mm)	13.1	18.8	18.8
Max spiral voltage (kV)	± 2.5	± 3.3	± 2.3

The longitudinal phase acceptances for the central region are of the order of ± 20 degrees in the second and third harmonic modes and somewhat less for the first harmonic mode. The transverse phase space acceptances have been found to be larger than 100 π mm mrad for the inflector and the central region.

The simulated transmission from a DC beam through the spiral inflector and the central region is about 8 %, and the largest observed one has been about 7 %.

5. ACCELERATION

5.1. Trim Coil Settings

The trim coil settings have been determined with a slightly modified version of FIELDER.[5] A constraint not to allow big changes in currents between two subsequent trim coils was added. This leads to a "smooth" behavior of the trim coil currents when increasing the beam energy. Originally, FIELDER runs result to many discontinuities in trim coil currents as a function of beam energy when it tries to add a small local bump to the field with currents of opposite sign in two neighboring coils.

5.2. Extraction

The extraction consists of an electrostatic deflector, an electromagnetic channel EMC and two passive focusing channels. Precessional extraction method is used. Figure 5 shows the increase of turn separation for He^{1+} beam at 6 MeV/u.

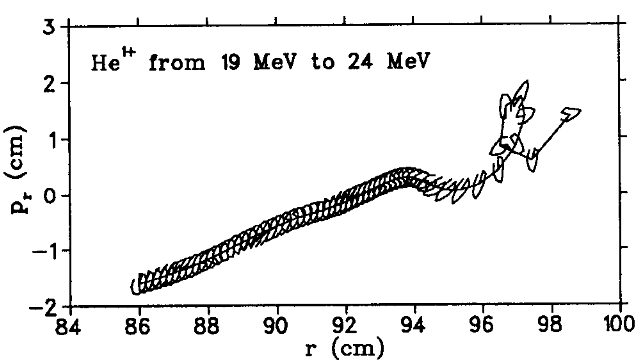

Fig. 5. Radial phase space of a He^{1+} beam prior to extraction at $\theta = 280$ deg. The tracked particles started at an energy of 10 MeV and at the same RF phase (0 deg) on an eigen ellipse.

Beam trajectories through the deflector, EMC and the passive focusing channels were tracked with the MSU Z^4 orbit code.[6] In the MSU code, the focusing bars are assumed to be saturated. In our version, the magnetization of the iron bars depend on the main field at the trajectory so that they get saturated at 1.07 T (round iron bars). Since the main field changes along one channel the magnetization in the code changes linearily with the main field. This assumption was used in the channel design. Field measurements showed that the magnetization differed somewhat from the assumption but the field gradient can be set to the design value by changing the radial distance of the bars. The observed beam shape after the cyclotron is horizontally wide which is also the result from orbit calculations where the focusing channel fields have been corrected to the measured values.

The experimental transmission through the extraction system shortly after the first extracted beam was 55 %, the transmission through the deflector being 74 %. This can be increased with proper centering of the accelerated beam and the transmission through the rest of the extraction system will be increased after correcting the focusing channel geometries.

6. DISCUSSION

Numerical ion optical studies have served as a tool to design some essential parts of the K130 cyclotron facility. The problems in the injection line originated from non-symmetrical endplates in the solenoids. In the axial injection line as well as in the inflector, in the central region and in the acceleration, the pre-calculated values for the settings have proven to coincide fairly well with those that have resulted to highest beam currents. Some small adjustments for the pre-calculated focusing bar geometries have to be done.

7. REFERENCES

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