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DESIGN OF THE AXIAL INJECTION SYSTEM FOR THE NSCL CYCLOTRONS*

F. Marti, J. Griffin and V. Taivassalo

Cyclotron Laboratory, Michigan State University, East Lansing, MI 48824

Abstract

The NSCL is designing an Electron Cyclotron Resonance source to be used in conjunction with its two superconducting cyclotrons, the K500 (in operation) and the K800 (under construction). The ECR beam will be injected through an axial hole. The high magnetic field in the cyclotron center (30 - 50 kG) limits the first orbit radius of curvature imposing strict limitations on the size of the deflection element used to bend the beam into the median plane. We have studied two different schemes to deflect the beam: electrostatic mirrors and spiral inflectors. The former are mechanically simpler, but the spiral inflectors give more freedom on the positioning of the first injected orbit. Results of these calculations as well as central region design and complementary focussing elements in the axial line are presented.

Introduction

Feasibility studies for an axial injection system in a superconducting cyclotron were performed by Bellomo et al. [1] considering the K800 as the model cyclotron and continued for the Milan cyclotron [2]. In this paper we describe the calculations performed to update those studies for our present requirements.

The axial injection line consists of: 1) a room temperature solenoid positioned just outside the yoke 109 cm away from the median plane; 2) a bunching system consisting of a first and a second harmonic bunchers separated by a drift space; and 3) a device, either electrostatic mirror or spiral inflector, for bending the beam 90 degrees into the median plane.

The previous studies [1,2] indicated the likelihood of using an electrostatic mirror with the beam off-axis excluding the use of magnetic bumps to center the orbits.

The difficulties associated with injection off-axis made this solution very unattractive. The electrostatic deflectors originally suggested to move the beam off-axis do not have a uniform field when placed in a tight space. Our goal is then to find a solution that does not require an off-axial beam.

Electrostatic Mirror

The space available for the central region will be determined by the ion with the smallest injection orbit. The ion with Q/u=0.5, B_0=36.2 kG and E=80 MeV/u was chosen as our test particle.

The injection voltage and the tilt angle of the mirror determine the magnitude of the electric field needed to bend the particle 90 degrees into the median plane. Fig. 1 shows the electric field E as a function of the tilt angle α. The electric field decreases when α increases, but at the same time the transit time gets larger and the transparency through the grid gets smaller (Appendix A in [1]). Lowering the injection voltage lowers the required electric field but makes the confinement of the beam more difficult during its transport.

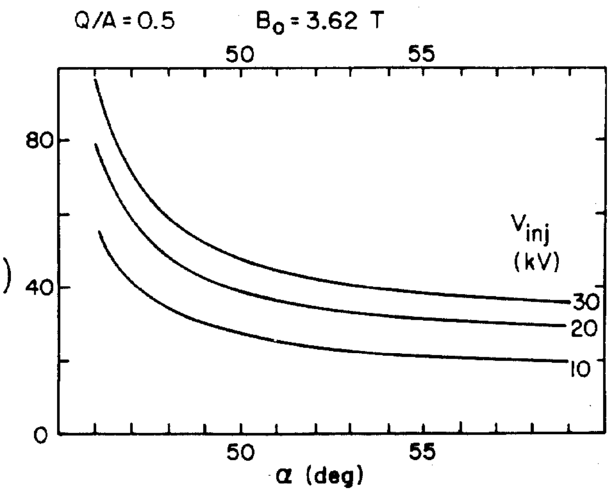

Fig. 1.- Electric field in the mirror gap for an ion with Q/u=0.5 in a B_0=36.2 kG magnetic field as a function of the mirror tilt angle α, for three different injection voltages.

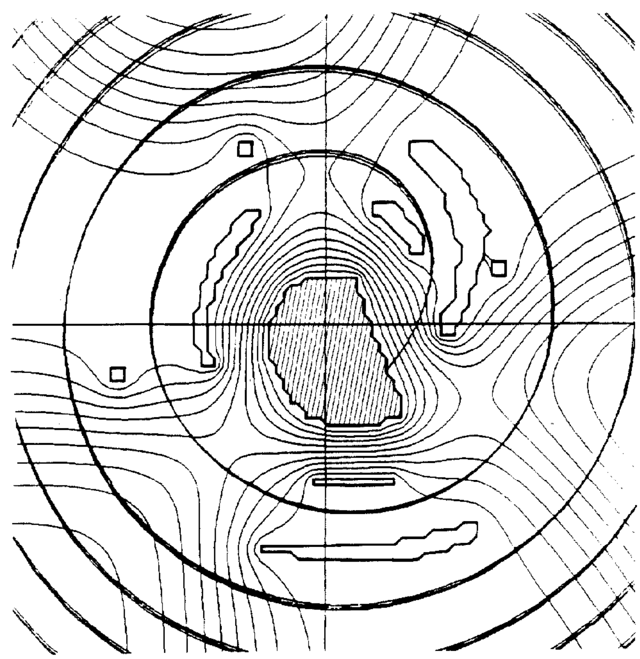

Fig. 2.- Central region designed for the spiral inflector high turn number case. The three orbits plotted have starting times τ_0= 250, 255 and 260 degrees. The voltage on the puller dee varies as $V=V_0 \sin(\tau)$. The equipotentials are shown for the case when all three dees are excited at the same voltage for easier identification of the mechanical components.

We have studied several combinations of injection voltages and tilt angles. Assuming that the electric field in the mirror is 35 kV/cm and the injection voltage is 20 kV (10 keV/u), we obtain α=51.7°. The value of 35 kV/cm comes from the test stand that the Orsay group [3] have built to test electrostatic mirrors under actual beam conditions. With this set of parameters, the orbits exit the grid at a large angle (66°) with respect to the normal to the grid in the median plane, making it difficult to clear the housing of the mirror. We can make the orbits exit at a smaller angle by making α smaller; but to keep the electric field below 35 keV/cm, we have to decrease the injection voltage to 10 kV. In this case we had to depend on the penetration of the RF field created by the puller to extract the ions from inside the mirror, but this field is not symmetric around the median plane due to the inclination of the grid. We tried different schemes to solve this problem but were not successful.

If we assume that the electric field can reach values close to 50 kV/cm (very close to the value used by SIN but for a larger mirror) we can use α=47.8° and V_{inj}=20 kV. The ions leave the mirror without any help from the RF field. A problem appears in the design of the central region with the post in the third dee (see Fig. 2) that helps to define the electric field and also holds together the upper and lower dees. There is no room to put this post between the orbit first turn and the mirror, making it necessary to place the post between the first and second turn which raises some questions about centering versus RF phase.

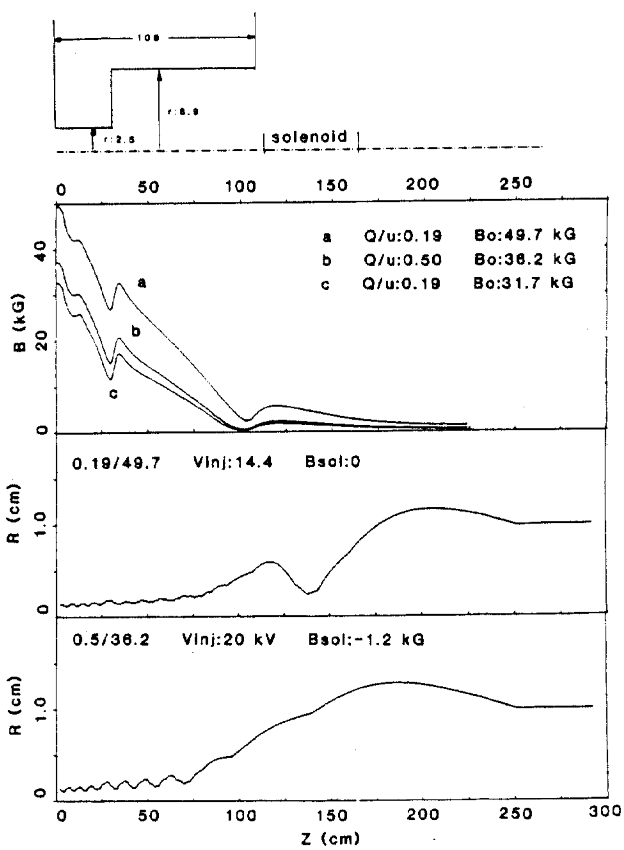

Fig. 3.- At the very top we show a sketch with the dimensions of the hole in the center plug (r=2.5 cm), the axial hole (8.9) and length of the yoke (109). The top graph shows the magnetic field computed with POISSON for three different excitations. Below we show the envelopes obtained tracking ions in the high and intermediate magnetic field case.

<u>Spiral Inflector</u>

Due to the difficulties associated with the electrostatic mirror, we decided to look into the design of a spiral inflector of the type built by Belmont and Pabot [4] at Grenoble. Traditionally this kind of inflector has been used in machines with larger injection orbit, while electrostatic mirrors are used in tighter cases [5].

As the overall size of our inflector cannot be larger than 2.5 cm in the median plane, the gap between the electrodes (0.4 cm) is significantly smaller than the gaps in previously built inflectors. The beam size is comparable to the gap, making it important to study the motion of the ions in a realistic electric field. We have computed the electric field inside the inflector using TRIUMF's RELAX3D4 code [6]. In this way we are able to include the edge effect of the electric field. We compared two different designs: one with slanted electrodes ($k \neq 0$ see [4]) and one with simple unslanted electrodes (k=0). In the unslanted design, the electric field vector applied on the central ray is in the plane defined by the central ray velocity and the vertical. The acceptance of the inflector with slanted electrodes was much smaller than the unslanted case, being this in agreement with the results from Pabot and from Root [7]. Although the unslanted inflector is not as flexible as the other one from the point of view of positioning the orbit center after inflection, we have opted for it.

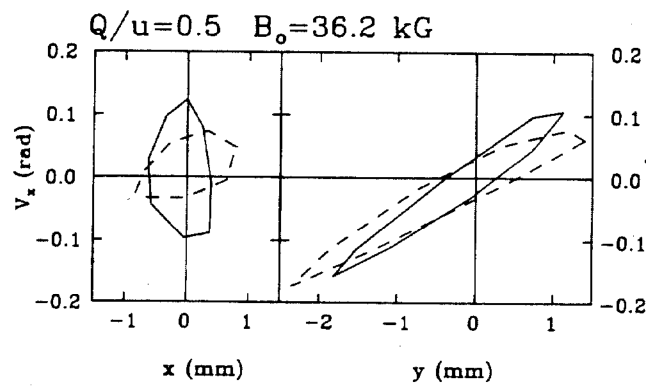

Fig. 4a.- Phase space after injection into the median plane for the ion with Q/u=0.5. The cross-section is perpendicular to the central ray and y is in the vertical direction. The solid phase space comes from a 100 π mm mrad phase space in the x direction at 3 m from the median plane. The dashed space comes from the y direction.

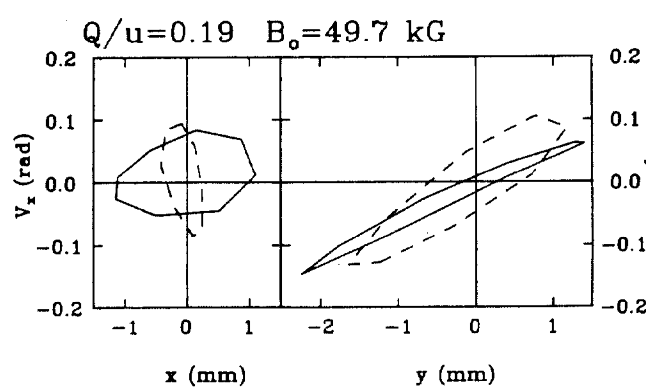

Fig. 4b.- Similar to Fig. 4a for the ion with Q/u=0.19.

The spiral inflector has several advantages over an equivalent electrostatic mirror. There are no grids to traverse, hence no corresponding beam degradation will occur. The electric fields required to bend the beam are much lower, which allowed us to design a more compact device.

We have designed a central region consistent with on axis injection of the beam into a spiral inflector. The central ray is centered within 0.03 cm after crossing the $\nu_r=1$ resonance. Fig. 2 shows the median plane orbit for the central ray and two other ions starting 5 RF degrees before and after the central ray.

We must note that the inflector forces us to use constant orbit injection. The injection voltage must be scaled for different ions. More than one inflector-central region combination will be required to cover the entire operating diagram.

Center Plug

The studies done by Bellomo et al. [1] showed that the sharp edge termination of the present center plug in the K500 (see Fig. 3 top section) was not well suited to axial injection when the beam was off-centered because of the high gradients produced in that region. A new plug geometry was designed to smooth out the field produced by the plug and at the same time keep the field on the median plane unchanged. and we calculated the phase space behavior for ions injected in different magnetic fields, covering the operating diagram. For on-axial beam injection, no significant difference was found between the old design and the new smoothed plug.

Orbit calculations

We have performed the orbit tracking from outside the yoke to the inflector entrance with a code that integrates the nonlinear equations of motion in a magnetic field.The field off-axis is obtained as an expansion in powers of r of the axial field. The axial field was computed with POISSON. The code switches on the electric field in the spiral inflector (calculated with RELAX3D) when the ions are 1.94 cm away from the median plane. When exiting the inflector the CYCLONE code tracks the ions through the central region.

Our calculations start 3 m away from the median plane with a 100 π mm mrad transverse phase space. The solenoid field is adjusted to minimize the nonlinear effects on the beam and decrease the time spread after injection due to the different path lengths.

Figures 4 a and b show the phase space when exiting the inflector for two typical ions. The nonlinear effects are obvious but the phase space does not appear too distorted. We must remember that the gap (0.4 cm) in the inflector is comparable to the beam size. The envelopes for these two ions are shown in the bottom sections of Fig. 3.

Figure 5 shows the RF time difference between the displaced rays and the central ray when exiting the inflector and when entering the inflector (dotted line). The time difference is already 14 degrees before the ions go through the inflector. This large difference is due to the high magnetic field and to the extended region in the axial hole that is under this high field (see Fig. 3). The particles have a large transverse velocity for a long section of their yoke traversal.Most of this time difference appears in the last 40 or 50 cm of the trajectory, which makes it difficult to compensate with a buncher positioned close to the median plane, because of the tight space inside the hole and the presence of the center plug.

This RF time difference will be worse in the case of superconducting cyclotrons operating in higher harmonics, like the Milan and Jyväskyla machines.

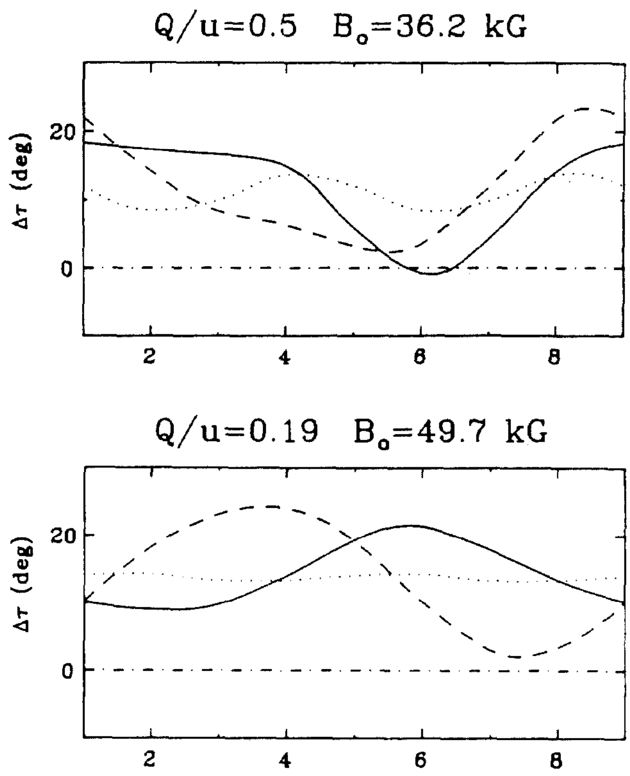

Fig. 5.- RF time differences for the particles on the boundary of a 100 π mm mrad phase space with respect to the central ray. The dotted line indicates the difference at the entrance of the inflector. The solid and dashed lines show the differences at the inflector exit for the points shown in Figs. 4a and 4b. The abscissa is just an arbitrary parameter around the boundary of the phase space.

Conclusions

Our studies indicate that the spiral inflector of the Grenoble type is a good choice to inflect the beam in the median plane, allowing us to inject on-axis, avoiding the complications of off-axis motion. A central region has been designed with good orbit centering. The time spread of the beam is surprisingly large and prevents us from obtaining a short beam pulse.

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