Modifications to the Injection System of the K800 Superconducting Cyclotron

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Abstract

The original design of the K800 cyclotron called for a pole tip geometry with a double spiral. After studying the feasibility of designing a stripping mechanism that would fit inside one of the dees, it was decided to use the simpler single spiral pole tips. In this paper we describe the calculations done to study the injection orbits.

Introduction

The K800 superconducting cyclotron will work as an energy booster for the beam extracted from the K500 cyclotron, now in operation at the NSCL. The injection will be done through a foil stripper near the center of the machine, "capturing" it in an accelerated equilibrium orbit corresponding to the injection energy. One of our basic constraints is that the RF frequency in both machines must be the same. As demonstrated in Ref. 1 this means that the injection radius depends only on the harmonic coupling ratio (HCR) h_2/h_1. The most used coupling ratios will be 3/1, 4/1, and 5/1, which give the following injection radii: 8.8, 6.6, and 5.3 inches. The linear width of the hills in the K800 is between 7.1 and 4.2 inches at those radii, with comparable values in the valleys. Obviously these small clearances make difficult the design of the stripping mechanism, which we require to change radius and angle so as to match the different ions and magnetic field levels, as well as being able to provide a large number of foils without opening the cyclotron to air.

The original design of the K800 injection scheme (Ref. 1) was based on the assumption that if possible the stripping mechanism should be placed in a hill and not in the valleys already occupied by the dees. Therefore it was decided to change the spiral of the sectors, and instead of having a negative spiral for all radii the spiral would reverse to a positive one for r smaller than 15 inches, which would have the effect of substituting hills for valleys in the central region where stripping occurs, (Fig. 2 in Ref. 1). This design has several drawbacks. The major one is that the pole tips and pole bases would have to be machined in two pieces, with the consequent increase in cost and the difficulties associated with the alignment of the two pieces, which must be done to high accuracy in order to limit the first harmonic field imperfections, which are so damaging in machines with tight spiral. Our experience with the K500 tells us that this is not an easy task. Other difficulties are related to the construction of the liner in the neighborhood of the kink between both spirals. This region would also produce a decrease in the vertical focusing frequency ν_z. The same kink would probably also limit the innermost radius of the beam probe, which moves on one of the hills, because negotiating the necessarily sharp turn would be mechanically very difficult. These drawbacks lead the design team to pursue the design of a stripping mechanism that would fit inside the dees. A feasible design was found that uses a train of stripping foils mounted on a chain that slides on an arm. This arm will hang from a support inside the dee stem and pivot around a point away from the machine center, thus allowing the foil to be positioned at different radii and angles. In the following sections of this paper we describe calculations done to study the injection orbits relevant to this new design.

Injection Orbits

From an analysis of the operating diagrams and of the coupling requirements of both cyclotrons (Ref. 1) we determined the range of stripping ratios (Q_2/Q_1) necessary for characteristic operating points in the K800 cyclotron. These included the maximum and minimum energies for fully stripped ions ($Q_2/A=0.5$) as well as high energy heavy ions ($Q_2/A=0.16$, 30 MeV/n U). We calculated the trajectories of these test ions assuming that they matched the equilibrium orbit of the stripped ion at the injection radius for different stripping foil angles. Appropriate angles were then selected so as to be accessible by the stripping mechanism motion and such that the different injection orbits had a common point outside the cyclotron where a steering magnet will be placed. A phase space that matched the radial and axial eigenellipses with a 6 mm mrad area was constructed around the central rays previously selected.

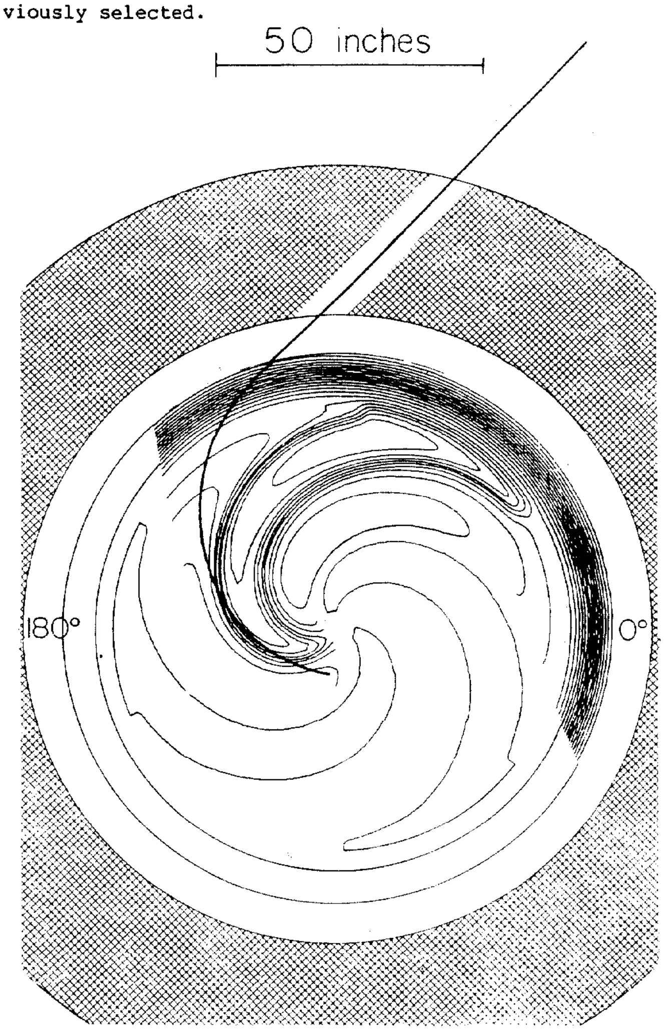

FIG. 1. Injection orbit into the K800 cyclotron of the $^{14}N^{2+}$ ion in the fully stripped ($Q_2/A=0.5$) 30 kG field. The shaded area represents the yoke. Two of the pole tips are shown. The third one has been replaced by the isogauss contours (every 2 kG). The ring between the pole tips and the yoke indicates the position of the coil. Observe the large gradients crossed near the coil and near the pole tip.

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In Fig. 1 we see an example of an injection orbit superimposed on an isogauss contour map of the magnetic field. The strong focusing and defocusing gradients that the particles encounter in their path make it necessary to include focusing elements. One of the simplest possible elements is a passive magnetic channel in the yoke, represented in our calculation by a bias field and a uniform gradient. Two different channel lengths were tried, avoiding the edge of the yoke where the field is lower. In Fig. 2 we have plotted the beam envelope as a function of the arc-length for the N^{2+} beam. This beam constitutes one of the worst cases studied. The envelope reaches a maximum size of approximately ± 25 mm. Comparing the angles indicated in this plot with the orbit in Fig. 1, we see that the two defocusing regions are associated with the main coil gradient and the pole tip edge.

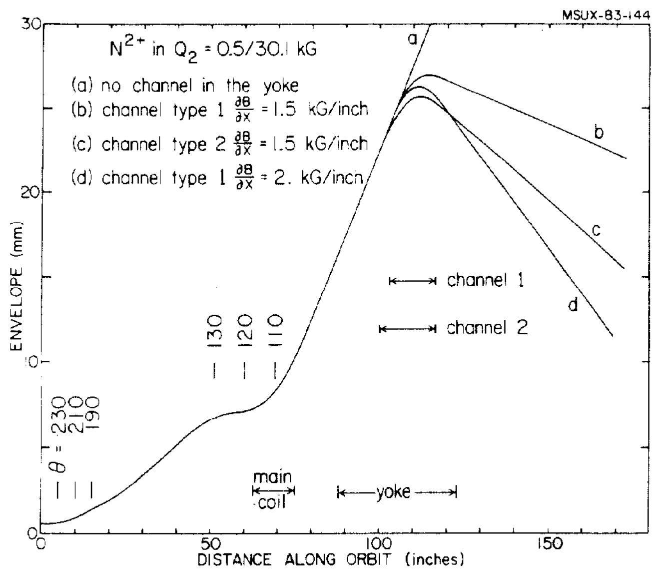


FIG. 2. Radial envelope of the beam whose central ray orbit was shown in Fig. 1. Two channels of different length have been tried. The effect of the channel gradient is shown by curves b and d. θ indicates the azimuth of the corresponding point in the central ray.

When ions with lower Q_1/A are injected in the same magnetic field they have trajectories that cross the coil area more parallel to the field gradient and also travel for less time on the hill edge, consequently they have a smaller radial envelope. We are studying the possibility of installing a focusing element in the region of the superconducting coil gradient. As the injection path varies sizably at this radius the element must be movable, complicating its design, and the vertical aperture available in that region is rather limited, (2 inches).

Figure 3 shows the radial and axial phase space ellipses at the steering magnet radius and at the stripping radius. The part of the beam that determines the size of the radial envelope is the large p_x points. In our analysis we have kept invariant the eigenellipse before and after stripping. In reality the angular dispersion will increase during stripping.

Focusing Channel in the Yoke

We have used as initial model for the magnetic channel the one used in the extraction system of the K500. This channel is described in Ref. 2. The requirements on the channel can be determined from the analysis of plots like the ones shown in Fig. 4a and 4b. An important result is that the gradient needed

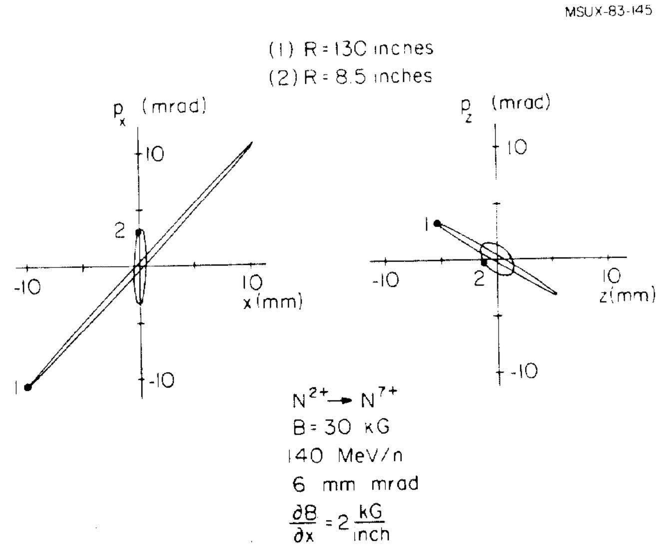


FIG. 3. Phase space behaviour for the beam shown in Fig. 1. The channel in the yoke is of type 1 and with a gradient of 2 kG/inch. The phase space ellipses are plotted at the steering magnet radius (130 inches) and at the stripping foil (8.5 inches). The dots indicate the corresponding points in the ellipse.

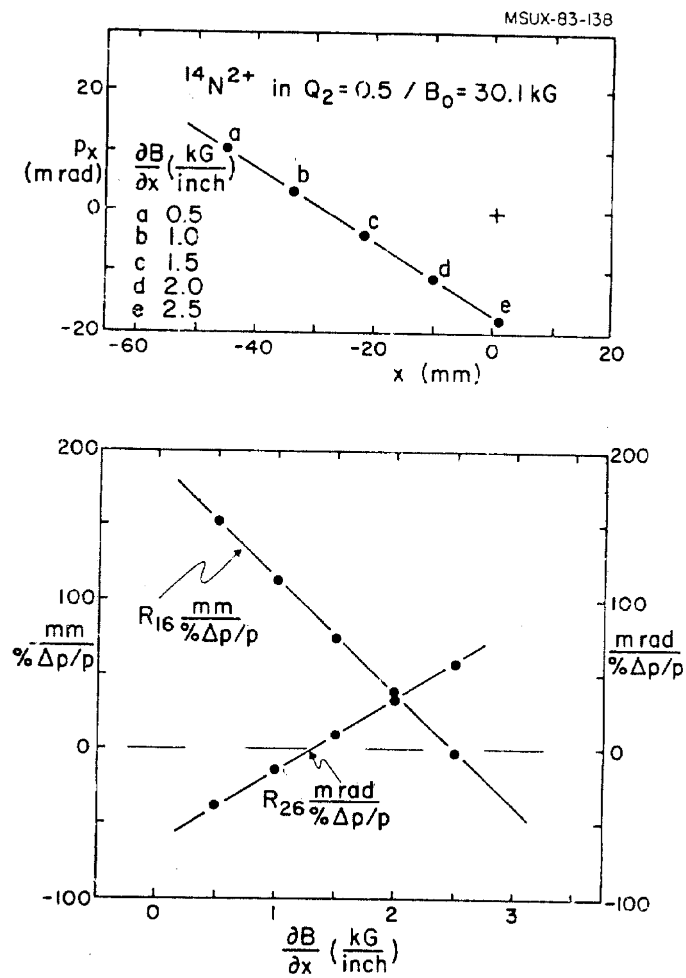
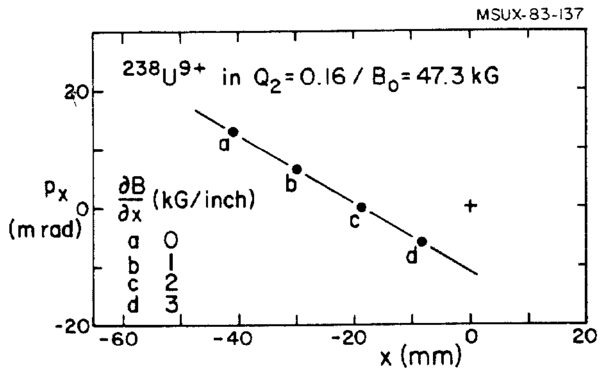


FIG. 4a. Upper plot shows the (x, p_x) of the point in the radial phase space ellipse at the steering magnet location that is farthest away from the origin. As the ellipse is quite elongated they measure to a very good approximation the size of the ellipse. The points are labeled with the gradient in the magnetic channel (type 1). The lower plot shows the energy dispersion terms for the same beams.



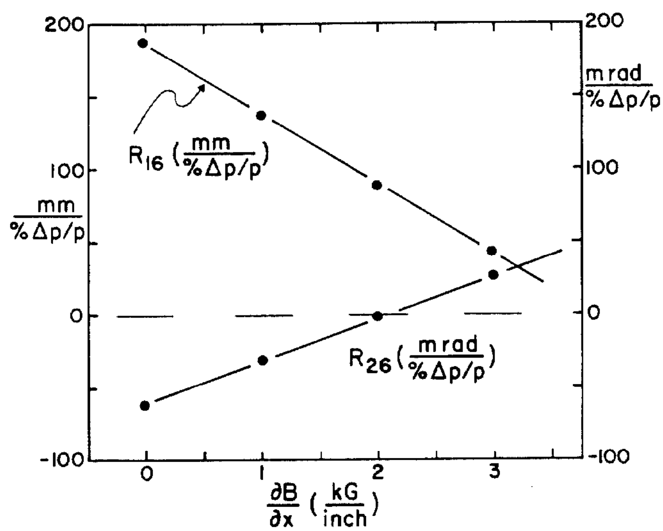


FIG. 4b. Similar to Fig. 4a but for a high magnetic field case, 47 kG.

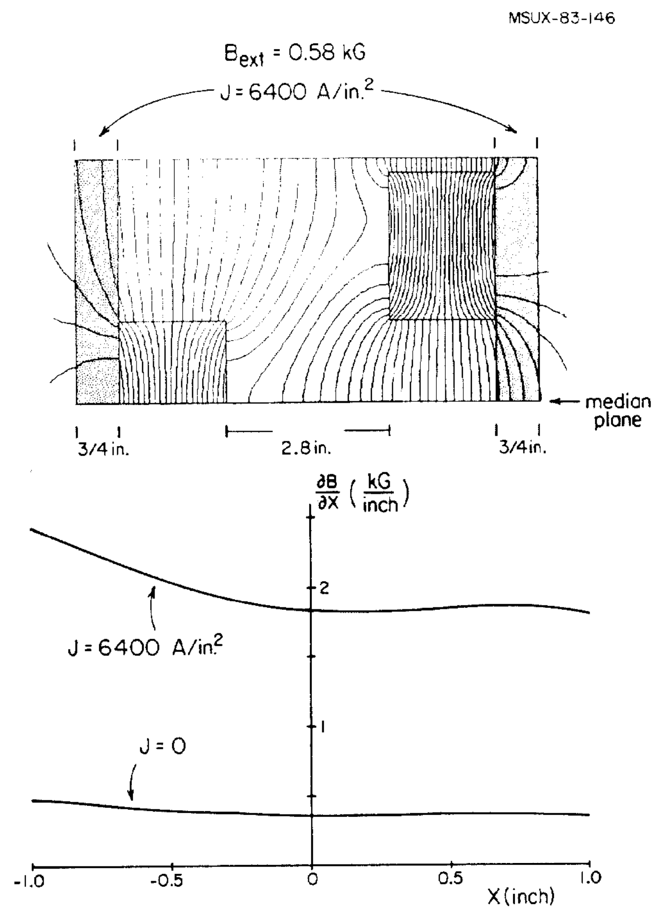


FIG. 5. Upper plot shows field lines obtained with "Poisson" in a two dimensional model for the focusing channel in the yoke hole. We assume symmetry with respect to the median plane. The external field is close to the low excitation field in the K800. A 3/4 inch current layer of 6400 A/sq. in. has been added to increase the gradient. The lower plot shows the field gradient with and without the additional current.

to obtain a reasonable energy dispersion and phase space size at the steering magnet does not scale like the field in the yoke hole, ruling out the possibility of using a passive channel. At low excitations (B=30 kG) there is just not enough field in the yoke hole (B=0.5 kG) to produce the required gradient. Initial studies for an active channel have been conducted with the code Poisson. We considered adding a room temperature coil on the outside of the channel (see Fig. 5) to enhance the gradient. It looks feasible to use wire like that used in the trim coils of the K500 (400 A in a 0.25 inch square, with water cooling) using three layers with a total thickness of 0.75 inches. This coil raises the gradient from 0.38 to 1.8 kG/inch in the low field case. Further work is necessary to improve the shape of the gradient.

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References

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