ANALYSIS AND TRANSPORT OF BEAMS FROM THE ECR ION SOURCE TO THE NSCL K500 AND K800 CYCLOTRONS*

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Abstract

The design of beamlines for the analysis and transport of beams from an ECR ion source to NSCL cyclotrons are presented. Alternative designs are presented along with the final system which utilizes solenoids for focussing and magnetic dipoles for bending. Performance of the actual system is discussed along with the design of the elements in the system.

Introduction

ECR ion-sources are powerful enhancers of cyclotron capabilities for heavy-ion beams. A vertical, room-temperature has been constructed and installed at NSCL[1] and is presently in use injecting the K500 cyclotron. Additional sources are under design. Some of these sources will be used to inject the K800 cyclotron when it becomes operational. To utilize these sources, beam transport/analysis systems were designed and one for the K500 has been installed. The challenge here was to design a system which had high resolving power (for beam analysis), high transport efficiency, and was easy to tune. Further economics entered in restricting the distance from the source exit to the first dipole as this distance set the pit and tunnel. Our solutions to these problems are outlined below.

Optics design

As part of the feasibility study for the ECR ion source, beam transport lines had to be designed. The first step in the design procedure was to determine the layout and optical criteria. The layout criteria were straightforward: 1) take the extracted beam from the vertical ECR(s) and put it into the horizontal plane, 2) transport the beam through the trenches to the axis of the cyclotron, and 3) turn the beam onto the vertical, central axis of the cyclotron. The three optical requirements on the beamlines are: 1) separate the desired ion species from the rest, 2) maintain reasonable beam size during transport to the cyclotrons, and 3) match the emittance of the beam to the acceptance of the injection system. The latter two requirements are functionally very similar and will be discussed below. Analysis of the beam can be accomplished by forming a small waist in the beam and simultaneously having as large a dispersion as possible. Dispersion is produced by bending and a waist by focussing; thus, analysis of the beam could be done with the dipole that bends the beam into the horizontal plane.

Before doing any design calculations for the beamlines the emittance to be transmitted must be determined. The emittance used in the initial study was 3 mm x 30 mrad (300 mm-mrad) in both planes. A calculation using this emittance and the LBL magnet system accurately reproduced the LBL calculated beam envelopes; thus, it was considered a good starting point for calculating the NSCL beam lines as the extraction geometry in the NSCL design is similar to that in the LBL source. Calculations to determine any changes in the emittance ellipse due to the different magnetic field geometry of the NSCL source vs. the LBL source were not complete at the time of the transfer line design study; so a match to the LBL emittance was considered the most reasonable. Likewise, the effects of the emittance mixing by the fringe field awaits the results from this study. (Note: the particle dynamics in a three-dimensional magnetic field, two-dimensional electric field, with significant space-charge, and multiple ion-species is a particularly difficult calculation which is still under investigation.)

After the beam has exits the ECR it must transported to the cyclotrons and be emittance matched to the injection system. The ECR beam will be injected into both cyclotrons, thus separate transfer lines are needed. The beam as extracted from the source will is approximately symmetric in the plane transverse to the beam direction (the beam may have some triangular character due to the hexapole); likewise it injects into the cyclotron center where the field is dominantly cylindrical (with some third-harmonic component) which would tend to maintain any symmetry in the beam. It would be most efficient if the transfer lines also maintain the symmetry of the beam from beginning to end. Possible choices for focussing elements are: 1) quadrupoles and 2) solenoids; electric options also exist but have been discarded to date based on the fact that electric elements would tend to destroy the beneficial effects of space-charge-neutralization needed for the more intense (> 50 μA) beams. Other laboratories have used both quads and solenoids so it was decided to study alternate configurations using quads and solenoids.

Some details were common to all designs. The first focussing element outside the ECR was a short solenoid; this is optically similar to the Glaser lens used in this location for the ECR's at LBL and Louvain-la-Neuve. All dipoles used are double-focussing with approximately equal focal lengths; this choice will maintain the beam shape as much as possible; another choice might minimize the gaps of the magnets, but large gaps do not pose an amp-turn problem with such non-rigid beams so gap-size was not considered an important parameter but was to be kept small during the design process if possible. The solenoid forms a waist at the object of the dipole that bends the beam into the horizontal plane; there is dispersion at the image waist of the dipole so the analyzing slits would be placed at the object and image positions of the dipole.

The results of the design study are shown in Figs 1 and 2. The solenoid-based designs proved optically superior to the quad-based designs with easily achieved, smaller, less tuning-sensitive envelopes. Practically speaking, the solenoid-based designs involve fewer and simpler-to-build elements. The solenoid strength required for the transfer lines is similar to that needed for the final injection into the cyclotron; so similar solenoids could be used.

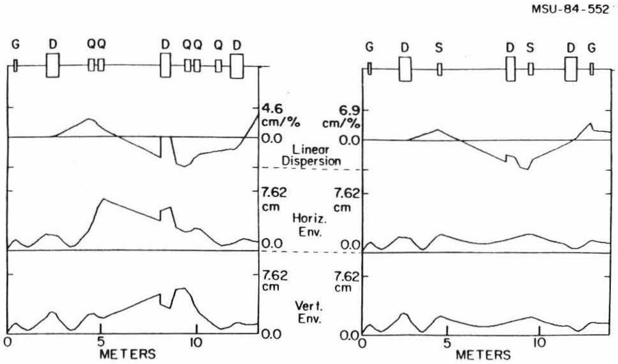

Fig 1. Plots of the element arrangements, horizontal and vertical envelopes, and the linear dispersion for the quadrupole (on the left) and solenoid (on the right) based transfer lines from ECR extraction to insertion on the K500 cyclotron axis. Dipoles are denoted with a "D", quads with a "Q", solenoids with an "S", and the Glaser lenses with a "G".
Note: the large discontinuity in the plots at the second (small) dipole is an artifact of the TRANSPORT calculation which required a axis rotation (x-y interchange) to make that dipole bend in the horizontal plane while the first and last dipoles bend in the vertical plane.

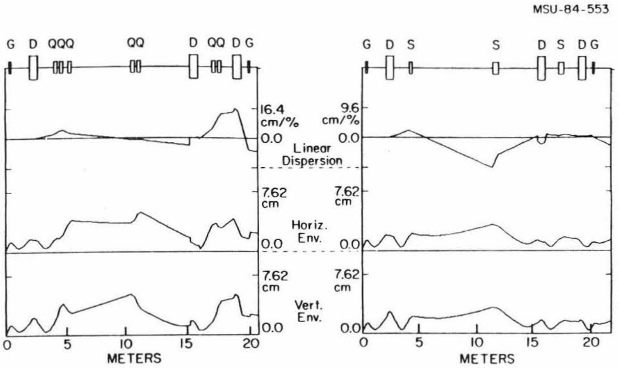

Fig 2. Same as Fig. 1 except for ECR to K800 axis.

Second order studies were made after the cyclotron injection conditions were better understood. The injection system could not accept the full emittance of the initial beamline calculations therefore this series used 5x20π mm-mrad in each plane. The final design for the region around the ECR extraction and for the vertical line into the cyclotron resulted in moving the last two focussing elements of the initial design a bit upstream. The second order effects were negligible for this emittance.

As a design option, mounting a small ECR ion source on the same axis as the cyclotron was considered. Such a mounting would greatly reduce the length of the beam transport, but would not simplify it's functions, ie. to analyze the beam into different M/Q species and to match the emittance of the source to the acceptance of the cyclotron. Before a major investment in design of an ECR appropriate for this task, the viability of the transport was considered an important question. Thus, the purpose of the design study reported here was to determine the minimum space needed for an analysis/transport system which would give acceptable M/Q resolving power (resolving power of 50 with the full beam and/or 100 with half the beam).

The essence of the straight design is to combine functions of separate elements of the other systems and to replace the first dipole with a Wien filter which gives sufficient resolving power. Three systems were tried. In all calculations, an emittance of π x 5 mm x 40 mrad was used in both planes. The three differed more philosophically than they differed in number or arrangement of elements. The first was the most flexible, most similar to the earlier designs, and longest. It used a short solenoid to make a waist at the object of the analysis system which consisted of a drift, y-focussing quadrupole, a wien filter (effective radius of curvature = .4 m and length = .5 m), another y-focussing quad, and a drift to the image location. The wien filter provides the "x" focussing and the quads provide the "y" focussing. After the momentum dispersed image, the beam is matched to the nominal acceptance of the cyclotron by a pair of solenoids; a pair of solenoids is not strictly necessary (as described below) but provide a measure of flexibility, especially when combined with the asymetric focussing of the quads. The second discarded the intermediate waist and one of the the last two solenoids. This system provides acceptable dispersion with reasonable envelopes and is 1 m shorter than the first system; it would not be as flexible, however. Interestingly, the resolving power of the present system is more than that of the earlier study using a 90 degree bending magnet; this is due to the earlier y-focussing (in the quads rather than on the magnet edges) which increases the "Karl Brown" integral. The shortest system discarded the initial Glaser lens altogether; this gave the shortest system, but the lack of flexibility was considered an over-riding negative aspect.

The injection study reported by Marti, et al.[2] had a solenoid as its final element before entering the yoke of the magnet. This is similar in beam size and shape to the beam at the last solenoid in the present transport systems. Thus, if we put the last solenoid of the systems at the edge of the yoke, we will have an estimate of how far the ECR exit must be from the yoke. For the longer system, this distance is about 4.5 m and it is about 3.5 m for the latter. In either case, even ECR would be at the bottom of the sub-basement or, even worse, in the sump. Either case would require major engineering changes in the source and great inconvenience in modifying and/or servicing the source.

Magnet design

Three basic magnet designs were needed to implement the beamlines described above: 1) solenoid, 2) dipole, and 3) steering magnets. The iron-yoked solenoid designs were done with POISSON. These calculations showed that a 15 cm bore solenoid of equal focussing power to a 10 cm Glaser lens had only slightly higher power consumption. The additional bore simplifies beamline assembly. For a 6.3 kG field, a yoke thickness of 1.9 cm is sufficient to give a result close to the infinite permeability result. The solenoids are 37.7 cm in length (magnetic and physical), have a 15 cm inner bore, use 55 turns of .64 cm square conductor in each of 12 layers, and use 13.7 l/min of water at 80 psi. The power, temperature rise, and current for several fields are listed in Table 1.

Table 1

ECR Solenoid Parameters

Central field (kG)	Current (A)	Power (kW)	Temp. rise (° C)
3.36	157	5.2	12
5.2	240	16.2	27
6.3	293	24.6	42

The dipoles were window-frame designs. The non-perpendicular pole-edges created a bit of a constuction headache. The winding of the coil was somewhat compromised from the optimum to ease coil winding, by making the coil ends perpendicular to the beam trajectory. In order to compensate for the extended fringe field, the magnets were mapped and shims installed. These shims will be empirically tuned by observing the image in the magnets' focal planes. The magnet parameters are : gap- 10.6 cm, pole width-15 cm, yoke mass-279 kg, peak field-2.5 kG, peak power-5.4 kW.

Small steering magnets were needed at several locations along the beamlines. These were quite simple magnets made of a square iron yoke with conductor wound around (i.e. if the conductor is inside the yoke on a given side, then it returns on the outside of the same side) the yoke. This design requires double the "usual" amount of conductor (which is still small because the desired field of 100 G requires little conductor) but allowed the x and y steering magnets to be superimposed. A POISSON calculation for equal x and y fields is shown in Fig. 3.

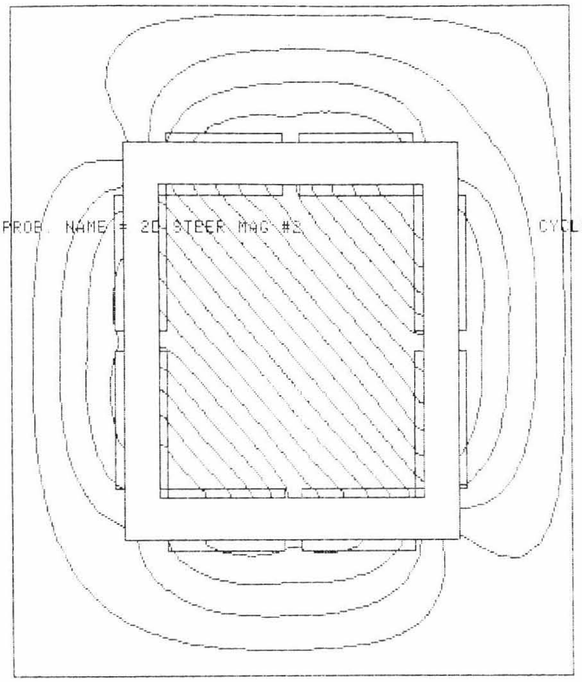

Fig 3. Flux-line plot of a POISSON calculation of the x-y steering magnet used on the K500 beamline.

Performance

The performance of the beamline has been quite good. A sample of the analysis capability is shown in Fig. 4; the emittance for this beam was about 60π mm-mrad in each plane. The transmission efficiency is also quite good. 80% of the analyzed beam is commonly tranported to the entrance of the cyclotron; studies will soon begin to understand where the 20% is going. Similar performance is expected for the beamline to the K800. An additional nice feature is that when the fields are scaled with the particle rigidity, the calculated setting match those that optimize the beam intensity.

Summary

The solenoid based transport system described here has proved quite effective for the analysis and transport of ECR beams to the K500 cyclotron. Tuning is easy and reproduceable with high efficiency. Components were inexpensive and perform well. These results are encouraging for the success of the transmission of beam to the K800 when it operates.

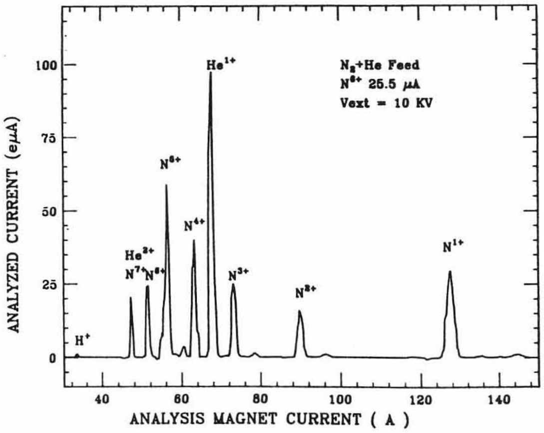

Fig 4. Plot of beam intensity on a faraday cup at the image slits of the analysis magnet vs. current in the magnet, ie. rigidity.

References

1. T.A. Antaya, et al, this conference.
2. F. Marti, et al, this conference

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