# BEAM EXTRACTION FROM THE NSCL K800 CYCLOTRON

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## Abstract

The design for beam extraction system of the NSCL K800 cyclotron magnet is presented. Descriptions are given for most detail choices in the design in a somewhat chronological order in regards to problems and solutions. Linear and nonlinear optics through the system are presented.

## Introduction

The use of of superconducting magnets for cyclotrons leads to a considerable cost saving. Extraction from these cyclotrons can be more difficult than in lower field magnets because of the strong radial defocusing of the beam in the sharply decreasing field near the extraction radius. Use of inert iron bars to form focusing elements has proved successful in extracting the beam from the NSCL K500 cyclotron. A similar scheme has been used for the NSCL K800 cyclotron. As well as focusing elements, deflection elements are constructed from iron pieces for this cyclotron. The overall design of the extraction system is presented here as well as some of the optical properties.

## Historical overview

The primary problem in extracting beams from high field magnets is that of breaking the beam free of the main field. Most extraction systems accomplish this feat by offsetting a fraction of the main field with an electric field. Fundamental limits on electric field over finite gaps are frequently reached for low field magnets; no way of tripling the electric fields has been found as it has for the magnetic field. Some systems use magnetic "channels", either active or passive, to pull the beam out. Unfortunately, the fields of these channels is not well localized and the design then entails accounting for the coupling of the extraction parameters into the internal beam dynamics.

In the case of the K500 cyclotron, a combination of precession with electric deflectors and passive magnetic focusing successfully pulled the beam from the machine. The three-fold symmetry of the outer trim coil set can be broken in order to produce a first harmonic in the field at the radius of the $\nu_r=1$ resonance and thereby drive the beam toward the entrance of the first electric deflector. The first deflector is then followed by a second which completes the process of breaking the beam from the internal field. The rapid fall-off of the main field produces a strong radial defusing of the beam which has to be countered. this is done by sets of inert iron bars arranged in set of three; each set of three (one one interior to the extracted beam and two exterior to it) form a nominal quadrupole plus dipole which serve to hold the beam together and further deflect the beam out of the machine. The coupling between the fringing fields of the extraction elements and the internal beam was sufficiently removed by including two "compensating" bars to control the first harmonics of the field near the $\nu_r=1$ resonance.

The case of the K800 cyclotron proved still more difficult. Where the K500 design had assumed electric fields of 140 kV/cm, these proved difficult, at best, to achieve. The K800 cyclotron has a design goal of 200 MeV/u where the K500 design upper limit is 80 MeV/u, a ratio of 1.6 in velocities. As the effectiveness of electric deflection relative to magnetic deflection changes inversely with velocity, the utility of electric deflection in the K800 design is only about 60% that of the K500 assuming the higher fields can be reached. This reduced deflection led to inclusion of passive magnetic deflection elements to help the electric deflectors. Unfortunately these elements were close enough to the internal beam to affect it in two ways. First, global compensation of the first harmonic in the field of these bars was untenable. This was remedied by introducing compensator images of the two elements nearest the internal beam; two images were used for each of the originals with one image at 120° and 240° from each original. This, of course, added considerably to the complexity of the mechanical drive systems for the extraction elements. The second problem came from the net change in the average field of these six elements; the phase-slip produced was too sharp and at too large a radius for correction by the trim coils. As there is a large range in the extraction radii (about 2.5 cm) for the broad range of particles and energies which the K800 is expected to accomodate, the problem could not be remedied with changes in the fixed steel configuration. A solution was found by adding extensions which gradually decrease in thickness to the elements which caused the problem. An example of one of these elements is shown in Fig. 1. These extensions strengthen the field just inside extraction elements and reduce the phase slip; tapering their profiles make their effects not have sharp edges. With the extensions fixed directly to the elements the compensation occurs where it is needed.

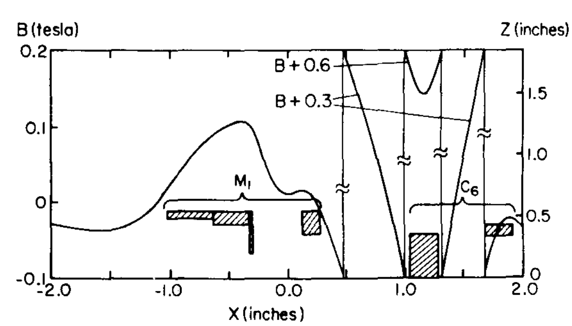


Fig 1. End view of first "cluster" in system; view includes M1 and C6. Field of cluster is plotted also. Extracted beam at M1 location is at x=0.0.

The last system described was successful in getting the full range of beams extracted from the cyclotron with electric fields not exceeding 120 kV/cm. The extension of the first element reached into an accelerating gap; significant sparking would have resulted. Several modifications were considered. A solution was found which utilizes a "double" element in the location of the original second element and eliminates the original first element. The two parts of the new element move independently; the inner affects the beam at the end of the first electric deflector and the outer at the exit of the second electric deflector. This system was the first to account for all effects mentioned above.

It became desirable to shorten the second deflector as it with its drives, high voltage rods, etc. occupied valuable portions of the cryostat inner wall which could be better used for mechanical supports of that wall. The deflector was shortened to one third of its original length. A magnetic dipole element was put in the space of the second third, the relative advantage of magnetic vs electric deflection again being used. The portion of the cryostat wall occupied by the final third of the electric deflector could then be left intact. Eventhough the new element is quite close to the internal beam, exact compensation with two image elements was not possible as one of these would have interfered with the first electric deflector. Compensation is accomplished with two single-bar elements at larger radii than the dipole element; an extension was added to the dipole element which matches the shapes of the fields of the dipole elements and the compensators over the last 2.5 cm of the internal orbit.

For a more complete description please see ref. 1.

## Layout of current system

A plan view of the extraction system is shown in Fig. 2. The system consists of two electric deflectors and 17 clusters of passive iron bars which can be moved independently in radius; the positions of these elements are listed in Table 1 along with the central fields and field gradients. The very long first electric deflector is hinged in two places in order to adequately match the particle trajectories.


Fig 2. Schematic plan view of K800 extraction system.

Both ends of each electric deflector are independently moveable; further the radii of the hinges are controlable. The "B1" element and its compensators are also pivoted at both ends. As is clear from Table 1,some of the elements occur at the same angles; this leads to considerable mechanical complexity. A drive system has been adopted which gives the independent motion by using a coaxial rod-and-tube configuration through the magnet yoke and coil cryostat; the outer cluster is connected directly to the rod and the inner is connected to the tube by thin plates which pass over the outer cluster in order to reach the inner location. For some beams, particularly those at lower magnet excitation, the full set of clusters over-focus the beam; At these energies, some focusing clusters with be withdrawn to a larger radius, in effect removing then from the extraction process.

## Calculational testing of the system

To date all development has been computational with calculated fields. Initial steps have been made with codes which were upgrades of earlier versions of MSU codes, SPIRALGAP being the primary code base code. The calculation of the average and flutter fields is described elsewhere.[2] The fields of the focusing bars were calculated in a uniform, vertical magnetization limit which permitted an analytic calculation. Use of the analytic equations consumes considerable computer time. A computer code has been developed for the FPS-164, with good compatibility for a VAX, which gives response times for internal orbits and extraction using the analytic equations commensurate with running in an interactive mode. The new code is prompting and menu driven. This code supercedes many earlier codes as it combines all their functions into a single package.

Table 1

| Label | position (degrees) | gradient (kG/in) | central field (kG) |
|---|---|---|---|
| E1 | 41-89 | < 125 kV/cm | |
| E2 | 151-174 | < 125 kV/cm | |
| B1 | 175-191 | -0.0 | 4.0 |
| M1 | 94 | 0.25 | 0.2 |
| M2 | 214 | 9. | 2.25 |
| M3 | 260 | 7.5 | 1.98 |
| M4 | 293 | 12. | 3.09 |
| M5 | 314.25 | 12. | 3.09 |
| M6 | 329 | 12. | 3.09 |
| M7 | 340 | 7.5 | 1.98 |
| M8 | 349 | 12. | 3.09 |
| C1 | 297-309 | B1 compensator | |
| C2 | 57-69 | B1 compensator | |
| C3 | 214 | M1 compensator | |
| C4 | 334 | M1 compensator | |
| C5 | 334 | M2 compensator | |
| C6 | 94 | M2 compensator | |
| C7 | 97 | M3-M4 compensator | |
| C8 | 144 | M5-M8 compensator | |

Further the code uses the initial calculated fields, the recent recalculations of those fields, and the measured fields. Each step of the design process was considered complete only if the system could extract a range of particles; these are listed in table 2 and their relation to the operating diagram of the cyclotron is shown in Fig. 3.

Table 2

| Q/A | 0.5 | 0.4 | 0.5 | 0.32 | 0.2 | 0.16 |
|---|---|---|---|---|---|---|
| E/A(Mev/u) | 200. | 160. | 140. | 120. | 47. | 14. |

A plot of six rays on an initial emittence circle of 1.3 mm radius are shown tracked through the current system in Fig. 4 for the Q/A=0.5 , 200 MeV/u case. These calculations included no axial effects on radial motion. A separate code was used to test these effects. This code included terms in the field up to fourth order in the axial coordinate. The results of a 5mm-mrad radial and 10 mm-mrad axial emittence tracked through an earlier version of the system (which used the long second deflector) for the Q/A=0.32,120 MeV/u case are shown in Fig 5. Studies of the current system with this code are underway.

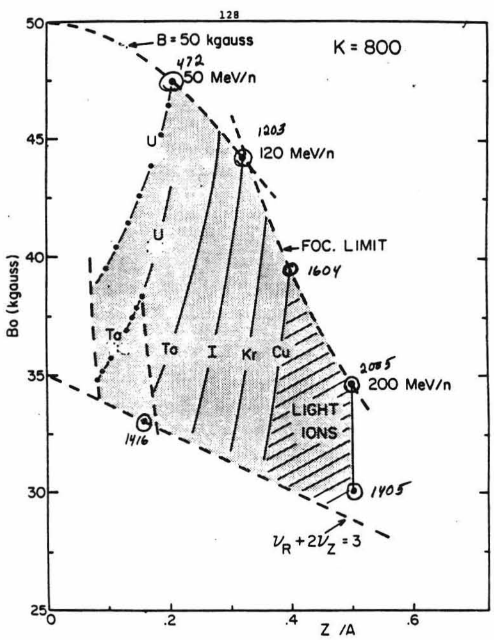


Fig 3. Operating region of K800 magnet with location of test beams noted.

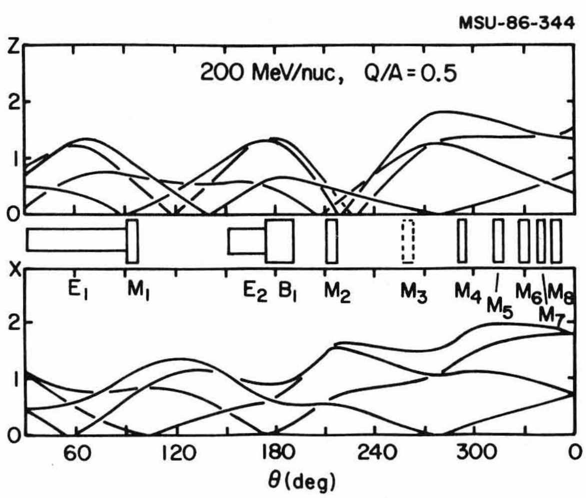


Fig 4. Linear axial and radial optics for Q/A=0.5, 200 MeV/u case.

Initial tests of the orbit properties of the cyclotron with measured fields have given no surprises. When the edge field data has been added to this data, extraction calculations with measured fields will be done.

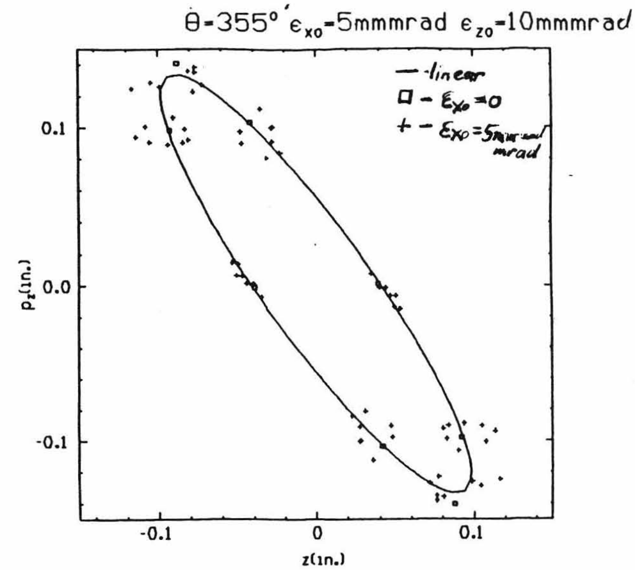


Fig 5. Results of non-linear (fourth-order) optics at the end of the extraction system for the Q/A=0.32, 120 MeV/u case with 5 mm-mrad radial and 10 mm-mrad emittances.


## Summary

A system for extracting beam from the K800 cyclotron over a broad range of particle and energies has been developed. The numerical evaluations of the system indicate the overall orbit dynamics behavior is reasonable. Nevertheless, studies will continue of alternate designs in order to improve the optics and simplify the mechanics.


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## References


1. D.Johnson, et al., NSCL report MSUCP-44 (1985) unpublished.
2. L.H.Harwood and B.F. Milton, this conference.



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