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DESIGN OF THE NSCL COUPLING LINE

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Abstract

The K500 and K800 cyclotrons at the National Superconducting Cyclotron Laboratory must be joined by a beamline which matches the emittance of the K500 to the acceptance of the K800. This paper describes the optical design of that beamline, with particular emphasis on the conceptual design process. Specific optical constraints are given along with the techniques used for meeting them. Beam diagnostics are also discussed. All magnets will be superconducting.

Introduction

A preliminary design study for the beam transfer line between the K500 and K800 cyclotrons under construction at the National Superconducting Cyclotron Laboratory (NSCL) was carried out in 1979.[1] Positioning of the two cyclotrons relative to each other was decided based on the results of that study. Preliminary designs for both isochronous and nonisochronous beam lines were presented. Since that time, the final beam extraction calculations have been done for the K500 cyclotron with some significant changes in some beam characteristics. There have also been changes in the characteristics of the injected beams for the K800, due primarily to the major redesign of the pole tip shapes. The physical layout of the transfer line has been somewhat restricted by installation of major items in the high bay, eg. the liquid helium plant has been installed in the high bay south of the K500. The west high-bay region is shown in Fig. 1. Additionally there is now increased emphasis on the isochronous version of the transfer line.

The purpose of this report is to describe the current status of the transfer line design, addressing the above restrictions. Where the earlier report basically gave a description of the problem and a solution to it, this report also goes into detail about the conceptual design process, the matching condition, and some secondary, but important, details, e.g. the techniques needed to tune the optics correctly.

Conceptual Design

The overall requirements for the transfer line are: 1) to get the beam from one cyclotron to the other, 2) maintain the pulse length (i.e. be isochronous), 3) have an achromatic double waist somewhere near its midpoint (to simplify the beam-line tuning and decouple the tuning of the K500 from that of the K800), and 4) match the emittance (including dispersion) of the beam to the acceptance of the injection channel of the K800 cyclotron. An auxiliary detail that must be addressed pertains to laboratory scheduling: for maximum flexibility, the K500 cyclotron should be able to provide beam for experiments in a stand-alone mode as well as being an injector for the K800 cyclotron. This, however, is not paramount in the considerations. A minimum system can be specified by applying the above requirements in turn. Some of them will be easy to fulfill, others more difficult.

I. Tuning simplicity

Tuning the elements of the transfer line is a delicate task, and any help that can be provided to the cyclotron operators by the optical design will be quite useful. We have chosen to have the transfer line divided into two major sections; the first section ending with an achromatic double waist and providing enough negative drift to make the entire transfer line isochronous. The second section emittance and dispersion matches this waist into the acceptance of the injection channel. The optical design and proper tuning are simplified by this choice: the design is broken into two nominally independent parts and a good tune for the first section of the system can be achieved independent of the tuning of the second section.

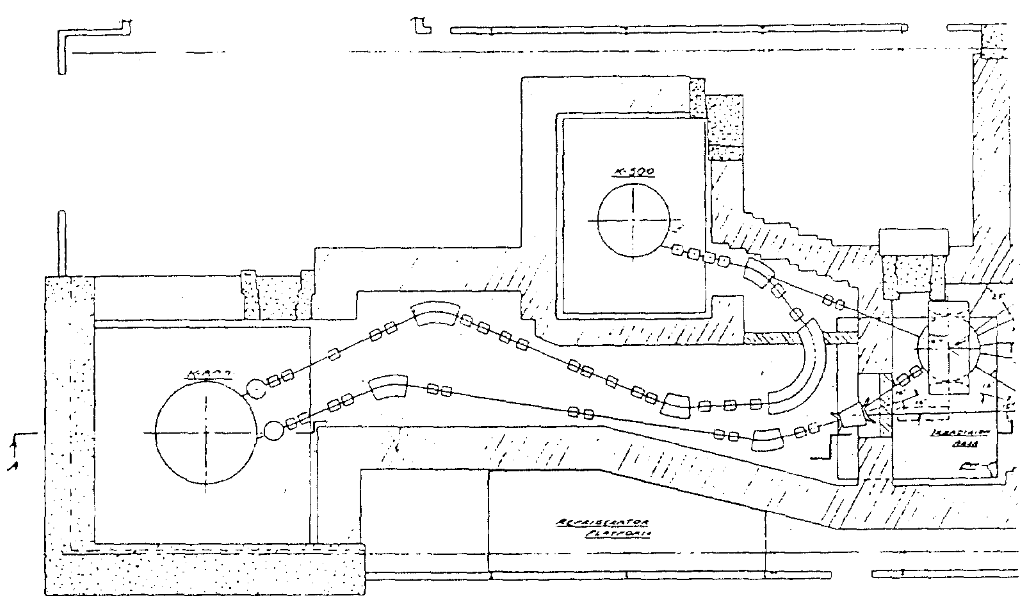

FIG. 1. Plan view of cyclotron area of NSCL Phase II high-bay.

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II. Connecting the two cyclotrons and isochronism

The most obvious element that is needed in the system is a large dipole (bend angle = 180 deg) to turn the beam toward the K800. This large bend is also useful for doing the isochroninzing since the pulse length term (for non-monoenergetic rays) is L- $\int d_x da$ (where L=length of system, d_x=linear dispersion, and da is an incremental angle of bend in a dipole); thus, if the bend angle is large, then the pulse length term can easily be made large. For a bend angle of 180 deg and L=30m, we need d_x to have an average value of 10 cm/%. This in itself is not a difficult condition to fulfill; however, fulfilling it simultaneously with the other conditions may well be. We will, at the very least, require a quadrupole before the large dipole to accomodate the wide range of values of d_x that the extracted beams will have. The resulting simple system is shown in Fig. 2a.

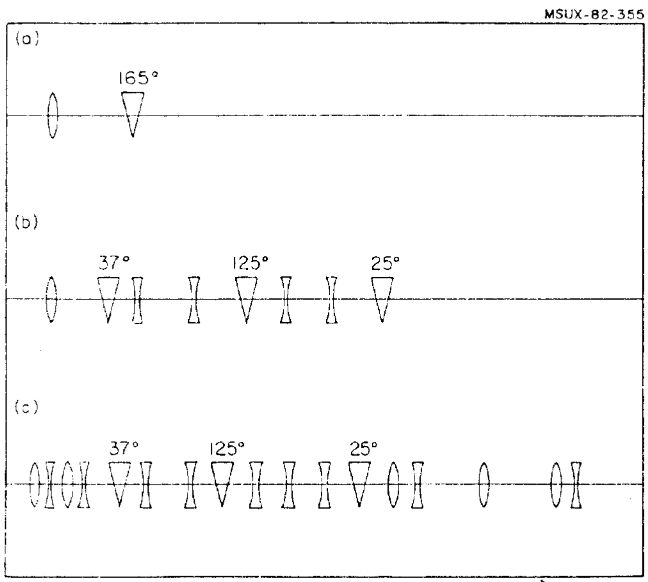

FIG. 2. Steps in conceptual design (convex shapes are x-focussing quadrupoles, concave shapes are y-focussing quadrupoles, and triangles are dipoles) of section of coupling line before the achromatic double waist. The requirements met by each step are: a) gets beam to K800 and is achromatic, b) all in a) plus beam is isochronous and permits scheduling flexibility (see text) c) all in a) and b) plus matches the monochromatic emittance of the K500 to a 3 mm x 3 mm achromatic double waist.

III. Scheduling and achromaticity

In order to minimize interference with the research program with the K500, a small dipole is needed early in the system to switch the beam between the experimental beam lines and the transfer-line. With this provision the K500 can operate in stand-alone or injector mode with minimal switching problems.

A third dipole is needed to make the beam achromatic at the double waist. Strictly speaking, this dipole is not needed. If one assumes that quadrupoles can adjust d_x and $(d_x)'$ to any desired values, then it is possible to make the system isochronous and achromatic with the two previously mentioned dipoles. Unfortunately, after solving the equations one finds that the large dipole would need a bend radius of about 17 m to accomplish this feat and would still have the large bend angle needed to send the beam toward the K800. The easier solution is to maintain a reasonable field (10-20 kG) in the large dipole and to add quadrupoles and the third dipole. We still need to control d_x and $(d_x)'$ at the entrance of the large dipole and thus need quadrupoles between the first two dipoles. Two optical conditions at each dipole require at least two quadrupoles before each dipole. For optimum effect, one quadrupole should be very close to the entrance of each dipole and one should be far away. All of the above requirements are met by the schematic system shown in Fig. 2b.

IV. Emittance matching

The emittance ellipse of the K500 is beam dependent as is the acceptance of the K800. We have already partially addressed the problem of these variations by separating the transfer line into two parts which meet at an achromatic double waist. The first section needs additional elements to make this possible. First, we see that d_x for the extracted beams ranges from 2 cm/% to -15 cm/%. The system we have specified so far would be hard pressed to accommodate this range. Therefore, we add three quadrupoles at the beginning of the system.

An example of the nominal settings for the first four quadrupoles follows. Assume d_x = -15 cm/%. To meet the isochronicity requirement d_x must be positive and large in the 165° dipole. To achieve this we make the first quadrupole strongly x-focussing such that d_x=0 between the second and third quadrupoles. These two quadrupoles can now be used in a y-focussing mode to prevent the beam from blowing up vertically without adversely affecting d_x. The fourth quadrupole is x-focussing; it sets $d_x' = 0$ and prevents a vertical waist. The latter is undesirable because the next y-focussing element is several meters away and the beam would blow up vertically too much; the former is the proper condition to enable the next quadrupoles to set d_x and d_x' to meet the isochronicity requirement. Obviously, if d_x were positive then the quadrupoles would run quite differently.

We have yet to provide the elements to form the double waist at the end of the first section. An infinite variety of quadrupole arrangements could work, but mathematically we only need two quadrupoles to achieve the double waist condition. Tuning sensitivity is increased by small waists, therefore we need at least two more parameters (i.e. quadrupoles) to control the waists' sizes. Another doublet or a symmetric triplet would work. For maximum flexibility we have chosen the triplet but regroup the elements into a doublet-singlet-doublet sequence. The resulting system is shown in Fig. 2c. Comparison with the earlier report[1] shows a remarkable resemblance between the two, indicating that the earlier design was accomplished with a minimum number of elements.

V. K800 injection

The K800 injection line has many fewer constraints on it than does the K500 extraction section. The injection line needs to simply take a beam with knowm emittance ellipses and dispersion (initially achromatic) and match it to the acceptance of the K800. This requires at least six quadrupoles (i.e. one each for linear and angular dispersions, radial and axial sizes and radial and axial ellipse orientations) and one dipole. In practice, it was found necessary to use eight quadrupoles to have sufficient flexibility, to keep the gradients reasonable, and to keep the beam inside the beam-tube. The injection beams are all quite similar, so a large flexibility was not necessary. A plan view of the resulting system is shown in Fig. 1. (Note: The finalized injection section has three quadrupoles before the dipole, not four as shown in the figure.)

VII. Additional Considerations

Early plans for the transfer line included a RF-based pulse selector and a RF-based pulse buncher between the cyclotrons. The former seems viable and remains in our plans; the latter has been eliminated. The extraction calculations indicate that the beams will have a sufficiently broad range of time-energy correlations that an efficient beamline could not be designed that would accomodate them all. The pulse selector will be placed either just before the first (small) dipole or between it and the second (large) dipole; this decision is pending a resonator design. The selector will deflect the beam vertically and unwanted pulses will be removed with slits at the double-waist position.

VIII. Beam monitoring

Tuning the transfer line will be nontrivial, and will require excellent monitoring facilities appropriately placed in the coupling line. We envision three major beam intensity realms: 1) there is enough beam to allow direct current integration to be effective, 2) current integration is questionable but observation with a scintillator (through an image intensifier, if necessary) is viable, and 3) direct integration of energy loss of beam particles is possible (this would be done with retractable ion-chambers). In all three cases it is possible to get x-y profiles of the beam intensity; this information will be quite important for tuning the line for a beam for the first time as it gives the operator a better comparison to the calculations than he would be starting from if he only had integrated beam on one or more slits. One parameter that will be difficult to measure is the achromaticity of the beam. We propose to do it by measuring the emittance of the beam in two places; if the two emittances are the same, then we will assume the beam to be achromatic between those two points. The emittance will be measured in the same fashion that the emittance of SLAC was recently measured since this technique requires only a single quadrupole and the ability to measure the beam's size at the quadrupole and a bit further downstream. The measurements should be made as close to the third dipole (where the beam should be achromatic) as possible and then as close to the entrance of the dipole in the injection section as possible, as this magnet will always add dispersion to the beam. Whether these locations are useable depends on the final designs of the beam monitoring system. Using these guidelines the system has been calculated using the computer code TRANSPORT.[2]

IX. Present status

The present system appears promising. The envelope sizes are reasonable everywhere as are the quadrupole gradients. The setup of the system looks straightforward, too. One can start with approximate quadrupole settings and quickly get a calculated solution. The solutions appear to be relatively easy to adjust for slight errors in field settings as these errors tend to cause the beam to blow up at measureable locations.

The calculations of the extraction and injection sections have used the calculated results of Fabrici, et al.[3] and those given in the report on the earlier transfer line study (specifically those for the injection criteria). The extraction calculations may be modified by the results obtained in the, as yet unfinished, emittance measurements of the K500. The final injection calculations must await the final injection study, which is in progress.

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