DESIGN OF THE EXTRACTION BEAM LINES FOR THE CHALK RIVER SUPERCONDUCTING CYCLOTRON

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Abstract

A versatile beam-handling system is being constructed to transport the beam from the Chalk River Superconducting Cyclotron to 9 different target locations. This highly modular design will allow the experimentalists the choice of achromatic or high resolution, and focussed or emittance matched beams at several target positions. In addition the QDDD spectrometer will be operable in dispersion-free, dispersion-matched and emittance-matched modes.

1. Introduction

The Chalk River Tandem Accelerator-Superconducting Cyclotron facility (TASCC) consists of a 13 MV tandem injecting into a K=520 (MeV/Q^2) superconducting cyclotron[1,2]. The cyclotron should produce a good quality beam for ions from Li through U. The 95% emittance area is less than 2.5 π mm-mrad for the heaviest beams and under most conditions is less than one half this value. The energy spread can be as low as $\Delta E/E$ = 1/2000, and the bunch length is of the order of 150 ps FWHM. In order to preserve and facilitate the use of these properties, a flexible beam transport system has been designed which allows the experimenters to choose the mode of operation which optimizes those beam properties most important to his experiment. This versatility is achieved by making maximum use of symmetry in a highly modular design.

In this paper, we will discuss the requirements and the methods used to realize the design.

2. Design Requirements and Philosophy

The most important design requirements were as follows:

1) To make the most efficient use of the existing building. (See figure 1.)

2) To be an analyser for the cyclotron beam in order to provide a means of precision RF amplitude and hence energy control.

3) To provide the most flexible range of beam properties possible at each target location. In particular, the excellent fast-timing property of the beam must be preserved at the charged particle facility[3] (T3) the "8π" γ-ray spectrometer[4] (T4) and the "correlation table" (T5) so that time of flight and time correlation studies can be carried out. This implies that the beam transport system must be at least achromatic.

4) To provide dispersion and emittance matching for the QDDD spectrometer[5].

5) To design a modular system that will simplify beam set-up and operation.

The overall design approach was to make maximum use of symmetry with maximum modularity. A high degree of symmetry is required[6,2] in any event if achromatic beam transport is to be achieved. For a modular design to be meaningful and for it to meet the above requirements it must produce identical beam properties at each target location. The only way this can be achieved is to employ modules that have a magnification of unity ($|m| = 1$).

The TASCC beam transport system has been designed such that in its basic mode of operation, the absolute value of the magnification is unity ($|m|=1$) in both the horizontal (X) and the vertical (Y) planes at every target location. The basic unit is composed of two modules (the first of which is the cyclotron analyzer) possessing antireflection symmetry[7] and connected by a symmetrizer unit that can change the symmetry of the transport system. Increased beam line length is

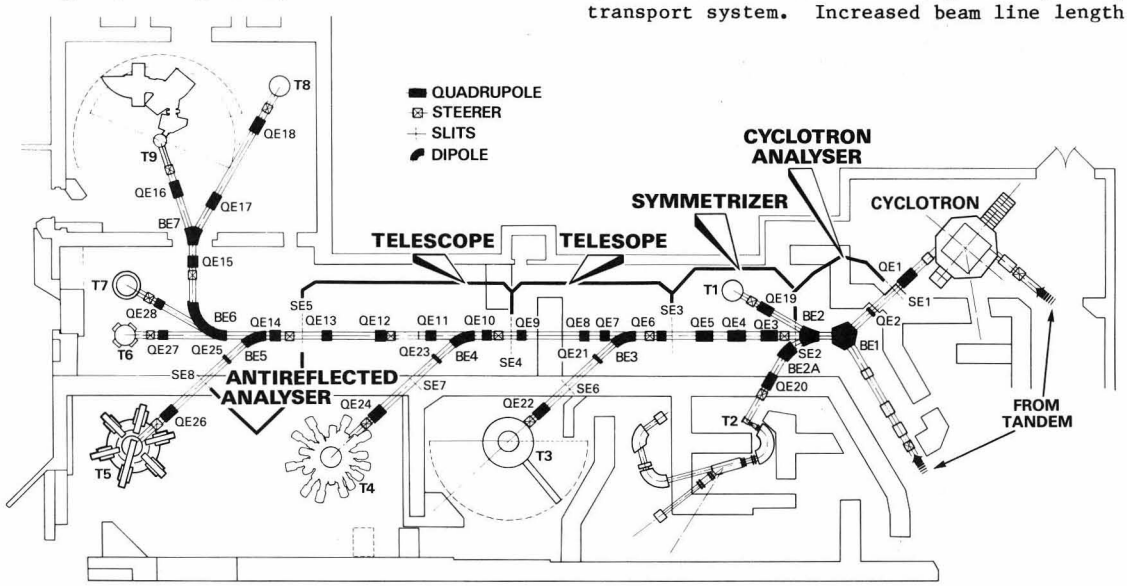

Fig. 1: Layout of the extraction beam lines for the TASCC facility.

obtained by adding telescopic insertions having a magnification of -1. (See Fig. 1.) The QDDD spectrometer (T9) will be dispersion matched with the aid of BE6 and the two doublet lenses QE14 and QE15 as shown in Fig. 1. Emittance matching of the beam at all target locations is achieved with the last triplet lenses or pairs of doublet lenses. The dispersive properties of the beam are controllable at all target locations except T1, T2 and T6.

3. Operation of the Major Subsystems

In all of the following discussions the notation of Brown[6] is used. The 6x6 transfer matrices are denoted by boldface type or by the symbol [ ]. Reference to sub-matrices will be evident from the context.

3.1 Cyclotron Matching Lens

The primary objects for the beam handling system are the slits SE1. The 4-element lens QE1 matches the beam from the cyclotron to form a double waist at SE1 with some control over the X and Y beam sizes. This beam is then imaged at each target location with $|m|=1$.

3.2 The Cyclotron Analyser

The cyclotron analyser, **M** , is composed of the lens QE2 and the dipole BE1. An inverted image (m=-1) of SE1 is produced at SE2 (See Fig. 1) in both the X and Y planes. The linear momentum dispersion d_x=15 mm/% and the focal lengths are F_x=-17 m and F_y=-1.5 m. Thus the analyser is nearly telescopic in the X-plane.

3.3 The Telescopic Insertions

The operating principle of the telescopes is shown schematically in Fig. 2. The unique feature of these insertions is that the center elements of what would normally be quadrupole triplets are split in two and form very thick lenses. The thickness of these lenses can be varied without affecting the overall optical properties. The first cells of the two telescopic insertions straddle the dipoles BE3 and BE4. As in all telescopic systems

$$\mathbf{M}^t = \mathbf{J} = \begin{vmatrix} -1 & 0 \\ 0 & -1 \end{vmatrix} = [L]\ [F]\ [L]\ [L]\ [F]\ [L] \qquad (1)$$

in both the X and Y planes where [L] is the matrix of the drift length connecting the principal planes of the equivalent thin lens [F]; the focal length must be F=L where F is the focal length of [F] and L the length of [L].

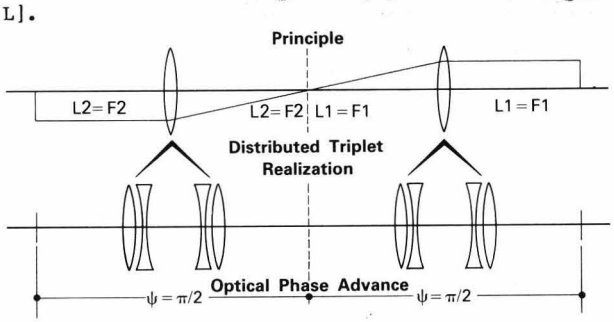

Fig. 2: Design principle of the telescopic insertions.

3.4 The 3-Lens Symmetrizer

The 3-lens symmetrizer is composed of the 3 equally spaced quadrupole triplet lenses QE3, 4 and 5 (Fig. 1). In the equivalent thin lens notation used in (1) we can write

$$\mathbf{S} = [L]\ [-f]\ [L]\ [F]\ [L]\ [-f]\ [L] \qquad (2)$$

The signs of the focal lengths of [-f] are shown explicitly. We must find the solution of **S** such that the magnifications $(\mathbf{S})_{11} = (\mathbf{S})_{33} = \pm 1$ with the inverse local lengths $(\mathbf{S})_{21}$ and $(\mathbf{S})_{43}$ independently adjustable. The solutions of (2) fall into two classes; Class 1: the magnification m=+1 in either the X or Y plane. The solution for f is unique, f = L/2. If we write f and F in units of L then

$$\mathbf{S} = [F] = \begin{vmatrix} 1 & 0 \\ 4+1/F & 1 \end{vmatrix} \qquad (3)$$

Clearly if F = -1/4, then **S** = **U** , the unit matrix. Class 2: m=-1. Here f and F are dependent and the result is

$$\mathbf{S} = \mathbf{J}\,[F] = \begin{vmatrix} -1 & 0 \\ -1/F & -1 \end{vmatrix} \text{ with } \frac{1}{F} = \frac{2(1-1/f)}{(2-1/f)} \qquad (4)$$

If f=1 then 1/F=0 and **S** = **J** .

4. The Basic Symmetries of the Beam Matching System

Target locations T3, T4 and T5 (Fig. 1) are reached by three dipoles that are a reflection, **R** , of the cyclotron analyser, **M** , rotated through 180° to form an antireflected analyser **A** = **RJ** . These dipoles are connected by telescopes **J** . Thus,

$$[T3] = \mathbf{E\,A\,S\,M} \qquad (5a)$$

$$[T4] = \mathbf{E\,A\,J\,S\,M} = \mathbf{E\,R\,S\,M} \qquad (5b)$$

$$[T5] = \mathbf{E\,A\,J\,J\,S\,M} = \mathbf{E\,A\,S\,M} \qquad (5c)$$

E represents the matching lenses QE22, 24 or 26.

The operation of reflection, R, antireflection, A, and inversion J form an Abelian group with multiplication table:

	U	R	J	A
U	U	R	J	A
R	R	U	A	J
J	J	A	U	R
A	A	J	R	U

We need only study (5a) in detail since the solution for the others is obtained immediately from the group table. Hence there are only two basic modes of operation **R M** or **A M** with sub-modes dependent on the focal length F of **S** .

4.1 Doubly Dispersive (a) and Telescopic (b)

(a) If **S** = **U** we obtain the doubly dispersive solution

$$\mathbf{M}_{dd} = \mathbf{A\,U\,M} = \mathbf{A\,M} \qquad (6a)$$

(b) If **S** = [F], and $1/F = 4-2/F_x$

we obtain the telescopic doubly dispersive solution

$$\mathbf{M}^t_{dd} = \mathbf{A}\,[F]\,\mathbf{M} \qquad (6b)$$

4.2 Non-dispersive(a), Telescopic(b) and Achromatic(c)

(a) If $S=J$, we obtain the non-dispersive solution

$$M_{nd} = A\,JM = R\,M \tag{7a}$$

(b) The telescopic and non-dispersive solution is obtained from (6b) with $S = J\,[F]$.

$$M^t_{nd} = A\,J\,[F]\,M = R\,[F]\,M \tag{7b}$$

Here $(M^t_{nd})_{16}=0$, $(M^t_{nd})_{26}=3/2\ d_\theta$ and $1/F=-2/F_x$ in (4).

(c) The achromatic solution is obtained when $S = J\,[F]$ and $1/F=-9/F_x$.

Thus we have

$$M_{ach} = A\,J\,[F]\,M = R[F]\,M \tag{7c}$$

Here both $(M_{ach})_{16} = (M_{ach})_{26}=0$. A telescopic solution is not simultaneously possible in the X-plane. The X-plane focal length $1/(M_{ach})_{21}=2.5$ m which is still quite long.

A telescopic solution is always possible in the Y-plane, independent of the choice of the X-plane dispersion. The solution is

$$1/F = -2/F_y \text{ for both}$$

$$S = [F] \text{ and } S = J\,[F] \tag{7d}$$

5. Dispersion, Emittance and Kinematic Matching

Matching the beam to the experiment usually implies adjusting the beam parameters such that the energy and/or the angular resolution of the detector is maximized. Beam matching is also obviously dependent upon the kinematics of the reaction, the energy loss, straggling and multiple scattering in the target. The target geometry is shown in Fig. 3. Inspection of Fig. 3 leads immediately[8] to the following transformation, T, for the beam coordinates in the nuclear reaction:

$$T_{11} = \partial x_c/\partial x_b = \cos(\alpha-\gamma)/\cos(\gamma) \tag{8a}$$

(Note: $T_{11}=1$ if $\gamma = \frac{1}{2}\alpha$)

$$T_{22} = \partial\theta_c/\partial\theta_b = 1;\ T_{33} = T_{44} = 1 \tag{8b}$$

$$T_{51} = \partial\ell_c/\partial x_b = [\frac{v_c}{v_b}\tan\gamma+\sin(\alpha-\gamma)/\cos(\gamma)] \tag{8c}$$

$$T_{62} = (\partial\delta_c/\partial\theta_3)\dagger = \frac{1}{P_3}(\partial P_3/\partial\theta_3) = K \tag{8d}$$

$$T_{66} = (\partial\delta_c/\partial\delta_b) = (P_b/P_c)/(\partial P_c/\partial P_b)$$

$$= C\dagger\dagger \tag{8e}$$

where P_b, v_b and P_c, v_c are the central momenta and velocities of the incoming and outgoing particles respectively. All other matrix elements are zero. In general, the subscripts b and c refer to the incoming and outgoing beam coordinates (Fig. 3).

† Here we made the approximation that $\theta_c\approx\theta_3$.

†† K and C are the commonly used symbols for these terms. The T matrix defined here is similar to but not identical to the R matrix in ref. 8.

The target or reaction transformation clearly does not conserve phase space. The reaction angle θ_3 can take all values allowed by the kinematics within the aperture of the detector.

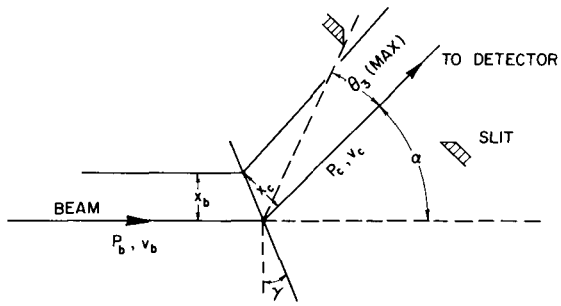

Fig. 3: The target geometry and parameters of the nuclear reaction transformation.

Because the reaction angle θ_3 and the initial angle θ_b are uncorrelated, their sum is the convolution[9] of the distribution functions of the two coordinates. The variance of the convoluted distribution is the sum of the variances[9] of its components:

$$\theta_c^2 = \theta_3^2 + \theta_b^2 + \theta_s^2 \tag{9a}$$

$$\text{where } \theta_3^2 = \int_{-\theta_3(\max)}^{\theta_3(\max)} \theta^2\,P(\theta)d\theta \tag{9b}$$

and θ_s^2 is the variance of the multiple scattering angle in the target.

Similar expressions hold for ϕ_c in the Y-plane. The tails of the distribution defined by θ_c will be intercepted by the slits (see Fig. 3), but since $\theta_3^2 \gg (\theta_b^2 + \theta_s^2)$ in most experiments the effect is small. Space does not allow a more rigorous discussion here. The momentum (energy) straggling δ_s convolutes with the kinematic terms in a similar manner.

We denote the beam matching system up to the target by B and the target plus detector by $D = [\ ]\,T$ where $[\ ]$ is the transform connecting the target to the detector.

5.1 Matching the QDDD Spectrometer

The spectrometer is actually a QDMDD device where M stands for a kinematic correction multipole. The spectrometer is located at T9 in Fig. 1, and bends to the left. Thus the "detector" matrix is

$$D = [\text{QDMDD}]\,JT = \Sigma\,J\,T \tag{10a}$$

and the beam matching transform is (see Fig. 1 and section 3)

$$B = [\text{QE16}]\,[\text{QE15}]\,[\text{BE6}]\,[\text{QE14}]\,U\,S\,M \tag{10b}$$

For a magnetic spectrometer, the system is matched when we have minimized the line width on the focal plane, with respect to the initial beam parameters[6] σ_θ, and the kinematic aberrations K. The line width at the focal plane of the spectrometer is given by[6,9].

$$\sigma_f = D\,[\,\sigma_b + \sigma_T\,]\,D^t = D\,\sigma_c\,D^t \qquad (11)$$

with $\sigma_b = B\,\sigma_o\,B^t$

where σ_o is the mean-square beam matrix at SE1 and is assumed diagonal (double waist) in the X and Y-plane coordinates; σ_T is a diagonal matrix consisting of the terms (9) $\theta_3^2 + \theta_s^2$ and δ_s^2 .

Expanding (11) and retaining only the term $(\sigma_f)_{11} = x_f^2$, the mean square width on the focal plane, we obtain:

$$x_f^2 = D_{11}^2\,\sigma_{11} + D_{12}^2\,\sigma_{22} + D_{13}^2\,\sigma_{33} + 2D_{11}\,D_{12}\,\sigma_{12} + 2D_{11}\,D_{13}\,\sigma_{13} \qquad (12a)$$

where σ_{ij} is an element of σ_c .

The matrix **D** can be written as a 3x3 matrix in the X-plane since we are not interested in bunched beams.

$$D = \begin{vmatrix} T_{11}\,\Sigma_{11} & M-K\Sigma_{16} & C\Sigma_{16} \\ T_{11}\Sigma_{21} & \Sigma_{22} & C\Sigma_{26} \\ 0 & -K & C \end{vmatrix} \qquad (12b)$$

where M is proportional to the quadruple strength of the kinematic correcting multipole in the spectrometer. On adjusting M such that $D_{12}=M-KS_{16}=0$ we obtain kinematic matching: Thus, expanding (12a) further and collecting terms, we obtain

$$x_f^2 = (T_{11}\Sigma_{11}B_{11})^2 x_o^2 + (T_{11}\Sigma_{11}B_{12})^2\,\theta_o^2 + (T_{11}\Sigma_{11}B_{16} + C\Sigma_{16})^2\delta_o^2 + (C\Sigma_{16})^2\,\delta_s^2 \qquad (12c)$$

By adjusting **B** to obtain either a focus or a telescopic transformation at the target, $B_{12}=0$, and the term in θ^2 vanishes leading to emittance matching[8]. Finally if we set $B_{16}=-C\Sigma_{16}/(T_{11}\Sigma_{11})$ then the term in δ_o^2 vanishes and we have dispersion matching; for a matched beam (12c) reduces to

$$x_f^2 = (T_{11}\Sigma_{11}B_{11})^2\,x_o^2 + (C\Sigma_{16})^2\,\delta_s^2 \qquad (12d)$$

In our system, the adjustment of **B** to obtain matching is made by making a course adjustment with **S** such that the dispersion of BE1 adds to or subtracts from that of BE6 and then by adjusting QE14 and QE15 one obtains the required value of B_{16}, the condition $B_{12}=0$ and the standard value $B_{11}=-1$. In fact x_f^2, (12d), can be further reduced by minimizing $|B_{11}|$.

5.2 Matching T3 through T8

We assume it is the energy resolution that should be maximized to match these target locations. However, the procedures are identical for the optimization of time or angular resolution. Here,

$$D = [L]\,T \qquad (13)$$

where L is the target-detector distance. Substituting (13) into (11) and retaining only the term $(\sigma_f)_{66}=\delta_f^2$, we obtain

$$\delta_f^2 = K^2[B_{21}^2\,x_o^2 + B_{12}^2\,\theta_o^2 + B_{13}^2\delta_o^2 + \theta_3^2 + \theta_s^2] + (C^2-2KCB_{23})\delta_o^2 + C^2\,\delta_s^2 \qquad (14a)$$

If **B** is made telescopic and non-dispersive (see sect. 4.2) then $B_{21}=B_{12}=B_{13}=0$. Furthermore, if B_{23} can be adjusted such that $C^2-2KCB_{23}=0$ then (14a) reduces to

$$\delta_f^2 = K^2\,(\theta_3^2 + \theta_s^2) + C^2\,\delta_s^2 \qquad (14b)$$

which is completely independent of the initial beam emittance, σ_o. The latter step is not always possible. Nevertheless, we can always choose **B** to minimize δ_f^2 within the range of adjustment of the system.

In this manner, we can match the beam to targets T3 through T8 with the exception of T6 which can only be emittance matched.

6. Conclusions

From the above discussions, we see that the design objectives have been met and we have a modular highly symmetric beam transport system capable of matching the beam to the experiment at most target locations.

7. References

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