SEMI-AUTOMATIC PRODEDURES FOR MATCHING THE EMITTANCE OF THE INJECTED BEAM TO THE CHALK RIVER SUPERCONDUCTING CYCLOTRON

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A system of programs and procedures has been developed that allows efficient matching of the MP Tandem beam to the superconducting cyclotron.

1. Introduction

The Chalk River Tandem Accelerator-Superconducting Cyclotron project (TASCC) consists of a 13 MV tandem injecting into a K=520 (MeV·A/Q^2) superconducting cyclotron[1] (see Fig. 1). In order to minimize the radial and axial betatron amplitudes in the cyclotron, and to maximize the quality of the extracted beam, precise 6-dimensional emittance matching to the cyclotron is required.

This paper will deal with semi-automatic procedures for matching the emittance of the beam to the continuously variable optical properties of the cyclotron in order to meet its rather stringent yet variable acceptance phase space.

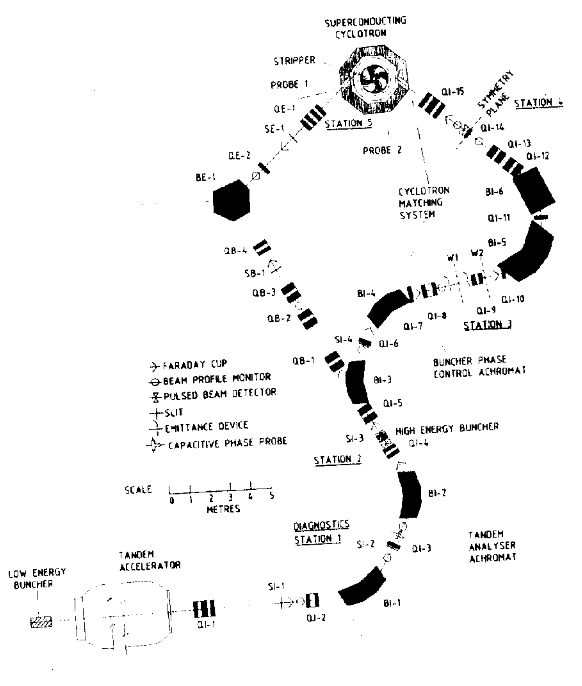

Fig. 1 Layout of the Injection System for the Chalk River Superconducting Cyclotron Laboratory

2. Cyclotron Injection

The Chalk River cyclotron employs charge-exchange injection using a 20 μg/cm^2 C foil stripper at the inner equilibrium orbit[1]. The injection optical properties of the cyclotron vary widely as a function of the mean magnetic field and charge ratio. For example, the radial and axial focal lengths span a range from 20 to 36 cm and from 36 to 80 cm respectively while the corresponding linear magnifications (m_x, m_y) each vary by a factor of about 1.5.

Furthermore the injection trajectories also cross 3 RF accelerating gaps resulting in an accelerated system having $\det|R_c| < 1$ where R_c is the 6 x 6 cyclotron injection matrix.

3. Cyclotron Matching - General Philosophy

For optimum operation, the cyclotron requires a waist with a specific size at the stripper in each plane of the 6-dimensional phase space volume. The matching philosophy[2] is to produce an achromatic solution at the cyclotron stripper such that the transverse phase space can be adjusted independently of the longitudinal phase space. To ensure this, the phase space matching transform must be diagonal in the x and y planes.

In order to produce achromatism, the longitudinal dispersion of the cyclotron must be exactly cancelled by terms generated by dispersive elements external to the cyclotron. To achieve this cancellation one must have a high degree of symmetry. A variation of reflection symmetry[2] is used (**MFM**) where M is a 4 x 4 matrix in the bending plane and **F** is a thin matching lens. The principal symmetry plane passes through QI14 (see Fig. 1) so that QI15 and the cyclotron are identified with M, QI14 with **F** and the elements QI10 through QI13 inclusive are adjusted such that in all important respects the transformation matrix is identical with M; thus we obtain **MFM**.

The system

$$R = \mathbf{MFM} \tag{1a}$$

is exactly achromatic with $R_{11} = 1$ and $R_{12} = 0$ when the RF accelerating voltage is off. With the RF on we have partially broken symmetry

$$R' = \mathbf{M'FM} \tag{1b}$$

where the system is longitudinally achromatic with $R'_{11} = 1$ and $R'_{12} = 0$. A point-to-point focus is produced in the axial (y-plane) with the linear magnification lying between 1 and 3.

The lens QI9 is used to diagonalize the transfer matrix from W1 (x-plane) and W2 (y-plane) to the cyclotron center, producing complete decoupling of the three emittance planes. Finally, the lenses QI1, QI7 and QI8 are used to produce waists at SI1(x-y), W1(x) and W2(y) with the correct beam sizes. The longitudinal waist is now achieved by adjusting the high-energy buncher (HEB). In order to achieve solutions over the operating range, QI9, QI13 and QI15 must be movable lenses.

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The design is highly modular, separating the various functions into distinct areas, none of which influences earlier areas. This modularity is important in achieving acceptable solutions in theory but is even more important in realizing the solutions in practice. As well as the modularity, two other points of design philosophy are worth noting. These are: firstly the decoupling of the longitudinal and transverse phase spaces and secondly the use of telescopic imaging to reduce the dependence of the solutions on the emittance of the beam[2].

4. Semi-Automatic Matching Procedures

A flow chart of the matching procedures is shown in Fig. 2. All programs except BPMFOUR, PBMFOUR, EMIT1 and BTSSET run on the CRNL CYBER system. The above-mentioned programs run on the PDP-11/44 control computer. Although the programs 'EQULO, BUNCHSIM and SUPERGOBLIN' provide essential input to CYCMATCH, they will not be discussed in detail and are shown for the sake of completeness. Briefly, EQULO calculates the equivalent drift lengths through the tandem and estimates the transverse emittance at the exit of the tandem. BUNCHSIM uses information from EQULO and SUPERGOBLIN to estimate the longitudinal emittance and SUPERGOBLIN[3] calculates the injection transfer matrix of the cyclotron.

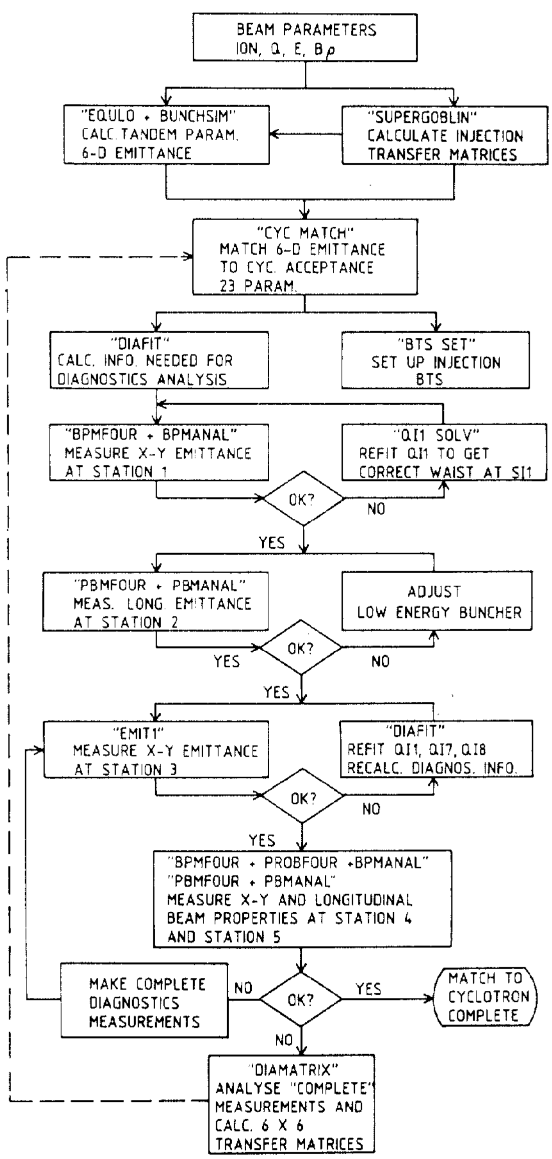

Fig. 2 Flowchart for the semi-automatic procedures for matching the beam to the superconducting cyclotron.

Once the input information is available, the cyclotron matching proper begins. It is basically a 6 or 7 step procedure in which the major decision points require human intervention (diamonds in Fig. 2). The steps are as follows.

STEP 1: The program CYCMATCH[4] uses the injection transfer matrix, which represents the beam transform of the injection trajectories from a radius of 1.24 m to the injection equilibrium orbit of the cyclotron, to calculate the strengths of the lenses QI15 (STEP 1 and 2 of ref. 4), QI10 and 11 (STEP 3[4]), QI12, 13 (STEP 4), QI14 (STEP 5), QI9 (STEPS 6 and 7). The positions of the movable lenses QI15, QI13, QI9 are also determined. At this point, the system is longitudinally non-dispersive and diagonal in the transverse plane, with transport matrices[2,4]

$$R'_x = \begin{bmatrix} -1 & 0 \\ 0 & \zeta \end{bmatrix} \quad R'_x = \begin{bmatrix} m & 0 \\ 0 & 1/(\zeta m) \end{bmatrix} \quad R'_x = \begin{bmatrix} a & L_{eff} \\ c & b \end{bmatrix} \qquad (1)$$

The solution at this point is independent of the beam emittance.

The 6-dimensional emittance of the tandem is matched to the acceptance requirements of the cyclotron in STEP 8 of ref. 4, by adjusting the lenses QI1, 7, 8, and the high-energy buncher[5]. In STEP 9[4], the 23 parameters - that is, the gradients of QI1, 7, 8, 9, 10, 11, 12, 13, 14, 15, the positions of QI9, 13, 15, the distance from W1 to W2 (see Fig. 1) and the high energy buncher amplitude - are output to a file that can be transferred to the control computer.

CYCMATCH is a powerful automatic program, capable of matching the wide range of beams to be used at the TASCC facility. The program provides a detailed output at each step and as well checks the validity of the solutions and provides diagnostic messages if the solution fails to meet minimum convergence requirements. All parameters must lie within their operating ranges.

STEP 2: The output file of CYCMATCH is tranferred to the program BTSSET on the PDP-11 control computer, which automatically sets up the beam transport system. All elements not explicitly mentioned scale with Bρ. All matching quadrupoles have been calibrated to an accuracy of 0.1% and the rest are known to an accuracy of better than 0.5%[6].

The output file of CYCMATCH is also used by the program DIAFIT to predict beam properties and needed transport matrices at diagnostic stations 1 through 5[7].

STEP 3: The programs BPMFOUR and BPMANAL are used to make beam diagnostics measurements[7] at diagnostics station 1 (see Fig. 1). BPMFOUR reads the data obtained by the two beam profile monitors (BPM) and uses a Fourier transform technique with a Gaussian band-pass filter to remove noise and background. The beam centroid, intensity and RMS width are calculated along with their errors. When an appropriate[7] set of data has been accumulated, it is analyzed by BPMANAL which uses a least squares technique to calculate the x and y phase space ellipses and their respective emittances along with estimates of the errors on these quantities. At station 1, an appropriate set consists of the RMS widths at the BPM's, with QI3 on and off, plus the slit width (SI2) and the beam intensity ratio.

If the phase ellipses and the emittances deviate significantly from the predictions of DIAFIT, then the program QI1SOLV is used to reoptimize the settings of QI1 to produce a double waist at SI1. QI1SOLV uses the output of CYCMATCH plus the phase space parameters measured above as input. Because the system is well calibrated, one iteration is usually sufficient. When convergence is achieved we proceed to STEP 4.

STEP 4: The longitudinal phase-space ellipse and emittance are measured at station 2[7]. PBMFOUR is identical to BPMFOUR except that it reads the output of the Pulsed Beam Monitor (PBM1). The output of PBMFOUR is the RMS bunch length in ns, its error, the total intensity in the peak and its error. After an appropriate set of between 5 and 9 measurements[7] as a function of buncher amplitude and stripper gas pressure, the program PBMANAL uses a least squares technique to calculate the longitudinal phase-space ellipse and RMS emittance area.

The output of PBMANAL is used to adjust the buncher amplitude. Convergence is obtained in one iteration.

STEP 5: Accurate transverse beam emittance measurements are made at station 3 with a double slit type emittance device[7,8]. The program EMIT1, drives the device and calculates the 95%, 68% and true RMS emittance ellipses and areas.

If the results of EMIT1 are not consistent with the predictions, which they cannot be if the emittances are very different from those used in STEP 1, then DIAFIT uses the measured emittance parameters at station 3 to recalculate the strengths of QI1, 7, 8 and the HEB amplitude with a procedure identical to that used in STEP 8 of CYCMATCH. Convergence usually occurs in one iteration. DIAFIT recalculates all the diagnostics information as in STEP 2 and outputs an updated version of the parameter table which can be read by BTSSET. If all parts of the injection BTS system are functioning correctly, we now have a match of the 6-dimensional emittance of the tandem beam to the cyclotron.

STEP 6: The procedures described in ref. 7 are used to check the beam properties at diagnostics stations 4 and 5. BPMFOUR reads and reduces the data from the two BPM's at station 4 and the two differential probes[1] in the cyclotron. This information, along with the emittance areas measured in STEP 5 and the transfer matrices obtained from DIAFIT are used by BPMANAL to calculate the phase space ellipses at QI14 and the cyclotron stripper. PBMFOUR measures the bunch length at PBM2[7] (station 4). If these results are consistent with the predictions of DIAFIT (see STEP 5), then a match is confirmed; if not, then an extensive "complete" set of measurements is made.

STEP 7: If the results of STEP 6 are not satisfactory, a complete set of diagnostics measurements is made in which QI8 is varied[7] and the phase-space is measured at stations 3, 4, 5 including the dispersive parameters. Three sets of measurements at station 3 lead to 6 at stations 4 and 5 as QI14 is turned off to obtain full information (see STEP 3 and ref. 7). Furthermore the HEB and the beam momentum are varied to obtain values for the dispersive matrix elements[7]. The program DIAMATRIX uses this information along with the equation of constraint $\det|M| = 1$ in both x and y planes and the relation

$$\begin{bmatrix} \ell_x \\ \ell_\theta \end{bmatrix} = \begin{bmatrix} M_{21} & -M_{21} \\ M_{22} & -M_{12} \end{bmatrix} \begin{bmatrix} d_x \\ d_\theta \end{bmatrix} \qquad (2)$$

to obtain, by least squares, the transfer matrices from W1 to QI14, QI14 to cyclotron and W1 to the cyclotron.

After the faulty region and faulty optical elements are identified the process can be iterated again (see dotted line in Fig. 2) starting with CYCMATCH.

5. Conclusions

All of the procedures described here have been thoroughly tested with simulated data and have been shown to work for reasonable errors. (All least-squares analyses are weighted by the errors of the measurement, and the errors of the fitted parameters are output.)

The procedures have been tested with a 27 MeV carbon 2+ beam (which would produce 31 MeV/u carbon from the cyclotron) at diagnostics stations 1, 2 and 3 (See Fig. 1). Consistent and reproducible emittance measurements were obtained at stations 1 and 3. These data have been used by the program QIISOLV and DIAFIT to achieve the correct phase-space match.

Longitudinal phase-space measurements have been made at diagnostics station 2 and successfully analyzed. The results were as expected.

The simulations and beam tests to date give us confidence that the procedures will provide a powerful means of matching the tandem beam to the superconducting cyclotron.

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