A NEW MODEL FOR A 500 MEV BEAM LINE AT TRIUMF

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Abstract

The program INTRAN that was developed at TRIUMF has been used to test a new model for the high current (150 uA) 500 MeV primary beam line. An older model is discussed first to indicate the reason it was felt that a new model of the beam line was required. The development of a new model and its applicability are then discussed.

1.   INTRODUCTION

TRIUMF is a sector-focussed H^- cyclotron; its six sectors are arranged in a pinwheel shape. Extraction of beam is accomplished by intercepting the circulating H^- beam with a thin carbon foil that strips the two electrons from the H^- ions and produces an H^+ or proton beam. Because this proton beam is of an opposite charge to the circulating H^- beam, the proton beam is deflected out of the cyclotron. Proton beams are extracted at energies varying from 180 MeV to 510 MeV and intensities from a few nanoamperes to 150 microamperes.

At present, as many as four beams may be extracted simultaneously into four different beam lines, each of which runs at a different energy and a different intensity. Of these, the primary beam line that feeds the experiments in the meson hall is called beam line 1A. This beam line routinely operates at an energy of 500 MeV and beam currents of 150 µA to maximize meson production at its two production targets 1AT1 and 1AT2. It is the modelling of this beam line up to the first target 1AT1 that is the subject of this paper.

The proton beam is guided to the target by conventional quadrupole, dipole, and steering magnets. An optics program such as TRANSPORT [1] or INTRAN [2] may be used to compute the settings of these elements to produce the desired beam properties at the target locations and to predict the beam size along the beam line under those conditions. Of course, a realistic model of the beam line is necessary in order that reasonable results are obtained for the actual beam line.

This paper will start with a discussion of the old model— its creation, configuration, and file structure. Then the discussion will turn to why an attempt has been made to replace the old model with a newer model. The intent would be to make the new model the reference model for tuning beam line 1A and to reflect the present status of the beam line.

2.   THE INTRAN PROGRAM AND ITS DATA FILE STRUCTURE

In this study of beam line 1A, I have used INTRAN (INteractive TRANsport), an optics program developed at TRIUMF. Because INTRAN uses TRANSPORT as a subroutine, it too represents elements of a beam line with matrices and calculates the effect of the elements by matrix multiplication. INTRAN allows the user to interactively change element settings and to display the results of such changes in both graphical and tabular form. As examples, the beam envelope or accumulated transfer-matrix elements may be plotted as a function of distance along the beam line. Phase-space ellipses may be plotted at any point along the beam line. Similarly, beam parameters and transfer-matrix elements may be tabulated along, or at any point in, the beam line.

Input data for INTRAN follows the same prescription as that for TRANSPORT and may be created with a text editor. At TRIUMF, an input data file describes the beam line as a sequence of

elements from the extraction foil to the end of the beam line. These elements consist of a description of the initial beam followed by a list of the various magnets, their magnetic properties, and the distances between them. Also included are specifications of specific calculations to be done.

For the specific case of beam transport on beam line 1A, the input data file can be considered to be split into a description of three general regions.

Region 1:   1a)   Parameters that describe the beam at the stripper foil. These are:
the horizontal half-width of the beam x (cm),
the half-width of the horizontal divergence θ (mr),
the vertical half-width of the beam y (cm),
the half-width of the vertical divergence ϕ (mr),
the half-width of the longitudinal beam extent ℓ (cm),
the half-width of the momentum spread δp (%),
the momentum of the central trajectory p_0 (Gev/c).

        1b)   Parameters that describe the orientation of the phase-space ellipses at the stripper foil. In the case of beam line 1A only the orientations of the x-θ and y-ϕ ellipses are required. In TRANSPORT (and INTRAN) notation these are r_{21} and r_{43}.

Region 2:   2)   Transfer matrix from the stripper foil to the exit of the combination magnet. These elements are obtained from computer calculations based on fields measured in the cyclotron and transfer the beam from the foil to exit of combination magnet. In TRANSPORT notation these are the matrix elements $R_{11}, R_{12}, R_{16}, R_{21}, R_{22}, R_{26}, R_{33}, R_{34}, R_{43}$, and R_{44}.

Region 3:   3)   The beam transport components and their separations. Each transport element has its own code. Quadrupole parameters are its effective length (meter), pole-tip field strength (kG), and half-aperture (cm). Dipole parameters are its effective length (meter), magnetic field (kG), and field index *(n)*. Element separations are given in meters.

3.   OLD MODEL

Measurements of the magnetic field of the cyclotron allowed the calculation of the expected beam parameters at the stripper foil (regions 1a and 1b) and of the matrix elements required for region 2. These, together with the properties and locations of the beam-transport elements, were used to create an input data file called 1ASTD that described the beam optics of the beam line. I used this file to determine if the data is still valid for the present beam line. I ran INTRAN using 1ASTD as the input data file and obtained the predicted size of the beam spot at the first seven profile monitors of the beam line. A comparison of the predicted beam size with that of the observed spot size on 14 April, 2000 at each of the profile monitors is given in Tables 1A and 1B. The large discrepancies of the horizontal beam sizes at monitors 1VM3 to 1VM7 and of the vertical beam sizes at monitors 1VM1 to 1VM4.6 are obvious. Monitors 1VM2 to 1VM7 are secondary-emission profile monitors with a 3 mm × 3 mm (horizontal by vertical) wire spacing; that of monitor 1VM1 is 2 mm × 2 mm and that of monitor 1AT1 is 1 mm × 1 mm.

To isolate and understand why the discrepancies occurred, an examination of the data in the file 1ASTD was undertaken. I began by examining the data for each of the three regions noted in section 2 above. Of these, region 3 was the easiest part of the input data file to verify. The design specifications of the quadrupoles and dipole were checked to verify that these elements were properly described. Drift spaces between and locations of the elements were checked against blueprints of the beam line. Any errors in drift distances, quadrupole effective lengths and apertures or dipole effective length were corrected in the input data file.

The next step was to obtain accurate values of the quadrupole and dipole magnetic fields. To determine the quadrupole field the following equation from reference 3 was used.

$$B' = 2\mu_0 \eta \frac{NI}{R_0^2} \qquad (1)$$

with μ_0 = permeability of free space $= 4\pi \times 10^{-7}$ N $-$ A^{-2},

η = efficiency $= 1$,

N = the number of linked turns per pole,

I = the current in each turns in amperes,

R_0 = the radius of the aperture in meters,

B' = the quadrupole field gradient in Tesla per meter.

The dipole field was calculated from the following equation, also taken from reference 3.

$$B = \mu_0 \eta \frac{NI}{g} \qquad (2)$$

with μ_0 = permeability of free space $= 4$p ¥ 10–7 N $-$ A–2,

η = efficiency $= 1$,

N = the number of linked turns per pole,

I = the current in each turns in amperes,

g = the half-gap of the dipole in meters,

B = the central dipole field in Tesla.

Values for the currents that flow through the quadrupoles and dipole were obtained from the control system read-back. Those for N, R_0, and g that occur in the equations were obtained from the design specifications for these elements. The magnetic fields for the quadrupoles and dipole were calculated and up-dated in the input data file 1ASTD which was then renamed MG.txt.

The parameters of region 1 and region 2 were difficult to determine accurately because the 6 beam input values and the 10 matrix values of the transfer matrix dated back to the early 1970s. Further, the beam input parameters (i.e. the beam emittance) change with the tune and type of the ion source, the centre region of the cyclotron, and cyclotron tune itself. INTRAN has the provision of TRANSPORT to vary some of the physical parameters of the elements of the system and to impose various constraints on the beam design. The constraints imposed in this case were the actual beam sizes observed at the seven profile monitors on 14 April, 2000. The initial parameters varied were the 10 elements of the transfer matrix of region 2. A first-order run was made to fit the constraints and the new matrix values were saved to the input data file MG.txt.

The next step was to impose the same constraints but to vary the input beam (that is, the emittance) of the extracted beam. However, one small problem had to be dealt with before continuing; the first quadrupole was run in an asymmetrical configuration. It has the capability to steer the beam vertically by shunting some of the current away from the coil that effects the focussing/defocusing of the beam in the vertical plane. Because there is no real model for this particular configuration in INTRAN, all beam profile monitor printouts were made with the steering capability set to zero, thus giving the first quadrupole true quadrupole properties. A second first-order run was then made. The results, tabulated in Tables 2A and 2B, are seen to closely match the observed profiles on beam line 1A.

4. A NEW MODEL

Although the modified model MG.txt is a reasonable representation of the present beam line, I felt that I could improve the model. The region that I focussed on was the transfer matrix of region 2. This is a 6×6 matrix in INTRAN but for our purpose it can be reduced to a 5×5 matrix with R55 equal to unity and with the only other non-zero elements being the 10 listed in section 2. However, in varying these 10 elements INTRAN would choose to vary those just to fit the imposed constraints without regard as to whether they were physically meaningful. Consequently, I had little confidence in the results and decided that another method was needed to describe the beam path from extracted foil to exit of combination magnet.

The cyclotron pole faces look like an odd-shaped dipole. The INTRAN input data file for a (uniform field) dipole only needs the magnetic field and the effective length. A plot was obtained of cyclotron magnetic field along the path of the extracted protons from extraction foil to combination magnet exit horn. The plot was then segmented into regions of constant magnetic fields. Where non-linear fields existed small increments of distance were taken. These numerous dipole segments were then edited into the input data file MG.txt. Their effective lengths were taken as the actual lengths of the various segments. This approach was taken because the cyclotron magnetic field is vertical and uniform. It must be noted that there might be small region of the cyclotron in which the beam path is over the edge of a cyclotron pole and this could skew the results. By representing the cyclotron with a string of magnetic segments, the 10 transfer-matrix values could be removed and, the combination magnet could be added as a standalone device. A first-order run was done; the results are given in Tables 3A and 3B. The input file was saved and renamed NM.txt.

5. COMPARISON OF INPUT FILES 1ASTD, MG.TXT, AND NM.TXT

Tables 4A, 4B, and 4C compare the results of the three input data files. Table 4A lists the values of the emittance for input data file 1ASTD. The tabulated results are the emittance of the beam as determined in late 1970. The fitting routine of INTRAN was used to determine new values for the emittance used in the other input files. Table 4B lists the matrix elements of the transfer matrix that were used. Finally, Table 4C tabulates the changes made for in the magnetic fields of the eight quadrupoles and the dipole.

6. CONCLUSION

The INTRAN program was initially used as a training tool for understanding the beam optics and beam line transport devices. The input data file 1ASTD was used as a reference-starting model of the beam line 1A. After running the TRANSPORT program and comparing the results of the program versus the actual beam line profile monitor, it was apparent that the old model needed to be up-dated. The procedure was to correct any errors in the information data regarding the various devices like quadrupole, dipole and steering magnet. The distances between the devices were compared to those in blueprints. Once the old model was up-dated to reflect the present beam line 1A configuration, a second look at simplifying the model was undertaken.

Removal of the transfer matrix of region 2 of the input data would greatly simplify the model. This lead to regarding the cyclotron pole region as a sequence of many dipoles. The path of the beam from the extraction foil to combination magnet exit was calculated from magnetic field data taken done in 1970. At present, an NMR probe located in a region of stable magnetic field gives an accurate cyclotron magnetic field reading. It was felt that scaling the magnetic field reading throughout the beam extraction path might be feasible.

The only data to be up-dated was the emittance of the beam at the extraction foil. This left only four values to be determined. Two values the horizontal *(x)* and vertical *(y)* size of the beam can be determined by using various probes in the cyclotron to intercept the beam. These probes have current read-back capability.

The only difficult values to determine were the horizontal and vertical angular divergences of the beam at the foil. One method to determine these values would be to fit them with the fitting capability of INTRAN/TRANSPORT. However, a difficulty with this procedure is that the program will choose values that the chosen values may or may not necessarily be consistent with the known emittances. Further, the orientations of the phase-space ellipses must also be considered during the fitting procedure. Consequently, an alternate approach may be needed.

From a knowledge of the horizontal and vertical emittances at the ion source and the measured beam sizes from the probe measurements, approximate values for the horizontal and vertical divergences may be calculated. Although these computed values would represent upright phase-space ellipses at the stripper foil, they could be used as a starting point for further calculations, some of which could involve varying the r_{21} and r_{43} parameters to tilt the horizontal and vertical phase-space ellipses.

Validation of the new model will begin with a test scheduled in April, 2001. The procedure will be to change the magnetic field of a quadrupole and to observe the effect on beam sizes at the downstream monitors. These observed beam sizes will then be compared to the sizes predicted by INTRAN when the new model is used as an input data file.

7.   ACKNOWLEDGEMENT

References

[1]   K. L. Brown, F. Rothacker, D. C. Carey and Ch. Iselin, *TRANSPORT: A COMPUTER PROGRAM FOR DESIGNING CHARGED PARTICLE BEAM TRANSPORT SYSTEMS,* CERN Report 80-04, CERN (1980).

[2]   *INTRAN: A USER FRIENDLY INTERFACE TO TRANSPORT,* TRIUMF Computing Document TRI-CD-96-xx, TRIUMF, October 1996.

[3]   http://www-eng.lbl.gov/õsborn/magnet_design/magnet

TABLE 1A

A comparison between observed horizontal beam sizes and those predicted by the
original INTRAN data file

Profile monitor	1ASTD prediction mm	Observed 14 April, 2000 mm	Difference mm
1VM1	4.0	3.0	1.0
1VM2	2.6	4.5	1.9
1VM3	14.2	7.5	6.7
1VM4.6	23.2	5.3	17.9
1AM6	17.2	4.5	12.7
1AM7	15.2	6.0	9.2
1AT1	2.0	2.0	0.0

TABLE 1B

A comparison between observed vertical beam sizes and those predicted by the
original INTRAN data file

Profile monitor	1ASTD prediction mm	Observed 14 April, 2000 mm	Difference mm
1VM1	9.4	26.0	16.6
1VM2	3.0	13.5	10.5
1VM3	12.0	18.0	6.0
1VM4.6	7.0	19.5	12.5
1AM6	14.4	16.5	2.1
1AM7	4.8	4.5	0.3
1AT1	7.0	7.0	0.0

TABLE 2A

A comparison between observed horizontal beam sizes and those predicted by the
modified INTRAN data file

Profile monitor	MG.txt prediction mm	Observed 14 April, 2000 mm	Difference mm
1VM1	3.0	1.4	1.6
1VM2	4.5	2.8	1.7
1VM3	7.5	7.4	0.1
1VM4.6	5.3	6.2	0.9
1AM6	4.5	4.0	0.5
1AM7	6.0	4.2	1.8
1AT1	2.0	4.2	2.2

TABLE 2B

A comparison between observed vertical beam sizes and those predicted by the
modified INTRAN data file

Profile monitor	MG.txt prediction mm	Observed 14 April, 2000 mm	Difference mm
1VM1	26.0	26.0	0.0
1VM2	13.5	13.2	0.3
1VM3	18.0	18.8	0.8
1VM4.6	19.5	18.4	0.9
1AM6	16.5	18.0	1.5
1AM7	4.5	8.4	0.9
1AT1	7.0	9.6	2.2

TABLE 3A

A comparison between observed horizontal beam sizes and those predicted by the
further modified INTRAN data file

Profile monitor	NM.txt prediction mm	Observed 14 April, 2000 mm	Difference mm
1VM1	3.0	1.0	2.0
1VM2	4.5	3.6	0.9
1VM3	7.5	5.8	1.7
1VM4.6	5.3	6.6	1.3
1AM6	4.5	3.4	1.1
1AM7	6.0	2.2	3.8
1AT1	2.0	3.0	1.0

TABLE 3B

A comparison between observed vertical beam sizes and those predicted by the
further modified INTRAN data file

Profile monitor	NM.txt prediction mm	Observed 14 April, 2000 mm	Difference mm
1VM1	26.0	24.0	2.0
1VM2	13.5	12.2	1.3
1VM3	18.0	17.8	0.2
1VM4.6	19.5	18.6	0.9
1AM6	16.5	20.0	3.5
1AM7	4.5	8.2	3.7
1AT1	7.0	8.8	1.8

TABLE 4

A comparison of input parameters used in the three data files

A: The input parameters

Parameter	1ASTD	MG.txt	NM.txt
x (cm)	0.26800	0.17215	0.17215
θ (mr)	1.08100	0.05096	0.05096
y (cm)	0.67800	0.63279	0.63279
ϕ (mr)	0.66700	1.85495	1.85495
ℓ (cm)	0.00000	0.00000	0.00000
δp (%)	0.20000	0.38494	0.38494

TABLE 4B

The transfer matrices

Parameter	1ASTD	MG.txt	NM.txt
R_{11}	–0.06700	–0.06700	0.0
R_{12}	0.34800	0.34800	0.0
R_{16}	1.30000	1.30000	0.0
R_{21}	–2.95000	–2.95000	0.0
R_{22}	0.26000	0.26000	0.0
R_{26}	1.70000	1.70000	0.0
R_{33}	1.07000	1.11658	0.0
R_{34}	0.62700	0.61736	0.0
R_{43}	0.25600	–0.04733	0.0
R_{44}	1.08500	1.13774	0.0

TABLE 4C

The quadrupole and dipole field strengths

Parameter	1ASTD	MG.txt	NM.txt
1ACM			3.06557
1VQ1 (H)	5.55170	5.65966	5.65966
1VQ2 (V)	6.44503	6.33824	6.33824
1VQ3 (H)	6.49836	6.36351	6.36351
1VB1	9.55200	10.01889	10.01889
1AQ4 (H)	2.33930	2.37143	2.37143
1AQ5 (V)	4.01830	3.65279	3.65279
1AQ6 (H)	2.08420	2.0808	2.08086
1AQ7 (V)	3.97637	3.67084	3.67084
1AQ8 (H)	4.09420	4.55335	4.55335