TRIUMF EXTRACTION AND 500 MeV BEAMLINE OPTICS

R. Baartman, Y.-N. Rao, TRIUMF, Vancouver, Canada *

Abstract

The 2A beamline, one of the TRIUMF cyclotron primary extraction beamlines, is 60 m in length. It is now routinely operating up to 70 uA (proton beam) at 500 MeV for ISAC. ISAC requires a diffuse spot of specific size on the radioactive beam production target at the end of 2A. To help achieve this, we developed a program aimed at obtaining a better understanding and more accurate description of 2A optics and the extracted beam from the cyclotron. The beam sizes along 2A were measured with profile monitors and compared with theoretical predictions. During the course of this work, we discovered that the transfer matrix, involved in the optics calculations, between the stripping foil and the beamline entrance was incorrect. After correcting this error, we obtained good agreement between the measured and calculated envelopes. We report on the details of this work as well as on a measurement of the beam characteristics as a function of stripper foil thickness.

INTRODUCTION

The stripped 500 MeV H^- beam from the TRIUMF cyclotron passes through the cyclotron field, the fringe field and the combination magnet. The extraction path of 2A from the stripper through the combination magnet can be well approximated with a dipole with exit edge angle, followed by a drift. The bending angle, radius and the drift length are $23.38°$, 6.7 m and 3.0 m respectively. The edge angle for beamline 2A is known to be $59°$; this was found by fitting the optics against a raytrace calculation [1] through the cyclotron fringe field. But the raytracing calculation involves a fringe field map and this field map is a duplication of beamline 1 extraction port, because there was no fringe field survey for 2A extraction port. It is uncertain that the fringe field is the same for both extraction ports. This suggests that we use this bend-edge-drift approximation in the optics modeling, so that we can treat the edge angle as a fitting parameter. The optics in the vertical plane is very sensitive to the edge angle.

MEASUREMENTS

In order to achieve a more accurate description on the edge angle and thereafter the beamline optics, we carried out systematic measurements [2] with beam in the vertical plane because the vertical plane has no energy dispersion involved and also the vertical plane is more sensitive to the edge angle of the fringe field.

* TRIUMF receives funding via a contribution agreement through the National Research Council of Canada.

Beam Centroids

We used a B_r trim coil doublet 48/52 in the cyclotron to move the beam vertically at energy of $\sim$500 MeV, and then measured the vertical shift of the centroid of beam in 2A at 6 profile monitors; while the vertical shift of beam in the cyclotron was measured using an internal high energy probe (HE1). From the distributions measured at monitors we obtained the centroid position of the beam versus the change in B_r trim coil excitation. It appeared that all the measured data points at each monitor almost stay on a straight line that crosses the zero point.

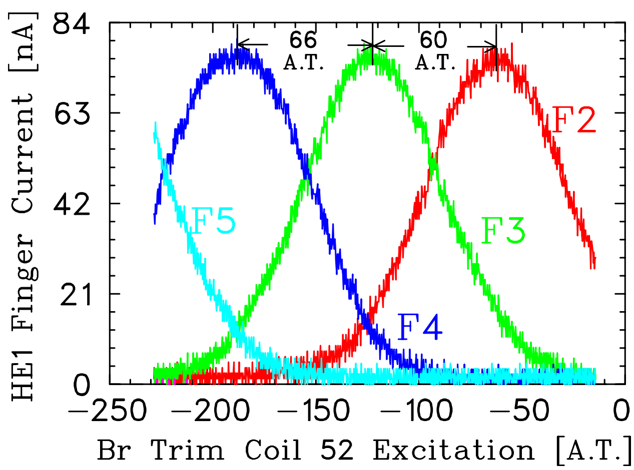

Figure 1: HE1 probe measured finger currents vs. the excitation of B_r trim coil 52.

Fig. 1 shows the HE1 probe measured finger currents vs. the excitation of TC52. A change of 60 or 66 Ampere-turn in the trim coil moves the beam centroid from one finger to the next. Each finger is 0.25 inch wide vertically, so we find the coil's driving strength to be 0.0040 ± 0.0002 inch/A.T. in average. For 30, 60 and 90 Ampere-turn changes, the vertical shift of beam centroid at HE1 is respectively 3.02, 6.05 and 9.08 mm. Whereas at 2A stripper location, the shift is 1.14 times, according to the results of static equilibrium orbit calculations.

Beam Sizes

We measured beam distributions with profile monitors through the whole beamline and then calculated the rms sizes. This was done with 3 foils of different thicknesses, i.e. 4.43, 2.87 and 1.99 mg/cm^2. As an example, Fig. 2 shows the profiles measured on monitor VM6 for these 3 foils. The beamline had been tuned so that from stripper to VM6 was "parallel-to-point" ($R_{33} = 0$). This was to investigate stripper scattering.

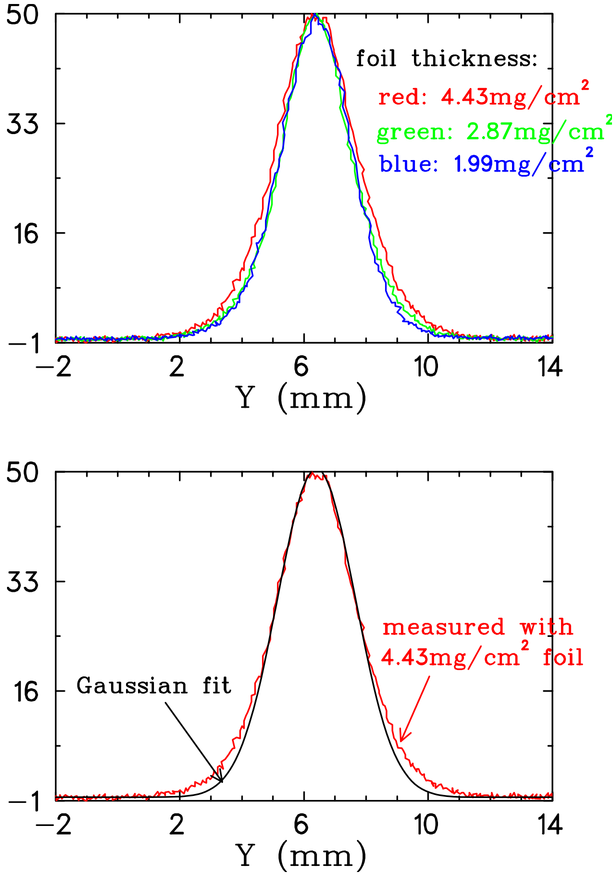

Figure 2: Top: The measured vertical profile of beam on monitor VM6 for 3 stripper foils of different thicknesses. The difference between 4.43 and 2.87 mg/cm^2 foils being relatively larger is because the multiple scattering in the 4.43 mg/cm^2 foil dominates the emittance. Bottom: A comparison between the measured profile and a Gaussian distribution. The core is just a Gaussian and the tails are due to the large angle scattering.

As for the size of the beam on the foil, this was found by differentiating the current as the beam was moved from finger to finger on HE1. See Fig. 1; we used F4+F5, plotted in Fig. 3 (top), and differentiated (bottom). In this way, we obtained the 2*rms size of the beam of 0.20 inch. Since $\beta_y \approx 31$ m, this implies a 4*rms circulating emittance of $0.8\,\pi$mm-mrad. At 2A stripper location, $\beta_y \approx 40$ m, so the size would be $0.20 \times \sqrt{40/31} = 0.23$ inch.

OPTICS CALCULATIONS

Beamline 2A consists of 4 dipoles and 16 quadrupoles (of which,however, only 14 are used). All the quadrupoles had been mapped and these maps were used to determine effective lengths and fringe field integrals. The remaining uncertainty is due to hysteresis effects and amounts to no more than about 1%.

We calculated the 2A optics with a single particle so as to model the beam centroid movement in the vertical plane.

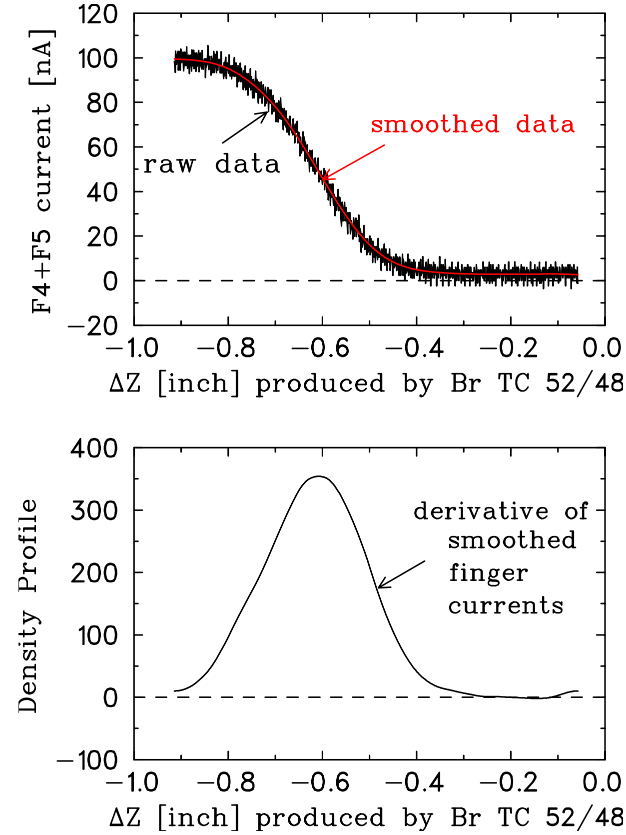

Figure 3: Top: HE1 probe measured finger currents sum (F4+F5) vs. the vertical position of the beam. Bottom: vertical distribution of the beam, derived by differentiating the current sum (F4+F5) w.r.t. the vertical position Z.

In the calculations, the measured shifts of centroid at the stripper and at monitors VM1,2,3,5,6 are fitted. We treated, as unknown, the angle of the beam centroid vertically as it leaves the foil, because the trim coil doublet does not only shift the position of the beam, but also changes the angle of the beam, according to the calculation of static equilibrium orbit. Using the data measured at 30 Ampere-turn change, the fit results in an optimum vertical angle of -0.18 mrad, but the fit is not good, as shown in Fig. 4. Then, we did the fit allowing the edge exit from the cyclotron fringe field to vary as well. The fit is good (see Fig. 4), but the edge angle is $-68.3°$, instead of $-59°$. The vertical angle of beam is -0.65 mrad. We then did the same calculations for the 60 and 90 Ampere-turn both cases. As a result, the edge angle is $-68.5°$ for both fits, while the vertical angle of beam is respectively -1.32 and -2.00 mrad. Both fits are as good as for the 30 Ampere-turn case.

In summary, all the 3 fits result in almost an identical edge angle, i.e. $-68.5°$, and also the vertical angle of the beam has almost the same scale factor as the Ampere-turn changes in the trim coils.

Further, we calculated the optics by doing fits to the beam sizes measured. Since the envelope in the beamline involves the scattering in the foil, we first calculated the scattering angle of the foil. Based on GEANT calculated in-plane scattering angle distribution of 500 MeV H^- beam penetrating a 5 mg/cm^2 carbon foil, we calculated and obtained a scattering angle of 0.35 mrad (2rms). This agrees with the value calculated from Molière's formula. The rms scattering angle is proportional to $\sqrt{\text{foil thickness}}$. We use this to scale the result to foils of other thicknesses.

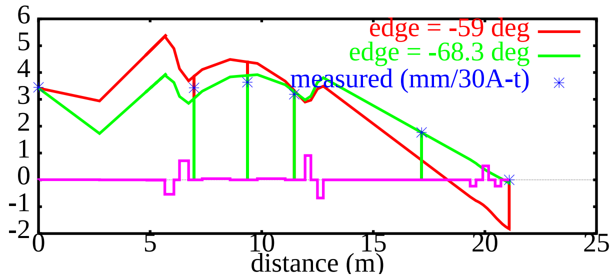

Figure 4: Beam centroid shift (in mm) measured vertically up to the monitor VM6 and the trajectory fitted. The vertical lines represent the location of the monitors. The fit with edge angle $-59°$ is not good, but the fitted $-68.3°$ angle is satisfactory.

We started a fit in the vertical plane only. For the 1.99 mg/cm^2 foil case, we used the measured beam sizes at monitors VM1,2,3,5,6, of values 0.48, 0.68, 0.57, 0.43, 0.24 cm. Also, we used the vertical beam size (2rms) at the stripper of value 0.579 cm, as stated above. We used the scattering angle of 0.221 mrad. We treated, as unknowns, the circulating emittance and Y' of the beam at stripper but before scattering. As for the edge angle of the fringe field, although it was already found, i.e. $-68.5°$, from fits made to the beam centroid, we still treated it as an unknown and allowed it to vary in the fit. The fit is good; the result is an edge angle of $-68.4°$ which is consistent with the previous result, the circulating emittance of 1.0 πmm-mrad, and Y' of -1.2 mrad.

Overall, there were 3 fitting parameters: circulating emittance, Y', edge angle. There were 6 vertical profiles. We also tried a fit with edge angle fixed at $-59°$, but the fit is obviously unsatisfactory.

In order to obtain more evidence about the edge angle being $\sim -68.5°$ instead of $-59°$, we extended the calculations for the vertical envelope through the whole beamline, and compared with the sizes measured on the subsequent monitors from M9 through M19. As well, we did fit in the horizontal plane, allowing the β_x, α_x and ϵ_x to vary. In the vertical plane the calculated beam sizes agree very well with the measured ones. In the horizontal plane, the fit is good as well, see Fig. 5. The resulting emittance ϵ_x on the foil but before scattering is 0.62 πmm-mrad; smaller than the vertical emittance. This is qualitatively consistent with the results of simulations of circulating beam impinging on the foil. These show that, as long as the foil is fully dipped into the beam vertically which is true most of the time in the cyclotron operation, then, for the beam hitting the foil but before suffering scattering, ϵ_y is larger than ϵ_x. However, the fit with edge angle of $-59°$ results in ϵ_x consistently larger than ϵ_y, for example, ϵ_x was as large as 0.7 πmm-mrad, while ϵ_y was only $(0.2-0.3)\pi$mm-mrad. This is not consistent with the 0.8πmm-mrad calculated from the circulating emittance.

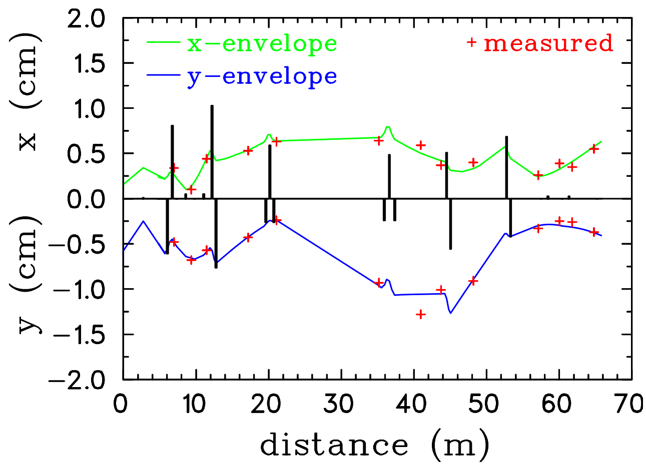

Figure 5: Measured and calculated beam sizes agree very well in the whole beamline. A total of 6 parameters were fitted to obtain the best fit.

We repeated the fits for the 2.87 mg/cm^2 and 4.43 mg/cm^2 stripping foils, and again found the best fit to be with edge angle of $-68.5°$.

REFERENCES

[1] R. Baartman, Y.-N. Rao, "Corrections to TRIUMF cyclotron stripper to combination magnet transfer matrices and computer program `STRIPUBC`," TRIUMF design note TRI-DN-05-4, Feb.7, 2005.

[2] Y.-N. Rao, R. Baartman, "Beamline 2A optics: Calculations and Measurements," TRIUMF design note TRI-DN-07-14, May 10, 2007.

