INVESTIGATION OF SPACE CHARGE EFFECT IN TRIUMF INJECTION BEAMLINE

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

Abstract

The TRIUMF cyclotron operates routinely at $200\,\mu$A extracted at 500 MeV. Because of growing demands for beam, up to $400\,\mu$A is envisaged: this would require ~ 1 mA from the H$^-$ ion source and injection beamline. The phase acceptance of the cyclotron is roughly 36°, so the local peak beam current just before injection would be higher than 4 mA. This leads to large space charge effects on the beam transverse envelope and longitudinal bunching efficiency.

The beam profiles and the bunching efficiency were measured for different currents up to $575\,\mu$A. These were used in space charge transport calculations to determine the beam optic properties and the space charge neutralization level. Extending the calculations to higher intensities, it is found that with the present double drift double harmonic bunching system, the bunching efficiency decreases dramatically above a dc current of $600\,\mu$A. To enable reaching the envisaged $400\,\mu$A from the cyclotron, it requires either raising the cyclotron phase acceptance from the present $\sim 36^\circ$ to 50° by for example increasing the energy gain per turn at injection, or by adding another fundamental harmonic buncher.

1 INTRODUCTION

The TRIUMF cyclotron injection beamline [1] is roughly 35 m in length, and is entirely electrostatic, containing approximately 80 quadrupoles. It has been running routinely with a cw current of $\sim 400\,\mu$A (H$^-$) at 300 keV, which results in $200\,\mu$A extracted from the cyclotron. In the future, it would be required to transport 1 mA in order to allow up to 400 μA extracted from the cyclotron. With 1 mA average beam current, the bunched beam will have a peak current of $\sim$10 mA. At such high peak currents and low energy level, the space charge effect on the beam transverse size and longitudinal bunching efficiency is large.

The longitudinal space charge effect on the bunching efficiency has been previously discussed [2]. Recently, we performed some measurements of the beam transverse size and bunching efficiency for various currents up to 575 μA. Actual operation of the beamline and calculations including the space charge effect have demonstrated that the high current tune of the beamline still works well for the lower currents; the observed beam spills mainly occur in the vertical section of the beamline (distance $>$ 900 inches in Figs. 1 and 3). Our goal is to find a reasonably standard tune for currents up to 1 mA; we therefore used these measured beam sizes in space charge transport calculations to determine the beam optic properties as well as the space charge neutralization level. Afterwards, we extended the calculations to higher intensities to investigate the bunching efficiency versus current with the present double drift double harmonic buncher system.

2 TRANSVERSE ENVELOPE

The beam widths were measured with 13 scanning wire profile monitors for various currents. As an example, Fig. 1 shows the beam widths (2σ) measured at dc currents 345 and 575 μA. In the horizontal periodic section, the beam width shows weak dependence on the beam current. It was suspected that there exists some space charge neutralization in the H$^-$ beam due to the ionized positively charged ions captured by the beam's potential well, though the beamline is electrostatic. So, an experiment was made to investigate the space charge neutralization level.

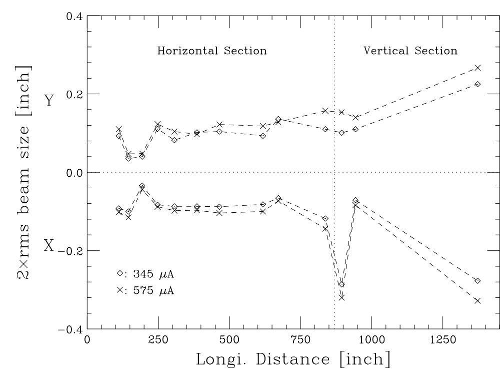

Figure 1: The beam sizes (2σ) at dc currents 345 and 575 μA. The data points are the measurements. The dashed line is only meant to guide the eye.

The first 4 scanning wires in the North-South section of line (250 inches to 500 inches in Fig. 1), are in a section of periodic transport. Each cell is 40 inches, and the phase advance per cell was varied from 30° to 90°. The beam current used was 686 μA, limited by the ion source. The vacuum pressure was 5.0×10^{-7} torr (H$_2$). For each setting of the quads, we got 6 or 8 parameters of beam size. Repeating this procedure 7 times, we obtained 46 valid parameters in total.

We used the computer code TRANSOPTR [4] to calculate the beam's optic properties in the presence of space charge effect. This code uses the F-matrix approach [3] in the beam transport design and calculation with the linear space charge force included. In the calculations, the code varies 7 parameters (the initial beam in both transverse planes, plus the current) by simulated annealing to achieve best match for the 46 values of beam sizes at the

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scanning wire locations.

Typically, the beam size is $2\sigma = 3$ mm, with an uncertainty of ± 0.15 mm. The uncertainty relates mainly to the difficulty of exactly determining the background noise level. Best fit for the effective current was $580\,\mu$A, while the actual H^- current is $686\,\mu$A, so the neutralization factor may be $1-580/686 = 15\%$. The rms deviation of the fitted and measured profile sizes was, however, 0.05 mm, i.e. less than the measurement uncertainty. Fitting with an effective current equal to the actual current resulted in an rms deviation of 0.08 mm; still smaller than the measurement uncertainty. We conclude that the results are consistent with no neutralization. In view of the fact that the beamline is electrostatic and that only a small fraction of the beamline could have external fields which are small compared with the space charge potential of a few volts, this is not surprising.

The KV envelope equation is

$$\begin{aligned} 0 &= \frac{d^2a}{ds^2} + k_x a - \frac{\epsilon_x^2}{a^3} - \frac{2K_{sc}}{a+b}, \\ 0 &= \frac{d^2b}{ds^2} + k_y b - \frac{\epsilon_y^2}{b^3} - \frac{2K_{sc}}{a+b}. \end{aligned}$$

For our parameters, $K_{sc} = 4 \times 10^{-6}$ at 1 mA, 300 keV. For a beam size $a = b = 2.5$ mm and an emittance $\epsilon_x = \epsilon_y = 5.0\,(\pi)$mm-mrad, we see that the emittance term and the space charge term are equal at 1 mA. For our experiment, the beam current was limited by the availability of the current out of the ion source. With $686\,\mu$A, we were still working in a regime where the beam envelope is dominated by the emittance. Hence the observed beam size shows weak current dependence in the horizontal section as shown in the Fig. 1.

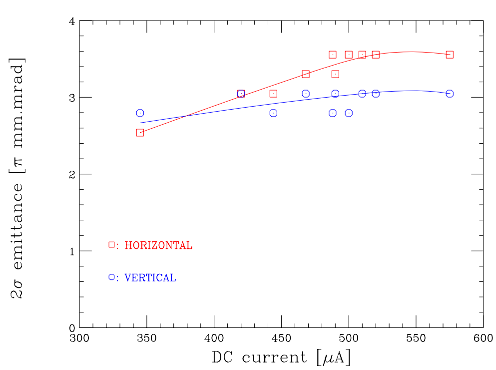

Figure 2: Fitted beam emittance (2σ) vs. current.

In a separate experiment, profiles were taken as a function of beam current. The resulting fitted emittance is shown in Fig. 2.

With bunching, the local space charge density in the beam just prior to the injection is increased by a factor of 5 to 10. (The phase acceptance of the cyclotron is roughly $40°$.) This causes space charge to become increasingly dominant as the beam travels along the injection line, leading to a growth in the transverse size of the beam. Shown in Fig. 3 are the calculated bunch dimensions along the injection line. Compare with Fig. 1.

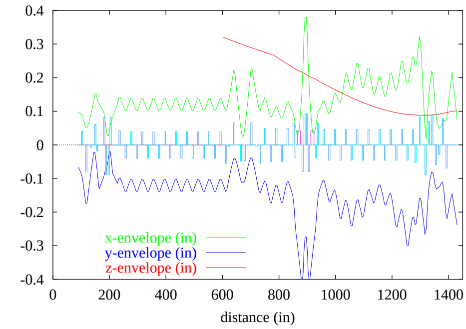

Figure 3: Calculated beam envelope size (inches) at $800\,\mu$A, showing transverse growth due to decreasing bunch length. The red line represents the bunch length divided by 20.

3 BUNCHING EFFICIENCY

To quantitatively investigate dependence of the bunching efficiency on the beam intensity, we used the computer code SPUNCH [5] to simulate the longitudinal dynamics of the beam with space charge. This code also includes the effect of images in the surrounding vacuum pipe. We assumed an upright elliptic acceptance of $\delta\phi = \pm 18°$ and $\delta p/p = \pm 0.5\%$, and an average pipe radius of 12.7 mm; the beam transverse average radius is 3.0 mm according to above measurements. As an example, Fig. 4 plots a sequence of particle distributions in longitudinal phase space. The calculated bunching efficiency is shown as a function of beam current in Fig. 5, where the machine operational results (approximately equal to the transmission efficiency from the last injection line beam stop to the extraction plus another $\sim$6% loss due to the electromagnetic stripping and gas stripping) are plotted as well. An interesting effect shown in this calculation is that the bunching efficiency begins to drop above $600\,\mu$A. For instance, at $600\,\mu$A injection, the efficiency is decreased to 55%. This yields only $\sim 310\,\mu$A at extraction, including a 6% stripping loss. To enable reaching the envisaged $400\,\mu$A from the cyclotron, one way is to add another fundamental harmonic buncher situated at 2.4 m from the inflector, as proposed in ref.[2]. In such a way, the bunching efficiency is expected to remain above $\sim$65% (see Fig. 5).

Another way is to increase the phase acceptance of the cyclotron from the present $\sim 36°$ to $50°$ by raising the energy gain per turn at injection. This was already demonstrated by a late beam development experiment (see the diamond in Fig. 5). The lower dashed line shown in Fig. 5 is the calculated bunching efficiency using a $50°$ phase acceptance. At $800\,\mu$A for example, the $50°$ phase acceptance would improve the efficiency from 43% to 56%, resulting in the envisaged $\sim 400\,\mu$A at extraction.

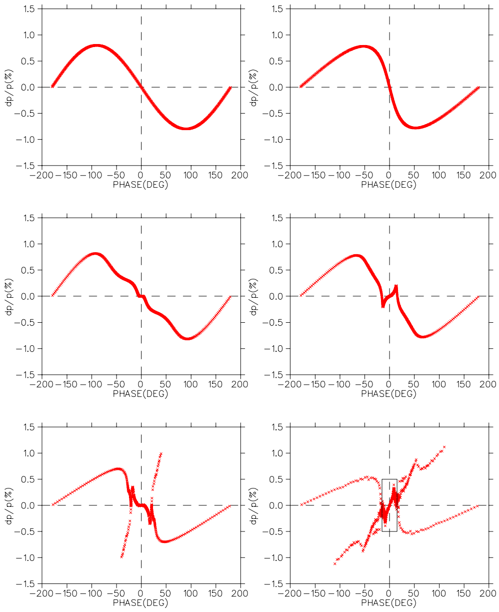

Figure 4: Simulated evolution of particle distribution in longitudinal phase space at 600 μA. From left to right and up to down, windows respectively correspond to the following locations in Fig.3: (1) z=603 inch; (2) z=781 inch; (3) z=902 inch; (4) z=1035 inch; (5) z= 1198 inch and (6) z=1430 inch. Of the 500 particles, 240 are lying inside the $\pm 18°$ phase window in the end.

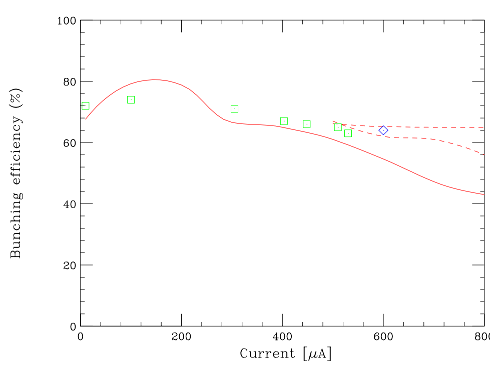

Figure 5: Bunching efficiency vs. beam current. The data points are the machine operational results: the 'diamond' was achieved with $\sim$50° phase acceptance due to an increased rf voltage. The solid line is the calculation result with 36° cyclotron phase acceptance. The lower dashed line is the calculation result for a $50°$ phase acceptance with the present buncher system; the upper dashed line is the calculated performace for the $36°$ phase acceptance but with the third buncher added.

4 CONCLUSIONS

Machine experiments have indicated that increasing the cyclotron phase acceptance to $50°$ from the present $\sim 36°$ by raising the energy gain per turn in the central region enables $\sim 380\,\mu$A extracted from the cyclotron, close to the future goal $400\,\mu$A. This encouraging result suggests that the space charge effect in the injection beamline at currents up to $800\,\mu$A is handlable. Calculations indicate that with an additional buncher acting as a "rebuncher", $500\,\mu$A is achievable. Further work is to model, in more details, the optics in the vertical section just upstream of the inflector as more information about the beam profile becomes available.

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