

THE TRIUMF HIGH EFFICIENCY BEAM BUNCHING SYSTEM

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Summary

A 300 keV H^- beam of up to 800 μA is transported along a 40 m long electrostatic beamline between the ion source and the TRIUMF Cyclotron. Two double-gap sinusoidal bunchers with independent phase and amplitude control, located midway in the beamline, are used to enhance the machine acceptance of the dc beam. The optimal performance occurs at injected currents around 200 μA with approximately 60% of the beam being accepted within a 30° cyclotron phase acceptance. Calculations taking into account longitudinal space charge effects explain the observed current-dependent acceptance. In the future, it is planned to raise the extracted current to 400 μA . In order to meet this requirement, the beamline optics has been reconfigured and additional bunching capability will be installed.

Introduction

The injection system for the 500 MeV H^- cyclotron at TRIUMF has been previously described.¹ Briefly, the H^- ions are produced by two external ion sources. An Ehler's type PIG source provides an unpolarized beam of up to ~ 1 mA within a normalized emittance of 0.2π mm-mrad by 0.07π mm-mrad.² The second ion source, a Lamb-shift type source, produces up to $\sim 1\mu A$ of 80% polarized H^- within a normalized emittance of 0.3π mm-mrad.³ The H^- beam from either one of these sources is transported at ~ 300 keV with about 80% efficiency along the 40 m long electrostatic injection beamline.¹ Presently currents of 130 μA (unpolarized) or 0.3 μA (polarized) of 500 MeV protons are routinely delivered to experiments. About 70% of the operational time is scheduled for high intensity operation.⁴

A layout of the injection beamline is given in Fig. 1. The dc beam is velocity modulated in the

horizontal north-south section of the beamline by two double-gap bunchers. The initial buncher operates at the cyclotron RF frequency (~ 23 MHz) while the other, located 4.54 m downstream, is tuned for the second harmonic (~ 46 MHz). The voltage and phase (relative to the cyclotron RF phase) of each buncher are independently adjusted to optimize the beam accepted by the cyclotron. This system permits approximately 60% of a 200 μA dc beam to be accepted by the cyclotron. Additional RF devices include a chopper to reduce the time width of the beam bursts entering the cyclotron and a 1 in 5 selector to increase the time between beam bursts from 43 to 217 ns. Also, a 1 kHz variable duty cycle pulser can be used to vary the average current without affecting the emittance or the peak current.

The facility is gradually being upgraded to meet the demands for higher extracted currents. Tests at high currents and calculations including the effects of space charge have confirmed that the current extracted from the cyclotron is restricted to less than 200 μA cw by beam spill in the existing injection system. This limit results from the constraints put on the beam by the chopper and by the optics which was designed to produce a narrow "cigar" shaped beam at the chopper slits. The polarity of a quadrupole in this region is being changed and the slits will be opened to permit a periodic focusing structure through the chopper section. A further constraint is that above ~ 120 μA extracted, the bunching efficiency decreases monotonically. It is foreseen that with the present bunching system, the ultimate goal of 400 μA extracted will be very difficult to attain since the acceptance of the cyclotron injection line is limited and it is difficult to increase the brightness of the source. The purpose of the studies described next was to determine methods of improving the bunching efficiency at high currents.

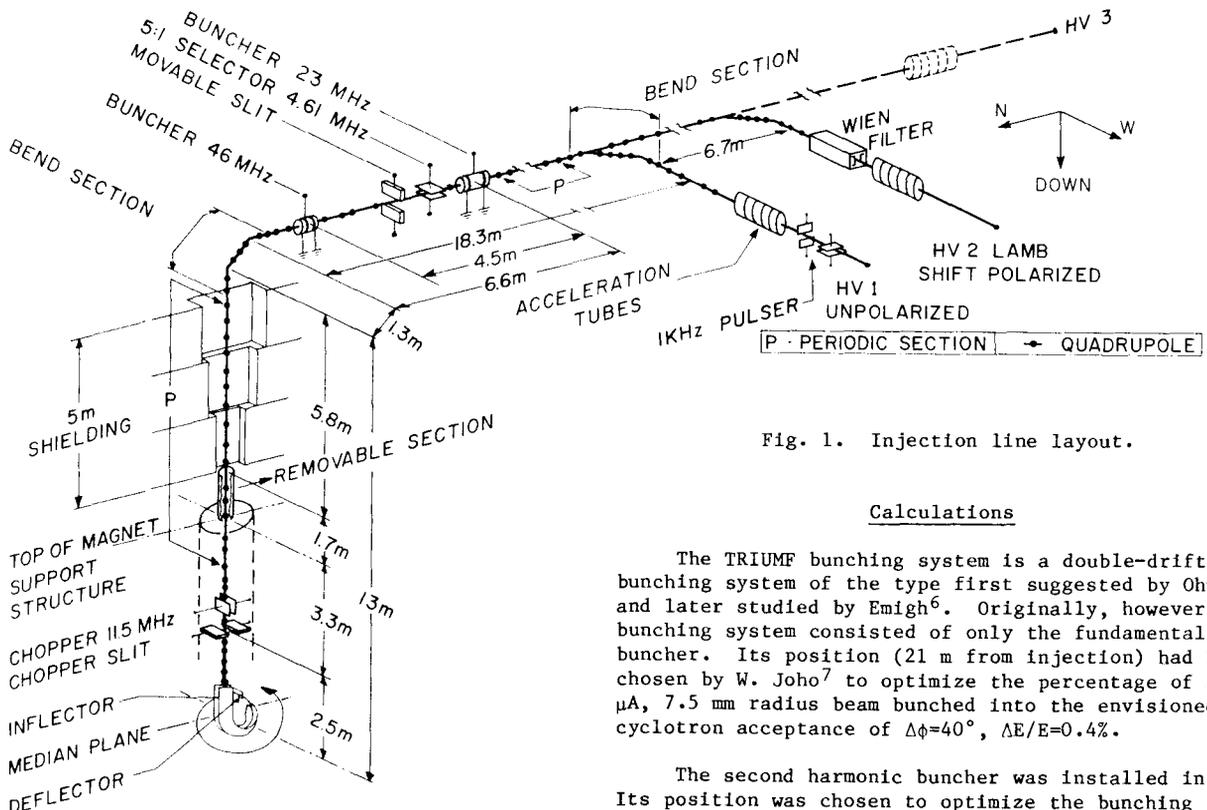


Fig. 1. Injection line layout.

Calculations

The TRIUMF bunching system is a double-drift bunching system of the type first suggested by Ohnuma⁵ and later studied by Emigh⁶. Originally, however the bunching system consisted of only the fundamental buncher. Its position (21 m from injection) had been chosen by W. Joho⁷ to optimize the percentage of a 500 μA , 7.5 mm radius beam bunched into the envisioned cyclotron acceptance of $\Delta\phi=40^\circ$, $\Delta E/E=0.4\%$.

The second harmonic buncher was installed in 1979. Its position was chosen to optimize the bunching

efficiency into 40° at extracted currents of approximately $120 \mu\text{A}$. The increase in bunching implies an increase in the energy spread of the injected beam. This could be tolerated since the energy acceptance of the cyclotron had been measured to be $\Delta E/E=1.2\%$, i.e., three times larger than the initial design - based on a well centred, uniform envelope, 40° wide accelerated beam⁷ - had envisioned. As a result, the 2nd harmonic buncher increased the percentage of beam accepted by the cyclotron by a factor of 1.5.

The performance of the double-drift bunching system is shown in Fig. 2 as a function of the injection line current. The rightmost experimental point (57% bunching efficiency at $490 \mu\text{A}$ injection line current) corresponds to $245 \mu\text{A}$ extracted from the cyclotron. (Gas and electromagnetic stripping of the H^- ions in the cyclotron reduce the accepted current of $490 \mu\text{A} \times 0.57$ to $245 \mu\text{A}$ extracted.) At the time of the measurement, the cyclotron phase acceptance was only 30° while the energy acceptance $\Delta E/E$ was 2%. The bunching system is more effective at filling the 30° phase buckets with a 2% energy spread than the larger phase intervals with a smaller energy spread. The cyclotron can be tuned for a larger energy acceptance at the expense of phase acceptance. The tuning criteria of maximum overall transmission from injection to extraction and minimum internal beam spill empirically lead to the lower phase acceptance solution.

In order to understand the measured bunching efficiencies and to study the feasibility of extracting $400 \mu\text{A}$ from the cyclotron a computer program, SPUNCH, was written. The program calculates the development of a dc beam in longitudinal phase space taking into account forces due to bunchers and to longitudinal space charge; transverse effects are ignored. In the longitudinal direction, one period of beam is modelled by N discs. All discs are identical, of constant radius, and each contains $1/N$ of the charge per bunch. Interaction forces between discs are calculated directly at each time increment using the analytic formula for the electric field from a disc with the approximation that the force that one disc exerts on a second is as if all the charge of the second disc were concentrated on axis. This model was first used by P.K. Tien et al.⁸ and has since been used by many others. In our case,

beam pipe shielding is taken into account by multiplying the free space force between two discs by a built-in "shielding function" which depends only on the separation of the two discs. This is a good approximation because the radius of our beam is no larger than one tenth the effective beam pipe radius (i.e. the average distance of the beam from nearest metallic objects). The results have been checked with PARMILA⁹, a beam transport computer code which takes into account both longitudinal and transverse space charge forces. Results obtained from SPUNCH are in good agreement with PARMILA calculations. In studying bunching we have found SPUNCH to be more convenient than PARMILA simply because from buncher to injection our beam line contains 47 quadrupoles. These are tuned simultaneously with the bunchers to ensure that the beam size is maintained within the acceptance of a series of collimators and skimmers. The focusing power of each quadrupole is required as input into PARMILA in order to obtain accurate results.

When using SPUNCH to calculate bunching efficiencies, an upright acceptance ellipse of full widths $\Delta\phi = 30^\circ$ and $\Delta E/E = 2\%$ was assumed. This gave a zero current (no space charge) bunching efficiency of 65% in excellent agreement with experiment (Fig. 2). For non-zero currents, comparison between experiment and calculation is more difficult because the average radius of the beam is not accurately known. However, the beam sizes required to make SPUNCH calculations agree with experiment are reasonable. For example, at $200 \mu\text{A}$ injected, SPUNCH gives a bunching efficiency of 73% for a beam radius of 3.8 mm. At $500 \mu\text{A}$ injected, the calculated efficiency matches the measured value if one assumes a beam radius of 7.6 ± 0.5 mm. Experimentally, we found that increasing the beam current beyond $500 \mu\text{A}$ dc in a low duty cycle mode simply increased the beam spill in the vertical section of the injection line without increasing the extracted current. Constraints along the beamline include cooled collimators and uncooled skimmers which restrict the beam radius to 6.4 mm and 19 mm respectively. Misalignments and a transverse magnetic field component will lead to a smaller effective aperture. Thus an upper limit of 7.5 mm for the average beam radius is reasonable.

Longitudinal space charge forces reduce the energy spread introduced in the beam by the buncher. For a given beam current (I), radius (a) and final phase spread ($\Delta\phi_f$), there exists a unique optimum value for the distance from the buncher to the accelerator. This distance can be found by calculating the drift length necessary for a bunch of length $\Delta\phi_f$ to debunch into a DC beam. We have used SPUNCH to make such calculations; the results are shown in Fig. 3. For four

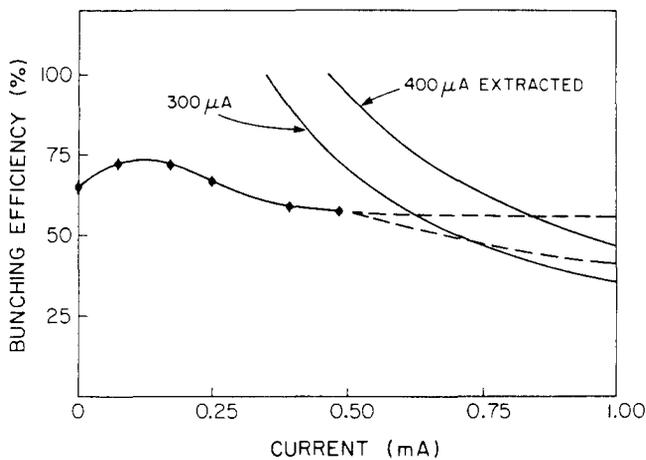


Fig. 2. Experimentally measured bunching efficiency vs. injection line current. The solid line joining the data points is meant only to guide the eye. The lower dashed curve is the calculated performance of the present bunching system. The upper dashed curve is the calculated performance with the proposed third buncher added. The two solid curves are contours of constant extracted current.

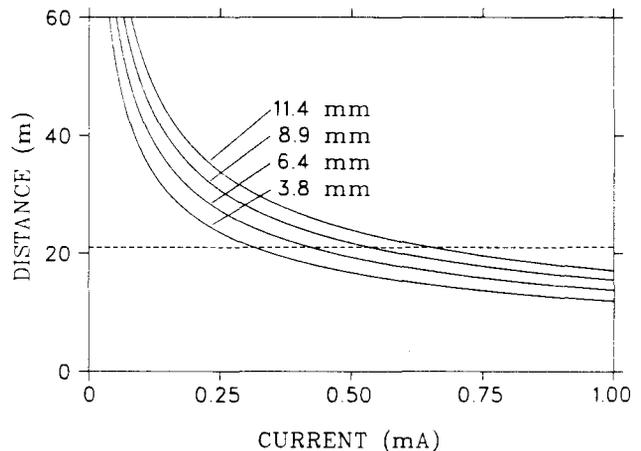


Fig. 3. Calculated optimum buncher-to-injection distance vs. injection line current for four different beam radii.

different beam radii and $\Delta\phi_f=30^\circ$, the optimum buncher to inflector distance is shown as a function of injection line beam current. One can see from this figure that indeed the present buncher position (dashed line) for a 7.5 mm diameter beam is optimal at 500 μA . One can see further that there are two methods of optimizing the bunching efficiency for currents larger than 500 μA . (1) Allow the beam radius to become larger than 7.5 mm. (2) Move the bunching system closer to injection. The first option is impractical because it would require a major redesign of the vertical section of the injection line to accept the larger beam size. (For 1 mA, the required beam radius is 20 mm). The second option looks more promising. Moving the present bunching system would decrease the bunching efficiency at low currents. However, we can in principle achieve the same effect as a sliding buncher by adding another fundamental harmonic buncher (a "rebuncher") somewhere between the existing system and the inflector.

In order to find the optimum position for such a buncher, SPUNCH calculations were performed with a 1 mA, 7.5 mm radius beam. (1 mA in the injection line could result in 400 μA extracted from TRIUMF if for example the bunching efficiency was 50% and the gas and electromagnetic stripping in the cyclotron totalled 15%). The phase spread of the beam was calculated as a function of position from the first buncher onwards. Also, the phase spread of a 30° bunch was traced backwards from the inflector. The optimum position for the new buncher would be where the phase spreads given by the two calculations were in agreement. We found this position to be 2.4 m from the inflector i.e. at the present location of the chopper. Moreover, this position was found to be relatively insensitive to $\Delta\phi_f$. For $\Delta\phi_f$ from 20° to 40° , the optimum location changed by less than 20 cm.

The upper dashed line in Fig. 2 is the calculated bunching efficiency vs. current using the 3rd buncher and $a=7.5$ mm. The lower dashed line is the calculated bunching efficiency for $a=7.5$ mm and using only the present bunching system. At 1 mA for example, the 3rd buncher will improve the efficiency from 42% to 56%. Also plotted in Fig. 2 are two contours of constant extracted current. (These assume an 85% survival rate from injection to extraction). The advantage of the 3rd buncher is apparent. For 300 μA extracted, we require 760 μA without the 3rd buncher and only 630 μA with it. Similarly, for 400 μA , we would require more than 1200 μA in the injection line with the present bunching system while with the third buncher added, only 840 μA will be required. With 840 μA average beam current, the bunched beam will have a peak current of ~ 10 mA. Studies with PARMILA are underway to determine whether the present injection line can handle such high peak currents.

A bonus of this scheme is that the added buncher can be used as a debuncher to decrease the energy

spread of low current beams. In particular, SPUNCH calculations predict that the third buncher, when run with its phase shifted by 180° from the high current mode, increases the bunching efficiency to 79%, which is useful for polarized operation.

Conclusions

The addition of a fundamental harmonic buncher situated 2.4 m from injection can be expected to improve the bunching efficiency at both low and high currents. At low (polarized) current the predicted increase in extracted beam for a given source current is 20%. At high currents (> 250 μA extracted) the improvement is as large as 30%. Between currents of 100 and 500 μA , the proposed new buncher can improve the flexibility of the injection system by making the bunching efficiency less dependent upon beam size.

Acknowledgements

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