

THE UPGRADING OF THE TRIUMF FACILITY TO 500 μ A OPERATION

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Abstract

Over the last few years, operational beam intensity levels at TRIUMF have been around 150 μ A at 500 MeV. As a result of recent improvements to the ion source and the rf resonator system, an extracted beam current of 420 μ A in a 50% duty cycle was demonstrated, and one week of 200 μ A beam production successfully completed. This gave confidence that the original design goal of 100 μ A cw operation can be raised to 500 μ A. Modifications will be necessary in several regions of the machine to prevent beam-induced damage or excessive activation of components. In particular, the axial injection line, the central region of the cyclotron, the external beam line and the primary production targets will be upgraded and new diagnostics and beam spill protection systems added. The dee voltage will be increased to above 100 kV and two auxiliary accelerating cavities will be used to provide an overall 1 MeV energy gain per turn over the 400–500 MeV region, resulting in a threefold reduction (to below 3%) of electromagnetic stripping losses. This paper will focus on present and future limitations to increasing the current and describe major design concepts of the program.

1. Introduction

The TRIUMF cyclotron was originally designed for maximum current of 100 μ A up to 500 MeV. This was achieved in 1977.¹ The addition of a second harmonic buncher downstream of the original fundamental frequency buncher in the 300 keV injection line has resulted, since 1980, in operation at routine levels of 150 μ A.² Recently, the intensity was raised to 200 μ A for a one-week production test. A peak current of 420 μ A was demonstrated in a pulsed mode. The progress in both maximum cw extracted current and pulsed peak current is illustrated in the histogram of Fig. 1, together with some of the major factors responsible for the steps. The recent achievements were due mainly to: 1) the installation of a new high brightness cusp-type H^- volume source and 2) the higher accelerating voltages at the dee gap, once the rf leakage in the tank was brought under better control.

These developments suggest that proton beam current for routine production of pion and muon beams can actually be increased by a factor of three above present levels. A number of improvements will be required, mainly in beam loss reduction and control, and improved remote handling of components in regions of high activation. If, in addition, the acceptance of the secondary meson channels is increased

by moving the channel front-ends closer to the production targets and through other optical arrangements, pion and muon fluxes larger by a factor five to ten can be envisaged, and the study of rare decays or other low cross-section processes facilitated.

The increase of the maximum production current to 500 μ A and the reconstruction of the target areas have therefore been included in the Five Year Plan recently proposed for the laboratory. The scope of the project would, however, be reduced, should separate funding for the proposed KAON factory materialize. In this case, higher pion and muon fluxes could be achieved with a 100 μ A proton beam at the 3 GeV energy of the booster for instance. Recent progress of the KAON factory project is described elsewhere at this conference.³

Future milestones of the high-intensity program are as follows. Firstly, 200 μ A will be made available routinely for beam production. In order to increase the total yearly integrated current beyond the present 330 mA and at the same time reduce the activation of the machine, an auxiliary accelerating cavity will be installed in the vacuum tank to double the energy gain per turn at the energy where electromagnetic stripping losses occur. Tests at currents up to 300 μ A cw will also proceed in parallel, but the capability of the extraction beam line of controlling and withstanding higher beam spills downstream of the production targets will have to be enhanced through added beam diagnostics and improved remotely handleable metal seal vacuum connections. Prototype water-cooled rotating targets are presently being developed to be used during these tests.

Whereas pulsed beam tests for peak currents of 500 μ A or more will be scheduled soon, cw tests above 300 μ A, and beam production above 200 μ A levels will have to await the installation of the new 1AT2 target assembly and the reconstruction of the secondary beam line front-ends. At the same time the installation of a second auxiliary accelerating cavity and a further increase in dee voltage should reduce stripping losses to compensate for extensive 500 μ A operation with a yearly integrated charge yield of ~ 1 A h.

2. H^- Ion Source and Injection Line

The TRIUMF cusp ion source has been previously described.⁴ It is a volume type dc H^- source which uses 0.32 T samarium-cobalt magnets arranged in ten paraxial rows on the outside of an all-copper cylindrical plasma chamber. Four additional rows of magnets across the back face of the chamber complete the plasma confinement. The front face, electrically isolated, has a 6.5 mm diameter extraction hole. An axially symmetric four-electrode structure is used to extract a bright 25 keV dc H^- beam. Optimum brightness (normalized) for a 81% beam fraction (90% emittance contour) was 14 mA/(mm-mrad)² at a current density of 5.6 mA/cm², corresponding to a normalized emittance of 0.15π mm-mrad and extracted current of 1.9 mA. Higher currents were measured with slightly increased emittances. The extraction hole and extraction optics have to be reoptimized for higher currents. Indications are that currents up to 10 mA can be provided with emittance within the 0.32π mm-mrad design acceptance of the 40 m long, 300 keV electrostatic injection line.⁵ However, diagnostics and beam loss protection have to be upgraded in the line before average currents can exceed 1 mA. High-intensity injection has therefore so far been based on the above high brightness beam, with peak current enhancement through bunching. Presently, up to the 420 μ A current extracted, we achieve bunching efficiency in excess of 50% using a fundamental and a second harmonic double drift bunching system. In comparison to the PIG source,⁶ the cusp source has the additional advantage of a stable beam output. Fast beam current transformers on the output beam show oscillations below 1% for frequencies up to 1 MHz. This facilitates the optimization of space charge dependent injection line tunes, and reduces overall beam spills.

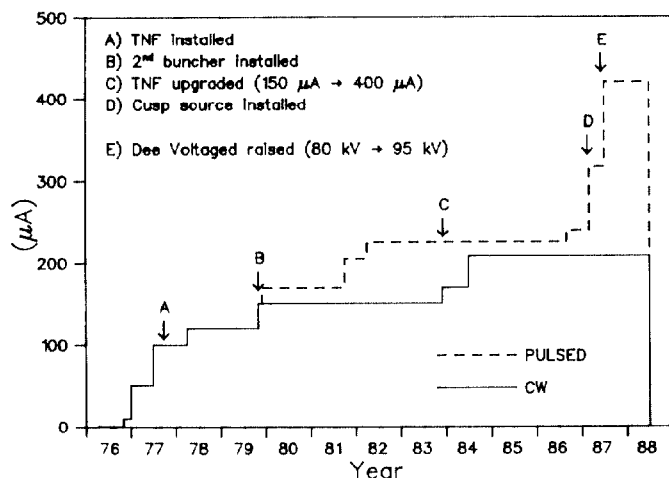


Fig. 1. Maximum extracted current and peak current vs. time.

3. Intensity Acceptance in the Central Region

Unlike proton cyclotrons which require separated turns for clean extraction, the TRIUMF (H^-) cyclotron intensity is not limited by turn broadening due to space charge forces acting over many turns. However, a fundamental intensity limitation arises from space charge defocusing in the first few turns where ν_z is small. Because of the electric focusing, ν_z depends upon rf phase⁷; particles which arrive at the dee gap too early are vertically defocused. As a result, space charge effectively narrows the cyclotron phase acceptance. Experimentally, we have found this loss to be $\sim 2^\circ$ per mA of (peak) current. (A tune shift calculation yields values of 1° to 3° /mA depending upon choice of the not-well-known effective vertical aperture for the beam.) Using this empirical relationship it can be shown that if the phase acceptance at zero intensity is $\Delta\phi(0)$ then there is an upper limit on the time-average accelerated beam intensity given by

$$I_{\max} = \left(\frac{\Delta\phi(0)}{56^\circ} \right)^2 \text{ mA} ,$$

which occurs when one-half of the zero intensity phase acceptance is lost. (An outer region loss of 10% due to gas and electromagnetic stripping is also assumed.) The maximum measured phase acceptance of 50° , corresponding to the maximum achieved rf voltage, yields $I_{\max} = 800 \mu\text{A}$ which requires a peak injected current of 13 mA. A peak current of 10 mA, compatible with the optics of the present injection line, results in $750 \mu\text{A}$ extracted current and 30° phase acceptance. 10 mA inside 30° can be achieved with a 10 mA source (unbunched case) or with a 1.5 mA source and bunching to 30° . Unbunched injection would require the centre resonator structure to be re-engineered to handle the beam power. On the other hand, bunched injection would require the reinstallation of a third buncher upstream of the inflector.² Inflector cooling to remove heat generated by beam spills arising from the additional energy spread produced by the third buncher would also be required. More simply, the goal of a $500 \mu\text{A}$ extracted beam would require only 5 mA peak current in a phase interval of 40° . Unbunched operation, implying a 5 mA source, is preferable because with negligible energy spread at injection the beam quality in the cyclotron would be better. With 50% bunching efficiency, a current of only 1.1 mA is required, available from the present source. Nevertheless, the injection line upgrade, including reconstruction of the relatively inaccessible vertical section, has still to take place for improved serviceability.

4. Upgrade of the Resonator System

An extensive study of the main resonating cavity has led to an understanding of the leakage problem and, hence, to its control. "Leakage" as used here refers to the excitation of higher-order modes – particularly TE_{310} and TE_{410} – in the volume formed by the beam gap and vacuum vessel. Vertical voltage differences across the ~ 10 cm beam gap can be in the range (200–800 V) supporting multipactoring, which causes heating of the segment strongbacks. Distortion of the segments and operational instability can result. The situation improved substantially when eight of the eighty segments (one segment in each of eight quadrants) were replaced by more rigid units. They were cooled on the beam side as well as on the rf side and aligned within ± 1 mm.⁸ In addition motor drives were installed in 64 locations to allow remote adjustment of segment tips. Leakage fields were reduced by an order of magnitude in several regions.⁹ Three more segments will be replaced in each quadrant for further leakage reduction and improved mechanical stability. Multipactoring reduction has already allowed increasing the accelerating voltage beyond the normal operational level of 80 kV.

In the experiments with beam currents up to $420 \mu\text{A}$ at 50% duty cycle, the dee was conditioned at 97 kV, and was set to 95 kV for operation. No system problems were encountered during this test. Beam loading had no substantial effect on the operation of the rf system. The instantaneous beam power was 210 kW with the resonator power approximately 1250 kW.

To improve transmission for the higher beam current, it would be desirable to operate the rf system nearer to the dee voltage corresponding to maximum tested power of the final amplifiers (1800 kW). This value, with 250 kW of beam loading, will limit the dee voltage to between 110 and 120 kV. Some of the components in the output combiners and in the output transmission line will then be operating near their maximum rated values. To improve system reliability, components such as vacuum capacitors or water-cooling systems or combiner waster loads will be improved or replaced. Further diagnostics for fast detection of breakdown and monitoring of operating values will be added.

5. Beam Loss Control in the Outer Region

Beam losses in the cyclotron have been previously described.¹⁰ Typically for 80 kV dee voltage, 8% of the beam is lost due to electromagnetic stripping, 4% due to gas stripping (5×10^{-8} Torr) and 3% is scraped by machine protection foils defining the vertical aperture for the beam. Losses produce activation, mainly at the periphery of the vacuum tank, roughly proportional to the power of the lost beam. Considering the different energy distribution of the losses, relative contributions to the activation can be estimated at $\sim 8\%$, $\sim 1.5\%$ and $\sim 2\%$, respectively. With lead shields covering the cyclotron tank walls during shutdowns, radiation fields are presently around 70 mR/h at the centre of the machine and about three to five times larger at outer radii. At these levels, although most of the tank maintenance can be performed remotely, quick hands-on component maintenance is still possible. When increasing the beam current from the present $150 \mu\text{A}$ to $500 \mu\text{A}$ a factor of three reduction in lost beam power should therefore be the minimum goal.

Electromagnetic stripping losses are by far the most serious and can be reduced either by extracting at lower energy (450 MeV) where the meson production cross section is lower or preferably by reducing the number of turns in the high energy region. This can be achieved in part by increasing the dee voltage from the present 80 kV to ≥ 100 kV, in part by adding two 92 MHz, 150 kV auxiliary accelerating cavities between 350 and 500 MeV to increase the energy gain per turn to ≈ 1 MeV.¹¹ Figure 2 compares the loss for three different dee voltages and illustrates the effect of two added cavities. An overall reduction of two-thirds is achieved. The cavities further provide a three-fold decrease in phase spread of the circulating beam. Operating at the fourth harmonic of the main rf, they somewhat limit the phase acceptance, but studies indicate that because of phase compression a $\pm 30^\circ$ phase spread should be accepted. A prototype cavity has already been built and tested at 50 kV. The cavity, coupling loop and tuning system performed as expected. The design of the final cavity is nearly complete and final fabrication has already begun. The 8 kW rf power

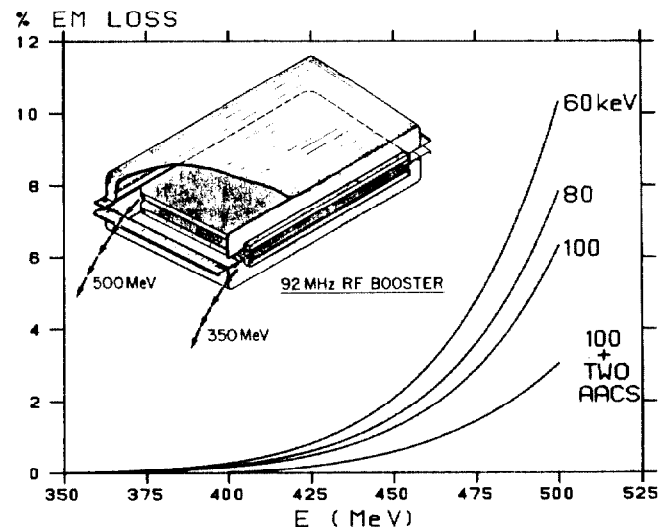


Fig. 2. Electromagnetic stripping loss vs. energy for different energy gains per turn. A schematic of an auxiliary cavity is included.

amplifier used for the tests will be upgraded, and it will serve as a driver for the final 150 kW stage presently under construction. The cavity will be installed within a year.¹²

Gas stripping losses scale with the beam current for a given pressure and number of turns. An increase in dee voltage to 100 kV and the reduced number of turns at the outside from the added accelerating cavities will provide an improvement of as much as 30%. Maintaining the tank pressure at the lowest possible level will be most important once electromagnetic losses are reduced.

As with gas losses, beam dynamic losses occur over a wide range of energies and are due to radial-to-vertical resonances, deviations of the vertical equilibrium orbits from the median plane or poor isochronism resulting in amplification of resonance effects. Improved matching of the injection line beam to the central region, unbunched injection, increased trim coil tuning capacity, and automated beam height and isochronism tuning procedures should reduce these losses by a factor of two to three.

6. Extraction

Stripping foil lifetime is affected by thermal evaporation of carbon and by changes in structure and mechanical properties caused by beam-induced lattice dislocations. The power input arises chiefly from the spiralling stripped electrons making several traversals of the 5 mg/cm foil. It is felt that evaporation will not be a concern at 500 μ A. Pyrolytic graphite foils were proposed initially because of their high thermal conductivity in the transverse direction; however, radiation damage effects cause the foil to curl after about 10^5 μ Ah, equivalent to ~ 4 d.p.a. This latter effect is, at present, determining lifetime. The study of thinner foils with a more graphitic structure is planned.

7. Beam Line, Diagnostics and Targets

In order to operate at 500 μ A several improvements to the proton beam line and beam line diagnostics are required. The magnets and vacuum components in the first leg of the beam line upstream of the thin 1AT1 target will be made radiation hard. The diagnostic system will be upgraded to allow on-line measurement of beam position and profiles for closed loop tuning. The present system consists of insertable multiwire profile monitors and secondary emission beam halo plates for high current trip protection. Scanning wire profile monitors will allow on-line tuning. Several mechanical designs are being evaluated. A prototype has been operated between 20 nA and 135 μ A. A 45 cm stripline sensor prototype is being tested and a 15 cm inductive position sensor has been installed 2 m upstream of the major production target. A copy of the Fermilab AM/PM processing system, tuned to 46 MHz, has been selected because of its wide dynamic range.

In anticipation of higher currents additional cooling has been added to the vacuum seals downstream of 1AT1 and the vacuum isolation window has been mounted on the gate of an automatic valve. A graphite collimator has been installed upstream of the thick 1AT2 target to protect the vessel. The indium vacuum seals in the vicinity of the targets are at present one of the major causes of downtime. Copper conflat flanges are under consideration. A number of other improvements are required. These include better shielding and air activation control, improved remote handling and component servicing within 3 m of the production targets and beam dump.

New target shields for both the thin 1AT1 and thick 1AT2 target stations are required with improved cooling. The present targets and beam blocker/collimator assemblies are housed in vertical stainless steel tubes welded to horizontal tube sections forming the primary and secondary beam lines. The array of pipes is contained in a monolithic target shield of lead and steel. The secondary beam line quadrupoles are outside of this shield. This arrangement will be

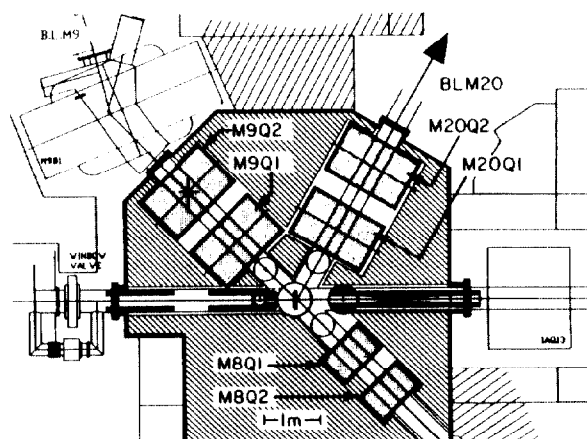


Fig. 3. Possible configuration for target station 1AT2.

redesigned to allow the front quadrupoles in the secondary channels to be moved inside the shield and therefore closer to the production target (see Fig. 3), resulting in an increase in the solid acceptance of the channels of 2–3. Several design options are being evaluated which differ in the arrangement of magnetic components and vacuum tube couplings. The options range from magnetic components in vacuum to completely welded vacuum tubes with magnets designed to be split for installation around the vacuum tubes. Development work on such magnets and improved radiation-hard service connections and vacuum joints is in progress.

The lead target which acts as a beam stop, and neutron generator for the thermal neutron facility (TNF), is designed to dissipate up to 125 kW of beam power. With the meson production target in place only 62% of the beam extracted from the cyclotron reaches the target with a degraded energy of ≈ 450 MeV. Of the incident beam power 25% is dissipated outside of the vessel, mainly as neutrons. At 500 μ A extracted, only 105 kW is absorbed in the target, well within the capability of the system.

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