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ACHIEVEMENT AND CONTROL OF THE 100 μA BEAM AT TRIUMF

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Abstract

TRIUMF has recently achieved its design goal of a 100 μA, 500 MeV proton beam to the meson production target. Beam losses are particularly critical along the 40 m long 300 keV electrostatic injection line where beam heating can cause metallization of the insulators. Activation criteria limit the spills at higher energies although the possibility of thermal damage cannot be excluded. A number of special devices have been built to control beam losses and simplify high current operation. These include a variable duty-cycle electronic pulser in the ion source terminal, halo monitors and non-intercepting beam transformers in the injection line, secondary emission spill monitors in the cyclotron and target protect monitors, capacitive and radiation monitors along the external beam line. The procedure followed in setting up high current beams and the special systems designed to maintain acceptable losses, will be described.

Introduction

On July 25, 1977 we extracted for the first time at TRIUMF a proton beam of 100 μA at 500 MeV, achieving one of our major design goals. The beam was transported down beam line 1 (BL1 in Fig. 1) and dumped onto a temporary beam stop placed immediately downstream of the meson production target T2. About six months later a beam of 120 μA, extracted at the same energy, was transported 15 m further downstream to a special beam dump designed as a source of thermal and fast neutrons (thermal neutron facility or TNF, see Fig. 1). More details about this neutron source and about the layout of the laboratory are given elsewhere.[1]

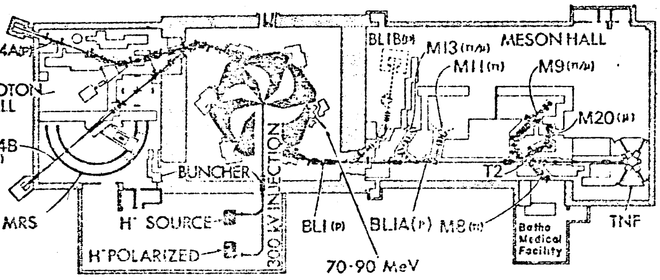

Fig. 1. General layout of the TRIUMF facility.

Currents of 80 to 100 μA down BL1 are presently scheduled for production at the rate of two or four shifts per month. In order to limit the activation in the machine, the average production current is kept around 10 μA. It is intended to raise the average current gradually in the future at a rate compatible with the improved reliability of components and with the upgraded remote-handling capability in the cyclotron tank. Currents up to 100 μA should be available routinely within two to three years.

The minimization and control of beam losses both during acceleration and along the external beam lines are, in a meson factory, of great importance in order to reduce shielding costs, activation of components, and thermal damage. At TRIUMF other aspects related to the production of a high intensity beam are peculiar to the particular nature of the machine, and include (i) the need for a bright and stable H⁻ source; (ii) the need for high transmission along the 40 m long 300 keV electrostatic injection line; (iii) the need for a very high vacuum in the cyclotron tank (between 10^{-8} and 10^{-7} Torr); (iv) the need for special shielding arrangements at the tank periphery to absorb and reduce the activation produced by gas and electromagnetic H⁻ stripping; and (v) the need for remote handling in the most active tank regions. Some of the aspects related to high current operation have previously been described.[2] Here we will describe the problems encountered and the instrumentation built in order to set up a stable and reproducible high current beam along the injection, acceleration and extraction systems.

Ion Source and Beam Formation

The ion source, the puller electrode and the main optical elements in the 12 keV region are shown schematically in Fig. 2.

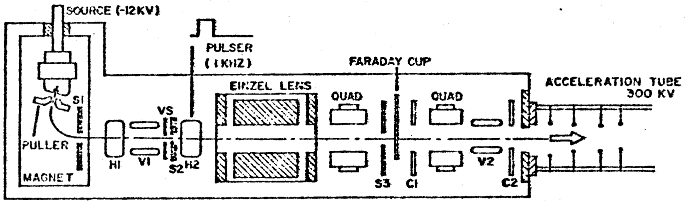

Fig. 2. Ion source and 12 keV region. S1 (5 × 12 mm²) S2 (11 × 2 mm²), S3 (5 × 5 mm²) are beam defining slits. VS is a variable slit. H1, V1, H2, V2 are horizontal and vertical steering plates. C1 and C2 are 300 V biased apertures.

The H⁻ source, of the Ehlers' type,[3] was supplied by the Cyclotron Corporation and originally measured to deliver 1 to 2 mA within the specified emittance of 0.32π mm-mrad. This source has since then been gradually modified to fit our requirements: (i) the aperture defining the diameter of the plasma column was reduced from 2.5 to 2mm; (ii) a new cooled tungsten anticathode was inserted above the arc chamber shortening the arc column from 2 to 1.5 cm; (iii) the gas conductance between arc chamber and the anticathode chamber was lowered; and (iv) the slit width was reduced from 1.2 to 1 mm. As a result the plasma oscillation related beam modulations (0.1-0.2 MHz), which were at times as high as 50% at high currents, are now easily kept below a few per cent by tuning the arc voltage and the H_2 gas flow.

The sparking between the -12 kV ion source and the surrounding electrodes was reduced from a few per minute at high currents to a few per hour by installing an 8 cm diam copper shroud around the anode block to disperse the electrons draining from the source-puller region. The filament lifetime is now above 150 h in normal operating conditions.

The reliable and stable behaviour of the source at higher intensities and the evidence that only 300 to 400 μA are required at the injection line entrance for extracting 100 μA at 500 MeV permitted us to reduce the size of the emittance-defining slits S1, S2, S3 in Fig. 2. The beam emittance is now 0.2π mm-mrad horizontally and 0.1π mm-mrad vertically, and currents up to 800 μA can be easily obtained with an arc current of 0.8 A. Optimum stability is achieved at a few hundred microamperes. As a result variable slits (VS in Fig. 2) are used to vary the beam current instead of the source arc current. The arc current is, rather, maintained constant to avoid changes in the beam due to space charge effects and thermal effects in the ion source puller region.

Essential for setting up the high current beam is a variable duty cycle pulser which applies a rectangular pulse of about 300 V to one of the deflecting plates H2. The other plate is maintained at ground so that the beam is only transmitted through S3 in voltage-off conditions. The repetition rate is 1 kHz, and the pulse duration can be varied continuously between zero and 990 μs with a 10 μs hole always present in the time structure. The pulser serves simultaneously two main purposes: it allows setting up a high intensity beam starting from a low average current but with the proper emittance and space charge conditions; at the same time it introduces a time variation in the CW beam produced by the source, so that non-intercepting monitors can be used along the injection line for transmission control.

Injection Line

The 12 keV H^- beam is accelerated through a 300 kV acceleration tube to the entrance of the electrostatic injection line, consisting of a horizontal and an axial section (Fig. 1). A large number of quadrupoles (~80 sets) and steering electrodes (~50 pairs) are used for the beam transport. The system and its behaviour at low currents has been described previously.[4] At high currents the experience with the 1:1 scale central region model[5] had shown that electrode sparking, melting of electrodes and metallization of insulators can be expected unless adequate protection against excessive beam power dissipation is provided.

The high current protection of the TRIUMF line is based on three main systems.

1. A system of non-cooled, current-reading halo electrodes are located in front of each quadrupole to protect against abnormal beam spills. The electrodes are at present grouped in eight sets corresponding to different beam line sections. Warning levels are set at 5 μA and source interruption levels at 8 μA.

2. A system of freon-cooled collimators (0.5 in. aperture) are installed to skim off the beam at eight strategic locations. The current signals from both the collimators and the halo sections are displayed on a 611 scope above the main console and provide a powerful diagnostic tool (Fig. 3).

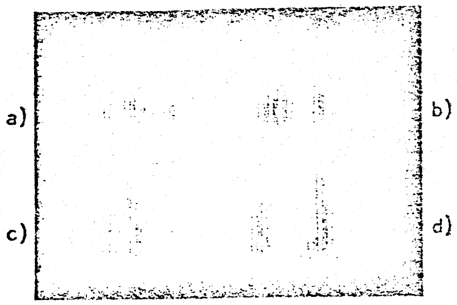

Fig. 3. Typical display on a 611 screen during high current operation: a) injection line halo electrodes; b) collimators; c) cyclotron spill monitors; d) beam line radiation monitors.

3. Two non-intercepting current monitors, one at the beginning and the other at the end of the injection line, measure the difference between the entrance and exit beam currents. This difference is not allowed to exceed 20-30 μA above the 9% loss due to vacuum. Beam stop and collimator currents are taken into account in a hardwired interlock system controlling the transmission. The monitor is a toroidal current transformer with its core wound from a 2 mil thick, 1 in. wide tape of superpermalloy material. The signal is amplified through a current amplifier, then converted to analogue signal via a dc restore circuit and a 5 Hz low pass filter. A single turn loop around the core permits calibration. The response to both a current increase at a constant 99% duty cycle and a current increase at constant peak, by varying the duty cycle, is given in Fig. 4. The non-linearity of the constant peak curve is due to a 5% droop in the pulsed beam signal and is related to the 50 Hz frequency response of the circuit. Since we are interested in differences this is quite acceptable.

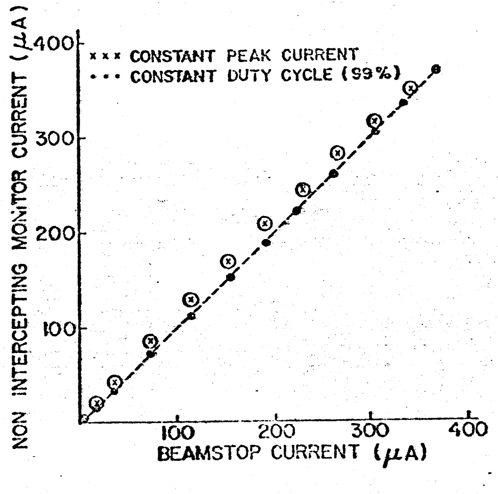

Fig. 4. The beam transformer reading as a function of beam current. Variable slits and the pulser duty cycle have been varied independently to obtain the two curves.

The Cyclotron

The transmission through the centre region is, in optimum conditions, above 40% and the phase acceptance has been measured to be as high as 45°.[6] This transmission is in close agreement with the value that can be deduced from the measured time distribution of the bunched beam shown in Fig. 5. The current accepted by a 10° wide phase interval, defined by the chopper system installed just above the inflector,[4] was recorded as a function of the buncher phase. The area within 45° around the peak, is in fact, about 45% of the total for both a 10 and a 350 μA beam. At higher intensities, with the bunching voltage kept constant at 3 kV, the peak is obviously wider due to longitudinal space charge, but it is still substantially within the cyclotron phase acceptance.

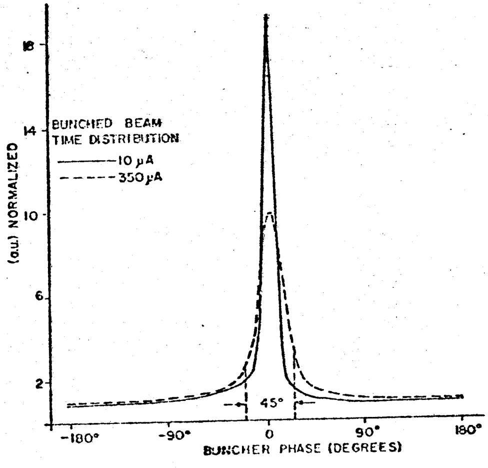

Fig. 5. The time distribution of the beam at injection for two different intensities.

Transmission curves through the cyclotron for a low intensity beam have been published elsewhere.[6] At 100 μA the transmission is not substantially different and the total loss between centre region and 500 MeV is within 15-20% of the accelerated beam, including magnetic stripping (8-10%), gas stripping (4%), and vertical beam losses (2-5%).[7] Since the fractional beam acceptance of the centre region is above 40%, the overall transmission between the exit of the 300 keV injection line and 500 MeV is well above 30%. Taking into account the 85% transmission through the injection line, the overall transmission between the injection line entrance and 500 MeV is above 25%.

These performances establish the lower limits for good transmission. Transmission control through the cyclotron has been set up in software using the signals from the non-intercepting monitors in the injection line and the stripping foil current. The main purpose of this software interlock is to prevent abnormal beam losses in the machine from producing thermal damage to resonators or other components. The reproducibility of the stripping foil current reading is within a few microamperes at 100 μA currents. An external Faraday cup has been used for absolute calibration.

The activation by vertical beam losses in the region above 70 MeV is controlled through a system of H^- beam scraping foils[7] attached to the resonators ±1 in. from the median plane. The layout and spill trajectories are given in Fig. 6. Secondary emission monitors collect the beam spills and give signals proportional to the lost current. The limit placed on the total current which can be spilled is 5% of the circulating beam. A software interlock ensures that this limit is not exceeded.

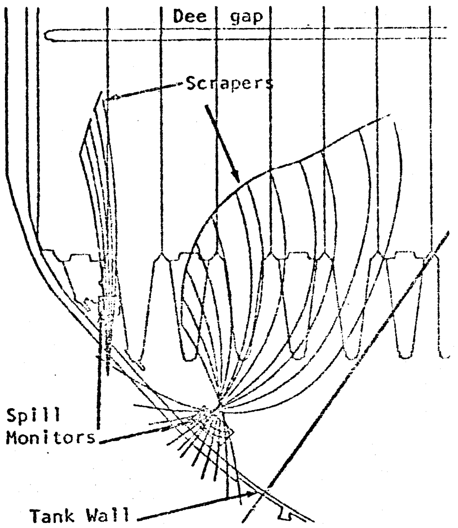

Fig. 6. The system for the control of vertical beam losses in the cyclotron. A symmetric system is installed in the opposite quadrant.

The residual activity measured recently in the tank with and without a system of 2 in. thick lead shields installed at the periphery,[2] is shown in Fig. 7. With lead in, the activity averages about 5 mrem/hour at the centre and 20 mrem/hour at the periphery. A hot spot of 125 mrem (lead in) and 250 mrem (lead out) corresponds to a point where beam losses are dumped by the scrapers. It is planned to reduce these losses by improving the phase dependent centering in the central region.[8]

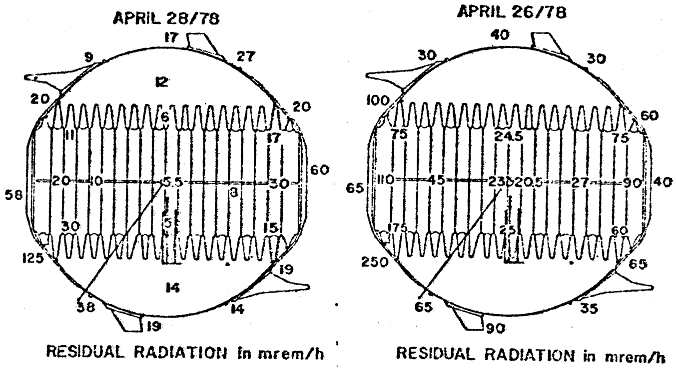

Fig. 7. Cyclotron tank activation with and without lead shields.

Extraction

The extraction foil[2] is pyrolitic graphite, 1 mil thick. The mechanical strength is adequate and the multiple scattering contribution to the beam emittance is not larger than that intrinsic in the beam.[2] The extraction efficiency is essentially 100%. The fraction of H° atoms emerging from the foil has been found to be about 0.05% and the fraction of H^- is negligible. Most of the heating (50 W at 100 μA) is due to the stripped electrons which spiral through the foil many times and are scattered over an area several times larger than the beam spot. At the present operating currents no substantial lifetime limitation has been observed. Foils were kept in the tank for several months without obvious sign of damage.

External Beamline

The section of beamline 1 upstream of T2 has low residual activity, because the halo of the extracted beam is quite low and there are no thin vacuum diaphragms or profile monitors permanently installed. Residual activity levels measured at 50 cm from the line vary from 55 mrem/hour at the combination magnet, to 10 mrem/hour 2 m downstream and stay well below 10 mrem/hour along the 40 m long line, rising again at the T2 region. This situation will change as soon as the thin target for meson production is inserted in beam line 1 for the M13 channel.[1] Downstream of T2 the beam spill due to the 10 cm Be target is about 30% and is mainly distributed on collimators and shielded beam scrapers; all elements are radiation hard and iron shields are situated very close to the line .

Thermal or radiation damage is prevented by a series of 20 scintillation counters. The signals from these counters can be displayed on the 611 scope (see Fig. 3), and provide audible warnings whenever trip levels are approached. Deviations from an initial tuned condition are anunciated.

Optics calculations show that a drift of a beam line element from its optimum value is most clearly revealed as a shift in position at the TNF. Consequently a halo monitor consisting of four quadrant-jaws set around a central aperture has been placed here. The current signals from the secondary emission electrons can be displayed on the 611 screen in the form of a cross. A mis-steered or defocussed beam appears as an elongation of one or more arms of the cross, and an interlock can be set through software to shut off the beam.

The signal produced by the ns microstructure of a non-intercepting capacitive probe along the line is amplified, integrated, and converted into an analogue signal. The system is still under development but currents as low as 1 μA can be detected and the reproducibility for currents up to 100 μA is within 1 to 2 μA. Work is in progress towards making the signal linear with current.

Operational Experience and Procedure

During the last year several 100 μA tests were scheduled and the tune was improved along the injection line and the cyclotron. A major step forward was the reduction of the 12 keV beam emittance at the source. Several aspects in the operational procedure improved. Previously the injection line tunes for high and low extracted currents were substantially different. With the lower emittance a solution has been found where only a few elements in the 12 keV region are adjusted to change from one current to another and the process takes 10 to 15 min using the variable slits at the source. Any retuning to optimize the transmission and spills is done at a reduced duty cycle. When a satisfactory tune has been established the beam duty cycle is increased.

The values of transmission for four different extracted currents set up in such a manner are shown in Table I. In all four examples the overall transmission is above 25% and the transmission through the cyclotron is above 30%.

Table I.

EXTRACTED CURRENT	10 μA	40 μA	70 μA	90 μA
300 keV exit to 500 MeV	31%	34%	35%	31%
300 keV entrance to 500 MeV	28%	29%	30%	25%

Another effect of the reduced emittance is that the 100 μA tune is less marginal in the injection line and can be reproduced much faster. With the RF and magnet stable it now requires only about two hours to set up a high extracted current. The ion source magnet current and the puller position are first adjusted to match the acceptance and the optics of the 12 keV region. Then with all optical elements set according to the master solution a pulsed 1% beam is tuned to the 500 MeV dump and when an acceptable transmission has been achieved, the duty cycle is raised to 10 or 20%. At the corresponding average extracted currents of 10 or 20 μA the spills are minimized. At these levels the readings can be extrapolated to 100 μA and can be compared to the nominal values. The duty cycle is finally increased to the 99% level. If the tune is successful the transmission remains fairly constant and spill and losses increase almost linearly with duty cycle as shown in Fig. 8. This was not always the case before our emittance improvement.

The system is still being developed for better reliability and higher currents. It is intended to install more collimators along the injection line to minimize the danger of thermal losses and to keep the beam centered within the size theoretically predicted. Source studies are now being done on a laboratory source to increase the intensity and the brightness of the beam. The aim is to be able to extract currents of up to 400 μA from the cyclotron.

The activation caused by electromagnetic stripping (occurring mainly between 400 and 500 MeV) can be reduced by extracting at a lower energy, say at 450 MeV, and by increasing the beam current to compensate for the lower pion production cross section. This technique is already being implemented whenever practical and a reduction of a factor of 50% to 100% in tank activation is expected at equivalent pion productions.

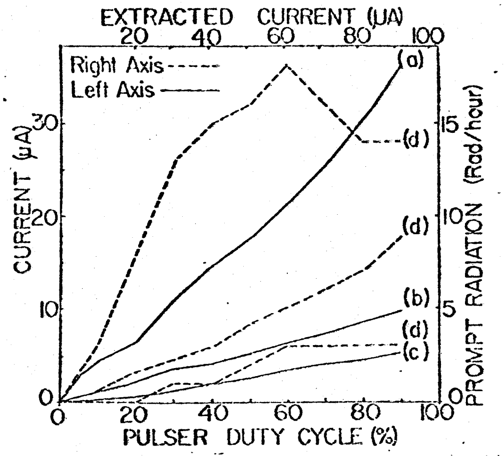

Fig. 8. Behaviour of beam losses as a function of the duty cycle: a) injection line collimators; b) injection line halo monitors; c) cyclotron spill monitors; d) beam line 1 radiation monitors.

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