# Operation of the TRIUMF (20-500 MeV) Proton Irradiation Facility

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*Abstract*— **The TRIUMF Proton Irradiation Facility can cover an energy range from below 20 MeV to 500 MeV using two extracted proton beam lines which operate into the same experimental area. The range of proton intensities is ideal for single event effect testing and high enough for some radiation damage testing of components. Neutrons, pions and higher intensity protons are also available at TRIUMF.**

*Keywords*— **proton, neutron, single event testing**

## I. Introduction

THE TRIUMF cyclotron in Vancouver, Canada is unique in North America in that monoenergetic proton beams from 65 to 500 MeV can be extracted over a wide range of intensities. In the TRIUMF cyclotron, negative hydrogen ions ($H^-$) are accelerated to energies up to 500 MeV and extraction of the beam is achieved by intercepting the beam with a carbon wire or foil which strips off the two electrons. The proton, having the opposite electrical charge, bends out of the cyclotron into one of four available beam lines. The extraction foil can be positioned to extract energies as low as 65 MeV and fractions of the circulating beam from the full intensity of 150 $\mu$A to less than 0.1 nA, although not all beam lines can handle the higher intensities. Energy changes can be made in less than 30 minutes and energies from 65 MeV to about 20 MeV can be obtained rapidly using a remotely-controlled degrader.

The energy range is well-matched to the range of energies of protons trapped in earth orbit and makes TRIUMF a versatile facility for space radiation effect studies. Although some related studies[1], [2] were carried out previously at TRIUMF a dedicated proton irradiation facility was not developed until 1996, financed in part with a grant from the Defense Research Establishment Ottawa (DREO) and the Canadian Space Agency. Since then many laboratory and commercial users from Canada and the US have made use of the facility[3], [4].

This paper describes the TRIUMF Proton Irradiation Facility (PIF) which consists of two separate proton beam lines which transport low intensity proton beams into the same test area. The lower energy beam line is routinely used in collaboration with the BC Cancer Agency for the treatment of ocular melanoma with 74 MeV protons and for radiobiological studies[5]. The equipment for this work can be easily reconfigured for proton irradiations of electronic components. The higher energy beam line transports 180 to 500 MeV protons into a second test setup nearby. Figure 1 shows a general layout of the area and Table 1 a list of relevant beam parameters. The intensities are matched to single event upset studies with fluences of $10^{10}$ protons/cm$^2$ achieved in a few minutes. The capabilities of TRIUMF in providing neutron and pion beams are also presented.

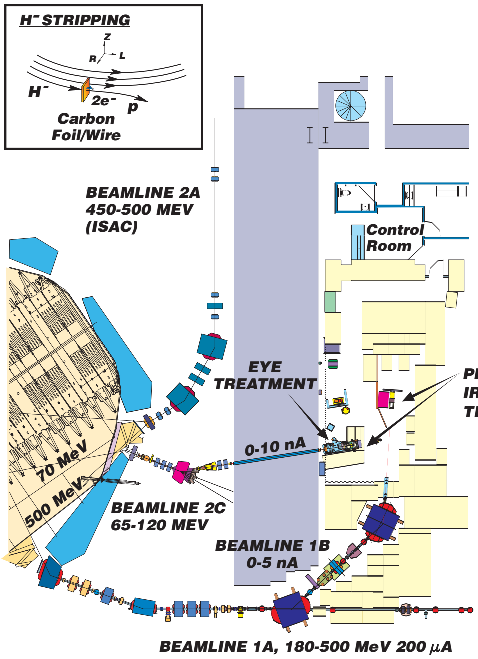

Fig. 1. Layout of the TRIUMF Proton Irradiation Facility showing the two beam lines entering the test area.

TABLE I

TRIUMF Proton Irradiation Facility Specifications.

| | BL1B | BL2C |
|---|---|---|
| Energy - MeV | 180-500<br>120-180<br>by degrader | 65–120<br>20-65<br>by degrader |
| Dose rate - Gy/minute | 0.5-2.0 | 10-20 |
| @ Field size cm×cm | 7.5×7.5 | 5×5 |
| Intensity - protons/cm$^2$/s | max $4\times10^7$<br>min $10^5$<br>$10^2$ possible | max $10\times10^7$<br>min $10^5$<br>$10^2$ possible |
| Field size cm×cm | max 7.5×7.5<br>min 2×2 | max 5×5<br>min 5 mm dia. |
| Dose uniformity | ±10% | ±5% |
| Initial beam intensity | 0.1-5 nA | 0.1-10 nA |

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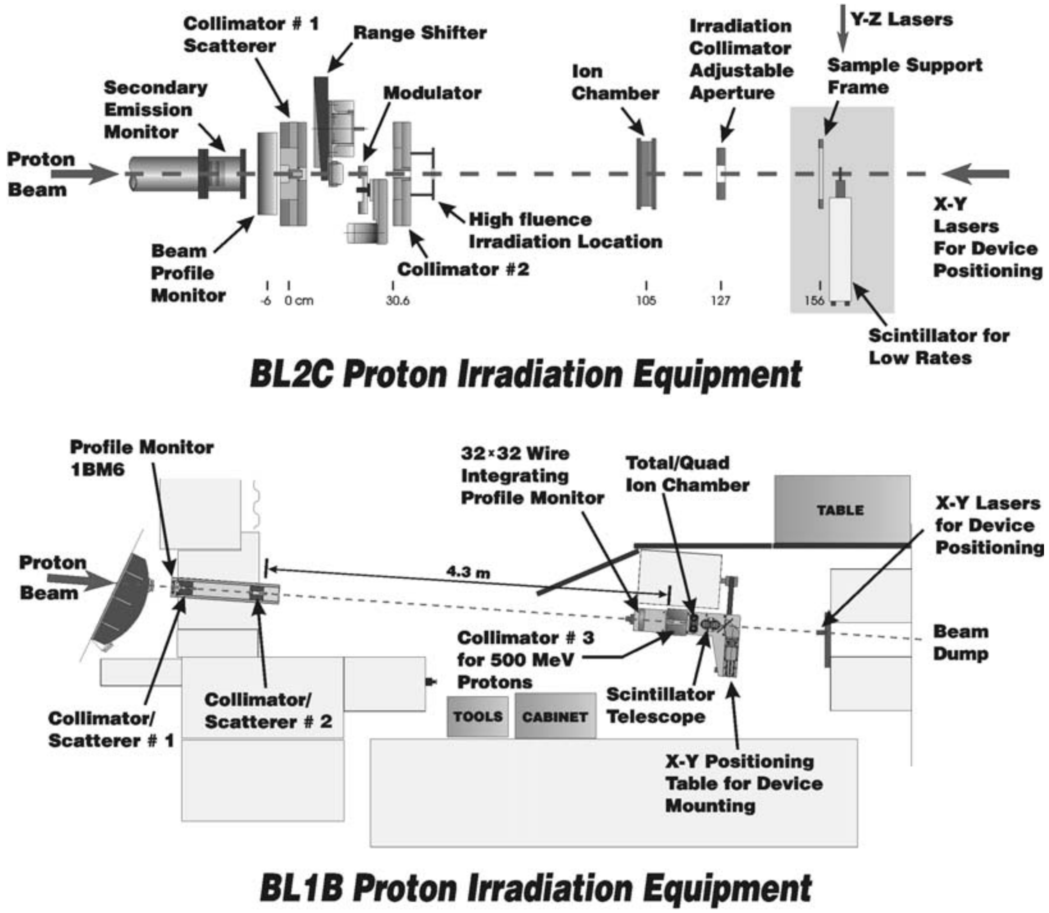

Fig. 2. Schematic layout of the irradiation equipment in beam lines BL2C (65-120 MeV) and BL1B (180-500 MeV).

## II. Beam Delivery and Dosimetry

Both beam lines use similar techniques for beam spreading, collimation and dosimetry. A schematic layout of the beam lines is shown in figure 2. The protons are initially scattered in a thin lead scatterer mounted in a first collimator and the tails of the scattered protons are removed with a second collimator. Beam line 2C has a remotely operated rotary wedge degrader or range shifter which can place from 0 to 40 mm of lucite in the path of the beam and vary the energy of the proton beam. Figure 3 shows the proton beam energy and width due to straggling for different settings of the range shifter and for two incident beam energies. Beam degraders for beam line 1B are manually inserted.

The beam intensity is monitored using a total/quadrant air ion chamber with 10 cm diameter active area and 7 mm gaps. The total plates of the ion chamber are read out using an Ortec 439 current integrator and the quadrant plates by a current to frequency amplifier. The quadrant readout of the ion chamber is used for beam centering. The ion chamber is calibrated using a laboratory-calibrated Exradin T1 0.05 cc chamber mounted at the test point. This is the same technique used for the cancer therapy treatments where 1% reproducibility has been achieved over several years for a standard setup at the treatment energy and for similar proton intensities. The ion chambers measure water equivalent dose so the corresponding proton fluence is calculated using energy loss tables from ICRU-49 and SRIM[6], or can easily be converted to dose in silicon.

A scintillator telescope of 1 cm$^2$ area, which counts individual protons, is also used for calibrating the ion chamber at low proton fluxes and the agreement between the fluences measured directly by the scintillator and by the ion chambers for beam line 2C is shown in figure 4. The ion chamber would be expected to give a higher fluence due to the presence of collimator-scattered protons which give a higher dose per proton and the scintillator counter loses protons due to inefficiency at the edges of the scintillator and rate effects. Some further work is needed to better understand the relative calibration at 116 MeV which shows a larger deviation than at the lower energy. Similar comparisons have been made in beam line 1B where the agreement is about 5% from 200 to 500 MeV.

The maximum size of the beam is 5 cm by 5 cm for the low energy beam line and 7.5 cm by 7.5 cm for the high energy beam line. Beam profiles are measured by scanning a diode or miniature ion chamber across the beam using a dedicated three axis scanner or by exposing Gafchromic Type MD-55 film which is then read out using a flatbed scanner and the optical density converted to dose.

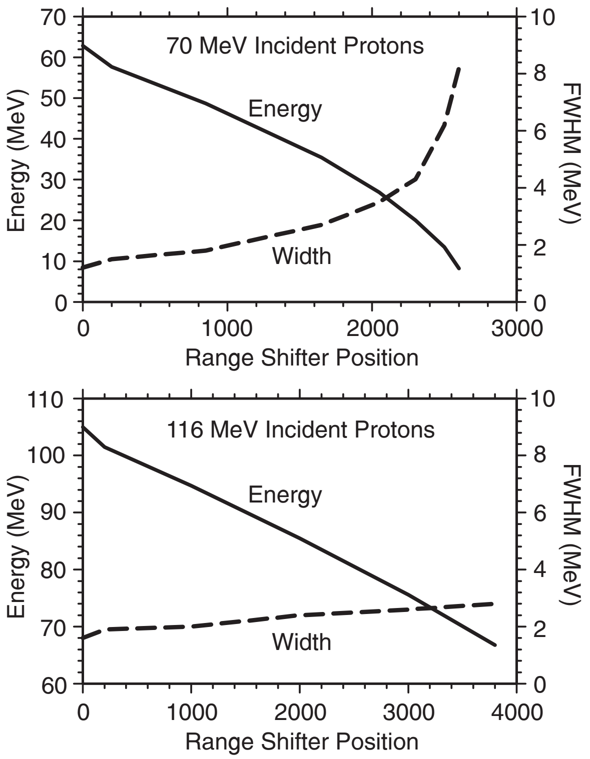

Fig. 3. Proton beam energy and calculated width due to straggling, as a function of range shifter position.

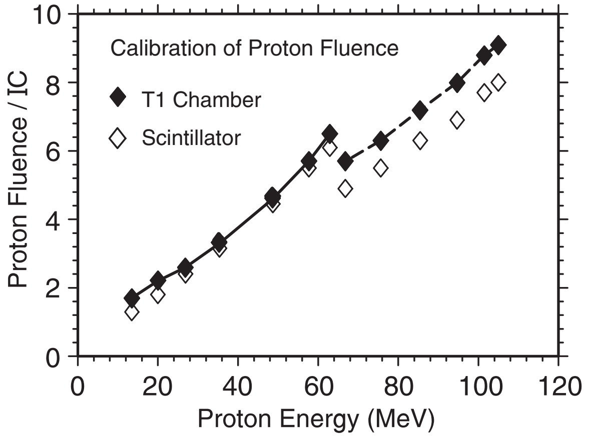

Fig. 4. Calibration of the proton fluence per IC monitor count using dosimetry and direct counting of protons.

Figure 5 shows a comparison of the two methods. As indicated from the scans, care must be taken in interpreting the Gafchromic film at the 5-10% level as artifacts can be introduced by the scanner. A variety of collimators are available for defining the beam shape for testing different sizes of electronic devices.

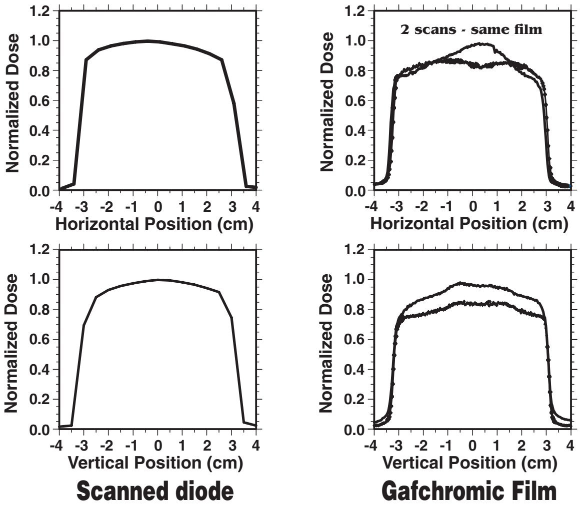

Fig. 5. Beam profiles measured at 116 MeV after a 5 cm x 5 cm collimator. On the left are scans using a small diode and on the right scans of an exposed Gafchromic film.

## III. Beam Control and Device Setup

The cyclotron operator sets the proton beam energy and intensity. The proton flux can be easily reduced by a factor of about 100 from the peak flux by adjusting the height of the stripping wire. An experimenter controlled beam blocker is provided for each beam line, which can be inserted in less than 1 second. The proton current is measured directly on the insulated blocker for the low energy line and a scintillator telescope, monitoring elastic scattering from a thin polyethylene foil, is used to provide intensity information for the high energy beam line. A dedicated control system is available for each beam line with either manual control of the blockers to start and stop irradiations or automatic termination of an irradiation after a preset number of monitor counts from the air ion chamber. Scalers record the relevant beam rates and fluences.

All irradiations are carried out in air. Devices to be tested are mounted on an X-Y position table or other support tables depending on the size of the device. Crossed laser lines from behind the device provide for easy alignment and this can be monitored remotely using a CCTV camera, enabling remote positioning. Cable lengths from the test device to the control area are about 25 m.

Experimenters are requested to minimize the number of accesses to the test area during beam operation by providing remote monitoring of their tests and remote positioning of test devices if practical. A motorized X-Y table with a 12" x 12" scan capability is available for experimenter use. Access to the test area has a turn around time of a few minutes and requires a dipole magnet to be turned off to satisfy the safety access requirements. The TRIUMF cyclotron operates as a multiuser facility so during PIF operation other beam lines are usually receiving beam. Therefore the cyclotron is not turned off for access to the test area, only the specific beam line.

## IV. Neutrons, Pions and High Intensity Protons

TRIUMF can also provide beams of neutrons, pions and higher intensity protons. At the PIF beam lines a roughly 1/E spectrum of neutrons up to the proton energy can be obtained by stopping the proton beam in a full thickness range absorber and setting up immediately downstream.

Fluences of neutrons above a few MeV of $10^5$/cm$^2$/nA protons can be achieved. The neutron energy spectrum has been calculated using FLUKA[7] for 500 MeV protons stopping in 180 g/cm$^2$ of steel and compared with a measurement using Bonner multispheres at a location 3.5 m downstream of the steel blocker. The Bonner sphere data was unfolded using the routine LOUHI to determine the neutron fluence and energy spectrum and both measured and calculated spectra are shown in figure 6.

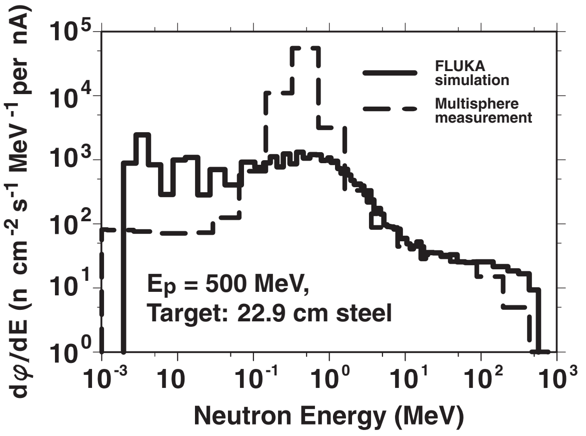

Fig. 6. The neutron energy spectrum measured 3.5 m downstream from the beam stop compared with a FLUKA simulation.

A more monoenergetic high energy neutron beam can be obtained from the TRIUMF CHARGEX facility which uses the $^7$Li$(p, n)$ reaction on a 220 mg/cm$^2$ thick lithium target at 0 degrees to produce a neutron beam (see figure 7). Here the peak fluence is about $10^5$ neutrons/cm$^2$/300 nA protons at 280 MeV. The beam size at this fluence is about 4 cm by 6 cm. The neutron energy spectrum has been determined by passing the neutrons through a liquid hydrogen target and measuring the momentum of the forward going protons from the $(n, p)$ reaction in a large magnetic spectrometer. The resulting spectrum near the peak neutron energy is shown in figure 8. There is a low energy tail of about 1% per MeV which could present some problem in interpreting the measurement of upset cross sections.

Pions with energies from 20 MeV to 300 MeV are available from two secondary channels M13 and M11. Fluxes of 1-10 x $10^7$ $\pi^+$/s are typical with the $\pi^-$ flux about a factor 5 lower. These beams have been used recently to measure single event upset cross sections[8].

Passive irradiations of components in higher fluences of protons ($10^{14}$ -$10^{15}$/cm$^2$) can be done using a rabbit system mounted on beam line 4B (180-500 MeV). The beam size is approximately 1 cm but could be increased by detuning quadrupoles. Radiation damage tests have also been carried out on beam line 4A at doses up to $10^{10}$ rads[9]. These facilities are not normally available for general use but if there was sufficient demand for such a service, they could be made available.

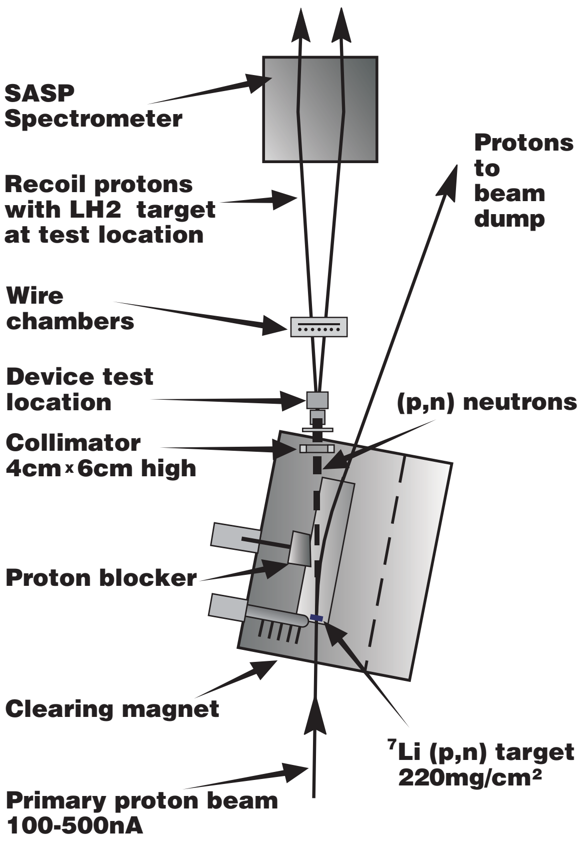

Fig. 7. Layout of the CHARGEX facility which produces monoenergetic neutron beams.

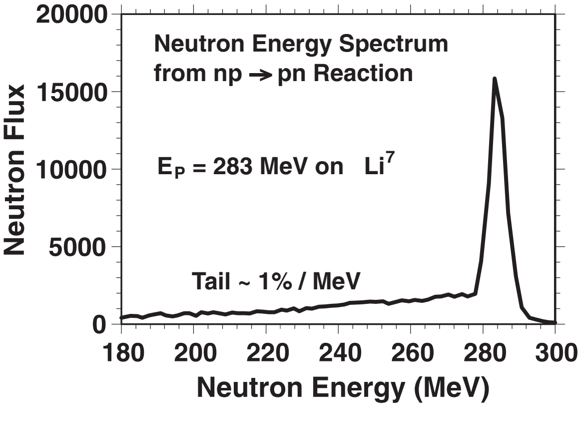

Fig. 8. The measured neutron energy spectrum for 283 MeV protons on a lithium target.

## V. BEAM SCHEDULING

Beam time at TRIUMF is scheduled approximately six months in advance. Typically one to two weeks are scheduled each year for PIF studies where both beam lines are available. Irradiations on the low energy beam line can be carried out monthly during the patient treatment weeks with little advance warning. There is no charge for researchers who submit proposals to the TRIUMF Experimental Evaluations Committee and have the proposal approved for beam time by this committee. For commercial and technological applications of beams, where publishable research is not the main goal, there is an hourly charge for beam usage.

## Acknowledgments

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