Development of a Large Area Neutron Beam for System Testing at TRIUMF

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Abstract—**A neutron flood beam has been developed for large scale electronic system testing. Low intensity protons are stopped in a lead absorber and the quasi-atmospheric spectrum of neutrons produced in the forward direction is utilized.**

I. Introduction

THE TRIUMF proton and neutron irradiation facilities PIF/NIF [1], [2] have been in operation since 1995 for protons and 2002 for high intensity neutrons. Monoenergetic proton beams from 65 to 500 MeV and degraded beams down to 15 MeV are routinely used for space-related testing. High intensity neutron beams are produced by 450 MeV protons stopping in a water-cooled aluminum beam dump on one of the high intensity proton lines. The neutron beam of dimensions 5 cm by 12 cm and fluxes of 3 x 10^6 n/cm2/s (>10 MeV) is accessed vertically by a long narrow slot in the surrounding steel shielding. The presence of the water moderator means that a significant flux of thermal neutrons (~25% of the high energy flux) is also present. While this arrangement is frequently used for small component and device testing the access is limited for larger systems and the flux is too great for high level system testing.

At the PIF facility a large area neutron beam has been developed by stopping energetic protons from either BL2C (116 MeV) or BL1B (500 MeV) in a lead absorber that completely stops the protons and then using the neutrons generated in the forward direction after the absorber. These neutrons have a spectrum similar to the atmospheric neutrons as the production mechanism is similar. The maximum flux of 10 MeV or greater neutrons is about a factor 10^7 higher than the sea level flux. The neutron beam is uniform to about 80% over transverse dimensions of 80 cm by 80 cm at a distance of 200 cm from the lead absorber. This beam is ideal for testing large electronic systems for effects from terrestrial or aircraft altitude neutrons. The maximum neutron rate is about a factor 100 less than at the TNF location. It can also be varied from more than 50,000 n/cm^2/s to less than 1000 n/cm^2/s by changing the proton current or the distance to the test point. Proton currents from 0.2 to 6 nA are used on BL2C and currents below 2 nA are used on BL1B when operating at 500 MeV to generate the neutron beams. Table 1 shows a summary of the beam rates, beam size and corresponding years of ground level and aircraft level operation. The variation of neutron rates has proven essential to satisfy testing requirements which range from assessing avionics components for long term regulatory compliance to complex ground level network systems with significant memory, processing and data transmission capabilities.

BL2C with a proton energy of 116 MeV stopping in a 20 mm lead absorber is more frequently scheduled for neutron use so there is more operating experience and calibrations for this beam line at different geometries. BL1B operating at 500 MeV with protons stopping in a 23 cm lead absorber has been used for neutron work but less frequently due to availability. Fig. 1 shows the usual arrangement for neutron testing on BL2C. A proton transmission ion chamber (monitor ion chamber) is used for determining the neutron fluence based on the proton current, calculation of the neutron energy spectrum and activation calibrations. A moderated BF3 counter [3] placed behind the test region is used for measuring the neutron attenuation.

TABLE I
NEUTRON RATES AND SIZE VS DISTANCE FOR BL2C

Neutron Energy/Size	Test Position – Distance to Lead Target			
	80 cm	140 cm	200 cm	250 cm
>1 MeV rate	38921	12709	6227	3986
>10 MeV rate	12379	4042	1981	1268
Beam width 80% cm	46	80	114	143
Years at Ground Level @ 14 n/cm^2/hour (>10 MeV) per nA-hour of Beam				
>10 MeV	363	119	58	37
Months at 40,000 feet @ 6000 n/cm^2/hour (>10 MeV) per nA-hour Beam				
>10 MeV	10.3	5.1	2.5	1.6

II. Neutron Energy Spectrum and Dosimetry

The neutron energy spectrum is calculated using the Monte Carlo code FLUKA-99 [4] which is a general purpose tool for calculations of particle transport and interactions with matter. The PIF geometries are relatively simple with a 1 cm^2 proton beam of 116 (500) MeV protons stopping in a lead block 20 (230) mm thick with the neutron spectrum and transverse distribution calculated at a distance of 140 (250) cm downstream in the proton direction. The numbers in parentheses refer to the energy and dimensions for the BL1B arrangement. Fig. 2 shows the calculated energy spectra for

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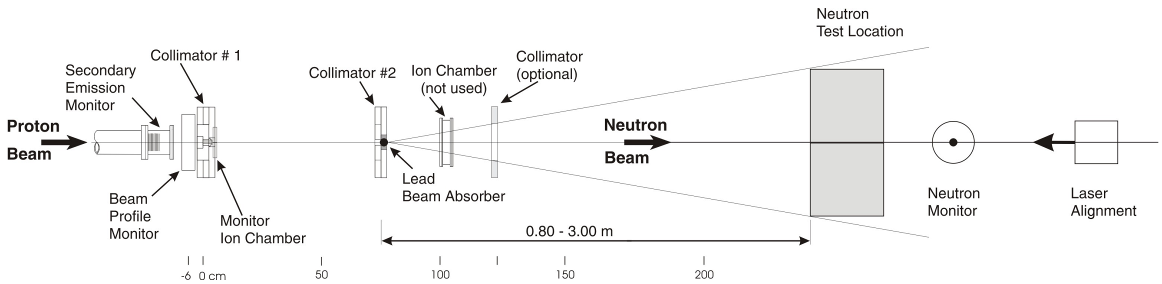

Fig. 1. Arrangement of BL2C for neutron testing.

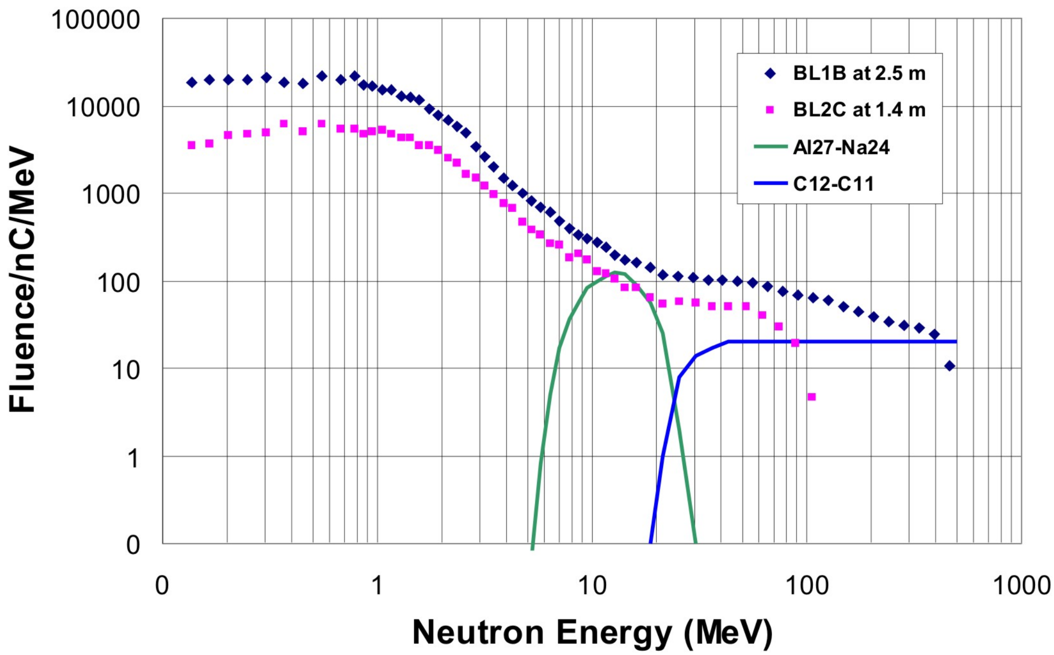

Fig. 2. Calculated energy spectra for neutrons produced at 116 MeV (BL2C) and 500 MeV (BL1B) together with the cross sections (mb) for the neutron activation measurements.

both energies together with the cross sections for the two activation measurements used to normalize the neutron flux.

Aluminum and carbon activations have been carried out for different geometries to determine the absolute neutron calibration vs. proton current and to confirm the longitudinal and transverse distributions of the neutron beam. Small plates of carbon or aluminum (typically 5 cm x 5 cm x 0.7 cm thick) are placed in the neutron beam and irradiated for periods of 30-60 mins. The gamma ray activity in these plates is then measured using a HPGe detector [5] calibrated for energy and efficiency. Carbon produces ^{11}C with a 20.4 min. half-life via the $^{12}C(n,2n)$ ^{11}C reaction and aluminum produces ^{24}Na with a 15 h half-life via the $^{27}Al(n,\alpha)$ ^{24}Na reaction. ^{11}C decays via positron emission to two 511 keV gammas and ^{24}Na decays via beta emission followed by 1.37 and 2.75 MeV gammas. Typical activities produced are in the range of 50-2000 Bq for ^{11}C and 10-50 Bq for ^{24}Na depending on location and duration of exposure.

Fig. 3 shows the calculated activity of a carbon foil irradiation based on the proton current and distance from the lead target compared with measurements. The activity would be expected to follow a $1/R^2$ dependence where R is the distance from the lead absorber. The agreement between the calculated neutron flux and that measured using carbon activation (sensitive to neutrons above 24 MeV) is better than 15%. These measurements were carried out over a three year period, indicating the reproducibility of the activation and proton current measurements.

The transverse distribution of neutrons has been calculated using FLUKA and measured by scanning the moderated BF3 counter across the beam. This neutron counter is sensitive to neutrons from 0.1 to 30 MeV. Fig. 4 shows that the measurements are in good agreement with the calculated distribution.

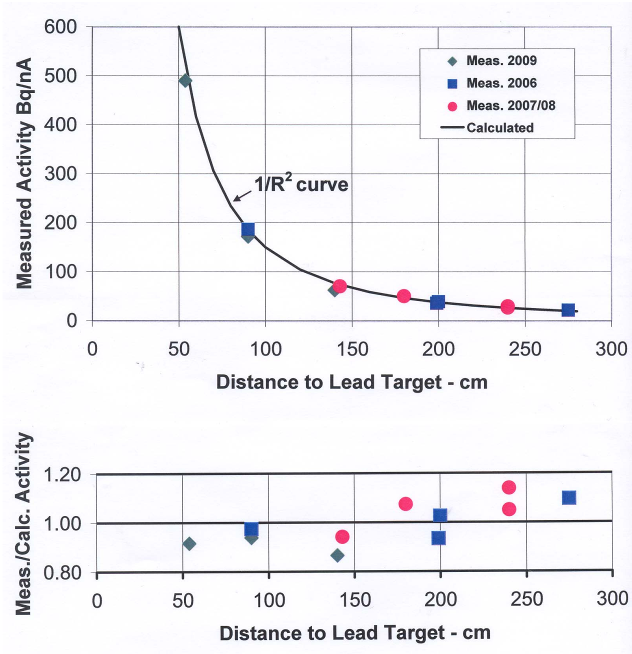

Fig. 3. Comparison of calculated and measured neutron activation levels of carbon vs. distance from the lead absorber.

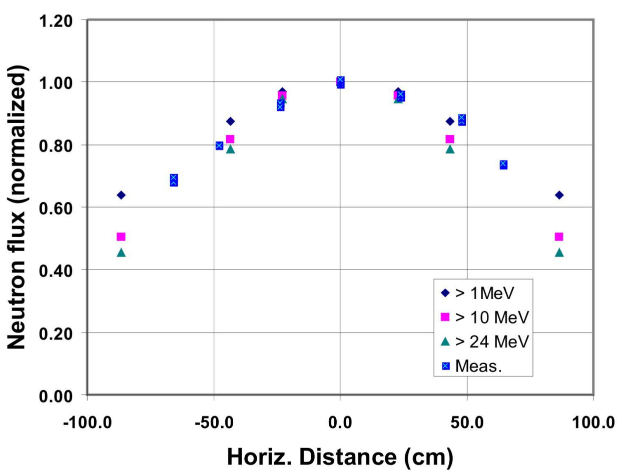

Fig. 4. Neutron beam profile at 1.4 m from lead absorber, measured and calculated for different energies.

III. Operating Experience with the "Flood" Beam

The flexibility and simplicity of the neutron flood beam has been well utilized since first development in 2005 and the facility is in high demand by users. Experience has shown that the ability to vary the neutron intensity over a large range is essential to accommodate the different testing requirements. The neutrons on BL2C are produced on a bare target with no significant shielding or collimation as shown in Fig. 5.

The 500 MeV arrangement is different in that the lead absorber is placed inside a 1.2 m thick concrete block with a 15 cm diameter hole. The most upstream position for the absorber provides a collimation of a factor 3 at a distance of 3.5 m longitudinally and 50 cm radially. However in general sensitive test equipment placed near to the device or system being tested requires local shielding. This is accomplished using stacked concrete blocks which can be configured for the specific setup. A thickness of 40 cm concrete decreases the high energy neutrons by a factor of 5-10 depending on location.

The directionality of the neutrons has proven useful in that it is possible to shield a sensitive component that is dominating soft errors within a larger system. This is accomplished by a 20 cm long steel shield of suitable cross section that is mounted directly in front of the offending component. This would be impossible to do if the neutrons came from all directions. Fig. 6 shows the shielding effect of concrete, steel and steel/polyethylene as a function of neutron energy.

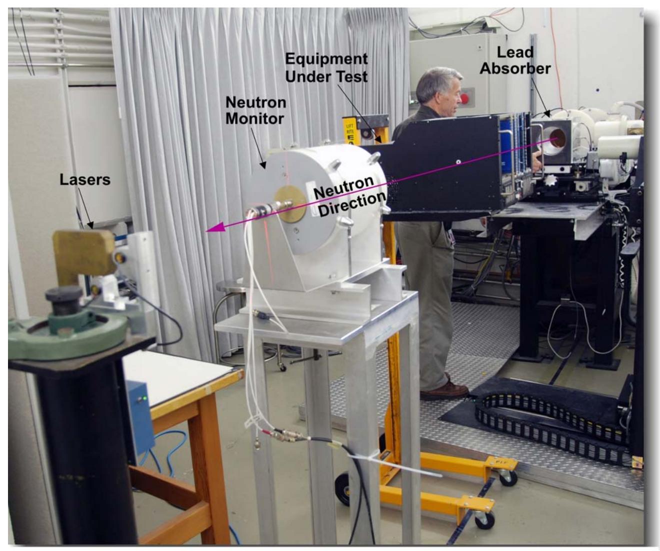

Fig. 5. Neutron test arrangement looking upstream into the beam.

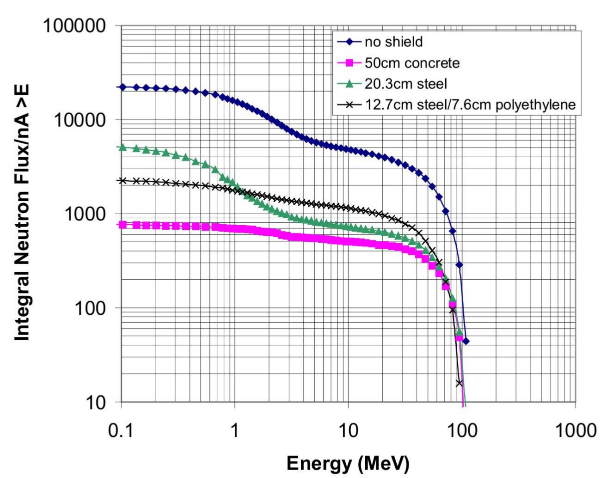

Fig. 6. Neutron shielding using concrete, steel and steel/polyethylene as a function of energy.

IV. Radiation and Activation of Components

Typical testing regimes call for longer periods of beam operation than for proton testing and, as the protons are stopping in the lead target rather than a low Z absorber, there is a higher level of residual radiation in the test area after running for many hours and after a 15 min. cool down. This radiation is dominated by the activation of the lead absorber so for the BL2C arrangement the absorber has been designed so that it can be moved quickly from its beam location to a nearby shielded container using a long-handled tool. This, together with the low proton current and efficient neutron production, has proven satisfactory to reduce any dose to the users to well below acceptable levels. As the lead beam stop for the 500 MeV beam is located inside a large concrete shielding block it does not present a radiation problem to the users.

After irradiation the components become mildly radioactive, although not as high as for direct proton irradiation which is normally carried out at higher fluxes. The irradiated components can be handled after a few minutes but cannot be shipped immediately off the site. The dominant activity after a short cool down to remove the short-lived positron emitters is ^{24}Na produced by neutrons on the aluminum housings of the system being tested or via reactions on silicon. As this activity has a 15 h half-life a wait of 2-3 days after irradiation is usually enough for meeting the radiation level requirements for shipping without restrictions.

V. Summary

TRIUMF now has a neutron testing capability that is well matched to the requirements for accelerated testing of large rack-size electronic systems in terms of beam size, energy and flux variability. Experience with a range of users for telecommunication, networking, avionics, power supplies and even balloon flight instrumentation has demonstrated the utility of this facility.

VI. Acknowledgment

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VII. References

[1] E. W. Blackmore, "Operation of the TRIUMF (20-500 MeV) Proton Irradiation Facility", 2000 IEEE Radiation Effects Data Workshop, no. 1, 2000.

[2] E. W. Blackmore, P. E. Dodd, and M. R. Shaneyfelt, "Improved Capabilities for Proton and Neutron Irradiations at TRIUMF", 2003 IEEE Radiation Effects Data Workshop, no. 149, 2003.

[3] REM/N counter available from CENTRONIC Ltd., Radiation Detectors, Croyden, CR9 OBG, UK.

[4] www.fluka.org

[5] GENIE™ 2000 system provided by CANBERRA Canada, Concord, ON, L4K 4N8.