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STATUS OF THE MACHINE PROTECTION SYSTEM FOR ARIEL E-LINAC

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Abstract

The Advanced Rare Isotope & Electron Linac (ARIEL) facility at TRIUMF consists of an electron linear accelerator (e-linac) capable of currents up to 10 mA at an energy of 30 MeV, giving a total available beam power of 300 kW. In addition, the e-linac can be run in pulsed operation down to beam pulses of 5 µs, and up to CW. A Machine Protection System (MPS) is required to protect the accelerator from hazardous beam spills and must turn off the electron gun within 10 µs of detection. The MPS consists of two types of beam loss monitors, a front-end beam loss monitor board developed at TRIUMF, and EPICS-based controls to establish operating modes. A trip time of 10 µs has been demonstrated, along with a 10^6 dynamic range and sensitivity down to 100 pA. This paper is focused on the current status of the beam loss monitor detection system.

INTRODUCTION

The Advanced Rare Isotope & Electron Linac (ARIEL) facility at TRIUMF currently has a 10 mA electron gun along with two cryomodules to accelerate the electron beam to 30 MeV [1]. The Machine Protection System (MPS) must therefore meet very strict requirements, made even more difficult by the fact the e-linac can operate in pulsed and in CW mode, and the requirement that the electronics not be located in the radiation environment. The MPS defines two types of beam spills: a catastrophic beam spill and a chronic beam spill. A catastrophic beam spill requires the MPS to trip the e-linac in <10 µs to avoid damage to beam components. A chronic beam spill, on the other hand, is a concern for activation of components for hands-on maintenance, but does not require an immediate trip since there is no concern of damage to components.

The requirement on the MPS for catastrophic spills is defined as the following: integrating 100 nC of the electron beam in 100 ms. This can occur by the following two scenarios:

$$10\,\text{mA} \times 10\,\mu\text{s} = 100\,\text{nC} \tag{1}$$

$$1\,\mu\text{A} \times 100\,\text{ms} = 100\,\text{nC} \tag{2}$$

Eq. 1 covers the extreme case of a beam spill of maximum current incident on a beamline, while Eq. 2 covers a beam spill of a smaller current or beam halo over a longer period of time. In reality, pulsed beam operation can cause a catastrophic spill at high peak currents and lower duty factors. A beam spill below the catastrophic spill scenario but greater than 1 W/m is considered a chronic loss and requires logging of the event, though not necessarily a beam trip (e.g. such an event can warn operators or scale back the duty factor).

The main components of the MPS beam loss monitoring are the beam loss monitors (BLMs) and the front-end TRIUMF beam loss monitor board (TBLM). There are two types of beam loss monitors which have been tested successfully with beam. The TBLM board is currently being deployed for commissioning of the e-linac up to 1 kW, though it meets the requirements for up to 300 kW of beam power.

BEAM LOSS MONITORS

The ARIEL MPS consists of two types of beam loss monitors: long-ionization chambers (LIC) (see Fig. 1) and scintillators, consisting of a small BGO coupled to a photomultiplier tube (PMT) (see Fig. 2) . There are three different lengths of LICs deployed; 1.5 m, 2m, and 3m, depending on the location and on space constraints. The LICs are filled with a constant flow of Argon gas for prompt charge collection. A positive high voltage is applied to the outer conductor, and the signal is taken from the inner conductor. The PMTs use a modified base with three different gain settings, corresponding to 1 dynode, 2 dynodes, or 3 dynodes of amplification. They are equipped with an LED housed inside the device, which will be used for calibration purposes and for self-checks to ensure each PMT is properly working.

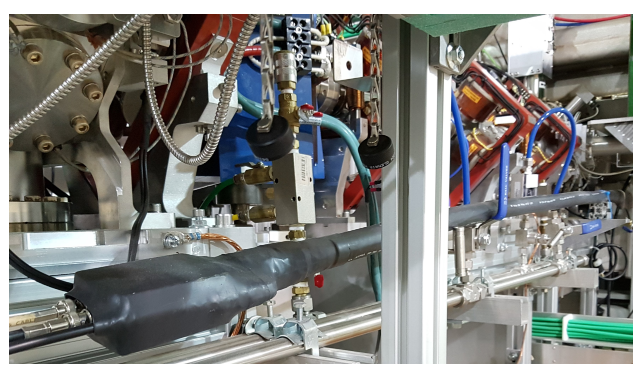

Figure 1: A long ionization chamber (black) located along the beamline in the e-linac. Note the 3 connectors seen coming from the left: an SHV connector to provide -500 V, a BNC signal connector, and a gas fitting to flow Ar.

Since the system has not been commissioned, the exact location of the BLMs, type of BLMs used, and the gain of the BLM are not yet finalized. Preliminary tests of both types of BLMs have demonstrated a range of 10^6, from 100 pA to 100 µA. This large sensitivity will meet both the catastrophic and the chronic loss requirements, provided the BLMs are positioned such that the ratio between the beam loss current

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and the BLM current is 100:1 (i.e. a 10 mA incident spill will give a 100 µA current from the BLM).

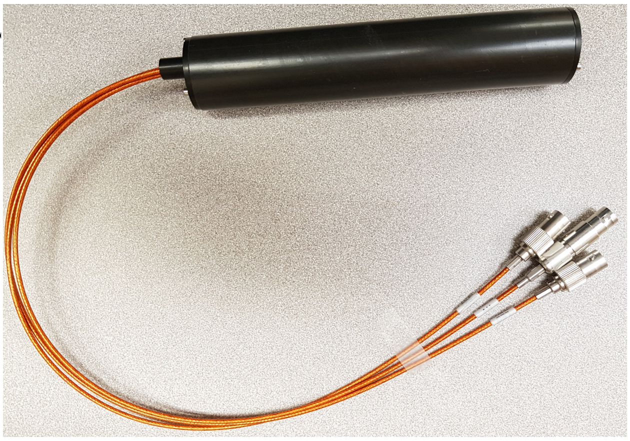

Figure 2: Picture of a PMT used as a BLM. The three connectors are for HV, signal, and an LED cable which provides power to a small LED installed in each PMT used for self-checks. Each PMT has three possible gain settings which can be changed via an internal jumper.

FRONT-END BOARD

The TBLM [2] was developed at TRIUMF and has been successfully tested in a lab setting. It is currently being deployed and testing with accelerated electron beam is under way. The beam loss monitors are each connected directly to the TLBM via a long (160 ft) cable. The TBLM integrates the incoming BLMs and if a pre-determined threshold is exceeded the TBLM sends a fibre-optic signal to a Fast Shutdown Module (FSD) [3] which trips the electron gun by shutting off the RF.

TBLM Design

The TBLM module, shown in Fig. 3, consists of a carrier board with a VME interface and 8 input channels made up of eight independent daughter cards, each containing the electronics necessary to capture the pulsed signal coming from the two types of BLMs. Each daughter card uses dual hardware integrators; while one is integrating the signal from the BLM, the other is discharging the previous integration. The daughter cards are each calibrated to within 1% of each other, with the calibrations being flashed onto the card. The hardware integration time is set to 100 ms with a total charge of 1 nC, hence the 100:1 ratio between beam loss and BLM response (refer to Eqs. 1 and 2). An ADC then samples the output of the integrator at 1 MHz, so that a continuous difference calculation of consecutive conversions results in a current reading every 1 µs.

Trip Conditions

The catastrophic trip condition is defined in the FPGA and consists of two different conditions, a "delta" trip (for large/fast losses) and a "100ms" trip (for lower losses). The

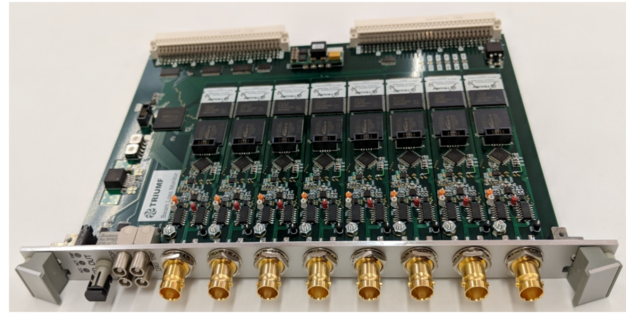

Figure 3: The TRIUMF beam loss monitor front-end board has 8 independent channels to read the current from either a PMT or LIC

"delta" trip occurs when the value of the difference calculation is above a configurable threshold. The "100ms" trip uses a 100 ms sliding window integration (100,000 consecutive readings are summed) and allows for continuous integration of the difference calculation values. The trip occurs when the sliding window integration value is above a configurable threshold. In principle, the "delta" trip condition is made redundant by the "100ms" trip condition. In practice, the "delta" condition is required for trips for losses which result in 1 nC of charge integrated on the order of tens of µs since the input signal has a large cable capacitance and therefore a rise time on the order of ≈15 µs.

The chronic loss is the sum of ten last value measurements (i.e. the last conversion value at the 100 ms mark) of the hardware integrators. This is also used for diagnostics since it allows for large sensitivity required for tuning and commissioning. The chronic loss does not generate a trip condition, though it can provide a warning to the operator.

Post-Mortem Data

The TBLM board stores up to 1 s of data in memory from the BLMs. This memory is frozen when a trip condition is met and can be interrogated via the EPICS interface. The memory can also be accessed in a diagnostic mode for commissioning of the BLMs. The data will be displayed via EPICS, showing 1 second of history leading up to a beam trip for each BLM. This will allow the beam operators to visualize the waveform for each BLM, synchronized in time, to determine where a loss took place and troubleshoot the cause of the beam spill. Additionally, an offline program will be developed to analyze the post-mortem data from all BLMs, as well as other devices, to pinpoint causes of beam spills.

EPICS Interface

The user interface of the TBLM is programmed via EPICS and provides the operator with both important trip information and diagnostic information. The TBLM will play a large role in the tuning of the e-linac via the chronic loss readings so the system will eventually provide a more visual representation of the tune through the beamline. Fig. 4 shows a screenshot of both a summary page for a single

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TBLM board, as well as an individual BLM channel. The summary screen provides relevant information in a compact manner for all 8 BLMs: trip status, HV status, 100 ms and delta trip values, and chronic loss (to be also used for diagnostics/tuning). The individual channel screen allows for changing the mode of the device (calibration mode disarms the trip and will only be used for commissioning) and for setting the various trip thresholds.

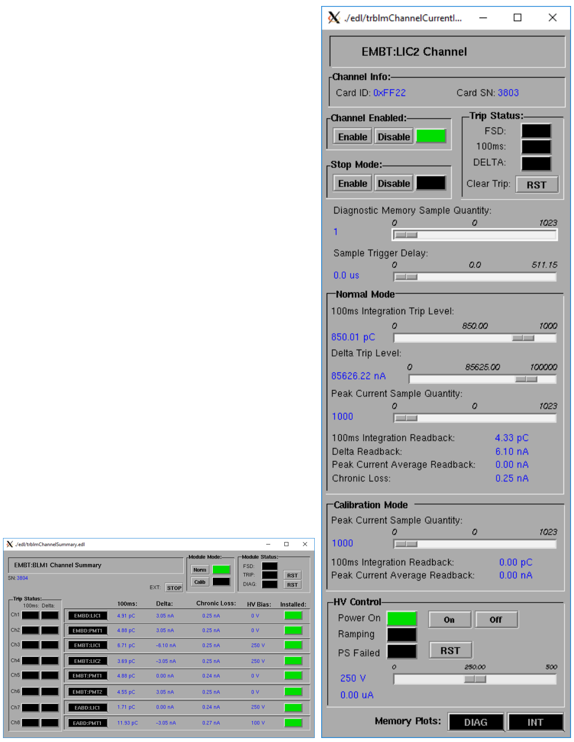

Figure 4: Screenshot of the EPICS display showing an overview of an 8 channel board (left) and a detailed look at a single BLM, in this case an LIC (right).

CURRENT STATUS OF THE MPS

The goal for 2018 is to commission the e-linac up to 1 kW at 30 MeV. The MPS is a necessary requirement for operation > 100 W, and commissioning is currently under way. The initial results indicate that both the BLMs and the TBLM meet the requirement specifications. The commissioning will be rolled out in phases; the first phase will involve the medium energy section at 10 MeV with only 3-4 BLMs, and the next phase will include the high energy (30 MeV) section.

Phase 1 Commissioning of MPS

The first step of the MPS commissioning will occur in the EMBT section (see Fig. 5), located after the injector cryomodule. In this section, the electron beam will have an energy of 10 MeV before being accelerated further by the 2nd cryomodule, which houses two SRF cavities to further accelerate to 30 MeV. Currently there are two LICs in the EMBT section, shown in red in Fig. 5. A third LIC may be added if deemed necessary for beam spill coverage. A PMT will likely be used initially for diagnostics to locate areas of large beam losses, though it is not yet certain if a PMT will be required for the MPS in that section. The commissioning plan is still in its early phases, though it will likely involve an iterative procedure wherein the beam is purposely spilled onto various beamline components using dipoles, steerers, and quadrupoles. This will be done at a very low duty factor so as to not damage any beamline components. Both the LICs and PMTs may have to be rearranged to ensure proper coverage, and thus "re-calibrated" to give a ratio between electron beam spill and BLM response.

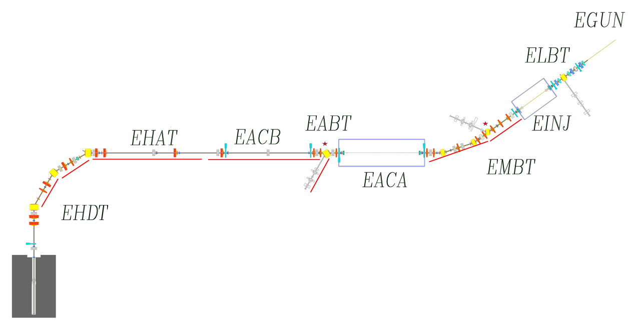

Figure 5: E-linac hall showing the tentative positions of the BLMs. The first cryomodule (EINJ) accelerates the 300 keV electrons to 10 MeV, while the 2nd cryomodule (EACA, housing two cavities) further accelerates the electrons to 30 MeV. The LICs, shown in red, are unlikely to vary significantly from this tentative position. The position of the PMTs, shown as a red star, is likely to change depending on where beam losses occur.

Phase 2 Commissioning of MPS

Upon successful completion of phase 1, the beamline after the EACA cryomodule, with a beam energy of 30 MeV, will be commissioned. This is a much large section of beampipe, as seen in Fig. 5, from EABT to EHDT. Currently 5 LICs of varying length are located along the beamline, though no BLM in this section has been tested with beam. As in the case of the 10 MeV commissioning section, the number and placement of PMTs will be determined during the commissioning phase. Once the second phase of commissioning is complete, the MPS will be fully functional and will allow for e-linac operation over 100 W. While the goal in 2018 is to commission the e-linac up to 1 kW, the MPS, once commissioned, will be capable of protecting the e-linac up to the full 300 kW of power.

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