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ADVANCEMENTS IN A CHERENKOV FIBER-BASED MACHINE PROTECTION SYSTEM AT TRIUMF'S E-LINAC*

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Abstract

A Cherenkov fiber-based shut-off system is being developed for TRIUMF's ARIEL e-Linac to provide a scalable, cost-effective solution for monitoring beam losses in high-radiation environments. The system uses a single 100 m long thin silica fiber with photomultiplier tubes at both ends, allowing sensitive electronics to be located outside the radiation area. This design is favorable over bulky ionization chambers and more expensive scintillation-based detectors, as it improves and simplifies deployment in complex environments, particularly the ARIEL beamline tunnel. The prototype demonstrates sub-10 µs response times and position-sensitive detection via the time delay between upstream and downstream signals. Ongoing work focuses on the achievable spatial resolution, the integration into ARIEL's operations control environment and the systematic evaluation of reliability and sensitivity. Compared to conventional long ionization chambers (LIC) and BGO-based detectors, the fibre-based system promises improved deployment flexibility and faster response times.

INTRODUCTION

TRIUMF e-Linac and ARIEL Tunnel

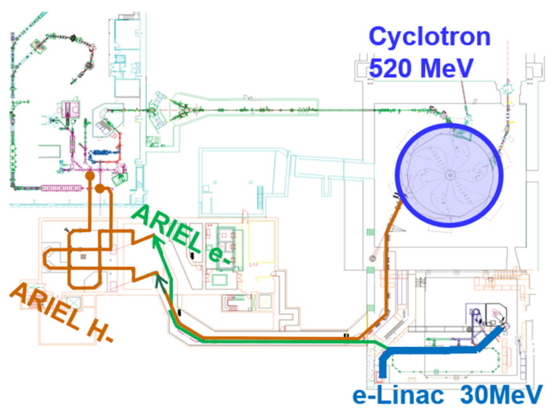

Figure 1: Outline of a part of the TRIUMF facility, highlighting the cyclotron, the e-Linac and the under-construction beamline tunnel to ARIEL.

TRIUMF, Canada's particle accelerator center, is at its core a 520 MeV cyclotron proton accelerator [1] for the production of secondary particles in particular radioactive isotopes. This will be complemented by the isotope production via photo fission induced by bremsstrahlung from high energy electrons. For this purpose a 30 MeV superconducting electron linear accelerator, the e-Linac, was installed. Most rare isotope production experiments can be adequately served by a 30 MeV, 3 mA electron beam [2].

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As shown in Fig. 1, the new ARIEL facility will have two target stations: one for the isotope production driven by the proton beam and one driven by the electron beam. Both accelerators shall deliver beam through the same tunnel. This under-construction beamline will be equipped with beam protection systems based on reliable beam loss monitors (BLMs), explained below. In addition to the ionization chambers and bismuth germanate (BGO) detectors already used at the e-Linac a Cherenkov fiber-based prototype system is planned for the tunnel with the potential to replace the current BLM system on the long run.

Current Beam Loss Monitors (BLMs)

As part of the Machine Protection System (MPS), which is the sum of all diagnostics in place to control the beam, the BLMs are two types of detectors:

- Long ionization chambers (LICs) placed along the beamline in roughly one meter distance.
- BGO scintillator-based detectors (shaped like microphones) with photomultiplier tube (PMT) readouts, placed a few centimeters away from the beamline and close to bending magnets for higher precision at these crucial points.

These two detector types combined and spread out in the described way provide reliable protection. Full and redundant protection is necessary as a 10 mA electron beam deviating from its intended path can damage the beamline. Such accidents are very expensive and a set back to any experiment timeframe. To prevent damage like this any malfunction must be detected and the beam shut down within a maximum of 10 µs.

CHERENKOV-FIBER BASED MPS

In addition to the existing BLMs a detector prototype has been installed at the beam line close to the e-Linac, which is, instead of ionization or scintillation, based on the Cherenkov process.

Cherenkov Principle

Cherenkov radiation occurs when charged particles exceed the speed of light in a medium. Therefore, the condition to be fulfilled would be $v_{\text{particle}} > c/n$ and hence the threshold Lorentz factor is $\gamma_{th} = 1/\sqrt{1-1/n^2}$. The refractive index n for quartz fibers is about 1.5. The minimal necessary kinetic energy can be derived from:

$$E_{\text{kin,th}} = (\gamma_{th} - 1)mc^2, \tag{1}$$

which results in 0.18 MeV for electrons and 321 MeV for protons. For protons, even lower energies can still be detected through secondary particle showers, whereas

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electrons require sufficiently high energies to release detectable signals. Secondary particle showers are created when the particle beam hits the metal beam line wall. In the high-energy section of the e-Linac and in the ARIEL tunnel (BL4A north), both 30 MeV electrons and 480 MeV protons are well above the Cherenkov threshold and can therefore be detected directly.

Why This Alternative?

Although the LIC and BGO-based MPS is sufficient, and is planned to be replicated in the ARIEL tunnel, a Cherenkov fibre based MPS could be advantageous in several ways:

- Lower initial and replacement costs as the components could be broken down to a single affordable quartz fibre and only two PMTs with their readouts. The deployment length could be 100 m of fibre.
- High radiation hardness, as electronics are placed remotely behind the shielding and only radiation hard quartz fibre remains in the high radiation environment.
- Highly adaptable and flexible installation as it is not bulky stiff LICs, but a thin bendable fibre. If the fibre is deployed within a tube, it also allows for remote replacement via shooting a new fibre through the guiding hose.
- Continuous coverage of the object with the possibility of position sensitivity via time-of-flight measurements. (Compare Fig. 2).
- Response time only limited by the speed of the electronics, as the Cherenkov light is created instantaneous.

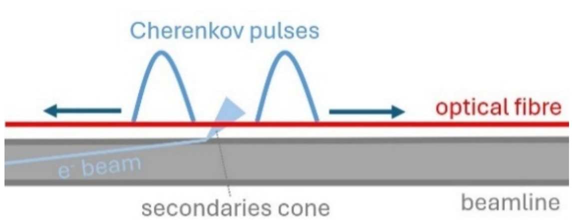

Figure 2: A charge shower is emitted at a certain location of the beamline either by inserting a intercepting diagnostics device (e.g. viewscreen) or tuning the beam into the wall (indicated here). The created Cherenkov light in the optical fibre by the charge shower travels along the fibre in both directions. The time difference in the arrival of the light pulses on the different fibre ends allow for the reconstruction of the position of the charge shower.

Prototype

The prototype set up consists of:

- A single 100 m long particularly radiation-resistant Cherenkov fibre (exail; IXF-RAD-MMSI-L-105-125-022-HT). Attenuation of 5-10 dB / 100 m at $\lambda =$ 400 nm [3].
- PMT 1 (Hamamatsu, H10720 series) with their power supply settings of 0.7 V supply, 5 V bias and <1 mA. Rise time of 0.57 ns.
- PMT 2 (Hamamatsu, R14755U-100) with their power supply settings of 1000 V and <1 mA. Rise time of 0.4 ns, suitable for the sub-10 µs machine protection requirement.
- Oscilloscope (Siglent, SDS2354X) for readout, providing a 350 MHz bandwidth and a 2 GSa/s sampling rate, sufficient for resolving sub-µs signals, remote control via internal ethernet network.

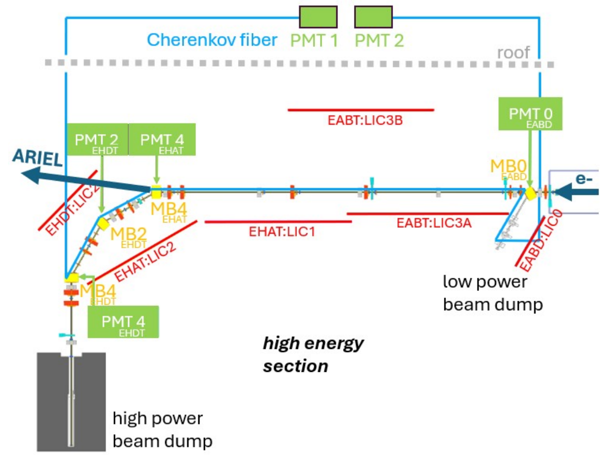

Figure 3: Schematic top view of the high energy section of the e-Linac with the different LICs, BGO-PMTs and Magnets (MBs). The 100 m Cherenkov fibre is affixed to the beamline for 20 m and routed through the shielding of to the hall roof for remote readout of the C-fibre PMTs.

In Fig. 3 it is shown how the fibre is placed in the high energy section of the e-Linac beam line. Both ends of the light guiding Cherenkov fibre are connected to the PMTs outside of the e-hall on its roof. This means the electronics are placed safely away from the high radiation environment of the accelerator.

Prototype Modification/Advancements

The first version of a Cherenkov fiber prototype was installed and commissioned on the high energy section of the e-Linac in 2021. With the beginning of this year different old and new electronics, PMT readouts and scopes, and implementations into the beam controls network have been tested. The scope mentioned in the prototype description is the recently used more modern readout with a control option via ethernet and therefore remote in the internal network. The trigger signal from the electron accelerator for pulsed operation could now also be included. The 1 GHz sampling rate enabled precise delay measurements between the two PMTs, which allows for potential position reconstruction along the fibre, as demonstrated in [4].

EXPERIMENTAL RESULTS

The prototype measurement has shown that it can indeed replace the LIC and BGO detectors. For this in the high energy beam line part of the electron accelerator a horizontal sweep is done with the different bending magnets there. During the sweep, the electron beam hits the beamline wall, creating a shower of particles, which generates a signal in all surrounding detectors. The duty cycle of the beam is turned down to 0.05 % to prevent any damage. If the sweep passes angle of 0 degrees, then there should be a signal drop to 0 as the beam passes the ideal beam position in the center of the beamline.

A comparison between the new prototype and the LIC & BGO detector system shows that the Cherenkov fibre signal represents an envelope encompassing the combined response of the LICs and BGOs (see Fig. 4). This means that it effectively captures beam loss events as detected by the current BLMs. The noise/baseline is higher for the fibre possibly due stray light entering the PMTs or particles being picked up along the 100 m of the fibre but not by the local LIC and BGOs shown in the plot.

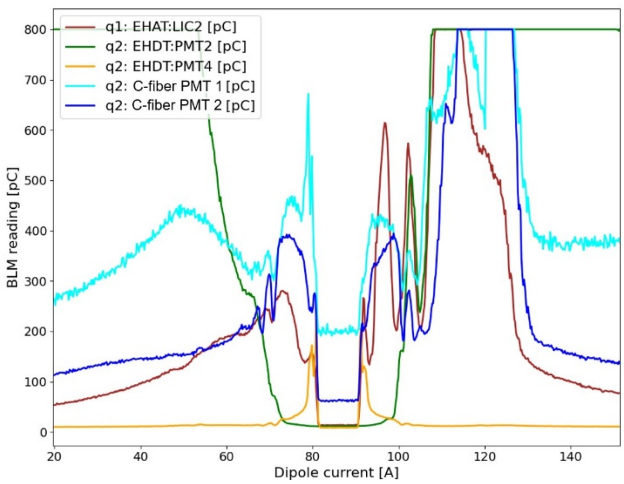

Figure 4: Horizontal sweep with changing the current of magnet MB2. Electron beam set to 200 µA, 30 MeV and 0.05 % duty cycle. Shown is a signal comparison of the Cherenkov fibre PMTs with LIC (LIC2) and BGO (PMT2&4) detector signals. The Cherenkov fibre signal envelopes the combined LIC & BGO measurements in a sense that a BLM reading threshold can be defined which lets the beam run at the designed magnet setting of ~85 A, but trips the beam at wrong steering settings.

Another set of experiments was carried out to determine the position of particle showers along the fibre. Steering the beam into the wall creates localized showers, but viewscreens were used to provide a more precise and repeatable method for determining positions. The chosen viewscreens were the most upstream and the most downstream position of the area covered by the Cherenkov fibre. As the pulsed electron beam hits the viewscreens a particle shower is created, which partially and via secondaries hit the fibre. The Cherenkov light generated in the fibre propagates towards both ends and reaches the PMTs after a time corresponding to the travelled distance divided by c/n, as the emission process itself is effectively instantaneous. The time delay between the two PMTs can be used to determine the position of the particle shower along the fibre (see Fig. 5). The first measurements yield an average timing uncertainty of about 10 ns, corresponding to a position uncertainty of ~2 m.

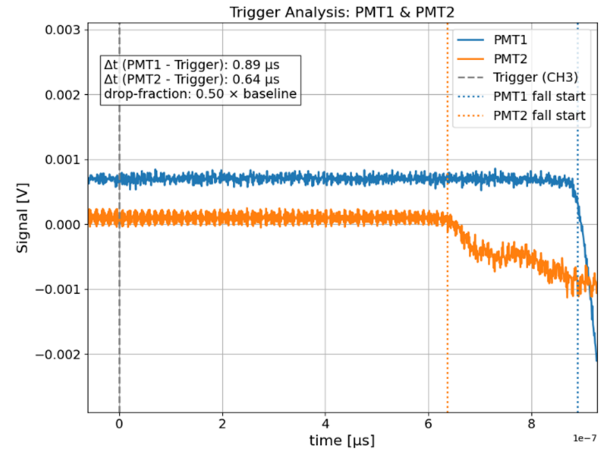

Figure 5: Showing the start of the falling flanks of the two PMTs, which indicates the photons hitting. CH1 and CH2 are the signal of the two PMTs, the first being terminated with 1 MΩ the second with 50 Ω, thus the different shape in the signal drop. If the starting of the falling flanks of the PMTs would overlap the charge shower would be in the centre of the fibre. The time-difference therefore indicates the position of the inserted viewscreen.

CONCLUSION AND OUTLOOK

The Cherenkov fibre-based beam loss monitor provides a promising alternative for machine protection in high-radiation environments. It demonstrated to be able to detect in sub-10 µs and successfully showed first rough position sensitivity in tests. For now, it complements and, in the future, potentially replaces the traditional systems based on LICs and BGO detectors. The extremely flexible installation, the fewer and more secure placed electronics, the simple replace mechanism and the general lower cost make this setup particularly suitable for complex beamline environments like the TRIUMF's ARIEL tunnel.

Future work will focus on position determination with continuous-wave beams, which presents a major challenge due to the lack of bunch structure. A related goal is to explore whether individual bunches can be resolved in the Cherenkov fibre signal, which would be particularly valuable in the planned ARIEL tunnel where an electron and a proton beam will run in parallel. A system capable of distinguishing between the two based on bunch structure would allow emergency shut-offs to selectively abort only the failing beam. In addition, we plan to extend the system to other beamlines, including the proton beamlines and the cyclotron, to achieve full beam-loss coverage rather than the partial coverage obtained so far.

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