



Novel radiation hard position sensitive detector using YAG:Ce fibers for ion beam instrumentation at FRIB

Olivier Philip^{a,*}, Irina Shestakova^a, Silvia Sýkorová^b, Petr Kynych^b, Jindřich Houzvicka^b, Marco Cortesi^c, Ian Pegg^{d,e}, Tanja Horn^{d,e}

^a Crytur USA Inc., Watertown, MA, USA

^b Crytur spol. s.r.o., Turnov, Czech Republic

^c Michigan State University, East Lansing, MI, USA

^d Scintille, Alexandria, VA, USA

^e Catholic University of America, Washington D.C., USA

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ABSTRACT

We are investigating the feasibility of a new detector concept for use in the beam line at the Facility for Rare Isotope Beams (FRIB). The detector is designed to withstand the high ion beam intensities and the high radiation environment while providing position, timing, and energy information. Based on the concept of a fiber detector, the device uses YAG:Ce crystals as sensing material, chosen for their extreme radiation tolerance to electromagnetic or hadronic exposure. The crystals are machined into long and thin rods which are laid out in orthogonal horizontal and vertical arrangements to obtain spatial sensitivity to impinging particles. The readout is performed at the extremities of the rods with strip Multi Pixel Photon Counters (MPPC) also referred to as Silicon Photomultipliers (SiPM) arrays model S13552 from Hamamatsu mounted on ribbon cables with connector ends.

1. Introduction

The Facility for Rare Isotope Beams (FRIB) is a scientific user facility where a large variety of isotopes can be produced for research in the fields of nuclear physics, nuclear astrophysics, and the study of the nuclear structure with applications in nuclear medicine and nuclear science [1]. FRIB will provide an unprecedented beam flux requiring new instruments with enhanced detection capabilities, particularly for beam diagnostics, tracking, and total energy measurements. Tracking detectors capable of withstanding FRIB intensities while providing high position, timing and energy resolutions are needed for almost every experiment. The ions to be detected range from ^{16}O to ^{238}U with energies from 40 MeV/u to 200 MeV/u and beam intensities up to 10^{12} pps (Fig. 1). Particle detectors play a crucial role as a beam diagnostics tool during the beam tuning, by providing a full characterization of the beam properties (i.e. 2D beam profiles, trajectory angles, and transmission efficiency through the beam line). In addition, they may provide event-by-event tracking/timing information (momentum, position, angle, ...) for the physics analysis of events recorded in the experimental area. Finally, they may also support long-term stable beam operations by providing a monitoring service for beam transport and machine protection. Stopping power, time resolution and position resolution are the critical parameters that allow for good particle identification.

2. Detector concept

Our concept follows the design of an orthogonal ribbon scintillating fiber detector [2] using radiation hard YAG:Ce scintillating fibers as sensing material. The fibers are held in a rigid frame with a readout sensor positioned at the fibers' end.

2.1. Scintillating material

Yttrium Aluminum Garnet ($\text{Y}_3\text{Al}_5\text{O}_{12}$) doped with cerium (YAG:Ce) is one of the most radiation hard scintillator materials tested under high fluence for use in high energy physics. During the tests, the samples were exposed to extreme doses of proton and gamma radiation [3] while their optical characteristics were monitored for signs of degradation. Figs. 2 and 3 show transmission curves and optical absorption measurements on YAG:Ce fibers before and after proton irradiation. These crystals are grown at Crytur in large homogeneous ingots from which long fibers can be machined (Fig. 4). The high refractive index fibers are kept bare and serve as light guides, bringing the scintillation signal to the MPPC strip sensor coupled at the fiber's extremities. Fig. 5 shows Geant 4 simulations of 40 MeV ^{16}O tracks into YAG material, confirming that the lightest ions can travel beyond one fiber thickness and deposit energy into the X and Y sensing fibers.

* Corresponding author.

E-mail address: olivier.philip@crytur-usa.com (O. Philip).

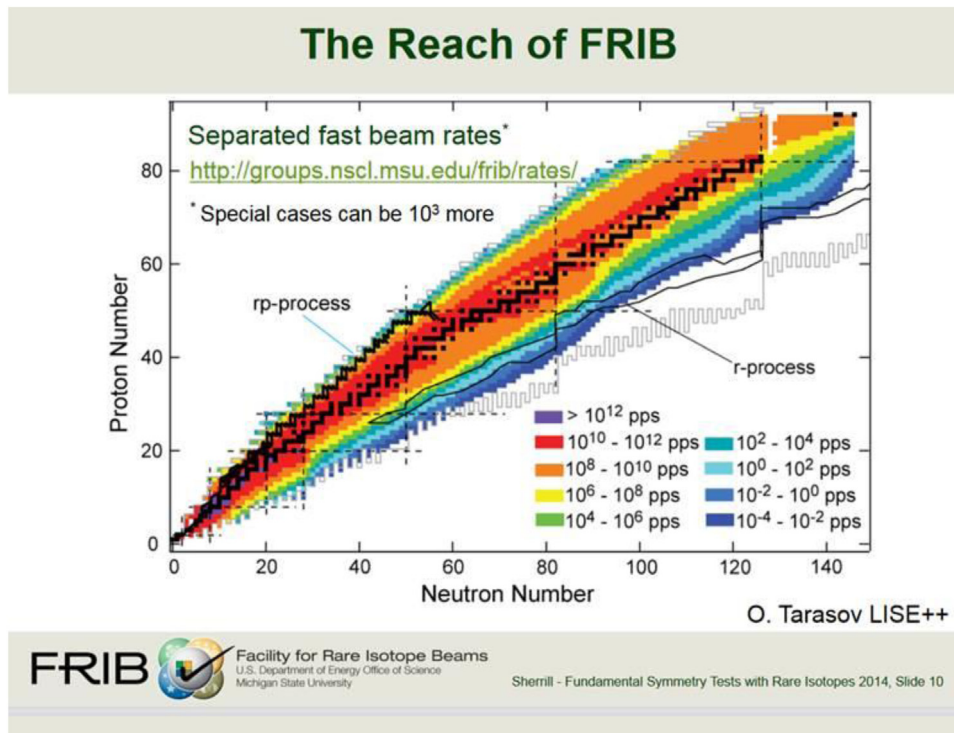


Fig. 1. Range and rate of production of nuclear isotopes at FRIB.

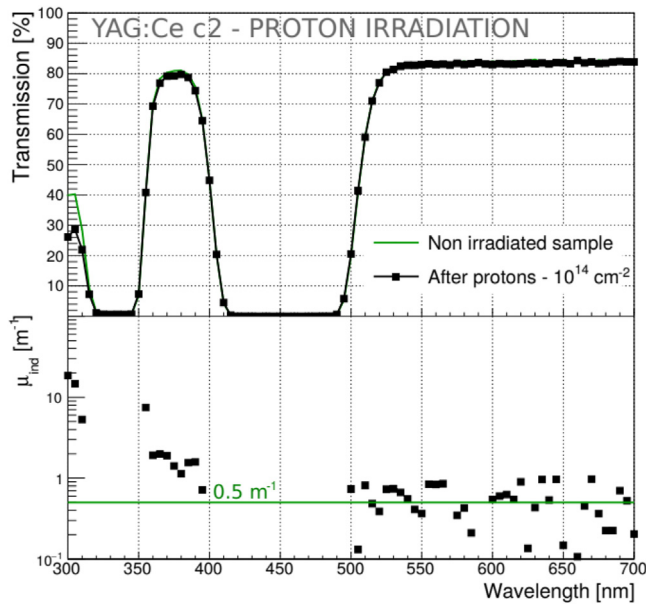


Fig. 2. From [3] Top: Transmission curves for YAG:Ce c2 crystals before irradiation (green line) and after irradiation with protons (black squared dots). Bottom: The calculated induced absorption coefficient μ_{ind} is reported for both irradiations, as a function of wavelength. Green line at 0.5 m^{-1} is drawn as reference value.

2.2. Detector layout

The detector consists of an array of scintillating YAG:Ce fibers aligned along the vertical and horizontal orientations. The fibers are separated from one another to avoid optical cross talk. A mockup assembly was built with $1 \times 1 \times 100 \text{ mm}^3$ fibers arranged in a supporting frame as shown in Fig. 6.

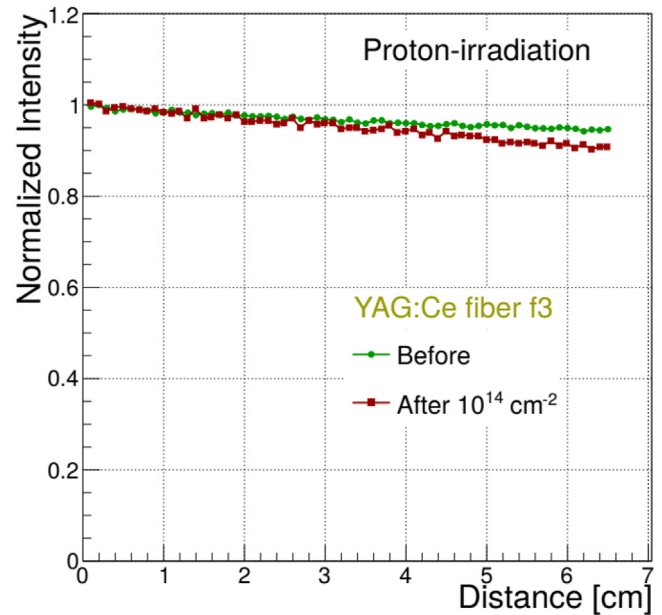


Fig. 3. From [3] Attenuation curves of YAG:Ce elongated samples before (green circles) and after proton-irradiation (red squares).

Fig. 7 shows a sketch of the cross-sectional view of the fiber arrangement relative to the ion beam and the position of the photosensitive strips at the end of the fibers. Fig. 8 shows the alignment of the fiber ends with the photosensor strips.

2.3. Photodetector

A working prototype was built using SiPM strip sensors from Hamamatsu, model S13552 SPL (with high quench resistance of $500 \text{ k}\Omega$).

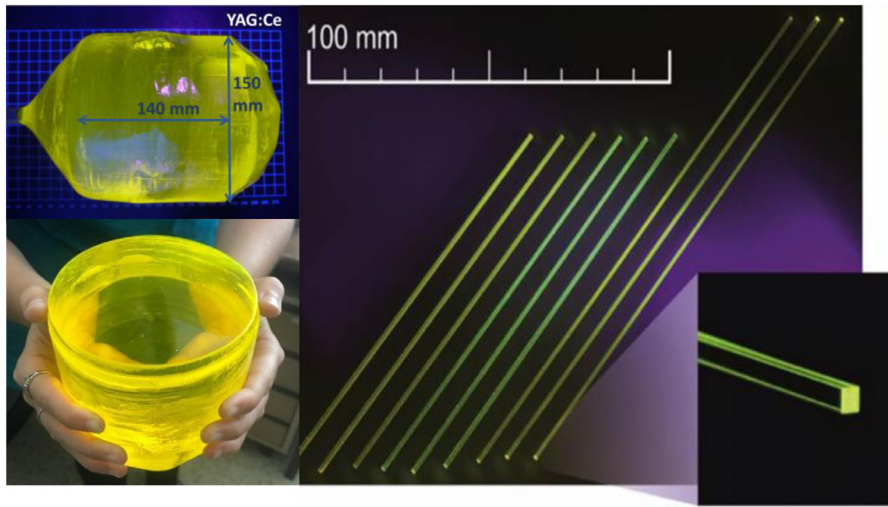
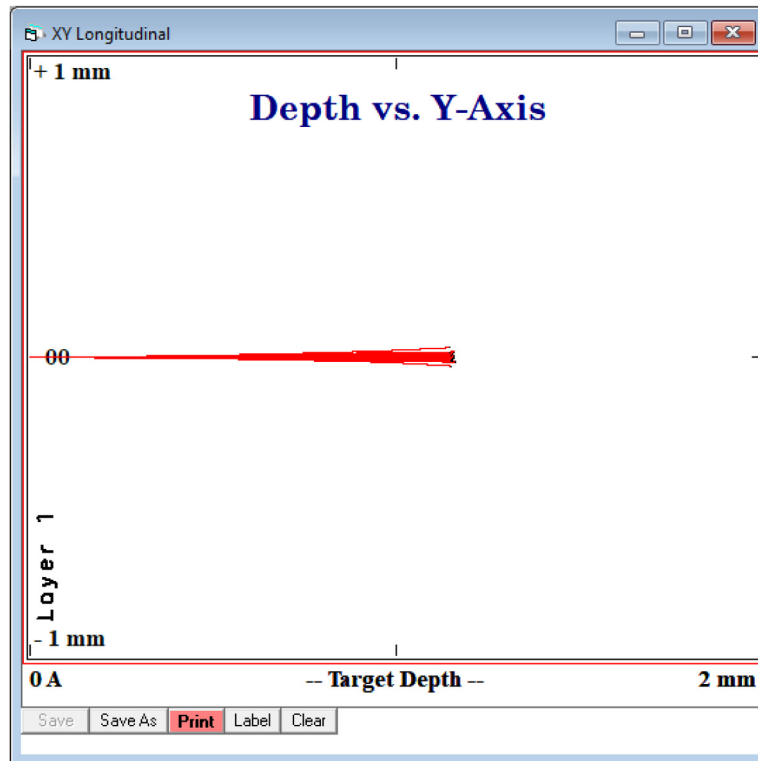


Fig. 4. YAG:Ce ingots and fibers produced at Crytur.

Fig. 5. Modeled range in YAG fiber for 40 MeV ^{16}O ions.

A sensor assembly, shown in Fig. 9, with flexible ribbon cable and connector was developed at Ecole Polytechnique Fédérale de Lausanne (EPFL) for the Large Hadron Collider Beauty (LHCb) large Scintillating Fiber (SciFi) tracker at CERN [4]. A custom printed circuit board was produced to connect to the sensor assemblies for biasing the SiPM strips and reading out the signals. The sensor is comprised of a 128-channel array of $1625 \times 230 \mu\text{m}^2$ pixels. Fig. 10 a shows an acquisition with a simple charge to digital (QDC-MDDP-32 digitizer) where the multi photoelectron peaks are well resolved. Fig. 10 b shows the spectral response of a single SiPM channel to a pulsed LED input.

3. Detector prototype and results

A functional prototype was built with shorter fibers using four MPPC strips for read out to prove the concept and for testing with

radiation. Fig. 11 shows the prototype with its array of 40 mm fibers and four Hamamatsu S13552 SPL units mounted on flex ribbons with connectors. This detector unit was tested with 5.5 MeV alpha particles from a ^{241}Am source to verify the functionality prior to testing with more energetic ions. Fig. 12 shows an oscilloscope trace acquired from one to the fibers of the functional prototype (59V bias on SiPM), with a rise time of 16 ns and 400 ns recovery time. A spectral acquisition for a single channel using a 600 ns integration time window is shown in Fig. 13 left. A curve fit indicates an energy resolution of 4.5%. Better resolution can be achieved by acquiring the light signal from both ends of the fiber. While the signal level is low for this 5.5 MeV alpha, the energy deposited by the ion beam will be greater and will produce larger signal levels as the least energetic beam is comprised of 40 MeV ^{16}O . The fibers do not have enough stopping power to completely stop

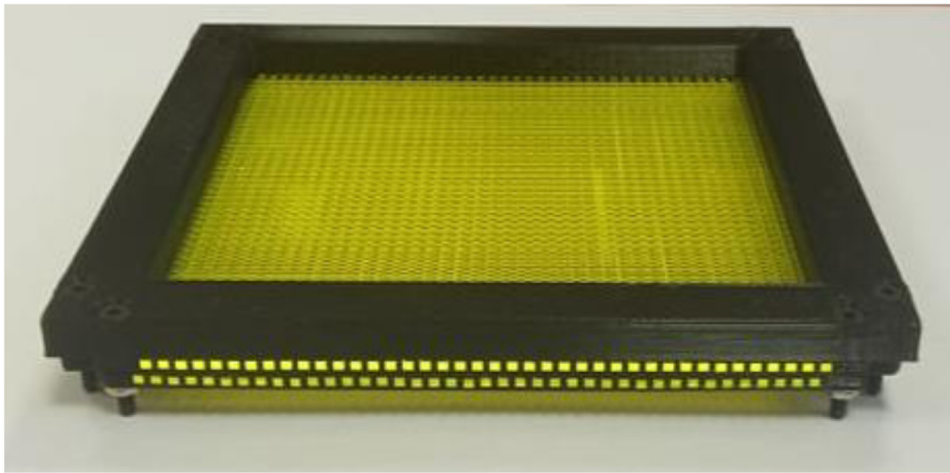


Fig. 6. Full scale mockup assembly with 100 mm long fibers showing the fiber arrangement in the frame holder.

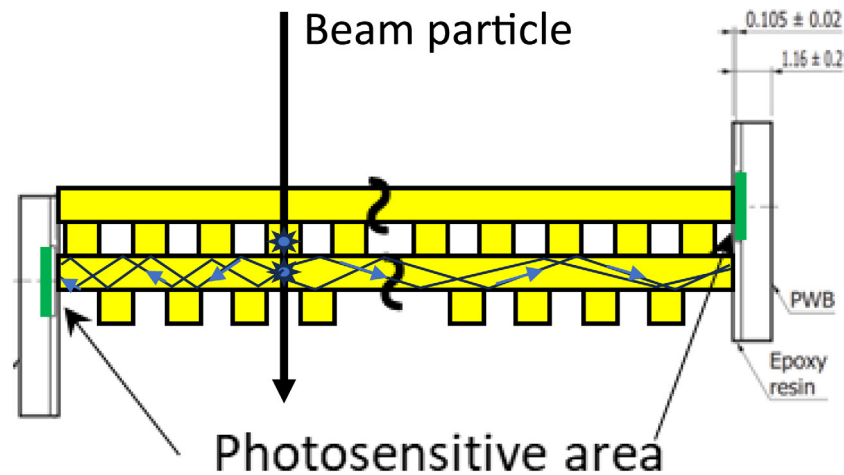


Fig. 7. Schematic view of the fiber arrangement showing that a beam particle will cross one X fiber and one Y fiber with scintillation light guided to the photosensor.

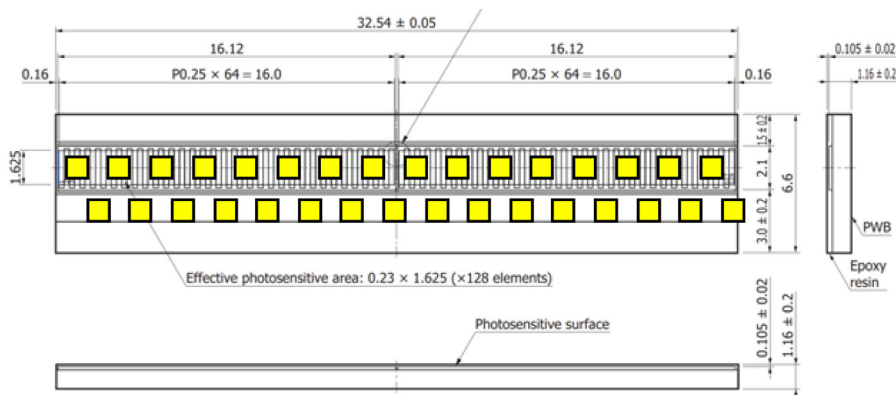


Fig. 8. Schematic view of the alignment of one row of fibers with the photosensor strip.

highly energetic particles and the detector is not expected to resolve the energy of these particles.

Fig. 13 right shows the light recorded from the full array (32 fibers) when the non-collimated alpha-particle source (^{241}Am source) was

placed on top of the detector. The counts along the arrays are computed by integrating the number of events around the 5.5 MeV peak recorded in each channel. The profile of the source (10 mm wide) is clearly defined and demonstrates the position sensitivity of the device.

SiPM for the SciFi tracker

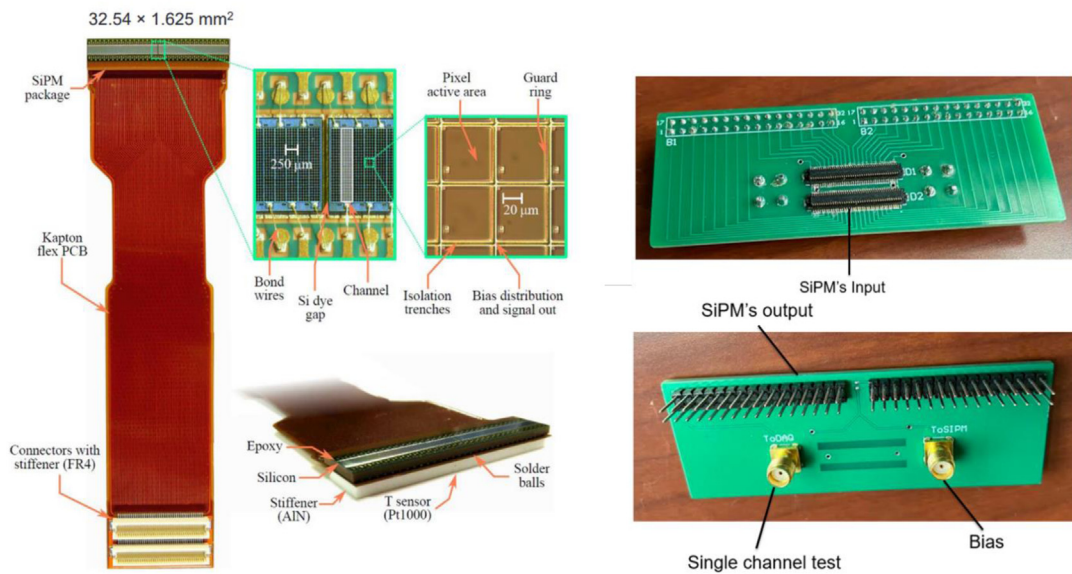


Fig. 9. Customized SiPM array produced by Hamamatsu (S13552) assembled on a ribbon with connectors (left) and custom PCB for signal readout and SiPM bias (right).

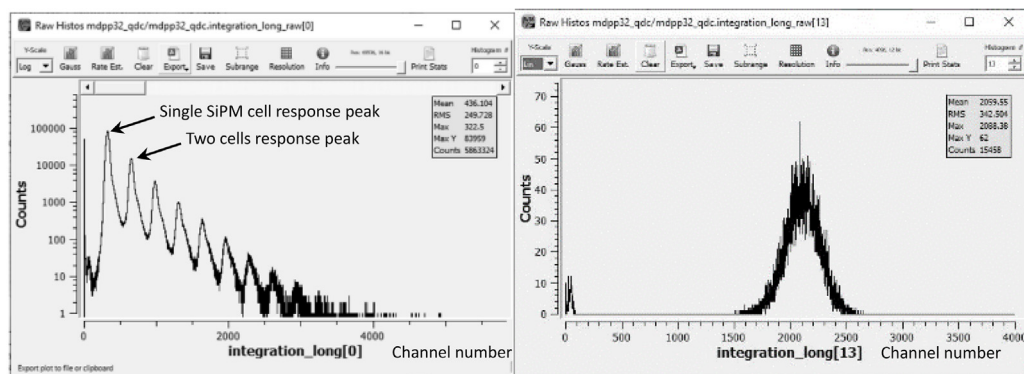


Fig. 10. Part (a) shows the discrete response of a SiPM channel under low level light illumination with distinguishable peaks for integer numbers of triggered cells Part (b) illustrates the spectrum of a single SiPM channel as response to a pulse LED.

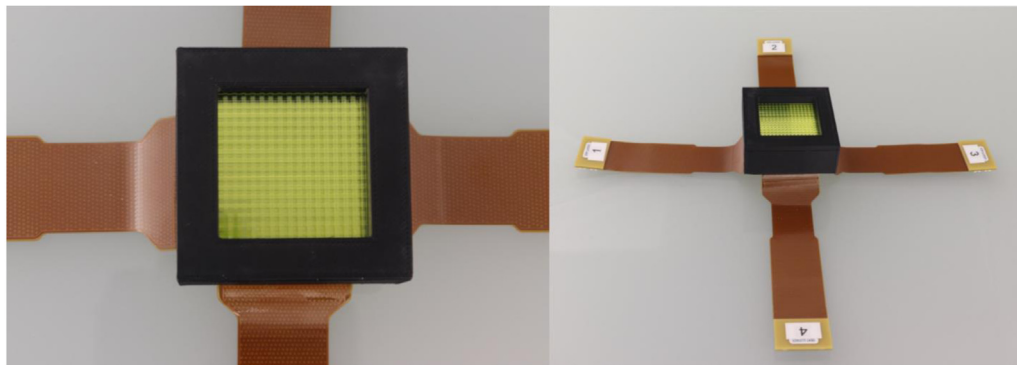


Fig. 11. Functional detector prototype built with 40 mm fibers and four Hamamatsu S13552 SPL MPPC sensors.

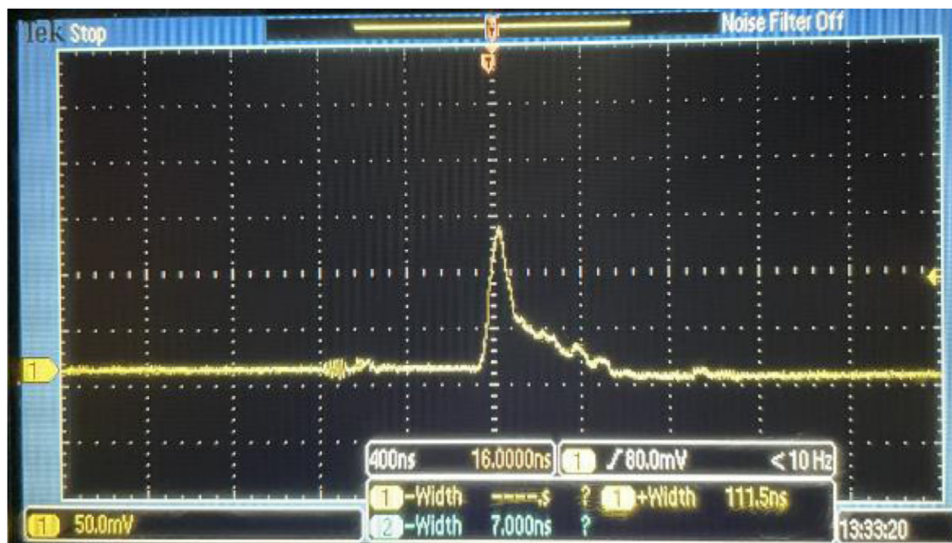


Fig. 12. Oscilloscope trace from detection of a 5.5 MeV alpha particle from a ^{241}Am source.

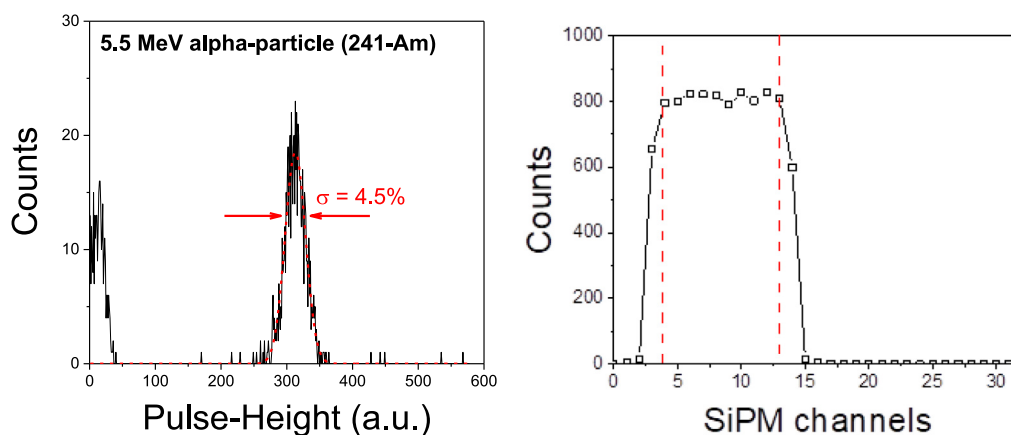


Fig. 13. Spectral acquisition for a single fiber channel 5.5 MeV alpha particle from a ^{241}Am source. Resolution=4.5% (left) and spatial profile of the source recorded by the detector (right).

4. Summary

The target beam conditions covered by our detector span a beam intensity and energy range of many orders of magnitude making it a potential diagnostic tool at FRIB for beam profile monitoring at different locations for cost effective beam tuning, beam particle tracking in the target station where magnetic field is too high for traditional tracking systems, beam diagnostics directly on the low intensity beam, calorimetry measurement for reaccelerated facility (ReA3 and ReA6) and at the FRIB Single Event Effects (FSEE) line, where beams have moderate energy (up to 40 MeV/u for ^{16}O at the FSEE line). This detector concept is also being considered for proton beam measurements in medical proton beam therapy. We are planning to continue the development of this concept with a large functional unit to be tested in the beam line at FRIB.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Dr. Guido Haefeli has kindly made available to us some assemblies with MPPC strips mounted on ribbon flex with connectors that were designed and produced by his group at EPFL.

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References

- [1] J. Wei, H. Ao, S. Beher, N. Bultman, et al., *Advances of the FRIB project*, *Internat. J. Modern Phys. E* 28 (3) (2019) 1930003.
- [2] K. Morimoto, F. Tokanai, I. Tanihata, Y. Hayashizaki, *Development of scintillating fiber imager*, *IEEE Trans. Nucl. Sci.* 47 (2000) 2034.
- [3] M. Lucchini, K. Pauwels, K. Blazek, S. Ochesanu, E. Auffray, *Radiation tolerance of LuAG:Ce and YAG:Ce crystals under high levels of Gamma- and proton-irradiation*, *IEEE Trans. Nucl. Sci.* 63 (2) (2016) 586–590.
- [4] O. Girard, M.E. Stramaglia, G. Haefeli, *Large pixel SiPMs for single photon detection in the new LHCb large area scintillating fibre tracker*, in: *PIXEL2018*, Vol. 14, Academia Sinica, Taipei, Taiwan, 2018.