The Mu2e-II Calorimeter
Letter of Interest for Snowmass 2021

Y. Davydov,[1] S. Donati,[2] R. Donghia,[3] B. Echenard,[4] F. Happacher,[4] D. G. Hitlin,[4] C. Hu,[4] D. Lin,[4] S. C. Middleton,[4] S. Miscetti,[3] L. Morescalchi,[2] J. Oyang,[4] E. Pedreschi,[2] H. Q. Pham,[5] F. C. Porter,[4] I. Sarra,[3] F. Spinella,[2] G. Tassielli,[6] L. Zhang,[4] and R.-Y. Zhu[4]

[1] *Joint Institute for Nuclear Research, Dubna, Russia*
[2] *INFN Sezione di Pisa; Università di Pisa, I-56127 Pisa, Italy*
[3] *Laboratori Nazionali di Frascati dell'INFN, I-00044 Frascati, Italy*
[4] *California Institute of Technology, Pasadena, California 91125, USA*
[5] *University of Virginia, Charlottesville, Virginia 22904, USA*
[6] *INFN Sezione di Lecce; Università di Lecce, I-73100 Lecce, Italy*

Abstract

The Mu2e calorimeter [1] consists of 1348 pure CsI crystals, comprising two disks, read out with custom Hamatsu SiPMs. The calorimeter performance is well-matched to Mu2e rates but may be challenged by Mu2e-II instantaneous rates and radiation levels that are three times higher. The required tolerance of a ten-fold increase in integrated radiation dose on the calorimeter readout electronics motivates study of appropriate rad-hard readout electronics at a level informed by the HL-LHC detector upgrades. This study group will consider alternative technologies, several of which are discussed herein, and foster their development.

The Mu2e-II calorimeter performance requirements on the energy (<10%) and time (<500 ps) resolutions are the same as those for Mu2e, aiming to provide a standalone trigger, track reconstruction seeding and particle identification as before. However, the Mu2e-II environment presents two serious challenges to the calorimeter system.

The factor of ten increase in integrated ionizing dose (10 kGy) and neutron fluence (10^{13} n/cm^2) for the crystals and a factor of three increase on the sensors, motivates consideration of more radiation-tolerant crystals and photosensors. Among the possible choices, we are concentrating on BaF_2 crystals with appropriate photosensors, although other solutions will also be explored. Second, the factor of three increase in instantaneous rates motivates faster electronics and a readout scheme to utilize the very fast component (0.6 nsec) of the BaF_2 UV scintillation light while suppressing or rejecting the larger, relatively slow (600 nsec) longer wavelength scintillation component. Development work on the crystals themselves, as well as on a variety of candidate photosensors, the related front-end electronics and the data acquisition system is needed to meet the Mu2e-II requirements. We list below a variety of R&D approaches being considered.

The Caltech crystal lab has been developing yttrium-doped ultrafast barium fluoride crystals [2] [3] [4] to confront the challenge of high event rates and the severe radiation environment. In 2017, they found that yttrium doping in BaF_2 is effective in suppressing the slow scintillation component with 600 ns decay time, while leaving the ultrafast sub-ns scintillation component largely unchanged. In a collaboration with SICCAS and Beijing Glass Research Institute, yttrium-doped BaF_2 crystals up to 19 cm long have been successfully grown, having a factor of as much as six suppression of the slow component. They also found that 25 cm long BaF_2 crystals are radiation hard up to 120 Mrad. This R&D will continue in collaboration with crystal vendors to optimize parameters, investigate the tolerance in Y-doping concentration along the crystal and further investigate radiation tolerance to neutrons as well as ionizing radiation.

The complementary approach is to develop photosensors with good quantum efficiency at the wavelength of the fast component, but suppressed efficiency for the slow component. A combination of Y-doped barium fluoride crystals read out with an effectively solar-blind photosensor should be able to meet the Mu2e-II requirements. Several different approaches are being pursued.

Bandwidth-limited filters can suppress the slow component of BaF_2 crystals. One example is an interference filter using thin layers of rare earth oxides. Such filters, comprised of up to 200-220 layers sprayed on the quartz glass substrate can suppress the scintillation light in the range 250-400 nm, which eliminates most of the slow component. In collaboration with St. Petersburg (Russia) companies, the Dubna group has produced and tested several samples of these filters [5]. The slow component was suppressed by a factor of four. However, these first samples also partially suppressed the fast component, due to the narrow bandpass in the 190-230 nm range. Applying a multilayer filter directly on the crystal surface could be practical for slow component suppression. Further R&D is needed in order to better suppress the slow component and increase the band pass in the 190-230 nm range.

Working with FBK and JPL, the Caltech group is developing a large area SiPM (nominally the same size as that used in Mu2e) that incorporates an integrated ALD filter having high efficiency at the 220 nm fast component and substantial extinction of the 300 nm slow component [6, 7]. Examples using a simple three layer filter have shown more than 30% QE at 220 nm, with excellent suppression of the slow component. New versions with a more sophisticated filter are being fabricated. A second phase of this development will produce a back-illuminated SiPM incorporating a delta-doped layer to improve the rise and decay times of the SiPM response, as has been demonstrated with delta-doped RMD APDs [8]. The delta-doping is also important to ensure the survival of the device under the intense UV photon flux produced in the BaF_2 to the ionizing backgrounds. Several rounds of development will be required to produce the final version of these SiPMs.

Another approach to filter fabrication is to use nanoparticles that selectively absorb UV light in the wavelength range 200-250 nm while being relatively insensitive to light with wavelengths >250 nm. Various tests have been done using nanoparticles mixed into Dow Corning PMX-200 grease, deposited directly on the resin surface of a Hamamatsu SiPM and mixed into transparent polycarbonate discs. The ratio of light sensitivity for wavelengths <250 nm to that >250 nm was found to be between a factor of 2 and 10 for the tested nanoparticle candidates. A program to optimize the nanoparticle concentration and thickness of a silicone cookie positioned betwwen the crystal and SiPM could prove to be fruitful. The idea is for the cookie to be insensitive to incident light between 250-350 nm while being highly efficient to the fast component at 220 nm that will be absorbed and re-emitted at larger wavelength ¿ 350 nm. This implementation of the unique properties of materials in nanoparticle form will provide a flexible readout that can be easily modified in the future if more efficient nanomaterials are developed. An alternative approach is the application of several atomic layers of nanomaterial directly on the face of a BaF_2 crystal. These studies are being done at ANL in a collaboration between the ANL HEP and NST Divisions and with the University of Texas at Arlington, [9]. Plans are to pursue both the nanoparticle-infused cookie and the nano-platelet approaches, choosing the most signal and cost efficient method for the Mu2e-II calorimeter upgrade.

The photosensor promising the best timing performance in a magnetic field is a microchannel plate photomultiplier. Two initiatives in this direction have been considered thus far. The large area LAPPD devices produced by Incom could be produced with a solar-blind photocathode. This would be a well-defined R&D project that has been explored by Caltech and Argonne. The Dubna group has already produced and tested a conventional MCP with a solar-blind photocathode.

The longevity of new photosensor technologies, whether SiPM or MCP-based, in the Mu2e-II radiation environment will have to be demonstrated. The radiation hardness of the Mu2e SiPMs to ionizing dose and neutron fluence is well-understood. However, the tenfold increase on the radiation level will require additional RD, informing the sensor selection and the cooling needs of the detector.

Mu2e-II will have an instantaneous rate of events about three times greater than Mu2e, and will generate of a data sample ten times larger; the integrated radiation dose on the electronics will also be ten times higher. Given the high rates, it will be necessary to reduce the shaping time and therefore the current 200 MHz digitizers may be inadequate.

Several solutions can be envisioned:

- A readout system based on fast TDCs + slow ADCs to assess the presence of pile-ups, connected to fast rad hard FPGAs. CERN has developed a new RH TDC, picoTDC, with 1 ps resolution and Xilinx foresee a new family of space grade kintex ultrascale FPGAs.

- A system based on fast ADCs, connected to high performance rad hard FPGAs, able to extract the hit parameters in real time, thus reducing the necessary bandwidth. Eventually those data could be used as trigger primitives and the raw event could be stored in large memories on the ROC, waiting for trigger accept/reject. This requires an additional L0 trigger system, but reduces the bandwidth from the ROC to the DAQ and the requirements on the PC farm.

- A custom rad hard IC with integrated logic, TDC and ADC.

CERN is developing new 10 Gb/s RH optical transceivers that could also be used in this project.

[1] N. Atanov *et al.*, "*The Mu2e Calorimeter Final Technical Design Report*," [1802.06341].
[2] R. Zhu, "*Very fast inorganic crystal scintillators*," Proc. SPIE Int. Soc. Opt. Eng. **10392** (2017) 103920G.
[3] J. Chen *et al.*, "*Slow Scintillation Suppression in Yttrium Doped BaF_2 Crystals*," IEEE Trans. Nucl. Sci. **NS-65** (2018) 2147–2151.
[4] C. Hu *et al.*, "*Development of Yttrium-Doped BaF_2 Crystals for Future HEP Experiments*," IEEE Trans. Nucl. Sci. **NS-66** (2019) 1854–1860.
[5] N. Atanov *et al.*, "*A Photomultiplier With an AlGaN Photocathode and Microchannel Plates for BaF_2 Scintillator Detectors in Particle Physics*," IEEE Transactions on Nuclear Science **67** (2020) 1760.
[6] D. Hitlin, "*Progress on a photosensor for the readout of the fast scintillation light component of BaF_2*," 2020. 15th Trento Workshop, Vienna, https://indico.cern.ch/event/813597/contributions/3727781/attachments/1990317/3318116/hitlin_UV_BaF2_sensor_Trento_200219-.pdf.
[7] B. Echenard *et al.*, "*Crystal and Photosensor Development for a Fast BaF_2 Electromagnetic Calorimeter*,". LOI for Snowmass 21 submitted to Topical Groups IF2 and IF5.
[8] D. Hitlin *et al.*, "*An APD for the Detection of the Fast Scintillation Component of BaF_2*," IEEE Transactions on Nuclear Science **63** (2016) 513.
[9] S. Magill *et al.*, "*Wavelength-shifting properties of luminescence nanoparticles for high energy particle detection and specific physics process observation*," Scientific Reports **8** (2018) 10515.