<u>LOI:</u> Advanced Optical Instrumentation for Ultra-compact, Radiation Hard EM Calorimetry Applications

Snowmass2021 Topical Areas: Instrumentation Frontier (IF) – (IF6) Calorimetry; and (IF2) Photosensors and Energy Frontier (EF) – (EF4) EW Physics: EW Precision Physics and constraining new physics; and (EF4) EW Physics: Higgs Boson properties and couplings.

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Abstract:
To address the challenges of providing high performance calorimetry in future high energy physics experiments under conditions of high luminosity and high radiation, we are conducting R&D on advanced calorimetry techniques suitable for operation in such environments, based on scintillation and wavelength-shifting technologies and SiPM technology. In particular, we are focusing our attention on ultra-compact radiation hard EM calorimeters with structures consisting of alternating layers of very dense absorber and scintillating plates, read out via radiation hard wavelength shifting (WLS) solid fiber or capillary elements and SiPM positioned either proximately or remotely, depending upon the radiation tolerance of the photosensors.

Research and Development Program:
Our approach to radiation tolerant EM calorimetry is based upon the following criteria: (1) Use of dense materials to minimize the cross sections and lengths of the detector elements; (2) Maintaining the Molière Radius as small as possible; (3) Use of radiation-hard materials; (4) Use of optical techniques that can provide high efficiency and fast response; (5) Keeping all optical paths as short as possible; and (6) Use of radiation resistant, high efficiency photosensors.

Guided by these criteria, prototypical modular structures we have been developing consist of interleaved absorber (typically 2.5mm thick W) and inorganic scintillator or ceramic scintillator plates (for example 1.5mm thick LYSO:Ce), with total depth in radiation lengths of $\geq 25\ X_0$ and no more than one absorption length λ. These materials yield very compact EM modular structure of dimensions of 14 x 14 x 114mm^3, with the 14mm transverse dimensions set by (and equal to) the Molière Radius.

This R&D program focuses on development and characterization of the scintillation plates, the waveshifter structures and the photosensors that comprise such modules. While substantial progress has been achieved, [1] further developments are essential to provide successful operation under FCC-hh environmental conditions.

Our primary goal is to achieve the desired endcap EM endcap energy resolution of:
$\sigma_E/E = 10\%/\sqrt{E} \oplus 0.3/E \oplus 0.7\%$ under FCC-hh operating conditions up to $|\eta| \leq 4$, noting that for $|\eta| \leq 2.5$, the environmental conditions are expected to be 100Mrad ionization dose and $3\text{x}10^{16}$ 1 MeV n_{eq} fluence.[2]

Our stretch goal is to aim beyond the FCC-hh endcap region and to operation in the FCC-hh forward region, where the operating conditions are a sobering 500 Grad ionization dose and 5×10^{18} 1 MeV n_{eq} fluence.[2] To reach this domain will require major further innovations in materials instrumentation and photosensor development.

Scintillator Plates: Promising candidates include RE3+ (Ce^{3+} or Pr^{3+}) activated bright, fast and radiation hard inorganic scintillators, such as LYSO, LuAG, GGAG, GYAG and GLuAG, in both crystal and ceramic form. We have measured radiation harness of LYSO crystals against ionization dose up to 300 Mrad, neutrons up to 9×10^{15} n_{eq}/cm^2 and protons up to 8×10^{15} p/cm^2. The results of these investigations served as a foundation for the LYSO+SiPM BTL detector for the CMS upgrade for the HL-LHC. We also found that radiation hardness of some novel scintillating ceramics, such as LuAG:Ce, are better than LYSO crystals, indicating promise for FCC-hh. Additionally, CsPbX3 plates (with X = Cl, Br, I, mixed Cl/Br and mixed Br/I) quantum dots (QD) featured with very bright and tunable emission with sub-nanosecond decay time over visible wavelength region will also be investigated.

Waveshifters and Waveshifting Elements: The waveshifting material must be contained within radiation hard optical transmission elements, to transmit the wave-shifted light to photosensors. Among the promising candidates are sealed quartz capillaries filled with WLS liquids spectrally matched to the scintillation plates. Candidate WLS dyes include DSB1, DSF1 for very fast decay times. Also under active consideration are alternative structures incorporating non-liquid, solid inorganic WLS materials such as Quantum Dot/glass composites, and long-wavelength emission fluorescent dyes ($\lambda \geq 540$nm) based on Excited-State Intramolecular Proton Transfer (ESIPT) fluors for improved long-distance optical transmission.

Photosensors: We have been developing photodetectors of very small pixel size (5-7 microns) based on silicon (SiPM) technology, with emphasis on wavelength optimization, high photo detection efficiency, low saturation, fast recovery and low temperature operation for radiation resistance (including on-board cooling). This program will develop and refine small pixel devices with especial emphasis on light detection in longer wavelength (green/red) and shorter wavelength (ultraviolet/violet) spectral domains. Additionally, we continue to develop pixelated Geiger mode devices in other (larger bandgap) technologies to meet the challenges of photodetection in the FCC-hh calorimetry environment for $|\eta| \geq 2.5$.

Testing: Performance of modular detector assemblies will be tested for performance and timing characteristics following radiation exposures that will include standardized test procedures, performance metrics, and monitoring tools. This includes plans to characterize the performance and radiation degradation of candidate solid state photodetectors.

Applications: The impact of this research and development program, while not experiment specific, is potentially broad and significant, and can be expected to inform further developments in high energy physics instrumentation. The technologies are versatile and can be applied in particle physics, nuclear physics, materials science, basic energy sciences and extended to medical physics and homeland security domains.

References:
[1] https://notredame.box.com/v/RadHardEMCal
[2] M. Aleksa, et al, Calorimeters for the FCC-hh, CERN-FCC-PHYS-2019-0003