Design and Prototyping of a High Granularity Scintillator Calorimeter

Project Summary:

Calorimeters have come to play an increasingly important role in high energy particle, astro-particle and neutrino experiments. Of particular interest to future experiments in these fields will be compact, high-granularity calorimetry which would allow improvements in position and energy resolution, imaging of spatial and temporal development of showers and tractability of high density particle environments. With this in mind we have been successfully investigating fine-granularity scintillator-Silicon Photomultiplier (SiPM) calorimetry, an option which capitalizes on the marriage of proven detection techniques with novel photodetector devices.

In this regard our focus has been on the design and prototyping of an integrated readout layer (IRL) consisting of a printed circuit board inside the detector which supports the directly-coupled scintillator tiles, connects to the surface-mount SiPMs and carries the necessary front-end electronics and signal/bias traces. Prototype IRLs were prototyped and successfully took beam at CERN in the 2014-15 period.

Concepts and implementations of an IRL carried out as part of this award promise to result in the next generation of scintillator calorimeters. The design would be applicable to both electromagnetic and hadronic calorimeters. Apart from conventional calorimetry in a variety of environments, the segmentation and compactness achievable would be of great interest to particle-flow calorimetry. Furthermore, the R&D has relevance for segmented crystal calorimetry which can have a wide range of applications including dual-readout calorimetry.

Project Description:

Over the past few years, our detector research and development efforts have been directed at using Silicon Photomultipliers (SiPMs) [1]-[2] for calorimetric applications [4]-[9]. SiPMs are multi-pixel photo-diodes operating in the limited Geiger mode. They have distinct advantages over conventional photo-multipliers due to their small size, low operating voltages and insensitivity to magnetic fields. The in situ use of these photodetectors [3] opens the doors to integration of the full readout chain to an extent that makes high channel count scintillator calorimetry entirely plausible. Also, in large quantities the devices are expected to cost a few dollars per channel making the construction of a full-scale detector, instrumented with these photo-diodes, financially feasible.

The main challenge for a scintillator-based calorimeter is the architecture and cost of converting light, from a large number of channels, to electrical signal. Our studies demonstrate that small cells with embedded SiPM photodetectors offer the most promise in tackling this issue. The very large number of readout channels can still pose a significant challenge in the form of complexity and cost of signal transport, processing and acquisition. The development of an Integrated Readout Layer (IRL) comprised of the scintillator, photodetector and front-end electronics is thus crucial in carrying the scintillator calorimeter design forward. Research into this integration has been the focal point of our work described in the following sections. Support received from the

NSF/DoE funded LCRD and Advanced Detector Research programs has been indispensable for this progress.

In general, for the IRL, we propose to have a printed circuit board (PCB) inside the detector which will support the directly-coupled scintillator tiles, connect to the surface-mounted silicon photodetectors and carry the necessary front-end electronics and signal/bias traces. Towards this goal we have made the following innovative design choices:

Significant simplification in construction and assembly ensue if SiPMs can be coupled directly (i.e. in a fiberless fashion) to the scintillator tiles. Equally importantly, the total absence of fibers offers greater flexibility in the choice of the transverse segmentation while enhancing electro-mechanical integrability of the design. Pioneering studies on the response and response uniformity of these directly-coupled tiles were carried out and conclude that with a spherical concavity machined into them, they give adequate response while exhibiting good response uniformity (see Fig. 1). Thus they are promising as elements of any scintillator calorimeter requiring fine segmentation. These results have been verified on the test-bench with a ^{90}Sr source and at the Fermilab test beam with high energy protons [10]-[11]. The fabrication of millions of spherically dimpled, uniform quality, precisely sized and optically isolated tiles can pose a significant challenge for which we have been investigating techniques like injection molding (see Fig. 2). In large quantities this technique results in low per part production costs which is ideal for a high granularity scintillator calorimeter. A staged production R&D program, carried out over a number of years, has led to the fabrication of spherically dimpled injection molded tiles which are comparable in response and response uniformity to their cast, machined brethren making a reasonably priced fine-granularity scintillator calorimetry all the more plausible.

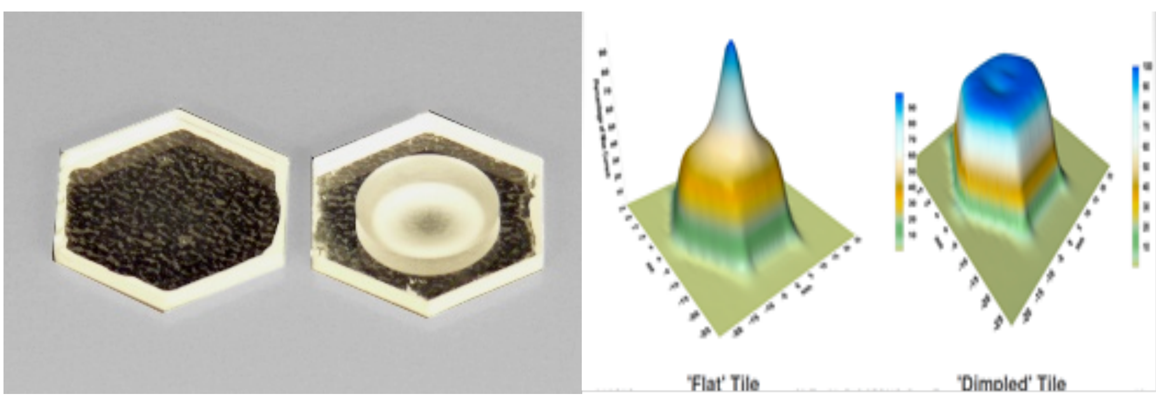

Figure 1: Flat and shaped scintillator cells (the cell surfaces have been faced with rumpled paper to ensure visibility).The response of the flat and shaped (or dimpled) cells to a radioactive source.

Mechanical considerations having to do with alignment of the scintillator with the PCB, placement of tiles with respect to each other and management of tolerances, point to the individual tiles not being an ideal unit for assembly of the integrated readout layer. In our design of the IRL, this issue is addressed by mating mega-tiles (or tile arrays) to the underlying PCB.

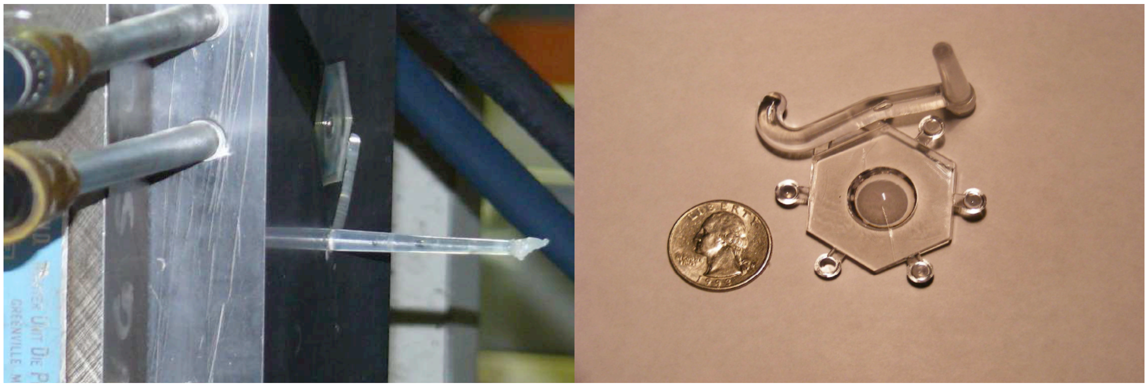

Figure 2: A hexagonal injection molded dimpled tile (right) produced with the injection mold die (left).

The mega-tiles are n x m arrays of tiles with thin layers of titanium dioxide epoxy between them which serves as the optical isolation and allows the array to be handled as a rigid unit (see Fig. 3). The task of placing the tiles is in this scheme then reduced to lowering the mega-tile on to the PCB and aligning the whole unit with respect to the sensors with just a couple of alignment pins. We have machined mega-tiles with great success and have obtained promising results on extending the approach to small injection molded arrays.

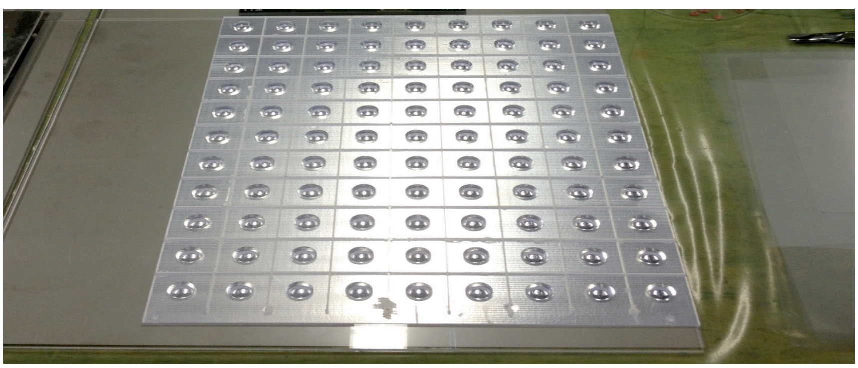

Figure 3: An example of a machined array of dimpled tiles a.k.a. Megatile.

The first IRL prototype was fabricated with Fermilab engineering support. The design was not optimized for any specific application but served as a rigorous proof-of-principle for our concept of the electro-mechanical integration required for fine-granularity scintillator calorimetry. Subsequently, IRL prototypes suitable for Linear Collider hadron calorimetry were fabricated. They respect constraints on the thickness of the IRL, the mechanical tolerances allowed, constraints on the power dissipation and issues associated with the assembly and commissioning of large scale systems. This phase of our R&D was carried out in co-ordination with CALICE/EUDET groups. This allowed for an optimal use of the available resources with our (NIUs) unique concept of the electro-mechanical integration of the scintillator-SiPM layer being implemented within a world-wide co-ordinated approach. A fully instrumented IRL prototype board carrying the CALICE front-end electronics and using surface-mount SiPMs directly coupled to a megatile were inserted into the CALICE/EUDET absorber stack and took beam at CERN in the 2014-15 period. While the IRL sat inside the absorber structure it was read out (as were all other instrumented layers of the stack) with the help of a Detector Interface (DIF) board sitting outside which was fabricated by NIU in collaboration with DESY and Fermilab.

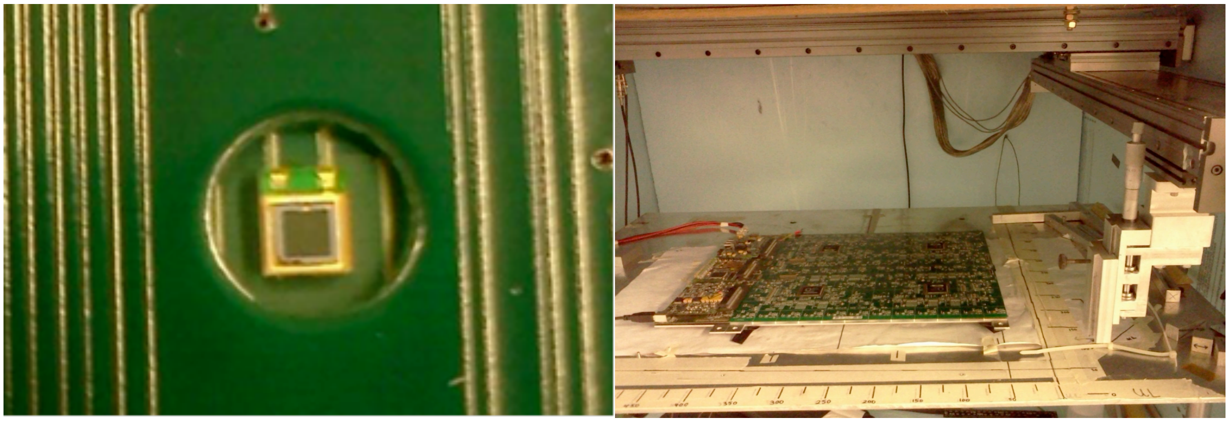

Figure 4: The IRL being tested with a source scanner (right). A close-up of the surface-mount SiPMs on the IRL (left).

The CERN test beam with the NIU IRL inserted in the CALICE/EUDET absorber wedge allowed for the rigorous testing of mechanics, calibration and particle responses under very realistic conditions. Commissioning of the IRL before and after insertion in the stack were first completed. The wedge was then moved to CERN and took beam with participation from NIU personnel in installation, data-taking and operations. The wedge consisted of a 30 layer steel absorber stack with 15 of it's gaps instrumented. The first eleven active layers were next to each other and contained one HBU (note NIU's IRL is a special kind of HBU referred to as SM_HBU or surface-mount Hadron Calorimeter Base Unit) each. An HBU is 144 channels. The remaining 4 layers had four HBU's each but were spaced out longitudinally to sample the shower generated by the incident particle at different depths.

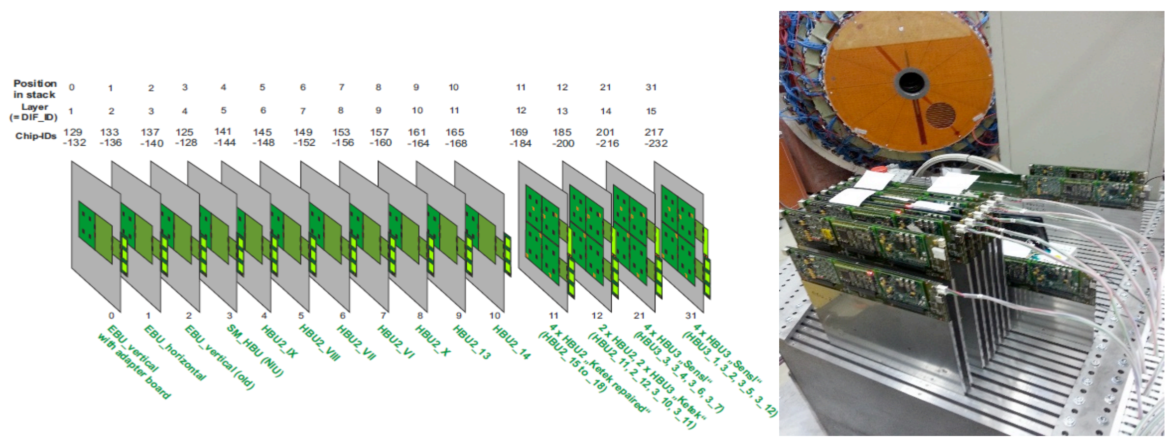

Figure 5: The CALICE test beam configuration (left). HBUs inserted in the absorber stack (right).

Results from the test beam establish the IRL approach as the most promising to take the design of a fine-granularity scintillator calorimeter forward. There have been a number of alternative approaches that have been investigated by groups in the CALICE Collaboration as far as the construction and assembly of the scintillator HCAL layer is concerned. The thinking has always been that the best option will be specified as the baseline design in the Technical Design Report.

It is gradually being realized by numerous groups that NIU's version of the IRL offers significant advantages. This has led to the establishment of a coordination group consisting of NIU, German and Russian groups under Zutshi's leadership to carry this design forward. The group is charged with examining and addressing all remaining issues related to the IRL design such that a fully technically specified solution can be obtained.

References:

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