Results of R&D on a new construction technique for W/ScFi Calorimeters

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Abstract. We report on results of an R&D program to develop new, simple and cost effective techniques to build compact sampling calorimeters utilizing tungsten powder and scintillating fibers. Such calorimeter detectors are under consideration for experiments at the planned Electron Ion Collider and the future upgrade of the STAR experiment at RHIC (BNL). In the first year of this R&D project we built two prototypes of very compact electromagnetic calorimeters and tested them at FNAL test beam T1018 in January 2012. Details of the construction technique, results of the test run and future plan will be presented.

1. Introduction
A high-energy polarized Electron-Ion Collider (EIC) will present new scientific opportunities to advance the understanding of cold nuclear matter and the spin structure of the proton in QCD with unprecedented precision [1]. Calorimetry is a critical component of a dedicated EIC detector. The requirements for calorimeters for this detector (end caps, barrel, very forward) differ significantly in terms of resolution, granularity and radiation hardness. All these calorimeters need to be compact and hermetic, in addition, they must be able to work in the presence of a magnetic field of about 2 T. Detailed requirements for these detectors are presently under investigation.

In addition, current RHIC experiments, both STAR and PHENIX, are planning for major upgrades to explore new physics opportunities along with the accelerator upgrade. The STAR experiment, for example, is working on a forward instrumentation upgrade to elucidate the dynamics that underlie the observed large transverse single-spin asymmetries in polarized $p+p$ collisions and explore the onset of gluon saturation in $p+A$ collisions. Important components of this program will require the ability to measure identified hadrons ($\pi^0$, $\eta$, $\Lambda$...) at large rapidity, charged hadrons, direct photons, $e^+ e^-$ pairs from Drell-Yan and $J/\Psi$ production, and jets, as well as di-hadron and $\gamma$+hadron correlations. A compact, highly granulated, compensated Forward Calorimeter System (FCS) is being pursued by the STAR collaboration for a future upgrade.

A scintillating fiber calorimeter technique [2, 3, 4] seems to be a suitable option for some part of the dedicated EIC calorimeter system and for the upgrade of the STAR forward calorimeter system. This technique allows construction of versatile compact and fine-grained sampling electromagnetic and hadronic calorimeters with good energy resolution, hermeticity, homogenity, timing and position resolutions [5, 6, 7]. We proposed to investigate new methods of construction of fiber calorimeters for possible application for EIC and STAR under the generic EIC detector R&D program sponsored by
the DOE nuclear physics and BNL. In the first year of this program we aimed at demonstrating the 'proof-of-principle' with construction and beam tests of small prototypes. The targeted electromagnetic energy resolution was chosen somewhere in between preliminary requirements for EIC and STAR, and is close to 12%/$\sqrt{E}$. In addition, the sampling fraction $f_s$ was kept close to 2% in order to satisfy the requirement of compensation for the STAR FCS system. The sampling term for energy resolution for such a detector is expected to be close to $2.7%\sqrt{(d/f_s)}$ where $d$ is the diameter of the scintillating fibers in mm [3].

2. Construction technique

Despite the simplicity of fiber calorimeters, building them is not a trivial process. Detector components have to be produced with very high tolerances to keep the detector homogeneous. In the past, extrusion, machining or rolling techniques were employed to produce the absorption plates. These processes were not simple. Usually construction of special machines and tooling to produce absorber plates were needed. Assembling these calorimeters is a labour intensive process, because multiple elements of the detector had to be handled essentially one by one. These factors contributed to higher costs for fiber calorimeters compared to scintillation plate detectors. Traditional techniques are also prone to limitations with respect to increased sampling frequency, because thinner absorber layers and thinner fibers become more and more difficult to produce and handle. Construction and assembly techniques for JETSET, KLOE and H1 (figure 1) calorimeters are described in [5, 6, 7].

A succinct description of our technique is the following: first we form a matrix of fibers and then the absorber is poured into this matrix. The main difference from previous techniques is that the individual elements of the calorimeter do not need to be handled separately.

![Figure 1](image_url)

Figure 1. Fiber/absorber structure of typical ScFi calorimeters [8] (left); fibers 0.5 mm in diameter, fiber spacing 0.9 mm. (right) Fiber/tungsten powder structure of one of our mechanical prototypes: square fibers 0.25 mm x 0.25mm, lower rows: round fiber 0.33 mm diameter, spacing 0.88 mm.

The first key element in our technique is the utilization of tungsten powder as an absorber. We used tungsten powder produced by Tungsten Heavy Powder, Inc. The properties of this powder (Technon® Ultra) are: particle size distribution 90% between 40 and 150 microns, bulk density 18.5 g/cm$^3$, tap density 11.25 g/cm$^3$. The chemical composition is: W > 99.3%, Fe < 0.05%, Ni < 0.05%, O$_2$ < 0.5%, others (Co, Cr, Mo and Cu) < 0.5%. This tungsten powder also has very good fluidity, an important property in our application. The only operation with the absorber material that needs to be performed is to measure the right amount of powder before pouring it into the fiber matrix assembly. The cost of this tungsten powder by weight is about 30% of the cost of 1 mm thick tungsten sheets. The powder is produced from scrap tungsten metal.

The second key element in our technique is a simple method of forming a matrix of scintillating fibers. The matrix is defined by a set of precision brass meshes produced by photo-etching. Typical mechanical tolerances for these meshes are 30 microns on overall dimensions for 300 micron thick
meshes and about 15 microns on center-to-center distances between the holes for the scintillation fibers. Scintillation fibers were cut to desired length by a thermo-cutter. This causes the end of the fibers to melt, forming a small drop which works as a stopper to prevent the fibers from slipping through the openings in the mesh. With all the meshes stacked together, the scintillation fibers are fed through by simply dropping about 500 fibers at a time into the container holding the meshes. With a slight tapping on the holding container all the fibers will flow through the set of meshes in a matter of a few seconds. For our latest prototype the whole process of forming a matrix consisting of about 1500 fibers took about 30 minutes. A short video clip explaining assembly process is available on-line [9].

The idea of using W powder as an absorber was briefly investigated by the UCLA group in 2003 with the construction and test of a small electromagnetic prototype at SLAC. The mechanical structure of the towers required a thin walled brass container to hold dry powder and fibers in place. It was later found that the assembly technique at that time was not perfect, leading to large transverse non-uniformities in the response of the detector due to variations of sampling fraction along the depth of the towers and possible displacement of the fibers during packing. A compact calorimeter requires very strict mechanical tolerances and very uniform internal structure to achieve theoretical resolution. To solve problems with non-homogeneity in the composition of the towers and at the tower boundaries we introduced intermediate meshes to hold fibers along the towers and developed a vacuum-assisted method to infuse optical epoxy into the tungsten powder/fiber assembly. Since the whole assembly becomes rigid and stable there is no need for any type of external container. This eliminates dead material in the tower assembly. These additional meshes also allow arrangement of fibers in an accordion configuration, a mechanical structure almost impossible to build with traditional construction techniques. The use of precision meshes and precise molding forms to produce sub-assemblies assured good mechanical tolerances and uniform spacing between fibers as well as uniform sampling fraction along the towers and from one tower to another tower. A few mechanical samples were examined for homogeneity. The variation of density along the towers was found to be within 1%.

Using this technique we constructed two small prototypes of electromagnetic calorimeters.

Figure 2. Matrix of fibers in the molding forms prior filling with tungsten powder (a). Finished block of ‘spacal’ type prototype before light guides were glued in place, as seen from the photo-detector side (b). Different stages of the gluing of the ‘spacordion’ prototypes from small sub-assembly units (c).

Each detector consists of sixteen towers. The main difference between these two detectors is the arrangement of the scintillation fibers. In the first detector (called a ‘spacordion’) we used Bicron BCF 12 [10] 0.33 mm diameter fibers spaced by 0.88 mm and arranged in an accordion shape as seen in figure 2 (a). In the second detector (called a ‘spacal’) we used KURARAY SCSF 78 [11] 0.47 mm diameter fibers spaced by 1 mm and placed parallel to long axis of the tower. The parameters of the ‘spacal’ prototypes are: final density of 10.17 g/cm³, radiation length – 7 mm, Molere radius – 23 mm, sampling fraction for electrons 2%. Each ‘spacal’ super module was glued from two subassemblies. Dimensions of the super modules are: 166 x 53.3 x 53.3 mm³. The average weight of super modules is 4636 grams. The difference in the weight of different super modules is about 0.5%. Each super module holds 3120 fibers. The composition of the towers at the front (first 2.5 mm) and
back sides (last 5 mm) is epoxy and fibers only. These regions are free from tungsten powder. That was made to achieve good quality optical surfaces by machining the ends of the super module (otherwise particles of tungsten powder scratch the fibers). For the test run the light from each ‘spacal’ super module was collected by 20 cm long tapered trapezoidal acrylic light guides enclosed in an Enhanced Specular Reflector (ESR) mirror pipe into a single photo-multiplier (Electron Tube 9125B). The front face mirror was made from ESR film and coupled to the front face of the super module with optical grease. PMTs were coupled to the light guides by optical grease. To verify the uniformity of light collection one super module was scanned across the front face of the detector with a 350 nm LED. Photographs of these prototypes are given in figure 2.

3. Results of the Test Run

The goal for the first year of R&D was to demonstrate ‘proof-of-principle’ with a beam test of the prototypes. The most important parameters for future developments are: energy resolution, more precisely, how close is the measured resolution to a GEANT4 prediction, and the absolute light yield.

The FNAL test beam setup T1018 in the Muon Test Beam Facility (MTBF) is given in figure 3. The absolute energy scale of the beam was set with a high resolution large lead glass block provided by the MTBF. The momentum spread of the beam below 4 GeV was estimated by previous T1005 test beams to be about 2.7% [12] which is consistent with our measurements with the lead glass calorimeter. At 8 GeV we estimated the momentum spread of the beam to be 2.3%. Electrons were identified with a threshold Cherenkov counter (standard equipment at the MTBF). Impact position was defined by a scintillation XY hodoscope (4.9 mm wide scintillation square rods readout by SiPMTs). Calorimeter prototypes were mounted on a movable platform at an angle of 3° with respect to the beam. The lead glass calorimeter was located just behind the detectors under test. To measure attenuation lengths and homogeneity along the towers all ‘spacal’ modules were re-arranged as shown in figure 3, the ‘spacordion’ was rotated 90°. In some tests two of the ‘spacal’ modules had their front face mirrors replaced with black absorber tape. To measure energy resolution of the ‘spacal’ the impact points were restricted to an area 2x2 cm² at the center of the spacial super module (corner of four towers, which represents the worst possible case for non-uniformities). The energy resolution for the ‘spacordion’ is derived from the energy measured by 3x3 towers clusters. To identify minimum ionizing particles (MIP) during longitudinal scans, signals in all four ‘spacal’ super modules (total depth ~30X0) and signal in the lead glass calorimeter located behind them, were all required to be within MIP peak. To verify the uniformity of response in the transverse direction the impact points in the central area of ‘spacal’ was selected by the hodoscope. Within 2x2 cm² the transverse non-uniformity measured with 4 GeV electrons is 1.4%. The light yield from the ‘spacal’ measured with a front mirror is close to 2000 photo electrons (pe) per GeV (PMTs were preselected and calibrated prior to the test run with single photo-electron response). The ESR mirror at the front face adds about 70% more light. In any case (with or without mirror) the contribution of the photo-statistics to the energy resolution is very small. The light yield from the ‘spacordion’ was measured to be close to 1000 pe/GeV. The beam settings at 4 GeV were somewhat questionable. It is possible that beam settings during calibration runs with the lead glass and during test measurements were different. The resolution results are presented as a raw (without any corrections) and with beam momentum spread subtracted. This correction is small at low energy. No other corrections were applied.
Figure 4. Measured energy resolution of ‘spacal’ and ‘spacordion’ prototypes compared with GEANT4 prediction.

The measured resolution for ‘spacal’ is very close to GEANT4 prediction (dotted line in figure 4). The energy resolution of a single ‘spacal’ super module is slightly worse than theoretical limit (solid line in figure 4) due to transversal energy leakage. Prior to the test run the expectation was that the energy resolution for the ‘spacordion’ should be somewhat better compared to the ‘spacal’ due to increased sampling frequency with about the same sampling fraction. That was not confirmed by the test.

Figure 5. Attenuation length for ‘spacal’ measured with MIPs and electrons.
The longitudinal scans with 8 GeV beam along the towers were performed to measure the uniformity of composition along the length of the towers and to measure the attenuation of light in the fibers. From a single data sample both MIP and electrons can be cleanly identified for the ‘spacal’. For the ‘spacordion,’ the position of the MIP peak was too close to pedestal, thus only electrons were used to measure the light attenuation length. The uniformity of composition was found to be better than 5%, (figure 5, data points (c)). Four points above the fit were excluded because they correspond to the 300 micron thick brass meshes which effectively shift the development of the shower. ‘Spacal’ 2 was located second downstream in the beam line as shown in figure 3. The attenuation lengths measured using MIPs with and without a front face mirror were close to what was expected. The same light attenuation length measured with electrons was much shorter, 106 cm vs 250 cm. The only explanation for this at this point is the difference in the spectrum of light produced by MIPs and particles in the electromagnetic shower, mainly the proportion of Cherenkov light. The attenuation length for the ‘spacordination’ was found to be close to 50 cm. The much shorter attenuation length of ‘spacordination’ partially explains the worse-than-expected energy resolution for this detector, which was late confirmed with GEANT4 simulations.

4. Conclusions
The ‘proof-of-principle’ for a new simple and cost effective method of building compact scintillation fiber calorimeters has been demonstrated. In principle, very high sampling frequencies and non-traditional arrangements of fibers can also be achieved with this method. We also learned that thin fibers (diameters smaller than 0.5 mm) will limit resolution due to a very short attenuation length. Wiggling of scintillation fibers significantly complicates assembly of the detector; in addition it probably caused some decrease in the attenuation length. We will not pursue these directions in our future R&D effort. There are a lot of questions beyond ‘proof-of-principle’ which need to be answered: mechanical integrity under load, light response under load, and challenging question of compact readout. An extension of this technique for wedge-shaped towers is also under consideration. We plan to address these questions in the near future.

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