One Page Summaries for eRD1 Report

March 5, 2021

1. **Developments for Homogeneous Calorimetry for EIC using Crystals and Glasses (CUA/Orsay)**

2. **Developments for a Tungsten Scintillating Fiber EMCAL and Iron Scintillator HCAL for EIC (UCLA)**

3. **New Developments for Tungsten Scintillating Fiber Calorimetry for EIC (BNL)**

4. **R&D on a Tungsten Shashlik Calorimeter for EIC (BNL/UNAB).**

eRD1: $PbWO_4$/Glass for EIC homogeneous calorimeters (1-page Summary)

The overarching goal of this R&D project has been to reach a level for both $PbWO_4$ and glass to be considered as active material for EIC calorimeters. These R&D activities are well aligned with the EIC UG Yellow Report Calorimeter and R&D needs. This project's main R&D areas are 1) $PbWO_4$ and SciGlass for a precision electron endcap electromagnetic calorimeter and other detector regions, 2) CSGlass for possible improvement of hadron calorimeter resolution. The R&D for $PbWO_4$ has been largely completed. The status of the glass R&D topics is described below.

SciGlass is a radiation hard material optimized to provide characteristics similar to or better than $PbWO_4$. SciGlass fabrication is expected to be cheaper, faster, and more flexible than $PbWO_4$ crystals. SciGlass is being developed by Scintilex, LLC in collaboration with the Vitreous State Laboratory at CUA. Tremendous progress has been made in the formulation and production of SciGlass that improves properties and solves the issue of macro defects. Scintilex has demonstrated a successful scaleup method and can now reliably produce glass samples of sizes up to ~10 radiation lengths. Simulations combined with initial beam tests at photon energies of 4-5 GeV suggest that high resolution competitive with $PbWO_4$ can be reached for $\geq 15\ X_0$. SciGlass has excellent radiation resistance (no damage up to 100 Gy electromagnetic and 10^{15} n/cm^2 hadron irradiation, the highest doses tested to date), response time of 20-50 ns, and good transmittance in the near UV domain. The SciGlass insensitivity to temperature is also a clear advantage over $PbWO_4$, which has a dependence of about 2-3%°C and has to be continuously monitored. The present samples have a density up to 5.4 g/cm^3, radiation length of 2.2-2.8 cm, and a Moliere radius of 2-3 cm. The areas of needed R&D for SciGlass include the final formulation optimization, scale up to block sizes $\geq 15\ X_0$, and beam tests to establish characteristics like energy resolution. The most critical items are to demonstrate scale up to block sizes $\geq 15\ X_0$ and to establish SciGlass characteristics with beam tests. The approximate timeline for completing the SciGlass R&D is about one year assuming R&D funds are available. The goal is to be ready for a day-1 detector. SciGlass could also be available for future detector upgrades. The estimated cost is $66.5k, which was approved in July 2020, but the funds have not yet been received.

CSGlass is optimized for the dual readout approach, where one compares the signals produced by Cherenkov and Scintillation light in the same detector. This approach has been a promising method to achieve better performance for hadron calorimeters. CSGlass is derived from SciGlass and expected to be similarly resistant to EM and hadron irradiation up to 100 Gy and 10^{15} n/cm^2, the highest doses tested so far. The CSGlass interaction length is comparable to crystals and should allow for small tower size. The anticipated space for the homogeneous calorimeter configuration could be similar to a binary system and may provide better resolution. The areas of needed R&D for CSGlass include the demonstration of CSGlass with sufficient UV transparency for Cherenkov light collection, clear separation of Cherenkov and Scintillation light of sufficient intensity (slow scintillation, > 500 nm beneficial), low cost, and characterization of CSGlass in the lab and with test beam R&D prototypes. The most critical items are the formulation optimization and production of CSGlass test samples. The approximate timeline for completing the CSGlass R&D is around three years assuming R&D funds are available. CSGlass could be ready for future detector upgrades. The estimated cost for this R&D is $60k/year for three years.

Summary: UCLA Group et al. Subproject on W/ScFi EMCal and Fe/Sc HCal development

Accomplishment to date:

- Experimental proof of feasibility of W/ScFi technology for very compact sampling electromagnetic calorimeters with energy resolutions varying from (7%-12%)/sqrt(E) for stochastic and (1-2)% for constant term. Several designs of prototype calorimeter utilizing the W/ScFi technology were built and tested with beams at FNAL during 2012-2016 period.
- Demonstration of new effective construction technology for sampling hadron calorimeters with good energy resolution. Two prototypes were built and tested at FNAL in 2014, 2019. A 30 ton HCAL for the STAR Forward Calorimeter System was constructed in 2020 using this innovative technology.
- Multi-year studies of SiPM characteristics in beam conditions close to those expected at high luminosity EIC. Notably, during Run 2017 at RHIC with 500 GeV pp data, our observation led to new understanding of mechanism responsible for the degradation of SiPMs responses after exposure to neutrons and ionization particles.
- Development of compact readout schemes using SiPMs for W/ScFi and Shashlyk type calorimeters (e.g., the STAR Forward Calorimeter System using SHASHLYK EMCal ~ 1500 channels instrumented in 2020) and WLS/SiPM for HCals (STAR Forward HCal 520 channels).

Assessment of technological readiness:

- We have demonstrated the W/ScFi and new HCal technology and it is ready for EIC. Analysis of the STAR Forward Calorimeter System data will provide detailed performance evaluation. We expect that this technology will meet the EIC physics requirement up to 2.5 pseudo-rapidity. In the very forward pseudo-rapidity above 2.5, new technology will be investigated if higher energy resolution is required.

Assessment of work remaining for TDR, ballpark cost estimate and timeline.

- Finish MC optimization hadron endcap calorimeter system optimization for the EIC reference detector.
- Construction and test of a full scale W/ScFi + Fe/Sc calorimeter system for EIC.
- Cost estimate will require engineering design of mechanical structure of calorimeter systems. In rough cost estimate can be extrapolated by scaling from the STAR Forward Calorimeter System construction project. Engineering design of the mechanical structure for the calorimeter and a thorough cost evaluation will be needed for TDR.
- Construction and test of full scale W/ScFi+Fe/Sc prototype will require approximately one and a half year. We hope to use the prototype construction project to build up the hadron endcap calorimeter consortium for the EIC reference detector construction.

Summary for the Development of Tungsten Powder Scintillating Fiber Electromagnetic Calorimeters for EIC (BNL)

Accomplishments to date:

The technology for a compact tungsten powder scintillating fiber electromagnetic calorimeter was originally developed within the eRD1 Consortium, starting with the initial developments at UCLA (as described above), and then later by BNL and UIUC, which developed this technology for full scale deployment in the sPHENIX calorimeter. The major accomplishments achieved by the BNL/UIUC group are:

- Development of 2D projective, 4 tower absorbers blocks in a variety of complex shapes that can used to form complete sectors and can be read out with a common light guide design.
- Extensive prototyping of various stages of design, including test beam measurements at Fermilab in 2014, 2016, 2017 and 2018. Results are published in two IEEE TNS publications, three conference proceedings and presented in many conference talks.
- Development of a cost effective, industrialized process for producing high optical quality light guides up to 1" long which were previously not available anywhere in the world.
- Development of an industrialized, mass production process for producing over 6K absorber blocks with a time period of approximately 1.5 years, including extensive QA and testing.
- Development of methods and procedures for producing 64 EMCAL sectors, each containing 384 2D absorber blocks, complete with cooling and readout electronics.
- Studies on radiation damage with SiPMs with gamma rays and neutrons, and developing and implementing procedures for stabilizing and controlling their gain during operation under radiation exposure. Results are published in an IEEE TNS publication.
- Initiated studies to utilize new larger area SiPMs to read out absorber blocks with greater efficiency and photoelectron yield (subject of this report).

Assessment of technological readiness:

We believe the technology for producing all of the components needed for a W/SciFi calorimeter for EIC is now extremely well developed and mature and is ready to be utilized if needed for other applications at EIC. However, there are still improvements that could be made relative to the sPHENIX calorimeter, such as increasing area of readout coverage of the blocks, improving the uniformity of response, and improving the energy and position resolution.

Assessment of work remaining for a TDR plus ballpark cost estimate and timeline.

The specifications for a new W/SciFi electromagnetic barrel calorimeter for EIC could likely be specified in a few months, once the new design was decided and given sufficient engineering and technical support. For use in an endcap calorimeter, it would be necessary to perform an engineering study to decide how to support the blocks and read them out, which would presumably take somewhat longer. The Total Project Cost (TPC) of the sPHENIX calorimeter is currently $5.1M but does not include labor at BNL. However, several hundred $K of additional funds outside the TPC, as well as a similar amount of EIC R&D funds, were also spent to develop the design and carry out much of the prototyping and testing.

Summary for the Tungsten Shashlik Calorimeter for EIC (BNL/UNAB)

Accomplishments to date:

The main purpose of this project is to develop a compact shashlik calorimeter using a tungsten alloy absorber that would occupy minimal space inside an EIC detector and also provide very good energy and spatial resolution. By reading out each WLS fiber in the shashlik design, one can effectively increase the transverse segmentation and measure the position and shape of electromagnetic showers, even within one Moliere radius, and therefore improve the ability to resolve single showers from pizeros at high momentum. This would then extend the reach of measuring direct single photons and related jet studies for many aspects of the EIC physics program.

The EIC R&D Committee recommended pursuing the concept of a W/Shashlik calorimeter with individual WLS fiber readout in July 2018. The project received its first funding in FY19 and was funded in FY20 but it did not receive any EIC funding in FY21, and therefore has only been ongoing for two years. During that time, the main effort was devoted to building a small, 3x3 module prototype using materials that were available from a prior project for NA64 at CERN. The modules were not optimized for use at EIC, but their constriction allowed us to develop some of the techniques that would be required to build such a calorimeter and to study some of its properties. This prototype was completed in early 2020, but further work on it stopped due to the pandemic. In July 2020, plans were proposed to construct a larger prototype that was better optimized for EIC but was not pursued due to lack of funding.

Without additional funding, our effort focused on performing simulations to compare the performance of a W/Shashlik calorimeter to a Pb/Shashlik calorimeter. In particular, we have focused on the PHENIX Pb/Shashlik design and have been studying its performance in its present form, which has rather coarse transverse segmentation. We also plan to investigate its expected performance if it were possible to re-instrument parts of the detector with individual WLS fiber readout and compare that to a W shashlik design. We present results on some of those preliminary studies in this report.

Assessment of technological readiness:

The technology for producing shashlik calorimeters is very mature and has been well understood for many years. This is primarily true for shashlik calorimeters with Pb absorbers but also applies for other types of shashlik calorimeters, including those with W absorbers, crystal scintillators and other variations. However, these detectors have typically only read out groups of fibers corresponding to a single tower. The concept of reading out each fiber, which was not possible or practical until the availability of small, low cost SiPMs, has never been proven.

Assessment of work remaining for a TDR plus ballpark cost estimate and timeline.

In order to demonstrate that this concept can improve the performance of a real calorimeter, we believe it would take approximately two years of R&D and development, including the construction of a moderate size prototype and testing it in the beam. Based on our experience with prototyping the sPHENIX calorimeter, we estimate that the cost for this would be in the range of $200-$300K.