Development of a forward calorimeter system for the STAR experiment.

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Abstract. We present results of an R&D program to develop a forward calorimeter system (FCS) for the STAR experiment at the Relativistic Heavy Ion Collider at BNL. The FCS is a very compact, compensated, finely granulated, high resolution calorimeter system being developed for p+p and p+A program at RHIC. The FCS prototype consists of both electromagnetic and hadron calorimeters. The electromagnetic portion of the detector is constructed with W powder and scintillation fibers. The hadronic calorimeter is a traditional Pb/Sc-plate sandwich design. Both calorimeters were readout with Hamamatsu MPPCs. A full-scale prototype of the FCS was tested with a beam at FNAL in March 2014. We present details of the design, construction technique and performance of the FCS prototype during the test run at FNAL.

1. Introduction

STAR is a large acceptance detector at RHIC. In the coming years the STAR detector system will continue to evolve through a series of upgrades towards superior detection capabilities and broader kinematic coverage, which will position STAR well for the p+p, p+A and A+A measurements and at the initial phase of an Electron Ion Collider (EIC) [1]. The STAR forward upgrade is mainly driven to explore QCD physics in the very high or low region of Bjorken $x$. At the core of the forward detector upgrade is the Forward Calorimeter System. This system, as shown in figure 1, will provide superior detection capability for neutral pions, photons, electrons, jets and leading hadrons covering a pseudo-rapidity region of 2.5-4.5. The design of the FCS is driven mainly by consideration of detector performance, integration into the STAR system and cost optimization. The FCS consists of a Spaghetti Electromagnetic (EM) Calorimeter (SPACal), followed by a lead and scintillator plate sampling Hadronic Calorimeter (HCal). The EM and HCal sections of the detector both are compensated calorimeters. Compensation (which requires small sampling fraction) provides the best possible energy measurement for single hadrons and at the same time keeps the system compact. To achieve good EM energy resolution in the calorimeter the sampling frequency in the EM section is kept...
sufficiently high with the choice of Scintillation Fiber (ScFi) technology. The SPAcal section will be made of tungsten powder and scintillating fibers in a spaghetti geometry. In order to do this, we have developed a novel construction technique through an EIC generic detector R&D project [2]. A prototype module was tested at a FNAL test beam in early 2012 and satisfactory performance of the detector was achieved [2]. Over the last two years we continued development of this technique through the STAR forward upgrade R&D and at present this technology is mature enough for mass production of W/ScFi modules. The proposed SPAcal has 120x80 towers. Active volume of a tower is approximately 2.5 cm x 2.5 cm x 17 cm corresponding to 23X_0 radiation lengths. The HCal section will be made of lead and scintillating tiles with each tower of 10 cm x10 cm x 81 cm corresponding to 4 interaction lengths. The sampling fraction and frequency were copied from the ZEUS Pb/Sc prototype [3]. We developed a novel construction technique for HCal to build the detector by stacking the tiles in-situ. This allows smooth integration in the STAR configuration. There will be 30x20 towers of HCal covering the same area as the SPAcal. Whenever possible, we also minimize the number of mechanical components and the construction and operation resources needed from the collaboration in order to carry out the forward upgrade project under the expected constraints for budget and other resources.

2. Description of FCS prototypes
A detailed description of the construction technique for EM sections can be found in [2]. A brief description of our technique is the following: first we form a matrix of scintillation fibers, then a powdered absorber is poured into this matrix. Residual air in the absorber is then replaced with epoxy, which turns the assembly into a rigid object. Different combinations of fiber arrangements and very fine sampling structures can be easily produced. Mechanical properties of the resulting W/ScFi assembly are close to that of structural steel, which allows hermetic, self-supporting structures to be built from this material. For the FCS EM section, we developed a method of building superblocks, each consisting of four individual towers, at once. This technique is mature enough to start the process of industrialization.

The HCal section is a stack of layers of absorber and scintillation plates. The easiest way to describe the assembly process is to imagine building an entire HCal block from LEGO style parts layer-by-layer. Figure 2 shows the basic mechanical structure of the HCal mechanical prototype. Holes in the bottom base plate of

![Figure 1. Planned upgrade of the STAR detector with a Forward Calorimeter System. Only the West side of the STAR detector is shown.](image1)

![Figure 2. HCal Mechanical Structure.](image2)
the detector provide locations of the absorber plates. Each absorber plate has four holes for dowel pins, two at the bottom and two at the top. Steel dowel pins (5 mm in diameter) position absorber plates with respect to the bottom base and top steel master plates. A single master plate covers one and a half rows of HAD towers, providing interlinks: between all absorber plates within one tower, between front and back steel plates of the HAD section and between adjacent rows of the HAD towers. The thickness of the absorber plates is 10 mm. They are made of lead-antimony alloy (4% Sb) and painted with white diffusive reflective paint (Sherwin Williams F63WC134). The gap between two adjacent absorber plates is 3.1 mm. Scintillation plates of thickness 2.5 mm (EJ-212) are placed inside these gaps. There are 63 absorber plates and 64 scintillation plates in a single HCal tower. Scintillation light from a single tower is collected with a 3 mm thick wavelength shifting (WLS) plate (EJ-280), which is placed in the gap between the two adjacent HCal towers as shown in figure 2. All scintillation and WLS plates are "floating" within each layer (there are no mechanical loads on these elements). Figure 3 shows an assembled HCal prototype. We assembled this prototype in place at the FNAL test beam to validate the construction technique. It took about eight hours for four people to build the sixteen-channel HCal prototype from the component parts at the test beam site.

The light collection scheme of the HCal was optimized to provide uniform and efficient light collection from all scintillation tiles along the depth of the HCal tower. All optical connections (except for coupling of the silicon photo-multipliers to the WLS) in the HCal were made through a thin air gap. We found that the best combination of reflective materials for the WLS plate is white diffusive reflector (Bicron BC-620) at the far end (from the photo-detector) and aluminized mylar at the back side (opposite to the edge of the scintillation tiles) of the WLS. The mylar film also serves as an optical isolator between HCal towers within one layer of the HCal. To achieve uniform light collection (within 10%) along the depth of the HCal tower, we placed a variable density filter printed on a clear mylar sheet inserted between scintillation tiles and the WLS plate. MC calculations show that without such a filter, the energy resolution of the HCal degrades by about factor of two for the energy range above 20 GeV compared to an ideal detector. Variation of light from tile-to-tile in the tower within 10% has negligible effect on energy resolution. Bench test measurements show that variation of the thin air gap between the scintillation tiles and WLS plate (due to mechanical tolerances required for HCal assembly) has a negligible effect on energy resolution of the detector as well. We found no degradation in light collection efficiency for unwrapped scintillation tiles placed between painted absorber plates compared to scintillation tiles wrapped in Tyvek.

We developed a new compact readout for the FCS. For both EM and HCal sections we decided to use silicon photo-multipliers (Hamamatsu Multi-Pixel Photon Counters (MPPC) S10931-025p). They are very compact, fast and insensitive to the magnetic field and sufficiently radiation hard for FCS readout in STAR [4]. The measured light yield (with a very efficient light collection scheme and PMTs) from the EM prototype in the test run in 2012 was 2000 p.e./GeV. We estimated that with 4 MPPC per tower for the EM section and with 8 MPPC per tower for the HCal section we will collect enough light to keep the contribution from photo-statistics to the energy resolution of the detector at a negligibly small level. The geometrical efficiency (ratio of active area of eight MPPCs to the output surface area of the WLS plate) of the light collection scheme for HCal is 8.2% and ~21% for EMcal.

Figure 3. A Sixteen channels HCal prototype.
towers.

A light collection scheme with WLS plates for HCal towers provides perfect light mixing. The situation is different for the EM section where light from the scintillation fibers is collected by the MPPC through a short (25 mm long) light guide/mixer. A bench test measurement prior the test run showed that with this scheme, non-uniformity of the light collection might be as high as 20% (difference between the hottest spots just under the MPPCs and at the corners of the towers). We decided to proceed with this scheme anyway to measure the absolute light yield with readout based on MPPCs and later redesign the light collection scheme for the EM section depending on results of the test run. The optical, mechanical and electrical integration of the readouts for the EM and HCal sections are given below.

Figure 4 A compact readout for the HCal section. The HCal FEE board is coupled with a WLS plate through Dow Corning 3145 RTV (left). Eight MPPC sensors mounted on the HCal FEE board (right).

We used two different sets of front end electronics to readout the FCS with the MPPC during the test run. The front end electronics for the HCal section is shown in figure 4. The HCAL front end board is designed for low power and reliable, low cost integration into a large detector system. The unregulated 90VDC input is regulated to the required SiPM bias voltage set by two DAC channels, one incorporating a thermistor. In this way, both the voltage and temperature compensation slope (to maintain a constant gain of the SiPM) are programmable. Signals from four SiPM’s are directly summed at the input of a single preamplifier, which is a regulated common-base stage using BFR92A transistors. The amplifier input impedance is very low, a few Ohms; as a result the high capacitance (1.3nF) of the four parallel SiPM’s does not limit the charge collection time as it would with a 50 Ohm input. The preamplifier is followed by a differential output driver providing a 4 V peak-to-peak signal to be used with low cost, low mass twisted pair cables to an external ADC system. The large signal swing and differential interface enables robust high dynamic range performance even if there is external EMI or ground noise in the system.

For readout of the EM towers, four MPPCs per tower were grouped so that all of them had the same gain at the same bias voltage. A single bias voltage was used for all sixteen channels. A simple resistive divider was used to set
the required bias voltage for individual towers. There was no temperature compensations of bias voltage for the EM prototype. Analog signals from these MPPCs were summed with the OPA691 operational amplifier. MPPC sensors for the EM prototype were first mounted on the FEE board, calibrated, and then potted with Dow Corning Sylgard 184 silicone. This silicone layer (~2 mm thick) served as an optical cookie and as a spring to keep the FEE board firmly attached to the light guide with a single plastic screw (visible at the center of the light guide in figure 5). The design of the light guide was not completely optimized prior to the test run. The light guide is an acrylic truncated pyramid with a height of 25 mm, base 25 mm x 25 mm and 13 mm x 13 mm at top. The distance between the centers of the MPPCs is 7 mm. Geometrical efficiency of the light collection scheme for the EMcal is approximately 21%.

3. Preliminary results of the test run.
The FCS system and a prototype of the EM central barrel calorimeter for a dedicated EIC detector were tested at the FNAL (experiment T1018) test beam facility in March of 2014. The data analysis and comparison with MC predictions are still in progress. The EM prototype of the central barrel calorimeter was built using the same technique as the forward EM prototype for the FCS. Towers for the EIC prototype had wedge shapes as required for a cylindrical geometry of the barrel central calorimeter. The readout of the FCS prototype was placed upstream of the incoming beam, while for the EIC EM prototype it was downstream during the test run. We used the same MPPC FEE assemblies to read out both EM prototypes during the test run.

![Figure 6](image_url)

**Figure 6** Eighteen channels, 18 X0 deep EM prototype of the central barrel calorimeter for a dedicated EIC detector (left). A sixteen channels, 23 X0 deep prototype of the forward EM calorimeter for FCS (right). Both prototypes used similar light collection schemes and frontend electronics.

We tested the response of the FCS system to hadrons, electrons and muons in the energy range 3-32 GeV. Electrons were identified with a differential Cherenkov counter (standard equipment at the MTBF). Impact position was defined by a scintillator XY hodoscope (4.9 mm wide scintillator square rods readout by SENSL SiPMs). We minimized the amount of material upstream of the calorimeters in the beam line to about 4 cm of scintillation counters. Additionally, FTBF personnel installed He-filled beam pipes between our apparatus and the upstream Cherenkov counter. The initial setup of our apparatus in the beam line is shown in figure 7. Two MTBF MWPCs (one is seen in figure 7) were used as additional monitoring devices during the beam energy scans to track reproducibility of the
beam settings at different energies. The HCal was oriented with a fixed angle (2.5 degrees) between the beam and primary axis of the HCal towers. The EM prototype was attached to the front steel plate of the HCal. The angle between the axis of EM tower and beam was kept at 4 degrees. All channels of the FCS were equipped with an LED monitoring system. LED monitoring signals and pedestals events were continuously recorded with a rate about 1 Hz most of the time during the test run. Preliminary analysis of these data shows that stability of the gain for HCal and EMcal front end electronics was better than 1% during a typical twelve hour shift of data-taking.

Figure 7 FCS HCal prototype at the beam line. Pb glass calorimeter in front of HCal was used for initial beam studies.

All MPPC’s were tested with a laser system prior the test run. With this system we measured that the gain of the MPPC assemblies for both HCal and EM prototypes were set equal to within 1%. We found that no additional tower-by-tower calibration of the EM prototype with the beam was required. This was expected after our previous beam test in 2012 when we measured excellent internal homogeneity of the EM modules built with our technique. The HCal required additional tower-by-tower calibrations with MIPs. For that an absorber was inserted into the beam line (8 GeV muon mode for the MT6 test line). A MIP peak was selected in each HCal tower using an isolation requirement (a single muon hit in a tower with no other energy deposition in the entire HCal). For calibrations with MIPs the EM prototype was removed from the beam line. We found that quite large corrections at the level of approximately 20% were required on top of calibrations made prior to the test run. About 10% of this shift can be explained by the alignment of the WLS plate and the MPPCs (both have a 3 mm active area, about 250 microns misalignment is possible due to positioning of the MPPCs on the FEE board). The rest should be attributed to the quality of optical components; one possible source is a difference in the response of the WLS tiles used in different HCal towers (concentration of dopants and attenuation length has not been measured for every WLS tile used in the HCal, we assumed that they are all identical). The response of the FCS to hadrons is illustrated in figure 8. In an ideal, completely compensated calorimeter system, the reconstructed energy of the incoming hadron is a simple sum of the energy deposited in the EM and HCal sections (assuming that the response in both sections is the same and energy independent). To obtain the best energy resolution for hadrons in the FCS we found that a weighting factor for the EM section should be energy dependent. This changes from about 2 to 1.2 for a beam energy range from 3 to 20 GeV and stays flat after that. With this energy dependent weighting of the energy deposited in the EM section, we measured e/h ratio for the FCS to be close to 0.95 and almost constant above 10 GeV as seen in the right panel of figure 8.
We did not perform any corrections due to leakages in the transverse and longitudinal directions in the FCS. Qualitatively, this result is close to MC predictions, however in our MC model we did not include some of the structural elements between the EM and HCal sections as well as the limited size of the prototype tested at FNAL. The questions of optimal weighting and e/h ratio in the FCS still need to be clarified with a MC for the exact geometry of the detectors used in the test run.

The response of the FCS to electrons is illustrated in figure 9. Due to non-uniform light collection with MPPCs the response of the EM section is dependent on impact position. For the preliminary results we present in this article we corrected the energy deposition in the EM section according to impact position and restricted the impact area only to the circle with diameter 1.4 cm at the center of the EM tower.

Local coordinates of the impact position were determined using calorimeter information only. We used a logarithmic weighting method with the cut-off parameter set at 3.8. The difference in the shapes of the response of the EM section in the X and Y directions is due to a tilt of the EM prototype of 4 degrees around the Y axis.
Summary plots illustrating the performance of the FCS prototype during the beam test are shown in figure 10. The response to electrons is almost linear, while the response to hadrons shows clear deviation from linearity above 15 GeV. The most likely reasons for this deviation are the weighting procedure of the fraction of energy deposited in the EM section and leakage from the FCS. We tested the HCAl section alone (with EM section removed from the beam line) and did not observe a similar deviation from linearity in this energy range. The energy resolution of the FCS to hadrons, shown in figure 10, is about 15% worse compared to MC predictions for the FCS at 10 GeV. One of the reasons is a transverse leakage from the FCS prototype, which was not taken into account for the test beam results. We also should mention that the energy resolution of the FCS in MC depends on the physics list used in GEANT4. We used a LHEP physics list, which we believe provides the most accurate description of the FCS. The electromagnetic energy resolution of the FCS prototype is close to MC predictions. There are two fits of our experimental results shown in figure 10. One assumed that the momentum spread of the beam is zero. In this case the stochastic term is close to 10% and the constant term is 1.7%. If we use our earlier (2012) estimates for the momentum spread of the beam of 2.7% below 4 GeV and 2.3% above this value, then the stochastic term becomes 11% and constant term is close to zero.

The absolute light yield measured in the EM section is about 400 pixels/GeV, with the front face of the EM prototype painted with the white diffusive paint BC-620. The measured absolute light yield for the HCAl section is about 130 pixels/GeV. MPPCs for both EM and HAD sections should behave almost linearly with these types of light yields for the energy range used in the test run. The light yield measured for the EM prototype is sufficient so we can introduce a mask between the scintillation fibers and light guide to make the light collection more uniform in future. Given the fact that the most recent generation of MPPCs already have much better PDE compared to MPPCs used in the test run (and anticipated future improvements in SiPMs), we believe that there is no need for any type of reflector at the end of the scintillation fibers. This significantly simplifies the construction of the EM section. According to our measurements in 2012, with EM prototypes equipped with a good mirror and with black tape at the end of the fibers, all
degradation in the energy resolution can be explained by photo-statistics, *i.e.*, degradation of light attenuation length in the scintillation fibers is not critical in this case.

Along with the FCS we tested a prototype of the central barrel EM calorimeter for EIC. A picture of this prototype on the beam line is shown in figure 11. The goal of the test run was to measure the response of this detector at different impact angles. The design of the prototype shares the same technology with the EM prototype for the FCS, except the geometry of the towers. A wedge-type geometry has always been technologically challenging for ScFi type calorimeters. We developed a simple construction technique for this type of geometry. The wedge shape is obtained by successively inclining meshes which form the matrix of scintillation fibers along the depth of the tower. This method is as simple as the method used for the traditional straight towers of the FCS. The sampling fraction and sampling frequency with inclined meshes slightly increases toward the front face of the towers. A Monte-Carlo calculation shows that this variation of sampling structure has a minor effect on the energy resolution of the detector. The goal of the test run was to measure response, energy resolution and absolute light yield in this detector as a function of impact angles. We performed beam energy scans for three different angles and tested three different light collection schemes. Since the light collection scheme for this prototype is similar to FCS EM detector similar problems with uniformity of light collection were observed. At shallow impact angles (detector was rotated along Y vertical axis) the non-uniformities in response along the X axis is almost vanished. For preliminary test beam results presented in this article we limited the impact area in the Y direction to 5 mm in order to minimize the effect of non-uniformity of light collection and leakage from the prototype due to its limited size.

![Figure 12](image)

**Figure 12** Response of the EM EIC prototype to electrons vs energy for different impact angles (left panel). Energy resolution $(p_0/\sqrt{E} + p_1)$ of the EM EIC for electrons vs energy for different impact angles (right panel).

Figure 12 summarizes the performance of the EM prototype for a central barrel EIC calorimeter during the test run. As predicted by the MC, the response of the detector only slightly depends on impact angle. A change in the slope for the fits at the left side of figure 12 can be explained by a slightly increased sampling fraction of the detector at more shallow impact angles. The energy resolution will be practically the same for the entire pseudorapidity range covered by the central barrel calorimeter for an EIC detector as shown at the right side of figure 12, which is again in reasonable agreement with MC predictions. The light yield measured for this prototype was 430, 530 and 600 pixels/GeV depending on the type of reflector at the front face of the detector and materials surrounding the light guides. The highest light yield was achieved with white diffusive paint at the front face of the detector (BC-620) and diffusive reflectors surrounding the light guides. We found that multi-clad scintillation fibers (Kuraray SCSF 78M) used for the EIC EM prototype only slightly
improves the light yield compare to single-clad fibers (Kuraray SCSF 78) used for the FCS EM prototype. There is no difference in performance of the EM prototypes when the readout was placed upstream (for FCS) or downstream (for EIC) of the detectors.

4. Summary
In 2012 we demonstrated a 'proof-of-principle' for a new simple and cost effective method of building compact scintillation fiber calorimeters utilizing tungsten powder. We continued development of this technique and tested two new EM prototypes designed for the STAR forward upgrade and future central barrel EM calorimeter for a dedicated EIC detector. Both prototypes were successfully tested in the test run at FNAL in March of 2014. We also developed a new construction technique for a high-resolution lead scintillation tile hadronic calorimeter. The FCS system designed specifically for the STAR forward upgrade is the perfect candidate for the forward calorimeter envisioned for the EIC dedicated detector for the outgoing hadron region. The performance of this system during test runs met our expectations. The compact readout scheme based on SiPM readout works well for the HCal prototype. For the EM sections, improvements in the uniformity of light collection have to be made in the near future. With the light yield measured at the test run, introduction of properly designed masks between scintillation fibers and light guides should solve the non-uniformity issue. A bench test measurements with existing prototypes, as well as final data analysis and MC simulation of the exact test beam configuration, presently is in progress.

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