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Design Studies of the Calorimeter Systems for the sPHENIX Experiment at RHIC and Future Upgrade Plans

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Design Studies of the Calorimeter Systems for the sPHENIX Experiment at RHIC and Future Upgrade Plans

C Woody and E Kistenev, for the PHENIX Collaboration

Physics Department, Building 510C
Brookhaven National Lab
Upton, NY 11973

E-mail: woody@bnl.gov, kistenev@bnl.gov

Abstract. The PHENIX Experiment at RHIC is planning a series of major upgrades that will enable a comprehensive measurement of jets in relativistic heavy ion collisions, provide enhanced physics capabilities for studying nucleon-nucleus and polarized proton collisions, and allow a detailed study of electron-nucleus collisions at the Electron Ion Collider at Brookhaven (eRHIC). The first of these upgrades, sPHENIX, will be based on the former BaBar magnet and will include a hadronic calorimeter and new electromagnetic calorimeter that will cover ±1.1 units in pseudorapidity and 2π in azimuth in the central region, resulting in a factor of 6 increase in acceptance over the present PHENIX detector. The electromagnetic calorimeter will be a tungsten scintillating fiber design with a radiation length ~ 7 mm and a Moliere radius ~ 2 cm. It will have a total depth of ~ 18 radiation lengths and an energy resolution ~ 15%/√E. The hadronic calorimeter will consist of steel plates with scintillating tiles in between that are read out with wavelength shifting fibers, It will have a total depth of ~ 5 interaction lengths and an energy resolution ~ 100%/√E. Both calorimeters will use silicon photomultipliers as the readout sensor. Detailed design studies and Monte Carlo simulations for both calorimeters have been carried out and prototype detectors have been constructed and tested in a test beam at Fermilab in February 2014. This contribution describes these design studies for the sPHENIX experiment and its future upgrade plans at RHIC.

1. Introduction

The PHENIX Experiment at RHIC is planning a series of major upgrades that will enable an extensive set of new physics programs over the next decade. This will involve replacing the current PHENIX Central Arm spectrometer with a new central spectrometer, sPHENIX, shown in Fig 1. It will utilize the former BaBar solenoid magnet and require the construction of two new large calorimeter systems, one electromagnetic and the other hadronic, covering ± 1.1 units in pseudorapidity and 2π in azimuth. These calorimeters, along with a silicon tracking detector, will form the basis of the new central spectrometer for sPHENIX. The hadronic calorimeter will be the first hadronic calorimeter ever used in a RHIC experiment. It will provide a measurement of the total jet energy and enable a comprehensive study of jets, di-jets and gamma-jet events in heavy ion collisions. With enhanced tracking capabilities, a detailed study of upsilon production in heavy ion collisions will also be possible. A detailed description of the sPHENIX experimental proposal can be found in [1].

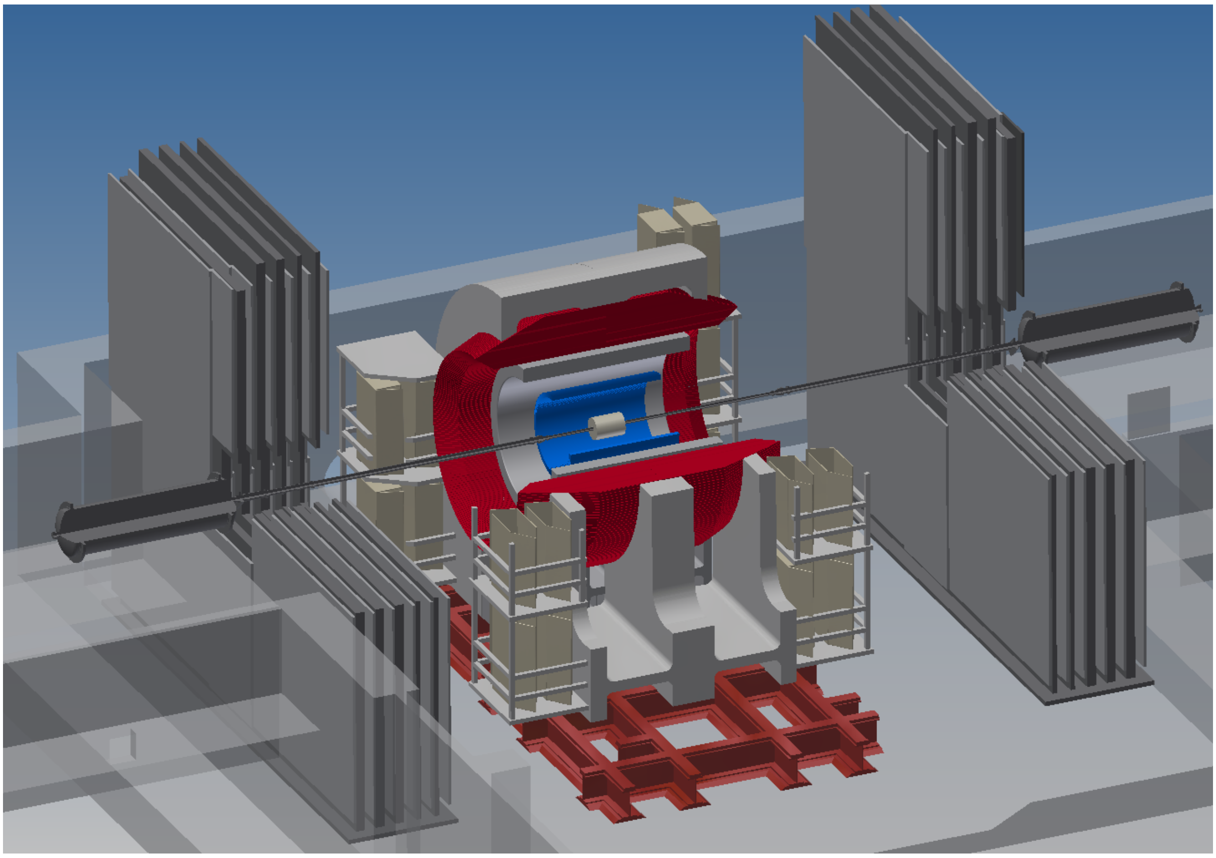

Figure 1. The sPHENIX detector utilizing the former BaBar solenoid magnet, new electromagnetic and hadronic calorimeters, and the current PHENIX silicon vertex tracker.

The new measurements from sPHENIX will allow an investigation of the properties of the Quark Gluon Plasma near the region of its critical temperature and provide detailed information about the phase transition. The flexibility of the RHIC collider also enables studies involving different ion species, comparisons with pp and pA collisions, including measurements of polarization and spin, and studying the energy dependence of these interactions over a wide energy range. The data obtained from RHIC will be complimentary to the data from the heavy ion program at the LHC, which operates at nearly fifteen times the center of mass energy and produces a much higher initial temperature, thus providing a complete and thorough investigation of the QGP and its properties.

The long range plan for RHIC is to transform the current heavy ion collider into an Electron Ion Collider (EIC) at BNL (eRHIC). It will have the capability for colliding polarized electrons with energies initially up to 21 GeV (and eventually up to 30 GeV) with hadrons up to 250 GeV and heavy ions up to 100 GeV/A. The greatly expanded kinematic coverage of eRHIC will allow a detailed study of the distribution of quarks and gluons, and their spins, inside the nucleus, and enable a broad new physics program to study nucleon structure and QCD in nuclei over a large range of x and Q^2.

A new suite of detectors would be added to sPHENIX to provide the additional measurement capabilities required to study ep and eA collisions, evolving it into a new spectrometer, ePHENIX, as shown in Figure 2. These would include additional tracking in the central region in the form of a fast, compact TPC and small angle GEM trackers, a central DIRC for particle id, a high resolution electromagnetic crystal calorimeter and additional GEM trackers in the electron going direction to precisely measure the scattered electron, and a new spectrometer in the hadron going direction. The hadron spectrometer would cover a pseudorapidity range of $1< \eta <4$ and would consist of more GEM trackers, a Gas RICH that utilizes a photosensitive GEM detector with a CsI photocathode for high

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momentum particle ID, an aerogel Cherenkov detector, and additional electromagnetic and hadronic calorimeters. A Zero Degree Calorimeter (ZDC) and Roman Pots would also be added in the forward direction. A more detailed description of these detectors, along with a discussion of the physics capabilities of ePHENIX, can be found in the ePHENIX Letter of Intent from the PHENIX Collaboration [2].

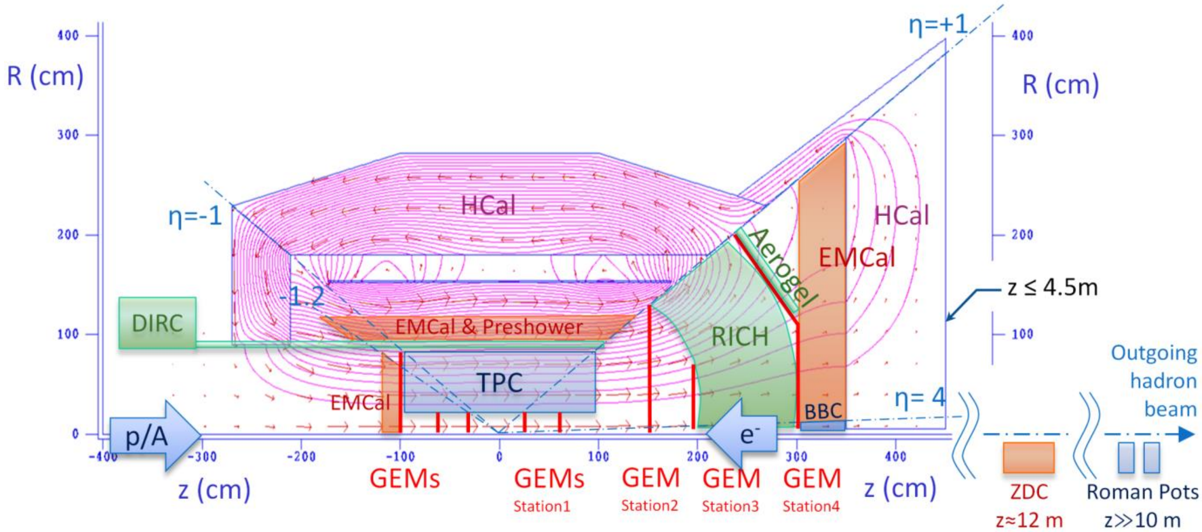


Figure 2. The ePHENIX detector for the Electron Ion Collider (eRHIC) at BNL. Additional detectors have been added to the sPHENIX spectrometer for studying ep and eA collisions.

Detector requirements

The main components of the sPHENIX spectrometer are the solenoid magnet, the two calorimeters and the silicon tracking detector. The BaBar magnet defines the magnetic volume of the spectrometer with a field of 1.5 T and also places constraints on where the electromagnetic and hadronic calorimeters can go. We are currently considering two designs, one with a portion of the hadron calorimeter inside the magnet and the rest outside, and another where the entire hadron calorimeter is outside. In the first configuration, the electromagnetic calorimeter would start at a radius of ~ 95 cm and extend to ~ 120 cm, including the space required for the readout. The absorber would consist of tungsten and scintillating fibers and would have a radial extent of ~ 13 cm (~18 X_0). The PHENIX group has been pursuing a design that would utilize tungsten plates and scintillating fibers oriented approximately parallel to the incoming particle direction, where the plates would either be tilted at a small angle, or have an accordion shape in order to avoid channeling of particles along the length of the absorber. The STAR group has been studying a similar design based on an absorber consisting of scintillating fibers embedded in a matrix of tungsten powder and epoxy. This design is reported on in a separate contribution to this conference [3]. Both designs are very similar. The absorber would have a radiation length of ~ 7 mm and a Moliere radius ~ 2 cm, but the sampling fraction for the PHENIX design is ~ 6%, whereas the STAR design has a sampling fraction ~ 2%. The energy resolution requirement for the EMCAL in sPHENIX is ~ 15%/√E, but is slightly more stringent for ePHENIX (~ 12%/√E). The segmentation requirement for sPHENIX is much higher than for ePHENIX in order to be able to measure jets in heavy ion collisions. The EMCAL would have a segmentation of approximately $\Delta\eta\times\Delta\phi$ ~ 0.025×0.025, leading to ~ 25K channels covering the central region of 2π in ϕ and ±1.1 in η.

The primary purpose of both the calorimeters is to measure jets in heavy ion collisions. However, for events containing jets in heavy ion collisions, there is a significant amount of energy deposited in the calorimeter from the large number of particles produced in the underlying event of accompanying soft collisions, and the fluctuations on this energy ultimately limits the jet energy resolution. As a result, the calorimeter energy resolution need not be better than the limitations imposed on the jet energy resolution by these fluctuations. The requirement on the energy resolution for the HCAL is ~ $100\%/\sqrt{E}$ for measuring jets over a momentum range from $p_T > 20$ GeV/c up to $p_T \sim 50$ GeV/c, and the segmentation is approximately $\Delta\eta\times\Delta\phi \sim 0.1\times0.1$.

The HCAL design has been described at the previous CALOR 2012 conference [4]. It utilizes steel plates and scintillating tiles that are read out using wavelength shifting fibers, where both the plates and the scintillating tiles are oriented parallel to the direction of the colliding beams. This allows the steel plates to serve as a flux return for the solenoid magnet. It also has the feature that the thickness of the plates (but not the scintillating tiles) increases with radius, and therefore the sampling fraction changes with radius. However, the calorimeter is divided into two longitudinal segments, which allows the ability to measure the longitudinal distribution of the hadronic shower, and therefore apply a correction for the longitudinal sampling fluctuations on an event by event basis. The plates will be tilted at an angle of approximately ± 15º in the ϕ direction for the front and back sections respectively in order to avoid channeling of particles passing through the scintillator alone. The total depth will be ~ 5 λ_{abs} (1 m) and the electromagnetic calorimeter will add another approximately 1 λ_{abs} in front. For the configuration where part of the HCAL is inside the magnet, there will be approximately 1 λ_{abs} inside and 4 λ_{abs} outside, and in the configuration with the entire HCAL outside, it would be divided with approximately 1.5 λ_{abs} in the front section and 3.5 λ_{abs} in the back section. Both sections will be divided into 22 towers in η and 64 towers in ϕ for a total of 2816 towers. The fibers from eight tiles will be bundled together to form a tower and will be read out with a single silicon photomultiplier.

The tracking system would initially consist of the existing PHENIX silicon vertex detector (VTX), but additional tracking layers would be added in order to measure heavy quarkonia, tagged heavy flavor jets and high-z fragmentation functions. These would be similar to the existing silicon tracking layers and would be placed at approximately 40 cm and 60 cm radius in order to provide the necessary momentum resolution for resolving the various upsilon states. In addition, a future preshower detector may be added that would enable the measurement of π^0's up to a $p_T \sim 40$ GeV/c.

2. Prototype Calorimeter Tests

Prototypes of both the HCAL tilted plate design and the EMCAL tilted plate design were constructed and tested in the MT6 Test Beam Facility at Fermilab in February of 2014 with beams of hadrons and electrons with momenta from 1 GeV/c up to 120 GeV/c. The 120 GeV/C beam was derived from the primary beam from the Fermilab Main Injector and was essentially purely protons, while a lower momenta, the beam consisted of a mixture of pions, electrons and muons. A Cherenkov detector upstream allowed for the identification of electrons and pions from 1 GeV/c up to 32 GeV/c. The detectors were tested individually and in tandem in order to study their performance in approximately the same configuration as they will be in sPHENIX. The layout of the detectors along the beam line is shown in Fig. 3. Each calorimeter was mounted on its own rotation platform that allowed it to be oriented at various angles with respect to the beam corresponding to both ϕ and θ. The EMCAL could be moved both vertically and horizontally, and the HCAL could also be moved vertically but not horizontally.

A common readout was used for the SiPMs for both calorimeters (Hamamatsu S10931-025P) that utilized a custom designed preamp and readout circuit that incorporated a programmable bias adjustment for each SiPM along with temperature sensors and feedback circuit that could automatically correct for the gain variation with temperature. Unfortunately, time did not permit fully testing this system during the beam test and the adjustments for the individual SiPM bias voltages to equalize the gains and the automatic temperature compensation was not applied during data taking.

The analog signals from the preamps were sent down ~ 15 m cables to a system of fast digitizing ADCs. The ADCs were previously used for the Hadron Blind Detector for the PHENIX experiment and digitized at a sampling rate of 65 MHz. An LED pulse system was also used for testing and calibration of all readout towers for both calorimeters.

2.1 Hadron Calorimeter

The hadron calorimeter prototype consisted of alternating layers of steel plates with scintillator tiles in between. The array of steel plates is shown in Fig. 3. The plate thickness varied from 2 cm in the front to 5 cm in the back with 8.5 mm gaps between the plates. The scintillating tiles were 7 mm thick and were coated with a UV reflective coating, and had a U-shaped groove in which a wavelength shifting fiber was embedded. The fibers from four tiles were bundled together into a small light mixing cavity and read out with a single SiPM, corresponding to one tower. They formed a 4x4 array of 16 towers for the front section and a similar array of 16 towers for the back section. The entire prototype measured 1.2 x. 1.7 x 1.3 m^3 and weighed approximately 4 tons.

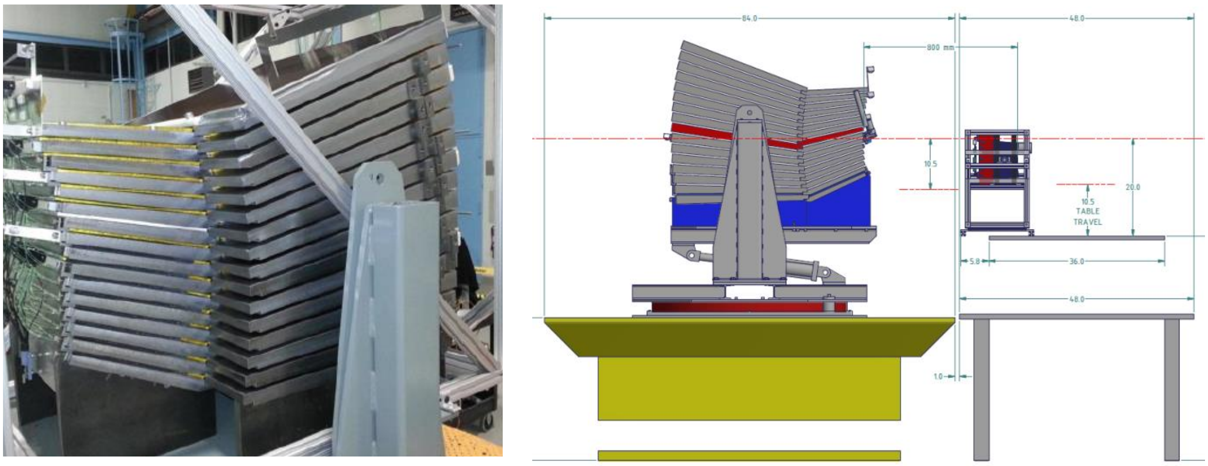
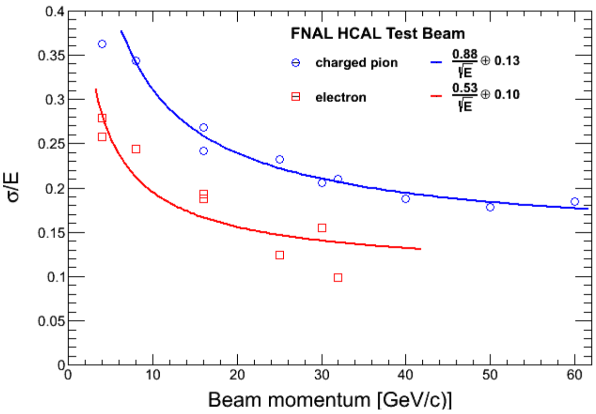


Figure 3. Left: Steel plate stack for the HCAL prototype calorimeter, Right: Layout of the prototype HCAL and EMCAL along the beam line in the test beam at Fermilab.

The analysis of the test beam data is still under way, but preliminary results indicate good performance from the calorimeter. Figure 4 shows the energy resolution for pions in the HCAL over a momentum range from 4 GeV/c to 60 GeV/c and gives a resolution of 88%/√E with a constant term ~ 13%. While this resolution is for single particles, it is within the acceptable range for measuring jets, and we expect the resolution to improve with further analysis. The rather large constant term we believe is due to uncertainties in the longitudinal center of gravity as measured by the ratio of the energy in the front and back sections which is used to correct for the longitudinal variation in the sampling fraction. This will be improved when the energy from the EMCAL is used in the analysis, and would also benefit from additional longitudinal segmentation of the HCAL itself. The energy resolution for electrons measured in the HCAL alone is also shown in Fig. 4 for momenta up to 32 GeV/c and gives a resolution of 53%/√E. The electron resolution would of course be significantly better using the EMCAL information, but measuring the electron energy in the HCAL allows an estimation of the e/π ratio, which gave approximately 1.2. The e/μ ratio was also found to be ~ 0.8. Finally, the right side of Fig. 4 shows the energy linearity for pions, electrons and muons and indicates good linearity over the measured energy range.



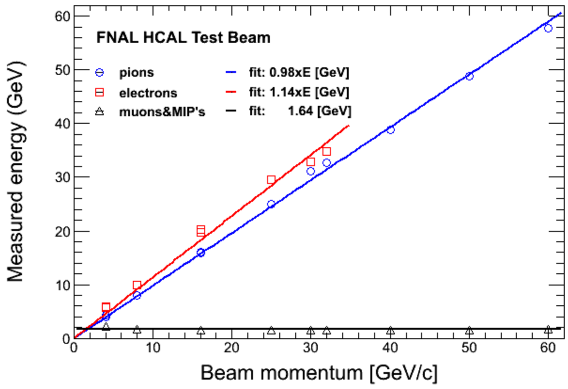
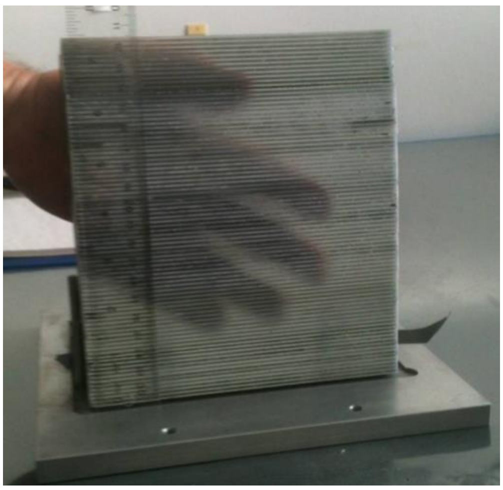


Figure 4. Preliminary data for the prototype hadron calorimeter. Left: Energy resolution for pions and electrons (note: electrons are measured only in the HCAL), Right: Energy linearity for pions, electrons and muons.

2.2 Electromagnetic calorimeter

The prototype electromagnetic calorimeter was constructed using a tilted plate design similar to the HCAL. It consisted of a stack of "sandwiches", where each sandwich was comprised of a pair of 0.5 mm thick flat tungsten metal plates glued together with a layer of 1 mm diameter scintillating fibers in between. When stacked together, this resulted in a tungsten absorber thickness of 1 mm and a nominal sampling fraction of 6.4%. A thin (~ 0.5 mm) spacer was imbedded at one end of each sandwich to produce a slight taper, which made the resulting absorber stack projective in one dimension (equivalent to the r-ϕ direction in sPHENIX). The fibers were also painted black over a length of ~ 2 cm at the readout end in order to produce a more uniform light output along the fiber, and the opposite end was covered with a reflecting mirror film (3M Enhanced Specular Reflector). Twelve sandwiches were stacked together to form a "tower module" and seven tower modules were stacked together to form the entire calorimeter.



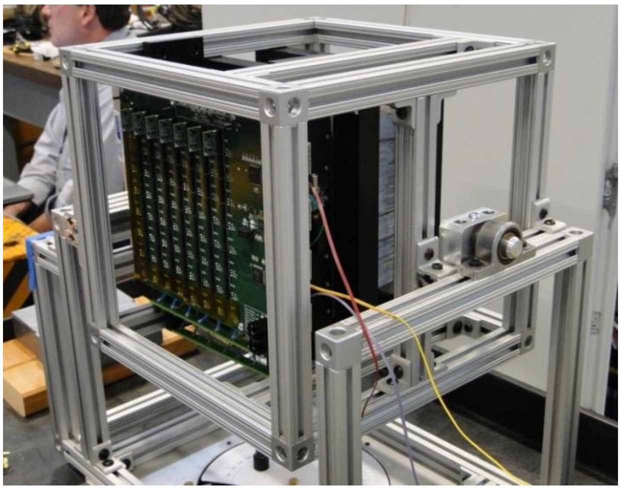


Figure 5. EMCAL prototype calorimeter. Left: Absorber stack, Right: Completed calorimeter mounted in rotation stand for testing.

Figure 5 shows the absorber stack for the prototype EMCAL along with the completed calorimeter after it was mounted in its rotation stand. Segmentation into 7x7 readout towers (each 2.5 x 2.7 cm^2) was accomplished by placing an array of light collection cavities over the back of the absorber stack. Each cavity consisted of a small plastic dome that was painted with a white diffusing paint (Labsphere 6080 coating [5]) and was read out with either a single or pair of SiPMs. Figure 6 shows the light collection module with the array of 7x7 towers. Due to the small area of the SiPM (3x3 mm^2) relative to the size of the tower, the overall light collection efficiency was only ~ 4.7%, and the non-uniformity (given by the ratio of the maximum to minimum response across the tower) was ~ 1.7 with a single SiPM readout. The total light output was measured during the test beam run and found to be ~ 180 p.e./Gev with a single SiPM.

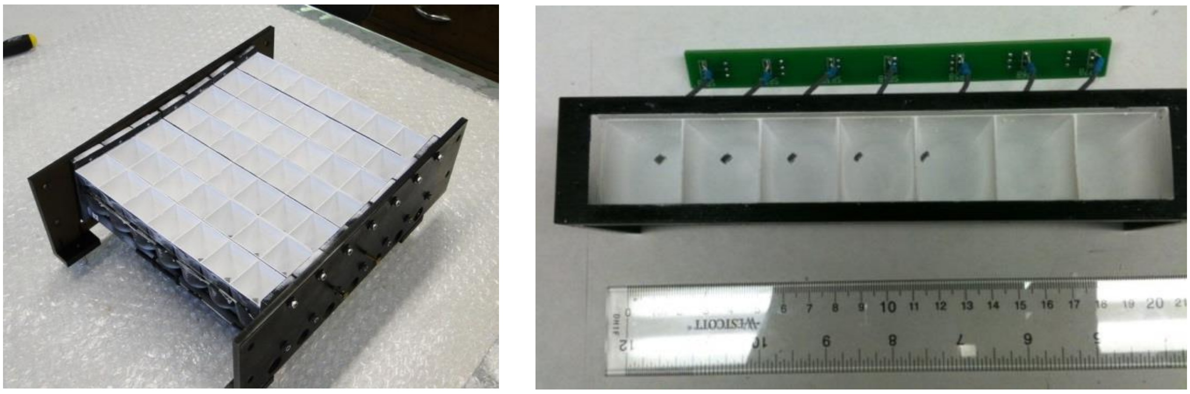


Figure 6. Left: Light collection module forming the 7x7 array of towers. Right: A detail of one row of 7 towers where the single SiPM is visible.

Analysis of the EMCAL data from the beam test is also still under way, but some preliminary results are shown in Figure 7. The plot on the left shows the sum of 3 rows of towers for a horizontal scan across the central row of towers with 8 GeV/c electrons, indicating a uniformity of ~ 5%. The plot in the middle shows the uniformity of the calorimeter measured along the vertical direction using 120 GeV/c protons and indicates a variation ~ 2%. The plot on the right shows the energy linearity of the calorimeter measured in two different orientations. The 90 degree position corresponds to the plates perpendicular to the incoming beam and the 20 degree position corresponds to the nominal orientation that the calorimeter would have in sPHENIX.

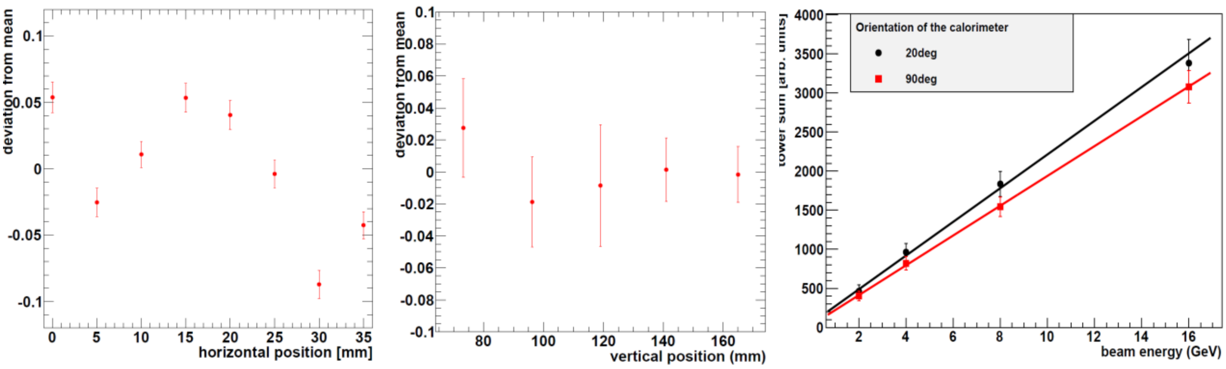


Figure 7. Preliminary data for the prototype EM calorimeter. Left: Uniformity for the sum of three rows of towers for a horizontal scan across the central row of towers with 8 GeV/c electrons, Middle: Longitudinal uniformity for a vertical scan along the calorimeter module with 120 GeV/c protons, Right: Energy linearity for the calorimeter module in two different angular orientations corresponding to the plates normal to the beam (90°) and in the nominal position the would be in for sPHENIX (20°).

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3. Summary and Conclusions

The PHENIX Experiment at RHIC is planning a major upgrade, sPHENIX that will include two new calorimeter systems. One will be a hadronic calorimeter that will provide a measurement of the total energy of jets produced in heavy ion collisions for the first time at RHIC, and a new electromagnetic calorimeter that will provide an independent measurement of the electromagnetic energy. Both calorimeters will cover a region of $\pm$ 1.1 units in pseudorapidity and 2π in phi. The requirements on the energy resolution for the two calorimeters is not particularly stringent due to the large background in measuring the jet energy from the fluctuations in the energy deposited in the calorimeter from the underlying event. The energy resolution requirement for measuring jets in the hadron calorimeter is ~ $100\%/\sqrt{E}$ and ~ $15\%/\sqrt{E}$ for the electromagnetic calorimeter. Prototypes of both calorimeters were built and tested in a test beam at Fermilab in February of 2014. Preliminary results from the beam test have been obtained and the analysis of the data is continuing. The sPHENIX experiment will also form the basis for a new detector for eRHIC, a future Electron Ion Collider at Brookhaven, which would include a suite of additional detectors for measuring polarized ep and eA collisions.

4. References

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