A Hadron Blind Detector for the PHENIX Experiment at RHIC

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***Abstract*— A Hadron Blind Detector (HBD) is being developed for an upgrade of the PHENIX experiment at RHIC. The HBD is a windowless Cherenkov detector, operated with pure CF_4 in a special proximity focus configuration. The detector consists of a 50cm long radiator, directly coupled to a triple GEM detector which has a CsI photocathode evaporated on the top surface of the upper-most GEM foil, and a pad readout at the bottom of the GEM stack. Detailed studies of the detector performance, including hadron rejection, figure of merit, N_0, number of photoelectrons and efficiency are presented. These studies include measurements performed with a UV lamp, an ^{55}Fe x-ray source and an ^{241}Am alpha source. Results will also be given on aging studies of the GEM foils and the CsI photocathode in pure CF_4.**

I. Introduction

A Hadron Blind Detector (HBD) is being considered as an upgrade of the PHENIX detector at the Relativistic Heavy Ion Collider (RHIC) at BNL [1]. The HBD will allow the measurement of electron-positron pairs from the decay of the light vector mesons (ρ, ω and ϕ) and the low-mass pair continuum in Au-Au collisions at energies up to $\sqrt{s_{NN}}$ = 200 GeV. From Monte Carlo simulations and general considerations, the main HBD specifications are: electron identification with very high efficiency (> 90%), double hit recognition better than 90%, moderate pion rejection factor of about 200, and a radiation budget of the order of 1% of a radiation length. The detector that is being developed is a windowless Cherenkov detector, operated with pure CF_4 in a special proximity focus configuration with a CsI photocathode and a triple GEM detector [2] with pad readout.

The combination of a windowless detector with a CsI photocathode and CF_4 results in a very large bandwidth (from 6 to 11.5 eV) and a very high figure of merit $N_0 \sim 900$ cm^{-1}. With these unprecedented numbers, one expects approximately 40 detected photoelectrons in a 50 cm long radiator, thus ensuring the necessary high levels of single electron efficiency and double hit recognition. The scheme foresees detection of the Cherenkov "blob" in a pad plane with a pad size approximately equal to the blob size (~10cm^2). This results in a low granularity detector. In addition, since the charge in the blob produced by an incident electron can be distributed over at most three pads, one can expect a primary charge of at least 10 photoelectrons per pad, allowing us to operate the detector at a relatively moderate gain of ~ 5x10^3.

This paper will report on the performance of the detector as a hadron blind device, including the hadron rejection factor and electron detection efficiency. We will also present results from a beam test performed at KEK using electron and pion beams, and on aging studies of the GEM foils with CsI photocathodes. Further details on these studies can be found in Ref. [3].

II. Experimental Results

A. Hadron Blindness

Figure 1 shows the detector used for the measurements of the hadron rejection and electron efficiency. It consists of a triple GEM detector, where the upper GEM foil has a thin layer of CsI deposited on top which serves as a photocathode. Another separate mesh electrode is placed 1.3-3.0 mm above the top surface of the upper GEM, creating a drift gap which can be biased either positive or negative. With positive bias, ionization charge produced in the gap is collected by the GEM, while with negative bias, ionization charge is forced away from the GEM and is collected by the mesh. Negative bias is the normal "hadron blind" mode for operating the detector, since ionization produced by charged tracks is not seen by the GEM. However, having a negative bias in this region also affects the collection of photoelectrons emitted form the photocathode, and one needs to adjust the field in this region in order optimize the charge track rejection and photoelectron efficiency.

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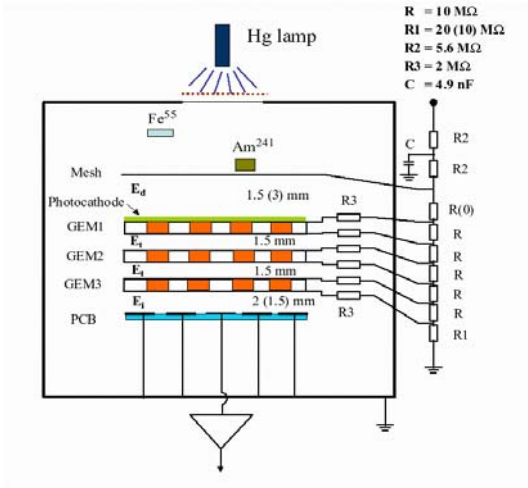

Fig. 1 Setup of the triple GEM detector and resistor chain. The Hg lamp, ^{55}Fe source and ^{241}Am sources were used for measurements with UV photons, X-rays and α-particles, respectively.

Figure 2 shows the charge collection measured as a function of the voltage across the drift gap (E_d) using a ^{241}Am alpha source. With positive bias, there is efficient charge collection for $E_d \geq \sim 500$ V/cm, while for negative bias ($E_d < 0$), there is a strong suppression of the charge collection signal.

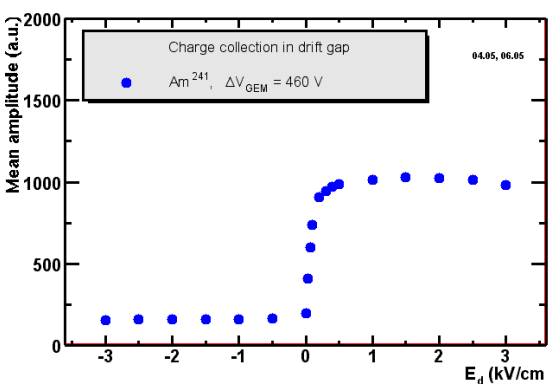

Fig. 2 Charge collection measured by the GEM detector as a function of bias voltage across the drift gap for a ^{241}Am source

Figure 3 shows the photoelectron efficiency as a function of bias voltage for both positive and negative bias. The photoelectron efficiency was determined by illuminating the CsI photocathode with a UV lamp and measuring the DC current at the last stage of the GEM detector. The relative efficiency was defined to be one at E_d=0. The efficiency exhibits a plateau at nearly 100% for $E_d > 0$, and drops off rather slowly for $E_d < 0$. This is an important and useful fact, since it allows us to bias the detector slightly negatively, which gives strong charged particle suppression, while at the same time preserving good photoelectron efficiency.

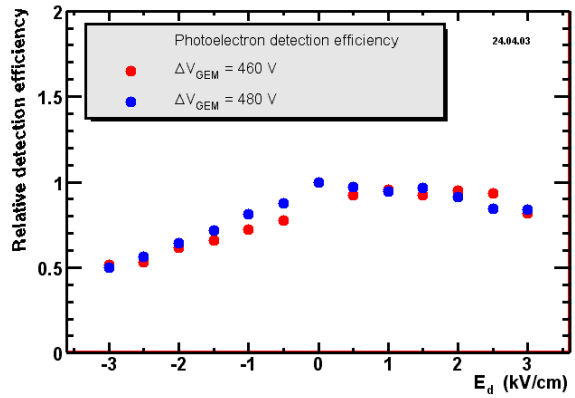

Fig. 3 Relative photoelectron collection as a function of bias voltage across the drift gap.

Figure 4 shows the "Hadron Blindness" of the detector, giving both the photoelectron collection efficiency and charge collection efficiency as a function of the bias voltage across the drift gap. From these curves, it is clear that one can achieve good hadron suppression by biasing the detector slightly negative ($E_d \sim$ -1 kV/cm), while maintaining a photoelectron electron efficiency of ~ 80%.

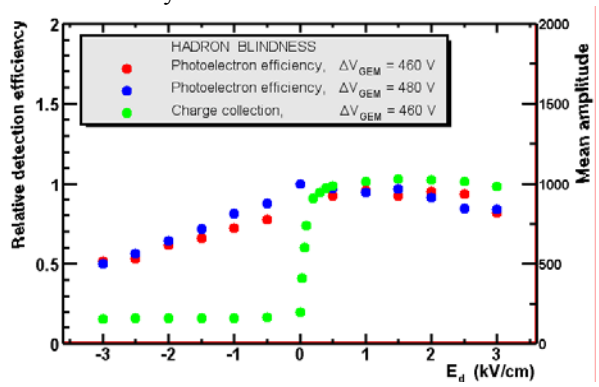

Fig. 4 "Hadron Blindness" of the detector showing photoelectron collection efficiency and charge collection efficiency as a function of bias voltage across the drift gap.

B. Quantum efficiency measurements

Figure 5 shows the spectrometer used to measure the absolute quantum efficiency of CsI coated GEM foils. The spectrometer contains a deuterium lamp and monochromator that illuminates the CsI photocathode along with a picoammeter for measuring the photocurrent. The deuterium lamp intensity is monitored using a phototube (PMT-1), and the quantum efficiency is determined by comparing the photocurrent produced by the CsI photocathode with the signal from a second phototube (PMT-2). A rotatable UV mirror is used to direct the light alternately from the CsI photocathode and the second phototube. The photocurrent produced by the photocathode is collected in charge collection mode as shown in Fig. 6.

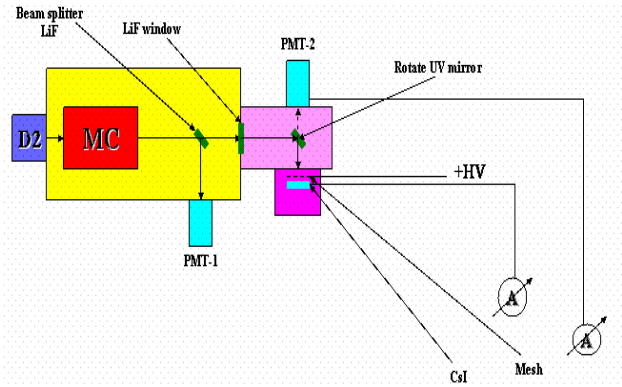

Fig. 5 Spectrometer used for measuring absolute quantum efficiency of CsI photocathodes.

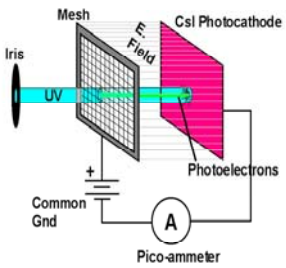

Fig. 6 Detail of photocathode and mesh configuration used for measuring photocathode current..

The quantum efficiency is computed using the relative currents measured in the two phototubes, and correcting for the transmission of the upper mesh and the active area of the GEM foils:

$$QE_{CSI} = \frac{QE_{PMT-2} \times I_{CsI}}{I_{PMT-2} \times C_1 \times C_2}$$

where C_1 is the optical transparency of the mesh (81%) and C_2 is the opacity of the GEM foil (83%). All currents are normalized to the current in PMT-1.

Figure 7 shows the CsI quantum efficiency as a function of photon energy, having converted wavelength into eV in order to compare with other measurements. Our data agree quite well with the data from Ref. [4} over the energy range from 6-8 eV. Our quantum efficiency measurement is limited by the transmission of the LiF window in the spectrometer, which cuts off at ~ 10.8 eV (~ 114 nm). Integrating from the CsI threshold (6.2 eV) up to this cutoff, one obtains an N_0 of ~ 414 cm^{-1}. However, if one extrapolates the measured curve to the short wavelength cutoff of CF_4 (11.5 eV), one obtains an N_0 of 915 cm^{-1}. This is an extraordinarily high value for N_0 for any Cherenkov detector, and shows the great advantage of having a windowless device, a highly UV transparent gas such as CF_4, and a photocathode such as CsI which is sensitive into the deep VUV.

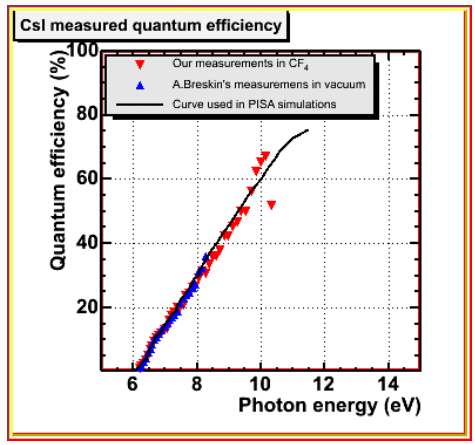

Fig. 7 Measured CsI quantum efficiency as a function of photon energy. Comparison is with Ref.[4}.

The quantum efficiency of the CsI photocathode was also measured in the presence of CF_4. Figure 8 gives the photocurrent of a photocathode measured with CF_4 compared to the same photocathode measured in vacuum, showing that the CsI quantum efficiency is not affected by the presence of CF_4. We note, however, that the CF_4 used in this measurement was extremely clean and the levels of oxygen and water contamination were very low.

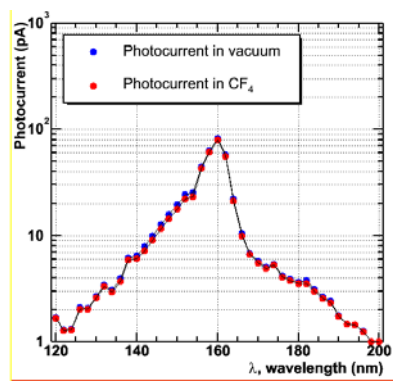

Fig. 8 CsI photocurrent measured in the presence of CF_4 compared to that measured in vacuum.

While the combination of high quantum efficiency and good UV transparency of the gas can in principle produce a very high N_0 for the Cherenkov detector, it is very easy to obtain a much poorer value due to absorption in the radiator gas. We have carried out a series of measurements to study the absorption in the VUV wavelength range as a function of the concentration of oxygen and water in the gas. Figure 9 shows a series of curves taken in argon for oxygen concentrations in the range from 0.43 to 476 ppm. The strong absorption band at ~ 1450 nm can clearly cause a significant loss of Cherenkov photons.

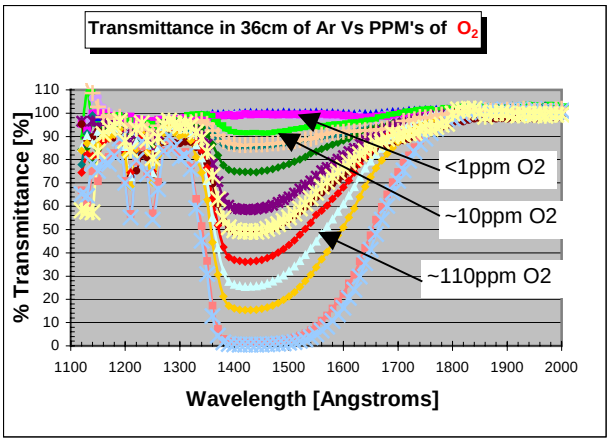

Fig. 9 Transmittance in argon for various concentrations of oxygen in the rage from 0.43 to 476 ppm.

Figure 10 shows the transmittance in argon for various concentrations of water in the range form 9.8 to 317 ppm. The data in Figs. 9 and 10 both agree very well with values of absorbance for oxygen and water in the VUV range published in the literature [5]. These data taken together make it very clear that one must keep the levels of oxygen and water down to very low levels (< 5 ppm of O_2 and < 10 ppm of H_2O) in order to maintain good VUV transmission, and hence high photoelectron yield, in the final HBD detector.

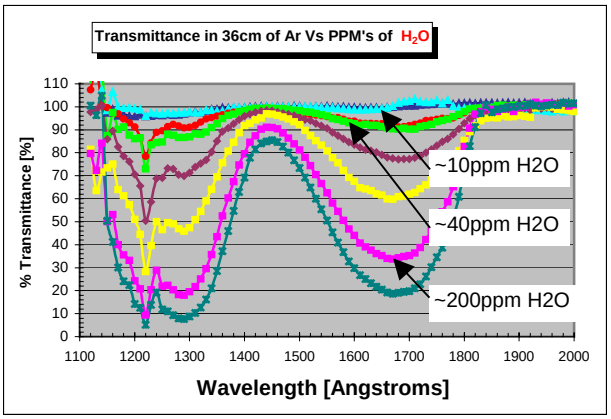

Fig. 10 Transmittance in argon for various concentrations of water in the rage from 9.8 to 317 ppm

C. *Aging measurements*

A series of tests were carried out to study the aging properties of the GEM detector and CsI photocathode in the presence of CF_4. These tests were carried out using a UV lamp to irradiate the photocathode, a picoammeter to measure the photocurrent from the mesh, and an ^{55}Fe source to measure the gain of the GEM detector. The photocurrent was kept to ≤ 1 nA/cm^2 and the gain was kept ~ 5-10 x 10^3. The photocathode was constantly illuminated for a number of hours, and the gain measured periodically during this time.

Figure 11 shows the results of these measurements. The red circles give the gain measured with the ^{55}Fe source, while the black squares give the gain measured with the UV lamp. Both measures of the gain agree quite well, indicating that neither the GEM detector nor the CsI photocathode were damaged by the radiation. The total integrated charge extends out to ~ 150 μC/cm^2. For comparison to what level of dose the detector would receive in PHENIX, we conservatively estimate that the total charge accumulated in one run at RHIC would be ~ 16 μC/cm^2. We therefore believe that aging of the CsI photocathode, even in the presence of CF_4, will not be a problem for the final detector.

It is interesting to note in Fig. 11 that the gain actually increases slightly with time and exposure. This effect is not completely understood, but could possibly be due to charging up effects in the GEM foils. This type of charging effect has been seen before in GEM foils [6], and is a separate subject that requires further investigation.

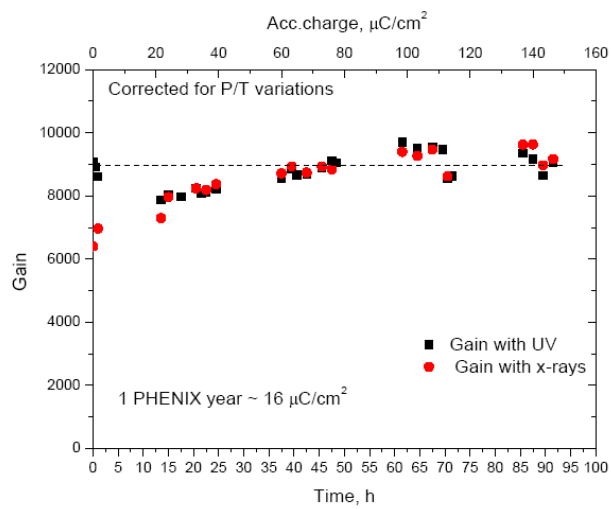

Fig. 11 Gain of a GEM detector with a CsI photocathode as a function of accumulated charge deposited by a UV lamp. Red circles give the gain measured with the UV lamp and black squares give the gain measured with an ^{55}Fe source.

D. *Beam tests*

The prototype HBD detector was also tested in a beam of pions and electrons at KEK. The detector consisted of a 50cm long radiator volume and triple GEM detector with the CsI photocathode housed inside of a vacuum tight stainless steel vessel. A retractable ^{55}Fe source was placed inside the vessel to monitor the gas gain, and a UV lamp was also permanently installed inside to monitor the performance of the CsI photocathode. The detector was assembled at the Weizmann Institute in Israel and filled with dry nitrogen before being sent to Japan. The CsI quantum efficiency was measured after arrival in Japan, and there was no significant degradation when measured in vacuum. However, when the detector was filled with CF_4, there was an apparent loss in quantum efficiency of approximately a factor of two. After much investigation, this was ascribed to UV absorption in

the gas used for the beam test, and not to a change in the actual photocathode quantum efficiency. Unfortunately, this absorbance prevented us from making a definitive measurement of the photoelectron yield in the beam. Nevertheless, from the measurements which were taken, and using a detailed Monte Carlo simulation of the effects of the absorbance, it was possible to estimate the expected electron signal and compare it to the measured signal for the pions obtained from the beam test.

Figure 12 shows the expected separation of pions and electrons in the HBD. The pion signal is from the measured test beam data taken at negative bias (E_d = -0.3 kV/cm), while the electron signal is from a simulation. The simulation included optical shadowing of the mesh in front of the CsI photocathode, but assumed no UV absorbance in the gas. This gave an average value of 33 photoelectrons for the expected electron signal, which is very well separated from the pion peak. It is clear that a cut on such a spectrum at ~ 60 channels (~ 7 pe) would give excellent pion rejection.

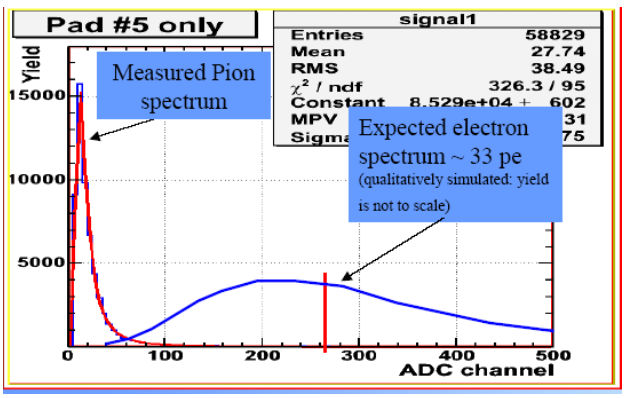

Fig. 12 Expected separation of pion and electron signals in the HBD. The pion spectrum is from measured test beam data at negative bias (E_d = -0.3 kV/cm) while the expected electron signal with an average value of 33 photoelectrons is from simulation.

Although the expected photoelectron yield and pion rejection is indeed very good, it is important that these quantities be measured under actual experimental conditions, and future tests are planned to confirm these predictions. As noted above, it is extremely important to keep gas impurities such as oxygen and water down to very low levels in order to preserve good transparency and maintain the high photoelectron yield. This places stringent requirements on the gas delivery system for the detector, as well as on its critical operating parameters

An additional study was also carried out to see how well the HBD detector would survive in the high particle multiplicity environment at RHIC. A separate prototype detector (different from the one used at KEK) was installed in the central region of PHENIX for a short test during a full luminosity run of gold-gold collisions. The detector consisted of a triple GEM detector, essentially identical to the one used for the KEK test, and was operated at gains of a few times 10^3 in both Argon/CO_2 (70/30) and pure CF_4. The detector was very stable during the entire test, which lasted ~ 8 hrs, showed only nominal gain variations of ± 10% (similar to what is typically observed in the lab), and exhibited no sparking or discharges. However, an increase in low energy background was observed at a signal level below ~ 50 electrons. This background was strongly correlated with the beam conditions, and was largely out of time with real beam-beam collisions. As such, it is not expected to present a problem in the operation of the HBD in PHENIX in the real RHIC environment. Further details on these tests can be found in a separate contribution to this conference [7].

III. Summary

An extensive program of R&D has been carried out to study the properties of a proposed Hadron Blind Detector (HBD) for the PHENIX experiment at RHIC. Due to its windowless construction, and when used with a deep UV transmitting radiator gas such as CF_4, this detector would have an unprecedented figure of merit as a Cherenkov counter (N_0 ~ 900 cm^{-1}), and would provide strong hadron rejection capabilities, even in a very high charged multiplicity environment. This detector will provide PHENIX with the opportunity to perform new physics measurements of low mass lepton pairs in heavy ion collisions, which will greatly enhance the physics program at RHIC. Many of the critical properties of this detector, such as operation in pure CF_4, hadron suppression, aging, and operation in the real RHIC environment, have now been measured and tested, and we believe such a detector can be built and operated at RHIC. The final design of a full working prototype of this device is now under way and will be installed for testing in PHENIX in a forthcoming run.

IV. References

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