A 10 MHz Beam Counter and a Multiplicity Detector for the E864 Spectrometer

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Abstract

The E864 experiment at BNL requires a beam counter and multiplicity detector system that can perform at an incident beam rate of $10^7$ Au ions per second. We have developed and tested a 150 $\mu$m thick quartz Cherenkov beam counter and a scintillator based multiplicity-trigger counter during the first run of this experiment in 1994. We obtained a time resolution of 78 ps for the beam counter at an incident beam rate $5 \times 10^5$ Hz and 100 ps at a rate of $1 \times 10^7$ Hz. Pulse height discrimination is used to obtain a minimum bias and a 10\% centrality trigger from the multiplicity detectors. The multiplicity counter has a time resolution of 250 ps.

1. Introduction

We report on a beam and multiplicity-trigger counter system that we have developed and tested for the E864 spectrometer at the Brookhaven National Laboratory (BNL). E864 is designed to search for rare composite states, stranglets and other novel forms of matter which may be produced in a small fraction of relativistic Au-Pb collisions at the BNL Alternating Gradient Synchrotron (AGS). The momentum of the Au beam at the AGS is 11.7 A GeV/c. The beam, veto and multiplicity counters constitute the front end of the E864 spectrometer. This spectrometer provides momentum, time of flight and energy (calorimetry) information for charged and neutral secondary particles produced in central (small impact parameter) Au-Pb interactions. In order to realize a sensitivity of $10^{-11}$ per interaction for the detection of rare particles within a
reasonable running period, it is required that the incident beam intensity be of the order of $10^7$ s$^{-1}$. Stable long term performance and good time resolution (80 - 100 ps) at these high rates were the central criteria that dictated the design and development of the beam and trigger counters.

As is well known, light emission of a solid scintillator rapidly deteriorates due to radiation damage when exposed to heavy-ion beams. To minimize radiation damage as well as the number of beam particle interactions in the detector material we have used a thin (150 µm) quartz plate for the beam counter. Cherenkov light emitted by a relativistic ion traversing the quartz plate emerges through the edges of the plate after a series of total internal reflections. Two photomultipliers (PMT) optically coupled to opposite edges of the quartz plate provide the beam counter with superior signal characteristics as compared to a scintillator counter of similar construction. Although this technique has been employed in other experiments [1], the reported results are at an incident beam intensity of about $10^6$ Hz, which is an order of magnitude less than the desired E864 beam intensity of $10^7$ Hz. Thus the main effort behind the development of our beam counters has been to achieve good time resolution at high rates while maintaining small PMT anode currents to prevent the deterioration of the photomultiplier tubes due to overheating of the dynodes. In Section 2 we describe the construction and signal characteristics of the beam counter and in Section 4 we give results on time resolution and stability.

The E864 experiment uses a multiplicity trigger to select central events, because in relativistic heavy-ion collisions there is a strong correlation between particle multiplicity and centrality. The E864 multiplicity detector is an annular piece of fast BC420 scintillator placed around the beam pipe 13 cm downstream of the target. The annulus is segmented into four quadrants and each quadrant is viewed by a photomultiplier. The centrality trigger is obtained by imposing a high discriminator threshold on the summed signals from the four counters. We discuss the multiplicity counter in detail, in Section 3.

Fig. 1 shows the entire beam and multiplicity-trigger counter assembly. The quartz Cherenkov beam counter is housed in a light tight box that is located on the extreme left side in Fig.1. In order to veto beam particles which are more than 0.5 cm away from the beam axis a quartz-Cherenkov hole counter is placed immediately upstream of the beam counter, within the same light-tight enclosure housing the beam counter. Another, larger hole veto counter made of scintillator is placed downstream of the beam counter to detect and veto those
events in which a beam particle interacted in the beam counter quartz plate. This counter also helps to veto events which have a beam particle accompanied by a halo of charged particles that originate from interactions in the upstream beam magnets and collimators. The target assembly and the multiplicity-trigger counters are shown on the right side in Fig. 1. Lead shielding placed between the target and the scintillator hole counter minimizes the possibility of triggering the veto counter by secondary particles backscattered from the target. Lead shielding upstream of the scintillator veto counter protects it from knock-on electrons (δ-rays) produced by the gold beam passing through the upstream apparatus.

2. The Quartz Beam and Hole Counter

2.1 Detector Assembly

As mentioned previously, the quartz Cherenkov hole-veto and beam counters are housed in a light-tight aluminium box with easily removable front and back cover plates for quick access. The photomultiplier tubes are mounted vertically with respect to the beam axis. To describe the optical part of the assembly in greater detail we provide in Fig. 2 a sketch of the two detectors from side (a) and perspective (b) views, where VC and BC are the hole-veto and beam counters, respectively. The quartz plates for both counters are mounted in PET (Polyester Terephthalate) frames. This material was chosen so that humidity changes will not affect the dimensional stability of the frame. Two 0.5 cm thick lucite plates embedded in the PET frame provide the optical coupling between the quartz plates and the front faces of the 2 inch phototubes. The top and bottom edges of the beam counter quartz plate and one edge of each of the veto counter quartz plates are held in narrow slits on the front face (i.e. away from the PMT face) of the lucite coupler.

Because the beam counter quartz plate (5 cm x 8.8 cm) is only 150 μm thick it is mounted in a way that minimizes the stress on the plate and simultaneously ensures excellent optical contact with the front face of the PMT. This is done by filling the slits containing the edges of the quartz plate with immersion oil (refractive index =1.515 ) as illustrated in the expanded part in Fig.2. The immersion oil is held in the slit by the capillary action of the liquid between the lucite and quartz plate surfaces. No dripping or draining of the oil was observed, regardless of the orientation of the frame. We chose Supersil-1 for the beam counter quartz plate because of its low radiation damage properties [2], and its property of being striation free in all three directions.
While mounting the plate, sufficient care has to be taken to ensure that no air bubbles are trapped in the immersion oil filling the slits. The width of the slit proved to be an important factor in achieving a bubble free quartz - lucite interface, and a width of 375 µm was used in the final design.

The hole veto counter uses a 1 mm thick Corning 2940 quartz plate. Because they are less fragile than the beam counter plate, these plates were optically cemented into the slits in the lucite. The hole veto counter consists of two "L-shaped" pieces, which when mounted with a small overlap as shown in Fig. 2(b), provide a center hole of dimension 1 cm x 1 cm. As each quartz plate of the quartz hole counter is viewed by only one phototube, the quartz plates need not be perpendicular to the beam. In fact, tilting the quartz plate by 10 degrees maximized the amount of Cherenkov light that reaches each phototube.

2.2 Photomultiplier Tube Base modifications

We have used Hamamatsu 12-stage photomultiplier tubes R4001 and R2059 for the hole and beam counters, respectively. These PMTs belong to the 1828-01 family of 2 inch phototubes with a rise time of 1.4 ns and transit time jitter of 0.6 ns [3] at the recommended operating voltage of 2500 V. These photomultiplier tubes were the most economical choice with adequate rise time and a sufficiently high anode current limit. It is important for high rate (10⁷ Hz) operation of PMTs to prevent voltage sag in the last dynodes, because such voltage sag will cause a degradation of the rise time of the signal. It is also important to maintain low PMT anode currents to prevent gain losses due to the overheating of the last dynodes. To satisfy both of these requirements we must operate the tubes at a low main voltage (∼1600 V), with high current voltage supplies on the eleventh and twelveth dynodes. This requires a modification of the base resistor chain as shown in Fig. 3. In addition to the external voltage supplies, we have also connected 4.7 nF capacitors to all the dynodes to provide a filter for high frequency noise.

2.3 Signal and Pulse Height Distribution

Figure 4 shows the pulses from the top and bottom PMTs of the beam counter observed on a 300 MHz analog scope during a ∼1s spill of 11.7 A GeV/c Au ions at a beam rate of 1.2 x 10⁷ Hz. The pulses have a rise time of about 2 ns, an average pulse height of about 30mV (50Ω termination) and FWHM of about 4 ns. These pulses were obtained after the original signals from the PMTs were split equally into two, and thus represent 50% of the original
signals. Comparisons of these pulses with those at lower rates (\(5 \times 10^5\) Hz) show no noticeable changes in the pulse height or pulse width. At an incident beam rate of \(5 \times 10^5\) Hz, we estimate the anode current to be about 4\(\mu\)A. At beam rates of \(1 \times 10^7\) Hz the anode current is about 80\(\mu\)A, well below the 200\(\mu\)A maximum anode current limit set by the manufacturers. We also note here, that for AGS beams of \(1 \times 10^7\) Hz, the ”average continuous anode” current for each beam counter photomultiplier is about 20\(\mu\)A, because the beam spills are at 4 sec intervals. By maintaining a low pulse height we have been able to operate these PMTs at sufficiently low anode currents, to ensure a longer lifetime for these photomultiplier tubes. We have also compared the pulses at the beginning and end of each spill during a high rate run and seen no pulse height variations. Any observed differences would suggest that the dynode voltages at the end of the resistor chain are sagging below their preset voltages, or the presence of a dynode heating effect.

The pulse height spectrum as measured using a Fastbus ADC (LeCroy 1881) is shown in Fig. 5. The least count for this ADC is 0.1 pC. The main peak of the pulse height spectrum is around ADC channel 850 and represents roughly a 40mV pulse that has been amplified 10 times, before being routed to the ADC input. This agrees quite well with the pulse height as seen in Fig.4, where the peak height of the outer envelope of the band is around 40 mV. The second smaller peak around 1700 can be identified as those events with 2 beam particles hitting the counter simultaneously. Third and fourth peaks, corresponding to the simultaneous passage of three and four gold ions, respectively, through the quartz plate are present at 2550 and 3400 ADC channels. A Gaussian fit to the main peak gives a sigma of 102 channels which represents a 12% width for the pulse height distribution.

### 2.4 Radiation Damage of the Quartz Plate

Although the beam counter was tested at high rates (\(1 \times 10^7\) Hz) during the 1994 run, most of the data taking was performed at a beam rate of \(5 \times 10^5\) Hz, for a total exposure of \(10^{11}\) Au ions. Comparison of pulses taken at the beginning and the end of the running period showed very little variation in the pulse height, thus suggesting little or no radiation damage to the quartz plate. However, during the 1995 run a gradual degradation of the pulse height was observed as the quartz plate was exposed to a beam rate of \(5 \times 10^6\)Hz for extended periods of data taking. The cause of this drop in pulse height was identified to be the accumulation of a thin film of material in and around the region where the beam passed through the quartz plate. This surface contam-
ination of the quartz plate adversely affects the total internal reflection of the Cherenkov light thus resulting in a loss of pulse height. It was found that the plate could be thoroughly cleaned using methanol, thus removing this surface deposition. Spectroscopic studies showed the surface film to be made of carbon and oxygen compounds.

It should be noted here that all components of the beam counter including the quartz plate was exposed to air. During the rest of the 1995 run, Nitrogen was circulated through the beam counter housing in an attempt to prevent the surface contamination of the quartz plate. Although this could have reduced the rate of accumulation, close examination of the quartz plate at the end of the run showed a faint spot on the quartz plate. For the forthcoming run in 1996 we are redesigning the quartz plate holder so that it can be operated in vacuum. Additional design modifications are also being implemented to facilitate quick changes of the quartz plate, if required, during the run.

3. The Multiplicity Detector

3.1 Detector Assembly

The E864 multiplicity detector covers the angular range from 16.6° to 45° (η = pseudo rapidity = 1.92 → 0.88) measured with respect to the beam axis. It is constructed out of four 1 cm thick scintillation counters that fit around the beam pipe as shown in Fig. 6. A sectional view along the beam is shown in Fig. 1. It is located 13 cm downstream of the target and is tipped at an angle of 8° to the vertical. Simulation studies have shown that as the beam traverses the target, δ-ray production would result in about 200 MeV being deposited in the scintillation counter. To remove this δ-ray effect we have shielded the entire active surface of the scintillator by a ~ 6 cm thick Heavymet [4] ring, around the beam pipe. As shown in Fig. 1 the counters are mounted on two moving stages that can slide towards or away from the beam pipe. Each counter is made of a fast (BC 420) quadrant shaped piece of scintillator viewed by a 2 inch Hamamatsu 1828-01 phototube with the same PMT base as described in Section 2. Booster voltages to the last two dynodes can be provided for high rate operation. Each PMT is equipped with an LED and a fiber optic channel so that long term behavior of the phototubes could be monitored in an independent manner. The operating voltage of the PMTs was set around 1600 V giving a 300 mV pulse height per counter for high multiplicity events. The signal from each PMT was first split into two equal
half-signals. Four half-signals from the four counters were combined using a Phillip Scientific 744 Fan-in/Fan-out module to generate a summed signal and this signal was discriminated to generate the three triggers (see next section) used for the fall 1994 run.

3.2 Trigger Scheme

Three different interaction triggers were developed for the E864 experiment. A minimum bias trigger (INT0) required that the sum of the pulses from the four multiplicity counters had a threshold greater than 10 mV. A centrality trigger (INT2) was implemented by selecting the events which had summed signals from all four counters greater than 340 mV. This trigger selected those events in the highest 10% of the multiplicity distribution. In addition, an intermediate multiplicity trigger (INT1) was obtained by triggering on the summed signals above a 200 mV threshold. Count down scalers were used to select some fraction of the minimum bias (INT0) and intermediate multiplicity events (INT1). All central event triggers (INT2) were recorded. A plot of the pulse height distribution of the minimum bias trigger is given in Fig. 7. The histogram represented by the dotted lines represents the 10% central events.

3.3 Comparison with Monte Carlo Studies

Because of the correlation between particle multiplicity and centrality a cut in the ADC value of the multiplicity counter translates into a selection of the impact parameter. To study the correlation between ADC value and centrality a Monte Carlo program was written. An event is simulated with GEANT [5] by sending a 11.71 GeV per nucleon gold ion through a 10% lead target. This ion produces $\delta$-rays until it interacts at a random depth in the lead target. This collision is simulated with the HIJET [6] event generator. The geometry for the study included the target, vacuum chamber, Heavymet shielding, and the scintillator multiplicity counter. All of GEANT’s physics processes were turned on for the simulation. The program simulates the number of photoelectrons expected after taking into account the energy deposited in the scintillator, the emission spectrum for the scintillator, the geometry of the detector, and the photocathode spectral response of the phototube. The photoelectron distribution from the simulated data appeared similar to the observed pulse height spectra from the experiment.

The results of the Monte Carlo study on the centrality selection of the multiplicity counter can be seen in Fig. 8. Fig. 8(a) shows the distribution
of impact parameters for three different cuts on the energy deposited in the multiplicity counter as obtained from the program. Fig. 8(b) shows the trigger probability for different impact parameters for different cuts on the energy deposited in the multiplicity counter as obtained from the program. The solid line represents a cut on the events with the 10% most energy deposited; the dashed line represents the 5% most energy deposited; the dotted line represents the 1% most energy deposited.

Fig. 8 demonstrates that the multiplicity counter can be used to roughly select the centrality of an event. For example, if we make a cut on events with the 10% highest pulse heights, we are selecting events with impact parameters corresponding to the smallest 10% of the impact parameter distribution that one would expect from a geometric impact parameter distribution 88% of the time. Even higher pulse height cuts result in higher centrality events, although with very high cuts the acceptance for these high centrality events also goes down.

4. Time Resolution and Stability

The times of arrival of pulses from the counters were digitized with Fastbus TDC modules (Lecroy 1872A) with a least count of 50 ps. The pulse heights for the beam counter pulses were 30-40 mV [7] and those signals were discriminated at a threshold level of 10 mV. Using the ADC information from each PMT we have slew corrected the TDC data independently for each counter. The slew corrected distribution of the time difference of the two counters \((t_B-t_A)\), at an incident beam rate of \(10^7\) Hz is given in Fig.9. The \(\sigma\) for this distribution as obtained by a Gaussian fit is 200 ps. From this value we obtain a single counter resolution of 141 ps, and an overall resolution of the two counter system of 100 ps, which is the uncertainty in the start time, \(t_0\) \((= 0.5(t_A+t_B))\) for the E864 experiment. At the lower beam rate of \(5 \times 10^5\) Hz our slew corrected time resolution is 78 ps.

The time of arrival of the pulses from the four multiplicity counters were also digitized using Fastbus TDC channels and each counter was slew corrected. We have defined the time as measured by the multiplicity counter to be the four-fold average of the individual times from the four counters. To obtain the time resolution of the multiplicity counter we give in Fig. 10 the distribution of the average time minus the start time as measured by the beam counter. When fitted to a Gaussian this distribution gives a \(\sigma\) of 250 ps which is the time resolution for our multiplicity counter.
5. Summary

We have developed and tested a beam counter and multiplicity detector system at an incident beam rate of $10^7$ Au ions s$^{-1}$. To our knowledge (based on published results) this is the first time a quartz plate as thin as 150$\mu$m has been successfully tested for a heavy ion beam counter. The beam counter has a time resolution of 100 ps at an incident beam rate of $1\times10^7$ Hz and an energy resolution of 12%. An important feature of this beam counter is the low average photomultiplier anode current (80 $\mu$A) drawn during a one second spill of $10^7$ Au ions. The scintillator multiplicity counter provides a minimum-bias, intermediate multiplicity and very high multiplicity (the highest 10% of the multiplicity distribution) triggers. The multiplicity counter has an overall time resolution of 250 ps. The beam counter and multiplicity detector system show good stability as the incident beam rate is varied from $10^5$ Hz to $10^7$ Hz.

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References

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[7] Other tests of quartz Cherenkov counters have used much larger pulse heights (example 800mV, Private Communication, Dana Beavis, BNL)
Figure Captions

Figure 1. The E864 front-end configuration of detectors consisting of the Quartz-Cherenkov hole-veto and beam counters on the left, a scintillator hole-veto counter in the middle, followed by the target assembly and Multiplicity-trigger counters on the right.

Figure 2. A sketch illustrating the optical assembly of the quartz hole-veto and beam counters; (a) shows the side view and (b) the perspective view.

Figure 3. The modified base for the Hamamatsu 1828-01 PMT with power supplies attached to the last two dynodes.

Figure 4. Beam counter pulses during a spill of $1 \times 10^7$ Au ions. The vertical scale is 20 mV/div and the horizontal scale is 5 ns/div.

Figure 5. The pulse height spectrum of the beam counter at an incident beam rate of $1.2 \times 10^7$ Au ions per second.

Figure 6. Beam’s eye view of the multiplicity-trigger counters.

Figure 7. The averaged (over the four counters) multiplicity detector pulse height distribution for minimum-bias (solid line) and 10% most central events (dashed line).

Figure 8. Monte Carlo study of the centrality selection of the multiplicity counter. The three different curves represent different cuts on the energy deposited in the multiplicity counter. The solid line represents a cut on the events with the 10% most energy deposited, the dashed line represents the 5% most energy deposited, and the dotted line represents the 1% most energy deposited. (a) Distribution of impact parameters (in fm) which pass a 10%, 5% and 1% cut on the energy deposited in the four scintillation counters in the multiplicity detector. (b) Trigger probability for a particular impact parameter event to pass a 10%, 5%, and 1% energy deposit cut.

Figure 9. The distribution of the time difference between the bottom (B) and top (A) PMTs of the beam counter. $\sigma(t_B-t_A) = 200$ ps and $\sigma(t_0)=\sigma(0.5(t_B+t_A)) = 100$ ps.
Figure 10. The averaged (over the four counters) intrinsic time resolution ($\sigma=250$ ps) of the multiplicity-trigger counter system.
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