A Cherenkov Beam Counter for Ultra-Relativistic Heavy-Ion Experiment

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Abstract

A beam counter system consisting of two sets of gas Cherenkov counter was constructed for ultra-relativistic heavy-ion experiments. The performance has been examined with sulphur ions of 200 GeV/c per nucleon. The intrinsic time resolution and the width of the pulse height distribution are 30 ps and 5 %, respectively, at a beam intensity of 2×10^6 ions/s. The detector was successfully operated for more than one month, although some reduction in pulse height was observed as a long-term variation.

1 Introduction

A beam counter system (abbreviated as CX hereafter) for the NA44 experiment at the CERN Super Proton Synchrotron (SPS) has been developed for measurement of ultra-relativistic heavy-ion beam. Of a number of experiment employing sulphur-ion beam of 200 GeV/c per nucleon which has been recently available at the SPS, the NA44 experiment measures one-particle spectra and two-particle correlation by means of a focussing spectrometer [1]. The spectrometer consists of two dipoles for particle bending, three superconducting quadrupoles for focussing, three sets of scintillator hodoscopes for particle tracking, and two gas Cherenkov counters and a uranium-scintillator calorimeter for particle selection. The sulphur ions are incident into a nuclear target placed at the upstream edge of the first bending magnet. The CX measures the sulphur ions just in front of the nuclear target and must be capable of counting the number of ions equivalent to an intensity of a few times 10^6 ions/s in order to give a precise normalization of cross sections. At the same time, the CX needs to discriminate contaminating ions which have a charge number different from that of the desired ions.

The secondary particles produced at the target are deflected and focussed by a series of dipoles and quadrupoles onto the first scintillator hodoscope. The particles go through two sets of threshold type gas Cherenkov counters and the second and third scintillator hodoscopes. The spectrometer sweeps over a narrow range of phase space, thereby detecting only a few particles at a time even in the high-particle-multiplicity environment. We must develop the ability to identify particles accurately, because two-particle interferometry employing kaons and protons is of urgent and particular physics interest, apart from the most popular pion interferometry. To this end, a high-precision time-of-flight (TOF) measurement is needed in addition to supplementary information

from the gas Cherenkov counters. As a typical TOF performance, the third hodoscope which is employed as a TOF stop counter has an intrinsic time resolution of 80 ps [2]. Since the flight path length from the target to the third hodoscope is 18 m, the TOF difference between pion and kaon at 6 GeV/c is 190 ps. This requires that the CX, which provides a timing signal for the beam particle's arrival at the target, must have a time resolution much better than 80 ps for good pion/kaon separation. Note also that a good TOF resolution enables us to reject neutron background in offline analysis. Finally, the CX must have adequate radiation hardness, since the radiation-damage effect increases drastically as the charge number of beam ions increases, while it must be able to operate stably for several months under a typical beam intensity of a few times 10^6 ions/s.

Various kinds of beam counters which employ solid scintillators or solid Cherenkov radiators have been used in relativistic heavy-ion experiments [3-6]. These detectors are, however, not able to meet all the above requirements simultaneously. We have chosen to use a gaseous Cherenkov detector. Since the number of Cherenkov photons is proportional to the square of the charge number Z of the beam ions, for $Z = 16$ we expect that an appreciable number of Cherenkov photons will be produced even for a gaseous radiator of reasonable length. Moreover, since the emission angle of the photons in case of the gaseous radiator is very small for ultra-relativistic ions, most of the emitted photons can be collected easily onto a photomultiplier using very simple optics, because the ion beam in question is thin and well fixed in space. The most important aspect of this detector is that, since the beam ions at this momentum are traveling at almost the speed of light, no measurable time lag occurs in arrival time of Cherenkov photons which are successively radiated along the beam path in a gaseous radiator. The radiation-damage effect is also greatly reduced by allowing the radiator gas to circulate. As a whole, the

CX has very small amount of effective material thickness compared with other types of solid detector, which effectively reduces unnecessary background. The CX was tested and installed in the NA44 experiment. It operated successfully for sulphur beams with an average intensity of 2×10^6 ions/s at 200 GeV/c per nucleon for more of one month, although some long-term deterioration was observed in the gain from the photomultiplier signals.

2 Counter Design

Figure 1 shows a side view of the detector system which consists of two identical counters CX1 and CX2 and a veto counter CXV. The reason why the CX contains two identical counters is to incorporate an internal control function. Since the CX's have much better time resolution compared with other counters, their intrinsic time resolution should be most accurately measured by themselves. The CX's detect Cherenkov photons emitted by the passage of beam ions in the gaseous radiator, whereas the CXV is a scintillation counter having a hole of 5 mm-radius through which the ion beam passes, and is used to cut off the beam halo and charged background produced upstream of the beam line. The CX consists of a gas container, a mirror of 50 μm-thick aluminum foil and a 2" photomultiplier (Hamamatsu H3378).

Pure nitrogen gas at a pressure of one atmosphere is flowed constantly and functions as a radiator. Nitrogen was chosen because it does not have appreciable absorption of Cherenkov photons. In addition to the fact, it is readily available and inexpensive. The value of the refractive index corresponds to a threshold momentum of 38 GeV/c per nucleon, which is well bellow the present beam momentum. The effective radiator

lengths are 15.5 and 20.5 cm for the CX1 and CX2, respectively. The Cherenkov photons are emitted at an angle of 1.4° from the beam direction and reflected vertically upward by the flat mirror set at 45° from the beam axis. The photons hit the photomultiplier window within a circular region of a radius of 6 mm, mostly around the center of the window.

Since the number of Cherenkov photons in a gaseous radiator is generally much smaller than that of scintillation photons emitted by a solid radiator, the pulse height of photomultiplier signal for the Cherenkov photons is correspondingly reduced. The photomultiplier must therefore have a fast response: the H3378 has a rise-time of 0.70 ns and a transit-time spread of 0.37 ns [7]. In addition to this, to accept as many photons as possible, the photomultiplier must be sensitive to UV components since Cherenkov photons have a maximum intensity in the UV region. The window of H3378 is made of quartz. In figure 2, we show the quantities relevant to Cherenkov photon detection as a function of photon wavelength. As seen from this figure the spectrum of Cherenkov photons accepted by the H3378 has a maximum in the vicinity of 200 nm and gradually decreases as the wave length increases, then drops rapidly above 400 nm. The photomultiplier must also work stably at a rate of 10^6 s^{-1} or more. At these rates, shortage of current supply occurs at a few dynodes in the final multiplication stages. This shortage causes sagging of output signal, resulting in degradation of timing performance. In order to compensate this shortcoming, we boosted current at each of the last three dynodes, i.e., 6- to 8-th dynodes. We also re-designed the voltage-divider circuit so that the bleeder current increases by 70 % than that of a standard voltage-divider model.

3 Experimental Results

We placed the CX at 0.5 m in front of the nuclear target of the NA44 focussing spectrometer at the H4 beam line of the SPS. Using the sulphur beam of 200 GeV/c per nucleon, we performed measurements of timing and pulse height output from the CX.

3.1 Time resolution

The time difference between output signals from the CX1 and CX2 was measured at various beam intensities ranging from 600 ions/s to 2×10^6 ions/s. Each measurement took a few hours depending on physics program of the NA44 experiment. As a typical example, figure 3 shows the distribution of the time difference in question at the intensity of 1.0×10^6 ions/s. When the distribution is fitted to a Gaussian form, a rms resolution of 42 ps is obtained. Assuming that both the CX1 and CX2 have the same intrinsic time resolution, the intrinsic time resolution of each counter is found to be $42/\sqrt{2} = 30$ ps.

In figure 4, the intrinsic time resolution is shown as a function of the beam intensity, where we see that even at the maximum intensity of 2×10^6 ions/s, the resolution remains at a level of 30 ps. This resolution is much better than that of the third hodoscope as required in the introduction.

3.2 Pulse height distribution

Figure 5 shows the pulse height distribution of the CX's at a beam intensity of 1.0×10^6 ions/s, where the pulse height of the CX's is defined by the square root of the product of each pulse height from CX1 and CX2. We see a clear peak representing the sulphur-ion signal of interest and a broad peak at around twice the channel of the first peak. The first peak is fitted well to a Gaussian distribution with a mean of 372 channel and a rms

resolution of 4.8 %.

Figure 6 shows a scatter plot of the pulse height from each event versus a microscopic beam intensity, which is a beam rate at a very short interval, immediately before the event occurred. The microscopic intensity was obtained with a number of beam ions counted by the CX's at an interval of two successive triggered events, divided by the time interval measured with a scalar value of 1 MHz time clock. We see a horizontal band at the pulse height of about 380, and another group at around 750. The second group appears only at high intensities, and the two groups are clearly separated. We, therefore, conclude that we do not see sagging effects of the pulse height of photomultiplier signals at the beam intensities up to 2×10^6 ions/s, and that at higher intensities beam ions yield two times more photons than the primary beam ion. We could naturally interpret that the second peak may be caused by those events in which two ions are incident within a single ADC gate width. This hypothesis may explain the asymmetry of the single sulphur peak and the considerable amount of tail component between the two peaks in fig. 5, because a preceding or succeeding beam ion, which arrived at around the boundary of ADC gate opened by a beam ion of interest, always causes additive effects in the pulse height of the interest. It should be noted that the probability of such double-ion-incident event rapidly grows up being in proportion to the square of beam intensity as the beam intensity increases. In fact, we do not see the second peak in the data measured at the beam intensities below 10^5 ions/s. The ADC resolution improved slightly to be 4.0 % as the beam intensity was lowered down to 600 ions/s.

The CX has been operated for more of one month with the sulphur beam of the average intensity of 2×10^6 ions/s. The pulse height of output signals showed a gradual decrease by 30 % during this period. This long-term deterioration could not be recovered.

4 Discussion

As for the time resolution, the time spread of photon arrival at the photomultiplier comes from (a) the velocity difference and (b) the path length difference, between the Cherenkov photons and the incident ions. However, numerical estimates of both (a) and (b) show that these effects are negligible, less than 0.4 ps. Thus, our value of ≤ 30 ps may be limited by the H3378 photomultiplier and/or the present readout electronics.

Now we discuss the width of the pulse height distribution. As the Cherenkov process occurs stochastically, the number of Cherenkov photons fluctuates statistically, thereby resulting in fluctuations in the pulse height. However, since the number of photons produced by a single incident ion does not depend on the beam intensity, its statistical fluctuation should be independent of the beam intensity. If the width of pulse height distribution were only due to the statistical fluctuation of the photon number, the width would be accordingly independent of the beam intensity. We observed, however, a broadening of the width from 4.0 % to 4.8 %, when the beam intensity was increased from 600 to 10^6 ions/s. This implies that at least at the higher intensity some effect other than the photon number fluctuation contributes to the width.

If we assume that at the lower intensity, the width is entirely due to the fluctuation in the number of photo-electrons N_e, we have

$$N_e = (1/4.0\%)^2 \cong 630$$

for the CX's. On the assumption that the contributions from the two CX counters are identical, this number would be expressed as

$$N_e = 2\pi\alpha Z^2 L \int \eta(\lambda)\kappa(\lambda)\{1 - 1/\beta^2 n^2(\lambda)\}d\lambda/\lambda^2,$$

where η is the product of quantum efficiency and mirror reflectance which are shown in

fig. 2, κ is the transparency of the radiator gas for Cherenkov photons, β is the velocity of incident ions, n is the refractive index of the radiator, and L is the total radiator length of CX1 and CX2. If we consider that the transparency κ is always 100 % for the entire region of the wavelengths on interest, the integration over the entire region gives the maximum estimate for the number of photo-electrons, resulting in $N_e = 1850$. On the other hand, if we assume a cut-off wavelength at 200 nm in the transparency, the integration above 200 nm results in $N_e = 1550$. In both cases, the predicted values are 2.5 - 3 times larger than that estimated from the statistical fluctuation. This discrepancy, if taken at its face value, means that the above assumption is not good and there exists an additional effect which increases the width, other than the fluctuation of N_e, although its origin is unknown at present.

It should, however, be noted that even though the experimental value is considerably poorer than the theoretical value, the CX has a capability of discriminating ions with their charge number different by one unit from the sulphur ions by using the pulse height distribution. Since the nearest possible charge number is 15 in the present case and the ratio of Z^2, which is proportional to the pulse height, is $(15/16)^2 = 0.879$, with the observed value 5 % of the width, we can discriminate ions with $Z = 15$ from those with $Z = 16$ at a level of two standard deviation.

5 Conclusions

We have constructed a beam counter system consisting of two sets of gas Cherenkov counter CX1 and CX2 for ultra-relativistic heavy-ion beams. The Cherenkov radiator is pure nitrogen gas at 1 atm with the radiator length being 15.5 and 20.5 cm for the CX1 and CX2, respectively. The Hamamatsu H3378 photomultiplier has been modified by

attaching a current booster to the dynodes of the last three stages and by re-designing the voltage-divider circuit to increase the bleeder current by a factor of 1.7 than that of the standard circuit.

The CX system attained the intrinsic time resolution of 30 ps for the sulphur ions of 200 GeV/c per nucleon at the beam intensity $\sim 2\times10^6$ ions/s. The resolution improves up to 23 ps as the beam intensity decreases down to 600 ions/s. The pulse height distribution of the output signal is well reproduced by a Gaussian form with a rms resolution of 5 % at 10^6 ions/s. This pulse height resolution enables us to discriminate any beam ions from sulphur ions by means of the pulse height distribution at a confidence level of two standard deviations. The observed deviation in the pulse height distribution is 60 - 70 % larger than that estimated from the statistical fluctuation in the number of photo-electrons theoretically predicted. As a long-term variation, 30 % reduction of pulse height is observed after a continuous operation for one month at an average intensity of 10^6 ions/s.

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Figure captions

Fig. 1. Side view of the CX system.

Fig. 2. The left ordinate should be referred for spectral dependence of the mirror reflectance, and of the quantum efficiency of photocathode material which takes into account an absorption effect in the PMT window, while the right ordinate is for Cherenkov photon yield in nitrogen gas at 1 atm, and for the theoretical estimate of photo-electron yield per radiator length of 1 cm per photon wavelength of 1 nm.

Fig. 3. The time difference spectrum measured between the CX1 and CX2 at a beam intensity of 1.0×10^6 ions/s. The curve is a Gaussian fit and the zero point on the abscissa is taken arbitrarily.

Fig. 4. The intrinsic time resolution as a function of the beam intensity.

Fig. 5. Pulse height distribution at 1.0×10^6 ions/s with a Gaussian fit.

Fig. 6. Scatter plot of the pulse height versus the microscopic beam intensity.