Nuclear Instruments and Methods in Physics Research A 640 (2011) 49–53

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Luminosity measurement in H1

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ARTICLE INFO

Article history:
Received 15 March 2010
Received in revised form
12 December 2010
Accepted 27 December 2010
Available online 14 January 2011

Keywords:
Luminosity
HERA
HI
Bremsstrahlung
Fitting method

ABSTRACT

The HERA luminosity was determined by measuring the flux of bremsstrahlung photons emitted at zero degree off electrons in the field of protons in the interaction region. After the HERA upgrade, the H1 Collaboration developed a new luminosity system which measured all the emitted photons in a bunch crossing. We describe the expression of this photon flux in the luminosity detector which is used in the simulation of the detector. The total energy method, based on the measurement of the bremsstrahlung photon energy flux in the calorimeter, is the standard method for the off-line luminosity measurement. In this study, we propose a new method to calculate the luminosity. This new method is based on the shape of the bremsstrahlung photon energy spectrum measured in the luminosity detector. The two methods are compared. A good agreement is observed.

1. Introduction

During the years 2000/2001, the electron–proton collider HERA was stopped for a machine upgrade aiming for an increase of instantaneous luminosity by decreasing the beta function at the colliding points. The new mean value of the instantaneous luminosity was about $1.7\times10^{31}\ \mathrm{cm^{-2}\,s^{-1}}$. For the luminosity measurement in the H1 experiment [1], the machine upgrade implied a harder synchrotron radiation spectrum[2] due to the increase of the curvature of the electron beam in the interaction region. The dose deposited in the detector used for the luminosity measurement was about 0.25 MGy/year. This high level of radiation have led the H1 collaboration to design a new calorimeter complemented by a synchrotron radiation shielding. Between April and June 2007, HERA has operated with low-energy proton beam. In this work, we study only high energy runs.

The particles in HERA beams were grouped in bunches spaced by 96 ns. Up to 220 bunches could be stored in each HERA rings. To study the beam related backgrounds, the electron and protons bunches were grouped into trains having slightly different structure resulting in a number of non-colliding pilot bunches.

At HERA, the luminosity was determined by measuring the flux of bremsstrahlung photons emitted at zero degree off electrons in the field of protons in the interaction region. The photon energy spectrum is well described by the Bethe–Heitler cross-section modified according to the *Beam Size* effect [2–5].

Several methods were used to calculate the luminosity in H1. For instance, during data taking, the luminosity is monitored by counting the number of events for which the total energy in the photon detector is above 5 GeV [6]. A more accurate method based on the measurement of the bremsstrahlung photon energy flux in the calorimeter is described below. In this study, we propose a new luminosity calculation method based on the shape of the photon energy distribution per bunch crossing measured in the luminosity detector.

2. The photon flux

The number of photons $N_\gamma^{\mathrm{BC}}(\varepsilon)$ emitted above an energy threshold ε per bunch crossing reads

$$N_\gamma^{\mathrm{BC}}(\varepsilon) = L_{\mathrm{BC}}\cdot\sigma_{\mathrm{BH}} \qquad (1)$$

where σ_{BH} is obtained from the Bethe–Heitler differential cross-section:

$$\sigma_{\mathrm{BH}} = \int_\varepsilon^{E_e^0} \frac{d\sigma_{\mathrm{BH}}}{dE}\,dE \qquad (2)$$

with E_e^0 the maximal possible energy of a bremsstrahlung photon, corresponding to the electron beam energy, and L_{BC} the luminosity of a single bunch crossing.

The total energy deposition in the calorimeter corresponds to the sum of all the emitted photons in a bunch crossing. These pile-ups cause distortions in the energy spectrum observed in the photon detector. The number of produced photons above a threshold ε per bunch crossing follows a Poisson distribution:

$$P(n) = \frac{\mu^n\cdot e^{-\mu}}{n!} \qquad (3)$$

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[2] Critical energy $E_c \approx 160$ keV instead of 34 keV.

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doi:10.1016/j.nima.2010.12.219

where μ is the mean value of the distribution and n is the number of photons. Therefore, the distribution of energy depositions in the calorimeter, originating from one or more photons, per bunch crossing is given as

$$\frac{dN^{\rm BC}}{dE} = \sum_{n=1}^{\infty} \frac{\mu^n \cdot e^{-\mu}}{n!} \cdot \mathcal{G}_n(E) \tag{4}$$

where $\mathcal{G}_n(E)$ is the probability that a group of n photons above a threshold ε has a total energy $E = E_1 + E_2 + \cdots + E_n$. The spectrum measured by the detector for n photons is equal to the convolution of n spectra corresponding to a single photon. $\mathcal{G}_n(E)$ may be expressed according to $\mathcal{G}_1(E_i) = dN_\gamma^{\rm BC}/dE$:

$$\mathcal{G}_n(E) = \int_\varepsilon^{E_e^0} \int_\varepsilon^{E_e^0} \cdots \int_\varepsilon^{E_e^0} \mathcal{G}_1(E_1) \cdot \ldots \mathcal{G}_1(E_{n-1}) \cdot \mathcal{G}_1(E - E_1 - \cdots - E_{n-1}) dE_1 \ldots dE_{n-1} \tag{5}$$

where E_e^0 is the energy of the HERA electron beam (27.5 GeV). By integrating Eqs. (1) and (4) for energy, the following result is obtained:

$$\int_\varepsilon^\infty \frac{dN^{\rm BC}}{dE} dE = \mu = \langle N_\gamma^{\rm BC}(\varepsilon) \rangle = \langle L_{\rm BC} \rangle \cdot \sigma_{\rm BH}. \tag{6}$$

The average number of photons per beam crossing μ is proportional to the average luminosity per bunch crossing. For a time interval Δt, the number of bunch crossings $N_{\rm BC}$ is

$$N_{\rm BC} = N_{Coll} \cdot f_0 \cdot \Delta t \tag{7}$$

where N_{Coll} is the number of colliding bunches and f_0 is the HERA frequency. By integrating Eq. (6) using a time interval Δt, we have:

$$\int_{\Delta t} \int_\varepsilon^\infty \frac{d^2 N^{\rm BC}}{dE\,dt} dE\,dt = \mu \cdot N_{\rm BC} = \mu \cdot N_{Coll} \cdot f_0 \cdot \Delta t = \mathcal{L} \cdot \sigma_{\rm BH} \tag{8}$$

where $\mathcal{L} = \sum_{i=1}^{N_{Coll}} \int_{\Delta t} {\rm L}_{\rm BC}^i\, dt$ is the integrated luminosity and ${\rm L}_{\rm BC}^i$ is the luminosity of the colliding bunches i per bunch crossing.

3. Photon detector

The new photon detector of the H1 luminosity system was a Cherenkov fibre sampling calorimeter composed of 69 layers of optical quartz fibres sandwiched between tungsten radiator plates. The fibres of each layer were grouped in 12 strips of 10 mm and disposed in the two orthogonal directions, X and Y, to provide a position measurement. The calorimeter had transversal dimensions of 120 mm × 120 mm and a depth of 25 radiation length (X_0).

A beryllium filter was installed in front of the photon detector to shield it against the large flux of synchrotron radiation photons. To obtain a five order of magnitude attenuation, the depth of the filter was set to $2X_0$ [7,8].

The DAQ of the luminosity detector stored for each BC the individual sums of the x and y-segmented planes in histograms according to the BC type (Colliding, e/p-Pilot, Empty). These histograms were built every second for on-line analysis, summed over 4 min and stored for off-line analysis [9].

3.1. Detector response

The photon energy measured is distorted by the response of the detection and acquisition system (filter, detector and electronic components), and an effective cross-section of detection can be defined as

$$\frac{d\sigma_{\rm det}(E_s)}{dE_s} = \int_0^\infty R(E_i, E_s) \cdot \frac{d\sigma_{\rm BH}(E_i)}{dE_i} dE_i \tag{9}$$

where E_s and E_i are the measured and incident energies of a photon, respectively.

The impact of the filter was studied using a full simulation. It is modelled as the sum of three functions of E_i and x_f, the ratio between the energy measured and the incident energy. The first function describes photons passing unaltered the filter leading to a detector response linear with incident energy. Low-energy photons may deposit all their energy in the filter, leading to a peak at $x_f = 0$. In this region the response is described by an exponential function of the inverse of E_i. For larger energies a third function treats a pre-showering in the filter, leading to an energy loss described by a flat distribution in x_f for $E_i < 0.5$ GeV and by a Gaussian for an incident energy above 0.5 GeV [8].

Tests were carried out at CERN in 1999 and 2000, using electron beams with energies between 6 and 100 GeV. The energy resolution of the calorimeter using either only the Y or only the X strips was measured to be $\delta(E)/E = 27.5\%/\sqrt{E[{\rm GeV}]}$ [7]. At low energy, the detector has an energy threshold $\varepsilon_{\rm det}$, given by the minimum energy required for a photon to interact according to the Compton effect in the first tungsten plate, and for the electron released to reach the first row of fibres and produced some Cherenkov light. This threshold is 5 MeV for the x-segmented planes and 10 MeV for the y-segmented planes. Indeed, the photons have to pass through two tungsten plates before reaching the first y-segmented planes fibres.

The electronic noise spectrum caused by the photomultipliers, reading and shaping electronic components, and cabling has been measured in experimental conditions. It can be modelled by two overlaid Gaussian functions. Their average values are artificially offset by 48 ADC channels in order to observe the entire signal.

The response function of the whole detection system, $R(E_i, E_s)$, is the convolution of the filter, detector and electronic component response functions.

The low-energy cut-off of the detector is $\varepsilon_{\rm det}$ and we can express the cross-section:

$$\sigma_{\rm det} = \int_{\varepsilon_{\rm det}}^\infty \frac{d\sigma_{\rm det}}{dE_s} dE_s. \tag{10}$$

Therefore, Eq. (8) may be expressed:

$$\int_{\Delta t} \int_{\varepsilon_{\rm det}}^\infty \frac{d^2 N^{\rm BC}}{dE\,dt} dE\,dt = \mu_{\rm det} \cdot N_{Coll} \cdot f_0 \cdot \Delta t = \mathcal{L} \cdot \sigma_{\rm det} \tag{11}$$

where $\mu_{\rm det}$ is the mean number of photons produced in a bunch crossing and measured by the detector.

3.2. Background processes

There were two sources of background when measuring the luminosity.

3.2.1. Synchrotron radiation

The filter did not completely absorb synchrotron radiation. A small amount of photons crossed the filter and deposited their energy in the calorimeter. Synchrotron radiation was a continuous flow of low-energy photons, which was proportional to the current of the electron bunches. Energy deposited in the detector was due to some photoelectrons following a Poisson distribution. A shift of the spectrum by several hundred MeV and a widening of the pedestal were observed.