The New H1 Luminosity System For HERA II

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Abstract

At HERA, luminosity is determined on-line and bunch by bunch by measuring the bremsstrahlung spectrum from e-p-collisions. The H1 collaboration has built a completely new luminosity system in order to sustain the harsh running conditions after the fourfold luminosity increase. Namely, the higher synchrotron radiation doses and the increased event pile-up have governed the design of the two major components, a radiation resistant quartz-fibre electro-magnetic calorimeter, and a fast read-out electronic with on-line energy histogramming at a rate of 500 kHz. An overview of the different components of the new luminosity system is given, and the commissioning status is reported.

1 Luminosity measurement at HERA II

Since the start of operation in 1992 of the electron-proton collider HERA ($E_e = 27.5\,\mathrm{GeV}$,$E_p = 920\,\mathrm{GeV}$), the luminosity measurement has been performed by detecting bremsstrahlung gammas emitted by electrons in the interaction region. Ordinarily, the instantaneous luminosity is calculated by dividing the counting rate of gammas over a certain energy threshold by the visible Bethe-Heitler cross-section. [1]. The accuracy of this measurement is chiefly determined by the precision of the energy measurement of the photon.

In autumn 2001 the electron-proton collider HERA resumed operation after a one-year shutdown for a major machine upgrade aiming at a fivefold increase of instantaneous luminosity to $\sim 7.4 \cdot 10^{31}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. This increase is mainly achieved through a complete redesign of the interaction region with stronger focusing. In particular, super-conducting combined function magnets are introduced inside the collider detectors H1 and ZEUS[2].

Due to the smaller bending radius of these magnets, an order of magnitude more synchrotron radiation power is emitted by the electrons in the interaction regions. Furthermore, the critical energy increases from 35 keV(HERA I) to 160 keV(HERA II) giving rise to a synchrotron radiation spectrum extending into the region of $\approx 1\,\mathrm{MeV}$ where the photon absorption cross section for most materials is minimal. This is illustrated in fig. 1 where the entire synchrotron radiation energy spectrum and its penetrating part (i.e. passing two radiation length of lead) are compared for HERA I and HERA II. Since the bremsstrahlung gammas are emitted inside the synchrotron radiation fan, efficient shielding

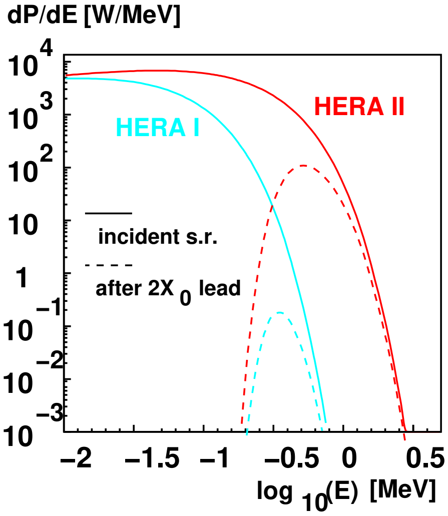

Figure 1: *Synchrotron radiation power spectrum for HERA I and HERA II*

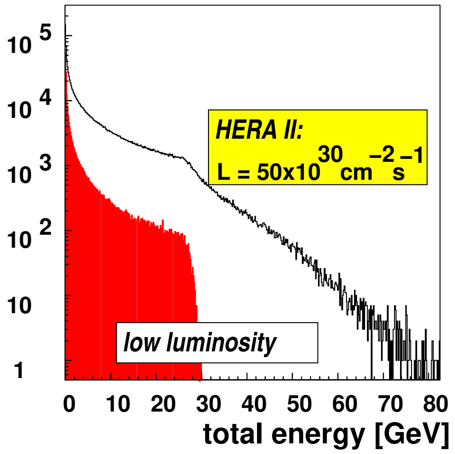

Figure 2: *Bremsstrahlung spectrum for low and HERA II luminosities*

and radiation hardness were a prime concern for the design of the new photon detector.

The second major design constraint stems from the increase in luminosity itself: At maximum design luminosity, in average 0.5 photons above 5 GeVand 1.5 photons above 0.5 GeVare emitted in one bunch crossing, i.e. every 96 ns. In order to limit rate-dependent signal overlap that would heavily bias the rate measurement, the detector pulse formation and shaping has to be sufficiently fast. However, pile-up of bremsstrahlung photons in one bunch crossing is unavoidable at high luminosities, and will induce a distortion of the observed energy spectrum as shown in fig.2. Therefore, in order to correctly assess the pile-up effect and correct for it by unfolding, it is necessary to histogram the energy spectrum with high statistical accuracy. Also, the suppression of low energy photons due to the finite size of the beam spot (so-called Novosibirsk effect) is expected to become sizeable after the upgrade [3]. A precise measurement of the energy spectrum will be useful in estimating the influence of this effect.

2 The new photon detector

The new photon detector of the H1 luminosity system is a Čerenkov sampling calorimeter with tungsten radiators and quartz-fibres as the active medium read by photo-multiplier tubes. A detailed description of the new photon detector as well as a summary of the beam test results can be found in [6]. Quartz, or more precisely, synthetic fused silica, is known to be the most radiation resistant optical material, and quartz-fibre calorimetry has proven suitable for the use in high-radiation environments since several years [4, 5].

In the environment of HERA after the upgrade, however, the intense synchrotron radiation would result in doses of the order of 10^{10} Gy per year, and has to be reduced by at least four orders of magnitude by the use of an appropriate shielding. Simultanaously, it is desirable to limit the degradation of energy measurement by dead material in front of the detector. Materials with a low atomic number Z constitute the best compromise between these two competing requirements, because gamma radiation in the MeV region is attenuated and — what is even more important — diluted mainly by Compton scattering ($\propto Z$) whereas the high energy bremsstrahlung gammas interact chiefly through pair creation ($\propto Z^2$). In the present case, two radiation lengths (70 cm) of Beryllium are used for attenuating the synchrotron radiation by almost five orders of magnitude.

While Čerenkov calorimetry naturally satisfies the requirements of high radiation hardness and fast pulse formation, the relatively low light yield of Čerenkov radiation has to be compensated by a very low volume ratio of passive to active material (1.68). Moreover, radiator plates and quartz-fibre planes are finely interleaved resulting in a very low sampling frequency of 0.36 and thus minimising sampling fluctuations. Tungsten has been chosen in order to keep the effective Molière radius low (17.2 mm). The total depth of 25 radiation length ensures a good energy confinement. Furthermore, the fibres are oriented at an angle of 45 deg, i.e. close to the Čerenkov angle of highly relativistic particles in quartz, with respect to the incoming particles in order to maximise the collection of Čerenkov light originating from the shower core. The overall light yield in this configuration is approximately two times higher than for a fibre orientation parallel to the incoming particles.

The photon detector has to measure precisely the gamma energy but also the impact point position in order to provide an online monitoring of the electron beam tilt to the machine, as well as for the determination of the detector acceptance. In order to fulfil the simultaneous requirements of position measurement in two orthogonal directions (x and y) and the corresponding optimum fibre orientations, a strip geometry has been chosen leading to a more complicated mechanical design than in a tower geometry. In a strip geometry, the same granularity is achieved with a much lower number of readout channels than in a tower geometry, however at the cost of horoscope ambiguities which are not a prime concern in this application. The fibres of each layer are grouped in 12 strips of almost equal width of approximately 10 mm. With horizontal and vertical strips interleaved, two orthogonal coordinates of the shower centre, y and x respectively, can be measured with the same precision.

The energy response of the calorimeter has been measured with an electron beam of energies varying between 6 and 100 GeVduring beam tests at CERN in 1999 and 2000. After inter-calibration of the individual channels to the percent level, the energy resolution $\sigma(E)/E$ has been measured to be $27.5\%/\sqrt{E[\,\mathrm{GeV}]}$ for the sum of x or y strips separately ,and $19.2\sqrt{E[\,\mathrm{GeV}]}$ for the sum of all strips. The ratio of $\approx \sqrt{2}$ of these two values indicates that the horizontal and the vertical fibre layers sample the shower independently.

3 Electron tagger at 6m

For calibration purposes it is useful to detect also the scattered electron of the bremsstrahlung process since the energies of the final state electron and photon add up to the electron beam energy. The scattered electron is bent away from the nominal electron orbit towards the collider centre by the dipole field components

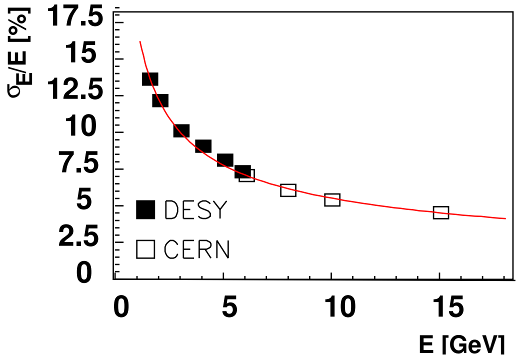

Figure 3: *Energy resolution of the electron tagger ETAG6m*

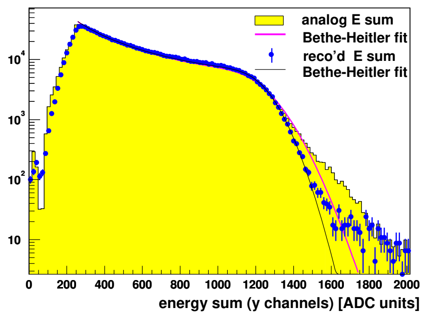

Figure 4: *Bremsstrahlung spectrum measured by the photon detector.*

of the magnets in the interaction region. Besides this ancillary function, the detection of the scattered electron is vital for the study of interactions of protons with quasi-real high-energy photons at HERA.

The existence of an energy range in which the detection of the scattered electron is possible depends entirely on the particular geometrical configuration of magnets and on the available space. In the case of the HERA upgrade, it was possible to install an exit window inside the air gap of the first (warm) quadrupole GI1 at 6 meters from the interaction point. The energy of the scattered electron is measured by a very compact calorimeter (ETAG6m) located inside the quadrupole's air-gap. In this configuration, the acceptance of the electron tagger ETAG6m is 100% for bremsstrahlung electrons between 5 GeVand 8 GeVand above 75% for electrons from photo-production between 6 GeVand 9X GeV.

The ETAG6m is a lead spaghetti calorimeter with a high volume fraction of scintillating fibres (Pb:Fibres=1:2.26) of which only the active volume of $78 \times 24 \times 2000\,\mathrm{mm}^3$ is located in the magnet's air-gap. The light is collected by light guides and then conducted by flexible fibre bundles to photo-multiplier tubes. The calorimeter has a matrix granularity of six cells in the horizontal direction and two cells vertically, providing an impact position measurement capability. Position reconstruction is necessary for two reasons: First, the lateral shower leakage, especially in the vertical direction, due to the limited size of the detector has to be corrected for depending on the beam position. Second, the impact point information can help to improve the energy measurement by exploiting the correlation between these two, since the super-conducting magnet and in a lesser degree the quadropule magnet GI1 act as a spectrometer.

The ETAG6m has been tested in electron beams at DESY (1.5–6 GeV) and at CERN (6–15 GeV). In these tests, the energy response has been found to be linear within one percent, and the energy resolution of $17.5\%/\sqrt{E[\,\mathrm{GeV}]}$ in agreement with Monte-Carlo simulations (cf.fig. 3).

4 Front-end electronics and Data acquisition

Due to constraints in the beam geometry of the straight section, the photon detector is located at a distance of 103 m, i.e. quite far away from the interaction point, inside the HERA tunnel, a crowded, high noise, high radiation environ-

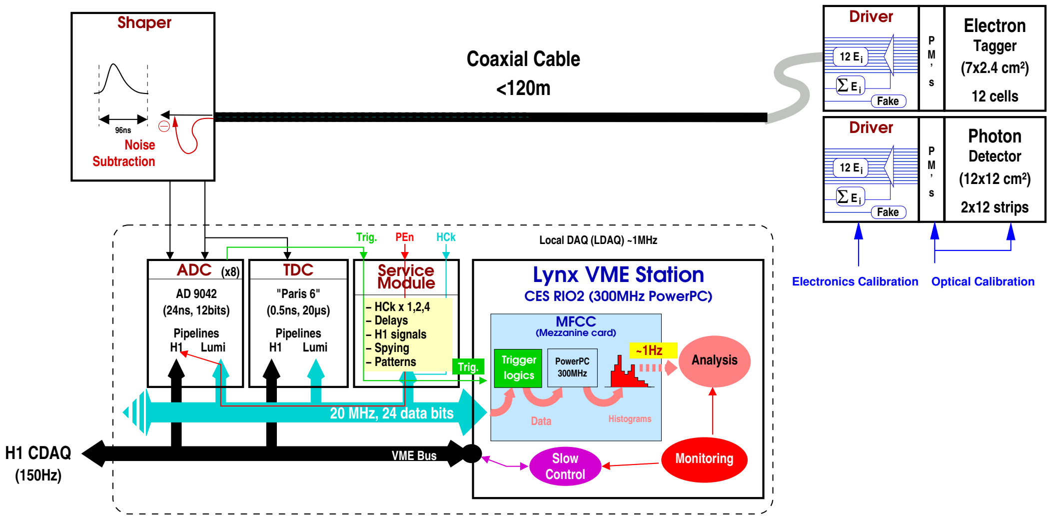

Figure 5: *Schematics of the electronics of the H1 luminosity system*

ment which furthermore is inaccessible during normal operation. Hence, most electronics system had to be placed in the (accessible) H1 experimental hall, as far as possible, However, for a coaxial cable length of 125 m per electronics channel this implies fighting pulse overlap due to dispersion, signal loss due to attenuation (10dB), and common mode pick-up noise. The analog electronics chain has been designed to address each of these topics.

The individual channels are pre-amplified in the tunnel and a fraction of each amplified signal enters an analog sum of twelve channels. The advantage lies clearly in the twelve-fold reduction of coherent pick-up noise on these analog sum signals. Consequently, all three of these pre-amplifier boards are located as close as possible to their respective group of PMTs (Photon detector x-strips and y-strips, ETAG6m). Furthermore, each board has one channel with the pre-amplifier input shorted to ground. This "blind" channel is dedicated to the analog subtraction of the low frequency noise picked up along the coaxial cable. Typically, a reduction of collected noise at 150 Hz from 80 to 8 mV has been measured.

At the other end of the transmission line, the individual and sum pulses have acquired a slow time component. After subtraction of the blind channel, this dispersive effect is reversed by a pole-zero compensation and a RC-CR filter especially tailored to match the coaxial cable type and length. The resulting pulse drops to less than one percent of its maximum value within 72 ns. Finally, the initial pulse amplitude is restored by a 10dB amplification. The measured intrinsic noise of 0.55mV on the individual channels (0.96 mV on the sums) is attributed mainly to the shapers.

Each signal is sampled permanently four times per bunch crossing (i.e. every 24 ns), digitised with 12 bit precision, and stored in two independent pipelined buffers. The read-out of the first pipeline takes place through a standard VME bus, and is initiated by the central data acquisition (DAQ) of H1 at a rate of typically 150 Hz. The second pipeline is read out by the dedicated luminosity

DAQ through a custom 24 bit custom bus operating at 20 MHz. For every event and for each channel, be it an individual channel or a sum, two samples are read out: the pulse maximum and the pedestal for event-by-event subtraction.

The dedicated luminosity DAQ system is built entirely from commercially available components (multi-function computing core (MFCC) board on RIO2 station operating under Lynx OS) and has two major modes of operation: In the bunch train mode it performs the fast, high statistics histogramming of energy sums bunch by bunch for the luminosity measurement. In the triggered mode all channels are read out for beam position measurement and calibration. The bus function, the trigger logic, the sequencing, formatting, and the output register are all realized in the FPGA of the MFCC board. The energy histograms and event data are accumulated in the MFCC memory, and then transferred from there to the RIO station approximately every second, where further processing, such as on-line luminosity determination and beam position are performed.

5 Commissioning and Calibration

The luminosity system has been progressively installed in 2001 during the HERA shutdown, and commissioned during the start-up in autumn 2001. During this phase, detector counting rates and a coarse beam position monitoring were supplied to the machine.

The luminosity measurement requires the energy response of the photon detector to be calibrated. By adjusting the high voltage levels on the PMTs the channel responses have been equalised coarsely to within about 10-20%. After this pre-calibration, inter-calibration coefficients are calculated off-line by applying an iterative method on the response spectra of single channels. These inter-calibration coefficients can be used for further high voltage adjustments.

The absolute energy scale is determined by fitting the Bethe-Heitler spectrum — smeared with the detector resolution — to the distribution of the analog energy sum. The spectrum of the (pre-calibrated) analog sum and of the sum of (fully inter-calibrated) channel response is shown in fig. 4. The effect of the calibration can be observed as a steepening of the high energy edge of the spectrum. From a fit of the Bethe-Heitler formula for bremsstrahlung to the sum response spectra one determines the energy scale. During the start-up of HERA when beam currents and therefore instantaneous luminosity are rather low, event pile-up effects can be neglected. A preliminary luminosity measurement is performed by dividing the counting rate above some well determined energy threshold by the corresponding integrated cross-section.

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