4 Luminosity system and electron tagger

The luminosity system serves several purposes. Its main task is a fast relative luminosity measurement with a statistical precision of $\sim 2\%$ at nominal beam conditions. It also provides electron beam monitoring for the HERA machine, absolute luminosity measurement in the interaction region with an accuracy of $\sim 5\%$, tagging of photoproduction events and energy measurement for electrons scattered under small angles and for photons from initial state radiation.

4.1 System Overview

The luminosity is determined from the rate of Bethe-Heitler events $et \rightarrow ep\gamma$ [24]. The main source of background is bremsstrahlung from the residual gas in the beam pipe, $eA \rightarrow eA\gamma$. At design luminosity these events are expected at 10% of the $ep \rightarrow ep\gamma$ rate, but can be subtracted using data from electron pilot bunches. The luminosity is calculated as

$$L = \frac{R_{tot} - (I_{tot}/I_0)R_0}{\sigma_{vis}}$$

where R_{tot} is the total rate of the bremsstrahlung events, R_0 is the rate in the electron pilot bunches, I_{tot}, I_0 are the corresponding electron beam currents and σ_{vis} is the visible part of the $ep \rightarrow ep\gamma$ cross-section with acceptance and trigger efficiency included.

The luminosity monitor detects scattered electrons and outgoing photons in coincidence. It contains therefore two arms: the electron tagger (ET) and the photon detector (PD). Since the angular distributions for both the electrons and photons are strongly peaked in the direction of the primary e-beam – at 30 GeV polar angles are of the order of $\theta \simeq O(m/E) \simeq 17$ μrad – the detectors have to be placed close to the beamline and from the interaction region in order to cover these small angles.

The general view of the luminosity system is shown in Fig. 9. Scattered electrons are deflected by a set of low-beta quadrupoles and a bending magnet located in the region $5.8 \text{ m} < -z < 23.8$ m, pass an exit window at $-z = 27.3$ m and hit the ET at $-z = 33.4$ m. The photons leave the proton beam pipe through a window at $-z = 92.3$ m, where the beam pipe bends upward, and hit the PD at $-z = 102.9$ m. A Pb filter (2 X_0) followed by a water Čerenkov (1 X_0) veto counter (VC) protects the detector from the high synchrotron radiation flux. From the p-beam side the PD is shielded by an iron wall of 2 m thickness. The VC eliminates events with photons interacting in the filter. Both the ET and PD can be remotely moved from the median plane of the e-beam during injection. This operation can be reversed within $1 - 2$ min with a position accuracy of ~ 100 μm.

The acceptance of the luminosity system for nominal electron beam conditions ($E_e = 30$ GeV, zero tilt) and the expected rates at the design luminosity of 1.5×10^{31} cm^{-2}s^{-1} are given in the Table 3. One of the main contributions to the systematic error in the absolute luminosity measurement comes from the dependence of the system acceptance on possible variations of the electron beam angle in the interaction region. This tilt, typically of the order of 100 μrad, is controlled by the position of the beam profile at the PD with high precision, of the order of 10 μrad. The corresponding corrections to σ_{vis} are taken into account already online and can be further improved during the offline analysis.

Quasi-real photoproduction events with $Q^2 < 0.01$ GeV^2 can be tagged by the ET in the energy interval $0.2 < E_{e'}/E_e < 0.8$ using both the PD and VC as a veto.

	unit	ET	PD
Energy interval, $E_\gamma/E_e = 1 - E_{e'}/E_e$		$0.2 - 0.8$	$0.004 - 1.0$
Polar angle acceptance interval	mrad	$0 - 5$	$0 - 0.45$
Average acceptance for $ep \to ep\gamma$	%	48	98
Average acceptance for photoproduction	%	36	–
σ_{vis}	mb	28	174
$ep \to ep\gamma$ rate for $E > E_{thr} = 4$ GeV [1]	MHz	0.4	1.3
Photoproduction event rate [1]	Hz	$20 - 30$	–
Aperture $x \times y$ (granularity)	mm^2	154×154 (7×7)	100×100 (5×5)
Chemical composition		TlCl(78%) + TlBr(22%)	
Radiation length (Moliere radius)	cm	0.93 (2.10)	
Crystal length (radiation hardness)	cm (Rad)	20 ($> 6 \cdot 10^7$)	
Energy resolution, σ_E/E [2]	%	$1 \oplus 10/\sqrt{E}$, (E in GeV)	
Position (time) resolution, $\sigma_{x,y}$ (σ_t) [2]	mm (ns)	$0.3 - 1.2$ (< 3)	

Table 3: Parameters of the luminosity system. [1] at design luminosity; [2] values reached at HERA.

4.2 Detectors

The design goals – high radiation resistance, good energy, coordinate and time resolution and compactness – were best met by a hodoscope of total absorption KRS-15 crystal Čerenkov counters. Their properties are summarized in Table 3.

Each calorimeter cell is viewed by a FEU-147 photomultiplier [25] with a 20 mm diameter cathode coupled to the crystal with an optical contact. The veto counter is viewed by two phototubes operating in different regimes, the first for photon detection, the second operating with increased voltage and reaching full efficiency for charged particles with a range exceeding 35 cm. Taking into account the material in front of VC, this corresponds to full efficiency for e.m. showers initiated by the photons with $E_\gamma > 1.5$ GeV.

Since the luminosity detectors operate at high rates up to few MHz, which may vary within one beam filling by a factor of 3 to 10, they are permanently calibrated during data taking using the energy constraint $E_{ET} + E_{PD} = E_{e-beam}$. Although the calibration coefficients may change within $5 - 20\%$, this method allows an absolute calibration with a precision of better than 1%. Figure 10 illustrates this energy correlation between the two arms.

4.3 Trigger and data acquisition

The different functions of the luminosity system required a special trigger and data acquisition concept, based on the two completely independent branches. The photomultiplier signals pass first differential preamplifiers close to the detectors and then, after 170 m or 100 m of fast coaxial cable pairs, respectively, are again shaped and amplified at the trigger electronics crate. This solution reduces noise and compensates for signal attenuation in the cables. Then the signals are split and analysed in two groups of FADCs (2×80 channels).

The first FADC group operates in a standard mode, similar to all other subdetector trigger systems (see Section 5.3.4). The trigger electronics discriminates the analog energy sums against the individually set thresholds, producing a dead time free trigger bit synchronized to the HERA beam crossing. Three basic trigger signals are available from the electron arm ($E_{ET} > E_{ET}^{thr}$),

Based on the offline γ - rate method				
Contribution to $\delta\mathcal{L}$	1993	1994		
	e^-p	e^-p	e^+p	shifted I.P.
1. Theoretical value for σ_{BH}	0.5%		0.5%	
2. Trigger efficiency	2.0%		0.3%	
3. Statistics, e-gas bgrd. subtraction	1.5%	1.3%	0.4%	3.3%
4. γ-energy scale (calib & resol.)	1.7%	1.1%	0.9%	1.7 %
5. Geometrical acceptance of γ-arm	0.7%		0.5%	
6. Multiple photon effect (pileup)	0.2%	0.3%	0.4%	0.3%
7. Counting and rounding errors	1.1%		0.5%	
Total error from lumi system	3.4%	2.0%	1.4%	3.8%

Table 4: Systematic error for the absolute luminosity measurement.

the photon arm ($E_{PD+VC} > E^{thr}_{PD+VC}$), and the veto counter. The main TE used so far for tagged γp physics was eTAG = ET$*\overline{\mathrm{PD}}*\overline{\mathrm{VC}}$. The front end readout and the data transfer to the central data acquisition are done by a program running on the FIC8230 master processor [26].

The second FADC group is controlled locally and completely decoupled from the H1 trigger system. Two triggers are used for the luminosity calculation and online detector calibration: ET$*$PD and ET$*$PD$*\overline{\mathrm{VC}}$. Any combination of 5 TEs can be permanently stored without dead time for each of the 220 bunches in a fast histogramming memory of 32$\times$220 channels. This memory contains the full information on all bunch related trigger statistics, e.g. the level of accidental coincidences. The online event processing includes fast reconstruction, calibration, trigger verification and calculation of the current luminosity and is performed on a second FIC8230 processor.

4.4 Performance

The system has been working successfully since April 1992. A typical example of the information provided by the luminosity system during $e-p$ collisions is shown in Fig. 11. For safety reasons lead-scintillator calorimeters were used in 1991 [27] during the running in phase of HERA. In the early phase, when HERA operated at 1% of the design luminosity, the detectors were active even during injection and ramping of the electron beam, which allowed the machine crew to better understand the beam dynamics and to adjust for collisions quickly.

The total integrated luminosity measured in 1993 and 1994 by H1 is shown in Fig. 6. The present understanding of the systematic error is summarized in the Table 4. Due to the redundancy in the trigger, the systematic error can be further reduced by combining the present method with other possible triggers (e.g. with the total photon flux measurements [28] etc.). The data sample taken with the help the eTAG trigger of the luminosity system was the starting point for all photoproduction results presented by H1 so far [29, 30].