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Abstract
The first measurement of the HERA collider luminosity by the ZEUS luminosity monitor is reported. The measurement was performed for collisions of 26.6 GeV electrons with 480 GeV protons. Over 4 weeks of HERA operation in November 1991 the measured luminosity has increased from $\approx 7\cdot 10^{26} cm^{-2}s^{-1}$ to $\approx 2\cdot 10^{28} cm^{-2}s^{-1}$ as a result of increasing beam currents and improved machine tuning.

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1 Introduction

On October 19th 1991 the first head-on collisions of 12 GeV electrons with 480 GeV protons were observed in HERA collider [1]. In consecutive weeks the energy of electrons was ramped to the value of 26.6 GeV and till the begining of December HERA delivered in total about 20 hours of luminosity in 26 separate runs[2]. The duration of runs varied between few minutes and few hours. At the beginning of the running periods electrons and protons were stored each in one bunch with currents of a few tens of μA. Later on an extra electron bunch was added (a "pilot" bunch) which had no proton partner and was used for background monitoring. At the end of the running period, during the last days of November, HERA was operating with 10 electron and 10 proton bunches, plus a pilot electron bunch.

The total electron and proton currents achieved at the end of running period were of the order of 2 mA and 1.5 mA respectively i.e. $\approx 180\mu A$ per electron bunch and $\approx 150\mu A$ per proton bunch. The nominal value of the designed bunch current is 1.5 times larger for electrons and 4 times larger for protons. During the whole running period there were many hours of only one beam circulating which allowed to investigate electron bremsstrahlung on the remnant gas molecules and to measure the background from the proton beam.

2 General Concept of Luminosity Measurement

The luminosity is defined by the formula :

$$R = L \cdot \sigma \tag{2.1}$$

where R is the rate of a chosen type of events, σ is their a priori known cross section, and L is the luminosity. The bremsstrahlung process $ep \to ep\gamma$ has been chosen for the luminosity measurement because it has a large cross section known from QED and a well defined experimental signature. The luminosity monitor of the ZEUS experiment detects the scattered electron and outgoing photon in coincidence.

2.1 Cross Section

The bremsstrahlung cross section σ_{BH} is given by the Bethe-Heitler formula [3] which for high energy ep collisions reads :

$$\frac{d\sigma_{BH}}{dk} = 4\alpha r_e^2 \frac{E'}{kE}\left(\frac{E}{E'} + \frac{E'}{E} - \frac{2}{3}\right)\left(\ln\frac{4E_pEE'}{Mmk} - \frac{1}{2}\right) \tag{2.2}$$

where:
k = photon energy and $k = E - E'$,
E, E' = primary and secondary electron energy,
E_p = proton energy,

M, m = masses of proton and electron,
α = fine structure constant,
$r_e = 2.818 \cdot 10^{-13}$ cm, classical radius of electron.

The values obtained from the integration of this cross section over the intervals of the final photon energy k, and the corresponding rates calculated assuming the nominal luminosity of $1.5 \cdot 10^{31} cm^{-2} s^{-1}$ are listed in Table 1.

Table 1.
Integrated Bremsstrahlung Cross Sections and Rates for an Electron Beam of 26.6 GeV ($L = 1.5 \cdot 10^{31} cm^{-2} s^{-1}$).

k Interval (GeV)	$\int(d\sigma_{BH}/dk)dk$ (mb)	Rate(ep) (kHz)	$\int(d\sigma_Z/dk)dk$ (mb)	Rate(eG) (kHz)
0.1 - 9.0	277.0	4155	1443	884
9.0 - 17.0	25.0	375	152	93
17.0 - 26.6	15.6	234	105	64
0.1 - 26.6	317.7	4765.5	1701	1042

Bremsstrahlung of electrons on the rest gas molecules has a much larger cross section and, since it has the same experimental signature as the luminosity process, represents a severe background. The corresponding formula for the cross section on molecule of charge Z reads [4]:

$$\frac{d\sigma_Z}{dk} = 4\alpha r_e^2 \frac{E'}{kE}\left[\left(\frac{E}{E'} + \frac{E'}{E} - \frac{2}{3}\right)\left(Z^2 L_{rad} + Z L'_{rad}\right) + \frac{1}{9}\left(Z^2 + Z\right)\right] \qquad (2.3)$$

where: L_{rad} and L'_{rad}, called 'radiation logarithms', are functions of the atomic form factor. In our case the appropriate approximation of these functions can be taken from the Fermi-Thomas-Molière model [5]:

$$L_{rad} = \ln(184 Z^{-1/3})$$
$$L'_{rad} = \ln(1194 Z^{-2/3}).$$

In the two last columns of Table 1 the corresponding integrated cross sections and rate values are listed for a mixture of $90\% H_2$ and $10\% CO_2$ [6]. These cross sections are by a factor of $\approx 5 - 7$ larger than those for ep bremsstrahlung. The corresponding electron-gas (eG) bremsstrahlung rates were calculated assuming a pressure of $5 \cdot 10^{-8} mbar$ in the beam pipe, a 12.6m long source of eG events and the nominal electron current of $58mA$. The only way of correcting for this background is to measure its contribution experimentally. In principle there are two ways to do it:

- seperate beams in space at the interaction region so that electrons radiate bremsstrahlung photons in collisions with the rest gas only;
- fill in extra electron bunches (pilot bunches) which will not collide with proton partners.

While using the first method of the background measurement one has to stop taking physics data in the second one it can be done simultaneously.

The angular distribution of the ep bremsstrahlung process reads as follows [7]:

$$\frac{d\sigma}{d\Theta} \sim \frac{\Theta}{((m/E)^2 + \Theta^2)^2} \qquad (2.4)$$

where E is the electron beam energy, m is the electron mass,
Θ - emission angle of photon w.r.t. electron beam direction.

For E = 26.6 GeV, $m/E \approx 19 \mu rad$. Thus all bremsstrahlung photons (and similarly the electrons) travel at very small angles w.r.t. electron beam direction and have to be detected close to the proton and electron beam pipes respectively. These physical conditions and the technical limitations imposed by the layout of the HERA beams magnets lead us to the configuration of the luminosity detector briefly described in section 3 of this paper.

2.2 Identification of Bremsstrahlung Events

Detection of final state electron and photon in coincidence with the bunch crossing signal plus the requirement that both measured energies add up to the initial electron energy should be sufficient to identify bremsstrahlung events. The identification of bremsstrahlung events can be disturbed by energy deposits in the calorimeters coming from radiation off the electron beam pipe (electron calorimeter), from synchrotron radiation and from the proton beam halo (photon calorimeter) and could lead to the spurious coincidences. Radiation off the electron beam pipe can be reduced (or entirely removed) by shielding the calorimeter against the electron beam pipe. The photon calorimeter can be protected against synchrotron radiation and proton beam halo by placing absorbers in front and behind the photon calorimeter. In addition deposits coming from the synchrotron photons and proton beam halo can be measured directly - see section 6 of this note. A selection on high energy photons and electrons reduces substantially the rate of spurious coincidences. As a result the electron detector has a large acceptance ($\geq 70\%$) for electrons in a finite energy window which scales with electron beam energy E; for E = 26.6 GeV is : ($9.6 \div 17.6$) GeV. This automatically sets the energy window for photons : ($9 \div 17$) GeV. The correlation plot of photon and electron energies detected in coincidence is a good cross check of the identification of bremsstrahlung events.

3 ZEUS Luminosity Monitor

The detailed description of the monitor can be found elsewhere [8,9,10,11,12]. The positioning of the electron (EDET) and photon (GDET) detectors is shown in Fig. 1 and the detectors are listed in Table 2. The collimator in front of the electron calorimeter should be treated as provisional and future tests will prove if it should be replaced or supplemented by the electron beam pipe screen along the stretch between window and calorimeter.

Table 2.
Detectors of the Luminosity Monitor

Component	Distance of entry face from I.P. (m)	Material	Shape/Size
Photon Detector			
Window	92.5	Copper-Berilium	Circle 50 mm radius, 1.5 mm , ≈ 0.1 r.l. thick
Filter	103.15	Carbon	Square $(175 \times 175) mm^2$, (0.5 - 3.5) r.l. variable depth
Čerenkov Counter	104.95	Air at n.t.p Al windows	Circle 100 mm radius, active length 1080 mm, two windows 3 mm each, in total 0.067 r.l. thick
Calorimeter	106.94	Absorber Pb Scintillator SCSN38	Square plates, $(180 \times 180) mm^2$, Pb 5.7 mm thick, SCSN38 2.8 mm thick, depth $22 X_0$
Position Detector	after 7 r.l. inside calorimeter	Scintillator NE102	Two crossed planes of fingers: 14 horizontally $(10 \times 10 \times 163) mm^3$, 16 vertically $(10 \times 10 \times 143) mm^3$
Electron Detector			
Window	27.29	Steel	69 mm radius, 1.5 mm ≈ 0.085 r.l. thick
Collimator	33.87	Lead 200 mm thick	Rectangular window, $(200 \times 50) mm^2$
Calorimeter	34.68	Absorber Pb Scintillator SCSN38	Square plates, $(250 \times 250) mm^2$, Pb 5.7 mm thick, SCSN38 2.8 mm thick, depth $24 X_0$

During the November runs the Č counter and the position detector were missing in the photon branch.

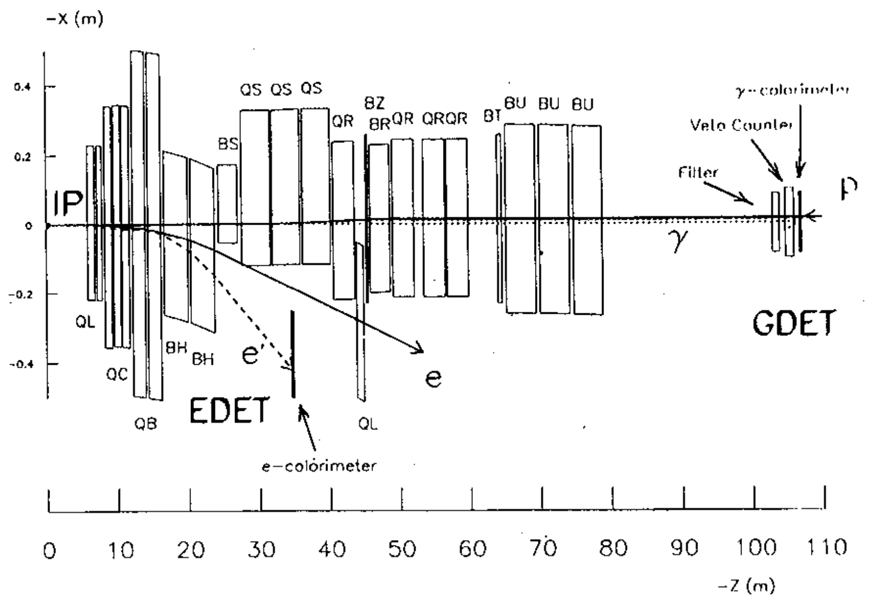

Figure 1: General layout of the luminosity detectors.

4 Calculation of Luminosity

4.1 Theoretical Formula

Knowing the geometry and currents of the bunches and the beam revolution frequency one can calculate the expected luminosity for a collider type of accelerator from the formula :

$$L = \frac{\sum_i N_e^i N_p^i f}{2\pi \sqrt{\sigma_{xp}^2 + \sigma_{xe}^2} \cdot \sqrt{\sigma_{yp}^2 + \sigma_{ye}^2}} \tag{4.5}$$

where : N_e^i, N_p^i are the numbers of electrons and protons in the i^{th} bunches,
σ_{ij} is the spatial spread of bunch j in i coordinate,
f is the beam revolution frequency.
It is convenient to define also the specific luminosity $L_{sp} = L/(\sum_i N_e^i N_p^i)$ which depends only on the geometry of the bunches and beam revolution frequency. The measured specific luminosity can be directly compared with this calculated from formula (4.5). This comparison is a good cross check of the reliability of measurement.

4.2 Experimental Procedure

The luminosity L is calculated from the rate of ep bremsstrahlung events R_{ep} using formula (2.1) : $L = R_{ep}/\sigma_{obs}$ where R_{ep} is the rate obtained from the total rate of bremsstrahlung corrected for electron-gas contribution and the observed cross section σ_{obs} can be written generally in the form:

$$\sigma_{obs} = \int A_{lumi} d\sigma_{theor} \quad (4.6)$$

where σ_{theor} is calculated from the Bethe - Heitler formula, A_{lumi} is the detector acceptance, and integration is performed over the phase space considered.

If one separates the colliding bunches in space or time then

$$R_{ep} = R_{coll} - R_{sep} \quad (4.7)$$

where R_{coll} and R_{sep} are the observed bremsstrahlung rates when bunches do or do not collide, respectively.

If the pilot electron bunches are used then

$$R_{ep} = R_{tot} - k \cdot R_{eG} \quad (4.8)$$

where:
R_{tot} is the total rate of bremsstrahlung events,
R_{eG} is the rate of bremsstrahlung events measured for the electron pilot bunches and $k = I_e^{tot}/I_e^{pilot}$ is the ratio of the total electron current to that in "pilot" bunches.

The detector acceptance A_{lumi} depends on many parameters and for practical calculations one has to make certain approximations. Given the configuration of our detectors during the Autumn running we have assumed that A_{lumi} can be written in the form :

$$A_{lumi} = A_{cal} \cdot T_g \cdot C_{sum} \cdot P_{veto} \quad (4.9)$$

where:
A_{cal} is the product of the photon and electron detectors acceptances weighted with the differential bremsstrahlung cross section,
T_g is the correction due to a non-zero axis tilt and angular dispersion of the electron beam (for tilt = 0 and nominal angular dispersion $T_g = 1$),
C_{sum} is the reduction of acceptance due to the cut on the sum of electron and photon energies,
P_{veto} is the probability that the photon is not vetoed by the filter and Č counter system and can be calculated from the formula: $P_{veto} = P_{fil} + (1 - P_{fil})U_{\check{C}}$, where P_{fil} is a probability that the photon passes filter without interaction, $U_{\check{C}}$ is a probability that Č counter does not veto when the photon interactes in the filter and it depends on the efficiency of the Č counter and the filter configuration.

All factors in formula (4.9) were calculated using the Monte Carlo (MC) simulation of the detector performance. In these calculations the approximation was made that these factors depend only on the electron and proton beam energies, on the electron beam tilt, on the cut value for the sum of electron and photon energies and on the filter thickness.

For each luminosity run the following parameters have to be supplied :

- electron and proton beam energies,

- electron bunch currents,
- proton bunch currents,
- chosen photon and electron energy limits and the cut on the sum of energies,
- electron beam tilt and dispersion,
- filter thickness.

It has to be pointed out that for luminosities per bunch crossing close to the nominal value an additional correction factor for the multiple bremsstrahlung events has also to be included.

5 Luminosity Runs

During the fall running of HERA, the ZEUS luminosity monitor has recorded 4 well documented ep luminosity runs on 5.11.91, 16.11.91, and in the period 30.11.91 - 2.12.91 for a total of 10.5 hours. Luminosities were calculated on-line and off-line with data taking, following the procedure described in the previous section. In these calculations factors T_g and P_{veto} in the formula (4.9) had to be put equal to 1 as we had no Č counter and had no information about a possible beam tilt and angular dispersion. The on-line calculation and data recording were performed with the help of a VME computer. Data recorded on the VME disc were then transferred to the IBM of the DESY Computing Center for off-line analysis.

5.1 Calibration of Calorimeters

Both calorimeters were tested and calibrated at DESY (up to 3 GeV) and at CERN (up to 10 GeV) with electron beams. It was found that calorimeter responses are linear with energy, fairly uniform as a function of hit position and have an energy resolution of $(18 \pm 2)\%/\sqrt{E}$ [13,14].

During the first runs with an electron beam in HERA in October, the calibration constants found at CERN tests were readjusted using the observed end point value of the bremsstrahlung photon energy spectrum, which must be equal to the electron beam energy, and fitting the distribution of the sum of electron and photon energies. These readjustements were then checked by a MC simulation of the calorimeter responses with MOZART [15].

The whole procedure of recalibration had to be repeated after 18.11.91 when one of the phototubes in electron calorimeter had to be exchanged. The corresponding comparison of the data and MC is shown in Fig. 2 and the final set of calibration constants is listed in Table 3.

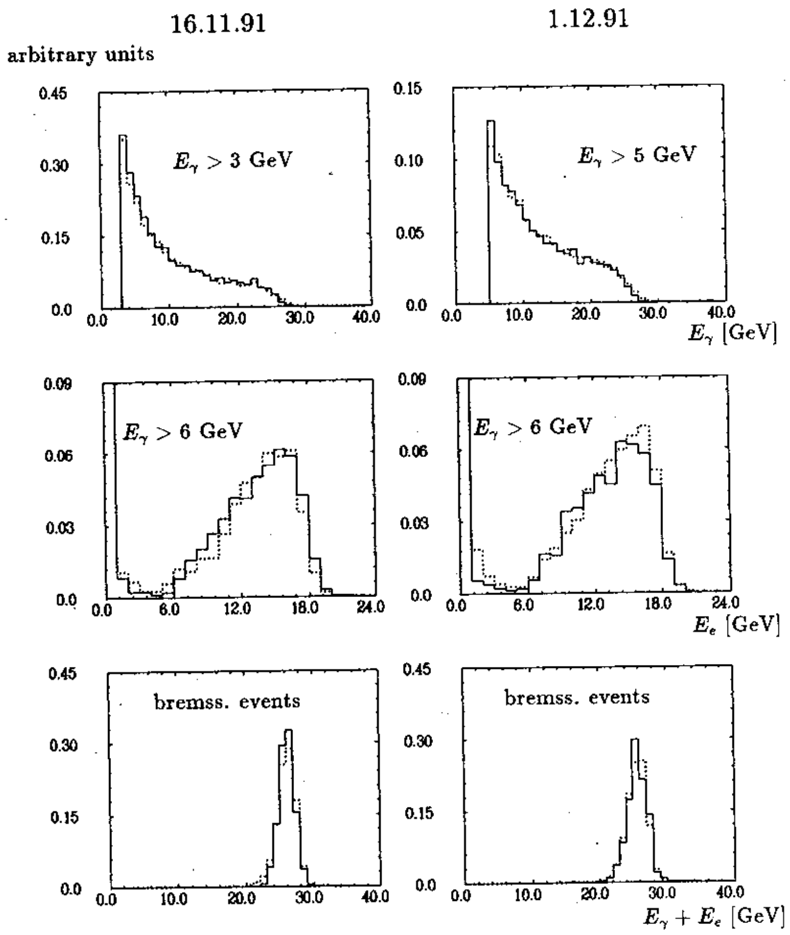

Figure 2: The experimental (solid) and MC (dotted) energy distributions of photons and electrons for the runs on 16.11.91 and on 1.12.91.

Table 3.
Calorimeters Calibration Constants and Energy Windows

ADC Number	γ		e	
	1	2	3	4
Before 18.11.91				
Slope (ADC/GeV)	6.2	6.1	7.2	7.2
Pedestal (ADC)	4	5	3	3
Energy Window (GeV)	6.0 – 16.9		7.9 – 21.8	
Window for Energy Sum $(GeV$	13.9 – 32.0			
After 18.11.91				
Slope (ADC/GeV)	6.2	6.1	7.9	7.9
Pedestal (ADC)	4	5	3	3
Energy Window (GeV)	6.0 – 16.9		7.6 – 20.2	
Window for Energy Sum (GeV)	13.6 – 32.0			

5.2 On-Line Measurement

The rates of bremsstrahlung events (per bunch crossing) were calculated using a hardware module and a local VME computer. They were displayed on a monitor as a function of the time which had elapsed since the beginning of the run. The display installed in the HERA control room was being updated after preselected time interval, $\Delta t \geq 1s$.

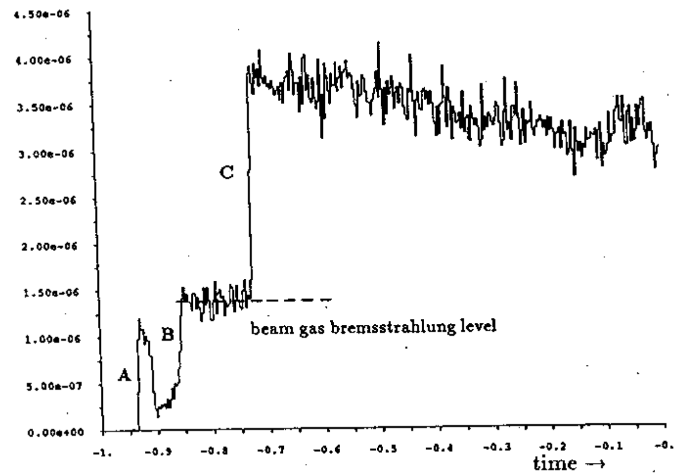

Figure 3: The on-line measured rate per bunch crossing of bremsstrahlung events as a function of the time (last hour) which had elapsed since the begining of the run on 5.11.91 (A. electron beam injection, B. electron beam ramping, C. start ep collisions).

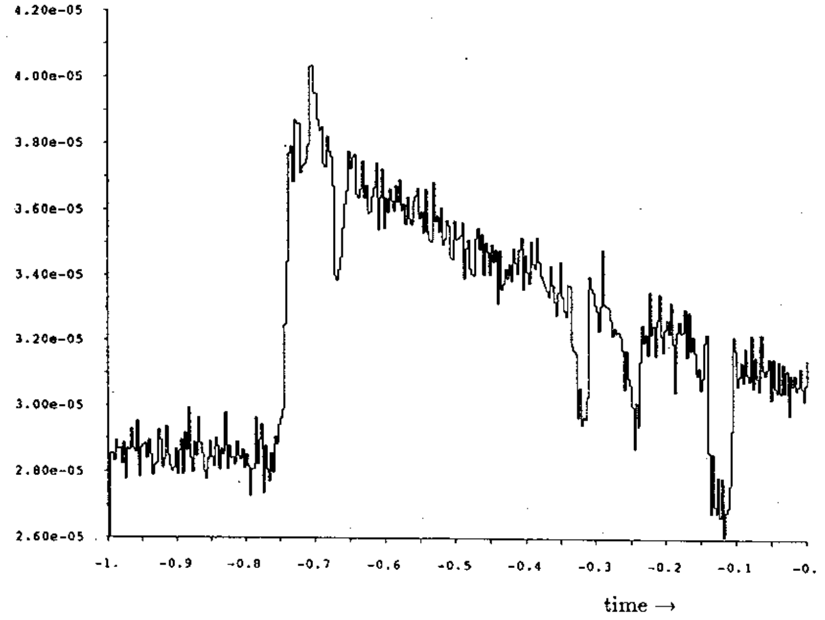

Figure 4: The on-line measured rate per bunch crossing of the bremsstrahlung events as a function of the time (last hour) which had elapsed since the begining of the run on 16.11.91.

During the whole running period of HERA only the total rate of bremsstrahlung events was calculated and displayed on-line. Both ep and eG collisions contribute to this rate. One way to see the effect from ep collisions alone was to separate electron and proton bunches in space. Transversal separation has been applied by moving proton beam. The effect of this operation is shown in Fig.3 and 4 taken during the runs on 5.11 and 16.11 respectively. The display shows first the rate when the electron and the proton bunches were separated in space and thus the electron bunch collided only with remnant gas molecules, and then the increased rate when the proton bunch was brought into collision with the electron bunch. The difference of the two rates equals the ep bremsstrahlung rate and directly measures the luminosity.

Similar measurements were repeated on 2.12.91 while HERA was filled with 11 electron bunches and 10 proton bunches - see Fig. 5. In this case the colliding beams were separated transversaly (just after the large loss of the proton beam which causes sharp decrease of the bremsstrahlung rate) for a very short time leading to an abrupt drop of the total rate which after bringing the bunches back to the collision mode has returned to its previous value. The size of the drop measures directly the ep luminosity.

Results of the on-line measurements are summarized in Table 4.

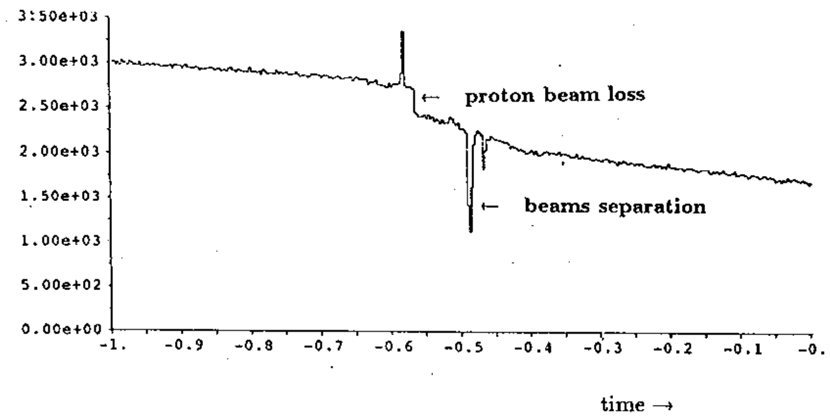

Figure 5: The on-line measured rate (Hz) of the bremsstrahlung events as a function of the time (last hour) which had elapsed since the begining of the run on 2.12.91.

5.3 Off - line Measurement

The off-line analysis has been performed using the data recorded on the VME disc. All recorded events satisfy the criterion that the deposited energy exceeds certain threshold value in any of the two calorimeters. The threshold value was $\approx$ 2 GeV for runs on 5.11 and 16.11 and $\approx$ 4 GeV for runs on 1.12 and 2.12.

Thus the samples of events recorded on disc are much larger than those used later on for luminosity calculation and they contain a large portion of spurious events (sizable energy deposit in one calorimeter and a very low deposit in the other one).

This can be clearly seen in the correlation plots of final photon vs final electron energy shown in Fig.6 for runs on 16.11 and on 1.12.91. A highly populated band of points around the line of constant sum of electron and photon energies, $E_e + E_\gamma = E$ (E = electron beam energy) is clearly visible, but also the general conditions of HERA such as the magnitude of the electron beam current, the focusing quality, the vacuum quality, etc. and the monitor acceptance reflect in these plots. The events which populate this band are the bremsstrahlung events. To select them the cuts on photon and electron energies as well as on their sum were applied. The energy windows chosen were the same as in on-line analysis and are listed in Table 3. For all runs considered, the rate of accidental coincidences (mainly due to multiple bremsstrahlung events, see section 4.2) was a small fraction ($\approx 2-3\%$) of the total rate and was included in the MC simulation.

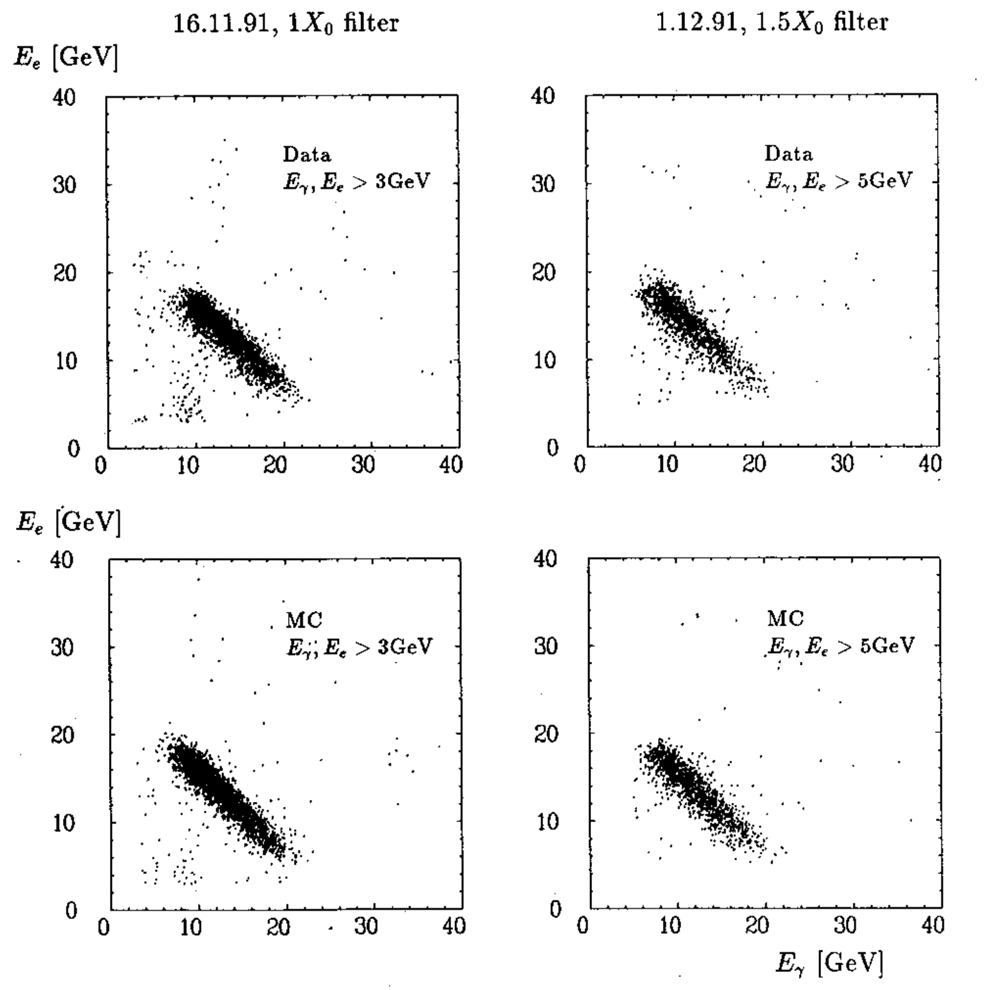

Figure 6: Correlation plots of electron energy vs photon energy, observed experimentally and reproduced in MC.

Table 4
Summary of Luminosity Runs[3]

ZEUS Luminosity Run Date/Time	Bunch Mode		Currents Mean Value (μA)		Luminosity Peak Value ($cm^{-2}s^{-1}$)	Luminosity Mean Value ($cm^{-2}s^{-1}$)
	B_e	B_p	I_e	I_p	$L_{on-line}$	$L_{off-line}$
5.11.91 1:15 - 2:35	1	1	57	145	$(7.0 \pm 1.4) \cdot 10^{26}$	$(5.8 \pm 1.2) \cdot 10^{26}$
16.11.91 6:05 - 6:40	2	1	180	100	$(2.9 \pm 0.5) \cdot 10^{27}$	$(3.0 \pm 0.6) \cdot 10^{27}$
30.11.91 6:50 - 11:00	11	10	1700	800	–	$(2.0 \pm 0.8) \cdot 10^{28}$
1.12.91 22:03 - 22:30	11	10	1625	1405	–	$(2.3 \pm 0.9) \cdot 10^{28}$
1.12.91 22:35 - 23:17	11	10	1290	1095	–	$(1.7 \pm 0.6) \cdot 10^{28}$
1/2 .12.91 23:20 - 00:10	11	10	940	535	$(1.2 \pm 0.4) \cdot 10^{28}$	$(0.8 \pm 0.3) \cdot 10^{28}$

The luminosity obtained in the on-line and off-line analyses are summarized in Table 4. The luminosity has increased gradually from $\approx 7 \cdot 10^{26} cm^{-2}s^{-1}$ at the beginning of November to $\approx 2 \cdot 10^{28} cm^{-2}s^{-1}$ at the end of November, i.e. by almost two orders of magnitude. During the first run on 1.12.91 the luminosity reached the value $\approx 4 \cdot 10^{28} cm^{-2}s^{-1}$ for the first few minutes and then decreased so fast so that the average for this run of 20 min is only $(2.3 \pm 0.9) \cdot 10^{28} cm^{-2}s^{-1}$. In Table 5 we present the comparison of the measured and expected specific luminosities. The measured specific luminosity has gradually increased as the machine tuning improve and reached a value close to the theoretical one.

[3] Values of currents were extrapolated from the values recorded by HERA, H1 and ZEUS experiments [15].

Table 5
Comparison of Specific Luminosities

Date of Run	L^{sp}_{exp} $(cm^{-2}s^{-1})$	L^{sp}_{theor} $(cm^{-2}s^{-1})$
5.11.91	$(4.1 \pm 0.8) \cdot 10^6$	$9.4 \cdot 10^6$
16.11.91	$(9.1 \pm 1.0) \cdot 10^6$	$8.7 \cdot 10^6$
1/2.12.91	$(9.3 \pm 4.0) \cdot 10^6$	$8.1 \cdot 10^6$

5.4 Comparison of Two Methods of Luminosity Calculation - Discussion of Errors

The on-line luminosity values were always obtained with the beam separation method. During the runs on 16.11 and on 2.12 we had the opportunity to compare two methods of luminosity calculation using the beam separation and pilot bunch techniques - see Fig. 4 and Fig. 5. Results are given in Table 4. The method of separation seems quite tricky as seen from Fig. 4, where separation of beams was tried several times during the run. In consecutive separations the counting rate dropped to different values, some of them inconsistent with the expected eG rate. This inconsistency may depend on how complete the separation had been and is reflected in the uncertainty of the luminosity determination with this method. Denoting this systematic error in the eG rate estimation (R_{sep} in formula (4.6)) by ΔR_{sep} and assuming that statistical errors can be neglected, one can estimate the luminosity error obtained with this method :

$$(\Delta L/L) = \sqrt{((\Delta\sigma_{obs}/\sigma_{obs})^2 + (\Delta R_{sep}/R_{sep})^2)} \qquad (5.10)$$

The corresponding error in the luminosity value obtained with the pilot bunch method, neglecting the errors on R_{tot} and R_{eG} in formula (4.7) , can be written in the form :

$$(\Delta L/L) = \sqrt{((\Delta\sigma_{obs}/\sigma_{obs})^2 + (\Delta k \cdot R_{eG}/R_{ep})^2)} \qquad (5.11)$$

In this case two factors play the decisive role : a) how accurately can one measure the ratio of currents k; and b) what is the ratio of eG to ep rates.

The uncertainty in σ_{obs} is that of our acceptance. Without the precise knowledge of the electron beam tilt and dispersion (no photon position measurement was available) a conservative 10% error in σ_{obs} should be assumed. Rough (conservative) values of other errors are :

- $(\Delta R_{sep}/R_{sep}) \approx 0.15$ (on 5.11 or on 16.11),

- $\Delta k/k \approx 0.10$,
- $k \cdot R_{eG}/R_{ep} \approx 2$ (on 16.11) or ≈ 4 (on 2.12).

Assuming these values one finds that the relative error in the luminosity calculation was $\approx 20\%$ for the beam separation method and $\approx 40\%$ (on 2.12) and $\approx 20\%$ (on 16.11) for the pilot bunch method. These values are shown in Table 4 and 5.

6 Background Discussion

Both calorimeters are exposed to background radiation which deposits some energy. These deposits either add up to those coming from the bremsstrahlung process or fake it altogether. Sources of background are different in electron and photon calorimeters.

The electron calorimeter is exposed to electromagnetic showers initiated by off beam energy electrons and leaking out of the electron beam pipe wall. A lead collimator (see section 3 of this paper) just in front of the calorimeter reduces this background significantly (we have checked this experimentally). Further reduction can be achieved by installing a lead screen along the electron beam pipe on the stretch from the window to the calorimeter.

The photon calorimeter is struck by both synchrotron photons radiated by beam electrons bent sideways (towards the center of the ring) on both sides of the straight section of the ring and by the proton beam halo particles. We will discuss these two types of background separately.

6.1 Synchrotron Radiation

To protect the photon calorimeter from synchrotron radiation a carbon filter of variable thickness was placed before it. For a fixed electron beam energy and assuming a stable trajectory, the intensity of the synchrotron radiation per bunch crossing should scale with the bunch current. During the November/December runs we have observed that this scaling was not satisfied. For instance in several runs performed on 28.11 with only an electron beam of 26.6 GeV circulating in the machine and electrons stored in 5 bunches (with average bunch current of 0.2 mA) we have measured the following synchrotron radiation signals per bunch crossing: $\approx$8 GeV for a 1.0 X_0 filter, $\approx$ 1.0 GeV for a 1.5 X_0 and <0.2 GeV for a 2.0 X_0 filter. These values were very high in comparison with the expected values and with the level of synchrotron radiation during the other runs. In Table 6 we present the calculation (for the nominal electron bunch current of 0.28 mA) of the total energy E_{sync} and number of synchrotron photons N_{sync} per bunch crossing hitting photon calorimeter for three values of the bending radius R_{bend}; in brackets the MC estimates of the energy measured in the calorimeter are quoted. For the case of 0.2 mA bunch current we therefore expect the synchrotron radiation signal of 0.03 GeV (for $1X_0$) and of 0.001 GeV (for $1.5X_0$) per bunch crossing which is considerably less than observed.

For the nominal electron beam trajectory the photon calorimeter is exposed to the synchrotron radiation originating in the quadrupoles just before and after the (straight) interaction region. However, even small variations of the trajectory (e.g. a small tilt of the electron beam axis) can change the flux and energy of synchrotron radiation hitting the photon calorimeter. This was observed during the run on 5.11 when changes in the beam optics during the procedure of HERA tuning caused an abrupt drop of the synchrotron radiation signal from ≈ 2 GeV down to 0.15 GeV per bunch crossing.

Table 6
Synchrotron radiation background for different bending schemes

Filter thickness	Electron beam energy=26.6 GeV					
	$R_{bend}^{nominal} = 1360$ m		$R_{bend} = 1000$ m		$R_{bend} = 700$ m	
(X_0)	E_{sync}(GeV)	N_{sync}	E_{sync}(GeV)	N_{sync}	E_{sync}(GeV)	N_{sync}
0.5	606	$0.58 \cdot 10^7$	$0.16 \cdot 10^4$	$0.14 \cdot 10^8$	$0.45 \cdot 10^4$	$0.31 \cdot 10^8$
1.0	27 (0.04)	$0.23 \cdot 10^6$	87 (0.36)	$0.62 \cdot 10^6$	291 (3.8)	$0.17 \cdot 10^7$
1.5	1.4 (0.002)	$0.10 \cdot 10^5$	5.3 (0.043)	$0.32 \cdot 10^5$	22 (0.51)	$0.11 \cdot 10^6$
2.0	$0.78 \cdot 10^{-1}$	523	0.36	$0.19 \cdot 10^4$	2.0	$0.79 \cdot 10^4$
2.5	$0.49 \cdot 10^{-2}$	29	$0.28 \cdot 10^{-1}$	131	0.20	688

We conclude that at least during the first months of HERA running a filter thickness of $\geq 2.0 X_0$ should be chosen. Only for a stable electron beam with a low level of the synchrotron radiation one can reduce the thickness of the filter to obtain better energy resolution. The results show also that during machine tuning the synchrotron radiation level can exceed by far the nominal value.

6.2 Proton Beam Halo

The photon calorimeter is shielded with 2.5 cm thick lead bricks from the backward direction and with 1 cm thick lead plates on all sides (top, bottom, left and right). This shielding is of course not sufficient to stop high energy particles from the proton beam halo and from showers initiated by them. To reduce this background we have placed the photon calorimeter so that at the moment when the bremsstrahlung photon emitted at the I.P. enters the calorimeter, the two closest proton bunches are ≈ 14 m from the calorimeter (one ≈ 14 m before and the second ≈ 14 m behind the calorimeter) [8]. Still, part of the halo signal ($10 - 15\%$) is included because of the width of PM signal (full width at the half maximum is $\approx 25ns$).

We measured the background deposits during the last runs on 1.12 and 2.12 when HERA was operated in the following mode: 11 electron bunches and 10 proton bunches. Therefore, for seven (empty) bunch crossings before the first genuine electron and proton bunch crossing, there were a full proton bunch and an empty electon bunch passing nearby the photon

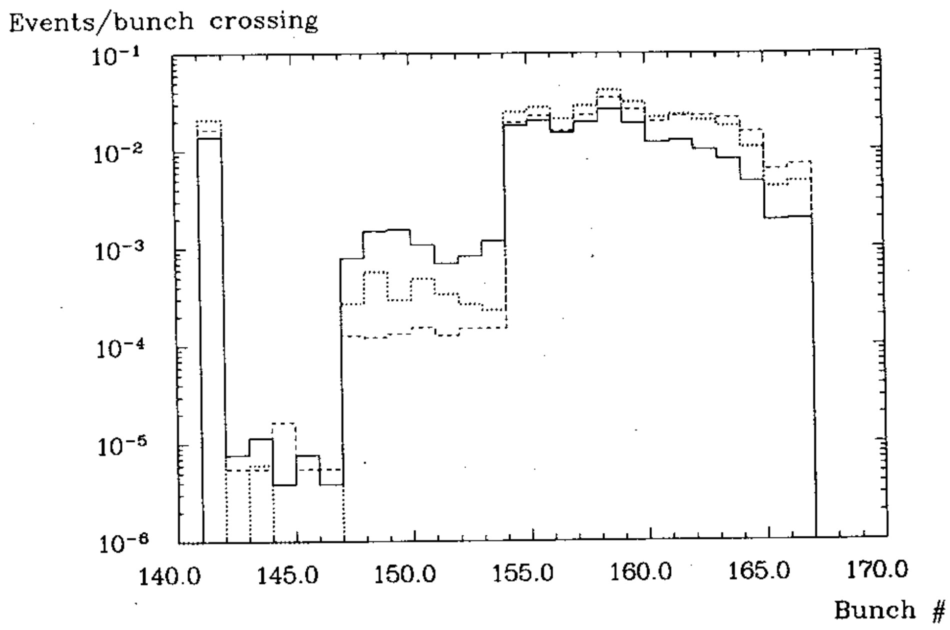

Figure 7: Dependence of the lumi monitor counting rate on the electron bunch number (run #1 - dashed line, run #2 - dotted line, run #3 - solid line).

calorimeter. So the deposit in the photon calorimeter for such bunch crossings must be due to proton halo particles only [4].

Table 7.
Proton Beam Halo Background

Run #	1	2	3
Mean Proton Bunch Current (mA)	0.15	0.12	0.07
Proton Beam Life Time (h)	>4	≈ 1.5	≈ 0.5
Number of Proton Halo Events per Bunch Crossing with a Signal in the Photon Calorimeter above 4.5 GeV	$1.4 \cdot 10^{-4}$	$3.5 \cdot 10^{-4}$	$1.4 \cdot 10^{-3}$

We have measured this background over a time interval of about 10 min in three cases: 1. just after the run started, 2. half an hour later and 3. 1.5 hour later. In Fig. 7 the number

[4] This method of the proton beam halo measurement for colliding beams is due to F.Turkot.

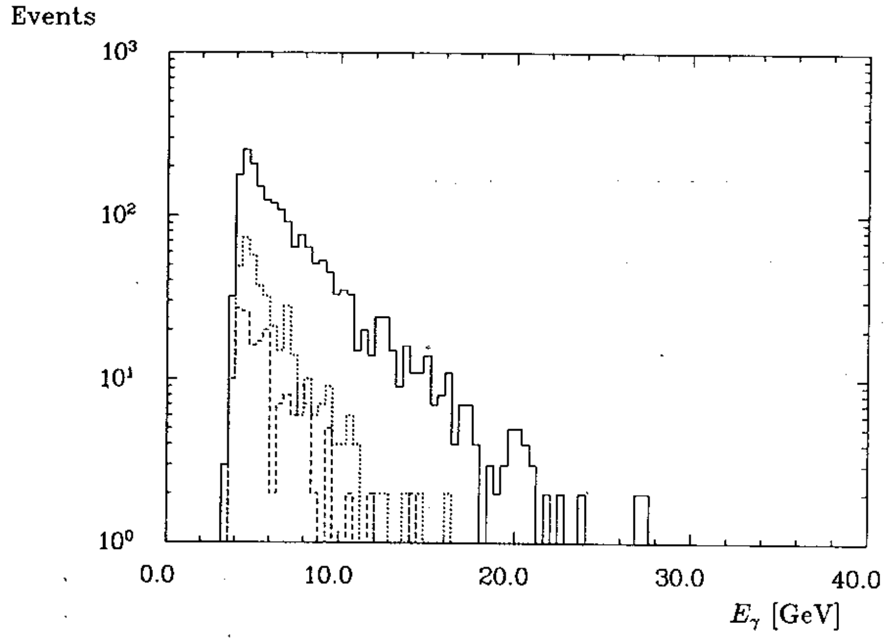

Figure 8: The energy spectrum of the proton beam halo background events detected in the photon calorimeter (run #1 - dashed line, run #2 - dotted line, run #3 - solid line).

of events with energy deposits above 4.5 GeV in the photon calorimeter or above 3.5 GeV in the electron calorimeter is plotted for consecutive electron bunch numbers (141 - 163). The signals from halo particles are clearly seen for bunches 147 - 153. For these bunches no deposits were observed in the electron calorimeter contrary to bremsstrahlung events detected for the full electron bunches 154 - 163. The energy distributions in these background deposits is shown in Fig. 8. It should be kept in mind that we catch only $(10-15)\%$ of the halo signal due to the timing condition (see above).

From Table 7 one can estimate that halo background deposits above 4.5 GeV will be seen in $(0.01-0.1)\%$ of the bremsstrahlung events depending on the HERA machine conditions. We conclude that this background is small.

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[16] We would like to thank our colleagues from HERA and H1 experiment who made available to us their records of currents.