

Measurement of the HERA Luminosity by the ZEUS experiment

1. Introduction
2. Luminosity measurement
3. Performance of the luminosity monitor
4. Luminosity calculation
5. Side applications of the luminosity detectors
6. Future – need of upgrade

1. INTRODUCTION

1.1. Luminosity

Luminosity is defined by the formula:

$$L = \frac{dN^{proc}}{dt} / \sigma^{proc}$$

where dN^{proc}/dt is the rate of events of a chosen process of the cross section σ^{proc} . dN^{proc}/dt has to be measured and σ^{proc} is the cross section known a priori and precisely (e.g. from theory) but should be corrected by adjusting it to these experimental conditions in which dN^{proc}/dt was measured

- the process should be chosen in such a way that it should have easily recognisable signature i.e. should be easy to identify experimentally and it should be large – fast, statistically meaningful measurement

Thus measuring dN^{proc}/dt and knowing σ_{corr}^{proc} one can calculate L in $[cm^{-2}s^{-1}]$

= instantaneous L in $[cm^{-2}s^{-1}]$

= integrated L in μb^{-1}

1.2. HERA collider

- beams of electrons or positrons are bunched and travelling in opposite directions;
- these bunches form trains separated by empty bunches;
- maximum 220 bunches separated by 96 ns time interval can be stored in one beam;
- the $e\bar{p}$ collisions are head-on;
- since there are empty (no particles in the bunches and full bunches) the three type of collisions are possible:
 - a) full electron bunch x full proton bunch
 - b) full electron bunch x empty proton bunch
 - c) full proton bunch x empty electron bunch

The bunches with no partner in the other beam (full_e x empty_p or full_p x empty_e) are called "pilot" bunches and are used for various corrections in further analysis).

- satellite bunches

The main bunch (with large number of particles) may be followed by few smaller with much smaller number of particles but within the time $\ll 96$ ns.

The existence of these bunches \equiv pain in the neck.

1.3. Luminosity in ep collider machine (HERA)

$$L_{coll} = \frac{\sum_i N_e^i N_p^i f}{2\pi \sqrt{(\sigma_{x_p}^2 + \sigma_{y_p}^2)(\sigma_{x_e}^2 + \sigma_{y_e}^2)}}$$

N_e^i, N_p^i - number of particles in the bunch

f - revolution frequency

σ 's \Rightarrow geometry of the beams

i - bunch index

- specific luminosity

$$L_{bp} = \frac{L_{coll}}{(I_e \times I_p)}$$

Where I_e, I_p are the circulating currents of electrons and protons.

This is a measure of quality of the beams and their focusing at the interaction point.

2. Luminosity measurement

2.1. Choice of the process

- bremsstrahlung of initial e^\pm in the field of proton:

$$ep \rightarrow e' \gamma p$$

(proton recoil is negligible)

$$\sigma^{proc} = \sigma_{B-H}$$

is large ≥ 20 mb (depending on photon spectrum cut)

= e', γ emitted at very small angles:

$$d\sigma_{B-H}/d\Theta_\gamma = \Theta_\gamma \left[\left(\frac{M_e}{M_e} \right)^2 + \Theta_\gamma^2 \right]^2$$

detectors of e' and γ has to be placed at the very large distances from I.P. i.e. electron detector at ~ 35 m from IP

photon detector at ~ 107 m from IP

(deep in the tunnel)

2.2. Detection set-up

(all following information based on '96 luminosity measurement)
- originally to avoid accidentals we decided to measure in coincidence e' and γ .

Later it turned out that detection of high energy photon (> 2 GeV) is so free from any accidentals that is sufficient for identification of bremsstrahlung photon.

- The detectors have to be possibly radiation resistive (high bremsstrahlung rate + synchrotron radiation discussed later);

- Detection set up is shown in figure - all detectors related to measurement of bremsstrahlung events are shown but we shall discuss only the photon detector;

= bremsstrahlung photons leave the proton beam pipe (it bends up)
at 92.5m from I.P through the copper-beryllium window

= follow the vacuum pipe (12.7 m long);

= go through the carbon filter $2X_0$;
(light material absorb the higher energies photons more effectively);

= enter the lead/scintillator sampling calorimeter $22X_0$ thick, at the distance of 107 m from the I.P. - the energy resolution $\sim 20\%/\sqrt{E}$;

= at the depth of $3X_0$ inside the calorimeter there is the position γ hit detector made of scintillator SCSN-38 fingers - the resolution is ~ 3 mm.

3. Performance of the luminosity monitor

In the plot the scatter diagram of $ADC_e \sim \sqrt{s} ADC_\gamma$ (both averaged over two phototubes in each calorimeter and pedestal subtracted) is shown.

A clear correlation between the two is observed and they add up to the electron beam energy of ab. 27.5 GeV

The ADC_γ distributions for electron colliding (full x full) bunches and pilot bunches (full x empty) are shown in the next plot.

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Corrections

3.1. Electron-gas collisions

they have the some signature as ep

and can be corrected for, only in a statistical way using the rate of pilot bunches (R^{PILOT})

$$R^{ep} = R^{TOT} - k R^{PILOT}$$

R^{TOT} - rate of ep $\rightarrow e'\gamma + e'Z\gamma$ + rate eZ $\rightarrow e'Z\gamma$

R^{PILOT} - rate eZ $\rightarrow e'Z\gamma$

$$k = \frac{I^{ep}}{I^{pilot}}$$

3.2 Pile-up

Especially at higher luminosity values (certainly after upgrade) probability of bremsstrahlung photon in a single bunch crossing (BC) is NOT NEGLIGIBLE !

Effects: 2 photons of energy < trigger value

fake 1 good photon;

2 photons of energy > trigger value

are detected as 1 instead of 2 photons.

At treshold of 5 GeV these two contributions CANCEL !!

3.3. Acceptance

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Can be determined only using the MC. The contour shown in Figure was defined by using the MC events, which were simulated assuming all the obstacles on the way of photon from the I.P. till the face of the photon calorimeter, the actual angular spread of the initial electron beam, the tilts of the electron beam axis, and smearing of the z position of the I.P.

For the nominal horizontal tilt of - 150 μ rad and no vertical tilt the acceptance was 98 % i.e. 98 % of photons emitted at I.P. reach the photon calorimeter.

3.4. Energy scale uncertainties

\equiv synchrotron radiation (~ 100 W at the face of calorimeter) needs filter. This filter reduces the energy measured in calorimeter in a statistical way for high energy photons - only average loss can be estimated $\Rightarrow E_{filter}$;

\equiv the gains and pedestals (ADC^{PED}) of the PMT's may change in time, the unstable read-out electronics \rightarrow all these introduces non-linearities (f_{nl}).

4 . Calculation of luminosity

In summary, the measured ADC_{γ} (averaged over the two PMT's readings) can be written in the form.

$$\overline{ADC}_{\gamma}^{corr} = C_{\gamma} \left[1 + f_{nl} (E_e - E_{\gamma}) (E_{\gamma} - E_{filter}) \right] + ADC_{\gamma}^{PED}$$

where C_{γ} is the calibration constant i.e. the conversion factor from energy (E_{γ}) to ADC counts.

The parameters C_γ , f_{nl} , E_{filter} and the energy resolution σ_0 are obtained from the fit of response function F_{e-gas} , to the $\overline{ADC}_\gamma^{corr}$ experimental distribution for $e-gas$ collision at 12 and 27.5 GeV.

$$F_{e-gas} = P \int_{0.1 GeV}^{F_e - M_e} \exp \left(- \frac{\left| E_\gamma - \hat{E}_\gamma \left(\overline{ADC}_\gamma^{corr} \right) \right|^2}{2 \sigma_0^2 E_\gamma} \right) \frac{d\sigma_{BH}^{egas}}{dE_\gamma} \frac{dE_\gamma}{\sigma_0 \sqrt{E_\gamma}}$$

P is normalisation factor $\hat{E}_\gamma \left(\overline{ADC}_\gamma^{corr} \right)$ is the reconstructed photon energy. ← 8

The observed cross section is then calculated for each trigger (2, 5, 10 and 10 - 16 GeV)

$$\sigma_{BH}^{corr} = \sigma_{BH} \frac{N^{sel}}{N^{all}} ; \quad \sigma_{BH}^{obs} = A_\gamma \sigma_{BH}^{corr}$$

σ_{BH}^{corr} is calculated on the basis of MC simulated events using the nominal values of the parameters. N^{sel} is the number of events selected for a given trigger and N^{all} is the number of all events with photon energy above 0.1 GeV. Correction for changing parameters is made by multiplying σ_{BH}^{corr} by the factor $f = \frac{\sigma_{BH}^{actual}}{\sigma_{BH}^{nominal}}$

Finally, the luminosity is calculated

$$L = R^{ep} / \sigma_{BH}^{obs}$$

(to account for the calibration constant C_γ changes, the fit can be repeated during the run)

4.1 checks & errors

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5. Other applications of the luminosity detector:

- measurement of the electron beam profile
- tagging of the photo production events
- measuring initial state radiative photons

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6. Upgrade

- need of thick filter $4X_0$
 - - need of active filter
- active filter measures the energy deposited (lost) in absorber

set up of active filter

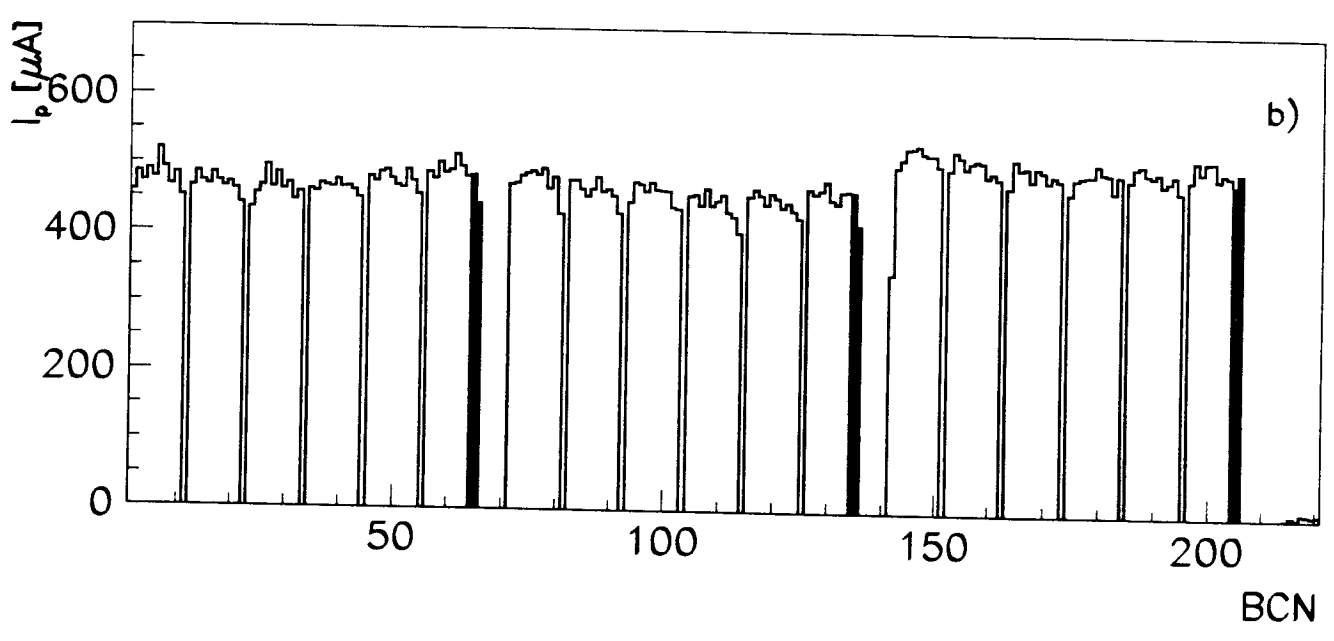
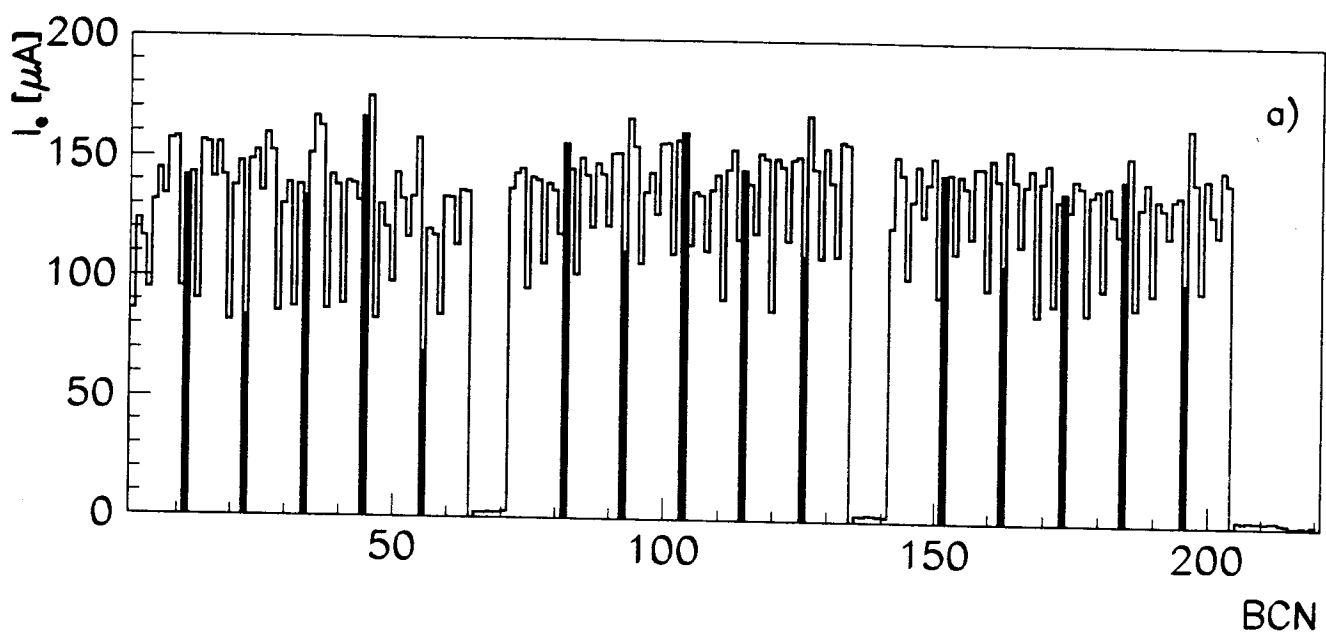
2X₀ carbon absorber

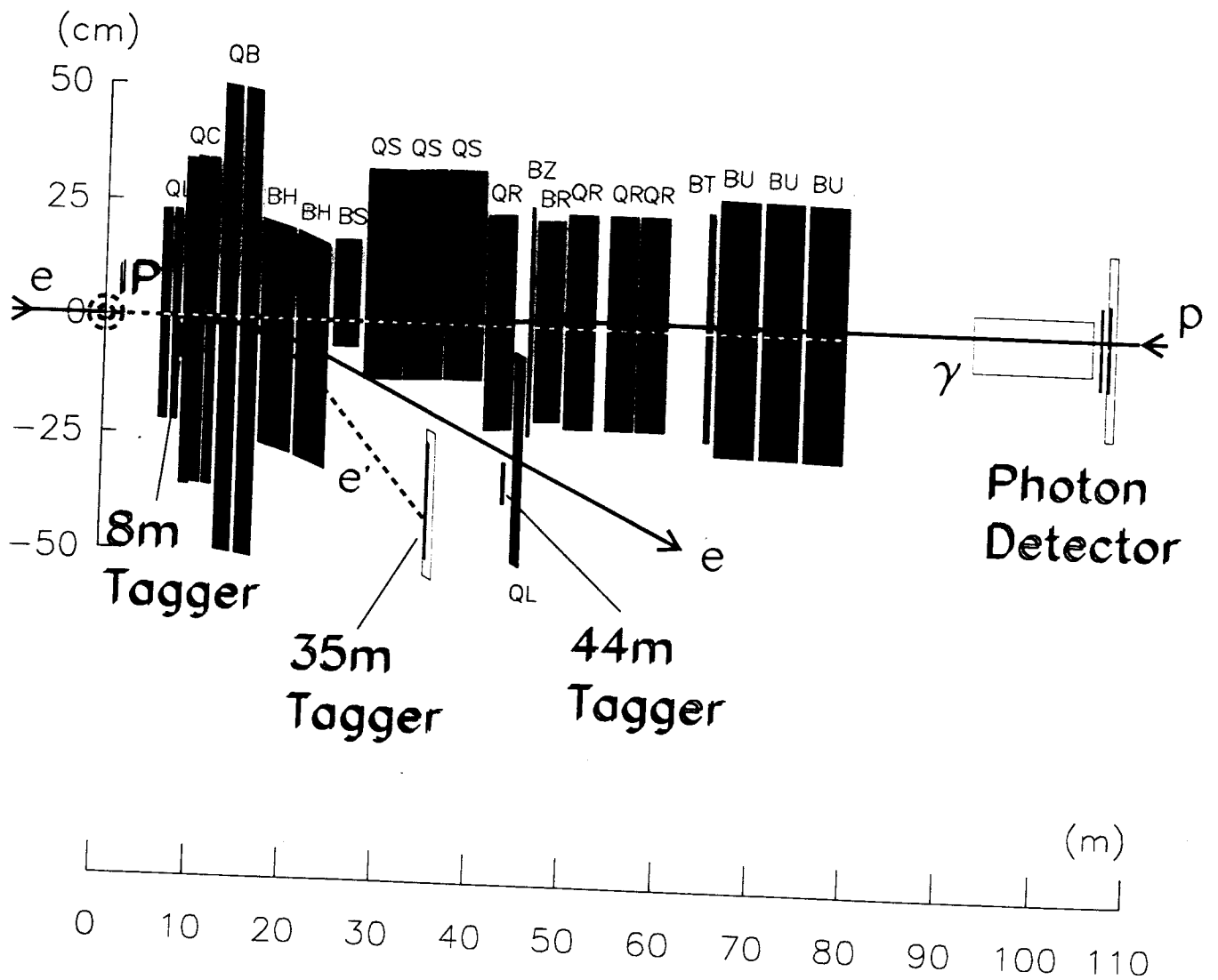
aerogel \checkmark counter

2X₀ carbon absorber

aerogel \checkmark counter

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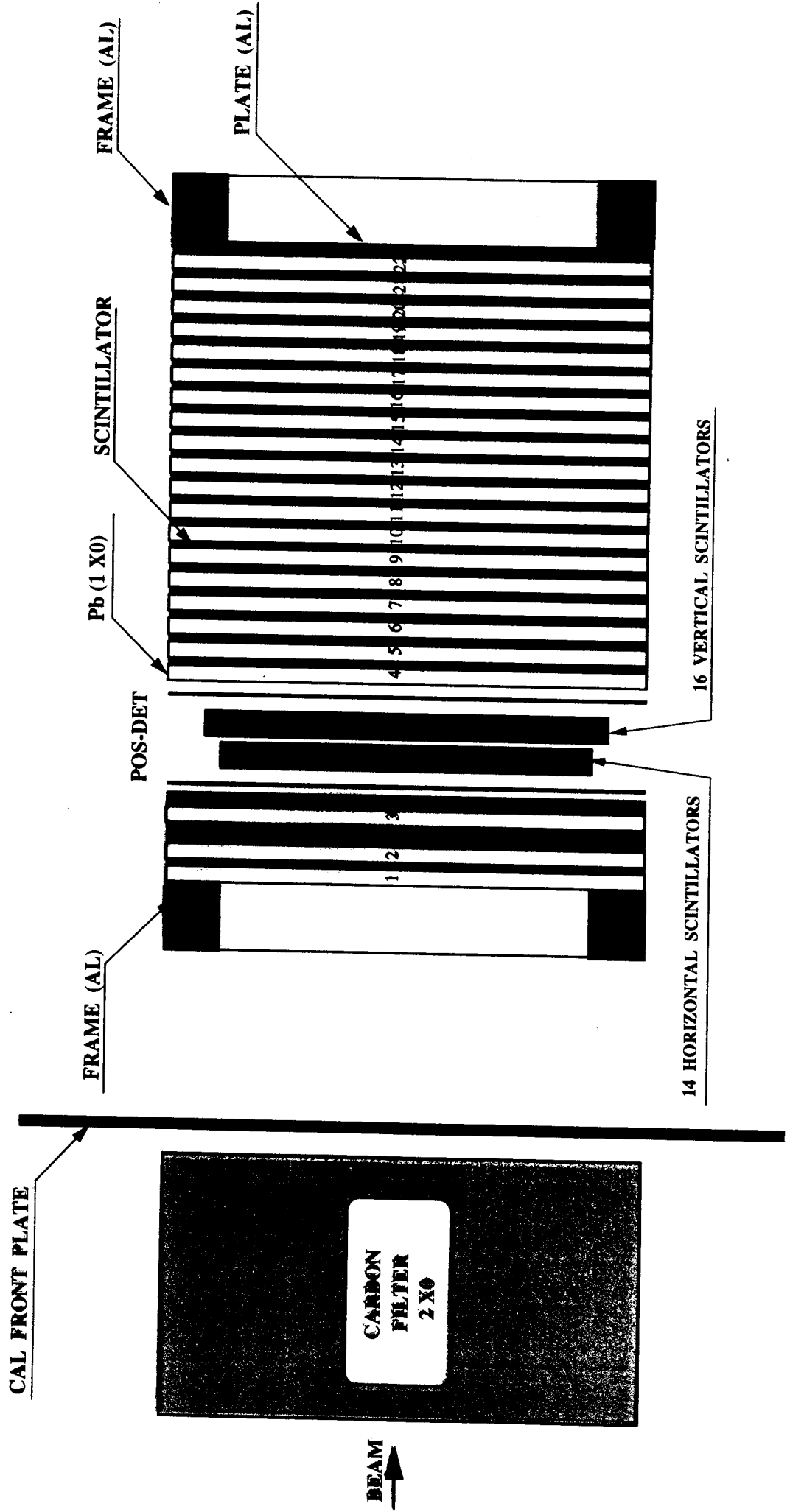




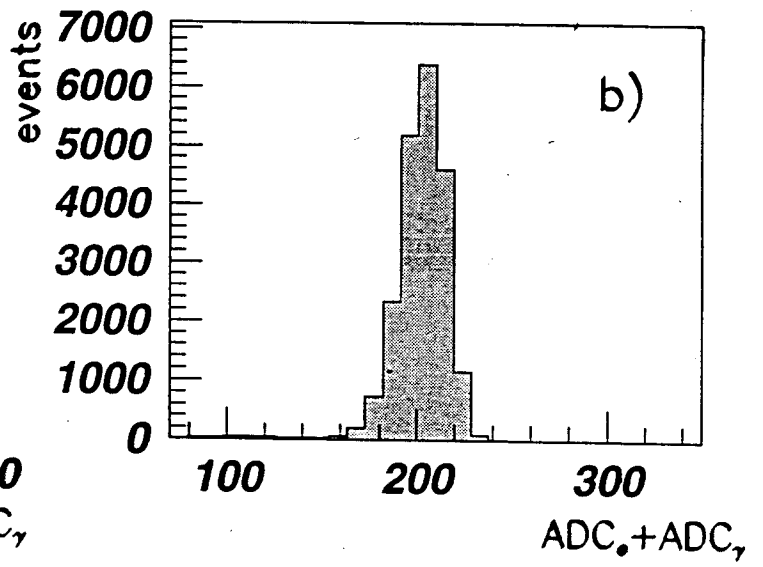
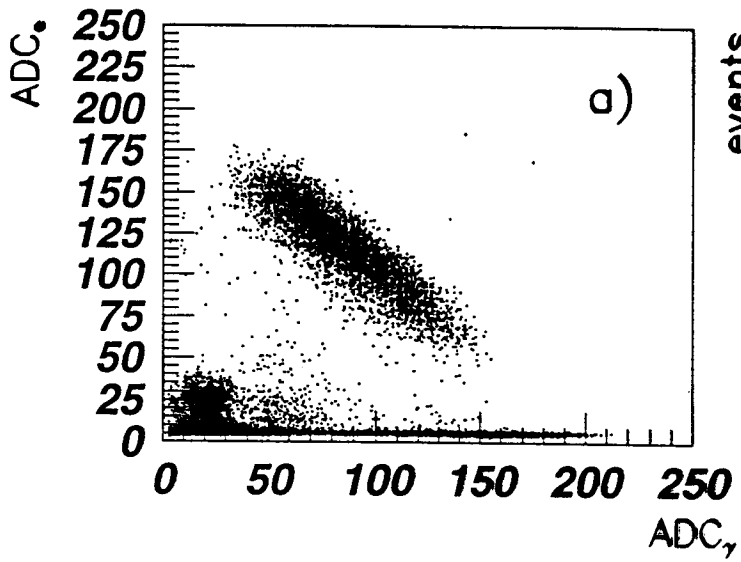
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PHOTON CALORIMETER (PB - SCINTILLATORS CONFIGURATION)

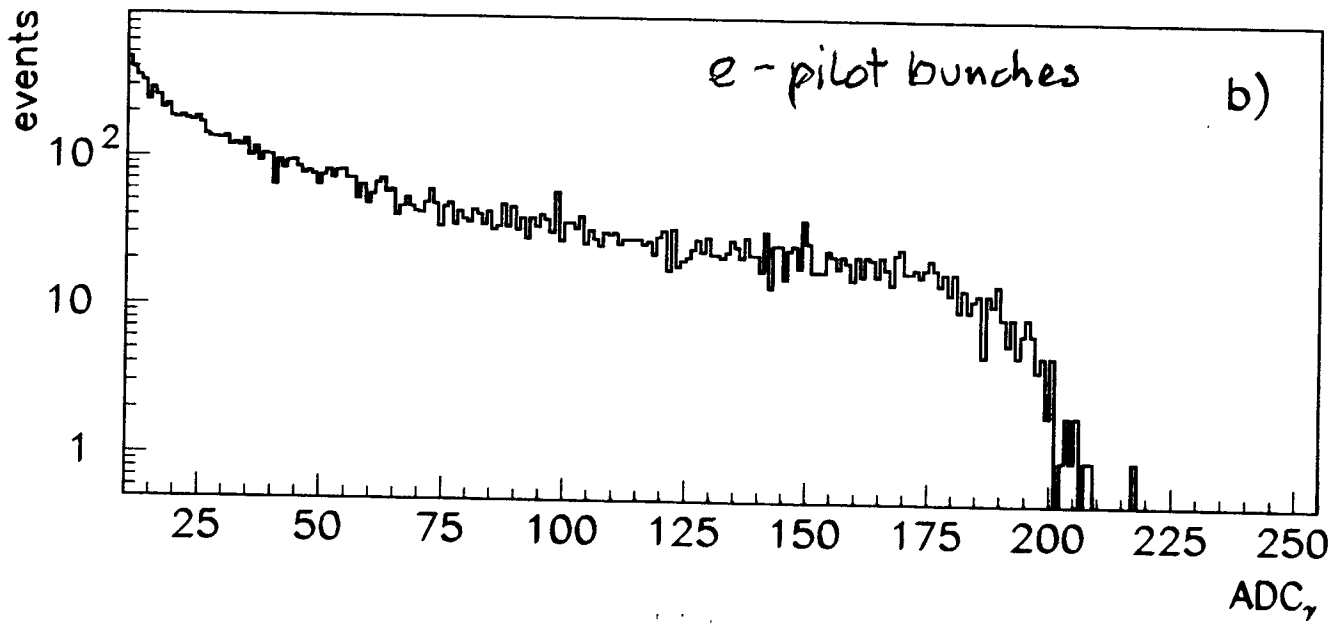
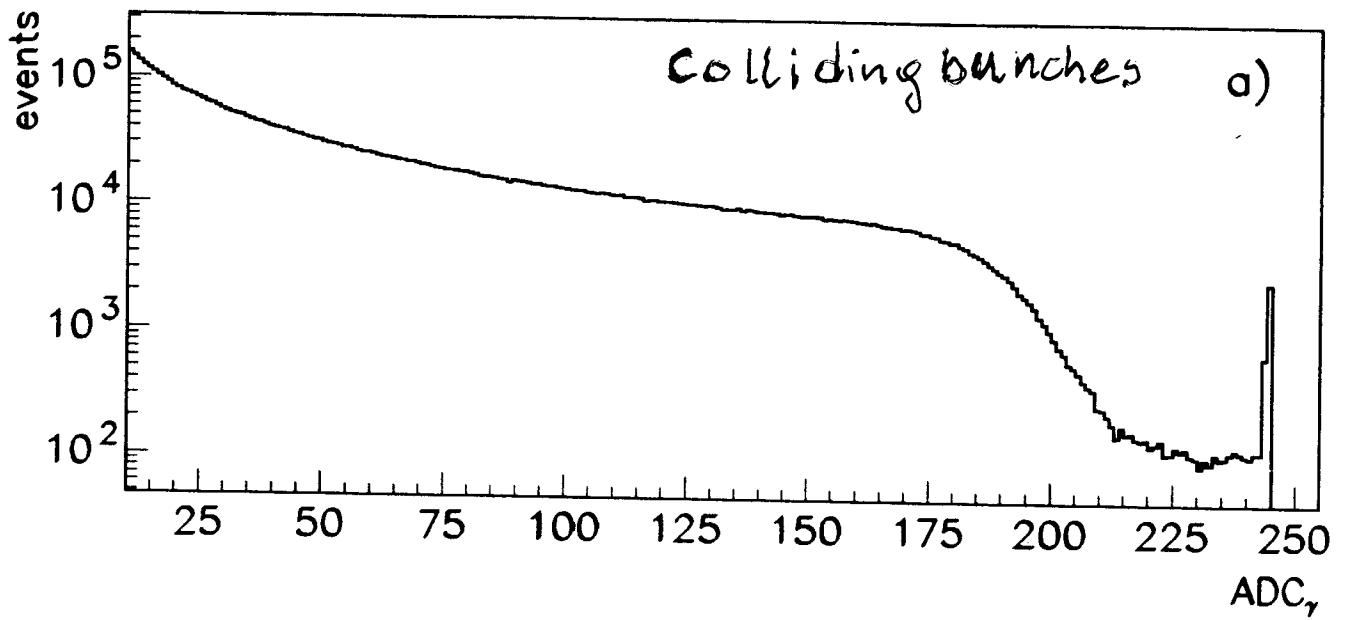
ZEUS - LUMI



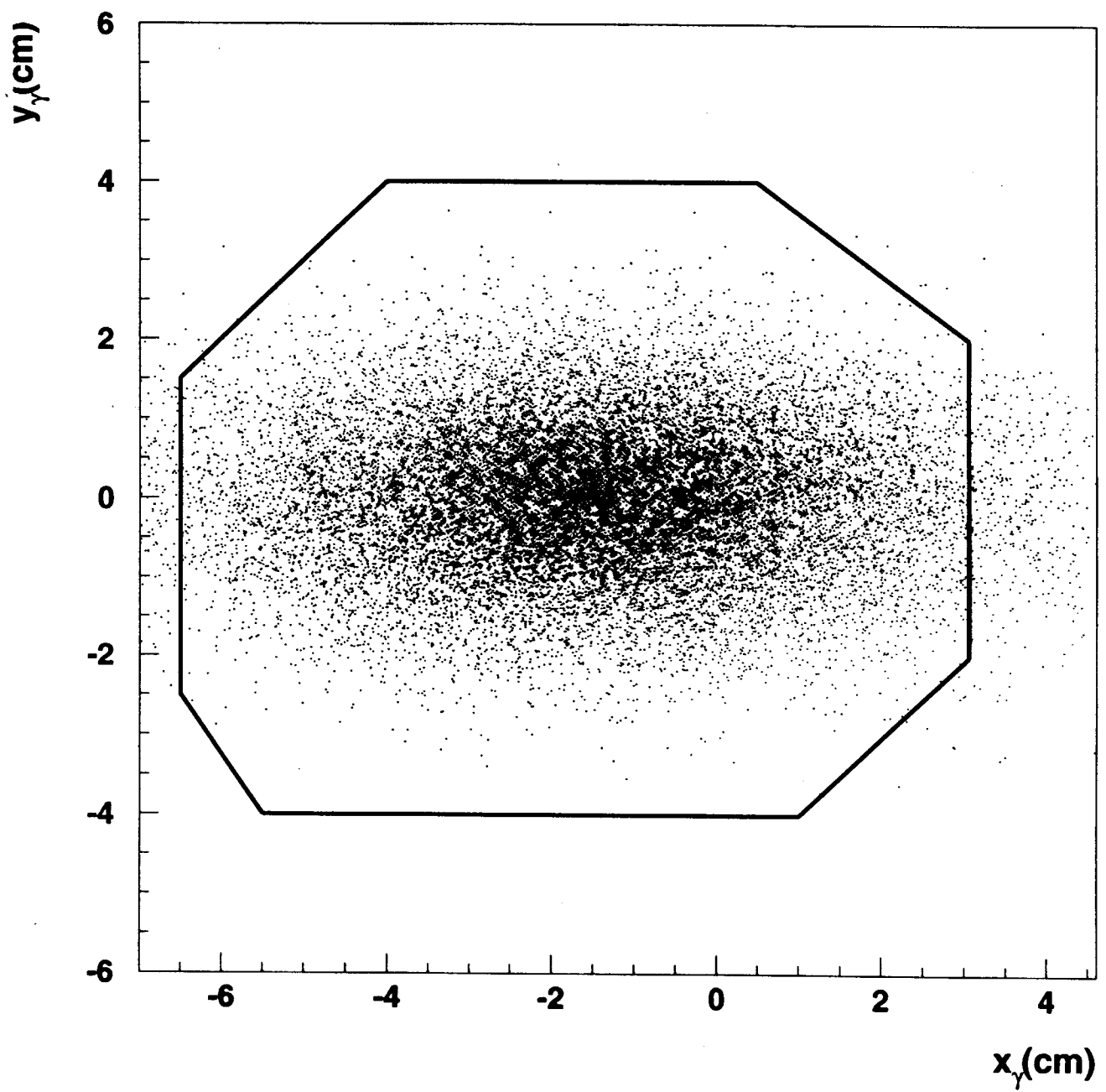
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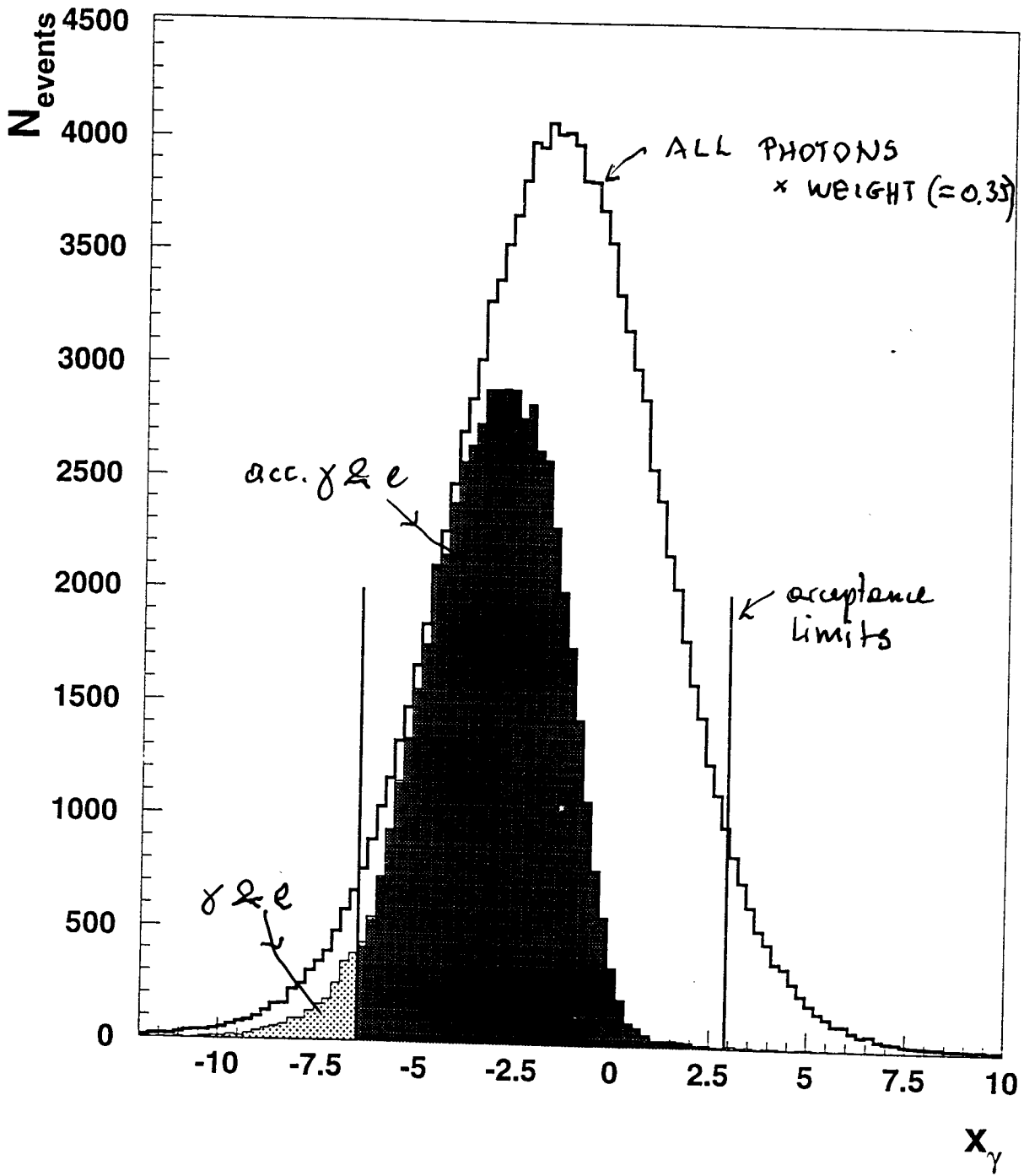


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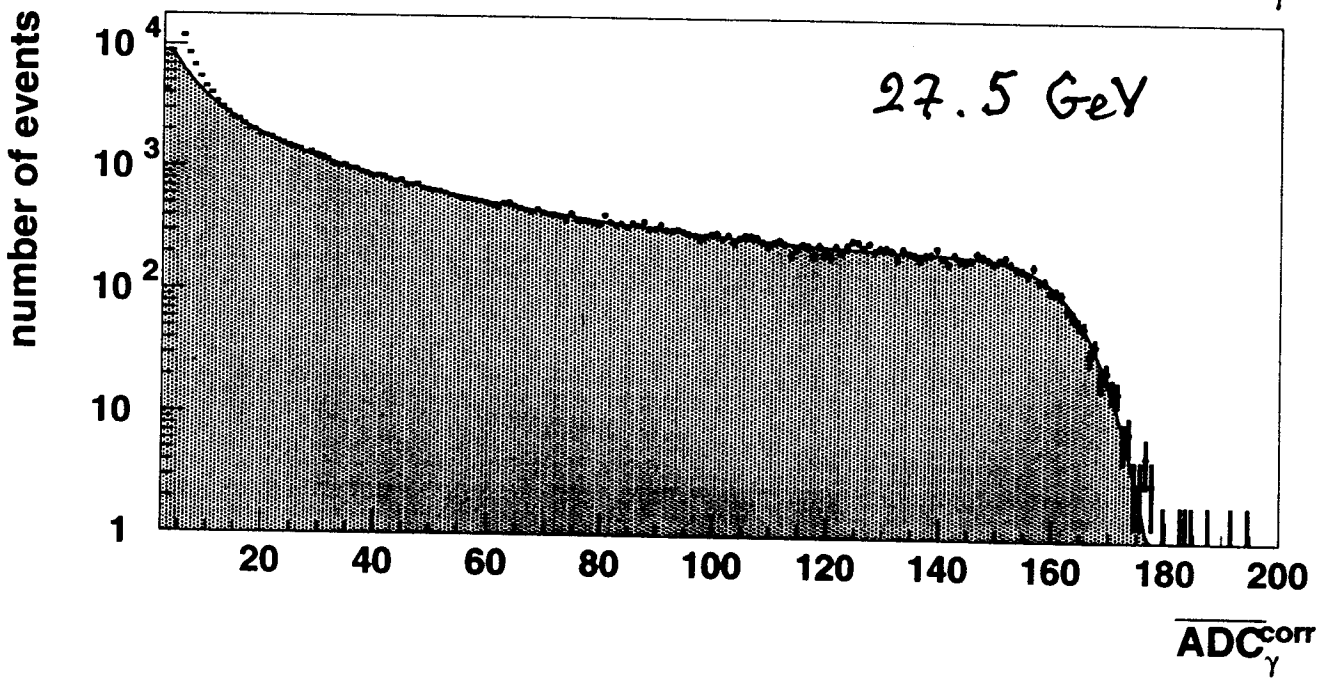
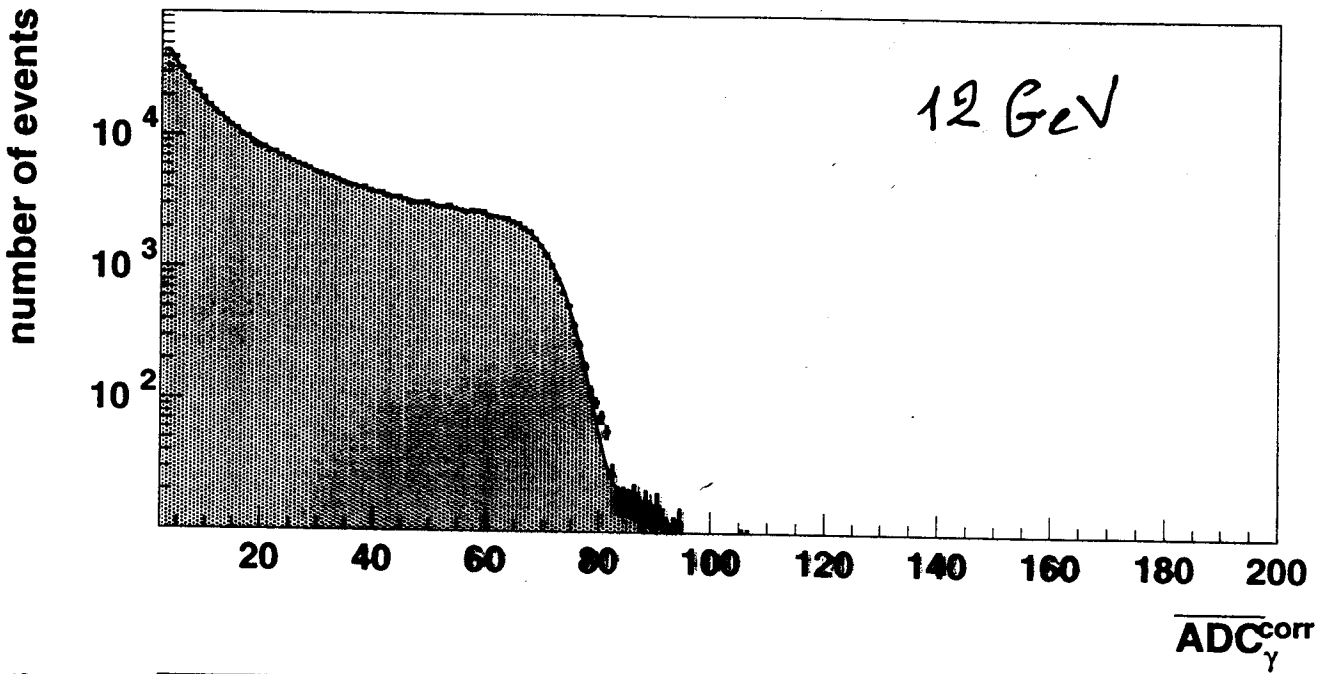


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MC

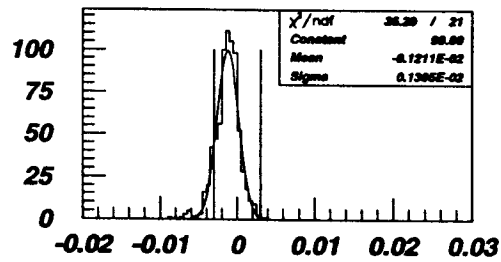
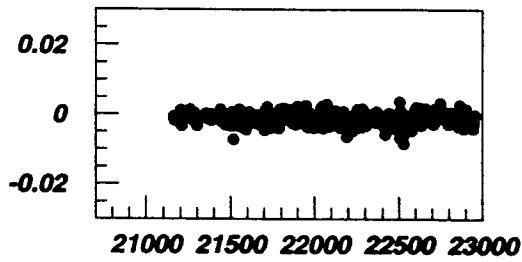


e-gar

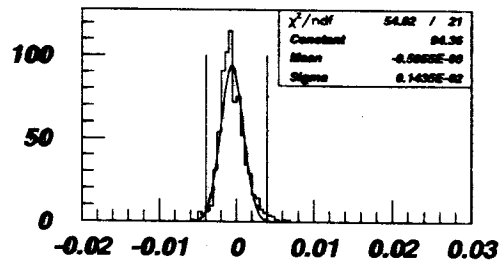
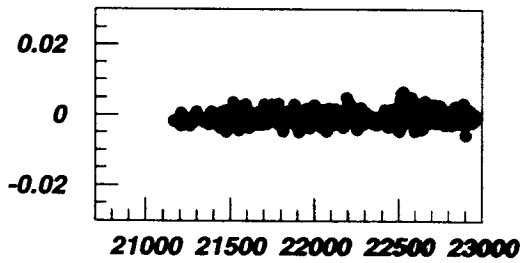


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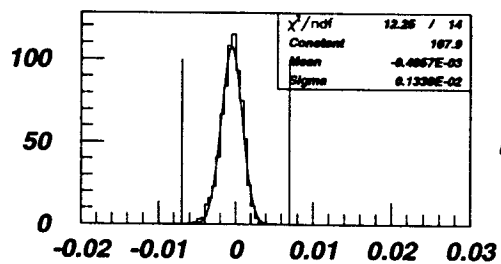
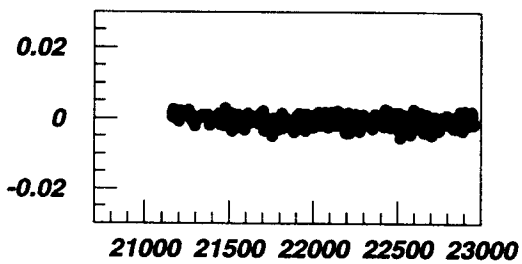
$$\Delta L/L = (L_5 - L_i)/L_5$$



$E_{TR} \geq 2 \text{ GeV}$



$E_{TR} \geq 10 \text{ GeV}$



$10 < E_{TR} < 16 \text{ GeV}$

Contribution	Trigger			
	2 GeV	5 GeV	10 GeV	(10 – 16) GeV
calibration constant	0.13%	0.20%	0.32%	0.08%
pedestal	0.16%	0.10%	0.07%	0.07%
ADC bins	0.5%	0.3%	0.2%	0.2%
detector response	0.7%	0.5%	0.5%	0.5%
Total energy scale error	0.75%	0.55%	0.6%	0.5%

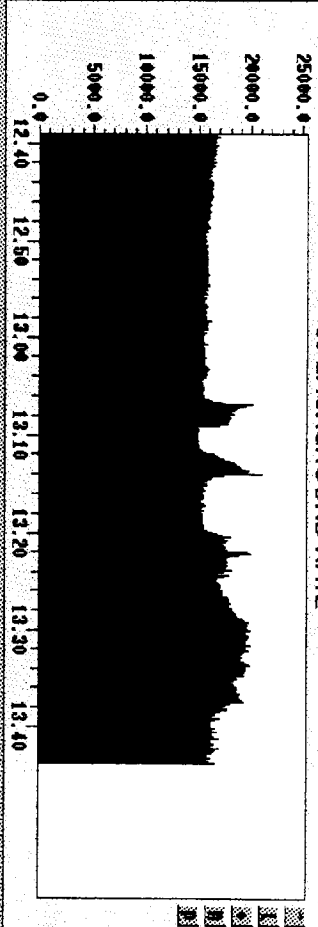
Table 1: Systematic errors of the luminosity measurement due to the energy scale uncertainty.

Contribution	Trigger			
	2 GeV	5 GeV	10 GeV	(10 – 16) GeV
acceptance error	0.8%	0.8%	0.8%	0.8%
cross section calculation	1.2%	0.6%	0.4%	0.5%
<i>egas</i> background subtraction	0.1%	0.1%	0.1%	0.1%
multiple events correction	0.11%	0.01%	0.11%	0.03%
counting error	0.1%	0.1%	0.1%	0.1%
energy scale error	0.75%	0.55%	0.6%	0.5%
Total error	1.7%	1.2%	1.1%	1.1%

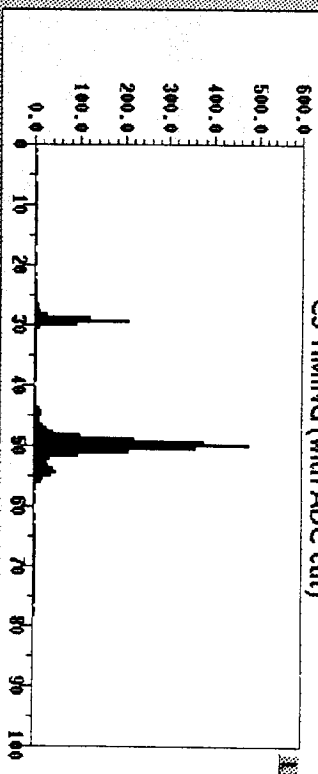
Table 1: Systematic errors of the luminosity measurement.

ZEUS 14/Oct/94 13:43 Lum. 1.718E+30 Specific: 3.259E+30 Integrated: 9.04 nb^-1

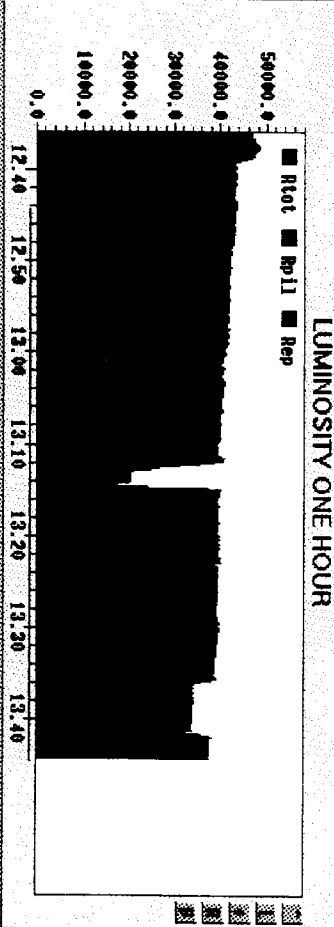
CS BACKGROUND RATE



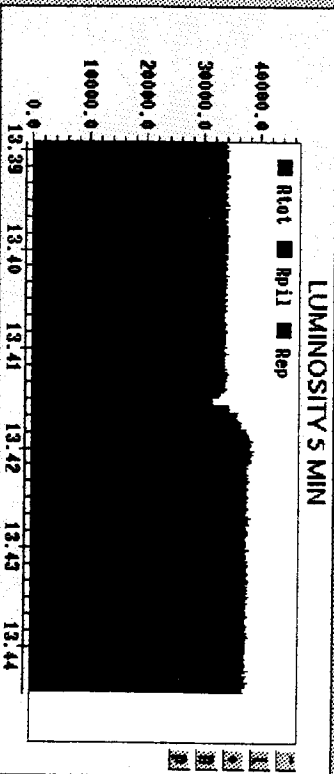
CS TIMING (with ADC cut)



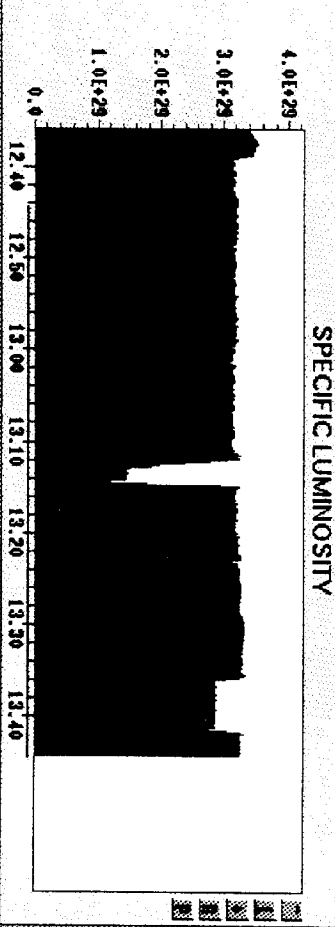
LUMINOSITY ONE HOUR



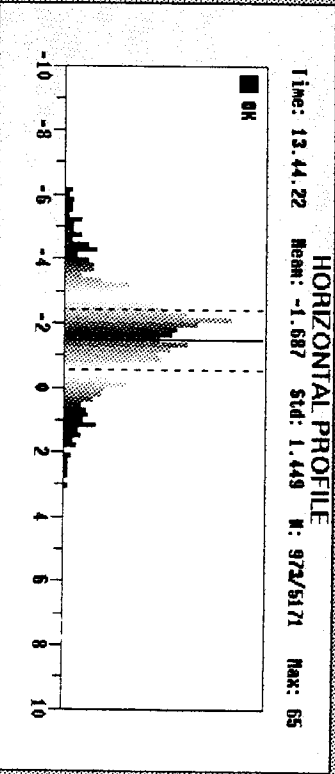
LUMINOSITY 5 MIN



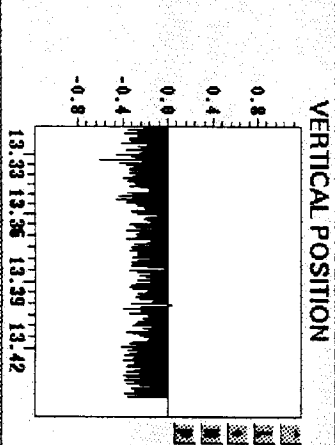
SPECIFIC LUMINOSITY



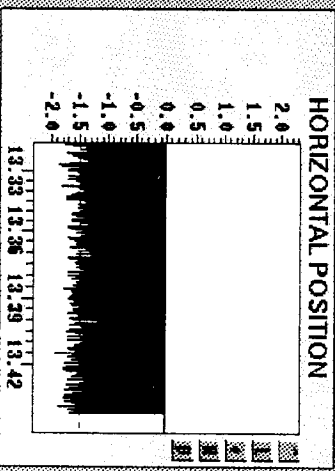
HORIZONTAL PROFILE



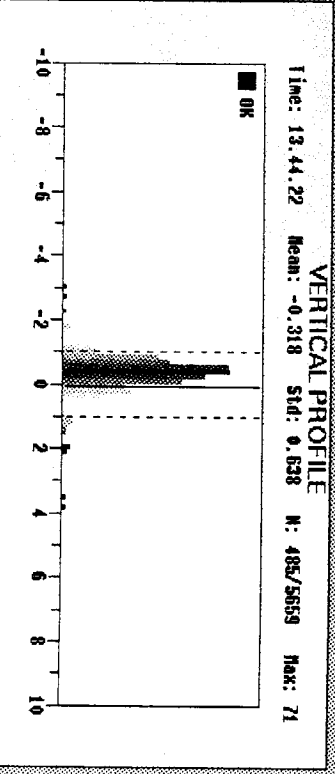
VERTICAL POSITION



HORIZONTAL POSITION



VERTICAL PROFILE



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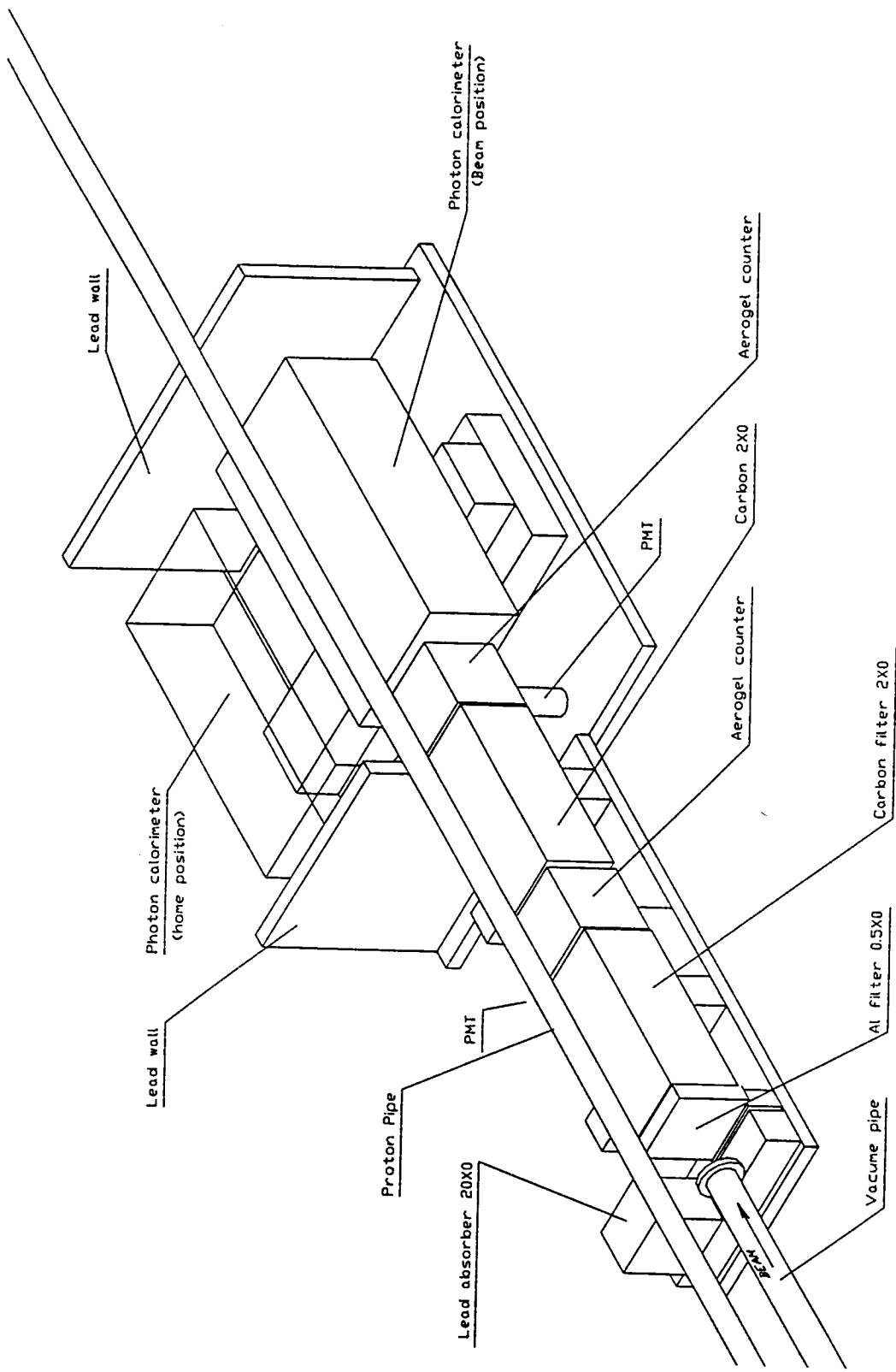


Figure 13: The overview of the proposed upgraded monitor.

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