Luminosity Measurement and Electron Tagging

1.1 Mission and Challenges

Luminosity measurement is an important issue for any collider experiment. At the LHeC, where precision measurements constitute a significant part of the physics programme, the design requirement is $\delta\mathcal{L} = 1\%$.

In addition to an accurate determination of integrated luminosity, $\mathcal{L}$, for the normalisation of physics cross sections, the luminosity system should allow for fast beam monitoring with a typical statistical precision of 1%/sec for tuning and optimisation of *ep*-collisions and to provide good control of the mid-term variations of instantaneous luminosity, L.

Rich experience gained by H1 [1, 2] and ZEUS [3, 4] Collaborations at HERA was used in the design studies of the luminosity system for the LHeC. In particular, one important lesson to be learnt from HERA is to prepare several alternative methods for luminosity determination.

For the LHeC we consider both Linac-Ring (LR) and Ring-Ring (RR) options as well as high Q^2 ($10^\circ - 170^\circ$ acceptance) and low Q^2 ($1^\circ - 179^\circ$ acceptance) detector setups. This spans over a wide range of instantaneous luminosity[1] $L = (10^{32} - 2 \cdot 10^{33})\mathrm{cm}^{-2}\mathrm{s}^{-1}$. Hence suitable processes for the three tasks outlined above should have the following minimal visible cross sections[2]:

- fast monitoring ($\delta\mathcal{L} = 1\%/\mathrm{sec} \Rightarrow 10$ kHz) – $\sigma_{\mathrm{vis}} \gtrsim 100\mu\mathrm{b}$,
- mid-term control ($\delta\mathcal{L} = 0.5\%/\mathrm{hour} \Rightarrow 10$ Hz) – $\sigma_{\mathrm{vis}} \gtrsim 100\mathrm{nb}$,
- physics sample normalisation ($\delta\mathcal{L} = 0.5\%/\mathrm{week} \Rightarrow 0.1$ Hz) – $\sigma_{\mathrm{vis}} \gtrsim 1\mathrm{nb}$.

The best candidate for luminosity determination is the purely electromagnetic *bremsstrahlung reaction* $ep \to e\gamma + p$ shown in Figure 1.1a, which has a large and precisely known cross section. Depending on the photon emission angle it is called either Bethe-Heitler process (collinear emission) or QED Compton scattering (wide angle bremsstrahlung). In addition, Neutral Current DIS events in a well understood (x, Q^2) range can be used for the *relative* normalisation and mid-term yield control.

While QED Compton and NC DIS processes can be measured in the main detector dedicated 'tunnel detectors' are required to register Bethe-Heitler events. For the latter, additional challenges as compared to HERA are related to the LHeC specifics: non-zero beam crossing angle in IP for RR option, and severe aperture limitation for LR option. Finally, for the high luminosity LHeC running one should not forget about significant pileup (L/bunch is $\sim 2 - 3$ times bigger as compared to HERA-II running).

1.2 Options

The huge rate of 'zero angle' electrons and photons from Bethe-Heitler reaction[3] makes a dedicated luminosity system in the tunnel ideal for fast monitoring purposes. However, it is

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[1] This also takes into account exponential reduction of L during the data taking in every luminosity fill.

[2] Statistical error has to be small in comparison with total error δL_{tot} in order not to spoil overall accuracy.

[3] Total cross section, $\sigma_{BH} \simeq 870$ mb for $60 \times 7000\ \mathrm{GeV}^2$ *ep* collisions at the LHeC.

usually very sensitive to the details of the beam optics at the IP, may suffer from synchrotron radiation (SR) and requires, for accurate absolute normalisation, a large and precisely known geometrical acceptance which is often difficult to ensure. On the contrary, the main detector has stable and well known acceptance and is safely shielded against SR. Therefore, although QED Compton events in the detector acceptance have significantly smaller rates they may be better suited for overall global normalisation of the physics samples. Thus the two methods are complementary, having very different systematics and providing useful redundancy and cross check for the luminosity determination.

To evaluate the main LHeC detector acceptance for NC DIS events and for the elastic QED Compton process `DJANGOH` [5] and `COMPTON` [6] event generators were used respectively. Different options for dedicated luminosity detectors in the LHC tunnel have been studied with help of the special `H1LUMI` program package [7], which contains Monte Carlo generation of the 'collinear' photons and electrons from various processes (Bethe-Heitler reaction, quasi-real photoproduction, e-beam scattering on the rest gas) as well as a simple tracking through the beamline.[4]

1.2.1 Use of the Main LHeC Detector

To estimate visible cross sections for NC DIS and elastic QED Compton events a typical HERA analysis strategy was used. That is: safe fiducial cuts against energy leakage over the backward calorimeter boundaries at small radii, safe (Q^2, y) cuts for NC DIS events to restrict measurement to the phase space where F_2 is known to good precision of $1-2\%$ and the F_L contribution is negligible, and elasticity cuts for QEDC events to reject the less precisely known inelastic contribution. In addition basic cuts against major backgrounds were applied (photoproduction in case of NC DIS and DVCS, elastic VM production and low mass diffraction in case of QED Compton).

The visible NC DIS cross section, $\sigma_{\rm vis}^{DIS}(Q^2 > 10{\rm GeV}^2, 0.05 < y < 0.6) \simeq 10$ nb for 10° setup and $\simeq 150$ nb for 1° setup. This corresponds to a $10 - 15$ Hz rate which is comfortable enough for mid-term yield control.

For elastic QED Compton events, the visible cross section, $\sigma_{\rm vis}^{QEDC} \simeq 0.03$ nb for 10° setup and $\simeq 3.5$ nb for 1° setup. Hence while for the latter sufficiently high rate is possible even for $L = 10^{32}{\rm cm}^{-2}{\rm s}^{-1}$, in case of 'high Q^2' setup the QEDC event rate is $4 - 5$ times smaller, thus only providing acceptable statistical precision for large samples, of the order 0.5%/month.

In order to improve this a special small dedicated calorimeter could eventually be added after the strong focusing quadrupole, at $z = -6$m. Such 'QEDC tagger' should consist of two movable stations approaching the beam-pipe from the top and the bottom in the vertical direction, as sketched in Figure 1.1b. This way detector sections will be safe with respect to SR fan confined in the median plane. The visible elastic QED Compton cross section for such a device is 4.3 ± 0.2 nb which significantly improves statistics for the luminosity measurement. The angular acceptance of the 'QEDC tagger' corresponds to the range $\theta = 0.5^\circ - 1^\circ$ which lies outside the tracking acceptance. Therefore calorimeter sections should be supplemented by small silicon detectors in order to make it possible to reconstruct the event vertex from the final state containing only one electron and one photon. These silicon trackers are also useful for e/γ separation and rejection of the potential background. Actual dimensions and parameters of this optional 'QEDC tagger' requires extra design studies.

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[4] The tracking has been performed by interfacing H1LUMI to GEANT3 [8] having LHeC beamline implemented up to ~ 110m from the IP.

1.2.2 Dedicated Luminosity Detectors in the tunnel

In case of the RR-option which implies non-zero crossing angle for early e/p beam separation, the dominant part of the Bethe-Heitler photons will end up at $z \simeq -22$m, between electron and proton beam-pipes (see Figure 1.1c). This is the hottest place where also a powerful SR flux must be absorbed. On the first glance this makes luminosity monitoring based upon the bremsstrahlung photons impossible.

There is however an interesting possibility. SR absorber needs good cooling system. The most natural cooling utilises circulating water. This cooling water can be used at the same time as an active media for Čerenkov radiation from electromagnetic showers initiated by the energetic Bethe-Heitler photons. The idea is based on two facts:

1. The dominant part of the SR spectrum lies below the Čerenkov threshold for water, $E_{\text{thr}} = 260$ keV, and hence will not produce light signal. Low intensity tail of the energetic synchrotron photons can be further suppressed by few radiation lengths of the absorber material in front of the water volume.

2. Water is absolutely radiation resistant media and hence such simple Čerenkov counter can stand any dose without performance deterioration.

The Čerenkov light can be collected and read out by two photo-multipliers as sketched on Figure 1.1d. The geometric acceptance depends on the details of the e-beam optics. For the actual RR design with the crossing angle ~ 1 mrad the acceptance to the Bethe-Heitler photons is up to 90%, thus allowing fast and reliable luminosity monitoring with $3 - 5\%$ systematic uncertainty.

Of course, such an active SR absorber is not a calorimeter with good energy resolution, but just a simple counter. It is worth noting, that similar water Čerenkov detector has been successfully used in the H1 Luminosity System during HERA-I operation.

In case of LR-option, electrons collide with protons head-on, with zero crossing angle. This makes the situation very similar to HERA, where Bethe-Heitler photons travel along the proton beam direction and can be caught at around $z = -120$m, after the first proton bending dipole. Essential difference is that unlike HERA, LHC protons are deflected horizontally at this place rather than vertically. Thus the luminosity detector should be placed in the median plane next to the interacting proton beam, p_1, as shown on Figure 1.1e. In this case energy measurement with good resolution is not a problem, so major uncertainty will come from the knowledge of the limited geometric acceptance. This limitation is defined by the proton beam-line aperture, in particular by the aperture of the quadrupoles Q1-Q3 of the low-beta proton triplet. Moreover, it might be necessary to split D1 dipole into two parts in order to provide escape path for the photons with sufficient aperture. First estimates show that the geometric acceptance of the Photon Detector up to 95% is possible at the nominal beam conditions. HERA experience tells, that the uncertainty can be estimated as $\delta A = 0.1 \cdot (1 - A)$ leading to the total luminosity error of $\delta L = 1\%$ in this case.

1.3 Small angle Electron Tagger

The Bethe-Heitler reaction can be tagged not only by detecting a final state photon, but also by detecting the outgoing electron. Since all other competing processes have much smaller cross sections measuring inclusive rate of the scattered electrons under zero angle will provide a

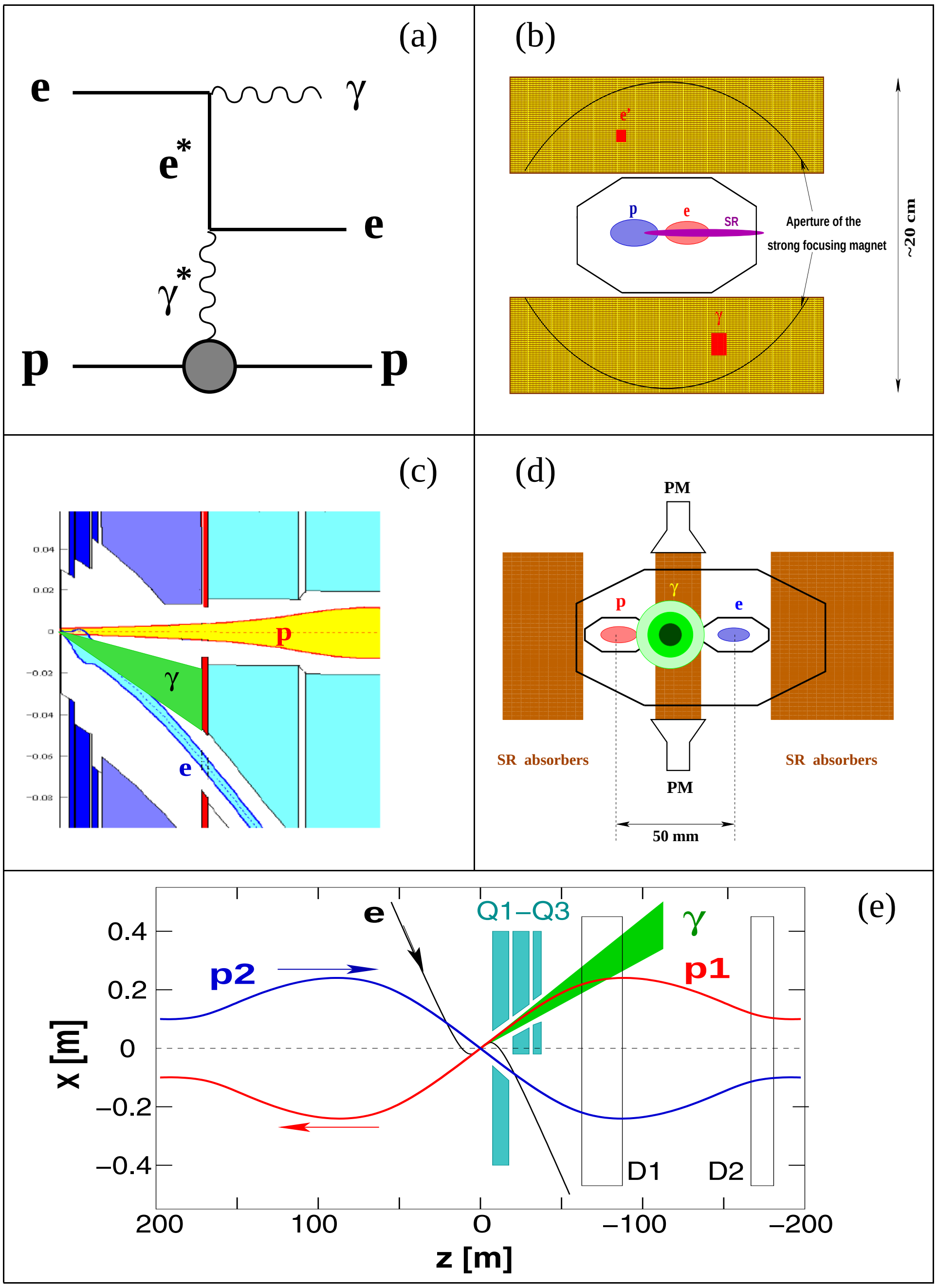

Figure 1.1: Options for the luminosity monitoring at the LHeC. (a) Feynman diagram for QEDC (γ^* pole) or BH (γ^*, e^* poles) processes; (b) QEDC tagger at $z = -6$m; (c,d) active SR absorber at $z = -22$m for RR-option (circles show 1-, 2- and 3-σ contours for BH photons); (e) schematic view for the LR-option with 3-σ fan of BH photons.

clean enough sample for luminosity monitoring. The remaining small background (mainly due to off-momentum electrons from e-beam scattering on the rest gas) can be precisely controlled and statistically subtracted using non-colliding (*pilot*) electron bunches.

In order to determine the best positions for the Electron taggers the LHeC beamline simulation has been performed in the vicinity of the Interaction Region for the RR-option. Several positions for the e-tagger stations were tried:[5] $z = -14$m, -22m and -62m. As one can see on the top part of Figure 1.2 all places provide reasonable acceptances, reaching approximately $(20-25)\%$ at the maximum. However, $z = -14$m and $z = -22$m most likely will suffer from SR flux, making e-tagger operation problematic at those positions.

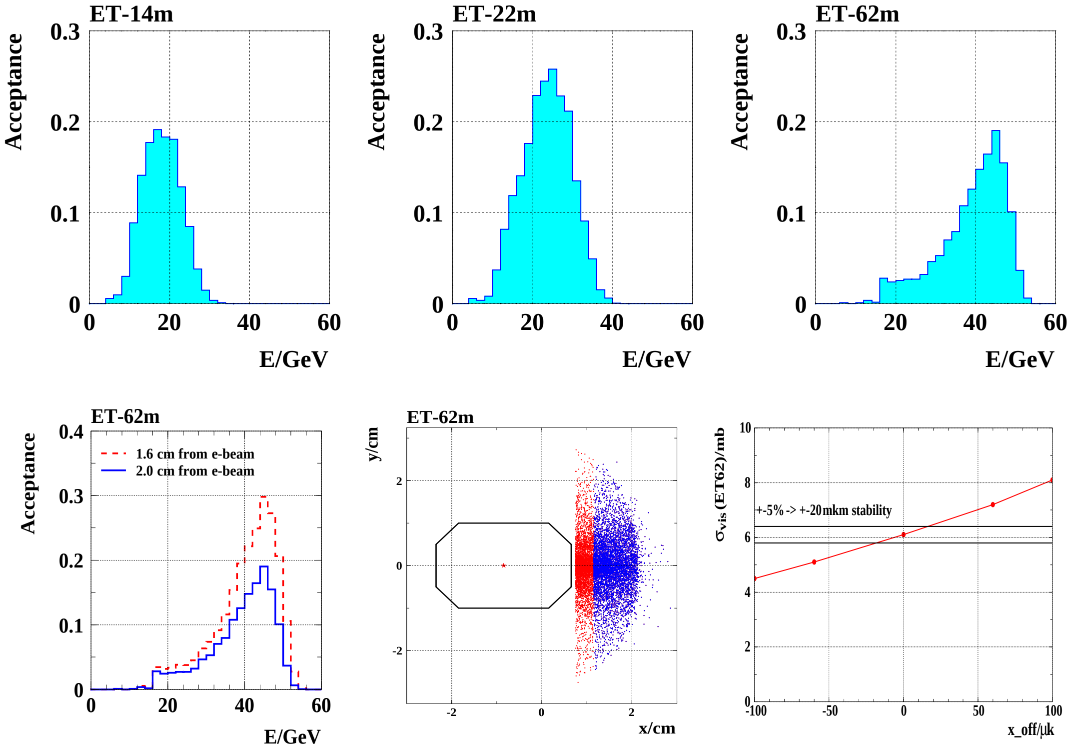

Figure 1.2: Top: acceptances of the e-taggers for Bethe-Heitler events at different z-positions from IP (RR-option). Bottom: variations in the acceptance of the e-tagger at $z = -62$m as a function of its position with respect to the e-beam axis and on the horizontal offset of the beam orbit at the IP.

The most promising position for the Electron tagger is at $z = -62$m. The actual acceptance strongly depends both on the distance of the sensitive detector volume from the e-beam axis and on the details of the electron optics at the IP, such as beam tilt or small trajectory offset, as illustrated on the bottom part of Figure 1.2. Therefore a precise independent monitoring of

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[5] For the station at $z = -14$m the electron dipole magnet should be split into two parts, while the region around $z = -62$m has sufficiently comfortable place for the Electron tagger, before the e-beam is bended vertically.

beam optics and accurate position measurement of the e-tagger are required in order to control geometrical acceptance to a sufficient precision. For example, instability in the horizontal trajectory offset at IP, x_{off}, of $\pm 20\mu$m leads to the systematic uncertainty of 5% in the visible cross section, $\sigma_{\mathrm{vis}}(ET62)$.

It is fair to note, that the magnetic field of the main LHeC detector was not taken into account in the simulation. The influence of this field is expected to be very small and will not alter basic conclusions of this section. Also, for the LR-option a similar acceptance is expected, although it may differ in shape somewhat.

In order to demonstrate that the ideas described in Sec. 1.2.2 and 1.3 are realistic a typical example of the online rates variations for the H1 Luminosity System at HERA is shown on Figure 1.3. The system utilised all three types of the detectors discussed above: a total absorption electromagnetic calorimeter for the Bethe-Heitler photons (PD), a water Čerenkov counter (VC) and the Electron tagger (ET6). One can see, that online luminosity estimate by every of those detectors is well within 5% in spite of significant changes in the acceptance due to electron beam tilt jumps and adjustments at the IP.

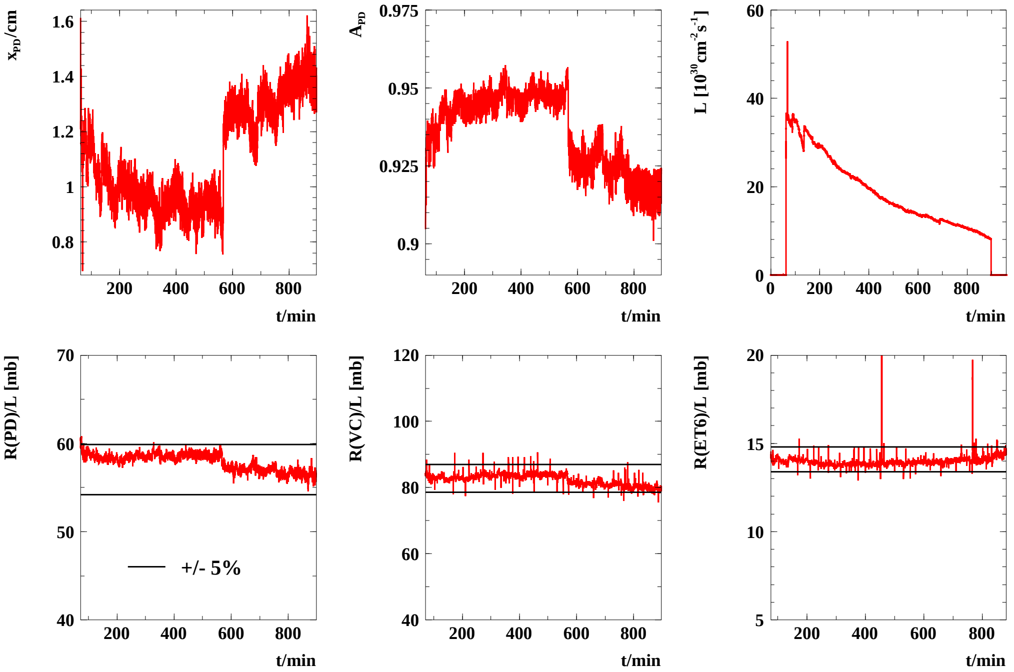

Figure 1.3: Online H1 Lumi System acceptance and rates variations in a typical HERA luminosity fill.

1.4 Summary and Open Questions

Accurate luminosity measurement at the LHeC is highly non-trivial task. As follows from HERA experience unexpected surprises are possible, hence it is important to consider several scenarios from the beginning and to prepare alternative methods for luminosity determination.

Statistical precision and systematic uncertainties for different methods of luminosity measurement are summarised in Table 1.1.

Method	Stat. error	Syst.error	Systematic error components		Application
BH (γ)	0.05%/sec	$1-5\%$	$\sigma(E \gtrsim 10\text{GeV})$	0.5%	Monitoring, tuning, short term variations
			acceptance, A	$10\%(1-A)$	
			E-scale, pileup	$0.5-4\%$	
BH (e)	0.2%/sec	$3-6\%$	$\sigma(E \gtrsim 10\text{GeV})$	0.5%	Monitoring, tuning, short term variations
			acceptance	$2.5-5\%$	
			background	1%	
			E-scale	1%	
QEDC	0.5%/week	1.5%	σ (el/inel)	1%	Absolute $\mathcal{L}$, global normalisation
			acceptance	1%	
			vertex eff.	0.5%	
			E-scale	0.3%	
NC DIS	0.5%/h	2.5%	σ ($y < 0.6$)	2%	Relative $\mathcal{L}$, mid-term variations
			acceptance	1%	
			vertex eff.	1%	
			E-scale	0.3%	

Table 1.1: Dominant systematics for various methods of luminosity measurement.

Precise determination of integrated luminosity, $\mathcal{L}$, is possible with the main detector utilising the QEDC process. $\delta\mathcal{L} = 1.5 - 2\%$ is within reach. Further improvement requires in particular more accurate theoretical calculation of the elastic QED Compton cross section, with $\delta\sigma_{\text{el}}^{\text{QEDC}} \lesssim 0.5\%$. To enhance statistical precision a dedicated QEDC tagger at $z = -6$m might be useful. This device could also be used to access very low Q^2 region, interpolating between DIS and photoproduction regimes.

Fast instantaneous luminosity monitoring is challenging, but several options do exist which are based upon detection of the photons and/or electrons from the Bethe-Heitler process.

- Photon Detector at $z = 110$m for LR option requires properly shaped proton beam-pipe at $z = -68 - 120$m from IP2.
- In case of RR option Bethe-Heitler photons can be detected using a water Čerenkov counter integrated with SR absorber at $z = -22$m.
- Electron tagger at $z = -62$m is very promising for both LR and RR schemes. It can be used not only for luminosity monitoring, but also to enhance photoproduction physics capabilities and to provide extra control of the γp background to DIS, by tagging quasi-real photoproduction events.

Good monitoring of the e-optics at the IP is required to control acceptances of the tunnel detectors to a level of $2 - 5\%$.

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