LUMINOSITY SCANS AT HERA

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Abstract

As demonstrated in many accelerators, luminosity scans can be used to measure the beam overlap integrals and to deduce the specific luminosity. In the electron–proton collider HERA these scans are performed by shifting the proton beam with respect to the lepton beam while recording the bremsstrahlung produced by the e/p collision. While the orbit of the 920GeV proton beam is not strongly affected by the beam–beam kick, the effect on the 27.5GeV lepton beam is very significant. When a wire scanner is used to determine the proton beam size, the luminosity scan can be used to determine the lepton emittances. Furthermore information about the correlation of horizontal and vertical phase space can be obtained from luminosity scans. For this purpose three evaluation methods are derived, one of which is applicable for arbitrary bunch profiles. In the test phase of the HERA luminosity upgrade this feature was used to identify coupling as source for a reduced luminosity.

1 INTRODUCTION

When the emittances of two head–on colliding beams and the beta functions of the optics are know, one can compute the specific luminosity $\mathcal{L}_s = \frac{1}{2\pi f q_1 q_2} \frac{1}{\Sigma_x \Sigma_y}$, assuming Gaussian transverse beam profiles which are not correleated in x–y space, i.e. the beam profile is upright. The Σ are given by the sigma parameters of the two colliding beams as $\sqrt{\sigma_1^2 + \sigma_2^2}$ and the circulation frequency f as well as the charges q_1 and q_2 of the particles in the two beams are used. The sigma parameters, e.g. σ_x, describe the width of the bunch profile projection, e.g. $\bar{\rho}(x) = \int_\infty \rho(x, y, z) dy dz$ on the horizontal.

When the beams are not necessarily Gaussian but have transverse densities ρ_1 and ρ_2, the specific luminosity is given by

$$\mathcal{L}_s = \int_\infty [\int_\infty \rho_1(x, y, z) dz][\int_\infty \rho_2(x, y, z) dz] \frac{dx dy}{f q_1 q_2} , \quad (1)$$

neglecting the hourglass effect [1]. During a luminosity scan, the distance between the center of the two beams is varied. The luminosity scan in x–direction is described by

$$\mathcal{L}_s^x(\Delta x) = \quad\quad\quad\quad\quad\quad\quad\quad (2)$$
$$\int_\infty [\int_\infty \rho_1(x, y, z) dz \int_\infty \rho_2(x - \Delta x, y, z) dz] \frac{dx dy}{f q_1 q_2} .$$

The luminosity scan in x direction gives information about

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the vertical density [2]:

$$\int_\infty \mathcal{L}_s^x(\Delta x) d\Delta x = \frac{1}{f q_1 q_2} \int_\infty \bar{\rho}_1(y) \bar{\rho}_2(y) dy . \quad (3)$$

For Gaussian projected densities,

$$\int_\infty \mathcal{L}_s^x(\Delta x) d\Delta x = \frac{1}{f q_1 q_2} \frac{1}{\sqrt{2\pi} \Sigma_y} . \quad (4)$$

A related method that also requires integrals over luminosity scans was used at the CERN ISR for luminosity calibration [3, 4]. We use three different methods to determine the overlap beam sizes Σ_x and Σ_y.

Method a) The standard deviation $\langle \Delta x^2 \rangle_{\mathcal{L}_s^x}$ of the luminosity scan is obtained by fitting a_x, b_x, and c_x of a bell curve $a_x \exp(-b_x (x - c_x)^2)$ to the data. Then one obtains $\Sigma_x = 1/\sqrt{2 b_x}$ and $\Sigma_y = 1/\sqrt{2 b_y}$ for uncorrelated Gaussian beam profiles in x and y. Then the luminosity scan data can be approximated by

$$\mathcal{L}_s^x(\Delta x, \Delta y) = \frac{1}{2\pi f q_1 q_2} \frac{1}{\Sigma_x \Sigma_y} e^{-\frac{\Delta_x^2}{2\Sigma_x^2}} e^{-\frac{\Delta_y^2}{2\Sigma_y^2}} . \quad (5)$$

Method b) It is assumed that both beams have Gaussian projected densities and equation (4) is used. The vertical overlap beam size is obtained from the horizontal luminosity scan with $\Sigma_y = (\sqrt{2\pi} f q_1 q_2 \int_\infty \mathcal{L}_s^x(\Delta x) d\Delta x)^{-1}$ and vice versa. The integral is evaluated by fitting a_x, b_x, and c_x of a bell curve $a_x \exp(-b_x (x - c_x)^2)$ to the data. Then one obtains $\Sigma_y = \sqrt{b_x} (\sqrt{2\pi} f q_1 q_2 a_x)^{-1}$ and vice verca. Also for these Σ_x and Σ_y, the luminosity scan data is given by equation (5) if the profiles have no x–y correlation.

Method c) For product densities $\rho(x, y, z) = \rho_x(x)\rho_y(y)\rho_z(z)$, the sum of the second moments $\langle x_1^2 \rangle + \langle x_2^2 \rangle$ can be obtained independent of bunch profiles,

$$\langle x^2 \rangle_{\mathcal{L}_s^x} = \frac{\int_\infty \mathcal{L}_s^x(\Delta x) \Delta x^2 d\Delta x}{\int_\infty \mathcal{L}_s^x(\Delta x) d\Delta x} \quad (6)$$

$$= \frac{\int_\infty \int_\infty \rho_{xp}(x) \rho_{xe}(x - \Delta x) dx \Delta x^2 d\Delta x}{\int_\infty \rho_{yp}(y) \rho_{ye}(y) dy}$$

$$= \int_\infty \int_\infty \rho_{xp}(x) \rho_{xe}(\tilde{x})(x - \tilde{x})^2 dx d\tilde{x}$$

$$= \langle x_1^2 \rangle + \langle x_2^2 \rangle ,$$

where equation 3 and $\langle x \rangle = 0$ for a centered beam has been used. It is important to note that no special bunch profile but only product distributions for the two beams were assumed to find

$$\Sigma_x = \frac{\int\limits_\infty \mathcal{L}_s^x(\Delta x)\Delta x^2 d\Delta x}{\int\limits_\infty \mathcal{L}_s^x(\Delta x)d\Delta x} ,\tag{7}$$

and equivalently for the y–direction. If the individual density distributions are Gaussian, the luminosity scan curves of equation (5) produced by method a) and c) agree. An additional agreement with the curve of b) is given when the density can be written as a product distribution, so that there is no correlation in x and y.

Methods (a) and (b) are restricted to data that can be fitted well by a bell curve. Method (c) does not have this restriction. On the other hand, the first two methods have the advantage that they can be evaluated even when the data points of the luminosity scan are too sparse to allow for an accurate evaluation of the integrals in equation (7). The most accurate method (c) requires many data points, even at large scan amplitudes Δx and Δy.

2   THE BEAM–BEAM FORCE

For HERA we have to consider two effects of the beam–beam force on the luminosity scan. Firstly the beam–beam kick leads to a displacement of the lepton beam from the proton beam that adds to the displacement that is produced by the symmetric bump during the scan. The orbit of the 920GeV protons, on the other hand, is hardly affected. Secondly the strength of the beam–beam lens changes during the luminosity scan. This leads to a changing beta function and therefore a changing lepton beam size during the luminosity scan.

The kick on an e^+ or e^- passing the proton beam in the distance (x, y) from its center is given by $\Delta \vec{r}' = -C_{bb}\partial_{\vec{r}} U(x, y)$ with $C_{bb} = \frac{q_p}{q_e}\frac{n_p r_{ce}}{\gamma_e}$, $r_{ce} = 2.8$ fm being the classical electron radius and γ_e being the positrons' relativistic factor. The number of protons in the colliding bunch is given by n_p. The beam–beam potential $U(x, y)$ is given by [5, 6]

$$U(x, y) = 2\pi \int\limits_0^\infty G^{\sqrt{\sigma_{px}^2 + t}}(x) G^{\sqrt{\sigma_{py}^2 + t}}(y)dt ,\tag{8}$$

using the Gaussian $G^\sigma(x)$ with standard deviation σ.

For the tunes Q_x^e, Q_y^e and the beta functions β_x^e, β_y^e at the interaction point of the electron ring without beam–beam force, this leads to an additional orbit shift of $\delta x = \frac{\beta_x^e}{2\tan(\pi Q_x^e)}\Delta x'$. When the symmetric bump separates the beams by the amount Δx_0, the actual distance Δx between the beams is thus given by the implicit solution of

$$\Delta x = \Delta x_0 + \delta x = \Delta x_0 - \frac{\beta_x^e}{2\tan(\pi Q_x^e)}C_{bb}\partial_{\vec{r}} U(\Delta x, 0) .\tag{9}$$

The luminosity scan therefore should not be interpreted as a function of Δx_0 but as a function of the implicit solution Δx in order to eliminate the effect of the beam–beam kick.

Additionally one can take account of the beam–beam lens and its disturbance of the beta function. This leads to a focusing error at the interaction point which is characterized by $\delta k_x = -C_{bb}\partial_x^2 U(x, y)$ and $\delta k_y = -C_{bb}\partial_y^2 U(x, y)$. The required first and second derivatives of the beam–beam potential $U(x, y)$ can all be expressed by products of Gaussians and error functions, so that evaluating $\delta k_{x/y}$ and finding a self consistent solution Δx of equation (9) numerically is straightforward and does not require additional approximations. Figure 1 describes the kick effect and the change of the beta function during the luminosity scan in HERA's phase-2 with design currents.
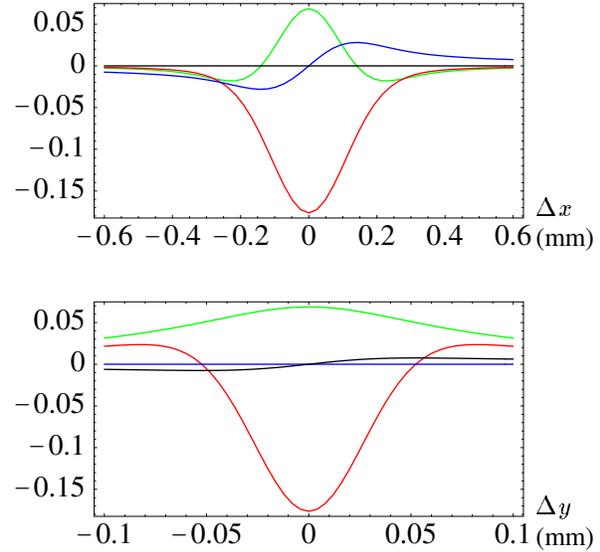

Figure 1: Perturbations due to the beam–beam effect during a luminosity scan in HERA's phase 2. In each figure the central curves describe the beam–beam displacements δx (blue) and δy (black) in mm. The lowest (red) and the highest (green) curves describe the relative change $\delta\beta_y^e/\beta_y^e$ and $\delta\beta_x^e/\beta_x^e$ of the beta functions respectively.

3   LUMINOSITY SCANS

A luminosity scan in x and y direction performed at the collider experiment H1 before the luminosity upgrade (phase 1) is displayed in figure 2 (top). Only after the beam–beam kick and the beam–beam focusing is taken into account, the methods a) and b) lead to somewhat similar curves in figure 2 (bottom). The fact that the two methods do not lead to more similar curves shows that the beam density can not be a product distribution in x and y. This indicates a coupling of the motion in the transverse planes and therefore decoupling and vertical dispersion correction was performed. In the subsequently performed luminosity scan all three evaluation procedures a), b) and c) lead to

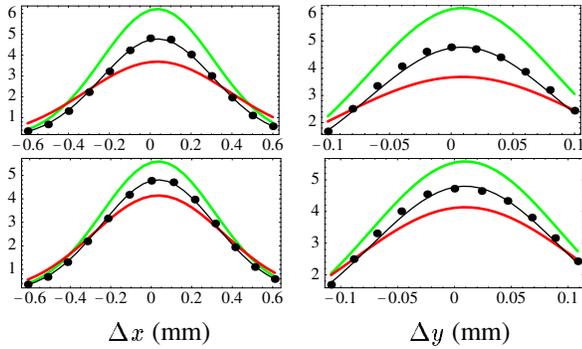very similar curves in figure 3.

Figure 2: The luminosity scan at H1 for the $72°$ test optics before the upgrade. Left: horizontal. Right: vertical. The curves show the luminosity data (dots) and a Gaussian fit (black) together with the luminosity (green, upper curve) expected by method a) and the luminosity (red, lower curve) expected by method (b) from the area under the fit. Top: before, Bottom: after taking into account the beam–beam kick and the beam–beam focusing.
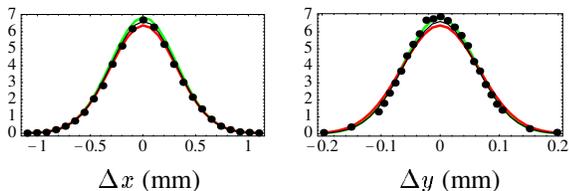

Figure 3: Luminosity scan at H1 after coupling correction. Left: horizontal. Right: vertical. The color code is as in figure 2.

During the ongoing commissioning procedure of HERA's phase 2 similar luminosity scans were performed. Figure 4 shows that a specific luminosity of $1.65 \cdot 10^{30} \mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{mA}^{-2}$ had been reached, which only slightly falls short of the design value of $1.82 \cdot 10^{30}$. Since no luminosity monitors were operational at the beginning of the commissioning, luminosity scans provided the only luminosity measurement at HERA.

The HERA proton beam size $\langle x_p^2 \rangle$ is obtained by fitting a Gaussian to wire scanner data. Together with the luminosity scan, the e^+ beam sizes were then determined. Figure 4 corresponds to $\epsilon_x = 21\mathrm{nm}$, which is very close to the design value of $20\mathrm{nm}$, and to an emittance coupling of 35%. A reduction of the emittance coupling would therefore have increased the specific luminosity to the design value. The presented evaluations therefore clearly distinguish between "local coupling" with a corellation in $x-y$ space as in figure 2 and "global coupling" with vertical emittance production as in figure 4.

4 CONCLUSION

Three methods of evaluating luminosity scans were presented, one of which does not rely on Gaussian beam pro-
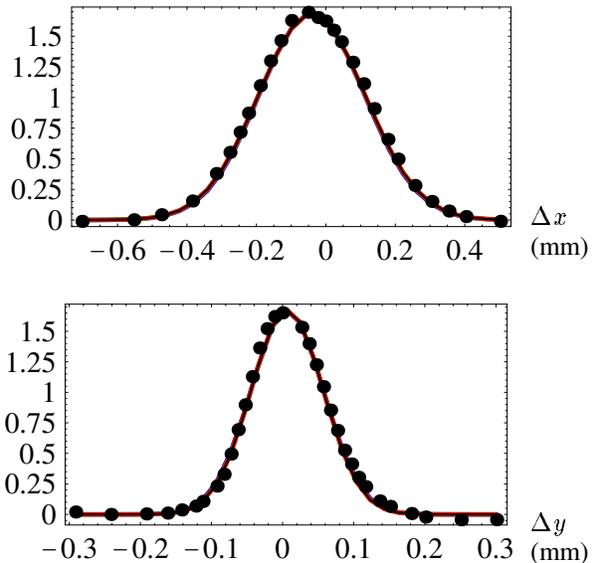

Figure 4: Luminosity scan at ZEUS after the upgrade. Left: horizontal. Right: vertical. The luminosity data (dots) and a bell curve agrees well with the luminosity expected by method a), b) and c).

files. Since the results of the three methods only agree when the density splits in a product of two transverse densities, a comparison of the three measurements gives a clear indication of phase space coupling. Luminosity scans have thus been used to verify decoupled accelerator adjustments at HERA, and it was used to verify that the design specific luminosity of HERA's phase 2 has nearly been reached.

5 REFERENCES

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