DIRECT OBSERVATION OF BEAM–BEAM INDUCED DYNAMICAL BETA BEATING AT HERA

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Abstract

The Hadron Electron Ring Anlage HERA at DESY provides collisions between a 920 GeV proton beam and a 27.5 GeV electron beam in two interaction regions. The strong beam–beam force which mainly affects the electrons induces a tune shift together with a dynamical beta beat. The latter leads to a modification of the transverse beam profile which can be observed in different profile monitors in HERA. The time–like evolution of the electron beam shape during luminosity tuning and before and after dump of the proton beam, averaged over all bunches, can be studied by means of a synchrotron radiation profile monitor. Measurements with a wire scanner allow to see the beam–beam force's influence on each individual bunch at the expense of resolution. The observations can be explained qualitatively in the frame of linear incoherent beam–beam interaction.

Table 1: Beam parameters typically used in HERA 2005 luminosity operation at the beginning of a luminosity run. N_b is the total number of particles per bunch, β_x^* and β_y^* are the horizontal resp. vertical beta functions at the IPs, and σ_x resp. σ_y are the horizontal and vertical beam sizes at the IPs without collision. The beam–beam tune parameter ξ as calculated from these values is listed in addition.

Parameter	Electron beam (e)	Proton beam (p)
Energy (GeV)	27.5	920
N_b	3.4×10^{10}	8.4×10^{10}
β_x^*/β_y^* (m)	0.63 / 0.26	2.45 / 0.18
σ_x/σ_y (μm)	112 / 30	109 / 28
ξ_x/ξ_y ($\times 10^{-4}$)	295 / 471	13 / 3.7

INTRODUCTION

The ensemble of charges inside a particle bunch produces a strong electromagnetic field involving an additional nonlinear force in beam–beam collisions at the interaction point (IP) of a particle collider. Depending on the charge of the counter–rotating beams this force is either focusing (opposite charge) or defocusing (same charge). The beam–beam interaction distorts the optical parameters in the ring and the resulting beat of the betatron function can be observed as a change in the transverse beam size.

At HERA a 920 GeV proton beam is brought into collision with a 27.5 GeV polarized electron or positron beam at two IPs for the high energy physics experiments ZEUS and H1. Since all data that will be shown has been obtained with electrons we only refer to them in the following. Table 1 lists beam parameters typically used for luminosity operation in the run period 2005 together with the beam–beam parameter ξ as calculated from these values. ξ is a measure for the strength of the beam–beam interaction which for small values and a tune far away from linear resonances is equal to the linear incoherent tune shift. From Tab. 1 it follows that the beam–beam parameter is rather asymmetric for both beams, i.e. the electron beam experiences a strong beam–beam interaction (large ξ) while the proton beam is nearly unaffected. The focal strength of the "beam–beam proton lens" (BBPL) acting on the electron beam in vertical direction even exceeds the one of a superconducting HERA mini–β quadrupole by about a factor of 5. As consequence the optical parameters of the electron beam are strongly distorted and the resulting beta beat can be observed as change in the transverse beam size in all profile monitors, c.f. Fig.1. The influence is clearly visible if the BBPL is switched off (i.e. the proton beam is dumped) or the beam–beam force is varied in time which is the case during luminosity tuning when the relative position between both beams at the IP is modified.

In the subsequent section a brief overview of the HERA electron profile monitors will be given before examples for direct observations of beam–beam induced dynamical beta beating will be shown.

HERA PROFILE MONITORS

In Fig.1 the positions of different profile monitors in the electron ring are shown together with the location of the high energy physics experiments. The luminosity systems of both colliding beam experiments ZEUS and H1 offer the

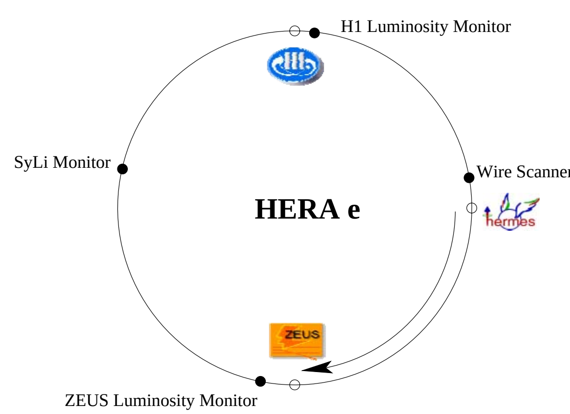


Figure 1: Location of profile monitors in the HERA electron ring together with the high energy physics experiments ZEUS, H1 and HERMES.

possibility to observe the time–like evolution of the electron beam shape at the IP under collisions. For this purpose the photon detectors of the luminosity systems measure spatially resolved the rate of photons from the Bethe–Heitler process $ep \rightarrow e'\gamma p$. While H1 is using a Cherenkov sampling calorimeter, ZEUS is using two independent detectors: a Pb–scintillating sandwich calorimeter and a photon spectrometer with reduced possibility of pile–up. Details about the luminosity systems can be found in Refs. [1, 2].

For permanent observation of the electron beam in each machine state from injection up to luminosity operation a synchrotron radiation (SyLi) profile monitor is installed which utilizes optical synchrotron radiation from the center of a bending magnet in the arc of HERA. The SyLi monitor delivers information about the time–like evolution of the beam profile, averaged over all bunches. The setup of this monitor is described in detail in Refs. [3, 4].

Two CERN–type wire scanners for measuring the horizontal and vertical beam profiles for each individual bunch are installed in HERA [5, 6] in a straight section close to the HERMES experiment where the dispersion in both planes is negligible. With scanner measurements time–like evolutions cannot be studied and their exertion is limited to low electron currents in order to avoid damage of the wire due to heat load.

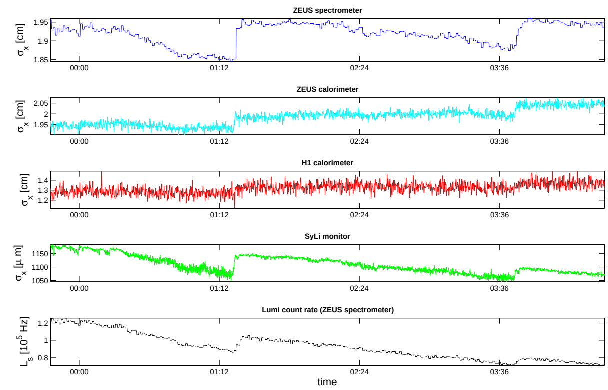
OBSERVATIONS OF BETA BEATING

In the following examples for the observation of dynamical beta beating are shown as they were typical for the HERA run period 2005.

In Fig.2 online data of the time evolution for the horizontal and vertical beam profile are plotted which were measured simultaneously with the ZEUS calorimeter, ZEUS spectrometer, H1 luminosity monitor, and SyLi monitor in a time interval of about 4 hours. As can be seen from this figure the beam profiles in both planes show strong variations as function of time. These variations are directly correlated with the variation in the luminosity count rate measured simultaneously which is shown for the ZEUS spectrometer in addition. This direct correlation between sudden increase in luminosity and variation of the beam size in the whole ring reflects the strong influence of the beam–beam force onto the electron beam. In order to increase the luminosity in the experiments the relative beam position of both colliding beams at the IP was changed with respect to each other. A change in the relative beam position results in a change of the BBPL's focusing properties onto the electron beam. The consequence is a sudden modification of the beta function which can be observed as variation in the transverse beam profile.

In order to achieve a qualitative statement about the beam–beam force's strength a situation is desirable where its influence can be turned off immediately. Such a measurement can be performed with the SyLi monitor at the end of a HERA luminosity run when the proton beam is

horizontal beam spot:



vertical beam spot:

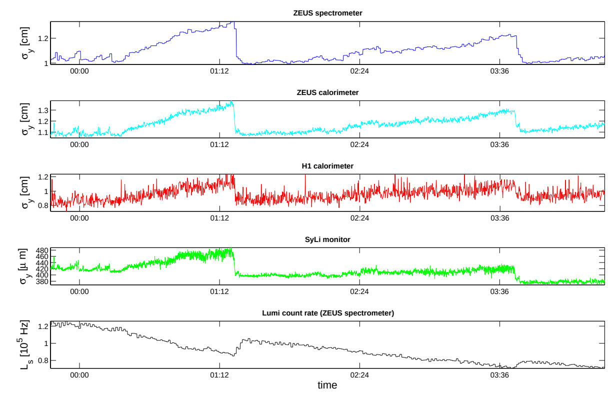


Figure 2: Online raw data of the horizontal and vertical beam shape as function of time, measured with different profile monitors in the HERA electron ring. The monitors in use are (from top to bottom): ZEUS spectrometer, ZEUS calorimeter, H1 calorimeter, and SyLi monitor. At the bottom of each figure the luminosity count rate measured simultaneously with the ZEUS spectrometer is shown.

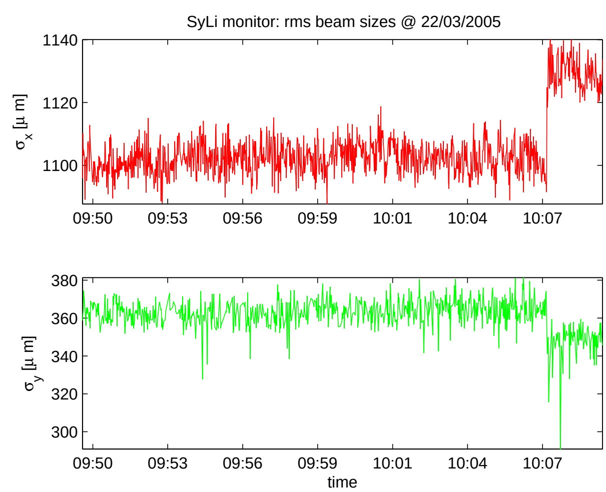


Figure 3: Time–like evolution of the electron beam profile during dump of the proton beam at 10:07, measured with the SyLi monitor.

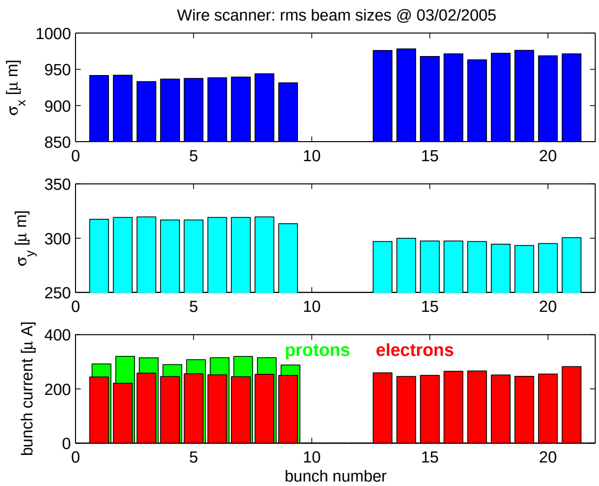


Figure 4: Bunch–resolved wire scanner profile measurements. From top to bottom: horizontal electron beam profile, vertical electron beam profile, electron and proton bunch currents.

dumped and the electron beam is still kept in the machine. In Fig.3 the result of such a measurement is plotted. From the determination of the beam sizes before and after the dump it is possible to extract a value for the beam–beam induced beta beat. The relation between change in beta functions $\Delta\beta = \beta_0 - \beta_{bb}$ and measured beam sizes σ is given by

$$\Delta\beta = \frac{\sigma_0^2 - \sigma_{bb}^2}{\varepsilon}$$

with ε the electron beam emittance and the index $0, bb$ indicates the undisturbed beam size (after dump) and the beam size with beam–beam force (before dump). With the nominal emittances ε_x = 20 $\pi\,\mathrm{nm\,rad}$, ε_y = 3.4 $\pi\,\mathrm{nm\,rad}$, and the data shown in Fig.3 a beam–beam induced beta beat of $\Delta\beta_x$ = (3.01 $\pm$ 0.07) m in horizontal and $\Delta\beta_y$ = -(3.57 $\pm$ 0.23) m in vertical plane is derived.

In the following these values will be compared to calculated ones based on the assumption of a linear incoherent beam–beam force. The assumption of a linear force is a strong simplification and indeed it was shown that the resulting beta beat is reduced by a factor of about 2 if a totally nonlinear beam–beam force is taken into account. Nevertheless for a rough estimation the linear ansatz is sufficient, the nonlinear model which is based on the calculation of the distorted emittance in the frame of canonical perturbation theory [7] is out of scope of this article and will be published elsewhere.

For the proton/electron beam parameters of the experiment shown in Fig.3 the beta beat at the location of the SyLi monitor is expected to be $\Delta\beta_x^{calc}$ = 3.55 m and $\Delta\beta_y^{calc}$ = -1.66 m. While in horizontal plane there is a fair agreement between measurement and beta beat calculation, the difference in vertical direction is a factor of about 2.

In order to study the influence of beam–beam induced beta beating with single bunch resolution a test experiment was performed with the wire scanner whose results are shown in Fig.4. In this experiment the first of two electron bunch trains, each containing 9 single bunches, was brought into collision with 9 proton bunches. The fill pattern can be seen in the bottom of Fig.4. In top and middle of this figure the measured electron beam profiles are shown for each individual bunch. As can be seen the horizontal beam size of the colliding bunches is smaller than the one of the non–colliding bunches, while for the vertical beam profile the situation is just opposite.

The simplified linear calculation of the beta beat at the position of the wire scanners shows indeed that the horizontal beta function decreases under the influence of the beam–beam force ($\Delta\beta_x^{calc}$ = 0.47 m) which results in a smaller horizontal beam size of colliding bunches, while the vertical beta function increases ($\Delta\beta_y^{calc}$ = -0.77 m) which leads to a larger beam size. However, the discrepancy between calculated beta beat and measured averaged change in the beta function of $\Delta\beta_x$ = (3.19 $\pm$ 0.20) m and $\Delta\beta_y$ = -(3.82 $\pm$ 0.19) m is larger than in the case of the SyLi monitor observations.

SUMMARY

The present article summarizes observations of the beam–beam induced dynamical beta beating at the HERA electron ring. It is shown that the strong beam–beam force acting on the electrons leads to a change of the transverse profile which easily can be observed with different profile monitors. Measurements performed with the SyLi monitor and wire scanners show a qualitative agreement with the assumption of linear incoherent beam–beam interaction. Furthermore it is pointed out that the SyLi monitor is a versatile tool to study the dynamics in beam–beam interactions, i.e. the time–like evolution of the beam profile if both beams are brought into collision or if the strong (proton) beam is dumped.

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