Measurement by tune coupling of the overlap of colliding bunches in HERA

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INTRODUCTION

In colliders using a single storage ring, particles and antiparticles travel in opposite directions on a common orbital path, so that head-on collisions at the interaction regions (IRs) are not difficult to arrange. For HERA, electrons and protons are stored in separate rings so that the beams must be actively steered into collision at the IRs. One means of measuring the collision alignment is to 'shake' one beam and observe the response of the other beam due to the modulation of the beam-beam kicks at the IRs. This is well suited to a two ring collider since the betatron tunes of the two beams may be independently controlled and measured; the method was used by Piwinski to monitor the collisions of electrons and positrons in the original two ring version of DORIS [1]. We here report on initial measurements of electron-proton collisions in HERA, made by exciting the electron beam at its horizontal betatron frequency and observing the response of the proton beam.

PRINCIPLE OF THE MEASUREMENT

The effect of the beam-beam kicks may be estimated from the the linear beam-beam tune shift for the protons, δq_p. A single kick from a collision with an electron bunch displaced by Δx_e at the IR would result in a free oscillation of the proton bunch with magnitude at the IR $x_p=4\pi\delta q_p\Delta x_e$. The proton bunch will respond resonantly to successive kicks from the electron bunch; if the electron frequency does not overlap with the distribution of proton tunes this response will be proportional to the inverse of the difference between the fractional electron and proton tunes, $x_p \sim \delta q_p x_e/(q_p-q_e)$. For $dq_p=0.0015$ and $(q_p-q_e)= 0.02$, as during our tests, this gives for bunches colliding head-on a proton oscillation amplitude at the IR about 10% that of the electrons.

The response for bunches not colliding head-on depends on the derivative with respect to displacement of the beam-beam force. For Gaussian beams, not necessarily of equal size, the result can be expressed in terms of the variables $X=x/\Sigma_X$ and $Z=z/\Sigma_Z$, with $\Sigma_X=(\sigma_{X1}^2+\sigma_{X2}^2)^{1/2}$ and $\Sigma_Z=(\sigma_{Z1}^2+\sigma_{Z2}^2)^{1/2}$ [2]. We have calculated the response for horizontal to vertical aspect ratios of 5:1 and 1:1. Figure 1 shows the horizontal beam-beam force vs. horizontal displacement and the magnitude of the induced oscillation (in arbitrary units). The response goes to zero (and changes sign) at $X\approx\pm1.4$; the response for the 1:1 aspect ratio (not shown) is practically identical. Fig. 2 shows the induced horizontal oscillation as a function of vertical position, for horizontally centered beams and for beams horizontally off center at X=1. This corresponds to the horizontal response measured during a vertical scan of the beams. Fig. 3 compares the vertical scans for beams at X=0 with 5:1 and 1:1 aspect ratios; the width of the response curve is strongly dependent on the horizontal beam size.

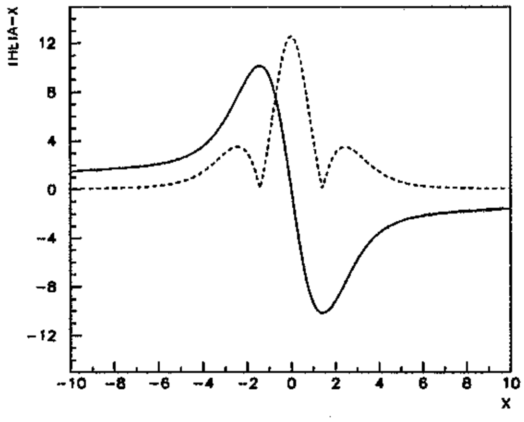

Fig. 1: Horizontal beam-beam force (solid line) and signal strength (dotted line) as a function of horizontal position for 5:1 horizontal to vertical aspect ratio.

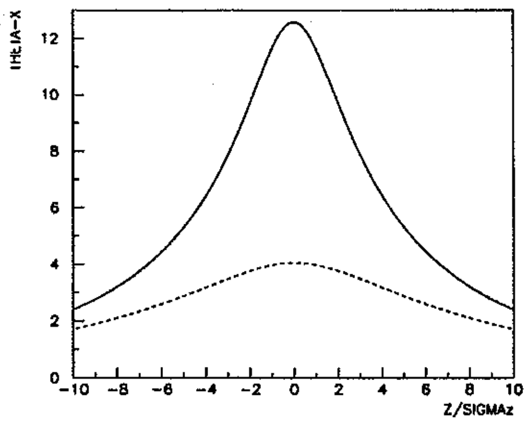

Fig. 2: Horizontal signal strength vs. vertical displacement for horizontal offsets of X=0 (solid) and X=1 (dotted), for 5:1 horizontal to vertical aspect ratio

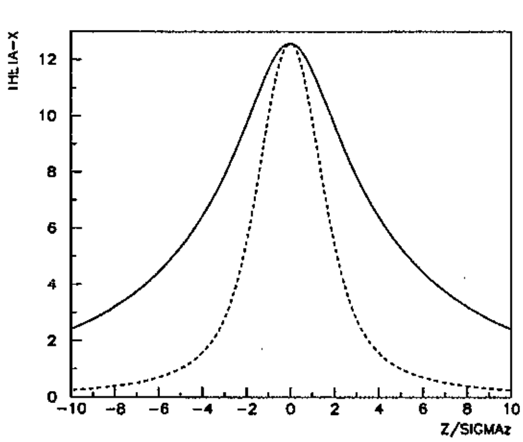

Fig. 3: Horizontal signal during vertical scan for beams with H:V aspect ratios 5:1 (solid) and 1:1 (dotted)

APPARATUS

The apparatus used is shown in figure 4. The electron bunch was driven at its horizontal betatron frequency by a tune controller system based on a phase-locked loop which couples the kicker frequency to the response from a betatron tune pick-up [3] . The kicker frequency signal was also used as the reference signal for a dual-phase lock-in amplifier detecting the horizontal tune signal from the proton bunch. The proton tune signal came from an 8.3 MHz resonant pick-up [4] similar to the 10.7 MHz 'Schottky' monitors used in the CERN SPS collider [5] . The estimated sensitivity of the pick-up is 5 W/mm, and the electronic noise level, referred to the input, about 3 nv/(Hz)$^{1/2}$. For the typical proton bunch current of 100 μA during the tests this gives already good sensitivity for sub-micron bunch oscillations.

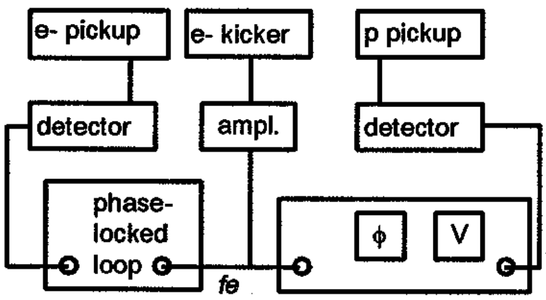

Fig. 4: Simplified schematic of the apparatus. *fe* is the electron betatron tune frequency.

MEASUREMENTS

Figures 5 and 6 show responses measured during horizontal and vertical scans of the beams. The measurements were made with a single proton bunch (40 μA at 480 GeV) and single electron bunch (300 μA at 26.7 GeV). The horizontal fractional tunes were q_p=0.264 and q_e=0.241 . The beams were kept well separated at the South IR and closed orbit bumps were used to move the one beam across the other at the North IR. The electron oscillation amplitude during the tests is not known but is estimated to have been 10-20 μm at the IR. For the vertical scan we have used the correction magnet kick strengths, the design optics, and beam emittances typical for this running period to fit the data to a curve for the expected aspect ratio 3.7:1, with beams horizontally centered. We do not have sufficient information to fit the data for the horizontal scan of fig. 6. The expected features were clearly observed, including a 180° shift in the phase of the signal in the secondary maxima. We also observed a large reduction in the proton lifetime near the peaks of the secondary maxima.

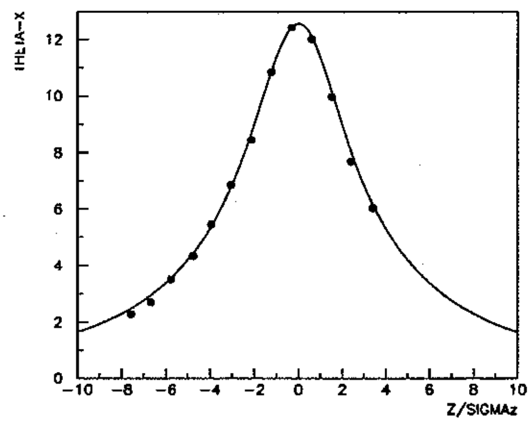

Fig. 5: Measured signal strength for vertical scan. The curve is calculated for an aspect ratio of 3.7:1

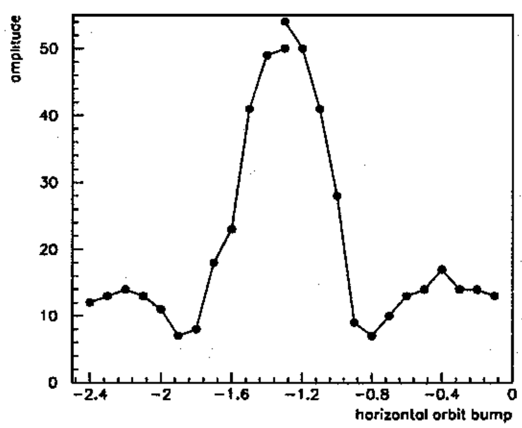

Fig. 6: Signal measured during horizontal scan; the horizontal scale is arbitrary. The solid line connects the measured points.

Future Use at HERA

We intend to use this system for monitoring collisions during luminosity runs in HERA; because of the fast response it is especially suited to the machine commissioning period, when the luminosity, and the rates in the luminosity monitors, are still orders of magnitude below the design values. There are several complications:

1) When beams are colliding at two IRs, the signal will be the result of the vector sum of the kicks at the two IRs. This suggests that at the beginning of a luminosity run the beams should be well separated at both IRs, and scans then made with closed orbit bumps at each IR with the beams separated at the other IR. In fact, to the extent that the bumps are truly closed, the vector change in the signal will be independent of the alignment at the other IR, so that it may be sufficient to bring the beams sequentially into collision.

2) For the initial collision of the beams, the effects on proton bunch emittance or lifetime of 'near-miss' collisions during a scan may be a problem. Observations during the initial luminosity runs of HERA were mixed, with little effect noticed during vertical scans, and with large decreases in proton lifetime observed during several horizontal scans. One possibility is to quickly bring the beams to their nominal collision state, trusting the stability of the machine over several hours, and then to make a scan about this approximately correct position.

3) Results from the first luminosity runs in HERA suggested that the collisions were reasonably stable over a period of several hours so that occasional scans to check the alignment may be sufficient. One may also imagine for a less stable machine that the beam positions could be continuously 'wobbled' , if necessary using closed bumps with different frequencies at the different IRs. For centered beams, only the even harmonics of the wobble frequency will be present.

4) Excitation of the proton bunch could lead to emittance growth. To the extent that the oscillation amplitude of the proton bunch remains in the sub-micron range and the measurements are made only occasionally, this should not be a problem.

5) Studies of the effect of ground motion on collisions in HERA predict that the beams may wobble against each other by roughly 0.1σ in both planes [6]. By using a strong signal and a sufficiently short integration time for the lock-in amplifier it should be possible to observe fluctuations in the <25 Hz range for which the ground motion effects should be important. Sensitivity should be improved by moving the collisions about 1σ off center .

6) The tests were performed with single colliding bunches. Multibunch operation raises several points: first, multibunch electron operation will require rather strong transverse feedback, so that the electron kicker system must be accomodated to the feedback electronics. Second, the signal from the proton tune monitor sums over all proton bunches, so that sensitivity may be lost in detecting the tune coupling signal from a single bunch during a 200 bunch fill. On the one hand, this may not matter, since emittance growth of a single proton bunch is not important for the luminosity and excitation may be increased as required. On the other hand, if all electron (and proton) bunches were excited, the excitation per bunch required for a fixed output signal strength could be drastically reduced. This would require excitation of the electrons in the 8.3 MHz multibunch mode detected by the proton tune monitor.

Acknowledgements

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