UNBUNCHED BEAM CLEANING IN HERA-P

C. Montag, J. Klute, DESY, Hamburg, Germany

Abstract

During luminosity operation of the HERA e-p collider, protons can be stored for more than 24 hours. Unpleasant proton backgrounds develop during long fills which have been traced to beam coasting outside the RF bucket. This causes a large problem for the data acquisition of the internal-wire target experiment HERA-B. We will discuss the origin of coasting beam and various cures. The most successful method is to excite coasting beam particles near the vertical betatron tune using a broadband kicker which fires in the dump gap of the proton bunch train.

1 INTRODUCTION

Since summer 1997 the internal-wire target experiment HERA-B [1] suffers from coasting beam due to the non-zero horizontal dispersion at the target. In some cases the interaction rate is completely dominated by unbunched particles, thus severly affecting the data taking efficiency. Though some production mechanisms of coasting beam could be identified, it was nevertheless not possible to eliminate this effect. Due to lack of a momentum cleaning scheme in HERA-p unbunched protons accumulate to a few mA during a typical luminosity run of more than 12 hours duration. Therefore a method of resonantly exciting the coasting beam particles by firing a fast transverse kicker within the dump kicker gap of the HERA-p bunch pattern has been developed.

2 POSSIBLE SOURCES OF COASTING BEAM

The unbunched beam contribution is determined by measuring the total beam current and the bunched beam current. The coasting beam contribution is therefore just the difference between these two measurements,

$$I_{\text{coasting beam}} = I_{\text{total}} - I_{\text{bunched}}. \quad (1)$$

As usual, the total beam current is measured with a DC current transformer (DCCT), while the bunch current is determined by integrating the current over a time range of $\pm 15\,\text{nsec}$ around the nominal bunch centers positions only [2].

Since some possible sources for coasting beam, such as intrabeam scattering or rf noise, also lead to bunch lengthening, the evolution of the bunch length has been observed during normal luminosity operation. Figure 1 shows the FWHM proton bunch length during a long luminosity run of about $22\,\text{h}$.

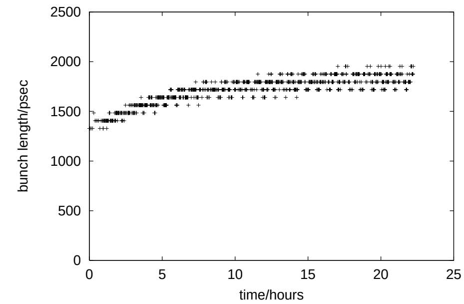

Figure 1: Measured FWHM bunchlength during a typical HERA run.

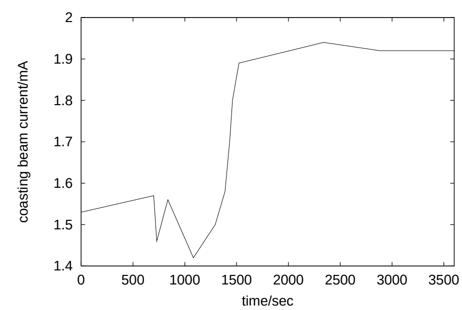

Figure 2: Measured coasting beam current when the HERA-B wire target is inserted (at about $1200\,\text{sec}$). The coasting beam contribution increases in a steplike manner just when the wire target reaches the beam.

2.1 *Energy loss at the target wire*

When the transverse oscillation amplitude of a proton is sufficient to reach the wire, the particle will lose some amount of its energy by inelastic scattering in the target material. This process continues until finally a deep inelastic scattering event occurs, or the proton gets lost at the collimators. Therefore the HERA-B wire target itself is a possible source of coasting beam. Figure 2 shows the coasting beam contribution when the wire target is inserted.

2.2 *Touschek scattering*

The Touschek lifetime τ_{Touschek} of a proton beam with N_b protons per bunch can be calculated as [3]

$$\frac{1}{\tau_{\text{Touschek}}} = \frac{r_p^2 c N_b}{8\pi\sigma_x\sigma_y\sigma_z \left(\frac{\Delta p}{p}\right)^3 \gamma^2} D(\epsilon), \quad (2)$$

with

$$\epsilon = \left(\frac{\Delta p/p}{\gamma\sqrt{\epsilon/\beta_y}}\right)^2. \tag{3}$$

σ_x, σ_y, and σ_z are the rms bunch width, height and length, respectively, while $\Delta p/p$ denotes the momentum acceptance of the accelerator. The classical proton radius is denoted by r_p, and c is the velocity of light.
With $\epsilon = 0.006$, $D(\epsilon) = 0.2$, $\gamma = 980$ for a $920\,\mathrm{GeV}$ proton beam, an average β-function of $\beta_y = 32\,\mathrm{m}$ and an RF acceptance of $\Delta p/p = 8 \cdot 10^{-4}$ we get for $\sigma_x = \sigma_y = 430\,\mu\mathrm{m}$, $\sigma_z = 0.3\,\mathrm{m}$ and a bunch population of $N_b = 7.3 \cdot 10^{10}$ for a $100\,\mathrm{mA}$ proton beam a Touschek lifetime

$$\tau_{\mathrm{Touschek}} = 1 \cdot 10^9\,\mathrm{sec} \approx 33\,\mathrm{years}. \tag{4}$$

This Touschek lifetime corresponds to a fraction of $4 \cdot 10^{-5}$ of the proton bunch current being lost from the RF bucket after a typical luminosity run duration of $12\,\mathrm{hours}$, which is approximately two orders of magnitude smaller than what is observed.

2.3 Intrabeam scattering

The growth time τ_p of the momentum spread within a bunch due to intrabeam scattering can be calculated as [4, 5]

$$\frac{1}{\tau_p} = \langle A\frac{\sigma_h^2}{\sigma_p^2}f(a,b,q)\rangle, \tag{5}$$

with

$$A = \frac{r_p^2 c N_b}{64\pi^2\gamma^4\epsilon_x\epsilon_y\sigma_s\sigma_p}, \tag{6}$$

$$\frac{1}{\sigma_h^2} = \frac{1}{\sigma_p^2} + \frac{D_x^2}{\sigma_{x_\beta}^2} + \frac{D_y^2}{\sigma_{y_\beta}^2}, \tag{7}$$

$$f(a,b,q) = 8\pi\int_0^1 \left(2\ln\left(\frac{q}{2}\left(\frac{1}{P}+\frac{1}{Q}\right)\right) -0.577\ldots\right)\frac{1-3u^2}{PQ}\,\mathrm{d}u, \tag{8}$$

$$a = \frac{\sigma_h\beta_x}{\gamma\sigma_{x_\beta}}, \tag{9}$$

$$b = \frac{\sigma_h\beta_y}{\gamma\sigma_{y_\beta}}, \tag{10}$$

$$q = \sigma_h\sqrt{\frac{2d}{r_p}}, \tag{11}$$

$$d = \min(\sigma_x,\sigma_y), \tag{12}$$

$$P^2 = a^2 + (1-a^2)u^2, \tag{13}$$

$$Q^2 = b^2 + (1-b^2)u^2. \tag{14}$$

Here r_p denotes the classical proton radius, c the velocity of light, N_b the number of protons per bunch, and $\beta_{x,y}$, $D_{x,y}$ the horizontal and vertical β-function and dispersion, respectively. $\sigma_{x_\beta} = \sqrt{\epsilon_x/\beta_x}$, $\sigma_{y_\beta} = \sqrt{\epsilon_y/\beta_y}$, and σ_s are the transverse and longitudinal bunch dimensions, while σ_p denotes the rms momentum spread.
Using the HERA parameters, we get

$$\tau_p = 7.0 \cdot 10^5\,\mathrm{sec}. \tag{15}$$

During a typical run duration of $12\,\mathrm{h}$, the initial FWHM bunch length of $20\,\mathrm{cm}$ growth to $23\,\mathrm{cm}$, which is about 50 percent of the measured bunch lengthening. Furthermore, this is an upper limit since the growth time τ_p increases with increasing bunch dimensions.

2.4 RF noise

The growth rate of the longitudinal emittance $\epsilon_s = \sigma_E\sigma_\Phi/\omega_{\mathrm{rf}}$ due to rf amplitude noise with an rms voltage V_{rms} can be calculated as [6]

$$\frac{\mathrm{d}\epsilon_s}{\mathrm{d}t} = \frac{1}{2}\frac{E_0}{\omega_{\mathrm{rf}}}f_0\sqrt{\frac{2\pi h\eta E_0}{eV_{\mathrm{rf}}}}\left(\frac{eV_{\mathrm{rms}}}{E_0}\right)^2, \tag{16}$$

while for a rf phase noise $\delta\Phi_{\mathrm{rms}}$ the corresponding expression reads [6]

$$\frac{\mathrm{d}\epsilon_s}{\mathrm{d}t} = \frac{1}{2}\frac{E_0}{\omega_{\mathrm{rf}}}f_0\sqrt{\frac{eV_{\mathrm{rf}}}{2\pi h\eta E_0}}\left(\delta\Phi_{\mathrm{rms}}\right)^2. \tag{17}$$

E_0, f_0, ω_{rf}, V_{rf}, and h denote the nominal particle energy, the revolution frequency, the rf frequency, the rf voltage, and the harmonic number.
Taking the measured bunch lengthening mentioned above, this could be explained by rf noise of $V_{\mathrm{rms}} = 440\,\mathrm{V}$ or phase noise of $\delta\Phi_{\mathrm{rms}} = 3.6 \cdot 10^{-6}$, respectively.

3 COASTING BEAM CLEANING BY RESONANT KICKS

For an efficient momentum cleaning, the ratio $|D_x|/\sqrt{\beta_x}$ at such a momentum collimator has to be maximized. Since a large number of boundary conditions have to be acknowledged in the HERA-p collimator section, there is practically no flexibility to improve this ratio at the installed collimators. As table 1 shows, this ratio has its maximum value just at the HERA-B wire target and the collimator WL 150. Since the target aperture has to be smaller than the collimator aperture, coasting beam particles are lost at the wire target rather than the collimator WL 150. Therefore a coasting beam cleaning concept by means of resonant dipole kicks has been developed.
Any particle lost from the rf-bucket will continuously lose energy due to synchrotron radiation, the energy loss per turn being about $9\,\mathrm{eV}$ for $920\,\mathrm{GeV}$ protons. Since HERA-p is operated above transition energy, coasting beam particles therefore drift in the forward direction with respect to the bunched beam. Using the momentum compaction factor

collimator	$\frac{|D_x|}{\sqrt{\beta_x}}/\,\mathrm{m}$
WR 94	0.0291
HERA-B target	0.0801
WL 19	0.0014
WL 105	0.0495
WL 150	0.0819

Table 1: $|D_x|/\sqrt{\beta_x}$ at the horizontal proton collimators and the HERA-B target, listed in the direction of the beam.

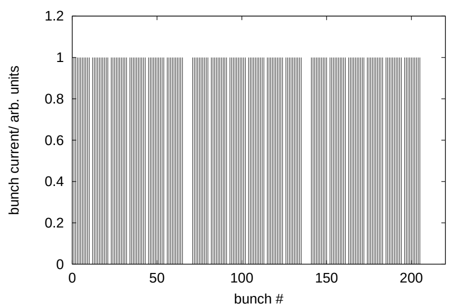

Figure 3: Proton bunch pattern, consisting of three bunch trains of 60 bunches each, with the dump kicker gap shown on the right.

$\alpha_p = 1.3{\cdot}10^{-3}$ and the bucket height of $\Delta p/p = 2{\cdot}10^{-4}$ as the minimum relative momentum deviation of the costing beam, the maximum time for a complete revolution with respect to the bunched beam is estimated to about $80\,\mathrm{sec}$ [7]. To remove the coasting beam, a fast vertical kicker belonging to the unused transverse feedback system is fired in the dump kicker gap (see fig. 3), thus exciting the coasting beam without disturbing the bunches. Since the betatron frequency of the coasting beam particles is spread over a small band due to different energies of the single particles in combination with the non-zero chromaticity, a noise signal with $50\,\mathrm{Hz}$ bandwidth is applied to this kicker in order to resonantly excite the unbunched protons.

Due to limited bandwidth of the power amplifier the primary signal of roughly $13.8\,\mathrm{kHz}$ is modulated with the bunch frequency of $10.4\,\mathrm{MHz}$. During their passage across the dump kicker gap, the unbunched protons drift over this modulated kicker signal, thus alternately receiving some 5000 excitation kicks, followed by the same number of kicks in the opposite direction leading to a cancellation of the excitation effect. Fortunately, due to the non-linearity of the HERA proton ring, a small emittance increase of the coasting beam still remains, finally leading to particle loss at the collimators.

As it has been observed, the reflected signal caused by an impedance mismatch between the amplifier and the kicker leads to an emittance increase of several bunches at the head of the bunch train. This effect could be minimized by adjusting the timing of the modulated signal such that

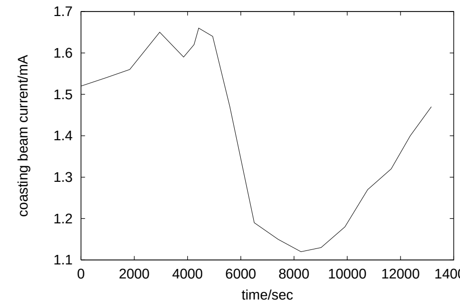

Figure 4: Measured coasting beam current when the kicker is switched on after several hours of running. The coasting beam contribution is reduced significantly. After switching off the kicker, the coasting beam current rises again.

these bunches are hit by the reflected signal just when it is close to zero [8].

Figure 4 shows the measured coasting beam current in the HERA proton ring when this coasting beam kicker is switched on after coasting beam has accumulated to about $1.65\,\mathrm{mA}$ during several hours of running. The unbunched proton current is significantly reduced to approximately $1.15\,\mathrm{mA}$ within about $2500\,\mathrm{sec.}$ It increases rapidly again after switching off the kicker.

4 CONCLUSION

Though some possible production mechanisms of coasting beam could be identified, it is nevertheless still unclear whether theere is a chance to eliminate the main source.

The coasting beam can be successfully removed by means of dipole kicks, but this requires careful tuning of the machine parameters. This situation could be improved by a specially designed kicker system which avoids modulation of the signal.

5 REFERENCES

[1] E. Hartouni et al., HERA-B Design Report, DESY-PRC-95-01, 1995

[2] R. Neumann, private communication

[3] J. LeDuff, Proc. CERN Acc. School, 1987

[4] A. Piwinski, Proc. 9th Int. Conf. on High Energy Acc. , Stanford (1974), p. 405

[5] A. Piwinski, Intrabeam Scattering, in: A. Chao, M. Tigner (eds.), Handbook of Accelerator Physics and Engineering, World Scientific, p. 126, 1999

[6] M. Syphers, Emittance Dilution Effects, in: A. Chao, M. Tigner (eds.), Handbook of Accelerator Physics and Engineering, World Scientific, p. 278, 1999

[7] C. Montag, First Results of HERA-B Machine Studies, in: G. Hoffstaetter (ed.), HERA Machine Studies 1998, DESY HERA 99-03, 1999

[8] C. Montag, Coasting Beam Studies, in: G. Hoffstaetter (ed.), HERA Machine Studies 1999, DESY HERA 00-02, 2000