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Intrabeam scattering and the coasting beam in the HERA proton ring

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Abstract

Undesired coasting beam of protons has been detected in the HERA proton ring in high energy storage operation. This mainly disturbs the operation of the HERA-B experiment, and can have some impact on H1 and ZEUS where it generates background spikes (depending also on the collimator settings). In this work we present a collection of data and facts, to be taken as starting point for further theoretical and experimental studies. We propose Intra Beam Scattering as a possible physical mechanism for creating the coasting beam and discuss the implications of this longitudinal dynamics model on observables such as the bunch length, energy spread, dc current and reaction rate at the HERA-B wires. The results seem to be in qualitative agreement with the measurements.

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1 Introduction

1.1 Coasting beam detection at the HERA-B wires

In HERA the stored protons circulate in bunches, captured in the stable bucket that is created by the double rf-system. After some time a certain fraction of the protons seem to escape from the stable bucket and circulate in a coasting way (non bunched). This coasting beam is seen at the outer wire of HERA-B.

If we scrape the coasting beam away by moving the wire towards the core of the beam and retracting it back by 2σ the reaction rate at the wire goes down abruptly. Then the reaction rate increases slowly until roughly 1 h later when the coasting beam reaches the wire again. This is seen as a plateau of the reaction rate at the wire (see Fig.11 in [1]).

This observation can be justified as follows. Once out of the rf-bucket the protons loose energy due to the synchrotron radiation losses. At 920 GeV the coasting beam particles loose 10 eV per turn. At the HERA-B wire location where the horizontal dispersion is $D = -0.47$ m these particles shift to the outer side with a speed of $\frac{\Delta p}{p} \times D = \frac{10 \text{ eV}}{920\times10^9 \text{ eV}} \times 0.47$ m per turn, which is about 1 σ(=0.75 mm) in 26 minutes. Therefore the coasting beam particles are drifting to the outer side of the vacuum chamber, at the location of the HERA-B wires, due to the energy loss per turn and the negative dispersion. The expected drift speed fits the measured time for the coasting beam contribution to arrive at the wire (see Fig.11 in [1]). This explains the observed background signal in the outer wires of HERA-B. In previous runs the energy of the protons was 820 GeV, at this energy the synchrotron losses per turn are twice smaller and therefore the drift speed of the coasting beam was twice slower.

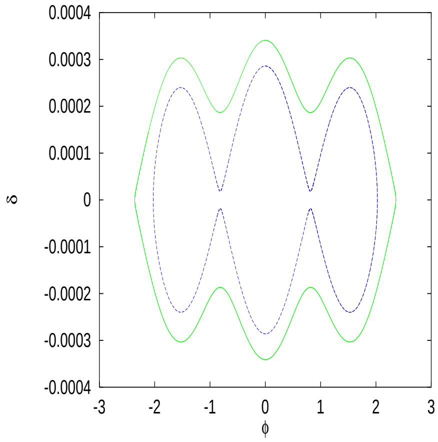
1.2 Stable bucket

At HERA-p the proton beam is stored and accelerated with a double rf-system that consists of cavities operated at two frequencies: 52 MHz and 208 MHz. At high energy the voltage is typically set to $V_{52\text{MHz}} = 2 \times 50$ kV (can be increased up to 2×110 kV, which has been done during studies) and $V_{208\text{MHz}} = 597$ kV (can be increased too, but has been kept constant during the studies). The stable bucket in phase space (δ, ϕ) is shown in Fig. 1-left for these values of the cavities voltages and $h = 1100$, $\alpha = 0.000127$, $E = 920$ GeV. Particles inside the stable bucket are bunched, whereas particles whose energy is out of the energy acceptance are coasting.

For a better qualitative understanding of the process we show in Fig. 1-right a three-dimensional view of the density distribution in the longitudinal phase space. It has been obtained by numerical integration of a Fokker-Planck equation that describes qualitatively this dynamical system [2]. We have taken into account the double rf-system, a noise source to induce a diffusion and synchrotron radiation energy losses (artificially strong for computational matters). The initial distribution was a bi-Gaussian function. The beam blows up due to the diffusion process, the spread in both δ and ϕ increases until the tails of the beam reach the separatrix. Particles outside the rf-bucket are unstable, their δ going towards more negative values. They can be lost at locations with high dispersion (momentum collimation) or, since their synchrotron tune changes continuously, they can be lost suddenly when they hit a resonance $mQ_s + nQ_x + pQ_z = q$ (with m, n, p, q integers and $Q_{x,z}$ the betatron tunes) [3].

1.3 HERA-B wires contribution to the coasting beam

The HERA-B wires are designed as an inner target for the halo particles (amplitudes bigger than 3σ). When the transverse oscillation amplitude of a proton is sufficiently large to reach the wire the particle looses some amount of its energy by inelastic scattering in the target material. This process continues until eventually a deep inelastic scattering event happens (roughly every 250 turns). The probability for a particle to hit the ribbon is such that we can assume a halo particle to hit the target every 100 to 1000



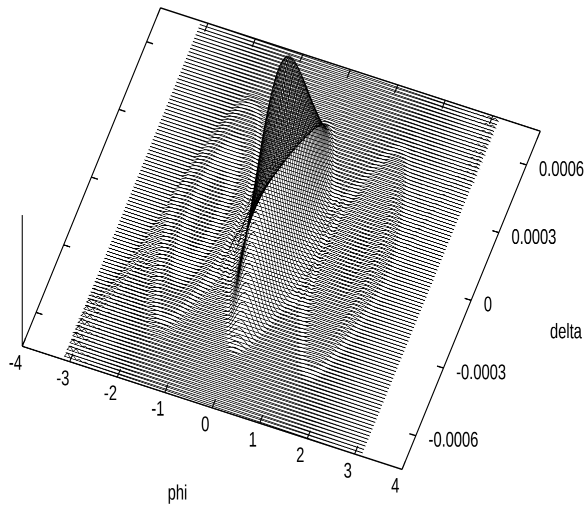


Figure 1: Left: Stable rf-bucket in the longitudinal phase space for $V_{52\mathrm{MHz}} = 2 \times 50$ kV and $V_{208\mathrm{MHz}} = 597$ kV. Right: density distribution when a diffusion process blows the longitudinal beam emittance up until the tails reach the separatrix. The particles jumping outside the stable bucket feed the coasting beam and are unstable.

turns. The energy loss Δp_{loss} per hit against the wires has a probability distribution with mean value

$$\overline{\Delta p_{\mathrm{loss}}} = 2\xi\{\mathrm{Ln}\frac{\epsilon_{\mathrm{max}}}{I} - 1\} \tag{1}$$

where for the proton with mass M, $\epsilon_{\mathrm{max}} = \frac{2m_e c^2 \beta^2 \gamma^2}{1+2\gamma m_e/M+(m_e/M)^2}$ is the maximum energy loss in a head-on collision, and I is the mean ionization potential of the Bethe-Bloch formula ($I \approx 10$ eV for elements heavier than the oxygen), ξ is a quantity which is proportional to the area density of the target being $\xi[\mathrm{keV}] = 153 \times Z/A\rho\delta_x[\mathrm{cm}]$ ($\delta_x = 0.05$ cm, $\rho = 2.7$ g/cm^3, Z=13, A=27) and $\xi \approx 10$ KeV for this material [4]. This gives $\overline{\Delta p}/p = 3 \times 10^{-7}$ (for 920 GeV). This process may kick some particles out of the stable bucket feeding the coasting beam.

It has indeed been seen that the coasting beam current increases sharply within about 100 s after the moment that the wires are moved inside the beam (see Fig. 2 in [5]). This time delay can be justified by the previous model: assuming that a halo particle hits the ribbon every 1000 turns, after half a minute a particle of the halo looses in average $\delta = 3 \times 10^{-4}$ and it is out of the stable bucket. Nonetheless it has been proved that *the coasting beam already exists for a fill of the proton ring which is not disturbed by the wires* [1].

2 Intra-beam scattering

Multiple Coulomb scattering or Intra Beam Scattering (IBS) of particles in a bunched beam by others in the same bunch can lead to continuous growth of the energy spread and/or one or both transverse emittances [6, 7]. Contrary to the first impression, for protons this growth becomes more rapid at higher energies due to an increasing unbalance of longitudinal and transverse temperatures [8]. Here we calculate the growth rates for particles in the HERA-p ring by using the standard formula.

2.1 Instantaneous growth rate

Neglecting the local variations of the beta-functions and dispersion and taking the average transverse beta $\overline{\beta_T} \approx \frac{C}{2\pi Q}$ (with $C \approx 6335$ m circumference and $Q \approx 32$ betatron tune) and average dispersion function $\overline{D} = \frac{C}{2\pi}\alpha$ (with $\alpha = 0.00127$ the momentum compaction factor), the growth rates for the energy-spread (and bunch length) and transverse emittances are determined by [8]:

$$\frac{1}{\tau_h} = \frac{1}{\sigma_\delta}\frac{d\sigma_\delta}{dt} \quad (2)$$

$$\frac{1}{\tau_x} = \frac{1}{\epsilon_x}\frac{d\epsilon_x}{dt} \quad (3)$$

$$\frac{1}{\tau_z} = \frac{1}{\epsilon_z}\frac{d\epsilon_z}{dt} \quad (4)$$

$$A = \frac{cr_p^2 N_p}{64\epsilon_x^N\epsilon_z^N\sigma_\delta\sigma_s\beta\gamma^2} \quad (5)$$

$$f(a,b,c) = 8\pi\int_0^1 dx(1-3x^2)\frac{1}{pq}(\log(0.5c^2(\frac{1}{q}+\frac{1}{p}))-0.5772) \quad (6)$$

$$b_0 = \frac{1}{2}(\frac{\gamma}{n_b})^{1/3} \quad (7)$$

$$q = \beta\gamma\sqrt{\frac{2b_0}{r_p}} \quad (8)$$

$$p = \sqrt{a^2+x^2(1-a^2)} \quad (9)$$

$$q = \sqrt{b^2+x^2(1-b^2)} \quad (10)$$

$$\sigma_x = \sigma_{x\beta}+\overline{D}\sigma_\delta \quad (11)$$

$$\sigma_{x\beta} = \sqrt{\overline{\beta_T}\epsilon_x^N/(\pi\beta\gamma)} \quad (12)$$

$$\sigma_z = \sqrt{\overline{\beta_T}\epsilon_z^N/(\pi\beta\gamma)} \quad (13)$$

$$\sigma_y = \frac{\sigma_\delta\sigma_{x\beta}}{\gamma\sigma_x} \quad (14)$$

$$\frac{1}{\tau_h} = A(1-(\overline{D}\frac{\sigma_h}{\sigma_x})^2)f(\sigma_y/\sigma_{x'},\sigma_y/\sigma_{z'},q\sigma_y) \quad (15)$$

$$\frac{1}{\tau_x} = A(f(\sigma_{x'}/\sigma_y,\sigma_{x'}/\sigma_{z'},q\sigma_{x'})+(\overline{D}\frac{\sigma_h}{\sigma_x})^2 f(\sigma_y/\sigma_{x'},\sigma_y/\sigma_{z'},q\sigma_y)) \quad (16)$$

$$\frac{1}{\tau_z} = Af(\sigma_{z'}/\sigma_y,\sigma_{z'}/\sigma_{x'},q\sigma_{z'}). \quad (17)$$

The growth rate $\frac{1}{\tau_h}$ at a given moment determines the instantaneous growth of the energy spread and bunch length ($\sigma_\delta(t) \approx \sigma_\delta(0)\exp t/\tau_h$ and $\sigma_t(t) \approx \sigma_t(0)\exp t/\tau_h$).

The parameters here used are: $c = 2.99792459\times10^8$ m/s $r_p = 1.535\times10^{-18}$ m, relativistic factors $\beta = \sqrt{1-\frac{1}{\gamma^2}}$, $\gamma = \frac{920\times10^3\text{MeV}}{938.25\text{MeV}}$, number of particles in the bunch N_p, particle density $n_b = \frac{N_p}{(\sigma_x\sigma_z\sigma_s)}$ $\epsilon_{x,z}^N = \frac{(\sigma_{x,z;IP})^2}{\beta_{x,z;IP}}\beta\gamma\pi$ (where $\sigma_{x,IP} = 0.190\times10^{-3}$m, $\sigma_{z,IP} = 0.05\times10^{-3}$m, $\beta_{x,IP} = 7.0$ m, $\beta_{z,IP} = 0.5$ m, as taken from the 1999 run). Some typical longitudinal rms are $\sigma_\delta = 0.00015$ and $\sigma_s = \sigma_t c = 10^{-9}\text{s}\times c$ and bunch population $N_p = 6.5\times10^{10}$.

Applying this to the parameters of the bunch under consideration we can get an estimate of the growth rate of the energy spread σ_δ and the bunch length σ_t. We compare the result with three bunch length measurements performed on two bunches stored with $V_{52\mathrm{MHz}} = 2\times110$ kV and $V_{208\mathrm{MHz}} = 597$ kV. The bunch population was $N_p = 7.1 \times 10^{10}$ in measurement number 1 (July 27, bunch 144) and $N_p = 6.5 \times 10^{10}$ in measurement number 2 (July 26, bunch 4). Measurement number 3 (July 29, bunch 74) was performed on a bunch with $N_p = 7.3 \times 10^{10}$ stored with $V_{52\mathrm{MHz}} = 2 \times 20$ kV and $V_{208\mathrm{MHz}} = 597$ kV. We take the initial measured σ_t (from this we calculate σ_δ) and bunch population N_p as the input parameters to get the initial growth rate. For this short period of time we assume that there is no dilution in the transverse emittances. In Fig. 2 we compare the expected growth of the bunch length as obtained from the IBS theory and the measured growth. For all the cases the growth rate agrees within a factor of two, which may be corrected by a more refined model of the IBS (taking into account local variations of the beta and dispersion functions), or may indicate that other sources than IBS contribute to the bunch lengthening.

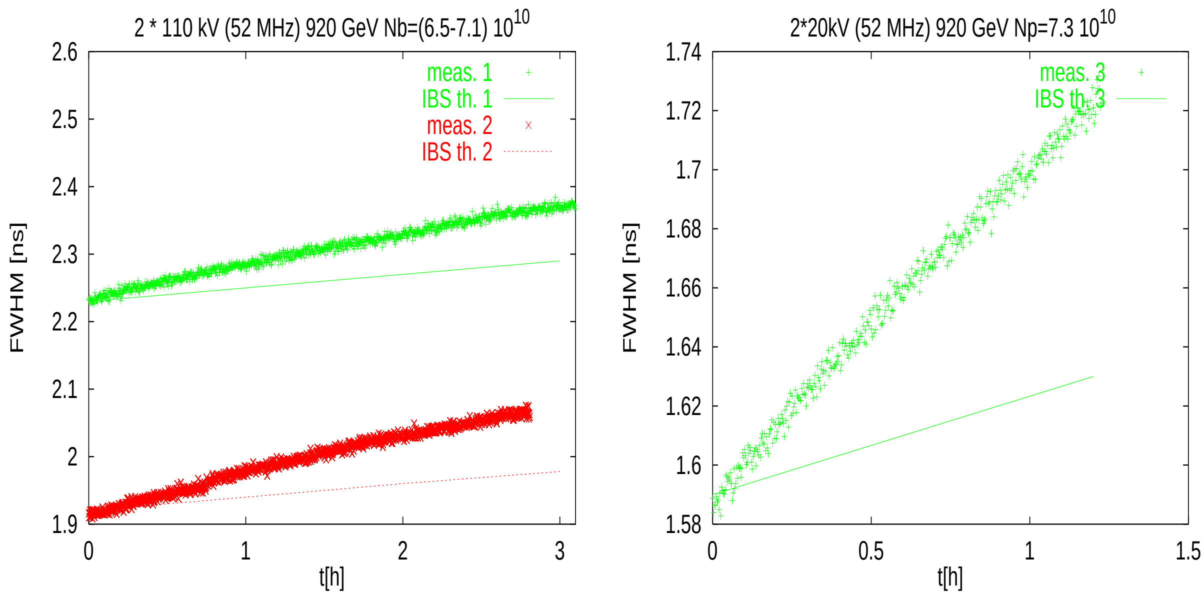


Figure 2: Comparison between measured FWHM (26,27,29 July 2000) and expected growth from IBS. For all the cases the growth rate agrees within a factor of two to three.

2.2 Coasting beam current

As the bunch longitudinal emittance is blown up due to the diffusion induced by the IBS more particles are pushed to the separatrix and get lost. We can estimate roughly the amount of bunched beam inside of the separatrix approximating the beam distribution by a Gaussian function and using the error function errf $(a) = 2\int_0^a \frac{1}{\sqrt{2\pi\sigma_\delta^2}} \exp{(-x^2/(2\sigma_\delta^2))}dx$ where a is the energy acceptance. We take for instance the measurement 2 (26/07/00, see Fig. 2), where the bunch size blows up from $\sigma_\delta = 0.00015$ to $\sigma_\delta = 0.000175$ in 3 hours and $a = 0.0003$. In Fig. 3 we show the corresponding blow up of the (Gaussian) energy distribution with the energy acceptance boundaries at $\pm a$. This corresponds to a loss of 4.2% of the bunch population over these 3 h. Assuming that all bunches in this run behave similarly (actually the bunch length varies up to 15% over one fill) and knowing that the initial current was 90 mA, this would give a loss of 3.8 mA in 3 hours which is in agreement with the measured bunched current decrement of about 4 mA between the 14th and 17th hour in Fig. 4. This is a strong indication that the measured bunch length and energy spread increment explains the measured decrement of bunched current (lifetime of the proton beam) and the build up of a coasting beam component. It should be mentioned that the accuracy of the bunched current measurements has not been evaluated carefully yet.

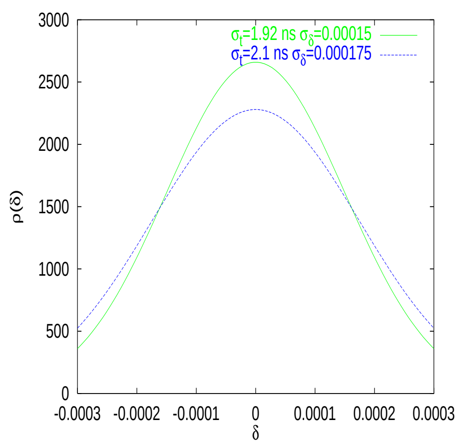


Figure 3: The longitudinal Gaussian distribution in δ blows up due to IBS, all the particles that are beyond the energy acceptance feed the coasting beam.

If the coasting beam generation is related to the IBS process, it should depend on the density of particles and therefore decrease for bigger emittances. In the HERA report [9] it was mentioned : "In order to study this effect, the transverse emittance of the stored proton beam was increased by a factor of about 2.5 at 150 GeV. After ramping this beam, no coasting beam was measured after 1.5 hours, which might indicate that intra-beam scattering is a possible source for coasting beam.". Evaluating from the IBS formula the bunch length growth for the same conditions of measurement 2, but with the two transverse emittances 2.5 times bigger, we confirm that the losses after 1.5 hours should only be of about 0.2% of the bunch population and the coasting beam component would be negligible.

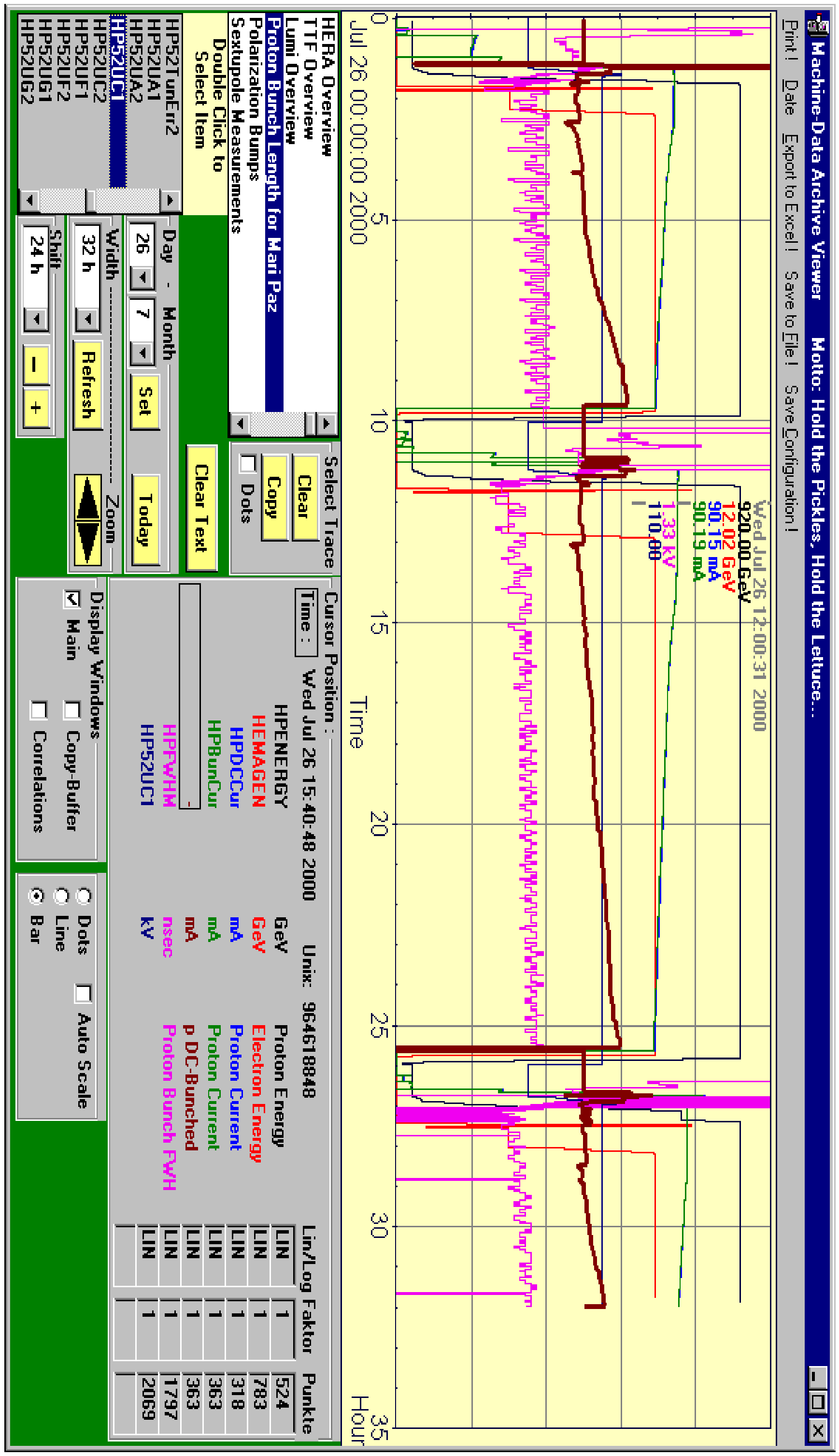


Figure 4: (26/07/00) As the bunch length increases the proton bunched current decreases. The measured bunch length and energy spread increment explains the measured decrement of bunched current of 4%, between the 14h and 17 h, and the build up of a coasting beam component.

The coasting beam circulates as a dc-component. There is a source of dc current (the particles escaping from the bucket) and various killing mechanisms: momentum acceptance, resonances, wires as well as a fast transverse kicker that has been implemented to kick the coasting beam away [5].

If the rf-acceptance is enlarged from a_1 to a_2 (by incrementing the voltage of the cavities when the beam is stored) it will take some time for the bunched beam to diffuse and reach the new acceptance limit. An experiment has been done where this has been observed (30/07/00). Initially the potential was set to $V_{52\text{MHz}} = 2 \times 20$ kV the energy acceptance was $a_1 = 0.000264$, at that moment the FWHM was 1.88 ns and, assuming a bunch population of 7.3×10^{10} (as in the measurement with similar settings of 29/07/00), the expected rate from IBS is $\tau_h = 65.5$ h. At 11 h the energy acceptance is increased to $a_2 = 0.000273$ by increasing the cavity voltage to $V_{52\text{MHz}} = 2 \times 50$ kV. The energy acceptance has been incremented by a 3%. There will be no losses until the beam tails reach the new acceptance. After 2 h, and assuming the IBS growth rate of $\tau_h = 65.5$ h, the energy spread σ_δ has also increased by a 3% and again particles jump over the rf-bucket and feed the dc current. After some time the voltage is again incremented to $V_{52\text{MHz}} = 2 \times 70$ kV, this increases the acceptance to $a_3 = 0.000277$ which is an increment of 1.5%, assuming the same growth rate as before (it should be slightly smaller), the bunch σ_δ will have increased by the same amount after roughly 1 h (or a bit longer).

This is indeed observed in Fig. 5: At 11 h after the change of the voltage the dc component decreases due to the fact that there is no source of dc current and only the killing mechanisms act. When the new σ_δ is such that the beam distribution reaches again the acceptance (after about 2 h) the dc current increases. At 15.5 h the voltage is increased again, the dc component decreases as expected until about 1 h later when the beam has diffused again and the tails reach the acceptance limit. Then, again, the protons jump out of the stable bucket and the dc current increases.

This confirms that the interplay between the growth of the energy spread σ_δ (and bunch length σ_t) and the energy acceptance has consequences on the coasting beam current. It is the underlying diffusing process that pushes the particles out of the stable bucket. This diffusion rules out Touschek scattering as the dominant effect feeding the coasting beam. The intervals of time required for the beam to diffuse also seem to fit with the IBS calculations.

2.3 Bunch lengthening

The instantaneous growth rate depends on the emittances and bunch density of the bunch. *From IBS theory one expects the growth rate to decrease in time as the emittances are blown up, and the bunch length to tend to an almost constant level*. This is seen in the measurements in a very reproducible way. See Fig. 6 showing data of several runs in a week. In general, after about 14 h, the bunch length reaches an almost stationary level at a value that is about $1/3$ bigger than the initial one. Simultaneously, as the bunch length and energy spread increase, the coasting beam current increases and the population of the bunch decreases.

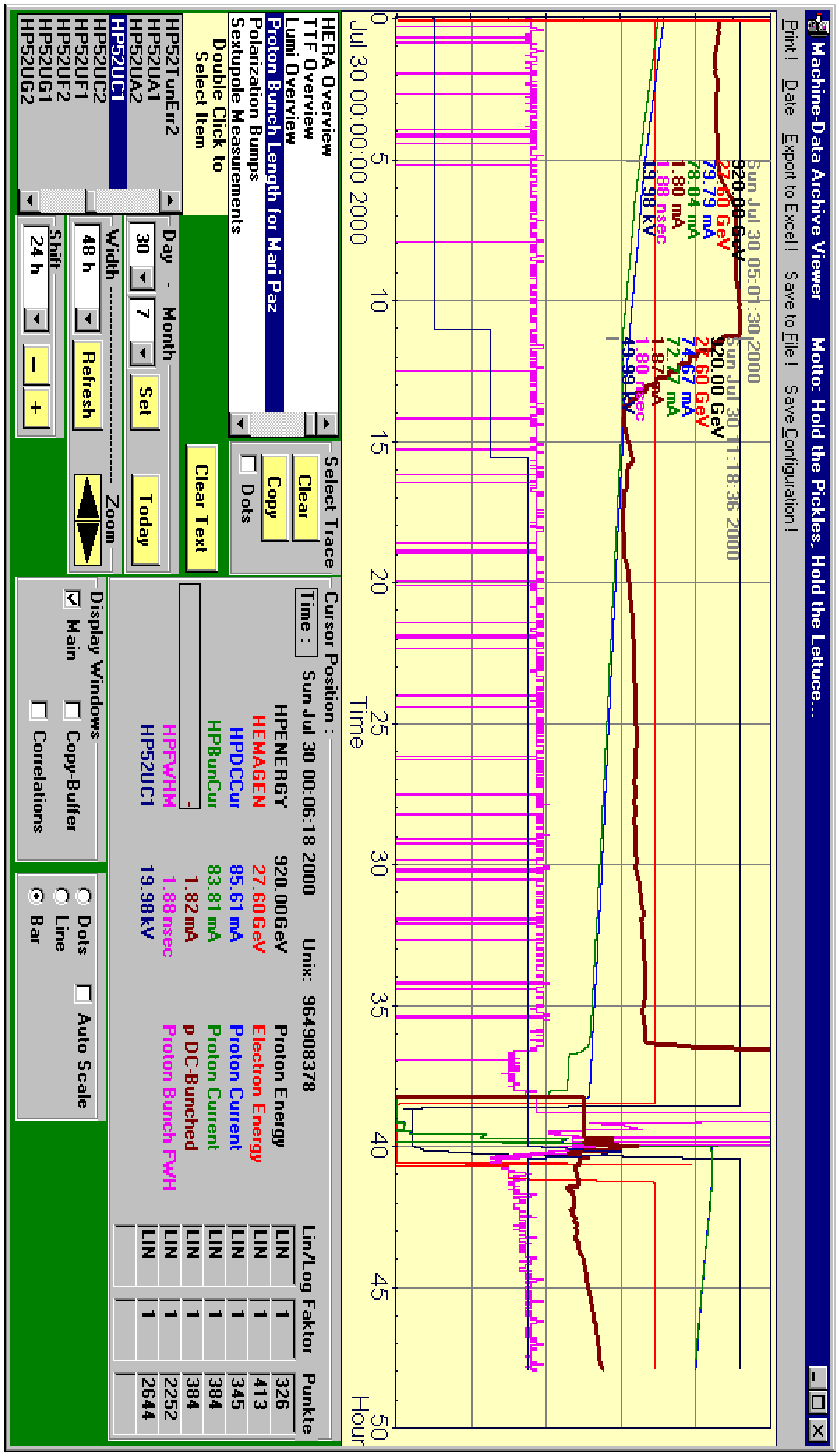


Figure 5: (30/07/00) At 11 h and 15.5 h the rf-voltage is increased, and with it the energy acceptance. For a short while there is no source of coasting beam and the dc current decreases. The coasting beam current increases again sometime later, when the longitudinal emittance of the beam has increased sufficiently and the tails of the distribution reach the new acceptance limit.

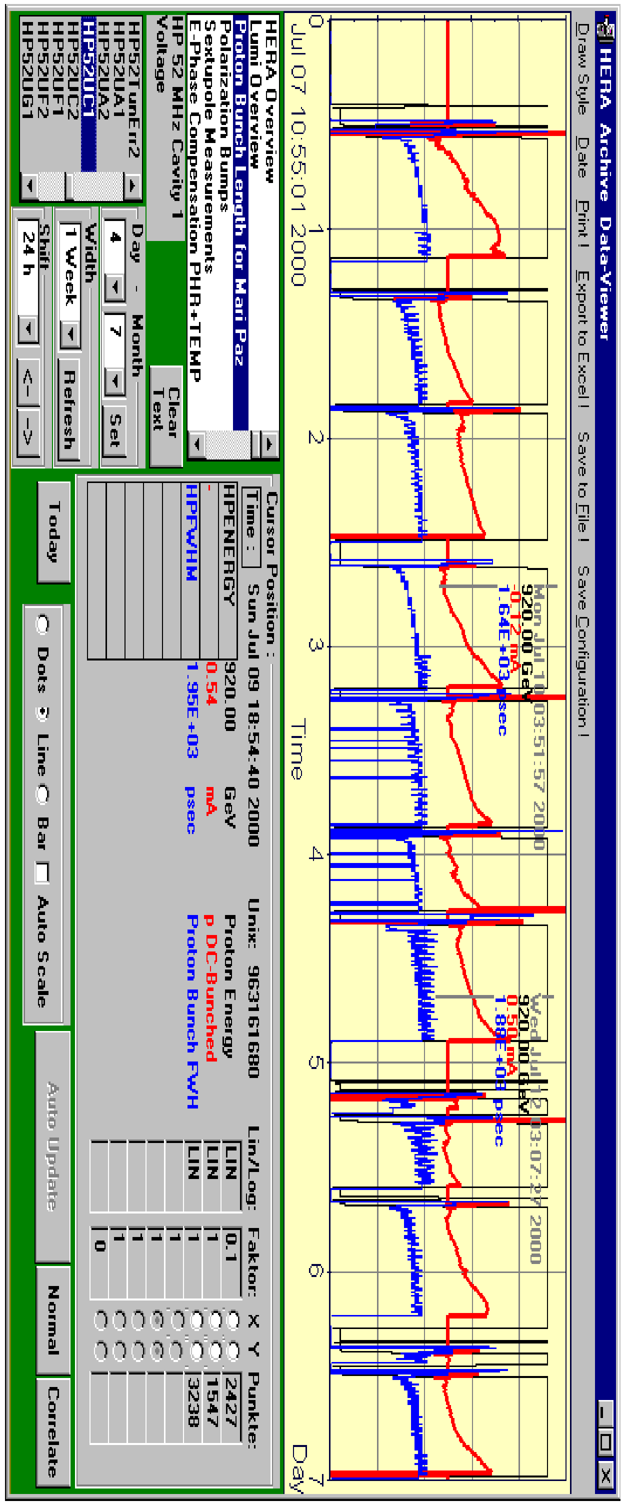


Figure 6: For several fills along a week, the bunch length tends after some hours to an almost constant level. The growth rate decreases in time as the emittances are blown up.

IBS induces a blow up in the transverse emittances, in the longitudinal bunch length and energy spread. Taking the instantaneous growth rates given in section 2.1 and applying this growth in small times steps (3 h) we can evaluate the evolution of these parameters. In addition the longitudinal diffusion induces particle losses. We have calculated the evolution of the FWHM for measurement 2 (26/07/00) first assuming a constant bunch population and then, for comparison, taking into account the corresponding bunched beam losses. The result is shown in Fig. 7. For both cases the bunch length growth rate decreases in time as the bunch is more and more diluted. If we also take into account the bunched current losses the behaviour is pretty similar to the measured bunch length growth shown in Fig. 4. The FWHM tends to a stationary value that is about $1/3$ bigger than the initial one. Over this time the transverse horizontal emittance has also increased considerably (roughly 9% dilution with respect to the initial value). The dilution process calculated from IBS seems to take 4 times longer than the measured one (since the instantaneous growth rate calculated from IBS is twice slower for the longitudinal bunch length and for the transverse emittance).

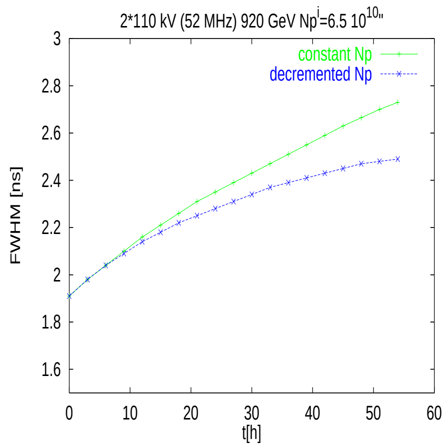


Figure 7: The bunch length growth rate decreases strongly in time. If we include the bunch population losses the FWHM tends to an almost stationary value that is $1/3$ bigger than the initial one.

3 Conclusions

In this paper we have proposed IBS as a possible physical mechanisms behind the coasting beam problem in the HERA-p ring. We have discussed the implications of this longitudinal dynamics model on observables such as the bunch length, energy spread, dc current and reaction rate at the HERA-B wires. The results seem to be in qualitative agreement with the measurements.

This work is intended to be a collection of data and facts, to be taken as starting point for further theoretical and experimental studies. To further validate this theory similar measurements should be performed at different energies, bunch populations and emittances (both longitudinal and transverse) monitoring all these parameters in a systematic way.

Summing up the main conclusions:

- The HERA-B wires can detect the coasting beam. These particles will naturally drift to the outer side with time, due to the synchrotron radiation energy losses and dispersion, and the speed of this drift has been confirmed with the wires by scraping, retracting and waiting for the coasting beam to arrive and give the same rate. Nevertheless, the wires cannot scrape the coasting particles whose amplitudes lie between 0 and 3 sigma (since then the wires would scrape also the core of the bunched beam).

- The HERA-B wires can add a contribution to the dc current. If this is the case this should be independent of the position of the wire (up, left, bottom, ..) but should depend on the number of halo particles that is affected by this. Nonetheless it has been proved that the coasting beam already exists for a proton fill which has not been disturbed by the wires.
- The bunch length increases very fast over 14 h up to a value that is about $1/3$ times bigger than the initial one and then increases much slower. This behaviour is absolutely reproducible and appears for every V of the cavities.

  The measured bunch length and the corresponding energy spread increment explains the measured decrement of bunched current (lifetime of the proton beam) and the build up of a coasting beam component.

  Rising $V_{52\ \mathrm{MHz}}$ the energy acceptance is increased. There is no source feeding the coasting beam until the size of the beam is such that the tails of the distribution reach the new energy acceptance. Therefore, it is the underlying diffusing process that pushes the particles out of the stable bucket. This rules out Touschek scattering as the dominant effect.
- Intrabeam scattering can explain the instantaneous bunch length growth at least within a factor of 2. Additional effects such as rf-noise might also induce a bunch length growth.

  The growth rate decreases with time and the measured bunch length tends to a limiting value as expected from IBS. If IBS is responsible of this effect σ_t should increase slower for bigger emittances (a measurement in 1999 seems to confirm that this is the case) and faster for smaller emittances. Special attention should be payed then for the luminosity upgrade.

4 Acknowledgements

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