ENERGY LOSS OF A SINGLE BUNCH IN THE CERN SPS

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Abstract

The dependence of energy loss on bunch length was determined experimentally for a single proton bunch in the SPS at 26 GeV/c. This was done from measurements of the synchronous phase as a function of intensity for different capture voltages. The results are compared with the expected dependence calculated from the resistive part of the SPS impedance below 1 GHz. Two impedance sources, the cavities of the 200 MHz RF system and the extraction kickers, give the main contributions to particle energy loss in very good agreement with experiment. The results obtained allow a better understanding of some mechanisms leading to capture loss of the high intensity LHC beam in the SPS.

INTRODUCTION

Studies of non-negligible capture loss of high intensity LHC beams in the SPS in 2003 have shown that loss behaviour and dependence on different beam and machine parameters could be explained by a non-zero synchronous phase ϕ_s on the flat bottom [1] which is the result of energy loss of the beam due to interaction with the machine impedance. This leads to a shortening of the bucket length which for high intensities becomes comparable to or even less than the length of the injected bunches. For the LHC beam the reduction of bucket length is around 0.5 ns (RF period is 5 ns) which corresponds to $\phi_s = 1.8$ deg. With many bunches in the ring and with feedback and feed-forward systems in operation this effect is not easy to measure. In this paper we present measurements of synchronous phase shift using single bunches.

In the absence of acceleration the synchronous phase ϕ_s is defined by expression

$$\sin \phi_s = U/(e\,V), \qquad (1)$$

where U is energy loss per turn and per particle and V is the voltage amplitude. The total energy loss normalised to the number of particles can be found by measuring the synchronous phase ϕ_s at different bunch intensities [2]. Below, the energy loss derived from synchronous phase measurements of single bunches (next section) is compared to the energy loss estimated from the known SPS impedances (last section).

MEASUREMENTS

Method

The change of synchronous phase with intensity can be measured by observing the variation of phase between the beam signal and either the signal obtained from a measuring loop in the cavity or the RF signal sent from the power amplifiers to the cavity. In the first case the signal contains information from both the applied RF voltage and the induced beam-loading voltage (energy loss) on the fundamental frequency. In the second case, the reference signal does not include the beam-loading voltage component and the phase shift with intensity is due to all other losses in the ring plus the energy loss on the cavity fundamental.

The synchronous phase was measured in the middle of the 26 GeV flat bottom (11.8 s long) by comparison between the time delay of the beam signal (wide-band pick-up) and the reference signal sent to the cavity. An absolute calibration of synchronous phase was obtained by extrapolating to zero intensity.

Data analysis

Measurements were made with bunches injected from the PS with the same longitudinal emittance of 0.3 eVs but two different sets of bunch length. These bunches were captured in the SPS with different voltages from 0.56 MV to 3 MV so that the final bunch length was determined by this voltage. Intensity was varied in the range $(0.2-1.4)\times 10^{11}$ using the vertical scrapers in the PS and was measured in the SPS. Raw data for the synchronous phase measured after capture in different voltages as a function of bunch intensity N is shown in Fig. 1.

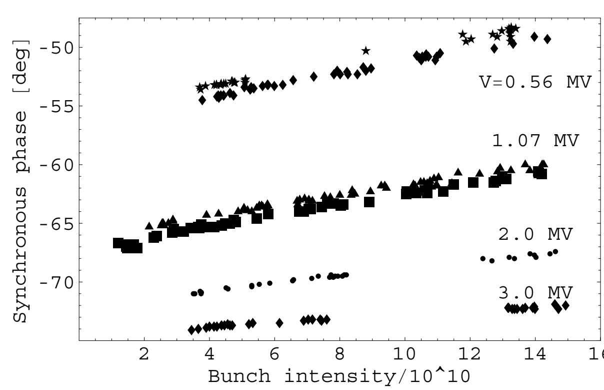

Figure 1: Raw data for synchronous phase measured as a function of bunch intensity for different voltages. Two sets for 0.56 MV and 1.07 MV correspond to two injected bunch lengths.

A linear fit of the form

$$\phi_{si} = \phi_{0i} + b_i \times (N/10^{10}) \quad [\mathrm{deg}], \qquad (2)$$

where $i = 1, ...6$ is the number of the measurement set (different voltage amplitude or PS setting), was applied to

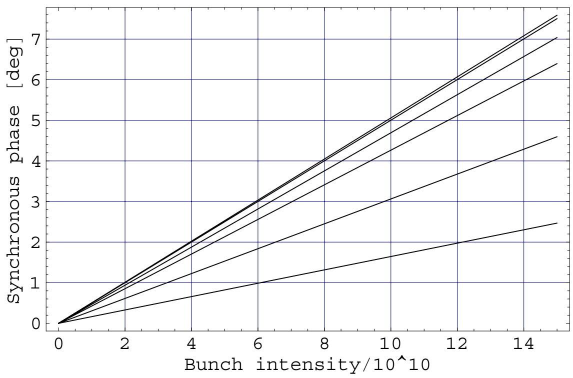

Figure 2: Linear fits to the raw data for the synchronous phase after removal of the constant offset ϕ_0, as a function of intensity for voltages (from top to bottom): 0.56 MV - 2 sets, 1.07 MV - 2 sets, 2 MV and 3 MV.

the raw data in Fig. 1. The results for $\Delta\phi_s(N) = \phi_{si} - \phi_{0i}$ are presented in Fig. 2.

The coefficients b_i from the linear fit (2) are related to the particle energy loss per turn, normalised to the bunch intensity $N/10^{10}$, by the expression

$$\bar{U}_i = \frac{U_i}{N/10^{10}} = \frac{\pi}{180^\circ}\, e\, b_i V_i. \tag{3}$$

In other words expression (3) gives the energy loss U for a bunch intensity of 10^{10} and scales linearly with intensity. For a constant energy loss one would expect $b_i V_i = const$ for $i = 1, ...6$. Values of the normalised energy loss $\bar{U}_i$ found from (3) are plotted in Fig. 3 for different voltages V_i. The fact that the resulting curve is not flat means that the energy loss U has a non-negligible dependence on the bunch length τ which was different in each measurement set.

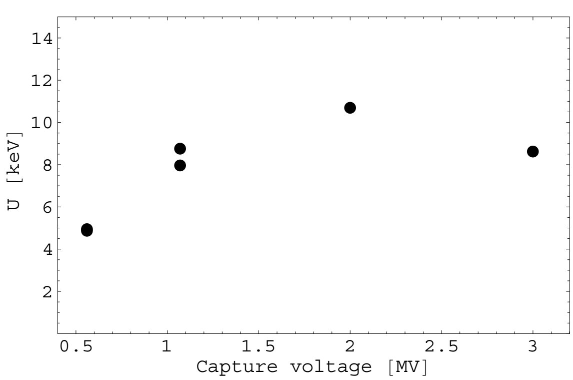

Figure 3: Normalised energy loss $\bar{U}_i$ (keV) as a function of the capture voltage found from (3).

Dependence on bunch length

In our measurements the bunch length varied in at least three different ways. First, it was possible to change the length of the injected bunches simply by using two different RF settings in the PS (spare 80 MHz cavity on and off). Second, due to different capture voltages in the SPS the bunch length at the time of the measurement, after filamentation, was also different. On top of this $\sim 10\%$ increase in bunch length for an intensity change of a factor of seven was recorded as well. The data for the bunch length measured in the SPS in the middle of the flat bottom for lowest and highest intensities are summarised in Table 1.

set number	spare in PS	V MV	τ_{min} ns	τ_{max} ns	τ_{avg} ns
1	on	0.56	3.4	3.6	3.50
2	off	0.56	3.4	3.7	3.55
3	on	1.07	2.9	3.2	3.05
4	off	1.07	3.0	3.3	3.15
5	off	2.0	2.7	2.8	2.75
6	off	3.0	2.6	2.9	2.75

Table 1: Bunch length (4σ Gaussian fit) measured for minimum and maximum intensities and their average value τ_{avg} in 6 different experimental settings.

The energy loss $\bar{U}_i$ presented in Fig. 3 for different voltages V_i is shown in Fig. 4 as a function of the corresponding average bunch length τ_{avg} from Table 1 (large circles). As can be seen the energy loss is larger for shorter bunches.

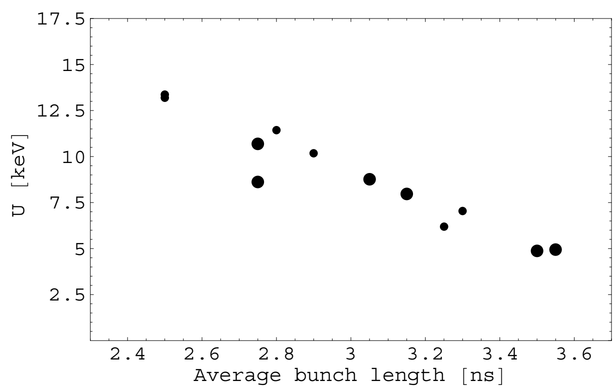

Figure 4: Normalised energy loss $\bar{U}_i$ (keV) before (large circles) and after corrections (small circles, see text) as a function of average bunch length τ_{avg}.

The fact that the bunch length increases with intensity and that the energy loss is smaller for longer bunches means that the energy loss found from the linear fit for the average bunch length is underestimated. This effect was treated by two different methods: by quadratic fit to the phase variation with intensity in Fig. 1, and by applying the dependence $U(\tau)$ found from the linear fit to make a second iteration to the data analysis, which give finally similar results [3]. The correction obtained by the second method was used together with two other corrections – a constant decrease of bunch length by 0.25 ns due to signal distortion in the long cable and a correction due to the dependence of the measured phase of the signal on its amplitude (small increase in energy loss $\propto V$). The application of these three corrections results in the measurement points shown in Fig. 4 (small circles) and Fig. 6.

THE LOSS FACTOR EVALUATION

The measured dependence of energy loss on bunch length can be compared with the curve calculated from the known resistive impedance and the given bunch distribution [4]. Below, these estimations are made for the SPS impedance and then compared with experimental results.

The energy loss of the bunch per turn and per particle can be found from the following expression [5]

$$U_b = -e^2 N k = -e^2 N \sum_n k_n(\sigma), \tag{4}$$

where for a Gaussian bunch the loss factor k_n due to the longitudinal impedance $Z_n(\omega)$ is

$$k_n(\sigma) = \frac{\omega_0}{\pi} \sum_{p=0}^{\infty} \mathrm{Re} Z_n(p\omega_0) \exp[-(p\omega_0\sigma)^2]. \tag{5}$$

Here ω_0 is the revolution frequency.

In the measurements σ varied in the range (0.6-0.9) ns so that impedances up to 1 GHz should be taken into account. Contributions to the energy loss $\bar{U} = |U_b|/(N/10^{10})$ from different SPS impedances below 1 GHz calculated for a Gaussian bunch are shown in Fig. 5.

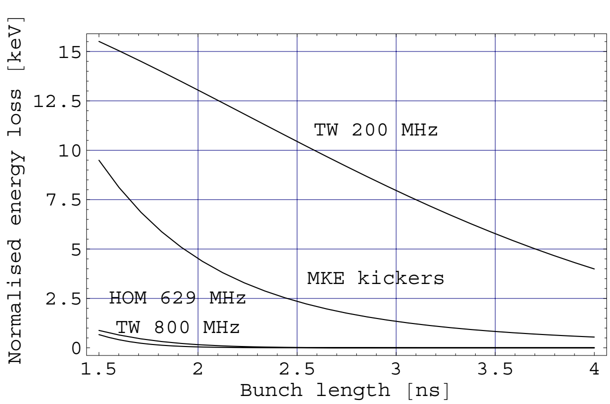

Figure 5: Contribution to energy loss $\bar{U}$ (keV) from different SPS impedances as a function of 4σ bunch length.

As can be seen, the energy loss is dominated by the loss in the fundamental impedance of the 200 MHz RF system (shunt impedance $R_{sh} \simeq 4.5$ MΩ, quality factor $Q = 140$) and the MKE kickers. The impedance of one MKE kicker below 1 GHz can be approximated by a resonator with frequency $f_r = 0.6$ GHz, $R_{sh} = 6$ kΩ and $Q = 1$. Contributions due to the main impedance of the 800 MHz cavities, total $R_{sh} = 1.94$ MΩ and $Q = 300$, as well as the HOM of the 200 MHz RF system, with $f_r = 629$ MHz, $Q = 500$ and $R_{sh} = 604$ kΩ, are much smaller.

The contribution to $\bar{U}$ from the resistive wall impedance is about 0.8 keV for a bunch with $\sigma = 0.6$ ns and decreases $\propto \sigma^{-3/2}$ for longer bunches.

The measured and estimated total energy losses $\bar{U}$ are presented in Fig. 6 as a function of bunch length.

For many bunches in the ring energy losses are different due to the change in beam spectrum. However for short-range wake-fields the contribution to the energy loss is the same. For $\tau = 3$ ns and $N = 1.3 \times 10^{11}$ the energy loss due to the MKE kickers alone is 20 keV which is sufficient to create a 0.3 ns gap between the buckets for the LHC beam captured in 2 MV. The re-installation of 5 of these kickers in the ring in 2003 can explain the increase in capture loss [1]. These energy losses are also responsible for kicker heating by the LHC beam [6].

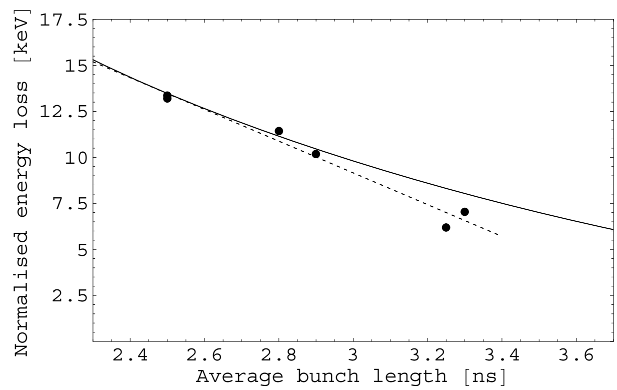

Figure 6: Normalised energy loss $\bar{U}$ (keV) calculated from the known SPS impedances (solid line) and measured from the phase shift (circles – measurement points, dashed line – their linear fit) for different bunch lengths.

In summary, the energy loss of a single bunch in the SPS was found from a measurement of the synchronous phase as a function of intensity. The use of different capture voltages allowed the dependence of energy loss on bunch length also to be measured. The same dependence evaluated from the resistive part of the SPS impedance, is in good agreement with the measured results.

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