CAPTURE LOSS OF THE LHC BEAM IN THE CERN SPS

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Abstract

The matched voltage of the LHC beam at injection into the SPS is 750 kV. However, even with RF feedback and feed-forward systems in operation, the relative particle losses on the flat bottom for nominal LHC parameters with this capture voltage can reach the 30% level. With voltages as high as 2 MV these losses are still around 15%, pushing the intensity in the SPS injectors to the limit to obtain nominal intensity beam for the LHC. Beam losses grow with intensity and are always asymmetric in energy (lost particles are seen mainly in front of the batch). The asymmetry can be explained by the energy loss of particles due to the SPS impedance which is also responsible for a non-zero synchronous phase on the flat bottom leading to large gaps between buckets. In this paper the measurements of the dependence of particle loss on the beam and machine parameters are presented and discussed together with possible loss mechanisms.

INTRODUCTION

In 2002 an LHC beam with nominal intensity and longitudinal parameters was accelerated for the first time in the SPS to top energy, 450 GeV. This proton beam consists of 3-4 batches each of 72 bunches. At injection the 4σ bunch length is 4.2 ns and the longitudinal emittance 0.35 eVs. Bunches are spaced at 25 ns, while the RF period is 5 ns.

In 2003 even higher intensities were achieved. However relative capture losses increased by almost 30% for the same batch intensity and capture voltage (Fig. 1). To obtain a nominal intensity LHC beam, 1.15×10^{11} p/bunch at 450 GeV, 15% more particles had to be injected into the SPS when using a 2 MV capture voltage. For smaller voltages capture losses were even higher reaching 40% for the match voltage of 750 kV (Fig. 2).

In 2003 a significant amount of machine development (MD) study time was devoted to this beam loss problem. Losses were measured at the end of the 10.86 s long injection plateau (26 GeV) and after the start of acceleration (30 GeV) with the beam current transformer (BCT).

Below, the loss dependence on different beam and machine parameters is presented, possible loss mechanisms are discussed and plans for MDs in 2004 which should help to verify the model are given.

LOSS FEATURES

As can be seen from Fig. 1 capture losses depend strongly on the batch intensity N so that the relative loss is proportional to N and the absolute loss to N^2. In these measurements with a voltage of 2 MV the number of batches did not have any evident influence on the beam losses.

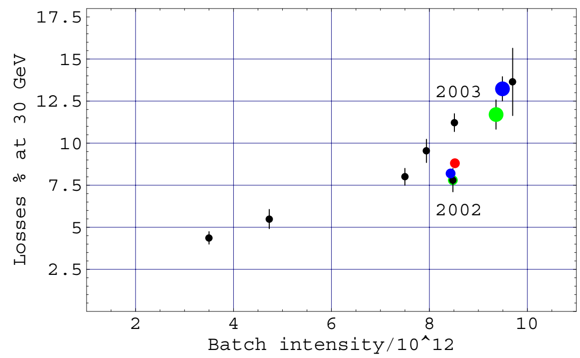

Figure 1: Dependence of relative beam loss on batch intensity measured in 2002 (group of three circles) and 2003 with 1 (black circle), 2 (red), 3 (blue) and 4 (green) batches in the ring. 2 MV voltage at 26 GeV.

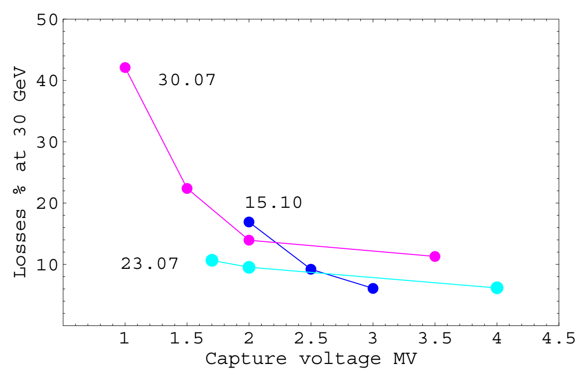

Figure 2: Dependence of relative beam loss at 30 GeV on capture voltage for a single batch with average intensity $N_b/10^{12} = 7.8$ (MD on 23.07), 9.7 (30.07), 9.3 (15.10).

At 3 MV capture loss is significantly reduced. The relative capture loss also clearly decreased as more batches were injected at 3.6 s intervals [2]. However with 3 MV at 26 GeV beam losses then appear later in the cycle so that the total (transmission) loss for 4 batches was around 12%.

The loss dependence on average bunch length at injection was also studied. Typically the bunch length varied along the batch by ± 0.3 ns from the average (nominal) value of 4.2 ns. The average injected bunch length could be increased by changing the bunch rotation time in the PS injector prior to extraction. As a result capture losses in the SPS increased from 16% to 20% for a capture voltage of 2 MV and nominal intensity. A significant reduction in injected bunch length was not possible in 2003, but may be achievable in 2004.

LOSS ASYMMETRY

In 2003 it was seen that injection losses have an asymmetric character; practically all lost particles moved away from the front of the batch rather than from the back. Above transition energy this implies that lost particles have or acquire some negative energy deviation. Fig. 3 shows the 200 MHz component during one revolution period, the signal from the batch in the centre (width 2 μs) and from the uncaptured beam (-40 dB wrt the batch) moving to the left and spreading out. The amplitude of the uncaptured particle signal decreases by 8 dB when the voltage V is increased from 2 MV to 5 MV. Note that for 5 MV the bucket half-height is 6.5×10^{-3} and the nominal bunch has a 2σ momentum spread of only 2.4×10^{-3}.

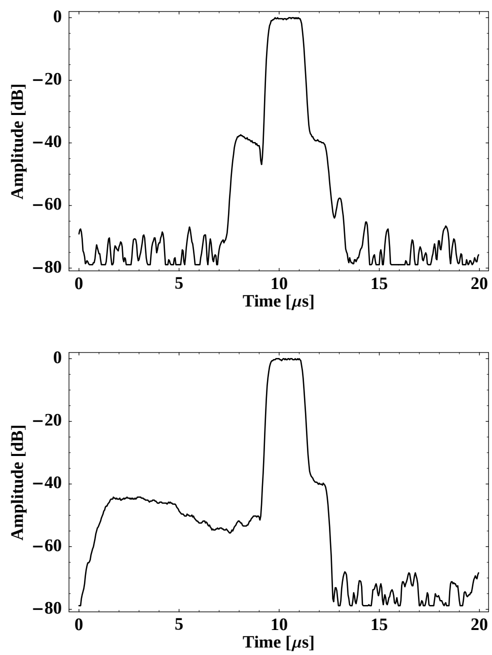

Figure 3: 200 MHz signal showing the asymmetric character of particle losses at injection for a capture voltage of 2 MV and at nominal intensity. The acquisitions were taken shortly after injection and a few seconds later.

Loss asymmetry could be reduced by small changes in B-field at injection ($\pm$2 Gauss) and f_{rf} (50 Hz), but then capture losses increased. A correct energy match between the PS and the SPS machines was also verified. Later, asymmetric motion of uncaptured particles was also observed following a sharp voltage reduction on the flat bottom and even during coasts indicating that some other explanation than energy mismatch is needed.

The asymmetric character of the beam loss can be explained by particles having energy loss due to the resistive impedance in the machine [3] and even possibly due to electron-cloud production. An energy loss U per particle leads to an accelerating-type bucket with a synchronous phase $\phi_s \simeq U/(eV)$ on the flat bottom. As a result gaps exist between the buckets and particle trajectories outside the bucket lead eventually to lower energy. The azimuthal size of the gap between buckets is $\delta\phi \simeq 2\sqrt{\pi \sin\phi_s}$. For a 0.5 ns gap one needs $\phi_s = 1.8$ deg at 200 MHz and $U/(eV) \sim 0.03$ or only $U = 60$ keV for $V = 2$ MV.

An observation in favour of this effect can be seen in Fig. 4. Most lost particles move directly to the left (not shown in this plot). However some particles with positive energy offset, when lost at injection, start to move to the right but later they lose energy, pass through the 0.5-1 ns gaps between the accelerating buckets, and then move to the left. The RF period is 5 ns.

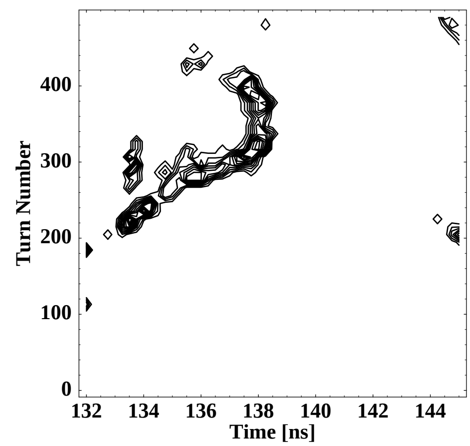

Figure 4: Measured density plot of particles lost at injection showing the effect of the accelerating bucket ($\phi_s \neq 0$) on the flat bottom ($dB/dt = 0$).

A decrease of the available bucket area produced by an energy loss U proportional to intensity and impedance can, in principle, explain the intensity dependence of capture loss and also its increase in 2003 after the installation of 5 kickers (MKE) in the ring having significant resistive impedance up to 1 GHz [3]. There are, however, some experimental facts which indicate that total capture losses are determined not only at injection itself but also by other processes occurring along the flat bottom.

LOSSES ON THE FLAT BOTTOM

Beam losses for different RF voltages at injection and along the flat bottom are presented in Table 1. Losses were reduced when the 2 MV capture voltage was raised to 3 MV after 10 ms in comparison with the cases at constant 2 MV or 3 MV. Using a 0.6 eVs (previously 0.5 eVs) bucket during the ramp reduced losses by only $\sim 1\%$.

Bunch shape evolution along the flat bottom depends on the voltage amplitude, Fig. 5. Bunch length (4σ from a Gaussian fit) increases for $V = 3$ MV and decreases for $V = 2$ MV with practically zero slope for 2.5 MV. Bunch peak amplitude decreases along the flat bottom in all cases, but with a slope which is on average twice as large at 2 MV [2]. Losses are smaller for higher voltage (Table 1).

V_{inj} MV	V_{fb} MV	ε_a eVs	N_{mean} 10^{10}	SD 10^{10}	loss %	SD %
2.0	2.0	0.5	952.3	21.9	16.9	1.2
2.5	2.5	0.5	933.6	14.7	9.2	1.0
3.0	3.0	0.5	931.4	12.7	6.1	1.2
2.0	3.0	0.5	915.0	18.5	4.7	1.1
2.0	3.0	0.6	917.0	18.5	3.7	0.6

Table 1: Beam losses at 30 GeV for different voltages at injection V_{inj}, on the flat bottom V_{fb} and voltage programmes during the ramp. Emittances ε_a correspond to 90% full buckets. One batch in the ring.

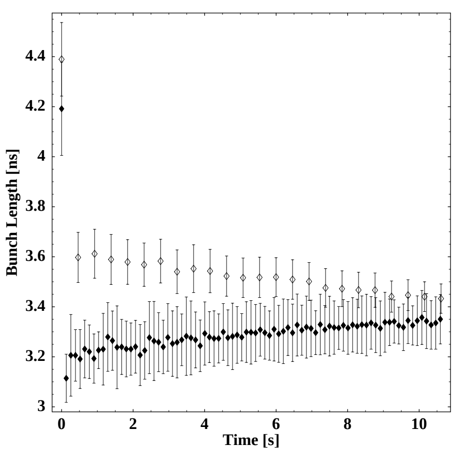

Figure 5: Bunch length evolution on the flat bottom for a constant voltage of 2 MV (top curve) and for the case of 2 MV at injection and 3 MV along the flat bottom (bottom curve). Average bunch intensity 1.25×10^{11}.

All these observations seem to be compatible with longitudinal diffusion out of the bucket due to RF noise [4]. For white phase ($\Delta\phi$) or amplitude ($\Delta V/V$) noise with power density $P_{\phi,V}$ and small ϕ_s the diffusion coefficient to first approximation can be written [5]

$$D(J) \simeq \frac{\omega_s^4(0)}{16\pi} \frac{J}{\omega_s(J)} P_{\phi,V},$$

where J is the action and $\omega_s(J)$ is the non-linear synchrotron oscillation frequency. Since the diffusion coefficient sharply increases towards the edge of the bucket, where $\omega_s(J) \to 0$, the intensity dependence of beam loss can be explained by a bucket reduction due to the energy loss, itself proportional to beam intensity. Additional bucket modulation along the batch due to beam loading can also contribute to this problem.

An increase in voltage on the flat bottom decreases both the rms bunch length and the relative energy loss $U/(eV) = \sin\phi_s$ (hence bucket size reduction), so that particles are further away from the separatrix.

A high voltage at injection decreases injection loss. However this also creates more tails due to filamentation. Capture in 2 MV with increase to 3 MV reduces the tails compared to a 3 MV capture, and also decreases losses due to RF noise along the flat bottom, also visible in Table 1. Since these flat bottom losses are dominant in comparison to the injection losses, the optimum value V_{inj} to minimise total loss could be even lower than 2 MV.

If the flat bottom losses dominate, relative losses should decrease with the number of batches in the ring since a batch spends on average a shorter time on the flat bottom. In this case the relative loss of 3, 2 and 1 batches in the ring should be close to the ratio 2:2.5:3. With 3 MV at 26 GeV we measured 1.9:2.6:3.2 [2].

Preliminary particle tracking simulations confirm this mechanism qualitatively for white noise. A reduction in σ (Gaussian fit) for 2 MV and an increase in σ for 3 MV is obtained with the same initial bunch lengths as in Fig. 5. This is true for both phase and amplitude noise. However amplitude noise does not visibly change the bunch peak amplitude contrary to measurements. The effect of phase noise on beam loss is the same at both 2 MV and 3 MV unless energy losses are introduced into the simulations.

In conclusion, analysis of existing experimental data shows that high capture losses, their increase in 2003 and their dependence on bunch intensity and voltage amplitude can be explained by the effect of RF noise in an accelerating-type bucket on the flat bottom. This accelerating bucket is produced by particle energy loss in the resistive part of the SPS impedance.

The present SPS beam-control system is based on low noise techniques developed for collider mode of operation (ppbar) [6]. Noise due to complex RF feedback circuits implemented recently for high intensity LHC beam has to be studied in 2004. A possible increase of bunch length with intensity in the injector can also aggravate the loss problem so that continuous monitoring is desirable.

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