Longitudinal instabilities in the SPS

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Abstract

Measurements made during machine depelopment (MD) periods over the last few years are summarised. While the sources of single bunch instabilities seem to be undestood, those for multi-bunch instabilities are still under study. Since the nominal LHC beam in the SPS was not yet available, studies of longitudinal emittance blow-up have been made on the present fixed target beam. Results from the recent MD with the LHC type beam and plans for 1999 are also reported.

1 INTRODUCTION

The SPS accelerator will be used as the injector for the LHC with beam intensity requirements close to that already achieved in the SPS, both for single bunch and total intensity. However in both cases bunch parameters were different and from the point of view of beam stability not always in favour of the LHC beam.

Single bunches with intensity of 10^{11} were accelerated in the $p\bar{p}$ era. At injection (26 GeV) emittance blow-up was observed from an intensity of 8.5×10^{10} for bunches with a momentum spread of $\frac{\Delta p}{p} = 3.2 \times 10^{-3}$ and bunch length $\tau = 3.3$ ns, [1]. The LHC beam at injection has $\frac{\Delta p}{p} = 2.0 \times 10^{-3}$ and $\tau = 4$ ns. If we assume a scaling of the threshold intensity proportional to $(\frac{\Delta p}{p})^2\tau$, then the nominal bunch intensity (1.1×10^{11}) is already well below the threshold.

In the fixed target cycle a record total intensity of 4.8×10^{13} was achieved for the beam filling $10/11$ of the ring. Measurements showed, [2], that in normal operation the longitudinal beam emittance at 450 GeV is around 2 eVs (0.2 eVs at injection).

The total intensity of the nominal LHC beam is only 2.6×10^{13}, however squeezed into $3/11$ of the SPS ring. Quite significant emittance blow-up in the longitudinal phase plane, from 0.5 up to 1 eVs, is allowed for the LHC beam before extraction at 450 GeV. However, if the value of emittance can be kept below 0.7 eVs, no additional RF system, neither in the SPS nor in the LHC, [3], is required to be installed for a clean SPS - LHC transfer.

The considerations presented above have motivated more detailed studies of beam stability in the SPS. We started with single bunch (1995-1996). More recent measurements were devoted to multi-bunch instabilities.

Analysis of intensity limitations for the fixed target beam due to instabilities can also be interesting for the possible future of the SPS as a neutrino source in the Gran-Sasso project. This subject was brought up in discussions during the workshop, [4].

2 SINGLE BUNCH INSTABILITY

The single bunch instability, more often referred to as the microwave instability, has a long history in the SPS. It was already observed for the first time in the 1977, [5], one year after the first commissioning of the SPS. It produced intensity limitations both for $p\bar{p}$ and lepton beams at injection. So far it was not harmful for the fixed target operation.

Measurements of the spectrum of an unstable single bunch injected into the SPS with RF off allowed the dominant impedances of the SPS up to 4 GHz to be seen, [6]. Apart from fundamental and high order modes of the 5 different RF systems installed at the moment in the SPS, less known sources were identified as well. They are:

- around 800 vacuum ports – cavity-like objects between dipole magnets all over the ring,
- 16 extraction septa.

These are elements with short-range wake-field, which nevertheless can couple a few consecutive bunches of fixed target (bunch spacing 5 ns) and even LHC beam (bunch spacing 25 ns). Measured in the laboratory the quality factors Q for different modes are of the order of 100, [7]. The vacuum ports modes have a high total value of R_{sh}/Q, which defines the instability growth rate $\mathrm{Im}\Omega$ in the case of narrow-band impedances ($\omega_r\tau < Q$):

$$\frac{\mathrm{Im}\Omega}{\omega_r} \simeq \left(\frac{Ne^2\omega_0|\eta|}{16\pi E_0}\frac{R_{sh}}{Q}\right)^{\frac{1}{2}}. \quad (1)$$

Here N is the bunch intensity, $\omega_0 = 2\pi f_0$ is the revolution frequency, E_0 is the energy, η is the slip factor, τ is the bunch length, R_{sh} is the shunt impedance and $\omega_r = 2\pi f_r$ is the resonant frequency of the impedance.

The model containing the impedances from the four elements (travelling wave RF systems at 200 and 800 MHz, extraction septa and vacuum ports) and consisting of 12 resonant peaks have been used in numerical simulations to reproduce bunch lengthening measurements, [8]. For most cases the R_{sh}/Q values were found from calculations and the Q – from the laboratory measurements. While the dependence of calculated and measured bunch length and peak line density are in general very close, it seems that some impedance is still missing in the present model.

The program developed to cure this instability, see [9], [10], includes shielding the guilty elements found.

3 MULTI-BUNCH INSTABILITIES

In the absence of the nominal LHC beam, we started studies of multi-bunch instabilities in the SPS on the fixed target

Beam	FT	LHC
injection energy (GeV)	14	26
extraction energy (GeV)	450	450
transition crossing	yes	no
RF system (MHz)	200	200
bunch spacing (ns)	5	25
filling pattern	10/11	3/11
number of bunches	4200	243
intensity/bunch	10^{10}	10^{11}
total intensity	4.3×10^{13}	2.5×10^{13}
long. emit. at inj. (eVs)	0.18	0.35
long. emit. at ext. (eVs)	1.2-2.0	0.5-1.0

Table 1: Parameters of fixed target and nominal LHC beam (FT) cycle. The comparison between the parameters of FT and nominal LHC beam in the SPS is shown in Table 1.

As one can notice the main difference between the FT and LHC beam is the much higher intensity of the LHC bunch. Another important parameter is bunch spacing.

In the fixed target cycle different signatures of instabilities are observed at injection, after transition crossing and towards the end of the cycle, [11]. We see bunch shape oscillations (different multipoles, from dipole to octupole, depending on cycle time and intensity) together with the growth of a wide band beam spectrum which reaches maximum amplitude on the flat top.

Our studies of multi-bunch instabilities could be divided into 3 parts: analysis of the effect on the beam, a search for sources and a study of possible cures. The results of the first two are presented below. The cures are summarised in [10].

3.1 *Effect on the beam*

The voltage for the FT cycle in normal-operation is shown in Fig. 1 together with the corresponding bucket area.

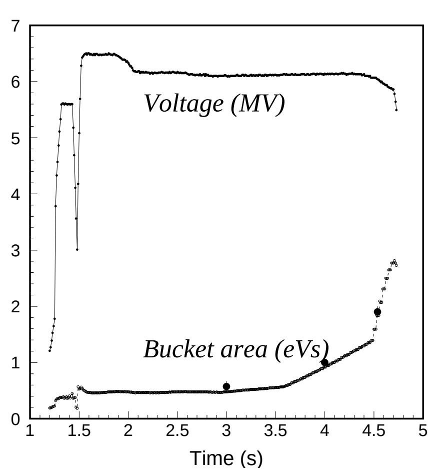

Figure 1: Normal-operation voltage and corresponding bucket area in fixed target cycle. Filled circles show estimated emittance for beam with total intensity 4.1×10^{13}.

For a low intensity bunch with emittance $\varepsilon = 0.18$ eVs (value at injection) the calculated variation of the bunch length during this cycle is shown in Fig. 2.

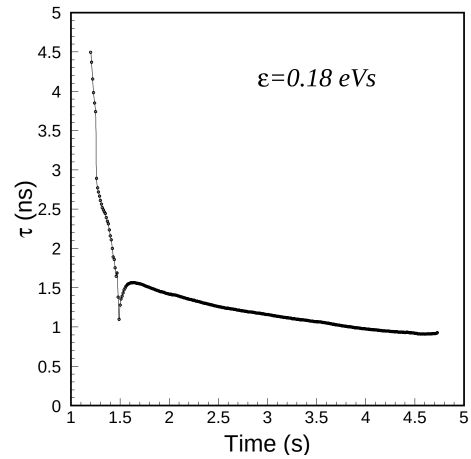

Figure 2: Calculated length of low intensity bunch for normal-operation voltage program in fixed target cycle.

Measurements of bunch length starting just after transition crossing, [2], done from bunch profile (at 0.85 of the peak line density) for beam with total intensity $N_{tot} = 4.2 \times 10^{13}$ are presented in Fig. 3.

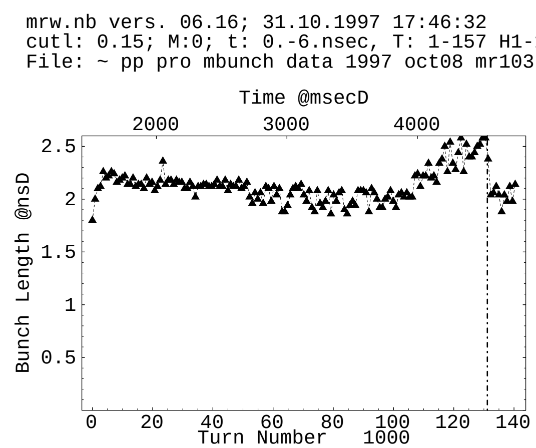

Figure 3: Measured bunch length of high intensity beam for normal-operation voltage program in fixed target cycle.

As one can see, at the end of the cycle instead of decreasing (as in Fig. 2 for constant emittance) the bunch length starts to grow. Emittance estimated from bunch length measurements at different moments in the cycle is shown in Fig. 1 (circles). After transition crossing bunch emittance continuously blows-up practically filling all space available in the bucket. At high intensity the longitudinal emittance increases from injection by almost a factor 10 (from 0.2 eVs to 2 eVs), filling completely the bucket. Reducing the voltage at any single point in the cycle immediately led to detectable beam loss.

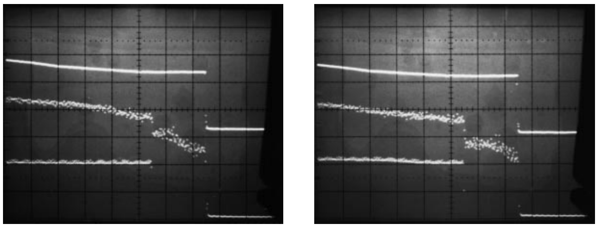

Figure 4: 200 MHz RF voltage (upper curve), peak detected signal (middle curve) and beam current (lower curve) for modified voltage program. Total intensity 4.1×10^{13} (left) and 4.2×10^{13} (right). Trigger 4.0 s, horizontal scale 0.1 s/div.

Beam behaviour with voltage programes different from normal operation was also studied, [2]. By gradually decreasing the voltage after transition (and keeping as long as possible the smallest bucket area without losses) for a total intensity of 4.2×10^{13} we were able to arrive to 445 GeV (first fast-slow extraction) with voltage 4 MV and smaller emittances (1.2 eVs) than for normal operation. In normal operation the voltage after transition crossing is kept at its maximum value, see Fig. 1. An example of these measurements for 2 different intensities is shown in Fig. 4, where for slightly higher intensity (4.2×10^{13}) beam losses could be detected from the beam current signal.

Bunch to bucket transfer to LHC without any additional RF system requires short bunches (< 1.7 ns) and therefore an increase of voltage before extraction. For such a voltage program emittance was growing at the end of the cycle faster again (1.3 eVs at 445 GeV).

Using different voltage programs we were able to find the minimum bucket area (for no observed losses) at the end of the cycle for almost fully (10/11) and partially (1/11, 3/11, 5/11) filled rings. Results of these measurements are shown in Fig. 5. Filled and empty symbols are data obtained with slightly different voltage programs, [12].

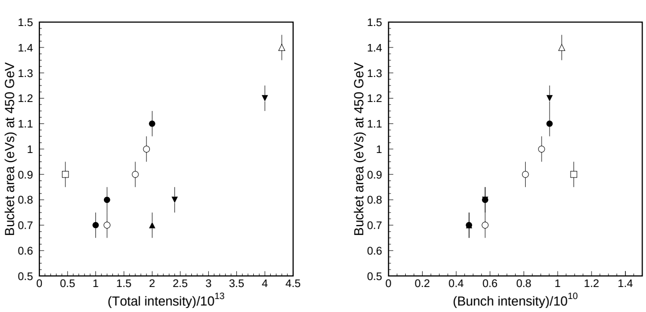

Figure 5: Bucket area for no observed losses at the end of the cycle as a function of total (left) and bunch (right) intensity for different filling patterns of the SPS ring: triangles - 10/11 of the ring filled, circles - 5/11 and square - 1/11.

In Fig. 5 (left) the final bucket area attained is plotted as a function of total intensity in the machine. For a given filling pattern, the emittance reached grows strongly with intensity. However there is also a notable dependence on the filling pattern. Plotting the emittance as a function of bunch intensity, as in Fig. 5 (right), clarifies the picture. Here the dependence on filling pattern is significantly reduced. It means that, to a first approximation, the longitudinal emittance at the end of the ramp is defined by the intensity per bunch and much less by the total intensity. Also one can notice that for a larger gap in the ring the beam is more stable. All this is an indication of short range wake fields.

Why are things getting worse towards the end of the cycle? For equally spaced bunches the threshold for coupled-bunch instability due to a resonant impedance, [13], [14], can be presented in the form:

$$R_{sh} < \frac{|\eta| E}{e I_0} \left(\frac{\Delta p}{p}\right)^2 \frac{\Delta \omega_s}{\omega_s} \frac{F}{f_0 \tau} x G(x), \qquad (2)$$

I_0 is the average beam current, $\frac{\Delta\omega_s}{\omega_s}$ is the relative synchrotron frequency spread and the formfactor $F \sim 0.3$ is defined by the particle distribution.

Function $xG(x) = x \min\{J_m^{-2}(\pi x)\}$, where $x = f_r \tau$ and $J_m(x)$ is the Bessel function of the order m, is shown in Fig. 6. At a given moment in the cycle the threshold is minimum for an impedance with frequency $f_r^{min} \simeq 0.43\tau$.

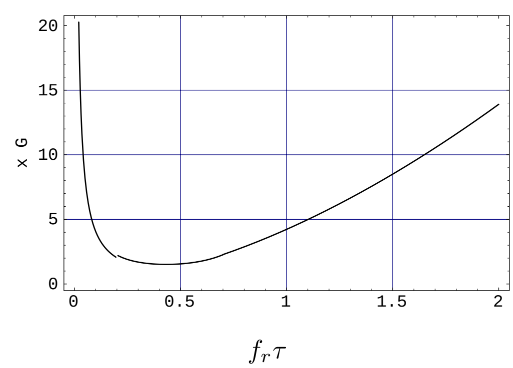

Figure 6: Function xG(x) from equation (2).

The instability threshold calculated during the normal operation FT cycle for emittance of 0.18 eVs and for the frequency $f_r = f_r^{min}$ which always corresponds to the worst case (minimum of function $xG(x) \simeq 1.5$) is drown in Fig. 7 as a lowest line.

The two other curves are examples for two different but constant resonant frequencies, which were chosen in such a way that, during the cycle, for one of them the working point in Fig. 6 is moving towards the minimum and for the second - away.

As one can see in all cases the threshold is decreasing from transition to the end of the cycle.

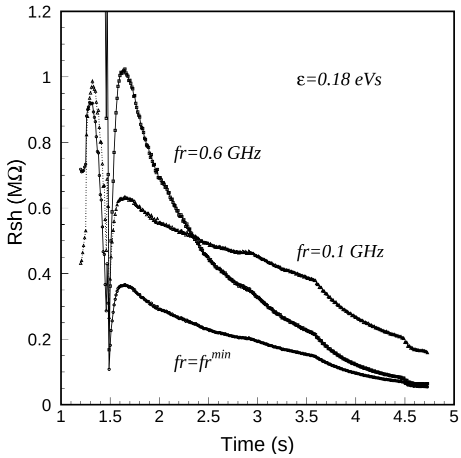

Figure 7: Coupled bunch instability threshold during normal operation in fixed target cycle for beam intensity 4.2×10^{13} and different resonant frequencies f_r.

Lowering the RF voltage leads to an increase in synchrotron frequency spread, but also to a decrease in momentum spread. As a result the threshold goes up but not as much as in the case of applying an additional higher frequency (800 MHz in the case of the SPS) RF system, [11], when a high synchrotron frequency spread can be kept simultaneously with a large momentum spread.

3.2 *Sources of multi-bunch instabilities*

We tried to identify sources of coupled bunch instabilities, mainly from measurements of the beam spectrum. However it turned out to be less evident compared to the case of a single bunch. Usually during instability a very broad spectrum is observed with a maximum around 600-700 MHz, see Fig. 8 (left).

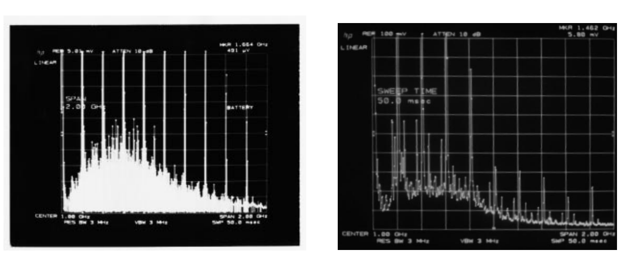

Figure 8: Beam spectrum from 0 to 2 GHz at the end of FT cycle for beam intensity 4.2×10^{13} (left) and 1.6×10^{13} (right). Horizontal scale 200 MHz/div, vertical scale linear.

The amplitude of this spectrum starts to grow after transition increasing towards the end of the cycle. This signal is not observed below transition nor just after. As intensity decreases the signal starts to grow later in the cycle. In general this behaviour is in good agreement with the calculated threshold, see Fig. 7. At high intensity the spectrum between RF harmonics lines contains many difficultly distinguishable peaks.

The stable beam spectrum has lines at frequencies pMf_0, where M is number of bunches in the ring (assuming equadistant bunches) and $-\infty < p < \infty$ is an integer. The envelope of the spectrum is defined by the Fourier transform of the bunch linear density $\lambda(t)$. Due to the beam gap there is an additional modulation of the spectrum at revolution lines around the main lines pMf_0.

Unstable beam spectrum due to a single resonant impedance at frequency f_r has peaks at frequencies

$$f = pMf_0 + nf_0 + mf_s.$$

Here $n = 0, 1... M - 1$ defines the phase shift $(2\pi n)/M$ between two adjacent bunches and can be found from equation $f_r = p_1 h f_0 + nf_0 + mf_s$, ($p_1$ is some integer). The mode number of the excited multipole $m = 1, 2...$ depends strongly on bunch length (approximately $m \simeq (f_r\tau)/2$). For a given m, the envelope of this spectrum depends on the particle distribution in the bunch and f_r, see [15]. Examples of the spectrum envelope calculated for different values of f_r and bunch distributions of the form

$$\lambda(t) = \lambda_0 \left(1 - \frac{4t^2}{\tau^2}\right)^{\mu+1.5} \qquad (3)$$

are shown in Fig. 9. They suggest that it is difficult to make conclusions about the resonant frequency of the driving impedance from the shape of the spectrum envelope (see measurements in Fig. 8).

In our studies we tried to find n - the coupled-bunch mode number both from the beam spectrum and from the phase shift between oscillating bunches. However the last method so far was less successful. Measurements of m were done from the mountain range display.

The analysis presented in the previous section gives some idea about the value of shunt impedance which can drive the coupled bunch instability during normal operation cycle. Comparison of threshold values with known sources of impedance, like the lowest HOM in the different RF systems of the SPS, see [7], suggests many possibilities. In fact the beam should already be already at much lower intensities (than 4.2×10^{13} for which the threshold was calculated in Fig. 7).

Indeed, for lower intensities clear signals were observed, see Fig. 8 (right). In a few cases sources could be identified as well.

In one MD in 1998 this was, for example, the fundamental mode of the 352 MHz RF system, when with non-optimal passive damping, R_{sh} was presumably more than 1.6 MΩ. With RF feedback on and 800 MHz RF system in bunch shortening mode, the threshold of instability was found to be at 8×10^{12}, [16]. This agrees with the threshold estimation from Fig. 7. After transition, the length of the low intensity bunch changes from 1.5 to 1.0 ns, see Fig. 2, so that for this impedance the threshold is close to the minimum as can be seen in Fig. 6.

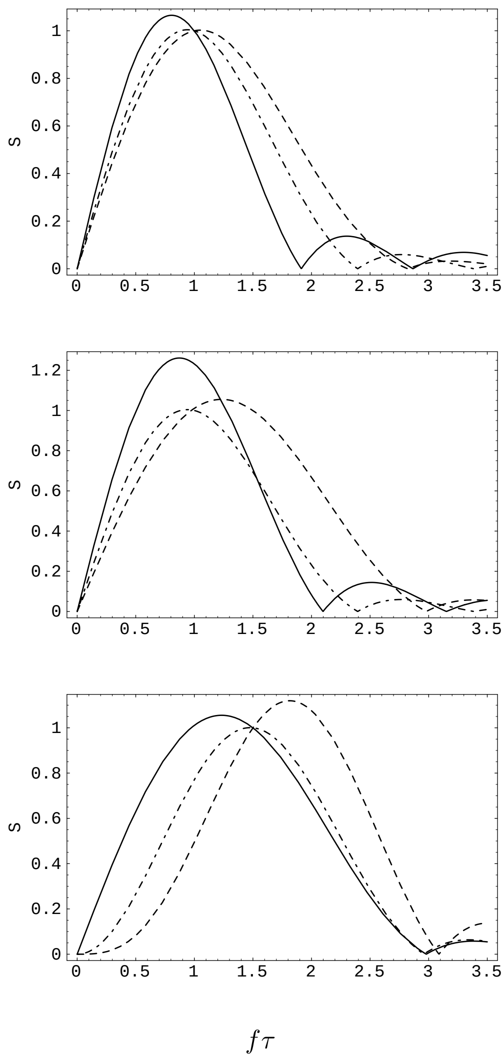

Figure 9: Top: beam spectrum envelope for $m = 1$, $f_r\tau = 1$ and μ = 0.5 (solid line), $\mu = 1$ (dash-dotted line) and $\mu = 1.5$ (dashed line). Middle: beam spectrum envelope for $m = 1$, $\mu = 1$ and and $f_r\tau$ = 0.5 (solid line), $f_r\tau = 1$ (dash-dotted line) and $f_r\tau = 1.5$ (dashed line). Bottom: beam spectrum envelope for $f_r\tau = 1.5$, $\mu = 1$ and $m = 1$ (solid line), $m = 2$ (dash-dotted line) and $m = 3$ (dashed line).

There are several candidates to explain the spectrum observed at an intensity of 4×10^{12} in another MD in 1998, where $nf_0 \simeq$ 87 or 113 were measured. One of them is the HOM in the TW 200 MHz RF system ($f_r = 912$ MHz), which will be in the SPS during LHC operation. Another possibility is the HOM in the standing wave 100 MHz RF system with $f_r = 288$ MHz (under the assumption that there is a problem with passive damping in some of the 4 cavities).

From threshold estimations during the cycle it is most probable that there is more than one source for the coupled bunch instabilities observed at high intensity. Significant contributions can come from the resonant impedances of the vacuum ports, which are also below the threshold at high energies.

4 LHC BEAM IN THE SPS IN 1998 AND FUTURE PLANS

In 1998 there were two MD periods with LHC type beam in the SPS. We had one injection from the PS with 83 bunches spaced by 25 ns. The intensity per bunch was varied in the range $(0.3 - 1) \times 10^{11}$. Emittance and bunch length were significantly larger than specified for the LHC beam, so that the bucket was practically full for the lower intensity and even satellite bunches were observed at higher intensity after capture into the 200 MHz RF system of the SPS.

There are some observations from the first MD on 1.09.98:

- We had strong head-tail instability leading to large beam losses at injection and during ramp due to imperfect correction of chromaticity.
- PS structure (7.6 MHz) was very visible, with more than 10 $\%$ variation in bunch intensities.
- The coupled bunch instability observed was identified to be due to the 352 MHz RF system.
- When the 40 MHz cavity in the PS tripped, we had 5 ns bunch spacing after capture in the SPS and the beam was more unstable longitudinally than before with 25 ns spacing.

In the second MD on 5 December chromaticity was corrected (OP group) and no head-instability was observed. We worked in storage at 26 GeV with intensity 3×10^{10}. Attempt to increase intensity per bunch to nominal value was unsuccesful for many reasons.

For 1999 we plan:

- Study of the stability of the LHC beam in the SPS

  - at injection (using p2 cycle) with both a single bunch (bunch lengthening) and many bunches,

  - during ramp (includes optimization of voltage program),

  - on the flat top (emittance measurements).
- Identification of sources of coupled-bunch instability using fixed target cycle (with variable intensity).
- Continued development of cures for instabilities.

5 ACKNOWLEDGMENTS

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