IMPEDANCE REDUCTION IN THE CERN SPS AS SEEN FROM LONGITUDINAL BEAM MEASUREMENTS

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Abstract

The longitudinal single bunch (microwave) instability of the proton beam in the CERN SPS, observed for the first time in 1977, became an important issue with the high intensity and high quality beams required for transfer to LHC. The main sources of impedance causing this instability were found in 1996 from measurements of the spectrum of unstable single bunches. During the 2000/2001 shutdown the major part of an impedance reduction programme was completed. Comparative beam measurements from before and after this programme are presented. While results obtained with short captured bunches allow us to see the overall bunch stability improvement, measurements with long bunches and RF off allow this impedance change to be distinguished at particular frequencies.

1 INTRODUCTION

Microwave instability in the SPS was observed in the past years in practically all operation modes: with leptons and protons, below and above transition energy, with RF on and RF off, and at debunching. It could be identified by the longitudinal emittance blow-up with intensity associated with high frequency (microwave) signals in the range above 1 GHz. Before LHC beam was available in the SPS, estimations showed that LHC bunches, injected into the SPS at 26 GeV (above transition) would be unstable well below nominal intensity, 1.1×10^{11} protons per bunch. Later, in 1999, continuous emittance blow-up of LHC beam was indeed observed on the flat bottom for bunch intensities above 3×10^{10}.

Different possible ways of removing this limitation were studied early in the project, including installation of extra quadrupoles to decrease transition energy in the SPS, more cavities to raise the momentum spread of the injected beam, an increase in extraction energy from the injector (PS) and others. Among them the most attractive cure was to eliminate the source of instability, at that moment unknown. A series of intensive beam studies, started in 1995, finally identified the impedance of the 1000 pumping ports in the ring as a main source of microwave instability. This was achieved using measurements of unstable bunch spectra with RF off, where all modes belonging to these cavity-like objects could be seen as resonant peaks [1]. Shielding these pumping ports involved not only complex design of sliding contacts, but also very hard installation work requiring the displacement of 400 dipole magnets [2]. This task was completed during the 2000/2001 shutdown.

The SPS impedance reduction programme also included the removal of all lepton equipment and the shielding or partial removal of different proton septa and kickers, which were suspected to be a source of instability observed in the frequency range around 400 MHz (for more details see [3]).

In this paper we report on the measurements done with similar bunch parameters before and after impedance reduction: with RF on to see the global effect on bunch stability and with RF off to see changes in detail.

Measurements showing the reduction in the transverse impedance are presented in [4].

2 LONGITUDINAL BUNCH STABILITY

Two types of comparative beam measurements were made in 1999 and 2001 with relatively short single bunches captured on the injection plateau at 26 GeV by the 200 MHz RF system: measurements of quadrupole oscillation frequency and bunch length as a function of intensity.

A voltage of 900 kV was chosen in 1999 to capture the highest bunch intensities without particle loss. Unavoidably this voltage was too high for matching at low intensities in 1999 and at all intensities in 2001, and led to quadrupole oscillations immediately after injection. Its frequency, measured from oscillations of the peak detected (PD) signal at different bunch intensities before and after the SPS impedance reduction is presented in Fig. 1.

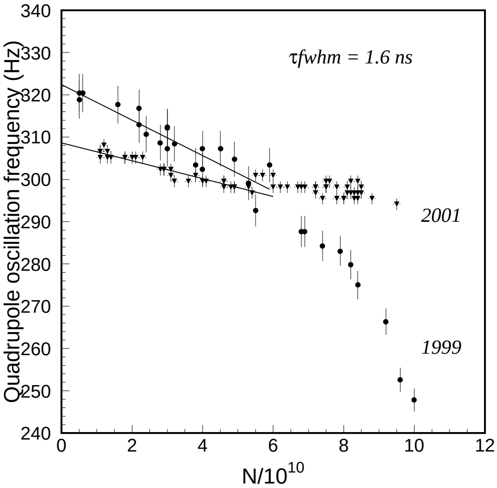

Figure 1: Quadrupole oscillation frequency measured from peak detected signal as a function of bunch intensity in 1999 and 2001.

The linear shift of quadrupole frequency f_2 with intensity N can be described as

$$f_2(N) = a - bN \times 10^{-10},$$

where a is the quadrupole frequency at zero intensity. The coefficient b is proportional to the low frequency inductive impedance $\mathrm{Im}Z/n$.

Coefficients a and b, measured from oscillations of the PD signal (a_1, b_1) and bunch length (a_2, b_2) for intensities up to 6×10^{10} for two different sets of initial bunch length τ_{FWHM} (full width at half maximum), are shown in Table 1.

Run	$\bar{\tau}_{FWHM}$ ns	ε (PS) eVs	a_1 Hz	b_1 Hz	a_2 Hz	b_2 Hz
1	1.87	0.25	308.6	5.6		
2	1.63	0.15	322.4	4.2	323.0	4.2
3	2.01	0.16	309.9	1.8	308.3	1.6
4	1.56	0.15	306.1	2.1	307.9	1.7

Table 1: Results of measurements. Runs 1 & 2 were conducted in November 1999, runs 3 & 4 in August 2001.

For comparable bunch parameters Table 1 shows on average a factor 2.5 decrease in $\mathrm{Im}Z/n$. This is very close to what one could expect from the impedance budget for $\mathrm{Im}Z/n$ in 1999 and 2001. Contributions from the different machine elements are shown in Table 2. All items were in the ring in 1999 and only the top three in 2001.

Element	No.	$\mathrm{Im}Z/n$ [Ω]
TW200-F cavities	4	4.9
TW200-HOM	4	0.25
TW800-F cavities	2	0.35
Lepton RF cavities	28	1.7
Pumping ports	900	3.0
MKE + MKP kickers	6	2.0
MSE + MST septa	8	0.1
Bellows	900	0.1
Total reduction		6.8

Table 2: Low frequency inductive part Z/n of different elements (1999).

Bunch length increases with intensity firstly due to potential well distortion ($\mathrm{Im}Z/n$) and then, above some threshold intensity, also because of emittance blow-up due to microwave instability. Bunch lengthening measurements, done in the same intensity range, see Fig. 2, were dominated in 1999 by the microwave instability with a threshold around 1×10^{10}, and in 2001 by the effect of potential well distortion. The 1999 threshold when scaled to LHC bunch parameters gives a threshold intensity around 4×10^{10} - very close to observations with LHC beam in the past (see above). No significant losses were observed in 2001 with bunch intensities up to nominal.

3 UNSTABLE BEAM SPECTRA

The same method which allowed us to find the dominant longitudinal impedances in the SPS ring [1] was used last year to see changes at particular frequencies during the implementation of the impedance reduction programme.

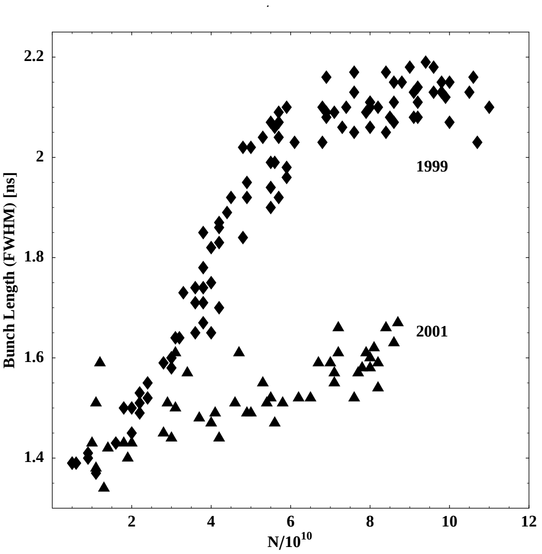

Figure 2: The bunch length (FWHM) measured 600 ms after injection as a function of bunch intensity in 1999 and 2001. Initial bunch length (FWHM) 1.6 ns, $\epsilon = 0.15$ eVs.

For these measurements, long (around 25 ns) single bunches were injected into the SPS at 26 GeV with RF switched off. Their small momentum spread ensures slow debunching and relatively fast instability growth rate (proportional to R/Q of the resonant impedance). This instability leads to line density modulation at resonant frequencies f_r of the guilty impedances. In frequency domain one can see the resonant peaks at f_r with width inversely proportional to bunch length (this is why long bunches are necessary). This data can be obtained from the Fourier transform of bunch profiles (as in Fig. 3, which shows a projection of a mountain range in frequency domain) or directly from a spectrum analyser (as in Fig.4, with the maximum amplitude at a given frequency recorded during some observation time). The last approach was used for frequencies above 2 GHz - the limiting frequency of the first method due to a 4 GHz sampling rate. In both cases a signal from the same wide-band pick-up was used to accumulate data from at least 10 bunches for each measurement.

In Figs. 3(a), 4(a) we present results of bunch spectra measurements made in 1999, which clearly show peaks at 200 MHz and 800 MHz due to travelling wave RF cavities, at 400 MHz due to kickers, and at 1.5 GHz, 1.9 GHz, 2.4 GHz and 2.8 GHz due to pumping ports. In 2001, with similar bunch parameters, all these peaks, except at 200 MHz and above 2.8 GHz, are practically invisible (see Figs. 3(b) and 4 (b)).

Without the emittance blow-up due to microwave instability the signal at 200 MHz reaches higher amplitudes than before, however its growth rate measured as a function of intensity is the same as before and very close to that found in simulations.

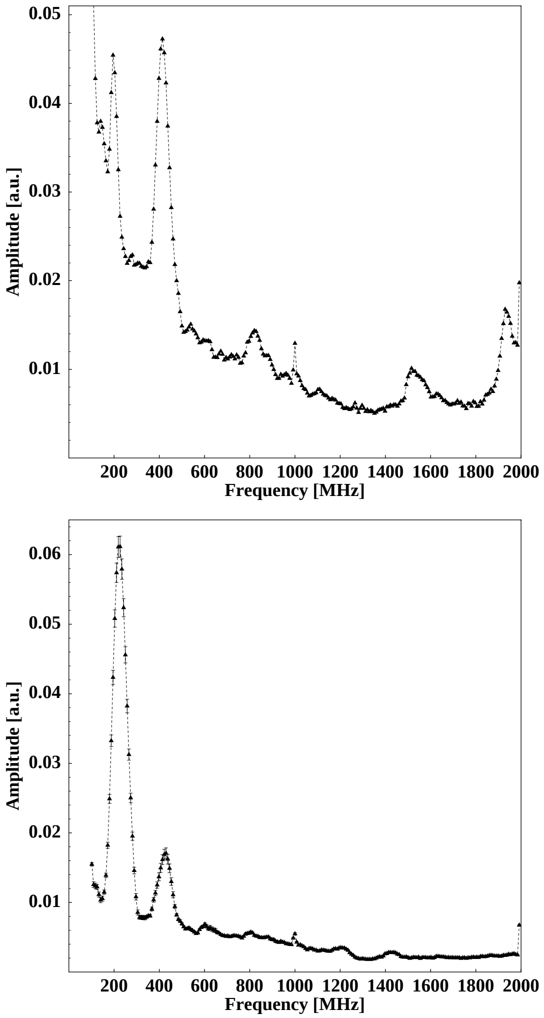

Figure 3: Average projections of Fourier spectra up to 2 GHz in 1999 (top) and 2001 (bottom). Bunch parameters: $N = 6 \times 10^{10}$, $\epsilon = 0.22$ eVs, $\tau = 25$ ns.

The nature of the high frequency signals above 2.8 GHz which were not removed (Fig. 4 b), is not yet clear. The cut-off frequency of the pick-up itself is around this value and more studies are necessary to clarify the situation.

4 SUMMARY

As a result of the recent impedance reduction programme the stability of a single bunch in the SPS is significantly improved. The microwave instability is not observed in the bunch length measurements of 2001 (intensities up to 10^{11} p/bunch, ε = 0.15 eVs), so that one can expect even the ultimate LHC bunch to be stable at 26 GeV ($N = 1.7 \times 10^{11}$, ε = 0.35 eVs). The life time of the LHC beam at 26 GeV in the SPS has clearly increased in 2001 and no losses were observed. Efficient shielding of the pumping ports is confirmed by the absence of high frequency signals in the beam spectra measurements of 2001. The screening and removal of MKE and MKP kickers led to the disappearance of the instability at 400 MHz.

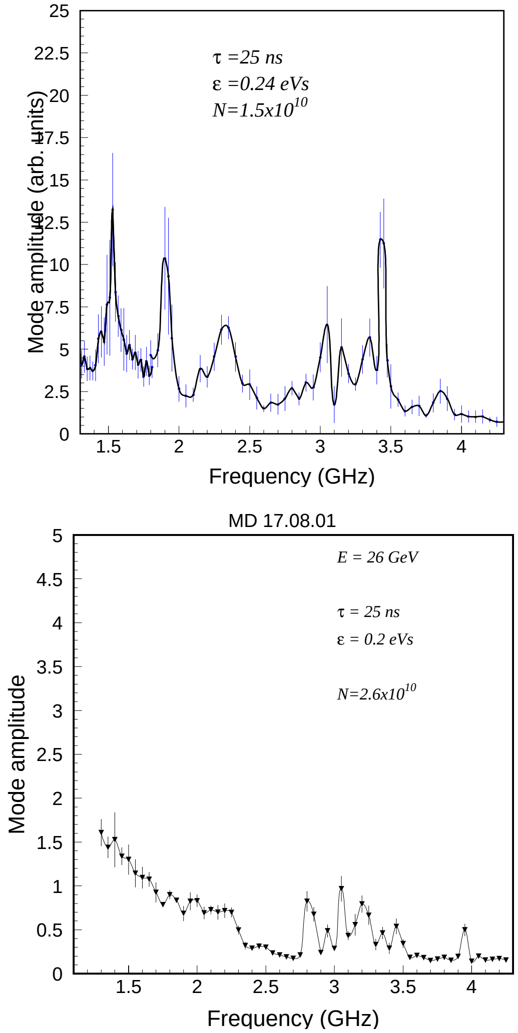

Figure 4: The mode amplitude scan at high frequencies in 1999 (top) and 2001 (bottom).

We thank G. Arduini, D. Manglunki, S. Hancock and the CERN PS and SPS operations groups for their help.

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