RF AMPLITUDE MODULATION TO SUPPRESS LONGITUDINAL COUPLED BUNCH INSTABILITIES IN THE SPS

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Abstract

Without specific counter measures, the LHC type beam in the SPS suffers from longitudinal coupled bunch instabilities. To get rid of them, the SPS impedance has been decreased in the last years and the operation of a high frequency Landau damping system has been established. In case of the absence of this Landau damping system one may alternatively introduce an RF amplitude modulation to stabilize the beam. We present results obtained by this method in the SPS and considerations for a potential increase of the longitudinal stability of the LHC.

INTRODUCTION

In the SPS, LHC type beams are accelerated from 26 GeV to 450 GeV. Without specific counter measures, they suffer from both longitudinal single and coupled bunch instabilities. As a result, the bunches show an increased tail population which could lead to losses at injection into the LHC due to uncaptured particles. To overcome these problems, the SPS impedance has been decreased and unused cavities have been removed [1, 2, 3]. Microwave instabilities are no longer observed at low energy, but coupled bunch instabilities still appear starting at energies between 200 GeV and 280 GeV up to high energy. To suppress these latter instabilities, a Landau damping RF system is used [2, 3, 4]. This system operates with a frequency of 800 MHz, which is four times the frequency of the main RF system (200 MHz).

The motivation for our study was to try another stabilization method using the main RF accelerating system. If the LHC itself suffers from unexpected longitudinal coupled bunch instabilities [5], such a method could be of great interest, since no higher harmonic system is foreseen.

A Landau damping system increases the incoherent synchrotron frequency spread, the spread of single particles within a bunch. Less particles in a bunch are resonantly driven by external harmonic excitations, for example beam loading transients caused by other oscillating bunches. The motion of the bunch centre is damped.

Alternatively one may increase the coherent frequency spread [6, 7, 8], that is the bunch-to-bunch frequency spread. Then, coupling between the different bunches is reduced and the whole multi-bunch beam is damped.

According to Sacherer [6], the coherent r.m.s. frequency spread S, required to damp a coupled bunch phase oscillation, has to be larger than the frequency shift due to the machine impedance. The coupling between the bunches can also be suppressed by an incoherent frequency spread s. For phase oscillations, the incoherent spread has to be four times the frequency shift.

The bunch to bunch frequency spread can be increased by a modulation of the RF amplitude (RF AM) locked on the beam revolution. At the SPS this method has already been applied in the past with the proton fixed target beam [9]. It is easily possible as the cavity filling times [10] are shorter than the revolution time.

REQUIRED COHERENT SPREAD

For LHC type beams in the SPS, the number of all bucket positions is 924. To fill the LHC, the SPS will accelerate three or four batches of 72 bunches with gaps of 8 bunch positions in between. For the present study we accelerated only one batch.

The relative r.m.s synchrotron frequency spread S/f_s due to an RF AM is given by the r.m.s. value of the individual synchrotron frequencies of the bunches. We applied a RF voltage change from the first to the last bunch from $V_\mathrm{m} + V_\mathrm{mod}$ to $V_\mathrm{m} - V_\mathrm{mod}$, where V_m is the mean value of the RF voltage. Considering the filling schemes, the coherent frequency spread as a function of the voltage ratio $V_\mathrm{r} = V_\mathrm{mod}/V_\mathrm{m}$ is then

$$\frac{S}{f_\mathrm{s}} \approx 0.295\, V_\mathrm{r} \quad \text{for} \quad V_\mathrm{r} \lesssim 0.5.$$

The SPS beam is already successfully damped longitudinally by the Landau damping system (800 MHz). Therefore, we can estimate the required frequency spread S/f_s due to an RF AM as follows:

The incoherent synchrotron frequency spread is given by the spread between the frequencies at bunch center and the bunch edge ($4\,\sigma$). Assuming a conserved standard emittance of 0.45 eVs (corresponding to the $4\,\sigma$ bunch length), these frequencies are determined for operation with only the 200 MHz RF system and for operation with the 200 MHz and 800 MHz RF systems together [11]. Normalizing the difference values with respect to the small amplitude synchrotron frequencies without 800 MHz results in the additional spread of $s/f_s = 0.245$, supplied by the 800 MHz system. It suppresses a bunch coupling having a relative frequency shift of up to one fourth of this value, $\Delta f_\text{threshold}/f_s = \frac{1}{4} s/f_s$ [6]. A relative coherent spread S/f_s, larger than this threshold value results in the same stability [6]:

$$\frac{S}{f_s} \geq \frac{\Delta f_\text{threshold}}{f_s} = \frac{1}{4}\frac{s}{f_s} = 0.062$$

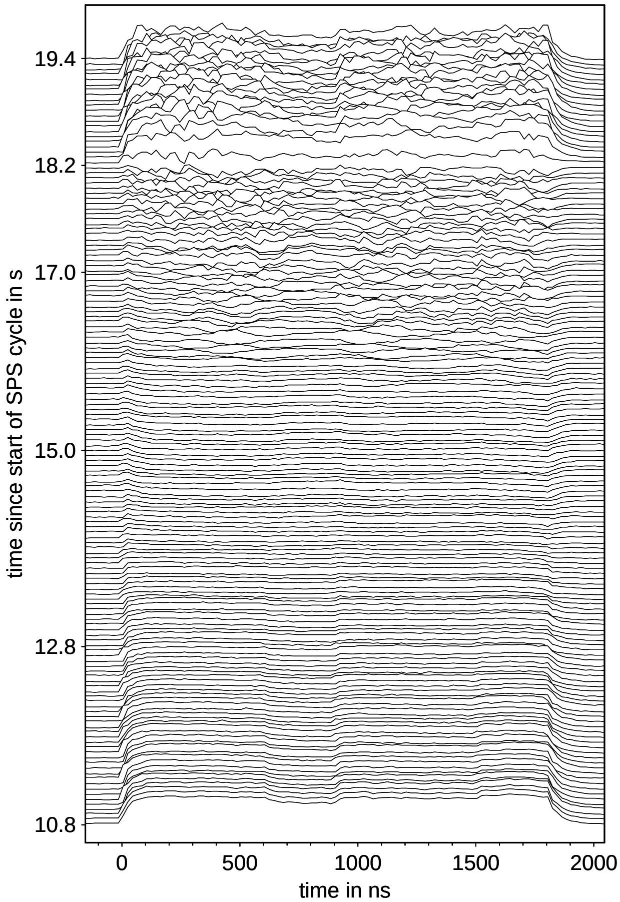

Figure 1: Mountain range measurement of the pick up signal of the 'longitudinal damper'. The 800 MHz system and the RF AM are switched off. At the end of the acceleration (18.2 s) the synchronous phase changes from 25.5° to zero.

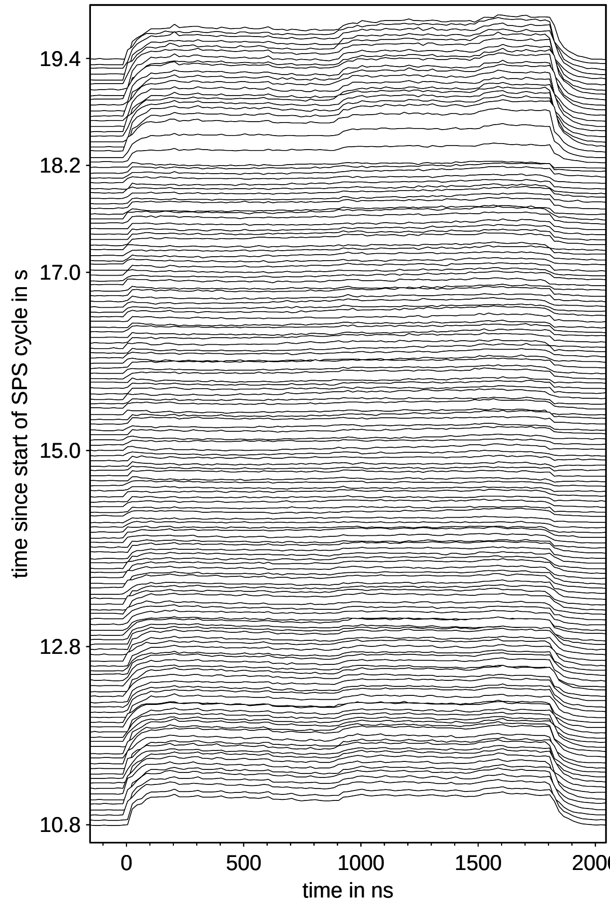

Figure 2: Mountain range of phase pick up. The 800 MHz system is off and the RF AM is switched on at 12.8 s (64 GeV).

This value has to be supplied by the RF amplitude modulation. It corresponds to a voltage ratio of $V_\mathrm{r} = 0.22$.

STABILIZATION DUE TO AM

RF amplitude modulation was used at energies above 64 GeV.

To observe coupled bunch instabilities in the SPS, we used the phase signal of the longitudinal damper. In the stable case, the signals are smooth along the bunch trains, in case of coupled bunch instabilities one observes ripples.

The measurements presented compare three cases: operation without the 800 MHz Landau damping system and without RF AM, operation with the 800 MHz system and without RF AM and operation without the 800 MHz system but with RF AM. The bunch intensity was $0.27\ 10^{11}$ protons per bunch, that is about one fourth of the nominal LHC intensity of $1.15\ 10^{11}$ protons per bunch.

Figure 1 shows a typical mountain range plot of the measured data in the case of operation with the 200 MHz system alone. After 16 s into the cycle, that is at about 280 GeV, the beam becomes unstable, observable as ripples on the phase pick-up signal.

Figure 2 shows the result when the SPS is operated without 800 MHz but with RF AM with a sufficiently high amplitude. The ripple observed previously vanished, the beam is stable.

The mountain range plot for the case when the 800 MHz system is in operation looks similar to Figure 2.

With RF AM the beam was stable for a voltage ratio of $V_\mathrm{r} = 0.16 \pm 0.02$. At the next smaller value measured $V_\mathrm{r} = 0.12 \pm 0.02$ the beam was unstable.

Afterwards, we increased the beam intensity in steps up to $1.01\ 10^{11}$ protons per bunch. The beam was still stabilized up to high energy, but there we observed an unstable behavior. The fact that the beam becomes only unstable at 450 GeV indicates that we are near the intensity threshold for RF AM with the voltage ratio of 0.16.

Even at high intensities, we observed no increased beam losses as compared to normal operation.

APPLICATION TO THE LHC

In the case of broad band impedances, bunches with nearly equal synchrotron frequencies will couple even if distant bunches have different synchrotron frequencies. Using sinusoidal modulation leads to relatively large zones at the turning points where successive bunches have comparable synchrotron frequencies and may couple. These zones are significantly reduced with triangular modulation.

Ideal, sharp cusps are not possible due to RF power and bandwidth restrictions. Triangular shapes with rounded cusps should be possible in the LHC for voltage ratios of $V_{\mathrm{r}} < 0.143$ [13, 14]. The maximum ratio can be obtained only if no RF power is needed for transient beam loading compensation.

Shorter bunches cause stronger wake fields than longer ones and, as a result, they couple more strongly to each other. If one operates near the instability threshold, bunches at the maximum voltage couple first and drive after some time the remaining bunches [12]. This effect is minimized by placing the area of maximum voltage in the beam dump gap.

Using the LHC filling pattern, we obtain a coherent frequency shift as a function of the voltage ratio of $S/f_{\mathrm{s}} \approx 0.303\,V_{\mathrm{r}}$. According to [5], Landau damping will suppress longitudinal instabilities in the LHC for frequency shifts smaller than $\Delta f_{\mathrm{threshold,\,Landau}} = 0.58\,\mathrm{Hz}$. Operating the LHC with an RF AM, we gain additional longitudinal stability. Keeping a technical margin of 50% for transient beam loading compensation, a voltage ratio of $V_{\mathrm{r}} = 0.072$ leads to an instability threshold of

$$\Delta f_{\mathrm{threshold,\,7.2\%\ AM}} \approx 0.51\,Hz.$$

By operating the LHC with RF AM we double the longitudinal stability, since

$$\Delta f_{\mathrm{threshold}} = \Delta f_{\mathrm{threshold,\,Landau}} + \Delta f_{\mathrm{threshold,\,AM}}.$$

The RF AM method may also become interesting in case of a demand for shorter bunches for an LHC upgrade. Shorter bunches have inherently less Landau damping and additional stabilization methods are necessary.

CONCLUSION

Longitudinal coupled bunch instabilities of LHC type beams in the SPS can be controlled by increasing the bunch-to-bunch synchrotron frequency spread with RF amplitude modulation. The achieved stability was comparable to the stability obtained by the 800 MHz Landau damping RF system in normal operation.

By using the values of the Landau damping system parameters in normal operation we estimated that a voltage ratio of $V_{\mathrm{r}} = 0.22$ was needed to obtain the same stability. In our experiments we found that a voltage ratio of $V_{\mathrm{r}} = 0.16$ was already sufficient to suppress instabilities up to $1.01\ 10^{11}$ protons per bunch. The difference between these values results certainly from the fact, that the 800 MHz values are optimized for accelerating LHC type beams consisting of four batches, whereas we accelerated only one batch. For accelerating four batches, the necessary voltage ratio for the RF AM will be higher.

The results show that a similar method should also work at the LHC if necessary. Using an RF AM at the LHC, we expect to increase the threshold for longitudinal instabilities by a factor of about two, without modification of the RF power amplifiers.

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