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Study of Different Operating Modes of the 4th RF Harmonic Landau Damping System in the CERN SPS

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Abstract

To study possible cures for multi-bunch instabilities observed with the present high intensity proton beam in the SPS, a fourth harmonic RF system was used during acceleration in bunch lengthening and bunch shortening modes of operation. The latter mode was found to be more efficient in controlling beam stability. We present an analysis of possible reasons.

1 INTRODUCTION

The SPS accelerator will be used as the injector for the LHC at present being constructed at CERN. At extraction to the LHC, 450 GeV, the longitudinal emittance of the bunches should be below 0.7 eVs, only 0.2 eVs above the injected value. One area of concern in satisfying this requirement is due to multi-bunch instabilities already observed in the SPS on the fixed target beam.

The fixed target cycle in the SPS accelerates protons from 14 GeV to 450 GeV crossing transition at 22 GeV. This is done with a 200 MHz RF system (harmonic number h=4620). Normally 10/11 of the ring are filled by bunches in every bucket with a maximum total intensity of 4.8×10^{13} protons.

Beam with parameters close to those required for LHC will be injected into the SPS for the first time at the end of 1998. We have used the existing fixed target proton cycle, which has similar intensity but different filling patterns in the machine, to study multi-bunch instabilities and their possible cures.

2 OBSERVATION OF MULTI-BUNCH INSTABILITIES

Multi-bunch instabilities are observed at injection and towards the end of the cycle, [1]. 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 (see Fig.1) which reaches maximum amplitude on the flat top.

As a result of these instabilities, at maximum intensity the longitudinal emittance increases 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 leads to beam loss.

At the moment the source of these instabilities is not clear but most likely is a mixture of the effect of 800 vacuum ports (which will be shielded during the next 3 years) and higher order modes in the five different RF systems of the SPS.

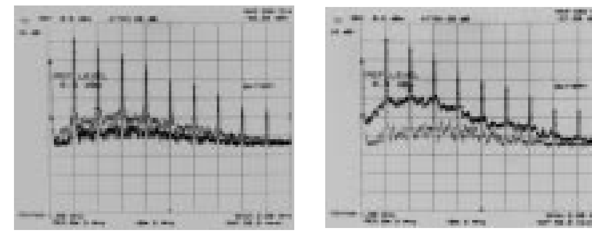

Figure 1: Beam spectrum from 0 to 2 GHz at 30 GeV without 800 MHz RF system (lower trace, left photo), with 800 MHz RF system in BL (upper trace in both photos) and BS (lower trace, right photo) mode.

We tried to cure these instabilities by increasing the synchrotron frequency spread and therefore Landau damping.

We first studied the possibility of increasing the synchrotron frequency spread in the bunch by modifying the voltage programme for the main RF system, [1]. By gradually decreasing the voltage after transition we were able to arrive at the flat top with smaller emittances (1.4 eVs) than for normal operation, where the voltage amplitude after transition crossing is kept at its maximum value. However bunch to bucket transfer to LHC requires short bunches ($<$ 1.7 ns) and therefore an increase of voltage before extraction. In this case emittance was also increasing, practically filling all space available in the bucket.

Below we consider the effect on Landau damping of the parameters of the higher harmonic RF system assuming that the voltage amplitude of the main RF system is fixed (in our case it was at the maximum value $\sim$ 6 MV).

For studies we used the existing fourth harmonic (800 MHz) RF system in bunch shortening (BS) and bunch lengthening (BL) modes of operation. Surprisingly in the latter case we not only did not observe any improvement in beam stability, but even some degradation, see for example the left photo in Fig.1.

Our difficulties in applying BL mode are similar to experimental experience in HERA, [2], where only BS mode is used for operation. Problems of operation in BL mode have also been faced in other machines, [3]. Below we consider possible reasons applicable to the SPS and maybe related to other accelerators as well.

3 EFFECT OF SECOND RF SYSTEM

In the double harmonic RF system the total voltage seen by the particle has the form

$$V = V_1 \sin\phi + V_2 \sin(n\phi + \Phi_2), \qquad (1)$$

where V_1 and V_2 are the voltage amplitudes of the main and high frequency RF systems, n is the ratio of harmonic numbers of the two RF systems (in our case n=4) and Φ_2 is the phase shift measured in radians at the higher frequency.

3.1 Zero amplitude synchrotron frequency

In action-angle variables the synchrotron frequency is a function of the action J. The synchrotron frequency spread $\Delta\omega_s$ in a bunch of emittance $\varepsilon = 2\pi J_b$ can be defined as the maximum of $[\omega_s(0) - \omega_s(J)]$ for $J \leq J_b$. For a monotonic dependence of $\omega_s(J)$, $\Delta\omega_s = \omega_s(0) - \omega_s(J_b)$. For a full bucket $\omega_s(J_b) = 0$. One usually expects that the synchrotron frequency spread in a double RF system is modified significantly in comparison with a single RF system if the synchrotron frequency at the center of the bunch $\omega_s(0)$ is also changed significantly from its previous value $\omega_{s0}(0)$. There are two possibilities, either it is reduced or increased. Due to the effect on bunch length they are called correspondingly bunch lengthening (BL) and bunch shortening (BS) modes of operation. In the first case the maximum change is obtained when the synchrotron frequency at the center of the bunch is zero. Together with the requirement of a quartic potential well at the bunch centre, this is what is usually called bunch lengthening mode in the literature, [4]. We will call this special case BLM mode.

In a double harmonic RF system

$$\omega_s^2(0) = \frac{\omega_{s0}^2(0)}{\cos\phi_{s0}}[\cos\phi_s + \alpha n \cos(n\phi_s + \Phi_2)], \qquad (2)$$

where $\alpha = V_2/V_1$ and the synchronous phase ϕ_s is connected with the synchronous phase in the single RF system ϕ_{s0} by the equation

$$\sin\phi_{s0} = \sin\phi_s + \alpha\sin(n\phi_s + \Phi_2). \qquad (3)$$

For a given value of V_2 one can find the phase shift Φ_2^m, which gives the maximum change in $\omega_{s0}(0)$, and determine the new synchronous phase ϕ_s^m. Let us assume that the change in synchronous phase $\Delta\phi_s^m = \phi_s^m - \phi_{s0} \ll 1$, then

$$\Delta\phi_s^m = -\frac{s\alpha\tan\phi_{s0}}{n\cos\phi_{s0} + s\alpha}, \qquad (4)$$

where $s = \mathrm{sgn}\{\cos(\mathrm{n}\phi_\mathrm{s} + \Phi_2)\}$ (s=1 for BL regime above transition and for BS below). The appropriate phase shift Φ_2^m can be easily calculated from eq.(3). Above transition this is

$$\Phi_2^m = -n\phi_{s0} - n\Delta\phi_s^m + \begin{cases} \arcsin\delta, & \text{BL} \\ \pi - \arcsin\delta, & \text{BS} \end{cases} \qquad (5)$$

where $\delta = \frac{s\sin\phi_{s0}}{n\cos\phi_{s0}+s\alpha}$. The opposite is true below transition. As one can, see for a stationary bucket ($\sin\phi_{s0} = 0$) the maximum change is obtained when $\phi_s = \phi_{s0}$, and then Φ_2^m equals zero or π.

For the proton cycle in the SPS, $\Delta\phi_s^m \ll 1$ is valid everywhere except very close to transition. We used formula (5) to programme the phase of the second RF system during acceleration for BL and BS modes of operation. Then the change in zero amplitude synchrotron frequency is:

$$\frac{\omega_s^m(0)}{\omega_{s0}(0)} = [1 + \frac{sn\alpha}{\cos\phi_{s0}}(1 + \frac{0.5\tan^2\phi_{s0}}{n^2 + sn\alpha/\cos\phi_{s0}})]^{1/2}. \qquad (6)$$

From this consideration it follows that for a given value of V_2, for $\alpha n \ll 1$ and small changes of $\omega_{s0}(0)$, BL and BS modes should have a similar effect. Indeed, in this case $\omega_s^m(0) \simeq \omega_{s0}(1 \pm 0.5\alpha n/\cos\phi_{s0})$. For larger values of the voltage V_2, such that $\alpha n \sim 1$, in BLM mode the change in central synchrotron frequency can be as big as ω_{s0}. For the same value of V_2 in BS mode this gives only a factor $\sqrt{2}$ increase in $\omega_{s0}(0)$.

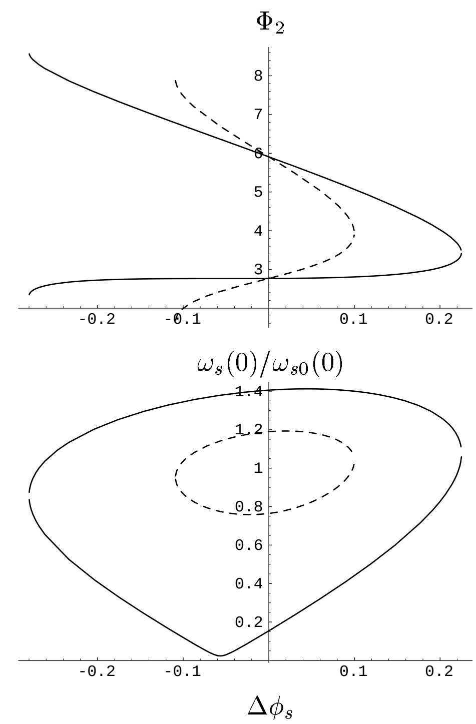

Figure 2: Phase shift Φ_2 and corresponding normalised synchrotron frequency $\omega_s(0)/\omega_{s0}(0)$ as a function of synchronous phase shift $\Delta\phi_s$ for $\phi_{s0} = 2.45$, $n = 4$ and $\alpha = 0.08$ (dashed line) and $\alpha = 0.188$ (solid line).

In Fig.2 we show $\omega_s(0)/\omega_{s0}(0)$ as a function of change in synchronous phase $\Delta\phi_s$ together with the phase shift Φ_2, which provides this change in synchronous phase, for $n = 4$ and $\phi_{s0} = 2.45$, the typical value for a large part (after transition crossing) of the cycle. The value $\alpha = 0.08$ was used in our experimental studies and $\alpha = 0.188$ corresponds to BLM mode. The latter can be found for given ϕ_{s0} and n from equation, [4]:

$$\alpha^2 = \frac{1}{n^2} - \frac{\sin^2\phi_{s0}}{n^2 - 1}. \qquad (7)$$

Upper parts of the curves in Fig.2 correspond to BS and lower to BL modes. As one can see the region of Φ_2 giving BS mode is much wider than for BL mode.

3.2 *Frequency spread in BL and BS modes*

Now let us consider the results of the choice of regime of operation of the second RF system on the synchrotron frequency spread inside the bunch.

In Fig.3 the normalised synchrotron frequency spread $\Delta\omega_s = [\omega_s(0) - \omega_s(J_b)]/\omega_{s0}(0)$ in a bunch with longitudinal emittance of $\varepsilon = 2\pi J_b = 0.3$ eVs is presented as a function of Φ_2 for the 2 different values of voltage amplitude used in Fig.2. In Fig.4 the synchrotron frequency is shown as a function of action J_b normalised to bunch emittance, for the same values of V_2 as in Fig.3, 1.15 MV (solid line) and 0.5 MV (dashed line), and the phase shifts Φ_2, which give maximum spread for $V_2 = 1.15$ MV in BL and BS modes.

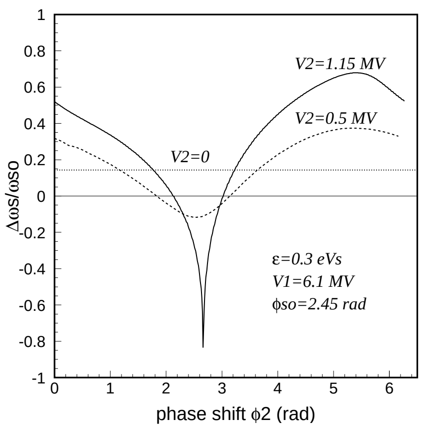

Figure 3: Normalised synchrotron frequency spread inside the bunch of 0.3 eVs emittance for 2 different values of voltage amplitude V_2 as a function of phase shift Φ_2.

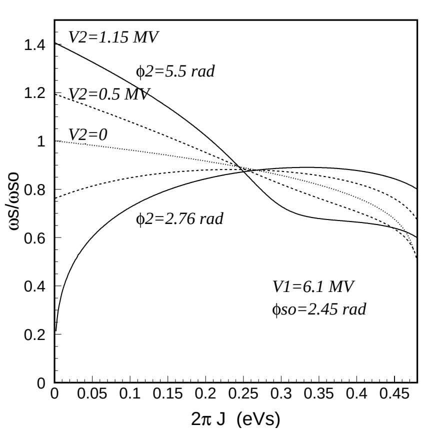

Figure 4: Normalised synchrotron frequency as a function of action normalised to emittance in a double harmonic RF system for BL and BS operation modes.

For $V_2 = 0.5$ MV the spread produced in BS mode is a few times bigger than in BL mode. What is also important, in BS mode the spread continues to grow with increasing emittance, so that after reaching the instability threshold the bunch has a chance for self-stabilization by emittance blow-up. This explains very well experimental results in the SPS (see Fig.1), where no improvement in beam stability was observed in BL mode with low amplitudes of V_2.

For this emittance of 0.3 eVs the optimum phase shifts Φ_2 in BL and BS modes are very close to values Φ_2^m obtained from consideration of maximum change in $\omega_{s0}(0)$, (see Fig.2). For BS mode the optimum phase shift Φ_2, giving maximum spread for given V_2, depends also on bunch emittance. In this example, for smaller emittances the optimum phase shift in BS mode decreases (for $\varepsilon = 0.1$ eVs this would be $\Phi_2 = 4.5$). However due to the quite flat dependence of spread on Φ_2 in BS mode this is not very important for operation.

For the higher value of V_2 the spread produced in BL mode becomes larger and larger while the region of phase shifts where it works gets smaller. In Fig.3 one can immediately notice the extremely narrow region in phase shift Φ_2 which gives a significant spread in BL mode.

Another important point concerning stability in the double harmonic RF system is related to the creation of regions where the derivative of synchrotron frequency $\omega_s'(J) = 0$, see Fig.4. The instability threshold for bunches with emittance reaching this region equals zero, [5]. Landau damping for particles in this region is lost and instability grows $\propto \sqrt{t}$. Measurements of bunched beam transfer functions done by noise excitation in the SPS on an intermediate flat top at 120 GeV with the double RF system in BL and BS modes, [6], showed in the first case a strong coherent signal with an amplitude 3 times larger than in the cases of a single RF system or double RF system in BS mode. This probably can explain the fact that beam stability when using BL mode was not improved but even degraded in comparison to the single RF system, see Fig.1.

This analysis shows that for producing the maximum synchrotron frequency spread BLM mode has an advantage only for bunches with very small emittances (in comparison with bucket area), see Fig.4, and the requirement of extremely accurate programming of phase shift between 2 RF systems during the cycle is the price to pay. In the absence of space charge effects and any requirements on bunch length increase, the regime of bunch shortening is more efficient and much easier to handle.

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