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CONTROLLED LONGITUDINAL EMITTANCE BLOW-UP IN THE SPS USING A 4TH HARMONIC RF SYSTEM

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The possibility of using phase modulation of the 4th harmonic RF system to produce controlled longitudinal emittance blow-up in the CERN SPS was studied experimentally. The choice of optimum RF parameters has found to be different from the case when the frequency of the additional resonator used for blow-up is much higher. The desired effect was obtained in a regime with large variation of the synchrotron frequency.

Keywords: Longitudinal emittance; High frequency cavity

1 INTRODUCTION

The longitudinal emittance of the LHC beam injected at 26 GeV from the PS to the SPS will be 0.35 eV s. The bunch length and longitudinal emittance at extraction from the SPS are defined by the 400 MHz RF system and by intrabeam scattering limitations to beam lifetime in the LHC. According to the latest information,[1] the longitudinal emittance can be in the range from 0.5 up to 1 eV s with a preference towards the lower value due to the problems of dynamic aperture in the LHC. In the SPS for stability reasons, the highest emittance is easiest to handle, however its transfer to LHC requires installing an extra RF system in the SPS 400 MHz superconducting LHC-type cavities. The optimum final bunch parameters will be

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defined after all measures forseen to reduce machine impedance and improve beam stability in the SPS have taken place.

The purpose of the experimental studies described here, see also Ref. 2, was to analyse the possibility of using the existing 800 MHz travelling wave RF system in the SPS with phase or amplitude modulation to produce controlled longitudinal emittance increase. This procedure has been operational in the PS since 1976,[3,4] where a 200 MHz RF system is used to blow-up the beam bunched at 9 MHz. Using a frequency 20 times higher than the main frequency for this purpose ensures a smooth and relatively fast (60 ms) process preserving the quality of the bunch distribution. This method is also used in the AGS, Brookhaven, since 1988.[5] The procedure has been studied in detail by means of numerical simulation in Ref. 6.

In the SPS, the 800 MHz RF system is proposed for blow-up of the beam bunched at 200 MHz. Due to the small harmonic ratio of the two RF systems available for this procedure the optimum choice of operational parameters becomes more critical.

The effect produced by phase or amplitude modulation of a high frequency cavity on the bunch can be explained,[7] using the theory of nonlinear resonances. The dependence of bunch blow-up on the different parameters of the system as predicted by theory has been checked experimentally in the PS.[8]

In the following section we present a brief summary of the theory fully described in Ref. 7. We analyse different conclusions which were checked experimentally. In the following part we describe results from measurement of the effect produced by phase modulation of the 800 MHz RF system on the bunch using different sets of RF parameters.

2 SUMMARY OF THEORY

In general the total voltage seen by the particle in such a system can be written in the form

$$V = V_0 \sin\phi + V_1 \sin[N\phi + \Phi(t) + \theta], \qquad (1)$$

where V_0 and V_1 are the voltage amplitude of the main and high frequency RF systems, $N = h_2/h_1$ is the ratio of the harmonic numbers of the two RF systems, θ is the phase shift between the two RF systems measured in radians at the higher frequency and the function $\Phi(t)$ represents the phase modulation:

$$\Phi(t) = \alpha \sin(\omega_{\text{mod}} t + \psi). \tag{2}$$

Here α and $\omega_{\text{mod}} = 2\pi f_{\text{mod}}$ are, respectively, the phase modulation amplitude and frequency. The initial phase ψ is not considered below since it should not influence the blow-up.[7]

To produce a significant change in bunch distribution, the resonance condition

$$k\omega_s(r) = l\omega_{\text{mod}}, \quad k, l \text{ are integers,} \tag{3}$$

should be satisfied. Here $\omega_s = 2\pi f_s$ is the synchrotron frequency which is a function of the synchrotron oscillation amplitude r defined by the equation

$$r^2 = 1 - \cos\phi + \frac{\dot{\phi}}{2\omega_{s0}^2}. \tag{4}$$

The value of r varies from 0 to 1 inside the bucket.

The high-frequency voltage applied produces a steady-state synchrotron frequency modulation

$$\Delta\omega_s(r) \simeq \varepsilon\omega_s(r)\frac{J_1(2Nr)}{r} J_0(\alpha)\cos\theta, \tag{5}$$

which is important to take into account[8] in condition (3). Here $\varepsilon = V_1/V_0$. This modulation is absent when $\cos\theta = 0$ ($\theta = \pi/2, 3\pi/2, \ldots$) or $J_0(\alpha) = 0$ ($\alpha = 2.4, \ldots$). The variation of synchrotron frequency inside the bunch for $N = 4$, $\varepsilon = 0.14$, $\alpha = 1.2$ and $\theta = 0$, $\pi/2$ and π is shown in Figure 1.

A change of modulation amplitude α also affects the "strength" of excitation which is proportional to $\varepsilon J_l(\alpha) J_k(2Nr)$. This implies that a high frequency RF system with low harmonic ratio N (as in our case $N = 4$) has little effect for large k and without precaution will affect the tail of the bunch more than the centre.

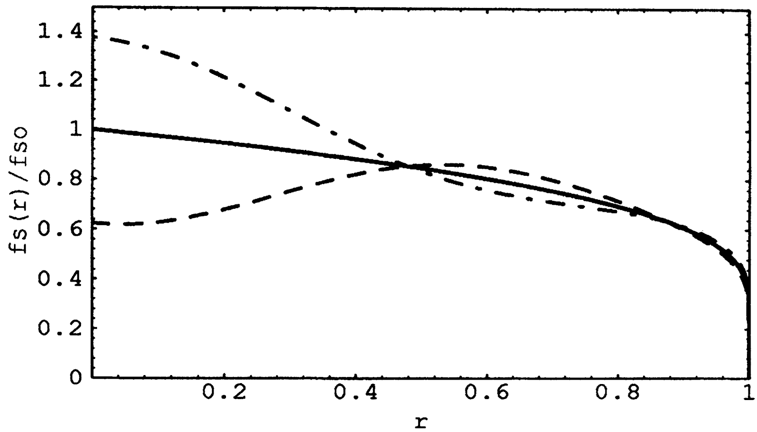


FIGURE 1 Normalised synchrotron frequency as a function of oscillation amplitude r for $N = 4$, $\varepsilon = 0.14$, $\alpha = 1.2$ and $\theta = 0$ (dotted–dashed line), $\theta = \pi/2$ (solid line, no modulation) and $\theta = \pi$ (dashed line).

The importance of the phase θ was underlined in Ref. 7 and then demonstrated in Ref. 8 where the difference in emittance blow-up of different bunches in the ring due to the noninteger ratio between the two RF systems was observed experimentally. Indeed for noninteger $N = \mathrm{Int}[N] + \Delta N$, the phase θ_n seen by bunch number n is $\Delta N 2\pi n$. In our case with $N = 4$, bunches should be identical after blow-up.

For $\theta = \pi/2, 3\pi/2$ resonances with an even value of $(k + l)$ are suppressed (such as, for example, with $l = 1$ and $k = 3, 5, \ldots$ in resonance condition (3)).

3 EXPERIMENTAL CONDITIONS

The main beam and machine parameters were as follows:

Initial parameters of the beam:

- beam energy: 450 GeV,
- bunch length: 1.7 ns,
- longitudinal emittance: 0.38 eV s,

- total intensity: $3 \cdot 10^{12}$ protons,
- number of bunches in the machine: 2×2000.

SPS RF system parameters:

- 200 MHz RF system: $V_0 = 2\,\text{MV}$,
- 800 MHz RF system: $V_1 = 280\,\text{kV}$,
- duration of excitation: $\Delta t = 300\,\text{ms}$.

Other RF parameters defined in expression (2), such as α, Ω and θ, were varied during the studies.

From the calibration of the instrument only the relative phase shift between the two RF systems is known. The absolute value of θ can be defined using the beam. We used both measurements with and without phase modulation. The point corresponding to $\theta = \pi$ was fixed from bunch shape observation (flat bunches) with the 800 MHz RF system on but without phase modulation. Later it was checked by the expected effect of blow-up at $\theta = \pi$ and $\theta = \pi/2$ (see below).

The effect of emittance blow-up was estimated from measurements of change in bunch length and particle distribution. For bunch length measurements we used longitudinal bunch profiles acquired as mountain range displays with a fast digital scope (4 GSample/s) at regular time intervals (see examples in Figures 4, 6 later in the text).

To describe changes in bunch distribution the length was measured at half bunch height (τ_{fwhh}) and at 10% bunch height ($\tau_{\max}$). Bunch lengths before excitation had a 10% scatter around 1.7 ns for $\tau_{\max}$ and 0.9 ns for τ_{fwhh} and are not shown in most of the figures. To see if the bunch still continues to oscillate the final bunch length measurements were taken twice, with a 10 ms interval, at 290 and 300 ms.

The main parameters used for operational blow-up in the CERN PS and the AGS are shown for comparison in Table I together with parameters from our studies.

TABLE I Parameters of RF systems used for blow-up

Machine	h_1	N	ε	Δt (ms)	α (rad)	k
CERN PS	20	$21 + 13/20$	0.2	60	π	4
AGS	12	$22 + 1/3$	0.3	50	π	2
CERN SPS	4620	4	0.14	300	1.1	3

4 VARYING THE 800 MHz RF SYSTEM PARAMETERS

4.1 Effect of Phase Shift between the Two RF Systems

In Figure 2 we present measurements of the bunch length as a function of the phase θ for

$$f_{\text{mod}} = 318\,\text{Hz}, \qquad \alpha = 1.8.$$

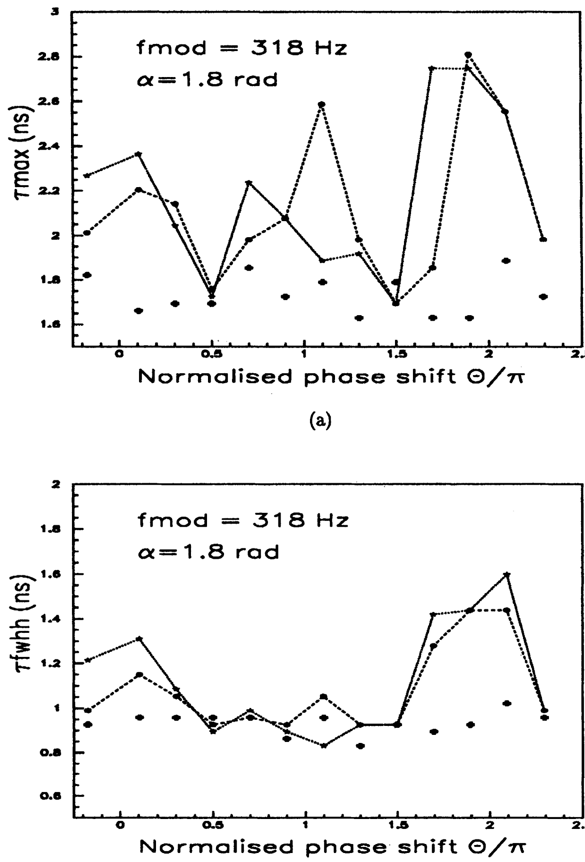


FIGURE 2 Bunch length τ_{max} (a) and τ_{fwhh} (b) as a function of phase shift θ between the two RF systems at 300 ms (dashed line) and 290 ms (dotted line) together with the corresponding initial bunch length (crosses).

The choice of modulation frequency corresponds to the third resonance, $f_{\mathrm{mod}} \simeq 3f_{s0}$, since the linear synchrotron frequency $f_{s0} = 106\,\mathrm{Hz}$ in 200 MHz bucket with $V_0 = 2\,\mathrm{MV}$. For odd values of k and l in the resonance condition (3) the theory predicts an absence of blow-up at $\theta = (2n+1)\pi/2$, where $n = 0, 1, 2, \ldots$ and a maximum effect at $\theta = n\pi$. This fact was also used for the absolute calibration of phase θ. The difference in effect for $\theta = 0, 2\pi$ and $\theta = \pi$ can be explained by the different type of steady-state modulation of the synchrotron frequency, which is proportional to $\cos\theta$, inside the bunch (see Figure 1).

4.2 Effect of Modulation Frequency

In this set of measurements we scanned the modulation frequency f_{mod} from 150 Hz up to 480 Hz with the other excitation parameters being constant and chosen as follows:

$$\alpha = 1.8, \qquad \theta = 1.5\pi.$$

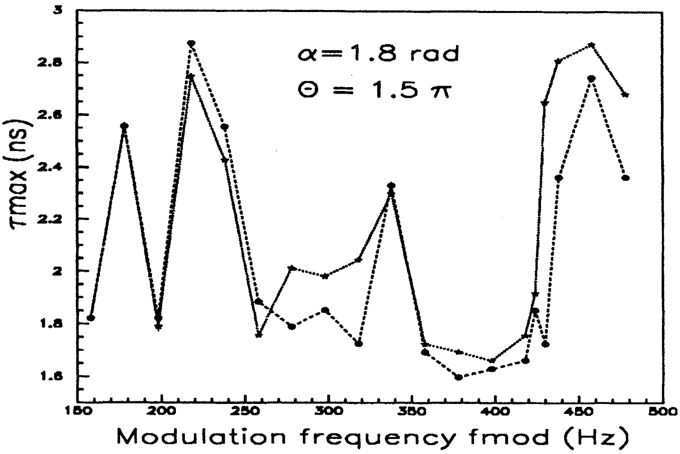
The value of θ corresponds to the situation where there is no steady-state synchrotron frequency modulation in the bunch and resonances with odd $k = f_{\mathrm{mod}}/f_s$ are suppressed. The measurements of the bunch length as a function of f_{mod} are presented in Figure 3. The sharp resonance peaks corresponding to $k/l = 1.5, 2, 3, 4$ can be clearly seen. For $k = 3$, the central part of the bunch (and therefore τ_{fwhh}) is not affected. Some effect coming from higher-order resonances can be seen in the tails (Figure 3(a)). The strong effect produced with $k = 4$ leads to the creation of significant tails in the distribution. The results of excitation with $\alpha = 1.8$, $\theta = 1.9\pi$ and $f_{\mathrm{mod}} = 458\,\mathrm{Hz}$ are shown in Figure 4 as a mountain range display. Note the octupole-type oscillations of the excited bunch.

4.3 Effect of Modulation Amplitude

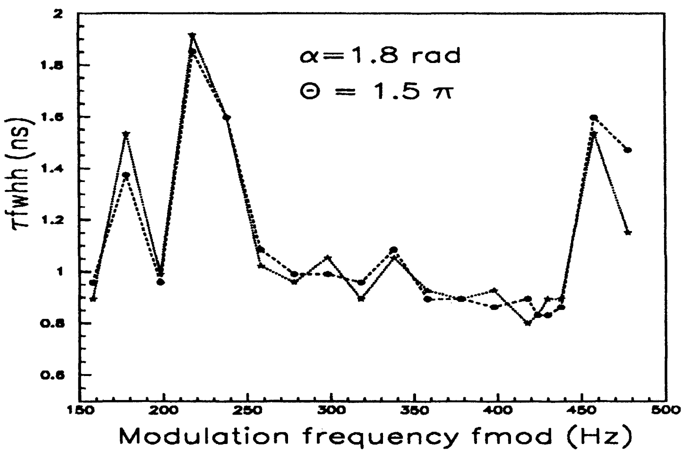
The last measurement we made was by scanning the modulation amplitude α. Other excitation parameters were fixed as

$$\theta = 1.9\pi, \qquad f_{\mathrm{mod}} = 318\,\mathrm{Hz}.$$

The results of this measurement are shown in Figure 5.



(a)



(b)

FIGURE 3 Bunch length τ_{max} (a) and τ_{fwhh} (b) as a function of modulation frequency f_{mod} at 300 ms (dashed line) and 290 ms (dotted line), $\theta = 1.5\pi$.

As one can see, over a wide range of the modulation amplitude ($0.75 < \alpha < 1.75$) both the centre of the bunch and the edges are affected. The excitation parameters in this range correspond to the case with a strong modulation of the synchrotron frequency inside

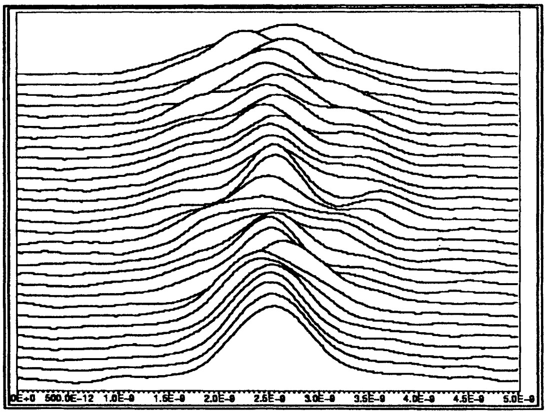


FIGURE 4 Mountain range display for beam excitation with $\alpha = 1.8$, $\theta = 1.9\pi$ and $f_{\mathrm{mod}} = 458$ Hz. The horizontal full scale is 5 ns, the vertical scale is 10 ms/trace.

the bunch. At $\alpha \sim 0$ the strength of excitation goes to zero as α^l and for $\alpha = 2.4$ modulation of the synchrotron frequency is absent (see expression (5)). It was found that the desired effect on the bunch distribution can be obtained for $\alpha \sim 1$. This is the case where, due to the significant increase of the synchrotron frequency at small r, the additional effect on the centre can be obtained due to lower resonances with $k = 2$ and $l = 1$. The results of excitation with

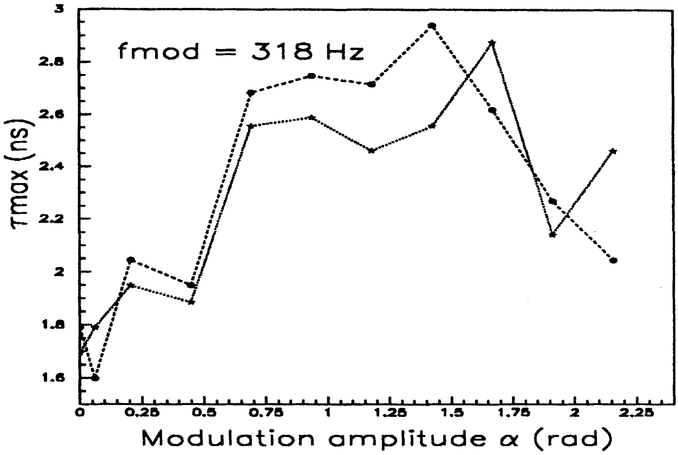
$$\alpha = 1.2, \qquad f_{\mathrm{mod}} = 318\,\mathrm{Hz}, \qquad \theta \simeq 0$$

are shown in Figure 6 as mountain range displays. During this excitation sextupole-type oscillations can be observed.

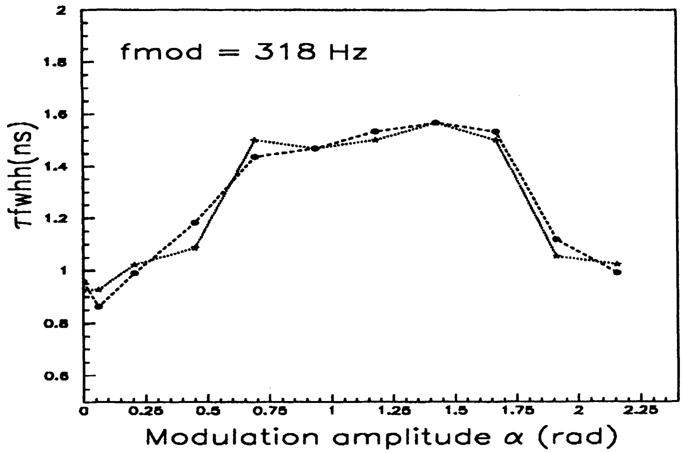
5 DISCUSSIONS

The possibility of using the 800 MHz RF system for controlled longitudinal blow-up on the 450 GeV flat top was demonstrated. It has been seen that, by resonant excitation, voltages at 800 MHz almost an order of magnitude smaller than the main RF voltage can produce sufficient emittance increase.

The choice of parameters suitable for this procedure is limited by the low harmonic ratio between the two RF systems. Using



(a)



(b)

FIGURE 5 Bunch length $\tau_{\max}$ (a) and τ_{fwhh} (b) as a function of modulation amplitude α at 300 ms (dashed line) and 290 ms (dotted line), $\theta = 1.9\pi$.

resonances higher than third order for the modulation frequency produces significant tails. The choice of $k = 3$ makes setting the phase shift between the two RF systems more critical, since no effect can be obtained with $\theta = \pi/2$ or $\theta = 3\pi/2$. Using the regime with

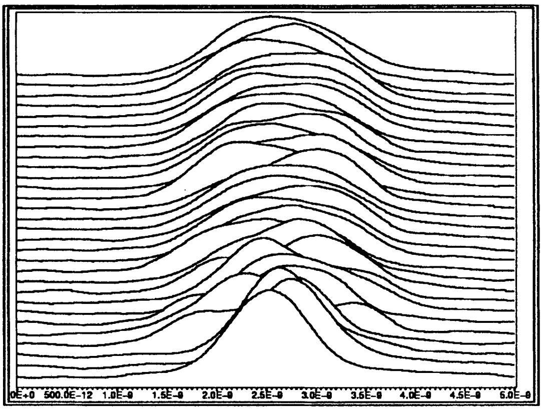


FIGURE 6 Mountain range display for beam excitation with $\alpha = 1.2$, $\theta = 1.9\pi$ and $f_{\mathrm{mod}} = 318$ Hz. The horizontal full scale is 5 ns, the vertical scale is 10 ms/trace.

steady-state synchrotron frequency modulation inside the bunch, it was possible to affect the centre of the bunch without creating large tails. Further studies are necessary to try and reduce the excitation time as much as possible and to eliminate the tails in the distribution.

We observed a difference in blow-up at higher intensities. With 50% more intensity coupled bunch-type instabilities were present. This will be a subject for separate study.

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