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COLLECTIVE EFFECTS AT VERY HIGH INTENSITY IN THE CERN-PS *

D. Boussard, E. Brouzet, R. Cappi, J. Gareyte

Introduction

The CERN-PS beam intensity is being steadily increased (1.55 10^{13} protons per pulse achieved). In addition, a change of harmonic number by debunching-rebunching is performed to allow a clean bunch-into-bucket injection into the SPS. Many collective phenomena had to be studied in this context lately, and selected results of interest to machine designers or operators are reported here. Topics covered are resistive-wall instabilities with peculiar characteristics due to space-charge detuning and fast-decaying wakes, microwave longitudinal instabilities, and problems associated with strong cavity beam-loading.

The Booster beam is injected in the CPS at 800 MeV on a rising magnetic field. A short intermediate flat-top at 1 GeV is used to make a longitudinal dilution necessary to accelerate intense beams through transition. The RF gymnastics preceding ejection towards the SPS are made on a 10 GeV/c flat-top.

Resistive-wall instability

For years the transverse collective behaviour of the CPS beam has been dominated by the single bunch, head-tail instability, generated by fast-decaying wake-fields [1]. After elimination of this problem by proper chromaticity control, the classical resistive-wall instability, in which many bunches are coupled by slowly-decaying wake-fields, could be seen and studied, and revealed some interesting properties [2].

Modes and growth rates

Fig. 1 shows the measured growth rates for the nine first coupled bunch modes (the CPS has 20 bunches, hence 20 modes possible, 10 of which may be unstable due to the interaction with the resistive-wall impedance).

The theoretical curve is derived from the now well established formula [3,4]:

$$\Delta\omega_m = \Delta\omega_c \, Z_\perp(\omega_o) \, \frac{\sqrt{2}}{m+1} \left[\frac{1}{\sqrt{M}} \, G\left(2\pi, \frac{n+\nu}{M}\right) F'_m(\chi) + \frac{1}{M}\sqrt{\frac{1}{B}} \; F^*_m(\chi) \right] \qquad (1)$$

where m is the "head-tail" mode (m = 0,1,2 ...) and n is the coupled-bunch mode (betatron phase shift from bunch to bunch $\Delta\phi = 2\pi\, n/M$). $Z_\perp(\omega_o)$ is the resistive-wall impedance at the revolution frequency ω_o (in the CPS, $\nu = 6.25$, $\omega_o = 2\pi \times .4\ 10^6$ at injection). B is the bunching factor, M the number of bunches.

$$\Delta\omega_c = \frac{c\ I}{4\pi\ \nu\ \gamma\ E_o(\mathrm{eV})}$$

I is the total intensity in the beam. $E_o = .938\ 10^9$ eV for protons. $G(2\pi,x)$ is the Courant and Sessler function [6], $F_m(\chi)$ and $F'_m(\chi)$ are form-factors [4] depending on the phase shift between head and tail of the bunch of length τ_L seconds.

$$\chi = \left(\frac{\nu\ \omega_o\ \xi}{\eta}\right)\tau_L$$

with $\eta = \dfrac{1}{\gamma^2_{tr}} - \dfrac{1}{\gamma^2}$; $\xi = \dfrac{d\nu/\nu}{dp/p}$ = chromaticity.

For a circular vacuum chamber of radius b, in a machine of radius R,

$$Z_\perp(\omega_o) = \frac{2\ R\ c}{b^3\ \omega_o}\frac{\rho}{\delta}\ (1+j)$$

where ρ is the surface resistivity, δ the skin depth. For a flat vacuum chamber of half-height H, b^3 must be replaced [5] by

$$\overline{r^3} = \frac{H^3}{2(\xi_1 - \varepsilon_1)}$$

where ξ_1 and ε_1 are Laslett coefficients. In the CPS, one has typically $\overline{r^3} = H^3$ in the vertical plane, and $\overline{r^3} = .4\ H^3$ in the horizontal plane. $Z_\perp(\omega_o)$ is 6 $10^5\ \Omega\,m^{-1}$ in the vertical plane.

The second term in the bracket in formula (1) represents the single bunch, short range interaction. Its contribution is added ($\chi > 0$) or substracted ($\chi < 0$) from the first term. Application of formula (1) to the CPS at 800 MeV injection energy gives maximum e-folding times of 1 ms in the vertical and 2.5 ms in the horizontal plane for zero chromaticity at an intensity of 10^{13} protons/pulse. Why coupled-bunch instabilities are observed only in the horizontal plane under these conditions will be explained later.

The good agreement seen in Fig. 1 between theory and experiment proves that in the CPS, up to 3 MHz, the resistive wall dominates the machine transverse coupling impedance.

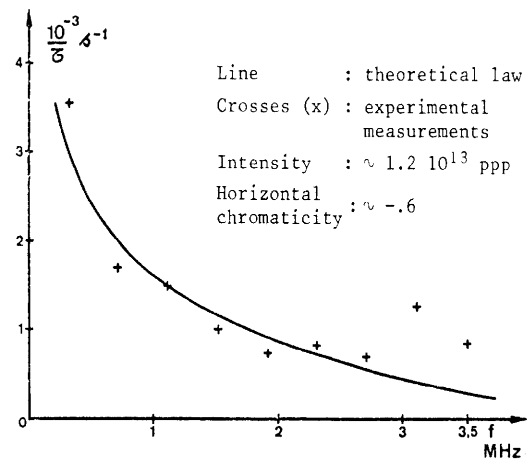

Fig.1 : Growth rates of coupled-bunch modes at low energy

Decoupling criterion

The local part of the Laslett space-charge ν shift changes the coherent tune ν_{coh} of the bunches according to their individual intensity. If the resulting bunch-to-bunch frequency spread

$$\Delta\omega_{rms} = \omega_o\ \Delta\nu_{coh}\left(\frac{\Delta N}{N}\right)_{rms}$$

exceeds the coupled-bunch mode growth rate, bunches will be decoupled [4,6,7]. This is well observed in the CPS at low energy. Table 1 shows that at injection, a $\Delta N/N$ of 1 to 2% will decouple the bunches in the vertical plane, but not in the horizontal one. This is why the theoretically faster-growing vertical instability is not observed. On the 1 GeV flat-top, after longitudinal emittance dilution, $\Delta N/N$ necessary for decoupling goes up, and in this situation coupled-bunch modes are sometimes seen in the vertical plane also. The large difference between vertical and horizontal coherent local Laslett ν shift comes from the flatness of the vacuum chamber.

* CERN, CH-1211 Geneva 23, Switzerland.

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Table 1 : Decoupling criterion

		$\Delta\nu_{coh}$ local	τ (ms)	$<\frac{\Delta N}{N}>_{rms}$ for decoupling - %
Injection - 800 MeV B = .3	V	-.028	1.0	1.5
	H	-.0008	2.5	20.0
1 GeV B = .45	V	-.012	1.0	3.5
	H	-.0003	2.5	53.0

Effect of fast-decaying wake-fields

On the 10 GeV/c flat-top, space-charge decoupling of the bunches is probably ineffective. Yet one observes the following: while still bunched at the normal RF frequency of 9.5 MHz, the beam never shows any sign of coupled-bunch instability. Once rebunched at 200 MHz on the contrary, it develops very clean coupled-bunch modes with the theoretically predicted e-folding time of 10 ms.

The explanation of this strange phenomenon might be the following: head-tail instability studies [1] have shown the importance of fast-decaying wakes (broad-band coupling impedance in the 100 MHz - 1 GHz range of the order of $3\ 10^5\ \Omega\ m^{-1}$). For moderately positive chromaticities above transition, these wakes have now a damping effect, stronger for larger head-tail phase shift χ. Short 200 MHz bunches present obviously a smaller χ than long 9.5 MHz ones, so they get less damping. In addition, their longitudinal density has been lowered in the debunching-rebunching process. Calculation gives a characteristic damping time of 2.3 ms at 9.5 MHz and 46 ms at 200 MHz. So the resistive-wall instability with a potential 10 ms growth time can show up in the second case but not in the first.

Feedback damping

Feedback loops acting in the horizontal and vertical plane all along the acceleration cycle are being built. As experience has shown that it is sufficient to damp only the first three low frequency modes, a tracking multi-channel system has been chosen. A reduced-performance preliminary version is working at present satisfactorily in the horizontal plane at injection.

Microwave instability

To perform a bunch-into-bucket injection into the SPS, the beam is quasi-adiabatically debunched and then recaptured at f_{RF} = 199.5 MHz (harmonic number h = 420) on the 10 GeV/c flat-top. A set of fixed-tune (199.5 MHz) cavities is installed in the PS for this purpose.

The debunching process is as follows: the 10 PS accelerating cavities (9.5 MHz at 10 GeV/c) are switched off and short-circuited in sequence such as to obtain a quasi-adiabatic voltage reduction, and a corresponding decrease of the total cavity impedance. At the end of the process only one cavity is powered; its voltage is then further reduced quasi-adiabatically to the practical minimum (5-10 kV, corresponding to partially filled buckets) and abruptly switched off and short-circuited. From there, the bunches theoretically stretch in phase space at constant momentum spread.

It has been recognized long ago that during the true debunching process (RF off), the initial momentum spread may increase considerably due to the so-called microwave instability. When the bunches stretch in phase space, the local value of the parameter $\Delta\beta\gamma^2/i$ ($\Delta\beta\gamma$ = half height in $\Delta\beta\gamma$ units, i = beam intensity) continuously decreases and it eventually reaches the threshold of the classical debunched beam instability. The relevant coupling impedance Z/n is in the GHz range and is due to the vacuum pipe discontinuities. The time t_i at which a given slice of the debunched beam reaches the threshold is approximately given, for a parabolic bunch shape by [8] :

$$\frac{Z}{n}\, t_i = \frac{.7}{\pi}\, E_o\, \frac{R}{hc}\, \frac{A\hat{\phi}}{I} \tag{2}$$

A and $\hat{\phi}$ are the beam emittance and the half bunch length in $\Delta\beta\gamma$, Rf phase units.

It is worth noting that any non adiabatic manipulation performed on the bunches, producing thin filaments in phase space can also trigger this instability. This has been currently observed on the PS and the SPS.

If the instability occurs a long time after the bunches have overlapped, the result is simply a more or less uniform filling of the phase space area without a significant increase of the total momentum spread of the bunch. The question of practical importance is: how long does the time t_i at which instability will occur need to be, compared to the typical debunching time t_d (first overlap) to ensure a negligible blow-up ?

Evaluating t_d in terms of machine parameters and putting $\alpha = t_i/t_d$, eq.(2) transforms into

$$\frac{Z}{n} = \frac{.7}{\pi^3\alpha}\, E_o\, \frac{n}{\gamma}\, \frac{A^2}{I} \tag{3}$$

The ideally debunched beam (in the case of the parabolic bunch) requires for stability:

$$\frac{Z}{n} \leq \frac{3 \times .7}{32\pi}\, E_o\, \frac{n}{\gamma}\, \frac{A^2}{I} \tag{4}$$

which only differs from (3) by the factor 1.08 α .

Various debunching experiments have been performed in the PS at several energies (1.7, 2.1 and 10 GeV/c, beam emittances being varied from 8 to 60 mrad). With a high frequency coupling impedance evaluated to about 25 Ω, they show that in order to ensure a smooth debunching under conditions very often found in practice (RF switched off abruptly before the buckets are full), α must be of the order of 10. In these conditions, eq. (4) shows the necessity of a pre-emptive increase of the beam emittance A in order to achieve a clean debunching-rebunching in the CPS at 10 GeV/c.

The 199.5 MHz RF cavities are used to provide a clean blow-up of the beam emittance. They are driven at multiples (21 or 24) of the normal accelerating frequency. As such they provide a strong dispersion of the synchrotron frequencies inside the bunch (strong Landau damping) but little blow-up. The blow-up is obtained by a phase modulation of the 199.5 MHz RF wave with respect to the bunch. A dedicated intermediate flat-top at T = 1 GeV (50 ms duration) allows a first blow-up from 8-10 mrad to $\sim$ 20 mrad. This suppresses the bunch-to-bunch instabilities during acceleration as well as transition losses due to the negative mass instability. A further blow-up to 50-60 mrad is achieved on the 10 GeV/c flat-top during the adiabatic RF voltage reduction.

Beam loading effects

Cavity compensation

When trying to reduce the RF voltage in order to debunch the beam, one usually finds a limit beyond which the synchronism between the RF wave and the bunches cannot be maintained. As the beam loading increases, the three servo-loops built around the cavity (phase, A.V.C. and tuning loops) are no longer independent and eventually become unstable. Pedersen [9] has shown that the stability disappears when the parameter $y = I_b/I_o$ (I_b = RF component of beam current, I_o = tube current) exceeds a threshold related to the loop parameters.

This effect is suppressed by the compensation loop which reinjects a current $-I_b$ in the cavity impedance via the power amplifier (Fig. 2).

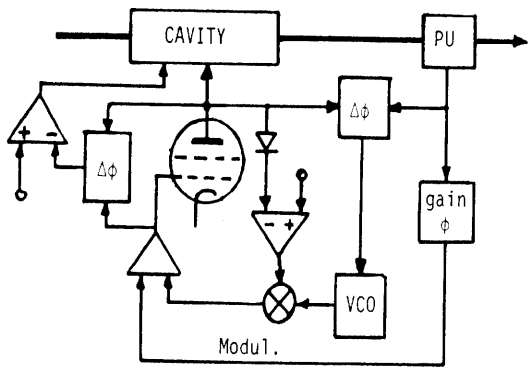

Fig. 2 : RF loops including compensation

The new vector diagram (Fig. 3) shows that the RF drive is now in phase with the total current flowing through the cavity impedance.

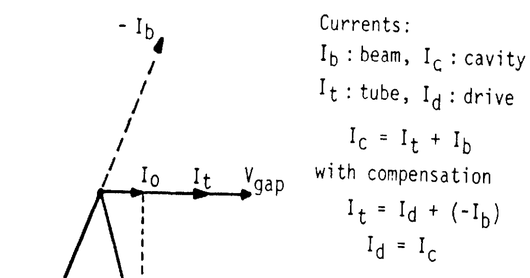

Fig. 3 : vector diagram of the RF currents

It is worth noting that the RF power delivered by the tube is exactly the same as before; only the RF drive has changed. A mathematical estimation of the stability of this new system using the same model as in (9) shows that the system is now completely stable, in the limiting case of a large bandwidth cavity [10]. The amplitude and phase loop responses are no longer affected by the beam loading, only the tuning loop has a different gain.

The RF signal proportional to $-I_b$ is obtained from a phase pick-up electrode. Proper adjustment of its phase and amplitude is made as follows: the RF drive of the cavity to be adjusted is switched off, while the other cavities accelerate the beam normally. One minimizes the voltage on the cavity gap, playing with the amplitude and phase of the $-I_b$ signal. Perfect cancellation of the beam induced voltage is not necessary (20 dB reduction is sufficient in the PS case). Cavity compensation is absolutely necessary for the high intensity operation of the PS at 10 GeV/c for quasi-adiabatic debunching, and at injection where it prevents a complete loss of RF voltage due to the transient beam loading effect.

Longitudinal instabilities

Fig. 3 shows that a strong beam loading results in a detuning of the RF cavity impedance, because the tube current and gap voltage are held in phase by the tuning loop. The cavity impedance being no longer precisely tuned at the RF frequency can excite coupled bunch instabilities. Growth rates are given by Sacherer [11]

$$\frac{\Delta\omega}{\omega_s} = \frac{1}{2\pi}\,\frac{R_s\,I}{V\cos\phi_s}\,\frac{1}{B}\,D\,F_n \qquad (5)$$

where ω_s is the synchrotron angular frequency, R_s the cavity shunt impedance, V the RF voltage, ϕ_s the stable phase angle, and F_n and D are form factors. D depends upon the beam loading parameter $y = I_b/I_o$ (Fig. 3). Looking for small mode numbers n and assuming the quality factor of the cavities $Q \gg 1$, one finds

$$\mathrm{Im}(D) = \frac{8\,n\,y}{hQ^3\left[\left(\left(\frac{2n}{h}\right)^2 - \left(\frac{1+y^2}{Q^2}\right)\right)^2 + \left(\frac{4n}{hQ}\right)^2\right]} \qquad (6)$$

which together with (5) gives the growth rate of the instability. Mode number 1 is dominant in the PS case ($h = 20$, $Q \simeq 50$), and is most dangerous when all cavities are working at a relatively low voltage.

Coupled-bunch dipole instability is observed in the PS at high intensity between injection and the 1 GeV flat-top where the beam emittance is blown up and the instability suppressed. Growth times are between 5 and 10 ms, which is in good agreement with equations (5) and (6). A feedback system working on the only dangerous mode ($n = 1$) has been built (same technique as in the CPS Booster [12]). The signal from a sum pick-up electrode is filtered around the 21st harmonic of the revolution frequency by a 2 path filter and fed back to the beam through one of the RF cavities. Satisfactory operation between injection and the 1 GeV flat-top has been achieved.

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