BEAM BREAKUP INSTABILITY IN THE CERN PS NEAR TRANSITION

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Abstract

Fast beam losses, due to a vertical coherent instability of high frequency, have been observed in the PS near transition energy, with the high-intensity single-bunch beam for the neutron Time-of-Flight facility (n-ToF). By increasing the longitudinal emittance, the beam could be stabilised. These phenomena can be described by the beam breakup theory, since near transition the longitudinal positions of particles are almost frozen, as in the linac case. Comparison between observations and theory, using Brandt and Gareyte's formula for single-bunch beam breakup in circular accelerators, shows good agreement.

1 INTRODUCTION

Several beam dynamics obstacles have been encountered during the setting-up of the high-intensity single-bunch beam for the n-ToF facility [1,2], and they were successfully cured to achieve the desired high bunch intensity of 7×10^{12} protons. One of them was a strong vertical instability near transition energy, already observed at a bunch intensity of 3×10^{12} protons, and leading to losses of about 30% of the beam in a fraction of a millisecond. Increasing the longitudinal emittance from 2 to 2.5 eVs, using the standard longitudinal blow-up with a 200 MHz cavity on the injection flat bottom, was sufficient to cure this instability. A good description of these phenomena seems to be given by the beam breakup theory, which had been developed to explain the mechanism of transverse instabilities in linear accelerators, before being extended to circular machines [3]. This formalism has to be used in the case of transverse instabilities, which are fast compared to the synchrotron period. The experimental observations are collected in Section 2, and are compared to the theoretical predictions in Section 3.

2 EXPERIMENTAL OBSERVATIONS

Figure 1 shows an instability visible on the single-turn vertical signal from a wide band capacitive pick-up, and Figure 2 represents the line-charge density of the bunch (several superimposed traces). It can be seen from Figure 1 that the head of the bunch is stable, while the tail oscillates at a high frequency of about 700 MHz. This means that the mechanism responsible for this instability is a single-bunch effect (short-range wake field) due to a high frequency resonator, where the head of the bunch excites the tail, leading to a dilution of the emittance in the best case, or to beam losses in the worst. Figure 2 shows that some particles are lost, and that they correspond to the particles with the largest vertical oscillations in Figure 1. The relevant beam and machine parameters are collected in Table 1.

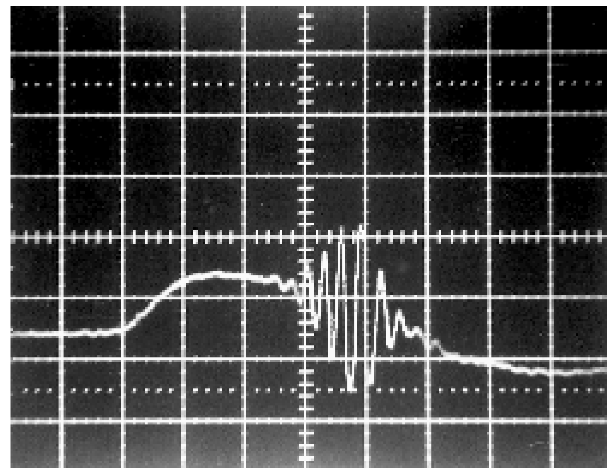

Figure 1: Single-turn signal from a vertical beam position monitor (the bandwidth is 100 kHz-500 MHz). The time scale is 5 ns/div.

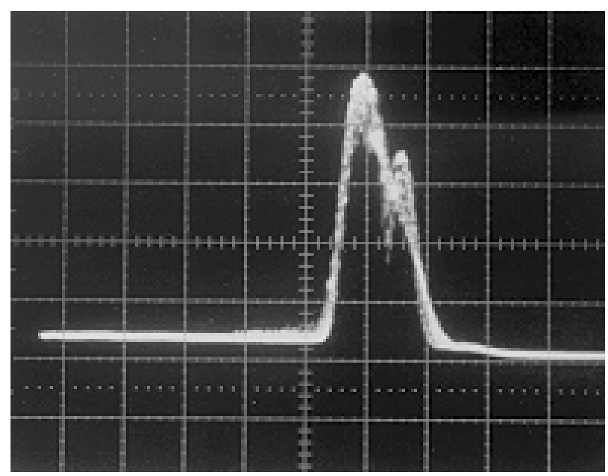

Figure 2: Several superimposed traces of the line-charge density of the bunch. The time scale is 20 ns/div.

This phenomenon is different from the mechanism of the head-tail instabilities [4,5], where the head and the tail of the bunch exchange their roles (due to the synchrotron oscillation) several times during the rise-time of the instability. The important point is that the betatron phase varies linearly along the bunch (from the head) and attains its maximum value at the tail. The total betatron phase shift between head and tail is the physical origin of the head-tail instability. In the present

Table 1: Beam and machine parameters.

Total beam energy	$E \approx 6.2$ GeV
Average machine radius	$R = 100$ m
Bunch intensity	$N_b = 3\times10^{12}$ p/b
Total bunch length	$\tau_b = 30$ ns
Transverse coherent tunes	$Q_{x,y} = 6.2$
Resonance frequency* (= vacuum chamber cut-off)	$f_r = 1.4$ GHz
Quality factor*	$Q_r = 1$
Longitudinal impedance*	$\lvert Z_l / p \rvert \approx 17\ \Omega$
Horizontal shunt resistance*	$R_{r,x} = 1$ MΩ/m
Vertical shunt resistance*	$R_{r,y} = 3$ MΩ/m

* For the broad-band resonator model of the coupling impedances [6]

mechanism, this is not the case. As described in [3], this instability is in fact equivalent to the Transverse Mode Coupling instability of Kohaupt in terms of coupling of head-tail modes [7] (which extends to the transverse motion, the theory proposed by Sacherer [8] to explain the longitudinal microwave instability through coupling of the longitudinal coherent bunch modes). However, the mode coupling formalism is adequate only when the intensity threshold is approached from below (i.e. when the coherent betatron frequency shift becomes comparable to the incoherent synchrotron frequency). When fast beam losses occur within a fraction of the synchrotron period, i.e. for the case well above threshold, the concept of head-tail modes loses its meaning. In this case, it seems more appropriate to describe the interaction between the beam and its surroundings in terms of beam breakup.

3 THEORETICAL PREDICTIONS

The beam breakup theory has been developed to explain the beam emittance growth and the transverse instabilities observed in linear accelerators. The mechanism of cumulative beam breakup in linacs can be stated as follows [9]. If a bunch in a pulse is displaced from the central axis of the linac for some reason, it excites a transverse deflecting mode in an RF cavity. The following bunches feel this field in that cavity and are deflected, even if they are on axis. These deflected bunches create fields of the same type in the cavities in the rest of the linac, which further deflect the following bunches, leading to emittance growth and subsequent beam loss.

Similar phenomena can take place in circular accelerators operating at or near transition, where the slippage factor $\eta = \gamma_{tr}^{-2} - \gamma^{-2} \approx 0$, since in this case the longitudinal positions of the particles are almost frozen, as in the linac case [3,10]. D. Brandt and J. Gareyte have derived a formula for the single-bunch beam breakup in circular machines from the theory developed in [9]. They have approximated a bunch by a train of short bunchlets and have applied Yokoya's formula for cumulative beam breakup in a train of bunches, with the initial condition that every bunch in the train has the same initial position offset. Furthermore, this computation has been done in the absence of acceleration and for the smooth approximation. The time between the bunchlets is chosen to be small compared to the decay time of the considered resonator ($2Q_r / \omega_r$) and the oscillation period ($2\pi / \omega_r$). They obtained the following equation, which gives the ratio between the transverse amplitudes of the tail after n turns performed in the circular machine and of the whole bunch at the beginning of the instability process,

$$\frac{u_n}{u_0} = \frac{1}{2\sqrt{2\pi}} \times \left(\frac{\Omega L}{\beta c} \right)^{1/4} \times \frac{\beta c}{L \omega_r} \times e^{\frac{-\varepsilon L}{\beta c} + \sqrt{\frac{\Omega L}{\beta c}}}, \quad (1)$$

with
$$\frac{\Omega L}{\beta c} = \frac{N_b e \beta c}{\omega_u (E/e)} \times \frac{\omega_r R_{r,u}}{Q_r} \times n. \quad (2)$$

Here, u stands for the horizontal x- or vertical y-coordinate, L is the bunch length (in metres), β is the relativistic velocity factor, c is the velocity of light, $\varepsilon = \omega_r / (2Q_r)$ is the damping characteristic of the resonator model of the coupling impedance, with ω_r the resonance frequency of the resonator and Q_r its quality factor, $R_{r,u}$ is the shunt impedance of the transverse resonator, N_b is the number of particles in the bunch, e is the elementary charge, ω_u is the betatron frequency and E is the total beam energy.

Applying Eq. (1) with the parameters of Table 1 yields a vertical growth parameter y_n/y_0=10 after n=584 turns, and y_n/y_0=35 after n=594 turns, i.e. 1.2 ms (see Figure 3). It means that if the closed orbit error is $y_0 \approx 1$ mm, the tail of the bunch will be lost on the vertical aperture, whose half width is 35 mm, in about 1 ms. Notice that this instability is not observed in the horizontal plane, since there the rise-time is much longer (see Figure 4). The horizontal growth parameter is x_n/x_0=10 after n=1751 turns, and becomes x_n/x_0=70 (the half width of the horizontal aperture is 70 mm) after n=1800 turns, i.e. 3.8 ms.

The beam breakup mechanism is essentially described by the exponential term of Eq. (1). An approximate formula, which gives the time (to within few percents) when the tail particles are lost, can be derived and is given by

$$\Delta t = T_0 \times \frac{\omega_u (E/e) \tau_b^2}{4 N_b e \beta c} \times \frac{\omega_r}{R_{r,u} Q_r}, \quad (3)$$

where T_0 is the revolution period and τ_b is the total bunch length (in seconds). It can also be expressed with respect to the longitudinal impedance (divided by the harmonic number of the revolution frequency $p = \omega / \omega_0$) for a circular vacuum chamber of radius *b*,

$$\Delta t = \frac{\pi}{4} \times \frac{Q_u \left(E/e\right) \tau_b^2}{N_b \, e R} \times \frac{b}{\left| Z_l / p \right|}. \quad (4)$$

Here, the classical formulae for the broad-band resonator model have been used, $Q_r = 1$, $\omega_r = c/b$ and $R_{r,u} = (2R|Z_l/p|)/(b^2\beta)$.

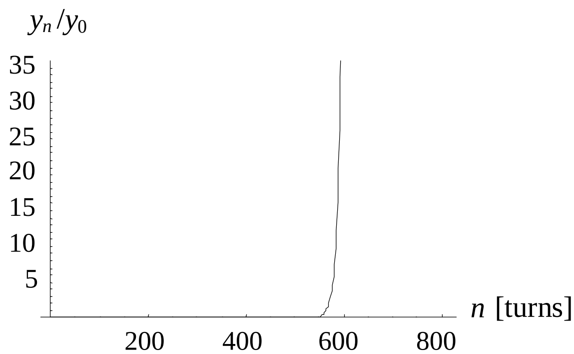

Figure 3: Vertical growth parameter y_n/y_0 vs. number of turns *n*.

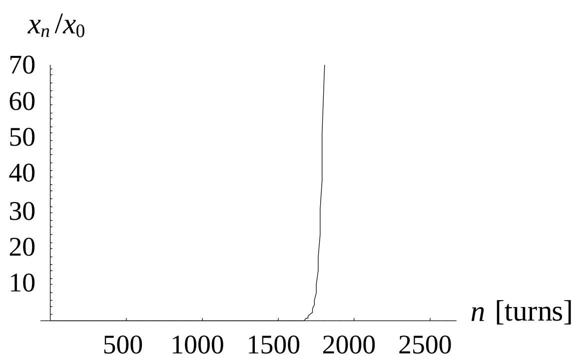

Figure 4: Horizontal growth parameter x_n/x_0 vs. number of turns *n*.

To prevent the fast vertical instability required increasing the longitudinal emittance from 2 to 2.5 eVs. This can be understood by the following arguments. First, applying Eq. (1) with the parameters collected in Table 1, but taking into account the effect of the blow-up (i.e. the bunch length is multiplied by $(2.5/2)^{1/2}$), yields a vertical growth parameter y_n/y_0=35 after *n*=733 turns, instead of 594 turns for the initial bunch length. The longer the bunch, the longer the rise-time (see also Eq. (4)). Furthermore, the acceleration has a damping effect on the instability since it increases the synchrotron frequency, exchanging therefore the roles of the head and the tail more rapidly. The other mechanism that could help stabilise the beam is the spread in betatron frequencies. The controlled longitudinal emittance blow-up increased the energy spread across the bunch, which induced a larger spread in betatron focusing through the chromaticity, and which was perhaps sufficient to compensate the defocusing effect of the wake field.

4 CONCLUSION

The fast single-bunch instability observed in the vertical plane of the PS near transition, with a bunch intensity of 3×10^{12} protons and a total length of about 30 ns, seems to be well explained by the beam breakup theory of Ref. [3]. Using the value of the PS vertical broad-band impedance, it predicts a loss of the tail particles in about 1 ms, to be compared to the measured loss in a fraction of a millisecond. Increasing the longitudinal emittance from 2 to 2.5 eVs was sufficient to cure this instability. This could possibly be explained by the increase of the bunch length (and the acceleration) and the increase of the spread in betatron focusing. Further work is needed to better understand the damping process.

More precise measurements of this instability could provide another method to estimate the PS coupling impedance.

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