OBSERVATION OF A FAST SINGLE-BUNCH TRANSVERSE INSTABILITY ON PROTONS IN THE SPS

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Abstract

The longitudinal impedance of the SPS has been reduced significantly by hardware modifications over the last years and the threshold for longitudinal instabilities increased accordingly. We now observe a fast transverse instability on high-intensity single bunches of low longitudinal emittance. The main observed signature and the threshold dependence on beam parameters is described and compared with theoretical expectations and simulations.

INTRODUCTION

The longitudinal impedance of the SPS has been reduced by a factor of ∼ 2.5 from 1999 to 2001 by modification and shielding of over thousand elements like vacuum ports [1, 2, 3]. The threshold for longitudinal instabilities (microwave instability) increased accordingly. However, the transverse impedance has only been reduced by ∼ 40% and this improvement was since then nearly cancelled by the installation of the extra equipment needed for the SPS as LHC injector (the MKE extraction kickers).

There is now strong evidence of a transverse single bunch instability in the SPS. The fast (less than a synchrotron period) loss of about 30% of protons of high-intensity bunches (about 1.2×10^{11} protons) at a low longitudinal emittance (∼ 0.2 eV s) disappears when the vertical chromaticity is strongly increased.

In the preparation of different types of beams in the SPS for the LHC, it had already been noticed, that beams of low longitudinal emittance become instable [4].

The studies reported here allowed to our knowledge for the first time to observe a transverse instability with protons in the SPS [5].

The basic SPS-parameters, relevant for the measurements, are summarized in Table 1.

Table 1: Basic SPS parameters (valid for these measurements).

Q_x	26.185	Horizontal tune
Q_y	26.13	Vertical tune
p	26 GeV/c	Beam momentum
α_c	.0019186	momentum compaction factor
$\gamma_{\rm tr}$	22.830	γ transition
η	.00061797	phase slip factor
$f_{\rm rev}$	43347.3 Hz	revolution frequency

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OBSERVATIONS

A first systematic study of the transverse stability of high intensity (1.2×10^{11} protons), low emittance ($\epsilon_l = 0.18$) single bunches was performed in September 2003. Both the peak and total current monitors showed sudden losses of about 30 % in less than one synchrotron period. An increase of the rf-voltage from 0.6 to 2 MV was not sufficient to cure the instability. A strong increase of the vertical chromaticity reduced the losses.

These observations were confirmed and the parameter dependence further studied in a second experiment in November 2003.

The values quoted for the longitudinal emittance and bunch length refer to values measured in the PS before extraction. Bunch length information was also recorded in the SPS. Under stable conditions, the bunch length observed in the SPS at 0.6 MV was on average about $4\sigma_t = 3.2\,\mathrm{ns}$.

Chromaticity scan

Figure 1 shows the observed relative intensities for the first 50 ms following the injection at $t = 0$ ms for very low and high chromaticity. The initial absolute intensity was about 1.2×10^{11} protons. The solid line labelled bct gives the total bunch intensity and the dashed line the peak intensity (sensitive to bunch length variations).

The results of a scan in chromaticity in terms of the fraction of the particles lost in the first 10 ms after injection are shown in Figures 2.

The periodic oscillations visible in the peak current are compatible with synchrotron oscillations at $2 \times Q_s$, where

$$Q_s = \sqrt{\frac{\eta\, h\, e\, V_{\rm rf}}{2\pi\beta^2 E}} = \sqrt{\frac{V_{\rm rf}}{57182\,\mathrm{MV}}} \qquad (1)$$

which is $Q_s = 3.24 \times 10^{-3} = 1/308.7$ turns or 7.12 ms for one synchrotron period at $V_{\rm rf} = 0.6\,\mathrm{MV}$.

COMPARISON WITH PREDICTIONS

We first compare with a simple approximate expression from [6], which combines fast beam-breakup, transverse mode coupling and post head-tail theory. It predicts the instability threshold in number of particles per bunch N_b in case that the bunch length in time units is long compared to the inverse broad band resonator frequency, $\tau_b = 4\sigma_t > 1/(2f_r)$. This is the case for the SPS where $4\sigma_t \approx 3$ ns and $f_r \approx 1.3$ GHz, $1/(2f_r) = 0.38\,\mathrm{ns}$,

$$N_b^{\rm th} = \frac{8\pi\, Q_{y,0}\, \eta\, \epsilon_l}{e^2\beta^2 c}\, \frac{f_r}{|Z_y^{\rm BB}|} \left(1 + \frac{f_{\xi_y}}{f_r}\right) . \qquad (2)$$

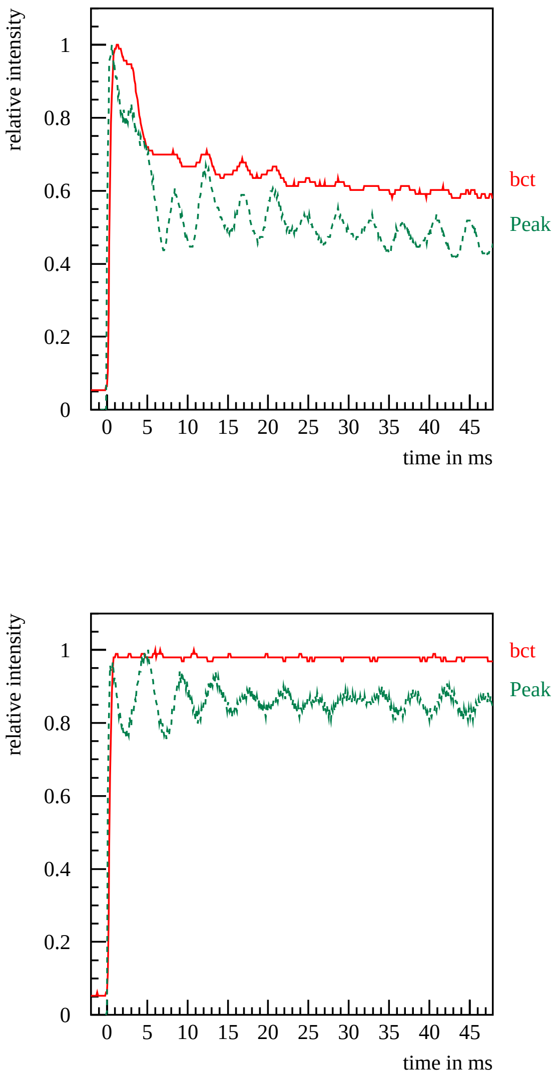

Figure 1: Injection at 0.6 MV. Low chromaticity $\xi_y \approx 0$ (top) and high chromaticity $\xi_y = 0.8$ (bottom). $\epsilon_l = 0.2\,\mathrm{eV\,s}$, $4\sigma_t = 2.7\,\mathrm{ns}$.

Here, $\epsilon_l = \beta^2 E\tau_b\,(\Delta p/p)_{\max}\,\pi/2$ is the longitudinal emittance (at 2σ in eVs) and f_r is the resonance frequency of the broad band resonator with peak impedance Z_y^{BB} in the vertical plane. The chromatic frequency is $f_\xi = \frac{Q'\,f_{\mathrm{rev}}}{\eta}$ and the relative chromaticity $\xi = Q'/Q$. For the SPS at 26 GeV, $\eta = 6.18\times10^{-4}$. With $\epsilon_l = 0.2\mathrm{eVs}$, $Q_{y,0} = 26.2$, a single broad band resonator with $Z_y^{\mathrm{BB}} = 20\,\mathrm{M\Omega/m}$ at $f_r = 1.3\,\mathrm{GHz}$ and zero chromaticity, the threshold predicted by Eq. (2) is about 10^{11} particles, which is in broad agreement with the observations.

The fast loss signature is also seen in simulations. Figure 3 shows simulations for the SPS for parameters similar to the experimental conditions illustrated in Figure 1. We used the head-tail code [7] and simluated the flat cham-

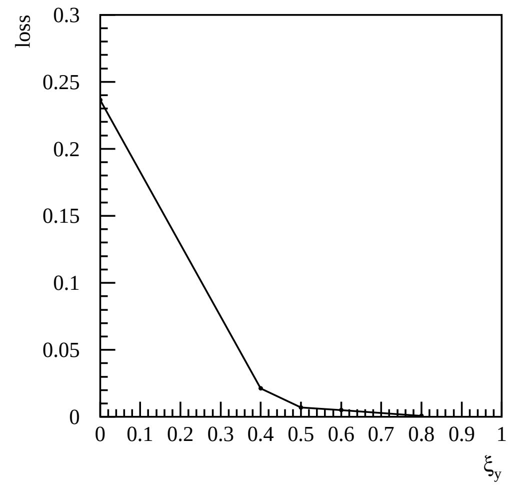

Figure 2: Fraction lost in the first 10 ms as function of the vertical chromaticity ξ_y. Injection at 0.6 MV, $\epsilon_l = 0.2\,\mathrm{eV\,s}$, $4\sigma_t = 2.7\,\mathrm{ns}$.

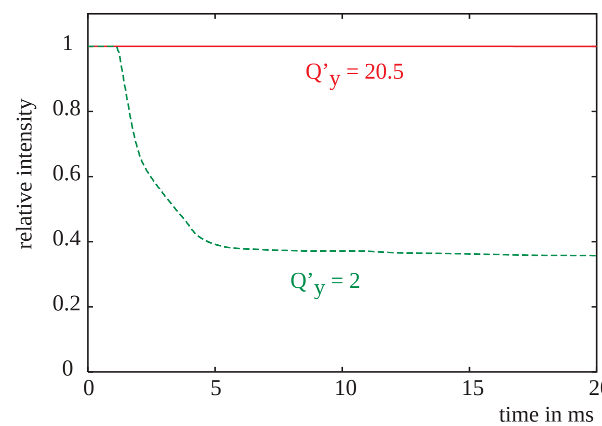

Figure 3: Simulation using the "Headtail" code. Relative intensity in the first 20 ms following injection of 1.2×10^{11} protons for low and high chromaticity.

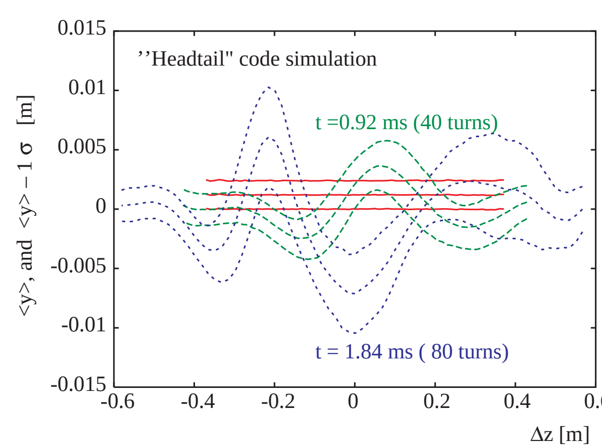

Figure 4: Vertical centroid with $\pm1\sigma$ bands at injection (red), and 40 and 80 turns later.

ber impedance of the SPS using a total bunch length of $4\sigma_t = 2.7\,\mathrm{ns}$ and a longitudinal emittance of $\epsilon_l = 0.3\,\mathrm{eV\,s}$. Space charge effects were not included for the simulation results shown here. Figure 4 was obtained from the same simulation and shows the vertical signal as it would be observed with a wide band pickup for the case of $Q'_y = 2$.

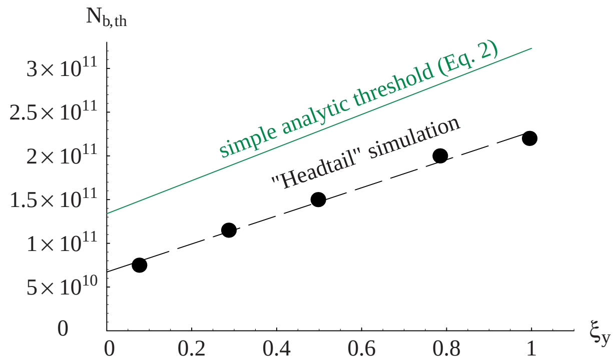

Figure 5: Instability threshold intensity as function of the vertical chromaticity.

Figure 5 shows the instability threshold as function of the vertical chromaticity $\xi_y = Q'_y/Q_y$. The linear dependence of the simple approximate Eq.2 is seen in the detailed simulation. We do not expect at present a perfect match in the absolute prediction of the threshold, due to uncertainties in the impedance model for the flat SPS chamber and differences in the input parameters. More work is planned to reduce these uncertainties.

SUMMARY

We report first observations of a fast transverse instablity of low longitudinal emittance proton beams in the SPS. The instability threshold depends on chromaticity. The observation matches predictions based on beam-breakup / transverse mode-coupling / post head-tail theory and can be well reproduced by simulations.

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