Beam Dynamics Effects in the CERN SPS used as a Lepton Injector

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ABSTRACT

When used as LEP injector the CERN SPS accelerates dense bunches of electrons and positrons. Due to the low injection energy the beams are prone to collective phenomena. However, the large spacing between bunches ensures that single bunch effects are the only limitation. Measurements of the evolution of longitudinal and transverse emittances, as well as observations of the transverse Mode Coupling instability and of the longitudinal microwave instability are reported and compared to calculations and computer simulations.

INTRODUCTION

The CERN SPS, which was originally designed to accelerate intense proton beams from 10 GeV/c up to 450 GeV/c has recently been upgraded in order to also be able to accelerate dense short bunches of electrons and positrons from 3.5 GeV/c to 20 GeV/c, in its role as LEP injector[1].

Since both the longitudinal and transverse coupling impedance of the vacuum chamber had been estimated from beam measurements with protons, it was possible to predict the threshold intensities for coherent instabilities in the new lepton régime, and from this to design the lepton injection chain in an optimum way. The first injection tests in 1987 showed that indeed the observed thresholds are very close to the predicted ones[2]. This report describes further observations and measurements done in 1988 on the dynamics of lepton bunches in the SPS. Both transverse mode coupling and longitudinal microwave instabilities are observed at injection as well as during the acceleration ramp.

THE CYCLE FOR LEPTON ACCELERATION

The particles coming from the CPS are injected at 3.5 GeV/c on a low energy magnetic front porch of 200 ms duration. Then they are accelerated to 20 GeV/c in about 300 ms. Since the damping times are τ_E = 4.5 s and $\tau_x = \tau_z$ = 9s at 3.5 GeV/c, leptons behave like protons at low energy: the decrease in the beam dimensions is essentially governed by the acceleration process. At higher energy the synchrotron radiation progressively dominates and on the ejection platform at 20 GeV/c the size is determined by the equilibrium between damping and excitation by synchrotron radiation. This is illustrated in fig. 1 where the measured values of beam size are shown and can be compared to the evolution of this parameter calculated by considering the same initial conditions.

CHARACTERISTICS OF INJECTED BEAMS

Whereas the nominal intensity of the LEP injection complex corresponds in the SPS to 8 bunches of 10^{10} particles each, the CPS is capable of producing single bunches of up to 5.10^{10} particles. This allows one to measure instability thresholds over a wide range of parameters at injection. By modifying the partition numbers and the RF voltage in the CPS it is possible to inject into the SPS bunches with different length and energy spread. The cases which have been most often used are shown below.

	Case 1	Case 2	Case 3
σ_E/E	$0.6\ 10^{-3}$	1.10^{-3}	1.10^{-3}
σ_s	16cm	16 cm	22.5 cm

With $\sigma_E/E = 10^{-3}$ it is possible by making use of the low frequency RF system of the CPS to increase σ_s up to 40 cm. The transverse emittances at injection are σ^2/β = 0.07 10^{-6} rad.m in the horizontal plane, 0.1 10^{-6} rad.m in the vertical plane.

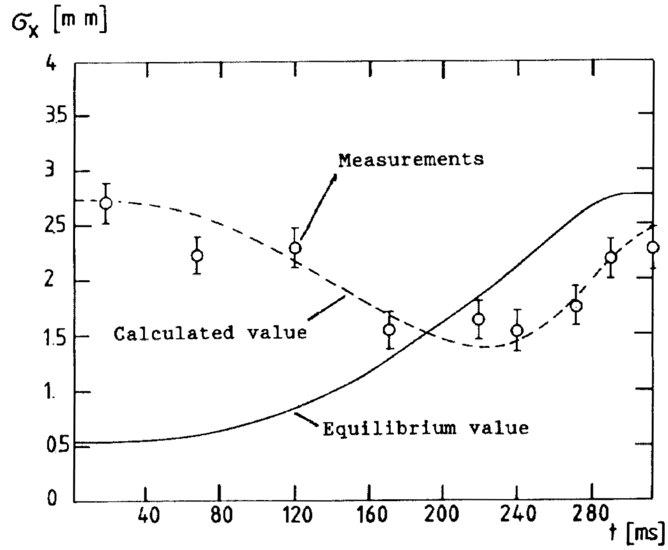

Fig.1 Horizontal beam size during acceleration

COLLECTIVE EFFECTS AT INJECTION

The most obvious phenomenon which appears when the intensity of the injected bunch is increased is a fast loss of part of the beam after only 10 to 40 revolutions in the machine. At the same time growing signals can be observed in a large frequency range around 1.5 GHz on a wide band vertical monitor. This happens in case 1 ($\sigma_E/E = 0.6\ 10^{-3}$, σ_s = 16 cm) at around 1.3 10^{10} particles per bunch, which is close to the predicted threshold for the transverse mode coupling instability. Well above threshold, the instability develops much faster than the synchrotron oscillation, and therefore the concept of head-tail mode is no longer adequate. In this case it is preferable to use the approach of the Beam Break Up theory developed for linear accelerators. It has been shown in ref. 2 that both mode coupling (below threshold) and Beam Break Up (above threshold) theories are useful to describe the observations.

In addition to transverse signals, longitudinal microwave signals are also detected soon after injection. Fig. 4, which displays a signal proportional to the bunch length all along the cycle, clearly illustrates the turbulent behaviour of the bunch length on the injection platform. Simulations with SIMTRAC[3] using the longitudinal broad-band impedance model proposed in ref. 4 for the SPS (Q = 6, Z/n = 6.4 Ω, fres. = 1.35 GHz) suggest a threshold for the longitudinal instability of 0.5 10^{10} particles for $\sigma_E/E = 0.6\ 10^{-3}$ (case 1) and 1.6 10^{10} for $\sigma_E/E = 10^{-3}$ (case 2). This is in good agreement with observations.

An interesting feature which is shown by the simulation is the following: when a bunch is injected well above threshold for the longitudinal instability, a fast increase of the energy spread occurs. This is confirmed experimentally in fig. 2, which shows the evolution of the energy spread measured along the cycle by comparing the horizontal profiles given by fast wire scanners, the first one located in a dispersion free section and the other at a place with a large dispersion. The energy dispersion measured soon after injection is two to three times the injected value. The slow decrease along the 200 ms injection platform can be explained by particle losses on nearby second and third order betatron resonances. These losses were diminished later on by reducing the value of the residual chromaticity, which together with a large energy dispersion creates a tune spread which cannot be accommodated in between these resonances.

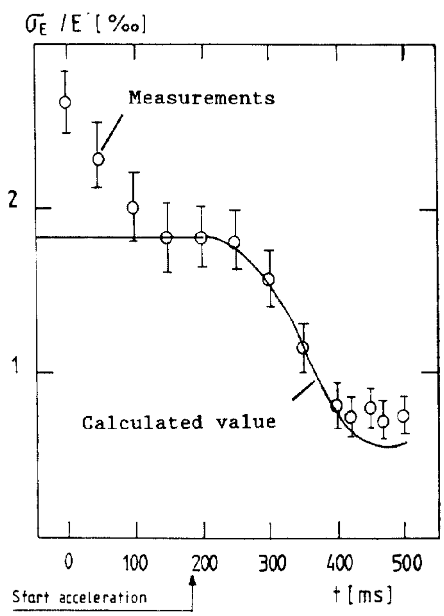

Fig. 2

Energy spread during the cycle

Both longitudinal and transverse instability thresholds can be raised by increasing the energy spread and the length of the injected bunches. The longitudinal threshold scales like $\sigma_s.(\sigma_E/E)^2$ while the transverse threshold scales like $\sigma_s.\sigma_E/E$. In order to increase the performance of the SPS as LEP injector, one should therefore increase both parameters as much as possible. The energy spread of the injected beam is limited to $\sigma_E/E = 10^{-3}$ in the CPS, while the acceptable bunch length is limited in the SPS by the wavelength of the 200 MHz RF system to around σ_s = 30 cm. However, the new 100 MHz system which is being commissioned for use in $\bar{p}$p collider operation is capable of capturing bunches twice as long and of accelerating them sufficiently so that they can be subsequently captured by the more powerful 200 MHz system. It was therefore interesting to measure transverse thresholds as a function of injected bunch length. The results are displayed in fig. 3.

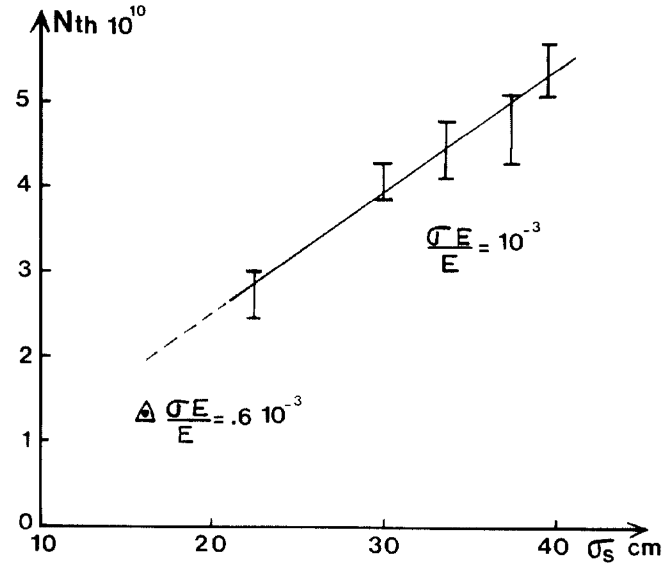

Fig. 3 Transverse mode coupling instability threshold variation with bunch length

COLLECTIVE EFFECTS DURING ACCELERATION

The important parameters of the SPS acceleration cycle are displayed in Table I including the theoretical bunch length equilibrium value $(\sigma_s)_o$.

Table I

t ms	E GeV	τ_E s	$(\sigma_s)_o$ cm	Simulation: σ_s cm	Simulation: transverse threshold 10^{10}	calculated longitudinal threshold 10^{10}
200	3.57	4.24	1.48	22.5	1.6	1.73
216	3.59	4.17	1.44	19.5	1.6	1.85
250	3.83	3.44	1.46	18.6	1.6	1.70
283	4.49	2.13	1.55	17.1	1.5	1.53
316	5.80	0.99	1.74	15.0	1.73	1.79
350	7.60	0.44	2.04	12.3	1.73	2.00
383	10.0	0.19	2.59	9.9	1.73	2.18
416	12.8	0.092	3.22	8.1	1.73	2.14
450	15.9	0.048	3.73	6.9	1.73	1.95
483	18.0	0.033	4.30	5.0	1.90	1.85

The bunch length σ_s decreases steadily during the acceleration cycle to reach the equilibrium value due to synchrotron damping only at the highest energy. This tends to counteract the natural tendency of the thresholds for collective instabilities to increase with energy. Since the bunch is not in equilibrium during most of the cycle, it is appropriate to simulate the whole cycle in a consistent way, starting from the beam parameters at injection. This has been done using again the program SIMTRAC[5].The coupling impedance assumed is the one recommended in ref. 4, a broad-band resonator with Q = 6, Fr = 1.35 GHz and $Z_L/n = 6.4\ \Omega$, $Z_T = 12.5\ \mathrm{M\Omega\ m^{-1}}$. Parameters at injection correspond to case 3 ($\sigma_E/E = 10^{-3}$, $\sigma_s = 22.5$ cm). The results show a moderate increase in the energy dispersion at injection, indicating the presence of microwave instability, but during the ramp the bunch length, displayed in Table I, evolves very much as calculated for low intensity: below the transverse threshold, the simulation shows no important longitudinal instability during acceleration. However, the last column of Table I shows the thresholds for the longitudinal instability calculated at each step from the values of the beam parameters produced by the simulation, using the formula:

$$N_{th} = \frac{2\pi\alpha E/e\ [4\sigma_s(2\Delta P/P)]^2}{e\ R_e(Z/n)\ F(\sigma)}$$

with $F(\sigma) = \omega_{res}\sigma_s/c$, α the momentum compaction factor. This indicates that the thresholds for both instabilities are very close indeed all along the cycle, and almost constant.

This may explain the following experimental observations. As already mentioned, the intensity captured in the SPS can be increased by injecting longer bunches (see fig. 3). At higher energy, when the bunch length decreases, these intense bunches may become unstable. However, the consequences are very different depending on which threshold is crossed first. If the transverse instability is dominant, a large fraction of the beam is lost (fig. 4a). If the longitudinal microwave instability starts first, the result is an increase of the bunch length, which pushes the transverse threshold to higher values, and no loss occurs. (Fig. 4b). The existence of a longitudinal instability towards the end of the cycle is also visible in fig. 5 which shows the measured bunch length for two different intensities compared to the calculated values: for the higher intensity the measured values rise above the calculated ones around 12 GeV (400 ms). A similar behaviour can be seen on the measured energy spread (fig. 2).

In the SPS up to now 4 bunches were simultaneously accelerated. Only one of them (bunch A) was used to pilot the RF phase loop. As a consequence, this bunch was probably injected and captured in a more efficient way than its followers. At any rate, it systematically suffered from a microwave instability during the ramp, and was transmitted without important losses (fig.4b). The other bunches, which did not show any longitudinal instability suffered important losses while high frequency signals could be detected on a vertical monitor (fig. 4a).

Finally, higher bunch intensities could be accelerated to top energy by artificially increasing the bunch size all along the ramp by RF shaking. In this way up to 2.6 10^{10} positrons could be accelerated in one bunch, which is 3 times the nominal intensity per bunch for LEP injection.

CONCLUSION

By observing the transverse mode coupling instability and the longitudinal microwave instability of lepton bunches in the SPS it is possible to evaluate the machine coupling impedance in a way which complements the measurements done previously with protons. The transverse mode coupling instability limits the maximum intensity per bunch which, however, can be increased to three times the nominal value by artificially diluting the bunch longitudinal emittance.

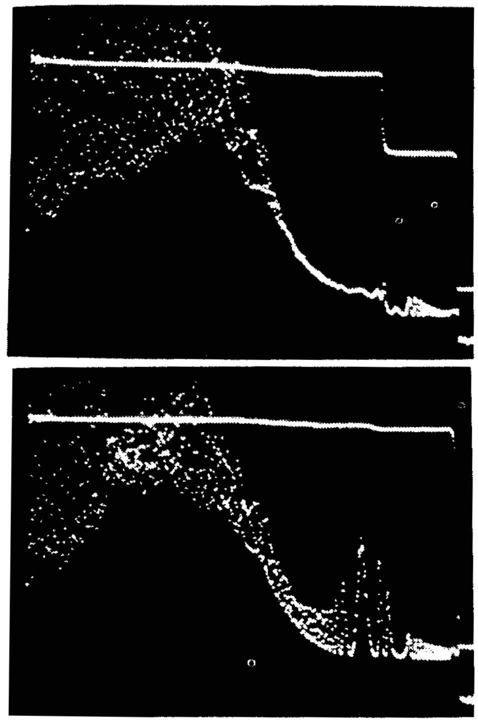

Fig. 4

H scale : 50 ms/div

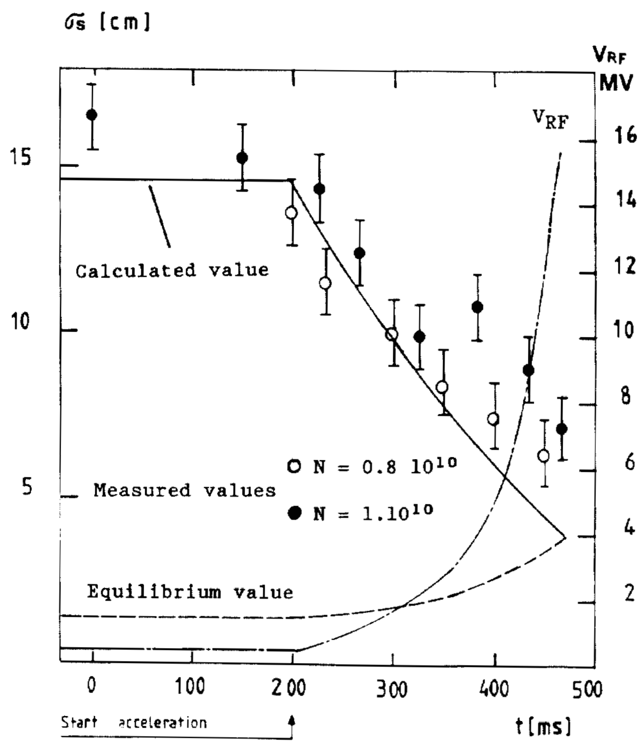

Fig. 5 Variation of bunch length

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