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ACCELERATION AND STORAGE OF A DENSE SINGLE BUNCH IN THE CERN SPS

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Introduction

CERN's plans to use the SPS as a proton-antiproton storage ring are described elsewhere in this Conference[1]. In this paper we report experiments in which protons were used in the SPS to test out some of the principal aspects of the scheme.

First tests of the lifetime of a normal SPS beam stored for several hours at 200 and 270 GeV were encouraging. The natural logarithmic decay time is in excess of 24 hours. However, in the proton-antiproton scheme, 200 MHz bunches containing fifty times the normal design population of particles are to be injected into the SPS above transition at 26 GeV, accelerated and stored. Lacking the hardware to inject at so high an energy, we first injected bunches of 10^{11} protons at 10 GeV accelerating them through transition but found it difficult to pass transition with more than 40% of this design population**. Nevertheless we report some interesting observations on head-tail and negative-mass effects which limited intensity during these tests.

Finally we succeeded in injecting intense single bunches above transition by lowering the Q of the SPS and were able to accelerate and store bunches of 10^{11} protons at 210 GeV. We found that the combined effect of longitudinal instabilities and r.f. noise limit lifetime during single bunch storage. Observations of these effects are reported and discussed.

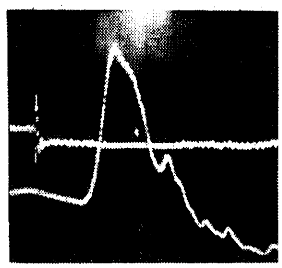
Storage of a Continuous Beam

The first tests were made by filling the SPS circumference with a low intensity proton beam (10^{12} protons). This was accelerated to 200 GeV where, during a flat top, the main power supplies and r.f. were switched to run continuously. Beam intensity measured with a d.c. transformer was logged and used to calculate lifetime. We found the continuous beam of 10^{12} protons could be stored easily with multipole and other correction systems dead. Fatter, more intense beams of 4×10^{12} decayed more rapidly until the chromaticity sextupoles were used to cancel the chromaticity at 200 GeV and reduce the Q spread across non-linear resonances. Beam decay was also sensitive to Q adjustment, the empirical optimum being $Q_H = 26.62$, $Q_V = 26.55$. These experiments were repeated at 270 GeV where a natural logarithmic lifetime of 30 hours was reproducibly recorded during the first hour or so of storage. This is close to the 50 hour life due to nuclear scattering calculated for the measured mean nitrogen equivalent pressure of 7×10^{-9} Torr. Coulomb scattering to the large dynamic acceptance of the SPS is likely to be small but may account for the discrepancy. We have not yet attempted to extend storage runs beyond two hours to check agreement between scattering calculations and beam dilation rates.

Acceleration of Intense Single Bunches

The CPS obliged by producing 4 ns long bunches containing more than 2×10^{11} protons by a bunch rotation manipulation. Such a bunch fits an SPS bucket (5 ns long and $A = \pi\ \Delta\beta\gamma\ \Delta\phi = 0.2$ radian at the normal 10 GeV injection energy). The peak current in such a bunch is 10 A and 100 times the normal SPS peak current. At 10 GeV/c the calculated Laslett Q_V shift for a bunch of 10^{11} p is about 0.16 and remains so to transition. Even after compensating the linear part of this shift the spread is too big to fit between uncompensated non-linear resonances. The maximum bunch population reaching transition was 0.6×10^{11} protons.

For a reason which is unclear but which may be due to loss to resonances, the longitudinal emittance arriving at transition is scraped down to 0.1 radian. Unfortunately this value corresponds to the calculated threshold for the onset of negative-mass instability[2] and this effect was clearly seen as a longitudinal blow up 2 ms after transition. A large fraction of the beam was lost either immediately or later as the bucket shrinks at $\sqrt{3}\ \gamma_{tr}$. Fig. 1 shows the strong microwave signals in the 3 GHz range (the limit of the diagnostics) which accompany the phenomenon. The observed e-folding time is about 0.3 ms. The effect was avoided by a pre-emptive blow up of the bunch prior to transition.



Upper trace : RF phase showing jump at transition.

Lower trace : band pass filtered (2.65-3.23 GHz) and detected pick-up signal

1 ms/div.

Fig. 1 : Negative mass instability after transition.

Strong head-tail instability in the transverse plane was observed as a loss close to transition accompanied by a microwave signal from a transverse beam position monitor (Fig. 2). The same phenomenon has been extensively studied in the CPS[3], where the high-frequency transverse coupling impedance attributed to enlargements and steps in vacuum chamber section has been measured. The growth-rate found in the SPS (τ = 1 ms) suggests an impedance $Z_\perp = 2.5\times10^6\,\Omega m^{-1}$, 5 times larger than the CPS one. Unlike the longitudinal coupling impedance Z/n, we expect $Z_\perp$ to scale as the machine radius (a factor 11 between SPS and CPS). However, a smaller fraction of the SPS has these changes in section, and the factor 5 does not seem unreasonable. CPS experience also predicts that although the instability can be avoided by making chromaticity close to zero throughout most of the cycle a negative offset before transition and a jump at transition to a positive offset are needed. The reason is that near to transition the head-tail phase shift is huge even for low chromaticity, and the transverse modes can couple to the high frequency impedance of the chamber. Such a jump from $\xi_{H,V} = (P/Q)\ dQ/dp = -0.8$ to $+0.8$ in 13 ms was made with the chromaticity sextupoles through transition. Its effect was to prevent instability up to 0.4×10^{11} protons/bunch but above this the instability reappeared, and to reach 10^{11} per bunch seemed very difficult.

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** When an earlier scheme to inject into the SPS at the cooling ring momentum of 3.5 GeV/c was tried, space charge Q shift and remanent field-driven non-linear resonances conspired to cause rapid beam loss. This scheme was abandoned.

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Upper trace : bunch intensity (2.8×10^{10} before loss).

Lower trace : vertical pick-up signal (pass-band 2.25-2.8 GHz).

Arrow shows transition

Fig. 2 : Vertical head-tail instability before transition $\xi = +.6$

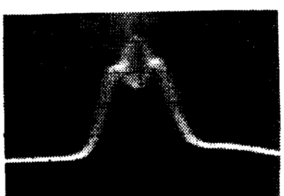
Rather than combat these impediments we chose to inject above transition. By lowering Q from 26.6 to 15.4 transition momentum falls from 21.3 to 13.4 GeV/c. The CPS-SPS transfer line, though it will be upgraded to 26 GeV/c in time for antiprotons, is at present limited to 15.8 GeV but this is just sufficient to inject above transition. In spite of the large α_p and ξ we were able to accelerate 10^{11} in a bunch to high energy.

Storage of Intense Single Bunches

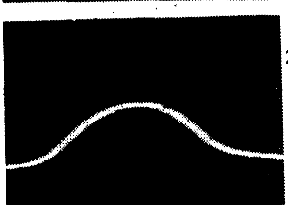
A number of experiments were made in which single bunches containing up to 10^{11} protons were stored. The longitudinal bunch motion was observed from a fast sum pick-up and the total charge within the bunch logged. Two distinct phases of development were seen. In the first "turbulent" phase, longitudinal coherent motion developed and subsided, leaving the bunch dilated but quiescient. During this phase, lasting 5 to 20 minutes decay rate was slow. In the second, "diffusion" period the dilated bunch appeared to leak out of the bucket with a shorter lifetime which varied from minutes to 2 hours depending on the parameters of the r.f. system.

The Turbulent Phase

The instabilities seen to grow in the first few minutes were of dipole, or more often quadrupole mode, higher modes appearing later (Fig. 3).



1. Quadrupole mode at beginning of turbulent phase



2. Quiescent bunch after end of turbulent phase

Fig. 3 : Single-bunch instability

Fast-growing coupled-bunch longitudinal instabilities are seen in the SPS when several bunches are accelerated and stored, and are well explained by current theories[4)], but theories predicting the growth of single bunch modes in the SPS conditions are hard to find. Growth rates of the Robinson mechanism[5)] and of the longitudinal head-tail effect[6)] are long when calculated for our parameters (in the latter case the e-folding time is minutes), and such slow instabilities are usually inhibited by Landau-damping.

However, it can be shown that a strong local interaction, the inductive wall coupling impedance, suppresses Landau-damping for the dense bunches considered. Then any instability mechanism, however slow, will eventually produce large coherent amplitudes and dilute the bunch phase-space. A recent work[7)] calculates exactly the stability threshold of longitudinal modes for this particular interaction.

We compute from this theory that for stability in the SPS

$$\frac{\Delta t^5 \, V}{N} > 1.14 \, \varepsilon_{m',m} \left|\frac{Z}{n}\right| \qquad (1)$$

where Δt is the bunch length (ns)
V the r.f. voltage (MV)
N the number of particles (10^{10})
Z/n is the inductive coupling impedance and
$\varepsilon_{m',m}$ are coefficients for the different modes.

The first dipole mode (1,1) is seen when a train of bunches is injected but is damped by the phase loop when only one bunch is circulating. For a single bunch the first unstable modes are the quadrupole mode (2,2) and a non-rigid dipole mode (3,1).

The constituents of the stability parameter (the left-hand side of Eq. 1) were measured before and after the turbulent period. Figure 4 shows the parameter trajectories for a number of runs. They straddle the thresholds for these modes computed for Z/n = 30 Ω, a value near to the one measured at the ISR[8)]. The dependence of the overshoot on initial distance from threshold can be clearly discerned.

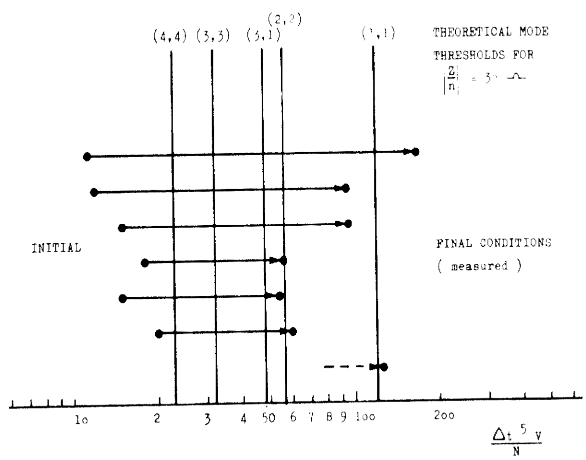


Fig. 4 : During turbulent period bunches blow-up until all possible coherent modes are Landau-damped.

The Diffusion Period

ISR experiments have shown how r.f. noise close to the synchrotron frequency causes a blow-up of the bunch area[9)]. The small amplitude oscillation theory predicts a blow-up rate $d\langle a\rangle^2/dt$ to be proportional to the noise spectral density of the frequency error measured at the bunch center $G_\Omega(\omega_0)$. The effect of the phase-lock loop, combined with the non-zero synchrotron frequency spread (S) inside the bunch is to reduce the influence of the noise source, G_e, by a factor proportional to S^2/β^2 (β being the loop gain at the synchrotron frequency).

$$\frac{d\langle a\rangle^2}{dt} = k \, \frac{S^2}{\beta^2} \, G_e \, . \qquad (2)$$

In our case, we start with bunches which are already quite big, as a result of the turbulent phase, and we do not observe a blow-up of the bunch area : the distribution does not change, but the beam intensity decays exponentially. These features may be described by a diffusion equation, applied to the particles distribution $\psi(a)$ in phase space. The diffusion parameter is proportional to the noise spectral density $G_\Omega(\omega)$ or $G(a)$, which, due to the phase loop effect, is a growing function of the particle oscillation amplitude a[9]. The boundary conditions are $\psi = 0$ at the bucket edge as particles are lost when crossing the separatrix, and the particle's flux at the bunch centre must be zero.

The diffusion equation has a general solution

$$\psi(a,t) = \sum_n \psi_n(a)\, \exp(-t/\tau_n) \quad .$$

The largest τ : $\tau = \tau_0$ gives the quasi-equilibrium distribution $\psi_0(a)$. $1/\tau_0$ is proportional to the noise spectral density at the bunch centre but depends rather little on the shape of the noise spectral density function $G_\Omega(a)$, as shown by several numerical examples[10]. Therefore we can write, as a first approximation :

$$\frac{1}{\tau_0} = k' \frac{S^2}{\beta^2} G_e \quad , \text{ k' being a constant.}$$

Fig. 5 is a plot of τ versus S^2G_e for various and widely different conditions obtained during the experiments. It shows a fair agreement with theory at constant phase loop gain. A large variation of G_e was easily obtained because the radial loop circuitry acts as a noise source around the synchrotron frequency, whose amplitude depends both upon the beam intensity (through the A.V.C. circuits) and upon the radial loop band-width. When the contribution of the radial loop becomes negligible, one is left with the true noise of the present r.f. system (last point on the curve, lifetime = 2 hours). The search for the contribution to the remaining noise lies ahead, but meanwhile we have yet to understand an anomaly, which was also found in the ISR, namely that we could not increase the beam lifetime by increasing the phase loop gain.

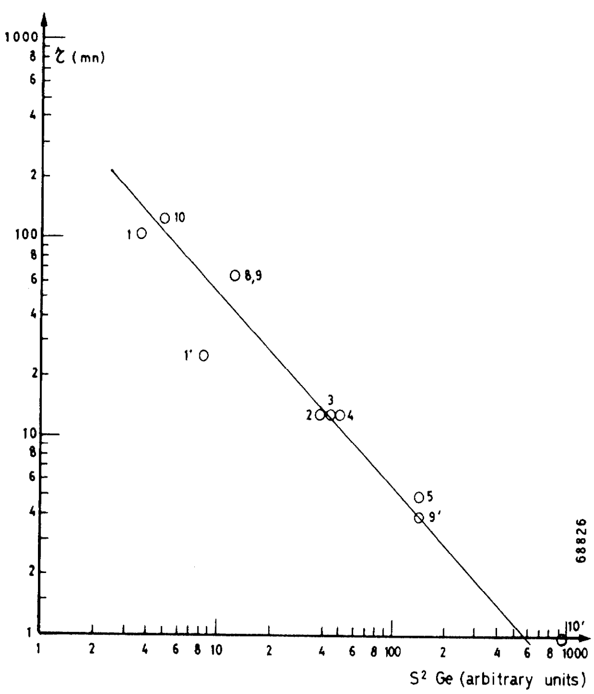


Fig. 5 : Beam lifetime dependence on frequency spread and noise level.

Conclusions

Simulation of proton-antiproton storage conditions in the SPS are well advanced and single bunches of 10^{11} particles have been stored successfully. Slowly growing longitudinal instabilities similar to bunch lengthening mechanisms in electron storage rings have been seen and studied. Although not directly destructive these latter promote beam loss due to r.f. noise and while considerable progress in reducing noise has been made a further order of magnitude is required before single intense bunches reach the 30 hour lifetimes of continuous beams.

Acknowledgements

Many practical problems had to be solved to enable the SPS to switch into storage operation and we would like to thank J.D. Pahud, K.H. Kuhn, G. Beetham, R. Bossart, T. Papis, A. Chapman-Hatchett, G. Schroeder and D. Thomas for their considerable contributions. In addition, none of this would have been possible without the CPS team who responded with enthusiasm to our requests for special conditions.

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