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Performance Limitations of the CERN SPS Collider

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Summary

The SPS has now accumulated more than 10 months of operation as a proton-antiproton collider spread over 3 long physics runs. During this time the peak luminosity has been pushed up to 3.5×10^{29} $cm^{-2}s^{-1}$ and the luminosity lifetime to almost 30 hours. Different physical phenomena limit the machine performance at various times during injection and storage.

The peak luminosity is governed by the number of bunches per beam and the emittance and intensity per bunch as well as by the horizontal and vertical beta values at the experimental insertions. Although the transverse emittances and antiproton intensity are defined by the injector chain, the proton bunch intensity is mainly limited by the microwave instability in the SPS itself. The low-beta insertions have been pushed to the limit of available quadrupole strength and chromaticity correction capability at the maximum storage momentum of 315 GeV/c (β_H = 1m, β_V = 0,5m).

The luminosity lifetime in the first few hours of storage is limited by the transverse emittance growth of the dense proton bunches due to intrabeam scattering[1,2]. As the store progresses, the proton bunch decay rate increases due to the growth of the longitudinal emittance (also through intrabeam scattering), finally becoming the dominant contributing factor in governing the luminosity lifetime.

The beam-beam interaction limits the usable area in tune space to a very small region free of 10th order resonances[3]. Consequently, the total tune spread must be kept below 0.025, allowing only 3 bunches per beam without separation at the unwanted crossings. Recent work has shown that the behaviour of the weak antiproton beam is quite significantly influenced by tiny periodic parasitic current spikes on the main dipoles.

Microwave Instability

Figure 1a) shows the proton bunch length measured in the SPS after capture at 26 GeV/c as a function of intensity, adjusted by vertical scraping on the first turn with constant injected bunch emittance and intensity. Figure 1b shows the longitudinal emittance computed from this data using the measured RF voltage corrected for the voltage induced by the low frequency inductive part of the coupling impedance[4]. ($Z_i/n \simeq 16$ ohms).

At low intensity, the emittance is constant and agrees well with that measured in the CPS before transfer. At a threshold of 9×10^{10} protons/bunch the onset of the instability is clearly visible. The threshold can be written in terms of bunch length L, voltage V (corrected for the wall impedance) and bunch intensity N,[5]

$$\left|\frac{Z}{n}\right| = F\left[\frac{LV}{Nech}\;\sin^2\left(\frac{hL}{4R}\right)\right] \qquad (1)$$

where F is a form factor of the order of 0.5, R is the machine radius and h the harmonic number.

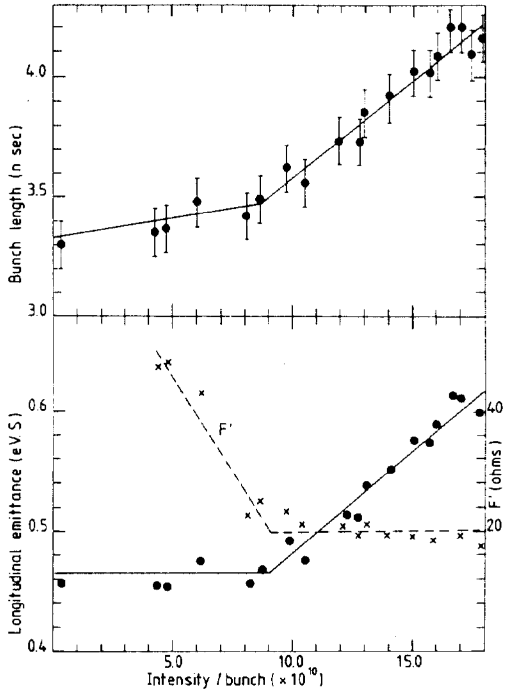

Fig. 1 Bunch length and longitudinal emittance as a function of bunch intensity.

In figure 1b the quantity (F') on the right hand side of equation 1 is plotted. Above threshold, this quantity is roughly constant, signifying an emittance blowup just large enough to provide Landau damping. No overshoot is evident. The value of Z/n of ~ 20 Ω deduced from these measurements is in reasonable agreement with that measured in other ways. Due to a longitudinal acceptance limitation later in the accelerating cycle, this emittance blowup limits the proton bunch intensity in storage to around 1.6×10^{11} p/bunch.

Intrabeam scattering

Intrabeam scattering produces a blowup of both radial and longitudinal emittance of the dense proton bunches. In the first few hours of a coast the longitudinal blowup has only a small influence on the luminosity lifetime through the weak dependence of luminosity on bunch length. The dominant contribution to the luminosity decay is through the radial emittance growth.

Figure 2 shows the radial growth rate $\dot{\varepsilon}/\varepsilon$ measured with the fast wire scanner throughout a long coast. The solid line represents the theoretical intrabeam scattering growth rate computed using the analytic smooth approximation[2] and instantaneous measured values of emittance and intensity. The

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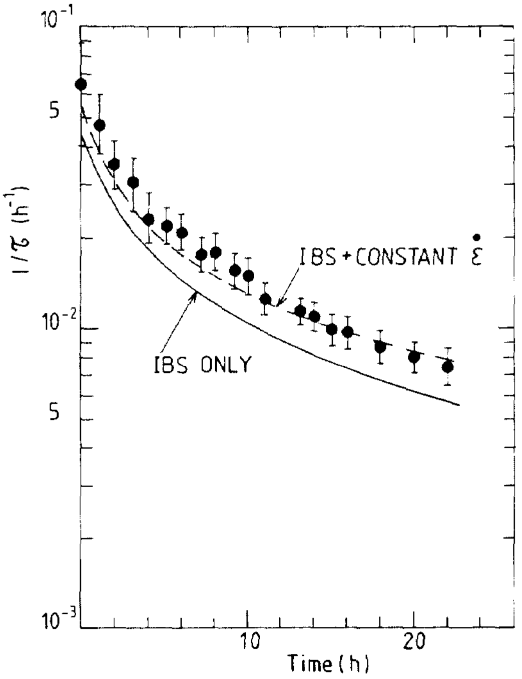


Fig. 2 Measured radial emittance growth rate $\tau^{-1} = \dot{\varepsilon}/\varepsilon$ compared with the theoretical intrabeam scattering rate. The dotted line includes a correction for gas scattering.

agreement with the experimental data is better if the constant emittance growth rate due to multiple Coulomb scattering with the rest gas, estimated to be of the order of 0.1π mm.mrad.h.$^{-1}$ (normalised), is added. The mean N_2 equivalent pressure for multiple scattering in the SPS is estimated to be of the order of 2×10^{-10} torr.

As the longitudinal emittance increases the proton bunch lifetime drops (fig. 3), eventually reaching an equilibrium value of around 50h. and becoming the dominant contribution to the luminosity lifetime of ~ 30h. Detailed measurements[2] have shown that the lifetime is intensity dependent and is thought to be due to intrabeam scattering of particles across the bucket separatrix, although no satisfactory theory of intrabeam scattering limited lifetime is available to compare with the experimental data.

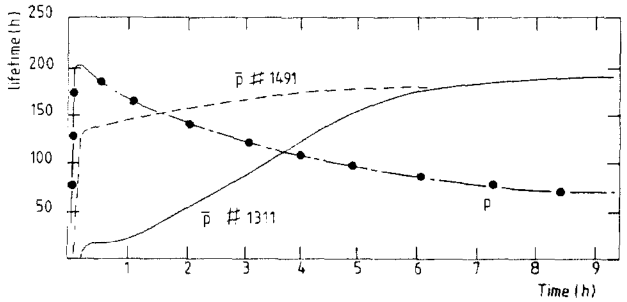


Fig. 3 Lifetime evolution of proton (dotted) and antiproton bunches. The proton decay rate remained essentially unchanged when periodic power supply spikes were suppressed. The antiproton lifetimes before (coast # 1311) and after (# 1491) are significantly different.

The Beam-Beam Interaction

The effect of 10th order beam-beam resonances on the lifetime of the weak antiproton bunches at the operating tune shift of 3×10^{-3} per crossing has already been documented[3]. Coupled with a very low lifetime (a few hours) self scraping of the antiproton beam has been observed, signifying preferential extraction of large emittance particles.

In normal operation the tunes are adjusted so that only small emittance antiprotons touch the main resonance $10Q_H = 267$. Nevertheless, for most of the 1984 physics run, some self-scraping during early storage was still observed. As an example, figure 4 shows the horizontal and vertical emittances of fill # 1311 measured throughout the coast. In the vertical plane the emittance reduction over the first few hours can clearly be seen. In the horizontal plane the blowup due to intrabeam scattering makes the effect less pronounced. The corresponding bunch lifetime of # 1311 is shown in figure 3. The bad initial lifetime is clearly correlated with the loss of large emittance particles.

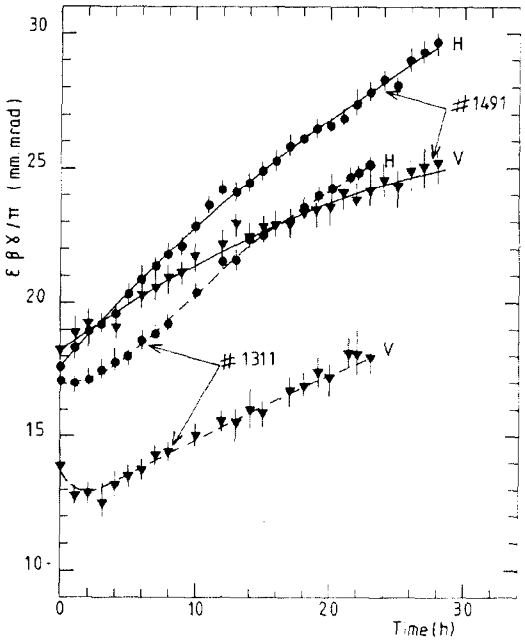
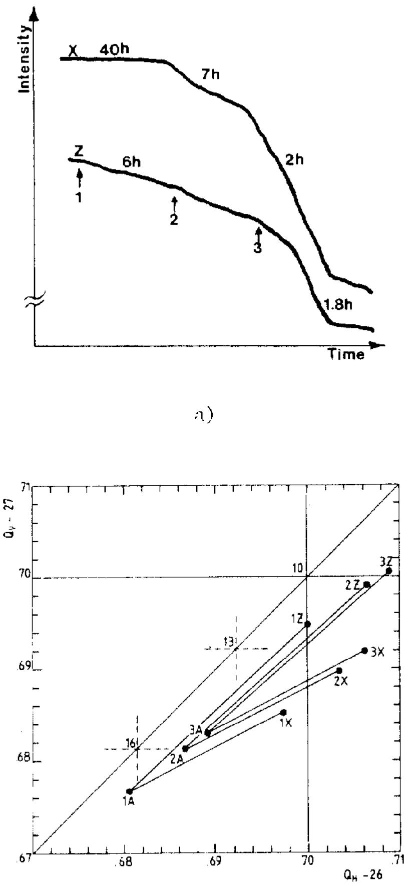


Fig. 4 Antiproton emittance growth during two long coasts before (# 1311) and after (# 1491) periodic power supply spikes were suppressed.

The situation changed quite significantly when it was found that the beams were being subjected to a tiny periodic excitation due to sharp current spikes propagating in the main dipole chain, which acts like a damped transmission line. The presence of this excitation can be observed as an excitation of the transverse Schottky signals[6]. The peak current variation $\Delta I/I_0$ is estimated to be of the order of 10^{-8}, corresponding to a kick amplitude of a few nanometers. Damping these spikes considerably improved the beam quality (fill # 1491 in figs. 3 and 4). The antiproton lifetime in early storage is improved considerably and no evidence of self-scraping was observed.

A quantitative explanation of this effect has not yet been found, although it clearly illustrates the precision of the power supplies required for good beam quality. However, computer simulation has shown that such spikes, coupled with a phase space already close to the stochastic limit, can give rise to a rapid amplitude growth. Similar results have previously been obtained for noise enchancement of beam-beam resonances[7].

With three bunches per beam, all beam-beam collisions are in regions with almost zero dispersion. In order to investigate the effect of a high dispersion collision, an experiment was performed in which one antiproton bunch (bunch X in fig. 5) was injected at a displaced azimuthal position in order to cross the proton bunches at a value of the dispersion of 5.4 m. The decay rate of this bunch was then compared with that of a reference bunch (bunch Z). crossing the proton beam at the nominal intersection points, as the tune is moved into the 10th order resonances, In figure 5 the measured tune of the proton bunch (A) is indicated together with the computed zero amplitude tunes of the two bunches X and Z, which cannot be observed on the Schottky signals due to their low intensity and large spread. The vertical tune shift of bunch X is about half that of bunch Z due to the high dispersion.



a)

b)

Fig. 5 a) Chart recorder output of intensity decay of two antiproton bunches X (high dispersion crossing) and Y (zero dispersion) as the machine tune is pushed towards the 10th order resonance. The measured lifetime is recorded at each step.

b) Tune values of protons (measured) and small amplitude antiprotons (computed) for the three points of fig. 1a). The vertical beam-beam tune shift of bunch X is half of that of bunch Z because of the high dispersion.

Initially the lifetime of bunch X is substantially higher than that of bunch Z since it is further away from the resonance. However, as the tunes are pushed up, both beams decay at the same rate. No clear enhancement of synchrotron sidebands due to the large dispersion could be observed with the very low synchrotron frequency ($Q_s \simeq 4 \times 10^{-3}$) of the SPS.

Conclusions

The most significant contribution to the luminosity lifetime is due to intrabeam scattering. This can be improved by a pre-emptive blowup of the longitudinal emittance in a larger RF bucket using a 100 MHz radiofrequency system under construction. This would also allow the microwave instability threshold to be raised. Operation with more than 3 bunches per beam will require beam separation at the unwanted collision points to reduce the beam-beam tune spread. Preliminary experiments with separated beams have given encouraging results[8].

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