SPS IMPROVEMENT REPORT NO. 154

First storage of $10^{11}$ protons in one bunch at 210 GeV/c
(runs of 4.12.78 and 18.12.78)

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1. INTRODUCTION

The specifications of the $p\bar{p}$ project demand that the SPS be capable of sustaining counter-circulating beams of protons and antiprotons for periods of 24 hours, while the beam collides in one or two low beta insertions. Each beam should consist of six bunches, equally-spaced around the circumference, and each bunch should contain $10^{11}$ particles, fifty times the SPS design value.

The first step in the feasibility study of this scheme was to show that a continuous, low intensity proton beam could be kept coasting for more than 24 hours in the machine\(^1\)). The second step obviously consisted in repeating this with one single bunch containing around $10^{11}$ particles. For a long time it proved impossible to accelerate such intense single bunches, as various phenomena prevented acceleration through transition\(^2\)). Nevertheless, even at $2 \times 10^{10}$ per bunch, it was already apparent that instabilities afflicted the single bunch and the storage lifetime was much less than that required. The solution eventually found to achieve higher intensities was to inject above transition, and for that purpose the machine tune was reduced from 26.6 to 15.4, in which case transition momentum drops from 22.2 to 13.4 GeV/c. In the first trial of this idea\(^3\)) the CPS beam was injected at 15.8 GeV/c on the rise of the SPS magnetic field, and it was possible to accelerate $5 \times 10^{10}$ protons in one bunch to 210 GeV/c, which was already a record. In the experiments reported here, injection took place at the same energy, but on an SPS magnetic flat-bottom.

In this way, almost $10^{11}$ particles per bunch were accelerated and stored. It became clear that during storage the bunch first executes a coherent motion which inflates the longitudinal emittance. Once this instability has died away, the protons diffuse out of the bucket rather rapidly. In a number of trials in which the parameters of the RF control loops were varied, we were able to show that this diffusion is due to RF noise. Reducing the bandwidth of the radial loop improves the lifetime considerably, but the best achieved to date is still two hours.
2. INJECTION AND ACCELERATION

The solution of injecting on the rise was chosen the first time to allow a preliminary tune-up of the machine with the normal beam injected on the 10 GeV/c flat bottom. In these experiments this was no longer considered to be necessary.

The cycle had a 9.6 s repetition period, a flat top at 210 GeV/c and at 400 GeV/c, and a flat bottom at 15.8 GeV/c. Injection was first made 120 ms before the beginning of the front porch field rise, to allow plenty of time for beam diagnostics. When the machine was thought to be optimized, injection time was displaced to 115 ms (5 ms before the rise) to reduce the flat bottom losses.

The advantages of injecting on a flat bottom are the following:

- RF buckets can be matched to long bunches (4 ns instead of 2 ns on the field rise) thus reducing the Laslett Q shift from 0.09 (uncomfortably large value for 2 ns bunches) to 0.045.

- beam diagnostics and RF set up are easier.

- injection field level adjustment is much easier. Previously it had to be done via CPS ejection timing changes.

After TT10 and injection kicker adjustments, tuning proceeds as follows:

- Crude B field adjustment to have some beam injected.

- Q measurement and correction. Chromaticity adjustment through the \( B_{\text{inj}}/B \) term to obtain the maximum betatron ringing time.

- orbit acquisition at the first turn.

- fine adjustment of B field to have centred orbit. Orbit correction.

- RF on. Phase offset adjustment to have no radial drift until radial loop is switched on.

- orbit correction at radial loop P.U.

- Q and chromaticity adjustment along the cycle.

The CPS intensity used was \( 3.2 \cdot 10^{12} \) (1.6 \( \cdot 10^{11} \) per bunch) and at the beginning the 20 bunches were injected. Under these conditions, both the fast and slow BCT's are blind for 1 ms after injection. This is very unfortunate, and will have to be corrected, because about half the beam intensity was lost between the last BCT in TT10 and 1 ms after injection, and no way could be found to improve on that. When the machine was thought to be properly tuned, the CPS was asked to send one bunch only. Usually, the intensity accelerated in the SPS in one bunch is higher than 1/20 of that accelerated in 20 bunches (reduced beam-loading).
With $1.6 \cdot 10^{11}$ p per bunch in the CPS, about $0.7 \cdot 10^{11}$ p were accelerated to top energy in the SPS. Increasing the CPS intensity to $2.2 \cdot 10^{11}$ per bunch, a maximum intensity of $0.85 \cdot 10^{11}$ (measured on the special bunch charge meter) or $10^{11}$ (measured on the BCT) was accelerated. It does not pay to increase the CPS intensity further because then the longitudinal emittance increases too much.

3. STORAGE EXPERIMENTS

Two different regimes are clearly seen when dense bunches are stored. During the first period, that we can call "turbulent", the bunch is short and exhibits coherent motion. Its lifetime constant is then rather long (many hours). During the second regime -- the "diffusion" period, say -- the lengthened bunch is coherently stable, but its lifetime is rather poor, and depends on the noise level of the RF system. The two regimes will be described and explained in terms of existing theories.

3.1 Turbulent period

The coupling of the beam with its surrounding is described by the notion of coupling impedance $Z/n$, the effect of it being a complex shift $\Delta \omega$ of the particles' oscillation frequencies\(^5\). One never knows in detail the total coupling impedance of a machine. Nevertheless, certain constituents can be computed or measured (RF cavity, smooth beam pipe). It has been shown at the ISR that at high energy, an important part of the longitudinal coupling impedance comes from the vacuum chamber inductance. $Z/n$ of 20 to 30 $\Omega$ have been measured, and it is generally agreed that all accelerators in operation to date have about the same inductive $Z/n$. This is a local interaction which cannot couple bunches together, but produces a real frequency shift which can counteract the Landau-damping provided by frequency spread in the bunch. We will try to explain the observations made in the SPS by invoking the dominant influence of this inductive impedance.

Observations

The longitudinal acceptance of the SPS at injection is about 0.2 radians. With 20 bunches (or even 5 bunches) injected, violent coupled-bunch instabilities take place during acceleration and the beginning of the flat top, so the beam blows up fast to 0.9 rad, after which it is perfectly stable.

With a single bunch, the emittance measured at the beginning of the flat-top is about 0.3 rad. The bunch is stable for some seconds or minutes, after which it slowly develops coherent motion on quadrupole, or less frequently dipole mode. This turbulent period typically lasts 5 to 30 minutes, during which time the bunch emittance slowly grows up to about 0.8 radians. At the end of the period, the motion becomes very complicated, and many coherent modes can be seen at the same time, bursting at a frequency of about 2 Hz. Eventually, the bunch stabilizes completely. Data are summarized in Table 1.
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<th>RF AM</th>
<th>Spacing 3x</th>
<th>Spread Intensity 10^11</th>
<th>Radial loop bandwidth Hz</th>
<th>Lifetime 1 r minutes</th>
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(Video tape by Walter Scandale)
5.

**Interpretation**

Usual dispersion relation analyses may be used to give the criteria for stability of the different coherent modes: the greater the intensity and coupling impedance, the greater the frequency spread in the bunch needed to provide complete Landau damping. However, this approach gives only a rough estimate in the case of strong interaction. A recent work\(^5\) calculates rigorously the stability limits in the case of a pure inductive impedance, and we will use its more precise results. When the spread in frequencies is given by the natural non-linearities of the RF bucket, the condition for stability can be written:

\[
\Delta t^5 > \varepsilon_{m,m'} \times 1.14 \frac{N}{V} \left| \frac{Z}{n} \right|
\]  

(1)

where \(\Delta t\) is the bunch length in ns, \(V\) is the RF voltage in MV, \(N\) the bunch intensity in \(10^{10}\) particles, and \(|Z/n|\) the modulus of the coupling impedance in ohms. \(\varepsilon_{m,m'}\) are coefficients found in Besnier's work\(^5\). \(m\) and \(m'\) are indices describing the double infinity of non-degenerate normal modes. For instance, the "rigid dipole" mode is \((1,1)\), \((3,1)\) being also a dipole mode, but with no centre of mass motion. \((2,2)\) is the usual quadrupole mode, etc.

Condition (1) can be written:

\[\xi > 1.14 \varepsilon_{m,m'} \left| \frac{Z}{n} \right| \text{ with } \xi = \frac{\Delta t^5 V}{N} .\]

The parameter \(\xi\) can be computed from bunch-length measurements made at the beginning of the turbulent period, and at the end, when the bunch becomes stable. Both values are plotted in Fig. 1, for the different storage experiments made. One can see how the bunch is far from stability at the beginning of flat-top, and progressively increases its length to finally end up in the stable zone. The parameter which has to be assumed is the coupling impedance \(Z/n\). A very plausible value of 30 \(\Omega\) has been assumed here.

With single bunches, the first dipole mode \((1,1)\) is damped by the phase-loop. The next unstable modes, as seen in Fig. 1, are the quadrupole \((2,2)\) and the first non-rigid dipole mode \((3,1)\). Contrary to this, with 20 bunches (case 1), coupled bunch modes with zero centre-of-mass motion averaged over the bunches can fool the phase-loop, and the rigid dipole mode \((1,1)\) can be excited. All this is well borne out by experiment, and shows up on Fig. 1.

In Fig. 1 one may also notice the following: the bunches starting with a large frequency spread (coasts 2,3,4) end up very near to the theoretical stability limit. Observation has shown only moderate coherent amplitudes for these experiments during the turbulent period. On the contrary, bunches starting with a small initial spread (coasts 5,7,8) develop large coherent amplitudes, and the result is an overshoot, larger for smaller initial spread. For coast 10 of Table I, the initial spread is very small, and the overshoot is so big that the representative point lies outside Fig. 1.

Of course stability is gained at the expense of bigger spread, which determines the behaviour of the bunch in the next phase.
3.2 Diffusion period

Storage of a bunched proton beam was already tested in the ISR several years ago\(^6\). It has been shown that the diffusion due to the noise of the system gradually increases the bunch size and eventually leads to particles being lost outside the bucket. In the SPS case the bunch shape does not change much, but particles are continuously spilling out of the bucket, giving a gradual decay of the bunch intensity.

Some results of the existing theory\(^6\)

In the absence of noise, individual particles inside the bunch oscillate with constant amplitude (loss-less resonators). To increase their energy (or oscillation amplitude) the perturbation must excite them precisely at their oscillation frequency. In other words, only the noise around the synchrotron frequency can produce a blow-up of the beam emittance\(^7\).

When a phase-lock system is present, its open loop gain becomes infinite at the synchrotron frequency (the beam being a loss-less resonator) and consequently any noise is reduced to zero at that particular frequency; therefore no blow-up occurs. Unfortunately, this is only true if all particles oscillate at exactly the same frequency. As we have seen in Section 3.1, a certain frequency spread must be present in order to stabilize the beam against coherent instabilities. This in turn means that the phase loop will only reduce the noise to a certain extent around the synchrotron frequency.

The effect of the noise is to gradually increase the bunch size. However, as particles approach the boundary of the bucket their frequency difference increases rapidly and hence, the effect of the noise. So we believe that, above a certain beam size, the particles will be rapidly lost outside the bucket. In this way, it is possible to relate the decay time of the bunch intensity

\[
\frac{1}{\tau} \frac{di}{dt}
\]

(i being the current in the bunch) to the diffusion rate \(dA/dt\) (A being the r.m.s. oscillation amplitude) measured at the bunch boundary.

This interpretation is suggested by the fact that the equilibrium bunch length was always more or less the same in all cases (3 ns), and significantly shorter than the full bucket length (5 ns).

It can be shown that the diffusion rate, or the beam lifetime, which in our case of big bunches is equivalent, is related to the frequency spread inside the bunch \(S\) and the spectral density of the electronic noise of the system \(G_e\) by the following relation:

\[
\frac{1}{\tau} = \frac{1}{\tau} \frac{di}{dt} = k S^2 G_e
\]

\(k\) is a constant of the RF system, depending on the point where the noise is measured.
Experimental results

The beam lifetimes were measured under various conditions of beam intensity (20 bunches or 1 bunch), frequency spreads, RF voltage and electronic noise (Table 1).

An important contribution to the electronic noise was found to be due to the radial loop. Reducing its bandwidth from the normal 1 kHz value to far below the synchrotron frequency, considerably improved the lifetime from minutes to more than one hour. On the contrary, when the noise level increases (e.g., by lowering the radial PU sensitivity, or when the beam intensity, at the end of the store, becomes very low) the lifetime decreases. These experiments suggest that the electronic noise $G_e$ is composed of two parts:

$$G_e = G_p + G_r$$

$G_p$ is the phase loop noise, depending essentially upon the quality of the circuitry,

$G_r$ is the radial loop noise, depending upon the total beam intensity ($1/I_0^2$) and the bandwidth.

Fig. 2 is a plot of measured lifetime versus the parameter $S^2G_e$ for the various and very different conditions, corresponding to the successive stores. The unknown parameter $G_p$ has been adjusted to fit the last measurement (point 10). There is a fair agreement between experiments and theory considering the very different conditions of the experiments which span over two orders of magnitude. It is worth noting that point No. 1, which deviates most from the straight line, corresponds to the initial 20-bunch case for which the initial assumption (constant bunch length) is not satisfied (the bunch actually shrinks during the diffusion period). Fig. 3 shows a typical example of two different decay times observed during the same store by changing the radial loop bandwidth and hence the electronic noise $G_e$.

In the last experiment (No. 10) the noise coming from the radial loop is negligible and we are left with the true RF noise of the present system.

Noise spectra

According to theory, the noise spectrum, measured on a particular point of the phase loop, should exhibit a dip at the synchrotron frequency, and the minimum noise level should correspond to the diffusion rate. During this experiment we have observed the noise spectrum at various points on the phase loop, especially at the input of the master oscillator.

The situation is clear when the electronic noise of the radial loop becomes very important (for instance, at the end of the beam life) as shown in photos 1 and 2. When the electronic noise level increases, the minimum of the curve does not move, which seems to indicate that this level does not correspond to the actual noise seen by the beam. As a
mater of fact, the lifetime calculated from the minimum noise level on photos 1 and 2 is only a few seconds and not minutes, as observed. The situation is the same as the ISR one where the minimum of the dip can only be observed by injecting an additional noise\textsuperscript{6}).

So far we have only considered the phase noise of the system, but the amplitude noise is also present as shown on photo 3. This photo displays the noise spectrum of the peak detected AEW signal, on which bumps at 2$f_S$ and $f_S$ are clearly visible. If it turns out that this amplitude noise is important, it could be reduced in the same way as the phase noise by a feedback system damping the quadrupole mode of the beam.

**CONCLUSION**

Storage of a single bunch of almost $10^{11}$ protons has been achieved in the SPS machine. This experiment has revealed the importance of two classes of problems: coherent instabilities and RF noise. They unfortunately set two conflicting requirements on one of the beam parameters, namely the synchrotron frequency spread inside the bunch.

The minimum frequency spread, which corresponds to the maximum beam lifetime, is determined by the coherent instability threshold. During these experiments, this threshold has been measured for the design $p$-$\bar{p}$ intensity, and therefore, the only way to improve the situation is to lower the noise of the RF system. For similar beam emittances the RF noise must be reduced by an order of magnitude in order to reach the design beam lifetimes.

If the injected beam emittance is very large, corresponding to an almost full bucket, these experiments suggest that the outer part of it will be rapidly lost. One should therefore give preference to the procedures which lead to the smallest injected beam emittance.

Reported by J. Careyte and D. Boussard
REFERENCES

1. SPS Improvement Report No. 66.

2. SPS Improvement Reports Nos. 127, 132, 141.

3. SPS Improvement Report No. 147.


5. B. Besnier, Thèse, Université de Rennes, France.


Fig. 1: Stability limits of coherent modes

$$\xi = \frac{\Delta t^5 V}{N} ; \quad \left| \frac{Z}{R} \right| = 30 \ \Omega$$

- theoretical limits: vertical lines
- experiments:
  - 1: 20 bunches
  - 2 + 8: single bunch
Fig. 2 : Beam lifetimes under various conditions
Fig. 3: Beam lifetime
0.5 mV r.m.s.

10 dB/div

BW = 4 Hz

\[ V_{RF} = 2750 \text{ kV} \]

\[ f_s = 295 \text{ Hz} \]

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\[ f_s = 350 \text{ Hz} \]

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1 mV r.m.s.

\[ f_s \quad 2f_s \]

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Photo 1
Spectrum at the oscillator input (100 kHz/V)

Photo 2
Spectrum at the oscillator input (100 kHz/V)

Photo 3
Peak detected AEW spectrum