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ABSTRACT

Recent improvements to the low-level radiofrequency system have resulted in a considerable increase in bunched beam lifetime. Single proton bunches have been stored for up to 18 hours. In the course of these studies, new instrumentation has been developed and other experiments relevant to $p\bar{p}$ operation have been performed.

1. INTRODUCTION

In order to obtain the design luminosity in the SPS p-$\bar{p}$ collider, tightly bunched proton and antiproton beams must be stored for many hours. Earlier work[1)] established the importance of radiofrequency noise in governing the bunched beam lifetime. Recent improvements in the low-level r.f. system have resulted in a considerable reduction of the noise with a consequent increase in lifetime to a level where other effects become important.

Although the phenomena which govern the lifetime of a single beam now seem to be well understood, there is still considerable uncertainty as to the limitations imposed by the non-linear beam-beam forces. In order to simulate this effect, a non-linear lens[2)] has been installed in the SPS. Preliminary experiments with protons have shown that the lifetime strongly depends on the lens strength and on the tune of the machine. In particular, resonances at least up to 10th order must be avoided.

During the course of the storage experiments, two new beam monitors were developed. A sensitive Schottky noise receiver has been built which allows observation of both debunched beams and single bunches. The transverse beam profiles can be measured using a fast wire scanner. This device has been used to measure the transverse emittance growth during long coasts.

Finally, the SPS coupling impedance has been measured from the growth time of head-tail and microwave instabilities. The low frequency reactive impedance has also been estimated from a measurement of the quadrupole mode transfer function.

2. IMPROVEMENT OF BUNCHED BEAM LIFETIME

The various sources of noise in the r.f. system are analysed elsewhere in these proceedings[3)]. Early bunched-beam storage experiments[1)] clearly showed that the lifetime was limited by noise in the radial loop due to the very low average beam intensity. This has been improved by controlling the r.f. frequency rather than the beam radial position. The noise of the frequency measuring device (0.4 rad/s/$\sqrt{\text{Hz}}$ around $f_s \simeq 230$ Hz) is further reduced by decreasing the bandwith of this loop to about 10 Hz (the practical limit imposed by VCO short-term stability) so that its effect becomes negligible.

The very large phase loop gain ($2\pi\times 57\cdot 10^3$ rad/s at f_s) makes the beam almost insensitive to the VCO and magnetic field noise, and explains why the lifetime was independent of the loop gain. In contrast, the noise of the phase measurement system is very important. For storage a new system has been designed which measures the beam-r.f. phase when the bunch passes through the pick-up and stores it until the next passage. The improvement gives a much better lifetime (Fig. 1). Making the loop gain infinite at f_s would cancel completely the VCO and magnetic field noise at that frequency[3]. The stability of such a loop has been successfully tested and will be considered for the final system, together with an improved phase detector.

According to theory[4] the lifetime should be proportional to the square of the absolute synchrotron frequency spread S. However, our measurements under various conditions of r.f. voltage and longitudinal emittance seem to indicate a dependence on the relative $(S/f_s)^2$ spread. In order to prevent beam blow-up due to longitudinal instability, a quadrupole-mode damping system was installed, which resulted in a factor of two increase in lifetime. Another advantage of this system is that it reduces the effect of the amplitude noise. Another way of achieving a small spread is to increase the r.f. voltage. Plans to install extra high Q standing wave cavities are under way.

An experiment was performed where 3 equispaced bunches were injected into the SPS on 3 consecutive CPS pulses. The required synchronisation of the two machines was made through an optical fibre link. The new phase detector only looks after one bunch during storage. As a result, the other bunches diffuse very rapidly due to the VCO noise at $n \times f_{rev} \pm f_s$ [3]. Independent quadrupole mode oscillations from bunch to bunch have also been observed, so for the final system damping of dipole and quadrupole mode must be provided for each bunch separately.

3. INSTRUMENTATION

3.1. Schottky Noise Receiver

A dedicated horizontal pick-up has been installed in order to monitor the Schottky signal from both bunched and debunched beams. It consists of a pair of aluminium electrodes each 3 m long which can be remotely moved close to the beam at high energy to obtain maximum sensitivity (signal power α (beam diameter/gap)^2). With a gap of 10 mm (115 pF interelectrode capacitance) the plates are made to resonate at $\sim$ 10.7 MHz with an air-cored coil placed at their centre point. A coupling loop acquires the signal and provides the match to 50 Ω. The 3 dB bandwidth of the resonator is $\sim$ 45 kHz, comparable with the revolution frequency of 43.35 kHz. The signal is amplified by a low noise amplifier, filtered then mixed to below 25 kHz in a single stage before analysis by an averaging FFT spectrum analyser. For measurements on bunched beams the coherent longitudinal components must be strongly attenuated to prevent saturation of the amplifiers. By carefully centering the pick-up, a rejection of $\sim$ 40 dB can be obtained. A narrow-band crystal filter (BW = 14 kHz) can be switched in between the pick-up and first amplifier to give a further rejection of $\sim$ 70 dB. Fig. 2 shows a typical scan at 240 GeV/c of a beam of $\sim 10^{12}$ protons. The lower trace give the horizontal signal of the bunched beam, where the synchrotron satellite sidebands of order 1 and 2 are visible. The central line should be infinitely narrow for a linear machine. Its finite width is due to power supply ripple. With the system as it stands, unbunched beam signals can be seen with a S/N ratio of 10 dB for 5×10^{11} protons circulating whereas with a single bunch useable signals are obtained with 10^{10} protons. Close to the main diagonal, vertical signals can also be obtained. The final system will have separate horizontal and vertical pick-ups with tunable coils so that the gaps may be varied.

3.2. Fast Wire Scanner

In order to measure the beam transverse profile in an almost non-desctructive way, a simple wire scanner[5] has been built. A 50 μm diameter beryllium wire is passed quickly (∿ 3 m/s) through the beam. The profile is measured by detecting the high energy secondary particles traversing a scintillator placed downstream of the wire and close to the beam pipe. The device is very flexible, allowing measurement of single dense bunches or debunched beams over a wide range of intensity and over the whole energy range of the SPS.

Figure 3 shows a typical profile of a single bunch of 3×10^{10} protons at 270 GeV/c. The discrete lines are due to the bunch traversing the wire on each revolution of the machine. The distance between the lines corresponds to a spatial resolution of 70 μm. The calculated emittance blow-up due to a single traversal is $3.7\times10^{-6}\pi$mm.mrad in the horizontal plane and $1.5\times10^{-5}\pi$mm.mrad in the vertical plane, compared with $6\times10^{-3}\pi$mm.mrad/h for gas scattering at the best pressure achieved during our experiments (∿ 6×10^{-9} Torr N_2 equivalent), so the perturbation of the beam for infrequent scans (< 10/h) is negligible. The final system will make use of the strong directionality of the secondary particle production by using two separate detectors symmetrically positioned with respect to the wire to measure both proton and antiproton profiles independently.

4. EXPERIMENTAL RESULTS

4.1. Long Storage Experiments

On a few occasions we had the opportunity to store beams for many hours. During these runs, both the vertical beam profile and the betatron Schottky lines were recorded. Fig. 4 shows the evolution of the vertical emittance in two experiments, one with a debunched beam and the other with a single bunch. The emittance growth is identical in both cases and is consistent with an equivalent pressure for multiple scattering of 10^{-8} Torr, which was in reasonable agreement with the measured pressure. As a confirmation that the blow-up was due to the gas, during one of the experiments the mean pressure was increased by a factor of 4. The emittance blow-up rate was observed to change accordingly.

Another phenomenon observed during a long coast with a debunched beam was a steady drift of the radial tune. This could be very well explained as a deceleration of the beam by synchrotron radiation[6] (8.7 MeV/h at 270 GeV/c) which, together with the measured chromaticity of + 0.2 gave a drift of the radial Schottky line of 7.4 Hz/h.

4.2. Impedance Measurements[7]

Knowledge of the coupling impedance is essential for the computation of beam stability. The real part of the transverse impedance can be deduced from the growth rate of the head-tail instability as a function of chromaticity. The results, fitted to a wide-band model[8], give $Z_T = 18\ \mathrm{M}\Omega\cdot\mathrm{m}^{-1}$. The longitudinal impedance has been measured in two separate ways. By injecting at 15.8 GeV/c and adjusting the longitudinal emittance and bunch length in the CPS, the threshold for microwave instability in the SPS can be reached. Measurement of the growth time as a function of frequency is consistent with a value of $Z_L/n = 16\ \Omega$. These measurements also reveal a number of sharp spikes which are probably caused by higher modes of the r.f. cavities. A measurement of the inductive impedance has been made from the quadrupole mode transfer function of a single bunch by modulating the r.f. voltage amplitude and detecting the quadrupole mode oscillations. With low intensity long bunches which are strongly damped, the incoherent central frequency can be measured as a discontinuity in the phase response. With high intensity short bunches the collective frequency can be measured from the amplitude response. This method gives $Z_L/n = 10\,\Omega$ averaged over the rather wide bunch spectrum ($\sim$ 1 GHz). The measured value of 10-16 Ω is considerably lower than previously estimated ($Z_L/n = 30\ \Omega$). Agreement between Z_T and Z_L/n is obtained if an effective chamber height of 40 mm is assumed compared to the geometrical average of 23 mm over the whole machine.

4.3. Non-Linear Lens Experiments[9]

The non-linear lens[2] consists of a pair of cylindrical current-carrying copper bars which may be accurately positioned above and below the beam. A pair of vertical scrapers allows the beam centre to be found and also acts as a well-defined aperture limitation against which beam lifetime can be measured. The strongly non-linear field generated by the lens drives high-order resonances which, with a suitable choice of beam energy and lens parameters, can be made comparable with the strength of resonances driven by the beam-beam forces. For example, Fig. 5 shows the resonance strength against order of one-dimensional resonances at 2 standard deviations of a round Gaussian beam with a linear beam-beam tune shift of 3×10^{-3}, which is the desired tune shift to reach design luminosity. This is compared with the stopband widths due to the lens at the amplitude of the scrapers under the conditions of two experiments. In the first at 150 GeV/c, the resonances above octupole were more than an order of magnitude weaker than the beam-beam stopbands. The beam could sit on 8th order resonances without any decrease in lifetime. The second experiment was designed to simulate more closely the beam-beam forces. The energy was reduced to 40 GeV/c and the beam blown up vertically with noise to fill a 2 πmm.mrad acceptance defined by the scrapers. This time, the lifetime depended strongly on lens current and working point (Fig. 6). The 8th order resonances proved to be catastrophic to beam survival whereas in a region free of resonances to 11th order there was very litte dependence of lifetime on lens strength. These results clearly indicate that the working point for $p\bar{p}$ operation must be free of non-linear resonances at least up to 10th order. The results are at least in qualitative agreement with a model based on single isolated resonances.

5. ACKNOWLEDGEMENTS

Too many people in the SPS Division contributed to these experiments to be named individually here. Nevertheless, we thank them all. In addition it is a pleasure to thank our colleagues in the CPS Division for their expertise and enthusiasm.

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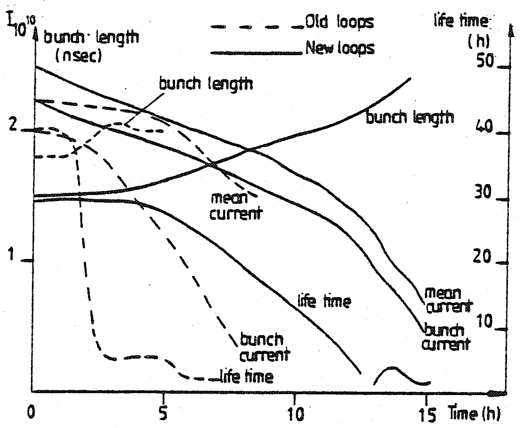

Fig. 1
Beam lifetime with old and new loops

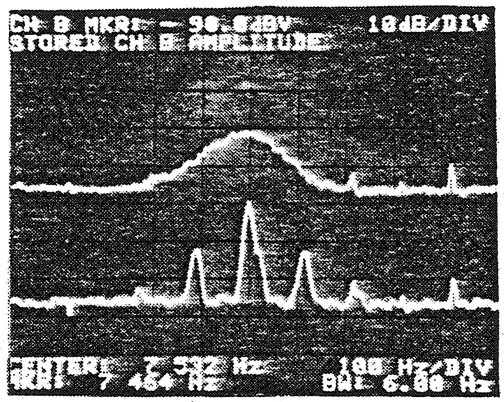

Fig. 2
Schottky signal from horizontal fast wave debunched (upper) and bunched (lower)

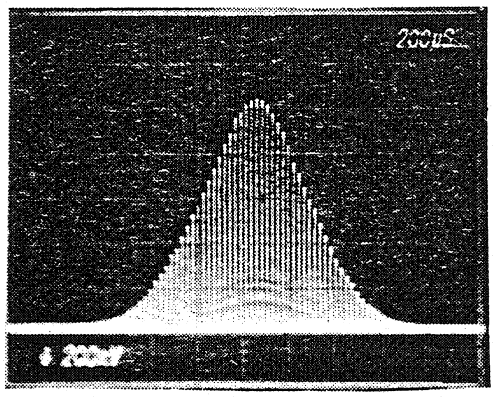

Fig. 3
Transverse beam profile of a single bunch

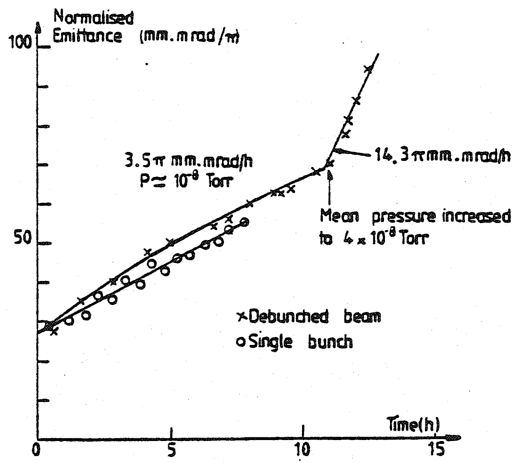

Fig. 4
Emittance blow-up during long coasts

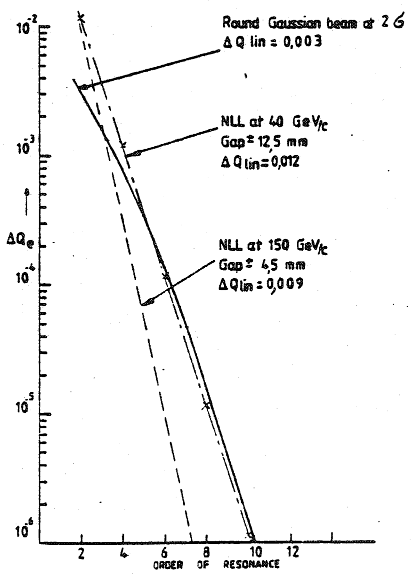

Fig. 5
Resonance widths as a function of order

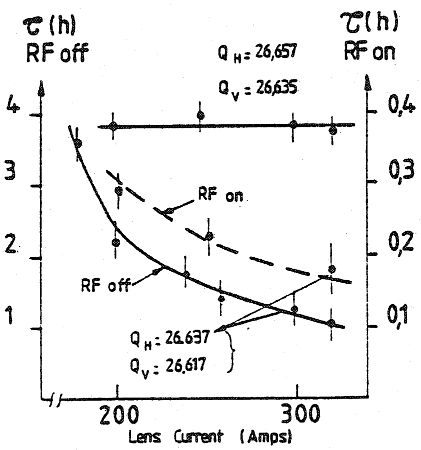

Fig. 6
Beam lifetime with non-linear lens at 40 GeV/c