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Beam Separation at the CERN SPS Collider

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Summary

The SPS proton-antiproton collider operates with a maximum beam-beam tune shift of about 3×10^{-3} per crossing. The allowable tune spread for acceptable lifetime is limited to less than 0.025[1] in order to keep the beams clear of 10th order beam-beam induced resonances. Therefore in order for the machine to operate with more than 3 bunches per beam (6 crossing points), beam separation is required at the unwanted collision points. A prototype scheme[2] using 4 electrostatic deflectors was used in the 1984 collider run in order to evaluate the feasibility of running the machine with separated beams.

By reversing the polarity of one of the separators it was also possible to produce a small crossing angle (± 175 μrad) at one of the experimental collision points whilst leaving the orbit around the rest of the machine unperturbed. This experiment is of some interest for the design of the large hadron colliders (SSC and LHC) under consideration at the present time.

Hardware

The separator layout is shown schematically in figure 1. The 4 tanks are arranged in orthogonal pairs. The first pair near quadrupoles 520 and 522 produce a global radial orbit deformation in the opposite sense for protons and antiprotons around approximately 5/6 of the ring. This deformation is compensated by a second pair of separators near quadrupoles 414 and 416. The orbit is not deformed between quadrupoles 416 and 520, the region containing the two experimental insertions (I4 and I5).

A separator unit consists of a pair of titanium alloy (6% Al - 4% Va) electrodes in a 3.2 metre long vacuum tank[3]. Normally, one of the electrodes is kept at ground potential whilst the other electrode is charged to a negative high voltage.

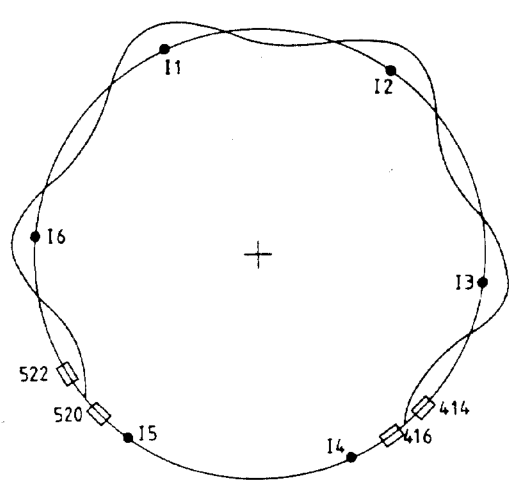


Fig. 1 Schematic layout of the separators

However, for the present application, two of the separators require the opposite sense of deflection. This was accomplished by turning one of the tanks (416) and using its normal negative high-voltage power supply, whereas for the other deflector the tank orientation was left unchanged and the floating electrode was connected to a positive power supply. No particular high voltage problems were encountered with this polarity at the separating field of around 30 kV/cm as long as the separator was pre-conditioned at a sufficiently high voltage (> 150 kV).

With three bunches per beam, maximum separation at the four unwanted crossing points requires that the radial tune shift per period over half of the machine be fixed at precisely $\pi/2$ per period - the so-called Q-split mode. This is possible because the radially focusing quadrupoles in the SPS are split into two separately powered families in order to allow simultaneous slow extraction to two experimental areas for the fixed-target program[4]. However, in order to cause minimum perturbation to the operating collider, the experiments reported below were performed using the normal machine lattice (equal strength in the two quadrupole strings). The price to be paid for this was that the orbit deformation was not maximum at the crossing points (figure 2). With more than 3 bunches per beam, Q-split is mandatory because the mid-arc crossings fall very unfavourably.

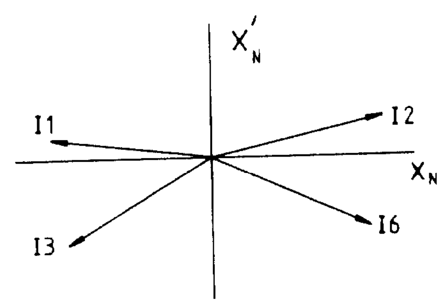


Fig. 2 Closed orbit deformation at the unwanted crossing points in the normalized phase plane.

Experimental Results

The required separator deflections were calculated using the AGS program with the standard machine configuration for physics runs (two low-beta insertions, β^*_H = 1 m, β^*_V = 0.5 m) but with the overall machine tune fixed at Q_H = 26.690, Q_V = 27.685. These (normally unacceptably high) tune values were chosen so that in later experiments involving the separation of protons and antiprotons, the antiprotons would straddle the harmful 10th order resonances. The effectiveness of subsequent beam separation in reducing the total tune spread and thereby moving the antiproton tune out of the resonances could then be assessed.

Figure 3 shows the difference between closed orbits measured with and without the separators. The maximum peak-to-peak orbit deformation was ± 4 mm.

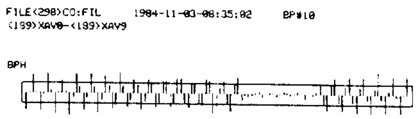


Fig. 3 Difference between two closed orbits with and without separation

The distance between the beam centres at the crossing point with the smallest separation (I3) would then be 5 mm, corresponding to 5.2 sigma between centres for Gaussian beams with a normalized emittance of 25π mm.mrad.It can be seen that the closed orbit is quite well compensated in the region between LSS4 and LSS5, the residual deformation being within the precision of the measurement (± 0.5 mm).

Several experiments were performed with separated beams. In all cases the protons and antiprotons were injected and accelerated without separation. After moving the electrodes to their nominal gaps, chosen to give sufficient voltage for good power supply stability, generally ≈ 100 kV, the tunes were adjusted to the reference values $Q_H = 26.69$, $Q_V = 27.685$. These tune values were invariably bad for the antiproton lifetime since the antiproton tunes are shifted upwards by about 0.02 in both planes with respect to the protons due to the (weak-strong) beam-beam interaction, placing them across the web of 10th order resonances before beam separation.

During the rise of the separators to keep the orbit bump compensated the voltages were brought up slowly in 5 kV steps for the strongest separator and proportionately for the three others.

Figure 4 shows a chart recorder output of the intensity of a single bunch of antiprotons during the separation. The initial antiproton lifetime is very bad because of the high tune. As the separation is brought up, the lifetime steadily improves as the antiproton tune, which is not measurable due to the low intensity and large tune spread, moves downwards towards that of the protons and out of the 10th order resonances. It should be noted that there is no indication of any adverse effect during partial separation.

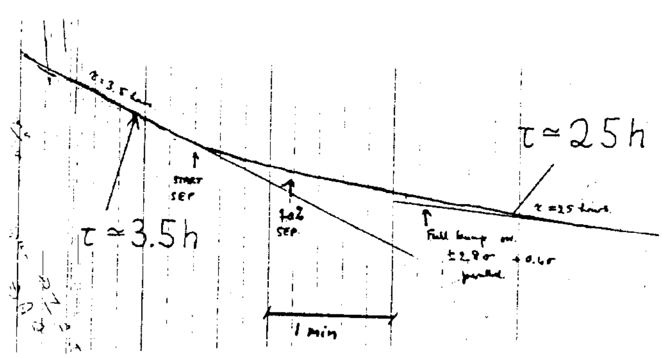


Fig. 4 Intensity decay of an antiproton bunch as the separation is brought up.

In order to evaluate the performance of the separators, they were used for two long physics coasts in which the beam centres were separated by 5.2 mm at the point of smallest separation, corresponding to ± 2.7 sigma for the normalized emittance of 25π mm.mrad (the emittance is defined as $\epsilon/\pi = 4\gamma\sigma^2/\beta^*$). The longest run lasted for 23 hours and the machine performance was at least as good as without separation. There is no reason that separation should improve the performance with three bunches per beam since the total tune spread without separation corresponding to a beam-beam tune shift of 3×10^{-3} per intersection can be accommodated in a region free of resonances up to 13th order (odd) and 16th order (even). Nevertheless, it was found that the precise control of the tune needed to maximize the lifetime and minimize the background in the experiments was considerably less critical than without separation.

It was possible to trim the separators around their nominal settings in order to make small parallel displacements of the beams at one of the experimental collision points (I4) and almost parallel displacements at the other ($\Delta\psi$ between I4 and I5 is 160°). It was found that the antiproton bunch lifetime was practically independent of the offset between the beam-centres. In order to check that this was not due to a favourable cancellation of resonance excitation terms between the two collision points, an experiment was performed in which one of the proton bunches was killed with the beams held off-centre so that a test antiproton bunch only experienced beam-beam collision at a single crossing point. The lifetime remained unchanged.

By measuring the beam-beam rate as a function of separation it is possible to measure the effective overlap integral of the two beams and to calibrate the luminosity (Van der Meer method).

Figure 5 shows the result of one such measurement performed in collaboration with UA1 at the end of a physics coast. The scan was limited in the positive direction because one of the separators required a change of polarity, which was not possible due to hardware limitations. The fact that the peak in the beam-beam rate is slightly offset shows that the computed bump was not perfectly compensated. The solid curve is a Gaussian fit to the measured data.

The counting rate R(d) as a function of the separation d between beam centres is given by

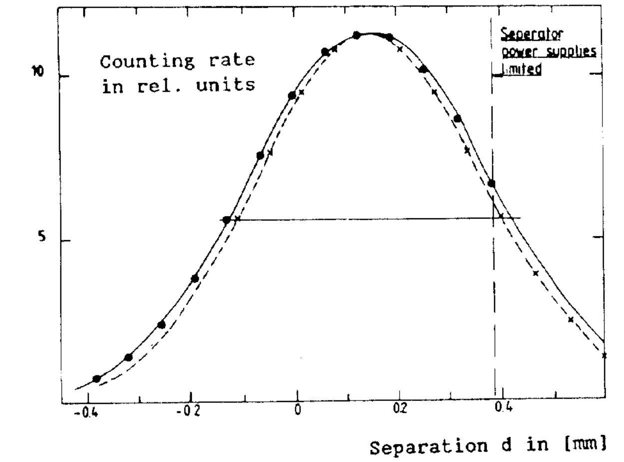
$$R(d) = \text{const.} \int_{-\infty}^{\infty} N_p(x)\, N_{\bar{p}}(x - d)\, dx\,, \qquad (1)$$

where $N_{p,\bar{p}}(x)$ is the particle density distribution in the horizontal plane. Assuming Gaussian distributions for both beams, the integral can be solved:

$$R(d) = \text{const.} \exp \frac{-d^2}{2(\sigma_p^2 + \sigma_{\bar{p}}^2)} \qquad (2)$$

It can be seen from the fit that the measured curve is indeed very close to Gaussian.

It is of interest to compare the measured overlap curve with that computed by measuring the beam emittance with the wire scanners at another location in the machine and assuming the theoretical Twiss parameters to evaluate the standard deviations of the



- • measured points from Van der Meer-scan
- —— gaussian curve fitted to measured points
- --- expected curve, calculated from beam width measurements (normalized to the maximum)

Fig. 5 Beam-beam rate as a function of the horizontal separation between beam centres at I5.

two beams at the crossing point. The expected overlap curve using this method is shown dotted in figure 5. The effective width of the two Gaussian curves are

σ (Van der Meer Scan) = 0.231 ± 0.002 mm
σ (Profile Measurement) = 0.218 ± 0.005 mm

The quoted errors are statistical errors. Both measurements have systematic errors, mainly due to the uncertainty in the precise values of the Twiss parameters.

Crossing Angle Simulation

It is known that beam-beam collisions with a large (~ 10 mrad) crossing angle can lead to unwanted effects, in particular to the excitation of synchrobetatron resonances[5]. The most popular scenario for the design of the large hadron collider (LHC assumes a small crossing angle of ~ ± 50 μrad. Consequently, it is of interest to simulate such a crossing angle at the SPS. By reversing the polarities of two of the separators through an interchange of the high voltage power supplies of 520 and 522 it is possible to make an orbit distortion between LSS4 and LSS5 leaving the orbit unperturbed over the rest of the ring and in such a way that the bunches cross at an angle at the intersection point I4. The maximum crossing angle was limited by the closed orbit distortion in the low-beta quadrupoles at 90° from the interaction point. The maximum angle achieved was ± 175 μrad.

In order to evaluate the effect of the crossing angle, a single proton bunch was injected together with two antiproton bunches. The first bunch (x) interacted with the proton bunch at the crossing angle (I4) as well as head-on at the diametrically opposite point in the ring (I1). The second antiproton bunch (Y) collided with the proton bunch head-on at two normal crossing points (I3 and I6). In this way it was possible to compare the behaviour of the two bunches under identical machine conditions.

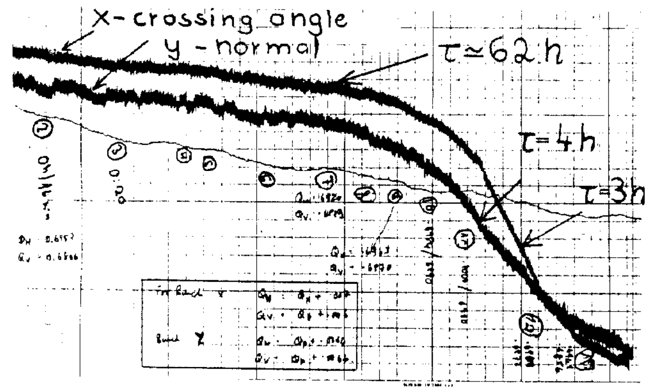


Fig. 6 Intensity traces of two antiproton bunches as the tune is moved upwards to touch tenth order resonances.
(Bunch x with a 150 μrad crossing angle
Bunch y without a crossing angle)

Figure 6 shows a chart recorder output of the intensities of the two antiproton bunches as the tune is slowly moved upwards into the 10th order resonances. The lifetime of both bunches is equally high until the proton tune reaches $Q_H = 26.694$, $Q_V = 27.685$. The tune of the small amplitude antiprotons is pushed upwards due to the beam-beam interaction by approximately 0.007 in each plane to touch the 10th order resonances and the lifetime starts to degrade.

There is no significant difference between the behaviour of the bunch with the crossing angle (in this case ± 150 μrad) compared with the bunch experiencing head-on collisions. By far the most significant result is the catastrophic effect of the 10th order beam-beam resonances. The crossing angle was later increased to ± 175 μrad with essentially the same result.

Conclusions

A trial separation scheme allowing beam separation by up to ± 2.7 σ at four out of six collision points has been installed and commissioned in the SPS. The experimental results show that the machine performance is much less sensitive to small beam displacements than previously expected. Good luminosity lifetime has been achieved during long physics coasts.

An experiment in which the beams were made to collide at a small angle of ± 175 μrad showed no adverse effects.

Acknowledgements

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