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BEAM SEPARATION EXPERIMENTS AT THE SPS COLLIDER

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1. Introduction

Operation of the SPS collider with 6 bunches per beam will require beam separation at the unwanted crossing points in order to reduce the total beam-beam tune spread to a tolerable level^{1),2)}. In order to test the feasibility of such a scheme, four electrostatic separators have been installed in the machine in order to produce a radial orbit deformation around most of the circumference so that with three bunches per beam, the bunches are separated at the 4 unwanted crossings. Several experiments were performed during the 1984 collider run in order to commission and evaluate the scheme, culminating in two long physics coasts with beam separation.

By reversing the polarity of one of the separators it was also possible to produce a small crossing angle at one of the collision points whilst leaving the orbit around the rest of the machine unperturbed. This experiment is of interest for the design of the Large Hadron Collider³⁾, where a small crossing angle is required in order to separate the beams in as short a distance as possible from the collision point.

2. Separator Layout

The separator tanks are arranged in two pairs near to radially focusing quadrupoles. The first pair near quadrupoles 520 and 522 are used to produce a global orbit deformation (in the opposite direction 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 (figure 1). The orbit is not deformed between quadrupoles 416 and 520, the region containing the two experimental insertions at LSS4 and LSS5.

With three bunches per beam, maximum separation at the four unwanted crossing points requires the radial tune shift per period

over half of the machine to be fixed at exactly $\pi/2$ - the so-called Q-split mode²⁾. However, in order to cause minimum perturbation to the operating collider, all separation experiments reported below were performed using the normal machine lattice. The price to be paid for this was that the orbit deformation was not maximum at the crossing points (figure 2). With six bunches per beam it will not be possible to operate in this mode because the mid-arc crossings will fall very unfavourably, so Q-split will be mandatory.

3. Hardware

The separators were originally constructed for measuring the luminosity by displacing the beams relative to one another at the experimental collision points and measuring the beam-beam rates. A separator unit consists of a pair of titanium alloy (6% Al - 4% Va) electrodes each 3 metres in length and 160 mm wide mounted in a 3.2 metre long vacuum tank (figure 3). The distance between the electrodes can be remotely adjusted between 160 mm and 20 mm. Technical details of the deflectors can be found elsewhere⁴⁾.

Normally, one of the electrodes is kept at ground potential whilst the other electrode is charged to a negative high voltage. 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 the only available 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).

4. Experimental Results

4.1 Closed Orbit Deformation

The first step was to measure the global orbit deformation in the presence of the separators. In order to get sufficient signal from the orbit measurement pickups this requires the CPS to work on harmonic number 20 (injecting a train of 20 bunches into the SPS).

The required separator deflections were calculated using the AGS program with the standard machine configuration for physics runs (two low-beta insertions, $\beta_H^* = 1$ m, $\beta_V^* = 0.5$ 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.

One problem encountered with the measurement of the orbit deformation with the separators on was linked with the fact that in the 20-bunch mode the RF system is controlled with a radial loop, keeping the radial position constant at a specific pickup location. Moving the beam at this pickup during separation then results in a change in RF frequency and consequently in beam energy. This was corrected by carefully adjusting the frequency to the same value with and without the bump.

Figure 4 shows the difference between closed orbits measured with and without the separators after compensating for the frequency drift. The maximum peak-to-peak orbit deformation was ± 4 mm. 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). The required deflection angles and electric fields at 315 GeV/c are summarized in the following table.

Separator	Deflection (μ rad)	Field (kV/cm)	Polarity
414	- 36.5	38.3	-
416	+ 14.3	15.0	- (turned)
520	- 9.6	10.1	-
522	+ 22.9	24.0	+

Fields for ± 2.6 sigma separation

Table 1

One side effect of such a horizontal separation is that the beams experience tune shifts in opposite directions as they pass off-axis in the chromaticity correction sextupoles. The tune shift in a single sextupole due to a displacement Δx is given by

$$\Delta Q_H = \frac{B_H}{4\pi} \frac{B''L}{B\rho} \Delta x \quad (1)$$

For the chromaticity sextupoles near radially focusing quadrupoles, $B_H \approx 100\text{m}$, $(B''L/B\rho) \approx 6 \times 10^{-2} \text{ m}^{-2}$, giving $\Delta Q_H = 2 \times 10^{-3}$. However, individual sextupoles of the same family are separated by approximately 180° , so a large amount of cancellation will occur. The measured tune shift due to the orbit bump was $\Delta Q_H = -3 \times 10^{-3}$, i.e. of the order of the tune shift due to a single sextupole. No vertical tune shift was observed.

This tune shift happened to be in an unfavourable direction since it pushed the proton and antiproton tunes apart. It could have been used to good advantage if the polarity of the bump could have been reversed, which is impossible without physically turning the tanks. Later computations with the optics program PATRAC⁵⁾, which is capable of calculating the tunes in the presence of a perturbed closed orbit, showed good agreement with the measured tune shift and will in the future allow the polarity of the bump to be better chosen. Nevertheless, the magnitude of the effect is small and was not found to be a great limitation during separation experiments.

4.2 Beam Separation

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.

Control of the separators during their rise is complicated by the fact that individual pairs are controlled by two different computers in different buildings and by the fact that the risetimes of all four power supplies are different. Therefore in order 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. This operation takes a few minutes, although it will be speeded up considerably when programmable high voltage power supplies become available.

Figure 5 shows a chart recorder output of the intensity of a single bunch of protons and 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.

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 $\epsilon/\pi = 4\gamma\sigma^2/B^*$). 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.

It is therefore concluded that the odd-order beam-beam resonances excited by off-centred beams in the operating tune region (13th order lowest) are not important at least up to a linear beam-beam tune shift of 3×10^{-3} per intersection under the conditions of these experiments (weak-strong with unequal emittances $\epsilon_p = 25\pi$ mm.mrad, $\epsilon_{\bar{p}} = 13\pi$ mm.mrad). Therefore, the required precision of the compensation of the global orbit deformation is much less critical than was previously expected.

4.3 Luminosity Scans

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 method⁶).

Figure 6 shows the result of one such measurement performed in collaboration with UAL at the end of a physics coast⁷). 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 centre is given by

$$R(d) = \text{const.} \int_{-\infty}^{\infty} N_p(x) N_{\bar{p}}(x - d) dx, \quad (2)$$

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

$$R(d) = \text{const.} \exp \left[\frac{-d^2}{2 (\sigma_p^2 + \sigma_{\bar{p}}^2)} \right] \quad (3)$$

giving a Gaussian curve with standard deviation $\sigma = \sqrt{\sigma_p^2 + \sigma_{\frac{p}{p}}^2}$. 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 two beams at the crossing point. The expected overlap curve using this method is shown dotted in figure 6. The effective width of the two Gaussian curves are

$$\begin{aligned}\sigma \text{ (Van der Meer Scan)} &= 0.231 \pm 0.002 \text{ mm} \\ \sigma \text{ (Profile Measurement)} &= 0.218 \pm 0.005 \text{ mm}\end{aligned}$$

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

5. Crossing Angle Simulation

It is known that beam-beam collisions with a crossing angle can lead to unwanted effects, in particular to the excitation of synchrotron resonances⁸⁾. The most popular scenario for the design of the large hadron collider (LHC) assumes a small crossing angle of $\sim \pm 50 \text{ } \mu\text{rad}$. 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 $\pm 175 \text{ } \mu\text{rad}$.

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.

The relevant parameters for the experiment were as follows:

	Protons	Antiprotons
IP (p/bunch)	1.4×10^{11}	1.4×10^9
ϵ_H (mm.mrad/ π)	22	12
ϵ_V "	21	12
β_H^* m	1	1
σ_H^* mm	0.13	0.095
σ_L cms	22.5	18
ΔQ_{BB} /interaction	-	.0035

Figure 7 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 $Q_H = 26.694$, $Q_V = 27.685$ (point (8) on the curves). 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 $\pm 150 \mu\text{rad}$) 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 $\pm 175 \mu\text{rad}$ with essentially the same result.

6. Conclusions

A trial separation scheme allowing beam separation by up to $\pm 2.7 \sigma$ 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 an angle of $\pm 175 \mu\text{rad}$ showed no adverse effects.

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APPENDIX

The particle densities of the beams are assumed to be Gaussian:

$$N_p(x) = \frac{\text{constant}}{\sigma_p \cdot \sqrt{2\pi}} \cdot \exp\left[-\frac{x^2}{2\sigma_p^2}\right]$$

$$N_{\bar{p}}(x) = \frac{\text{constant}}{\sigma_{\bar{p}} \cdot \sqrt{2\pi}} \exp\left[-\frac{(x-d)^2}{2\sigma_{\bar{p}}^2}\right]$$
(A1)

This is the particle density in the horizontal plane. d is the horizontal displacement of the $\bar{p}$ -beam.

The luminosity is proportional to the overlap integral. The overlap integral as a function of the displacement d is given by:

$$I(d) = \int_{-\infty}^{+\infty} N_p(x) \cdot N_{\bar{p}}(x) dx$$
(A2)

$$I(d) = \frac{\text{constant}}{\sigma_p \sigma_{\bar{p}} \cdot 2\pi} \exp\left[-\frac{d^2}{2\sigma_{\bar{p}}^2}\right] \cdot \int_{-\infty}^{+\infty} \exp\left[-\frac{x^2}{2\sigma_p^2} + \frac{x^2}{2\sigma_{\bar{p}}^2} - \frac{2d \cdot x}{2\sigma_{\bar{p}}^2}\right] dx$$
(A3)

An integral of the form $\int_{-\infty}^{+\infty} \exp(-ax^2 - bx) dx$ can be solved

$$\int_{-\infty}^{+\infty} \exp(-ax^2 - bx) dx = \frac{1}{2} \sqrt{\frac{\pi}{a}} \cdot e^{-\frac{b^2}{4a}} \cdot (1 - \text{erf} \frac{b}{2\sqrt{a}})$$
(A4)

Using this solution one gets after some arithmetic for the overlap integral:

$$I(d) = \frac{1}{\sqrt{2\pi(\sigma_p^2 + \sigma_{\bar{p}}^2)}} \cdot \exp\left(-\frac{d^2}{2(\sigma_p^2 + \sigma_{\bar{p}}^2)}\right)$$
(A5)

Effective beam width:

If the beams are not separated ($d = 0$) one gets

$$I = \frac{1}{\sqrt{2\pi} \sqrt{\sigma_p^2 + \sigma_{\bar{p}}^2}} \quad (A6)$$

For equal beam sizes ($\sigma_p = \sigma_{\bar{p}}$) this yields.

$$I = \frac{1}{\sqrt{2\pi} \cdot \sqrt{2} \cdot \sigma} \quad (A7)$$

Comparing the results for equal and different beam sizes it turns out that the beam sizes σ_x and σ_y in the luminosity formula have to be replaced by

$$\frac{1}{\sqrt{2}} \sqrt{\sigma_{xp}^2 + \sigma_{x\bar{p}}^2}$$

$$\frac{1}{\sqrt{2}} \sqrt{\sigma_{yp}^2 + \sigma_{y\bar{p}}^2}$$

References

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Fig. 1 Schematic drawing of the global orbit bump.

Fig. 2 Orbit separation at the unwanted collision points in the normalized phase plane.

a)

b)

Fig. 3 An electrostatic separator tank.

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MEAN	SIGMA	MAX	MIN	P/US	TIME	GEV	Q
-0.08	2.25	4.75	-4.22	108	-1	26.12	26.71

Fig. 4 Difference between two closed orbits without and with ± 2.6 sigma bump.

Fig. 5 Chart recorder output of antiproton bunch intensity during the rise of the separators.