BEAM-BEAM EFFECTS AND HIGH LUMINOSITY OPERATION IN THE SPS PROTON ANTIPROTON COLLIDER

K. Cornelis, L. Evans, A. Faugier, R. Schmidt

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1. INTRODUCTION

After some years of successful operation as a proton-antiproton collider the peak luminosity in the SPS has been pushed up to \( 3.6 \times 10^{29} \text{ cm}^{-2}\text{s}^{-1} \). The length of a typical store is about 20 to 30 hours. The luminosity lifetime, i.e. the time in which the luminosity decays from its initial value to 1/e, is 20 to 28 hours.

Through an upgrading of the proton antiproton complex a substantial increase of the luminosity is expected for the end of 1987. The major improvement will be an increase of the antiproton production rate coming from the new antiproton collection and precooling ring, ACOL, currently under construction. It is hoped that this rate will increase by about a factor of 10. /1/

In order to digest the higher intensity the SPS will operate with 6 bunches per beam instead of three. The intensity of the antiproton bunches is expected to increase by about a factor of 5.

This poses some problems to the SPS operation. The major problem arises from the increased strength of the beam-beam effect:

- The number of collision points increases from 6 to 12. The increase of the tune shift caused by the beam-beam interaction from 0.025 to 0.05 leads to a spread in the betatron frequencies of the particles which is bigger than the distance between dangerous resonances. Particles crossing the resonances can get lost.

- Up to now the intensity of the proton bunches is about 10 times higher than the p-bar bunch intensities whereas the emittance of the p-bar bunches is about half of the proton emittance (strong-weak beam-beam effect). By the increase of the antiproton intensity the intensity in both beams will be more similar (strong-strong beam-beam effect). This can cause the excitation of resonances which were not seen in the past.

The beam-beam effect limits the performance of the collider in coast as well as at injection. The limitations are pushed upwards by separating the beams with the help of electrostatical separators:
In coast: A substantial reduction of the strength of the linear beam-beam tune shift is achieved by separating the beams with the help of the separators. Some experiments done in 1985 showed that this keeps the particles away from destructive resonances. These experiments were done with a prototype separation scheme and 3 bunches per beam in coast at 315 GeV /2,3/. In this paper we report about the layout of the definitive separation scheme and the experiments done with it.

At injection: In order to inject and to accelerate 6 antiproton bunches in the presence of 6 proton bunches a new technique to inject the beams onto separated closed orbits was tried out: One separator was used at injection energy of 26 GeV and along the energy ramp up to 315 GeV to produce a global closed orbit distortion around the whole machine with opposite sign for protons and antiprotons.

With the help of injection separation and separation in coast 6 proton bunches and 6 p-bar bunches could be injected, accelerated and stored.

To reach luminosities in excess of $1-2 \times 10^{20}$ cm$^{-2}$ sec$^{-1}$ the SPS has to operate in a mode which is close to the strong-strong regime of the beam-beam effect. The experiments reported here strongly suggest that in this case the background level in the physics detectors will be increased and the lifetime of the beams will decrease due to the beam-beam interaction.

![Diagram: Energy vs Time](image)

**Fig. 1** Preparation Cycle for the injection of 6 antiproton against 6 proton bunches
2. LIMITATIONS CAUSED BY THE BEAM-BEAM INTERACTION

2.1 Injection phase and coast phase

In the SPS both protons and antiprotons are injected at an energy of 26 GeV and accelerated to 315 GeV (see fig. 1, a preparation cycle is shown where the set-up of the machine is done with protons only. When finally the antiprotons are injected the machine stays in coast). After the energy of 315 GeV is reached the beam optics is changed in order to reduce the betatron functions at the interaction point (the so-called squeezing). This injection and acceleration phase takes about 40 seconds. In order to avoid beam losses and emittance blow up of the beams the tunes have to be carefully chosen to keep the particles away from resonances up to the fourth order. The working point at the SPS was chosen between 26.666 and 26.75 for the horizontal plane and between 27.666 and 27.75 for the vertical plane. Because of the short duration of the injection phase the beams are not suffering from resonances of higher order than the fourth.

After the injection phase the beams stay in coast for up to 30 hours (coast phase). In order to obtain a good luminosity lifetime the intensity lifetime has to be as high as possible and the emittance blow up as low as possible. Furthermore the background rate in the experiments have to be kept below a certain level. To achieve that it was sufficient up to now to keep the tunes clear from resonances up to and including the tenth order. But with the increasing strength of the beam-beam interaction resonances of higher order become clearly visible (see also chapter 7).
2.2 Calculation of the tune spread in the beams

In order to choose an optimal working point the tune spread of the particles in the beams have to be calculated.

Mainly two different effects contribute to the tune spread:

- The incoherent tune shift of the particles in one bunch due to the self-fields of the bunch (Laslett-tune shift) /4,5/.

- The incoherent tune shift caused by the beam-beam interaction.

In both cases the tunes of the central particles are shifted by the maximal value, upwards in the case of the beam-beam interaction and downwards in the case of the Laslett tune-shift. As the amplitude of a particles increases the tune shift gets less.

2.2.1 Laslett tune shift

For the horizontal and the vertical plane the tune shifts are /4,5/:

\[
\delta Q_x = \frac{N \times r_p \times 1.5 \times L}{\sigma_1 \times \beta_x^2 \times \gamma} \times \frac{1}{4} \times \frac{\beta_x}{\sigma_x (\sigma_x + \sigma_z)}
\]

\[
\delta Q_z = \frac{N \times r_p \times 1.5 \times L}{\sigma_1 \times \beta_z^2 \times \gamma} \times \frac{1}{4} \times \frac{\beta_z}{\sigma_z (\sigma_x + \sigma_z)}
\]

with

- \(N\)...........number of particles in the bunch
- \(r_p\)........proton radius (1.5347\times10^{-18} \text{ m})
- \(\gamma\).............\(E[\text{GeV}]/0.938\)
- \(\beta\)..............\(\sqrt{1 - \gamma^2}\)
- \(\sigma_1\)........bunch length for a parabolic bunch (one sigma)
- \(L\)...........machine circumference (SPS: 6911.5 m)
- \(\beta_{x/z}\)......betatron function (mean value along the machine)
- \(\sigma_{x/z}\)......beam sizes (mean value along the machine)
The beam sizes are given by

\[ \sigma = \sqrt{\left( \sigma_x^2 + \sigma_x \right) \varepsilon_x} \]  
(3)

with

\[ \sigma_{x\beta} = - \frac{\sqrt{\beta_x}}{2} \]  
(4)

Betatron - part of \( \sigma_x \)

\[ \sigma_{x\varepsilon} = - \frac{\varepsilon_x}{2} D_x \]  
(5)

Dispersion part of \( \sigma_x \)

\[ \varepsilon_{x/z} \quad \text{normalized emittance} \]

\[ D_x \quad \text{Dispersion (mean value around the machine)} \]

\[ \varepsilon \quad \text{energy width} \]

with

\[ \sigma_{z\varepsilon} = - \frac{\sqrt{\beta_z}}{2} \varepsilon_z \]  
(6)

In the following we show that the Laslett tune-shift as a function of the energy decreases with approximately \( 1/\gamma^2 \):

In the equations for the Laslett-tune shift (eq. 1 and 2) a factor \( \gamma \) appears in the denominator.

The vertical beam size \( \sigma_z \) decreases with \( \sqrt{1/\gamma^2} \) (eq. 6).

The horizontal beam size \( \sigma_x \) decreases with less than \( \sqrt{1/\gamma} \), because the dispersion part of \( \sigma_x \) decreases with less than \( \sqrt{1/\gamma^2} \) (In eq. 4 the betatron part of \( \sigma_x \) decreases with \( \sqrt{1/\gamma^2} \). The energy dependence of the dispersion part (eq. 5) is contained in the energy dependence of the energy width \( \varepsilon \), which decreases by less than \( 1/\gamma \) )

For the factor \( \frac{1}{\sigma_{x/z} \left( \sigma_x + \sigma_z \right)} \) in eq. 1 and eq. 2 one can write:

\[ \frac{1}{\sigma_{x/z} \left( \sigma_x + \sigma_z \right)} = \text{constant} \times \gamma \]

The bunch length \( \sigma_{l} \) in the eq. 1 and 2 decrease only slightly with energy (\( \sigma_{l} \approx \gamma^{-1/4} \)).
Taking everything together one gets as a good approximation for the energy dependence of the Laslett tune shift:

\[ \delta Q_{\text{Laslett}} = \text{constant} \times \frac{1}{\gamma} \]

For the injection energy of 26 GeV, a bunch intensity of \(2 \times 10^{11}\) particles per bunch, a normalized emittance of 20 \(\pi\) mm-mrad, a bunch length of 0.42 m, and an energy spread of \(3.5 \times 10^{-5}\) one gets:

\[ \delta Q_z = 0.040 \quad \text{and} \quad \delta Q_x = 0.062 \quad (7) \]

(a mean value for the betatron functions of 50 m and a mean horizontal dispersion of 2 m are assumed).

The tune shift is negligible at the top energy of 315 GeV.

### 2.2.2 Beam-beam tune shift

The beam-beam tune shift for one interaction point is given by /5/:

\[ \delta Q_{x/z} = \frac{N \times r_p}{2\pi \times \gamma} \quad \frac{\beta_{x/z}}{\sigma_{x/z} \left( \sigma_x + \sigma_z \right)} \quad (8) \]

In this equation the betatron functions have to be taken at the interaction point. If the dispersion at the interaction point vanishes and the emittances for both planes are identical

\[ \varepsilon^*_x = \varepsilon^*_z = \varepsilon \]

we get:

\[ \delta Q_{x/z} = \frac{2 \times N \times r_p}{\varepsilon} \quad \frac{\beta_{x/z}}{\varepsilon \sqrt{\beta_{x/z}} \left( \sqrt{\beta_x} + \sqrt{\beta_z} \right)} \quad (9) \]

Eq (9) reflects the well known fact that the linear tune shift caused by the beam-beam interaction for a hadron collider is independent of the energy.
If the ratio between $\beta_x$ and $\beta_z$ is defined by

$$ R = \sqrt{\frac{\beta_x}{\beta_z}} $$

we get

$$ \delta Q_x = \frac{2 \times N \times v \rho}{\pi \varepsilon (1 + R)} \frac{R}{1 + R} $$  \hspace{1cm} (10) $$

$$ \delta Q_z = \frac{2 \times N \times v \rho}{\pi \varepsilon (1 + R)} \frac{1}{1 + R} $$  \hspace{1cm} (11) $$

With an emittance of 20 $\mu$mm mrad and $2 \times 10^{11}$ protons per bunch the linear tune shift on the antiprotons is:

$$ \delta Q_x = 0.0098 \times R/(1+R) $$ \hspace{1cm} (12) $$

$$ \delta Q_z = 0.0098 \times 1/(1+R) $$ \hspace{1cm} (13) $$

In the case of 3 bunches per beam the total tune shift in the SPS is:

$$ \delta Q_x = 0.031 \text{ and } \delta Q_z = 0.028 $$ \hspace{1cm} (14) $$

The values of $\beta_x$ and $\beta_z$ are equal at 4 of the crossing points, at the 2 crossing points used for physics $\beta_x / \beta_z = 2$. 
Fig. 2 Tune space occupied by the protons and antiprotons at injection

Fig. 3 Tune space occupied by the protons and antiprotons in coast
2.2.3 **Total Tune spread**

In fig. 2 and 3 the tune space occupied by the particles is shown for injection energy and coast energy. This picture reflects the optimal performance which was reached in the SPS up to now, a weak-strong beam-beam interaction with 3 against 3 bunches. The intensity is $2 \times 10^{11}$ particles per bunch in the proton bunches and the emittance 20 $\mu$ mm mrad. The calculated tune shifts from eq. 7 and eq 14. were taken.

During coast some of the antiprotons (fig. 3) are crossing tenth order resonances without being lost. These are the particles which experience the biggest tune shift in the beam center. Because their amplitudes are small the driving force for the resonance is much weaker than the driving force for the particles with big betatron amplitudes /6/. A similar argument yields for the protons near the third order resonance at the energy of 26 GeV.

Measuring the tunes an additional complication shows up: The coherent tune shift caused by the image forces in the beam pipe causes a measurement of the tune which is different from the single particle tune /4/. This effect, depending on the intensity, is in the order of $\delta Q_z = -0.03$ for an energy of 26 GeV and $\delta Q_z = -0.004$ at 315 GeV.

Another effect contributing to the tune diagram, the sextupolar tune shift in the presence of closed orbit distortions, will be discussed in chapter 4.

Higher order multipoles can also contribute to the tune spread. Their effects are smaller than the effects described above and not considered in this paper.

2.3 **Problems caused by the upgrading of the SPS**

The collider operating with a tune spread of the particles as shown in fig. 2 and 3 shows a good transmission during injection and good luminosity lifetime in coast, but any small change of the tunes already causes beam losses, lifetime and background problems.

Doubling the number of bunches to 6 per beam increases the beam-beam tune shift by a factor of 2 and results in an unacceptably machine performance.

The way out of this problem is the separation of the beams. The layout of the separation scheme and the way of setting it up will be described in the next section.
3. THE SETTING UP OF THE SEPARATION IN THE SPS

In the SPS separators are installed in order to produce a horizontal separation of the beams. The arrangement allows to eventually add later separators for an additional vertical beam separation /7,8/. The 3 meters long separators and their deflection plates are described in /9/.

3.1 Separation in coast

Two experimental insertions are installed in the SPS. From the 12 crossing points (in the case of 6 bunches per beam) only the 2 crossings in these insertions are used for physics. This allows a beam separation at the 10 other crossing points. In order to keep the number of separators minimal the beams are only separated at 9 crossing points. This can be achieved by one bump of three kicks. (see fig. 4). To achieve a sufficient kick strength three separator tanks are installed at position 522, two tanks at position 416 and one tank at position 520.

In order to achieve an equal separation at the crossing points the machine operates in the so-called Q-Split mode, i.e. the radial phase advance per period over half of the machine is fixed to precisely \( \pi /2 \) per period /10/. The field strengths in the separators are chosen in order to produce a beam separation of 6 sigma of the horizontal beam size (calculated with an emittance of 25 \( \pi \) mm mmrad) between the centres of the two beams (see table 1).

**TABLE I**

Field strength of the separators in the SPS for coast separation

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<tr>
<th>Position</th>
<th>Number of separator tanks at this position</th>
<th>Electric field kV/cm</th>
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<tr>
<td>520</td>
<td>1</td>
<td>2.9</td>
</tr>
<tr>
<td>522</td>
<td>3</td>
<td>28.0</td>
</tr>
<tr>
<td>416</td>
<td>2</td>
<td>25.6</td>
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Fig. 4 Geometrical arrangement of the separators in the SPS

Fig. 5 Beam displacements at the crossing points for coast separation (calculated)
From the optics and the field strength in the separators the beam displacements at the crossing points can be calculated (fig. 5).

In the setting up of the separation the first step was to produce a closed bump by three kicks. No residual orbit displacement is tolerable at the experimental crossing points because this would lead to a decrease of the luminosity. The separators were switched on with the precalculated strengths. The orbit was measured before and after switching on the separators. The difference of the two measurements is shown in fig. 6.

The residual perturbation of the closed orbit can be compensated in the following way: The field strength of two separators is changed in such a way that the closed orbit displacement at one particular monitor is changed without changing the angle of the closed orbit at this monitor. The orbit perturbation at this monitor is then compensated. The same is done at another monitor with a phase advance of 90 degrees from the first one. If the orbit is compensated at both monitors it is flat in the whole region. As a result the difference between the closed orbits with and without separation becomes less in the region between the separators (fig. 7).
3.2 Separation at injection

For electron-positron storage rings it is vital to inject the beams onto separated closed orbits because the beam beam tune shift scales like $\gamma^{-3}$. The separators are installed around the interaction points in order to produce a closed bump with opposite sign for both beams over the interaction region /11/.

In the SPS this technique cannot be applied because of the large number of interaction points. No space is available to install separators around each interaction point and such a scheme would be far too expensive. A more practicable solution is to produce a global closed orbit distortion around the whole machine with a small number of separators. The closed orbits of the beams are then different over the whole length.

The beams can be separated at most of the crossing points by only one kick from the separator at position 522 (fig.4). The maximal excursion of the closed orbit around the machine which can be achieved without hitting the aperture is about 17 mm. In order not to work too close to the aperture of the machine and the injection channel the field in the separator is reduced to achieve an orbit distortion with maximal excursions of 10 mm. The calculated closed orbit displacements at the crossing points are shown in fig. 8. The mean displacement is about 1.5 sigma of the horizontal beam size (calculated for an emittance of 20 $\pi$ mm mm rad).

In fig. 9 the tune shift as a function of the particle amplitude is shown for different values of separation /12/. For a distance between the beam centres of 3 sigma the linear tune shift is reduced to less than 0.2 of the value without separation.

When the energy of the SPS is ramped the distance between the beam centres goes down with $1/\gamma$ because the fields in the separators are not ramped. The horizontal beam size at the crossing points decreases with $\sqrt{1/\gamma}$. Expressed in units of the beam width the distance between the beams goes down like $\sqrt{1/\gamma}$. On the other hand the tune spread inside a bunch (Laslett tune shift) goes down like $1/\gamma^2$ so that by ramping the energy the total tune spread decreases.

For the SPS one problem with this injection scheme is the need for the so-called reinjection: The antiprotons are injected from the Antiproton Accumulator into the Proton Synchrotron (CPS), where they are accelerated to an energy of 25 GeV. From the CPS the particles are transferred to the SPS via a transfer channel (fig.10). The setting up of the two machines and the antiproton transfer channel is done by simulating the antiproton trajectory with protons that are going the opposite way, i.e. they are reinjected to the CPS via the antiproton transfer channel. Systems in both machines and in the transfer channels are adjusted to ensure that the bunch arrives in the CPS on the nominal closed orbit, with precisely the same energy and with minimum
injection oscillations.

beam displacement
(units: \( \sigma \))

crossing points
for 6\( p \) against 6\( \bar{p} \) bunches

Fig. 8 Beam displacements at the crossing points for injection separation (calculated)

\[
\frac{\Delta Q}{\Delta Q_{\text{lin.}}}
\]

Fig. 9 Tune shift by the beam-beam effect as a function of the amplitude of the particle for different values of beam separation
Fig. 10  Overview over the SPS and the CPS with the injection lines

well injected beam

injection with an injection error

closed orbit

betatron oscillation around around the closed orbit after bad injection

injection point

Fig. 11  Emittance blow-up by a mistuned injection
After having done the reinjection the antiproton bunches are injected from the CPS through the transfer channel into the SPS. Because the closed orbits of the protons and the antiprotons are identical the antiprotons are directly injected onto their closed orbit in the SPS.

If the setting up of the accelerator chain is not done carefully an emittance blow up of the beams is produced. Any emittance blow-up is irreversible because no damping mechanism exists. This happens when the antiproton bunches are not injected onto their closed-orbit in the SPS: The injected particles start to oscillate around the closed orbit (fig.11). Because all particles have slightly different betatron frequencies they will filament and fill up the emittance ellipse.

With the separators switched on exactly this happens: the closed orbit of the antiprotons is different from the proton closed orbit and the described way of doing the reinjection does not work.

The way out of this problem is to bring the protons onto the antiproton closed orbit during reinjection by reversing the polarity of the separator. The whole injection procedure is the following:

a) The separator is switched on with one polarity (+). The injection of the protons into the SPS is optimized. The transfer line magnets have to be adjusted such that the proton bunches are injected onto their closed orbit in the SPS.

b) The separator is switched to the other polarity (-). The injection for the protons has to be reoptimized, because the proton closed orbit in the SPS is now different. Reinjection to the CPS is done and systems in both machines and the antiproton transfer line are adjusted. The closed orbit of the protons in the SPS is identical to the closed orbit of the antiprotons which will be injected later.

c) The separator is switched back to (+). After the realignment of the proton transfer channel to get a good proton injection the SPS is ready to accept antiprotons.
Fig. 12  Tune shift as a function of beam separation, measured and calculated.

Fig. 13  Working diagram for 6 proton bunches against 6 antiproton bunches.
4. A SIDE EFFECT OF THE BEAM SEPARATION: SEXTUPOLAR TUNE SHIFTS

A beam going off centre through a sextupole experiences an additional quadrupole field. This leads to a change of the betatron tune /8, 12/: 

$$\delta Q = \frac{1}{\frac{1}{4} \pi} \cdot \beta \cdot k' \cdot l \cdot x_0$$

with 
- $\beta$........Beta-function at the position of the sextupole
- $k'$........strength of the sextupole
- $l$........length of the sextupole
- $x_0$........closed orbit deviation in the sextupole

If the orbit displacement is caused by an electric field this displacement is opposite for protons and antiprotons as well as the resulting tune shift. The size of this shift can be calculated by appropriate computer programs (e.g. PETROS /13/) and depends on the closed orbit displacement, the optics and the sextupole field distribution.

In fig. 12 the measured tune shifts and the calculated tune shifts are shown for both the horizontal and vertical plane. The measurement was done in coast at an energy of 315 GeV. The fields in the separators were brought up in steps and the tunes were measured using the Schottky signals of the bunches /14/.

A typical value for this tune shift is $\delta Q = 0.005$. For the injection separation the effect of this shift is negligible, whereas in coast it can shift the tune of the particles onto resonances and cause beam losses. Therefore one has to measure it carefully and eventually correct it.

The final working diagram is composed by the Laslett tune shift, the beam-beam tune shift and the tune shift caused by sextupoles. Because one cannot directly measure the p-bar tunes one has to rely on the computation of the different effects in order to draw the tune diagram.

For 6 against 6 bunches one comes to a working diagram like the one shown in fig. 13. The single particle tunes are 26.68/27.675 for Qx and Qz. The antiproton tunes are shifted upwards by the sextupolar tune shift, the protons tunes downwards. The Laslett tune shift is negligible because of the high energy. The tune spread is entirely caused by the beam beam interaction. An intensity of $2 \times 10^{11}$ for each of the proton bunches, $1 \times 10^{11}$ for the antiproton bunches and a normalized emittance of 20 $\pi$ mm mrad were assumed.
Fig. 14  Antiproton intensity as a function of time without injection separation in the presence of 3 proton bunches

Fig. 15  Antiproton intensity as a function of time without injection separation in the presence of 6 proton bunches
5. RESULTS FROM THE INJECTION SEPARATION

The experiments to test the injection separation were done in three steps, first with 1 antiproton bunch against 3 proton bunches, then 3 against 3 bunches and finally 6 against 6 bunches.

1 pbar bunch against 3 proton bunches:

Firstly an antiproton injection was tried out in the usual way without using the separators. This imposes no problems and the transmission in the SPS of the antiproton bunch is about 90%. The intensity of the antiproton bunch as a function of time is shown in fig.14. The tune at injection energy were adjusted to Qx=26.69 and Qz=27.705. The intensity of the antiproton bunch was $2 \times 10^9$, the proton bunches about $2 \times 10^{11}$.

1 pbar bunch against 6 proton bunches:

The second step was an injection under identical conditions, only against 6 proton bunches instead of 3. The result was a certain loss of antiprotons at injection energy and a total antiproton lost at the start of the energy ramp (fig.15). When the magnets are starting to ramp it is nearly impossible to avoid small tune changes in the order of $\delta Q = 0.005$. This can already be enough to cause a beam loss. In order to test the sensitivity against small changes of the tune the injection was repeated with a slightly higher tune, i.e. $\delta Qz = 0.005$. This caused a total beam loss at injection energy (fig.16).

After this experiment the separator was used for the next antiproton injection. Under identical conditions with the separator switched on no loss was detected (fig.17).

6 pbar bunches against 6 proton bunches:

The last step was the injection of 6 pbar bunches in the presence of 6 proton bunches. In order to inject all 12 bunches the duration of the injection platform had to be extended, because the time between the injection of two bunches is fixed to 2.6 seconds given by the CPS-cycle length. The injection was successful, the intensities of the 6 antiproton bunches with time are shown in fig.18. The total transmission from the Antiproton Accumulator to the SPS was about 70 percent, a number which is about the same as in the usual case of 3 against 3 bunches.
Fig. 16 Antiproton intensity as a function of time without injection separation in the presence of 6 proton bunches (0z slightly raised).
Fig. 17 Antiproton intensity as a function of time with injection separation in the presence of 5 proton bunches.
Fig. 18 Antiproton intensity for the injection of 6 antiproton bunches as a function of time with injection separation in the presence of 5 proton bunches.
Although the separation at injection reduces the tune spread by a substantial amount, the tunes have still to be adjusted carefully in order to place the tune of the beams between the resonances. The tunes cannot be lowered because this leads to an emittance blow up of the proton beam. This blow up occurs without losing particles. That can be explained by a detuning of the particles away from the resonance. The central particles are the closest to the resonance because they experience the maximum tune shift. A crossing of the resonance causes an increase of the amplitude of these particles. Because of the bigger emittance the Laslett tune shift decreases and the particles get free from the resonance.

The same mechanism pulls the antiprotons away from the fourth order resonance. The particles with small amplitude are closest to the resonance because they experience the maximal tune shift caused by the beam beam effect. The resonance leads to a growth of amplitude, a bigger amplitude causes a smaller tune shift and a detuning away from the resonance.

With injection separation the situation is somewhat different. Two observations were made:

- The emittance of the antiprotons after injection is much smaller than without injection separation (10 - 12 μ mm mrad instead of ≈16 μ mm mrad).

- A too high tune leads to a loss of particles and not to an emittance blow up. All the particles have nearly the same tune because the beam beam effect is reduced. If the beam is touching the resonance this leads to a beam loss because the particles with big amplitudes are stripped off. The emittance does eventually get smaller.
6. RESULTS FROM THE SEPARATION IN COAST

After the antiprotons were injected in the presence of 6 proton bunches the coast separation was still switched off. Fig.19 shows the intensity decay of the antiprotons. The intensity lifetime is less than two hours. Without beam separation the increased beam-beam tune shift due to 6 proton bunches in the machine pushes the antiprotons onto tenth order resonances and causes these losses. Switching on the separators results in a lifetime of more than 100 hours, a lifetime which is just as good as normal (see fig.19).

A direct measurement of the beam separation can be done at one of the crossing points. A luminosity monitor is installed /15/ which consists of some scintillators on both sides of the crossing point. The separation was brought up in steps and the counting rate in the monitor was measured (fig.20). With full separation the rate dropped down to nearly zero.

7. THE BEAM-BEAM EFFECTS IN COAST

7.1 Observations of Beam-Beam Effects in Coast

When the injection separation was first used to inject a dense antiproton beam with three bunches and a proton beam with three bunches a surprising observation was made /16/: The counting rate of the background in the experiments showed an enormous value (some ten kilohertz instead of about 200 Hz) and the lifetime of the protons was only about 10 hours instead of more than 100 hours /16/. This effect was observed with $1.5 \times 10^{11}$ particles in each of the proton bunches and $1.9 \times 10^{10}$ particles in each of the antiproton bunches.

This only occurs if dense antiproton bunches are injected. Pilot bunches used to test out the SPS with an intensity of $2 \times 10^9$ particles were injected without causing this effect.

From these experiments it is clear that the proton beam is suffering from the antiproton beam, i.e. an influence of the weak antiproton beam onto the strong proton beam.
Intensity of one antiproton bunch

Separation switched on

Fig. 19 Antiproton intensity decay in coast

Counting rate [Hz]

Fig. 20 Luminosity as a function of separation at one of the crossing points in the SPS
Fig. 21 Background counting rate in the experiment as a function of the vertical tune.

Fig. 22 Resonances up to the 25th order in the region of the working point in the SPS.
This cannot be explained by a tune shift which pushes the protons onto one of the known resonances up to the 10th order because the tune shift caused by the low intensity antiprotons is much too small.

Switching on the separators and separating at 4 from the 6 crossing point reduced the background rate by about a factor of 2 to 4, but still the background was unacceptably high.

Another experiment was performed to investigate the cause of this effect /16/: The vertical tune was kept at 27.577 whereas the horizontal tune was changed between 26.68 and 26.695. During these changes the background rate in one experiment was measured. This rate is about proportional to the lifetime but very small changes in the lifetime are difficult to measure whereas the background changes significantly. Fig. 21 shows the background rate as a function of the horizontal tune measured with the Schottky detector /14/. Fig. 22 shows the tune diagram between the 3rd and 10th order resonance and the way how the tune was changed.

The background rate increases monotonically as the tune is pushed upwards through the nest of 13th order resonances towards the 10th order resonances. Decreasing the tune towards the third order resonance reduces the rate. (If one would go further towards the third the rate would again increase. This could not be done because in this experiment the antiproton tunes were lower than the proton tunes and they got lost first). In this measurement the peak of the rate in the region of the 16th order resonance is evident. Other measurements did not show such a clear behaviour, but the general tendency is clear: The background rises when the tune is moved towards the 10th order resonance.

The observations indicate that higher order resonances are causing the high background. The 16th order resonance is the most probable candidate.

In order to understand this phenomena one has to compare all the parameters for the Beam-Beam effect in coast after using the injection separation and with a normal injection. We do this here for the case of 3 bunches per beam.

The intensities for protons and antiprotons are about the same in both cases, about $2 \times 10^{11}$ particles in each proton bunch and $1.5-2.0 \times 10^{10}$ antiprotons per bunch.

The normalized emittance of the proton beam is about the same, between 20 and 30 $\pi \text{ mm mrad}$ in both planes. Only the emittance of the antiprotons is always significantly different in coast after using the separators. Normally the emittance is about $16 \pi \text{ mm mrad}$, with separation only 9-12 $\pi \text{ mm mrad}$. 
Fig. 23  Resonance width as a function of amplitude for different resonances of even order (see ref. [lyn/])

Fig. 24  Emittance in coast as a function of time after an injection with a big antiproton emittance
7.2 Comparing the resonance widths

In the following we will compare the width of the 16th order resonance with the width of the 10th order resonance which is well known in the SPS.

The beam-beam potential creates higher order resonances. The width of these resonances can be calculated [3]. In fig. 23 the resonance width function is shown as a function of the particle amplitude for different even orders of the resonance [3]. Odd order resonances are only excited if the beams are separated. This case will not be considered here.

The emittances of both beams are different. In order to compare the width of the resonance we consider particles with an amplitude of 3 sigma. Protons with this amplitude are in the potential of the smaller antiproton beam at 3.75 sigma relative to the antiproton beam size, assuming emittances of 25 \( \pi \) mm mrad for the protons and 16 \( \pi \) mm mrad for the antiprotons. Antiprotons with 3 sigma amplitude are at only 2.4 sigma relative to the proton beam size.

If the beams have emittances of 25 \( \pi \) mm mrad (protons) and 9 \( \pi \) mm mrad (antiprotons) the protons are at 5.0 sigma, the antiprotons at 1.8 sigma.

For these values one finds the resonance width function in fig.23. The linear beam-beam tune shift serves as a scaling factor for the beam-beam effect. The multiplication of the resonances width function with the linear beam-beam tune shift yields the resonance width. The results of the calculation of the resonance width function and the resonance width are shown in table II.
<table>
<thead>
<tr>
<th></th>
<th>Resonance width function for</th>
<th>Resonance width = Resonance width function</th>
</tr>
</thead>
<tbody>
<tr>
<td>particles with 3 sigma amplitude</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>10th order</td>
<td>16th order</td>
</tr>
<tr>
<td>Proton with 3 sigma amplitude in a 16 mm mrad antiproton beam</td>
<td>4.10^{-3}</td>
<td>5.10^{-5}</td>
</tr>
<tr>
<td>Antiproton with 3 sigma amplitude in a 25 mm mrad proton beam</td>
<td>5.5.10^{-4}</td>
<td>&lt;10^{-6}</td>
</tr>
<tr>
<td>Proton with 3 sigma amplitude in a 9 mm mrad antiproton beam</td>
<td>6.10^{-3}</td>
<td>4.10^{-4}</td>
</tr>
</tbody>
</table>

From table II one can immediately understand that only the protons are suffering from 16th order resonances. The resonance width for them is $3 \times 10^{-7}$ and the resonance width for the antiprotons less than $10^{-8}$. In addition 10 times more protons have an amplitude bigger than 3 sigma because their intensity is 10 times higher. The extremely high background rate caused by the protons compared to the background rate caused by the antiprotons is also due to this much higher intensity.

The 10th order resonance width is for both kinds of particles about the same with $\approx 2 \times 10^{-6}$ which is about ten times higher than the resonance width for the 16th resonance.

### 7.3 Future Requirements

In the operation up to now with three bunches per beam the SPS is not limited by the beam-beam effect if the tunes are carefully chosen between 10th and 3rd order resonances. If the tunes are raised from their normal value $Q_x=26.585$ and $Q_z=27.680$ the background caused by the protons increases, this previously unexplained effect is caused by 16th
order resonances.

Because the emittance of the weak antiproton beam is much smaller than the proton emittance the beam-beam effect is not harmful for antiprotons in spite of the higher protons intensity.

A further decrease of the antiproton emittance leads to an excitation of 16th order resonances by the antiprotons and the lifetime of the protons decreases.

An increase of the antiproton emittance leads to a decrease of the antiproton lifetime because the antiprotons with big amplitudes get lost in the presence of 16th order resonances excited by the protons. This leads to the self-scraping of the antiprotons, i.e. the emittance decreases. This effect was observed after an antiproton injection with a big emittance of the antiproton beam (fig.24). The measurement was done with the Micron-wire-scanner at the SPS /17/.

If the intensities of both beams are different an operation with unbalanced emittances is optimal. The higher proton intensity and the lower antiproton emittance leads to a width of 16th order resonances which is about the same for both beams.

With an increase of the antiproton intensity this is no longer valid. In the case of about equal intensities the best is to have equal emittances.

For the future it is desired

a) to inject the proton beam with a smaller emittance. In the CPS an emittance of about 15 \( \mu \) mm mrad can be achieved. It must be ensured that this emittance can be conserved until the beam is in coast in the SPS.

b) to have a control over the emittances, i.e. an independently controlled blow up of the emittances is needed in order to adjust the emittances of both beams to a desired value, which may even depend on the intensity.

c) to have an individual control over the tunes of both beams. This can be done relatively easily because the beams are separated in the machine. At two positions where the beams are separated two sextupoles are needed to change the horizontal and vertical tunes independently. These sextupoles have to be installed at a position where the dispersion is zero to leave the chromaticity unchanged. In addition these sextupoles can be used at injection to gain tune space in both planes, i.e. to place the tunes of both beams at optimal working points. By that one can ensure that the emittances are not blown up by a mistuned machine during injection and energy ramping.
8. SUMMARY

By the upgrading of the SPS in order to achieve higher luminosities one major limitation is given by the increased strength of the beam-beam effect.

The upgrading has two different consequences for the beam-beam effect:

- **The increase of the linear tune shift and consequently of the tune spread in the antiproton beam is caused by the double number of proton bunches circulating in the SPS.**

- **The transition of the beam-beam effect from the weak-strong regime close to strong-strong regime is caused by the increased intensity of the antiprotons.**

Without precautions the increase of the tune spread leads to a substantial loss of particles at injection, because the tunes of the particles overlap 3rd and 4th order resonances. In coast the increase of the tune spread causes an unacceptable background level in the physics detectors and a reduced lifetime of the beams mainly caused by 10th order resonances because it is not longer possible to place the beams between 3rd and 10th order resonances.

By separating the beams at injection the tune spread is reduced to about 30 percent. The particles are kept clear from 3rd and 4th order resonance and the transmission from the moment of injection until the beams are coasting is the same as in the case with 3 bunches per beam. In coast the beam gets free from the 3rd and 10th order resonance. In addition the blow up of the antiproton emittance during injection becomes much less and results in a brighter antiproton beam at coast energy.

This leads to a machine performance which is similar to the performance with 3 bunches per beam except the increase of the luminosity by a factor of two.

The increase of the strength of the beam-beam interaction caused by the increase of the antiproton intensity poses more problems. The next higher order resonances above the 10th in the tune region where the SPS operates are resonances of 15th order.

Now the weak antiproton beam experiences the strong force from the proton beam, but because the antiproton emittance is smaller than the proton emittance the width of 15th order resonances is small.
Because of the increase of the antiproton intensity this operation with nonbalanced emittances is no longer reasonable, the emittance of both beams will be similar. For the antiprotons with big amplitudes the resonance widths for 16th order resonances will increase by about one order of magnitude.

Resonances of 16th order were already seen. Because of the reduction of the antiproton emittance after an injection with separators the width of 16th order resonances increases by about a factor of 10 due to the fact that the protons with big amplitudes are further outside relative to the antiprotons. This causes a very high background level and a beam intensity lifetime in the order of 10 hours for the proton beam (normally >100 hours). Similar problems are expected if the antiproton intensity will be increased by a factor of, say, 5.

Different techniques will be used to cure this effect:

- Separation reduced the width of these resonances by a certain amount, but even after switching on the separators the background level was unacceptable.

- In addition it will be necessary to place the tunes of both kind of particles individually at optimal locations in the tune diagram. This requires two groups of sextupoles at a position where the beams are separated.

- Furthermore an individual emittance control of the protons/antiprotons is desired in order to adjust the ratio of the emittances according to the intensities of the beams to achieve the optimal performance.

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