BEAM-BEAM EFFECTS IN THE STRONG-STRONG REGIME AT THE CERN-SPS

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1. Introduction

With the upgrade of the CERN antiproton production and accumulation complex a much larger number of antiprotons was available for the SPS proton antiproton collider run in 1988 than in the years before. The maximum stack of antiprotons in the antiproton accumulator (AA) exceeded $8*10^{11}$. With an extraction of 70% of the stack and a transmission efficiency between the AA and the SPS of about 70%, up to $4*10^{11}$ antiprotons in six bunches could be injected into the SPS. This resulted in more than $5*10^{10}$ particles in one bunch at injection. The antiproton bunches had normalized transverse emittances of 7π.mm.mrad which was smaller than the emittances for the proton bunches with 12π.mm.mrad.

Because of the increased antiproton intensity, the collider operated with six bunches per beam instead of three bunches per beam in the previous years. At each collision point the linear tune shift caused by the protons on the antiprotons was about 0.005. The linear tune shift of the antiprotons on the protons was about the same hence the SPS operated in the strong-strong regime of the beam-beam interaction.

In this paper we report the observations on beam-beam effects at injection and during store in the strong-strong regime and compare them with earlier observations.

2. The proton antiproton injection cycle

In Fig.1 the magnetic field, the total circulating current and the current of two selected bunches (proton bunch B and antiproton bunch Z) are shown for an injection cycle. First, 6 proton bunches are injected at an energy of 26 GeV at 2.4 s intervals followed by 6 antiproton bunches follow. Immediately after the injection of the last antiproton bunch the magnetic field is ramped until it reaches a value corresponding to the storage energy of 315 GeV. During the first seconds at this energy the optics is changed to reduce the β-values at the collision points with physics experiments from $7.0*3.5\ m^2$ to $1.0*0.5\ m^2$ (squeezing). After squeezing the conditions are stable.

If the bunches collide at all 12 crossing points the total tune spread exceeds 0.05. With such a high value for the tune spread the beams cannot be placed between destructive resonances. Therefore electrostatic deflectors separate the beams in the horizontal plane. At injection the beams are partially separated by one of the separators at all 12 crossing points. The field in the separator remains constant during acceleration until after the squeezing all three separators are ramped and in a few seconds the store separation is reached. In store the beams are separated over most over the circumference by a larger amount. They only collide head-on in the two experimental areas for UA1 and UA2 and at the midpoint in the arc in between.

The major part of the loss in Fig.1 is caused by the beam-beam interaction. With two beams losses are observed for both protons and antiprotons throughout the acceleration cycle as well as during the first few minutes of store.

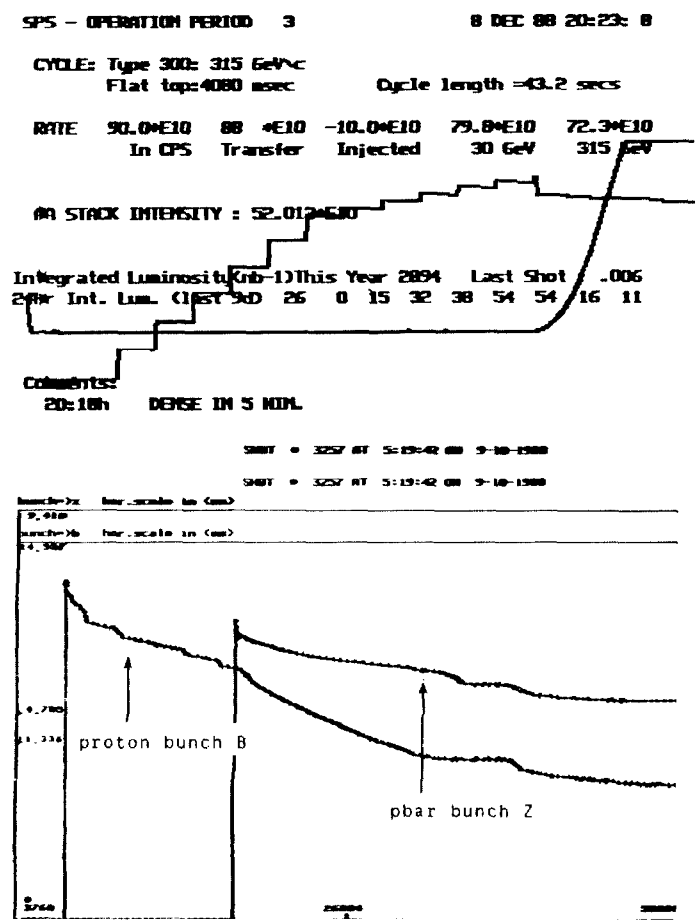


Fig.1a) Injection sequence of the SPS collider.
1b) Intensity traces of proton bunch B (vertical scale with zero surpression) and antiproton bunch Z for the first 50 s after injection.

3. Beam-beam effects at injection and acceleration

For protons alone the tune spread at injection is dominated by the space charge incoherent Laslett detuning being of the order of 0.03 for the horizontal plane and about 0.05 for the vertical plane. The particles occupy the space between 0.68 and 0.73 in the tune area, between resonances of third and fourth order (only the fractional part of the tune is given, see Fig.2 and [1]). Without the beam- beam interaction resonances of higher order than 4 are weak and do not cause beam loss.

In the following we discuss 3 different experiments:

a) a weak antiproton bunch is injected in the presence of 6 proton bunches without separation.

b) a strong antiproton bunch is injected in the presence of 6 proton bunches without separation.

c) a strong antiproton bunch is injected in the presence of 6 proton bunches with separation. This represents the operational conditions during the 1988 run.

For a weak antiproton bunch the tune spread caused by the space charge detuning is negligible. The tune spread due to the presence of three proton bunches is still acceptable. However, with 6 proton bunches the tune spread is too large for the antiprotons to be kept away from low order resonances (Fig. 2). The antiprotons are shifted upwards onto 4th order resonances and a substantial part of the bunch is lost (see the intensity trace of an antiproton bunch injected without separation in Fig.3).

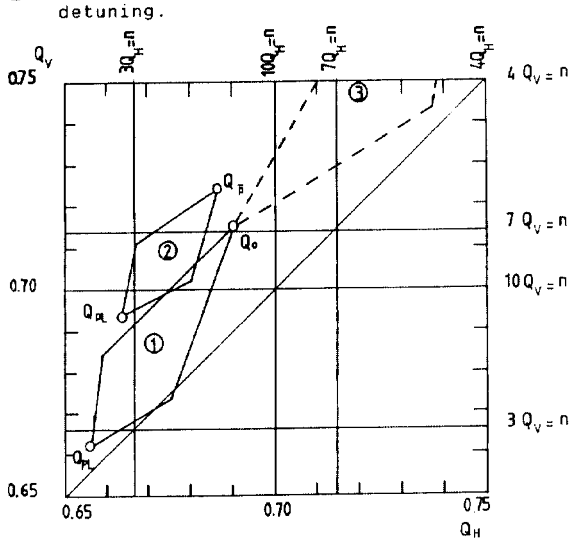
For a strong antiproton bunch the space charge detuning is similar to the the tune spread caused by the beam-beam effect. Both effects act in opposite direction, this leads to a partial cancellation of the beam-beam tune shift: the tunes for particles in the centre of the bunch are shifted upwards by the beam-beam force and downwards by the space charge detuning. Still, a substantial part of the beam is lost during injection. The loss can be explained as follows : the beam-beam tune shift and the tune shift by the space charge detuning is only similar for particles in the bunch centre. The space charge detuning decreases for particles in the tails of the bunch, whereas the beam-beam detuning is independent of the longitudinal position. Particles oscillate between the front and the back of the bunch. This leads to a change of the tune with the synchrotron frequency caused by the change of the space charge detuning. In the tails the particles are shifted onto the fourth order resonance and lost.

Partial separation of the beams at injection has several effects: The tune spread caused by the beam-beam interaction is reduced, the strenghts of the beam-beam induced resonances of even order are reduced and resonances of odd order are excited, which are not present without separation. In Fig.4 the detuning of particles for different amplitudes as a function of separation is shown. The detuning is calculated assuming round beams with a Gaussian particle distribution. In order to calculate the tune spread for the SPS at injection, the separation of the beams at the different crossing points is taken into account (see table 1).

Table 1: Separation between two beams for the 12 crossing points (in units of x/σ, with x...separation and σ the beam size of the antiprotons)

1	5.4	3	4.4	5	3.7	7	2.0	9	1.3	11	6.0
2	5.5	4	6.7	6	7.4	8	7.9	10	7.1	12	4.2

Fig.2) Tune diagram at injection :
① Protons, tune spread by Laslett detuning.
② Pbars with separation, tune spread by beam-beam.
③ Pbars without separation, tune spread by Laslett detuning.



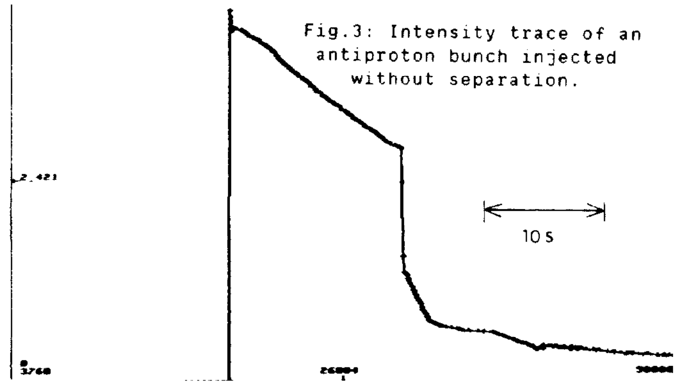


Fig.3: Intensity trace of an antiproton bunch injected without separation.

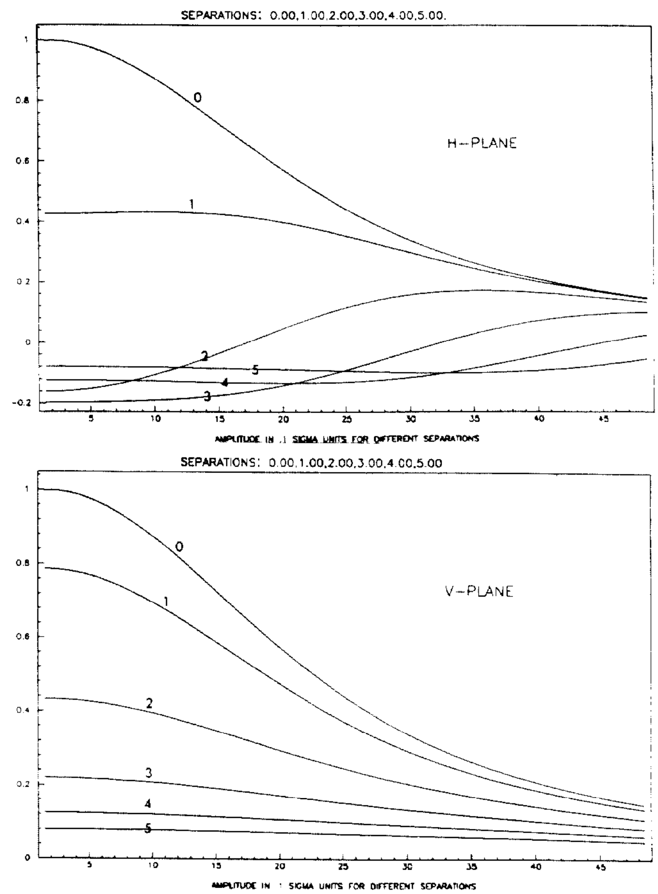


Fig.4) Detuning for different values for the separation in the horizontal plane as a function of the particle amplitude (0 to 5σ). The separation is given in units of σ.

For an intensity of $6.0*10^{10}$ for the antiprotons and $12.0*10^{10}$ protons per bunch and normalized emittances of 6π.mm.mrad for the antiprotons and 12π.mm.mrad for the protons the values for the tune spread are :
protons: horizontal : -0.0026, vertical : 0.0058
pbars : horizontal : -0.0027, vertical : 0.0075

The transmission of proton bunch B decreases after antiproton bunch Z is injected (see Fig.1). The transmission improves after the start of acceleration at about 70 GeV. This loss pattern was observed during the whole 1988 run. For each proton bunch the losses increase when one associated antiproton bunch is injected due to an insufficient beam separation at one of the crossing points (at crossing point 9 the separation is only 1.3σ compared to values up to 8σ at the other crossing points). Separation by a small amount is very unfavourable because odd (7th) order resonances are excited. Substantial part of the particles cross the 7th order resonance. This concerns mainly particles in the tails of the transverse distribution of the proton beam since it had a larger emittance than the antiproton beam.

4. Beam-beam effects in store

Since it was commissioned, the collider has operated in different regimes of the beam-beam interaction with parameters given in table 2.

TABLE 2: Typical beam parameters between 1985-1988

	before 1987	1987	1988
Number of bunches	3	6	6
Proton bunch intensity (10^{10})	15	12	11
Pbar bunch intensity (10^{10})	1.9	1.9	5
Proton emittance [π.mm.mrad]	25	25	12
Pbar emittance [π.mm.mrad]	12	7	7
Horizontal proton tune shift (10^{-3})	0.8	1.0	4.9
Vertical proton tune shift (10^{-3})	0.6	0.8	3.5
Horizontal pbar tune shift (10^{-3})	3.4	2.8	5.2
Vertical pbar tune shift (10^{-3})	2.4	1.9	3.7
Number of crossing points	6	3	3
Luminosity (10^{30} cm^{-2} s^{-1})	0.4	0.4	>2

In the first years of the collider the difference between the emittances of the two beams was moderate and sufficient to ensure stability of the antiproton beam, but not large enough to render the intense proton beam sensitive to the ten times weaker antiproton beam. The antiproton emittance increased along the injection platform due to particles in the bunch centre crossing the fourth order resonance. This led to an increase of the amplitude and a detuning of the particle away from the resonance. The dominant effect being observed is an increase of the emittance without particle losses.

With injection separation the emittances of the antiprotons were fully preserved, because the tune spread caused by the beam-beam effect is substantially reduced and the particles move away from the 4th order resonance. This created unfavourable conditions for the protons later at the start of the store: particles in the tails of the amplitude distribution are lost due to high (16th) order resonances (see [2],[3] and Fig.5). This not only reduced the lifetime of the protons to less than 10 hours at the start of the store, but also created intolerable high background rates for the physics experiments. The tolerable background rate for the experiments is in the order of some hundred Hz compared to rates of above 100 kHz which were measured at the start of store. During 2-5 h the rate decreased below a level of 1 kHz and the lifetime increased to about 25 h. In order to re-establish acceptable conditions within a shorter time the emittances of the antiproton bunches had to be increased in a controlled way during the first minutes of a store.

After the 1987 run measures were taken in order to balance the emittances of both beams by reducing the proton emittances. This was successfully achieved with an optimization of the proton transfer throughout the chain of preaccelerators and the SPS itself. During the run the emittance ratio $\varepsilon p/\varepsilon\bar{p}$ was slightly smaller than 2. Although the linear beam-beam tune shift on the protons was 4 times higher than in 1987, the situation was drastically improved. After acceleration a small fraction of the protons was lost during the first few minutes of store: particles with large amplitudes were ejected due beam-beam high order resonances. The backgound at the start of a store the was 1-2 kHz, decreasing in some minutes to an acceptable value for the experiments. The lifetime of the proton bunches increased during this time to about 50 hours.

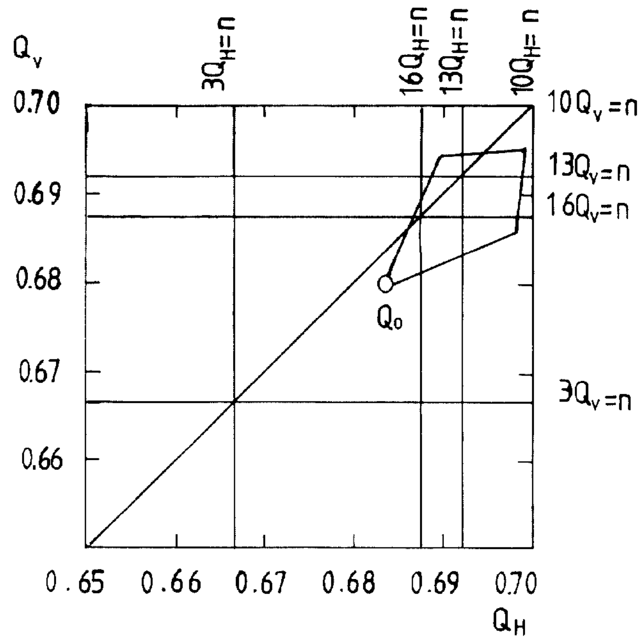


Fig.5: Tune diagram in store. The tunespread for protons and antiprotons in store due to the beam-beam force is similar. At the store energy of 315 GeV the Laslett space charge detuning is negligible.

5. Conclusions

For the operation with six bunches per beam and a linear tune shift of about 0.005 per collision a small fraction of the particles is lost during injection and acceleration due to the beam-beam interaction. In particular losses are caused by the 7th order resonance. Resonances of odd orders are created by the unsufficient separation of the beams at some of the crossing points. An upgrade of the separation scheme will reduce the losses.

During store the beam-beam force creates resonances of high order. If the emittances of both beams are similar, resonances up to 10th order limit the lifetime to very low values and therefore have to be avoided. If the emittance of one beam is substantially bigger than the emittance of the other beam, particles with large amplitudes in the bigger beam are sensitive to resonances of much higher order, in the SPS at least to the order 16. This leads to a reduced lifetime and to untolerable particle losses in the experimental areas.

6. Acknowledgement

The authors would like to thank the members of the operations group and machine studies group for their help with many measurements.

7. References

[1] J.Gareyte, Tune diagram during $p\bar{p}$ operation, SPS/AMS/Note/89-1

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