The beam-beam effect in the SPS proton antiproton collider for beams with unequal emittances

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1 Abstract

A serious limit of the performance of any storage ring is imposed by the beam-beam interaction. A single parameter is used to quantify this limit, namely the linear tune shift ξ. In order to keep the beams stable, ξ has to remain below a certain critical value. Experiments performed during the $Sp\bar{p}S$ collider run in 1989 demonstrated that the use of ξ is insufficient to parametrise the beam-beam interaction if the two beams have different sizes. In a particular experiment in which one antiproton bunch was colliding with one proton bunch, the intensity of the $\bar{p}$ bunch was reduced by scraping a substantial part of the particles. This reduces the intensity and the size of the $\bar{p}$ bunch as well as the linear tune shift seen by the protons. However the lifetime of the proton bunch decreased after the scraping. Resonances of order 13th and 16th, which are very destructive for large amplitude particles, could be identified. An amplitude dependent diffusion mechanism leading to eventual loss of particles was observed.

2 Introduction

Before 1987, the CERN $Sp\bar{p}S$ collider achieved in its first phase a maximum luminosity of about $4.10^{29}cm^{-2}s^{-1}$. In order to increase the luminosity the antiproton production and accumulation complex was upgraded and a much larger number of antiprotons was available from 1987 onwards. With the increased number of antiprotons in 1987 a surprising observation was made: an enormously high background rate in the physics detectors together with a low lifetime of the protons caused by the beam-beam force from the antiprotons on the protons was observed. On the other hand, the effect of the more intense proton bunches on the antiprotons was comparably small [1].

It was realized that this effect was due to the different sizes of the proton and the antiproton beams. The emittance of the protons was up to four times as large as the emittance of the antiprotons. After reducing the emittance of the protons for the 1988 run the background rate became acceptable and the collider achieved a luminosity of more than $2.10^{30}cm^{-2}s^{-1}$. A series of experiments was performed to study the dependance of the beam-beam effect when parameters like tune, emittances, intensities and the separation between the beams are changed. As it will be shown in the following, the experiments demonstrated that it is insufficient to use the linear tune shift as the only measure of the strength of the beam-beam effect, in particular when the colliding beams have unequal emittances [2].

3 Generalities on beam-beam effects

When one proton and one antiproton bunch collide, particles in one bunch experience a localised focusing field from the other bunch. This field is strongly non-linear and produces a dispersion of the tunes and an excitation of the non-linear resonances. For particles in the center of the bunch the tune is increased by the linear beam-beam tune shift. For increasing particle amplitudes the tune shift decreases (detuning). From the $Sp\bar{p}S$ tune diagram in coast (Fig.1) we notice that the particles which experience a large tune shift cross resonances of high order. To get a minimum tune spread, the beams are separated at all crossing points outside the regions with physics dectectors. From the theory of the beam-beam effect it is expected that a separation excites odd order resonances. Indeed some observations made during the high luminosity run indicated that 7th order resonances were limiting the collider performance during the injection and acceleration process and in an experiment the existence of 13th order resonances could be demonstrated.

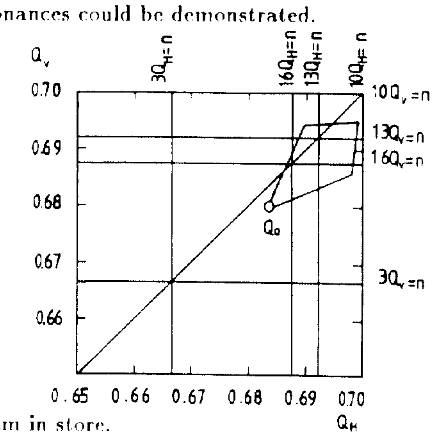

Fig.1: tune diagram in store.

4 Dependence of the beam-beam effect on the beam sizes

The experiment presented here was performed in order to demonstrate that the destructive effect of the beam-beam interaction is stronger for beams with different emittances than for beams with the same emittances. With one proton bunch and one antiproton bunch, colliding in 2 interaction points, the lifetime of the bunches and the background rate created in the physics detectors were measured as a function of the horizontal tune. The beam parameters are shown in the following table:

proton intensity	11×10^{10}
antiproton intensity	before scraping : 5.4×10^{10}
	after scraping : 2.76×10^{10}
proton emittance	horizontal : 22 $\pi mm \times mrad$
	vertical : 22 $\pi mm \times mrad$
antiproton emittance before scraping	horizontal : 30 $\pi mm \times mrad$
	vertical : 30 $\pi mm \times mrad$
antiproton emittance after scraping	horizontal : 23 $\pi mm \times mrad$
	vertical : 25 $\pi mm \times mrad$
ξ on protons	before scraping : 1×10^{-3}
	after scraping : 0.6×10^{-3}
ξ on $\bar{p}$	2.8×10^{-3}
number of I.P	2

In Fig.2, the background rate and the lifetime of the proton bunch are shown as a function of the horizontal tune before and after scraping the antiprotons. The background rate is a good measure of the beam stability and the rate can be separately observed for protons and antiprotons. Before scraping, we observed a small increase of the proton background rate in the region of the 16th order resonance, but no visible effect on the proton intensity decay rate. The $\bar{p}$ background rate increased slowly when moving through the 16th order resonance.
After reducing the antiproton emittance, we clearly noticed an increase of the proton background rate and of the proton decay rate compared to the first case. No effect was noticed on the $\bar{p}$.

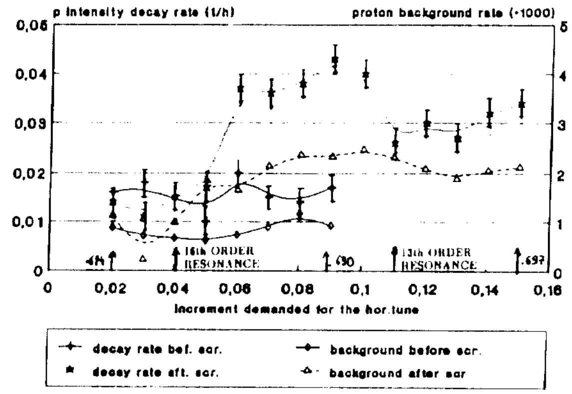

Fig.2: proton intensity decay rate and proton background rate as a function of the horizontal tune.
Although we reduced the linear tune shift by 40 % the destructive effect of the beam-beam interaction on the proton bunch increased after the scraping.

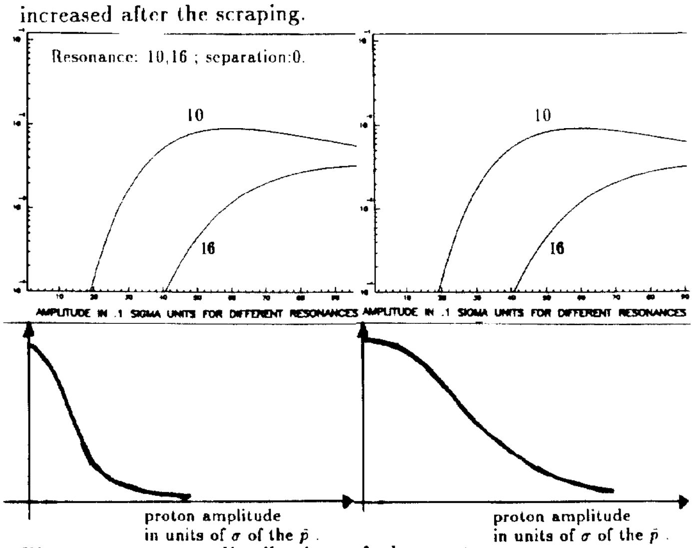

Fig.3: transverse distribution of the protons and resonance width functions seen by the proton beam before and after the scraping. The horizontal abscissa of both transverse distribution of the protons and resonance width is the proton amplitude in units of the r.m.s. $\bar{p}$ beam size.

These observations can be understood in the following way: in Fig.3 the "resonance width" function created by the $\bar{p}$ potential is plotted for 2 resonances (10th and 16th order resonances) as a function of the proton amplitudes [3]. The resonance width function is normalised to the linear beam-beam tune shift exerted by the $\bar{p}$ bunch on the protons. The abscissa is the proton amplitude, which is shown in units of the transverse standard deviation of the $\bar{p}$ beam size. A schematic drawing of the proton beam is shown below the curves of the resonances. By scraping the $\bar{p}$ beam we reduced its size and created a different equivalent potential seen by the proton beam. This causes more protons to oscillate in the non-linear part of the potential where they are affected by high order resonances (see the schematic drawing). Those resonances are very destructive for particles with large amplitudes and particle losses are observed.

5 Beam-beam effect as a function of the separation

In this experiment a proton bunch collides with two $\bar{p}$ bunches. At two points the beams collide head-on, at two other points they are separated by 6 to 7 standard deviations of the $\bar{p}$ beam size. Two horizontal tune scans have been done after $\bar{p}$ scraping, one with full separation and the other with a separation reduced by a factor 2. The beam parameters after the scraping are summarised in the following table:

proton intensity (per bunch)	7.5×10^{10}
antiproton intensity (per bunch)	1.4×10^{10}
proton emittance	horizontal : 24 $\pi mm \times mrad$
	vertical : 26 $\pi mm \times mrad$
antiproton emittance	horizontal : 7 $\pi mm \times mrad$
	vertical : 7 $\pi mm \times mrad$
ξ on protons	1.1×10^{-3}
ξ on $\bar{p}$	1.7×10^{-3}

The protons are unaffected by the beam-beam effect for a tune below the 16th order resonance (Fig.4). Above the 13th order resonance, when the tune approaches the 10th order resonance the protons are affected by the beam-beam effect in much the same way for the two values of the separation. Only in the region of the 16th and the 13th order resonances is the beam-beam effect much more destructive for a reduced value of the separation.

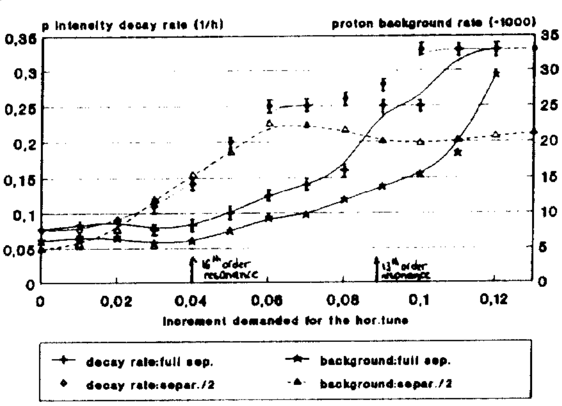

Fig.4: proton intensity decay rate and proton background rate as a function of the horizontal tune.

6 Observation of diffusion in the beam-beam effect

One way of understanding the beam-beam effect is as follows: the overlap of many higher order resonances [3] creates a stochastic area in phase space and leads to a diffusion of the particles and their subsequent loss. In the SPS, diffusion has been observed in another experiment: to study the dynamic aperture of the machine, non linearities are generated by 8 strong sextupoles distributed around the ring and parameters like tune, emittance and ripple on quadrupole power supply are changed [5] . A similar experiment was done in order to measure the diffusion rate as a function of the particle amplitude for the beam-beam interaction. The proton beam was placed in the nest of resonances of order 10 and six proton bunches collided with six antiproton bunches. The experiment is done in the following way (Fig.5): a collimator is moved close to the proton beam, scraping all the particles with an amplitude larger than a certain value. The scraping causes a spike on the background rate. Then the collimator is retracted by 2 mm. The background rate decreases immediately since the tail of the proton distribution does not touch the collimator anymore. After some time, the amplitude of some particles in the tails have increased by 2 mm (diffusion) and are scattered again on the collimator creating an increased background. This experiment was repeated for different positions of the collimator. Finally, we reduced the emittance of the $\bar{p}$ beam and measured the diffusion again for one of the collimator positions used before.

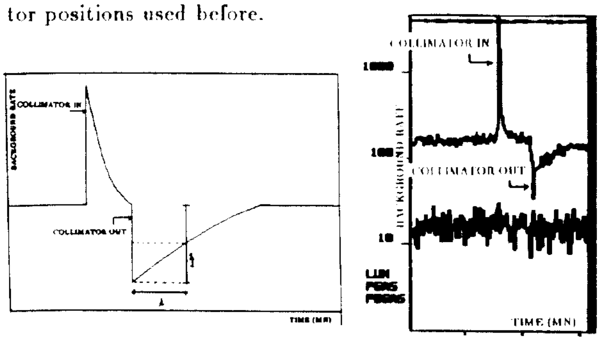

Fig.5: schematic drawing of the proton background rate as a function of time and the observed proton background rate as a function of time.

The result of the experiment is shown in the following table, where t is the time when the background rate of the protons has reached half its equilibrium value and d is the distance of the collimator from the beam center.

measurement number	sigma of $\bar{p}$ (mm)	d in units of sigma $\bar{p}$	t (sec)
1	.89	2.2	3
2	.89	2.0	3
3	.89	1.7	3
4	.89	1.5	3
5	.89	1.3	4.5
6	.89	1.1	6
7	.89	.9	60
8	.89	.6	330
9	.89	.4	600
10	.55	.7	69

The diffusion rate of the protons increases strongly with the amplitude of the protons. From Fig.3 it is clear that for a fixed resonance (here the 10th order resonance) the resonance strength increases with the particle amplitude. Particles near the bunch center are not affected by this resonance. When the $\bar{p}$ emittance is reduced, the diffusion increases. For the same collimator position the time constant t decreases from 600 seconds to 69 seconds, although the linear beam-beam tune shift on the protons is smaller. This result is consistent with the experiment described previously: the beam-beam effect is more destructive in the case of beams with unbalanced emittances.

7 Tune spectra

For all experiments we measured the proton and the antiproton tunes using a spectrum analyser which measures the Schottky signals induced in a parasitic transverse mode at 460 MHz in the travelling wave accelerating cavities. All measurements were taken in the horizontal plane.

For two degrees of freedom, the resonance condition is: $n_x Q_x + n_z Q_z = p$ where n_x, n_y and p are integers, p is the harmonic of the perturbation and Q_z and Q_y are the tune in the 2 transverse planes. If we add the synchrotron motion to this model, we get: $n_x Q_x + n_z Q_z + m_s Q_s = p$ (i) where Q_s is the longitud tune. From the theory developped by J.Bengtsson [4], we know that if we identify a peak on the spectrum taken in the horizontal plane which fullfills equation (i), it corresponds to the resonance $[(n_x+1); n_z; m_s]$. For the first spectrum (Fig.6), the proton tune is localised between the 16th and the 13th order resonances in the tune diagram. In this case, coupling resonances of order 16 are found. For the second spectrum (Fig.7), the proton tune is localised between the 13th and the 10th order resonances and coupled resonances of order 13 are then identified.

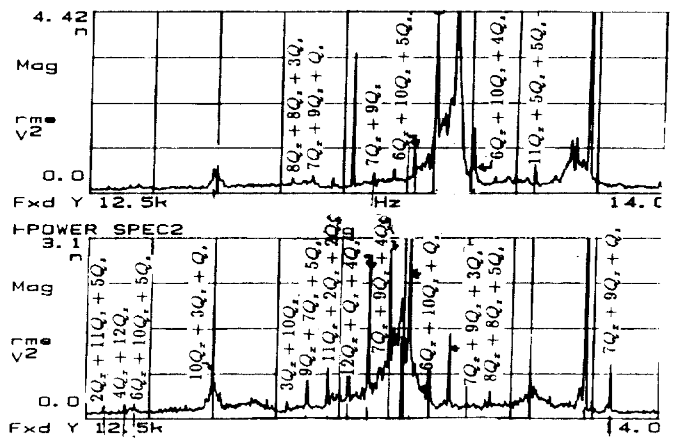

Fig.6 and Fig.7: proton spectrum in the frequency range from 12.5kHz to 14kHz.

This might be a very useful technique to identify the presence of resonances but the studies on this subject are not yet finished. It is not always obvious that the peaks are due to resonances because 50 Hz power supply ripple might manifest itself in the spectrums.

References

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