# Experience with the SPS collider

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# Overview of the Evolution of intensity and Emittance

| | Stage 1 | Stage 2 | Stage 3 | Stage 4 | |
|---|---|---|---|---|---|
| Bunches/beam | 3 | 3 | 6 | 6 | |
| Protons/bunch | $18\ 10^{10}$ | $15\ 10^{10}$ | $12\ 10^{10}$ | $11\ 10^{10}$ | |
| A-protons/bunch | $2\ 10^{10}$ | $2\ 10^{10}$ | $2\ 10^{10}$ | $8\ 10^{10}$ | |
| Proton emit. | 25 | 25 | 20 | 12 | μm/4 |
| A-proton emit. | 20 | 12 | 15 | 7 | μm/4 |
| Proton tune shift | .0005 | 0.0008 | .0008 | .005 | |
| A-proton tune shift | .0035 | .003 | .003 | .0044 | |
| | | | | | |

Injection separation

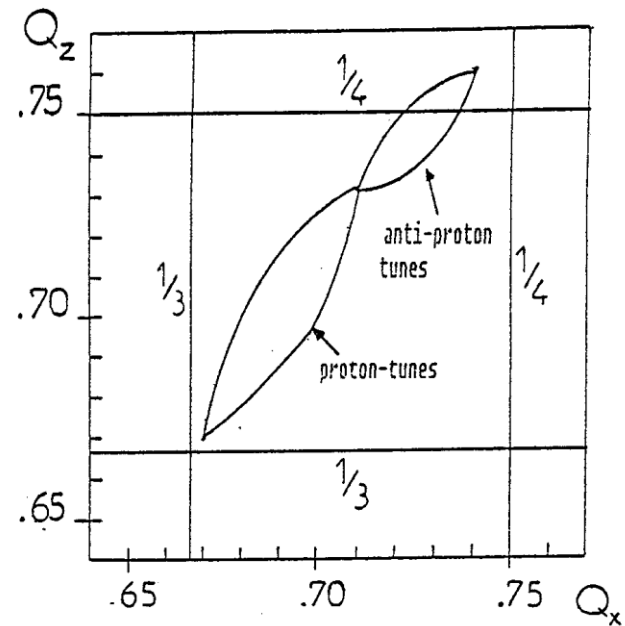
Control of bunch length at injection

Upgrade accumulator complex +100MHz cavities

# A big step forward : pretzel separation scheme in order to go from 3 on 3 to 6 on 6

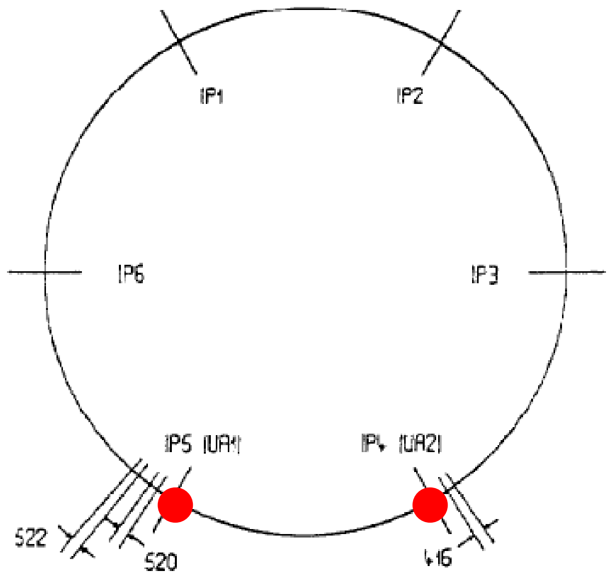
- Tune footprint for protons and anti-protons very different at injection energy. Anti-protons are dominated by beam-beam and protons by Laslett tune shift.

- With 6 on 6 (12 collision points) injection was just not possible.

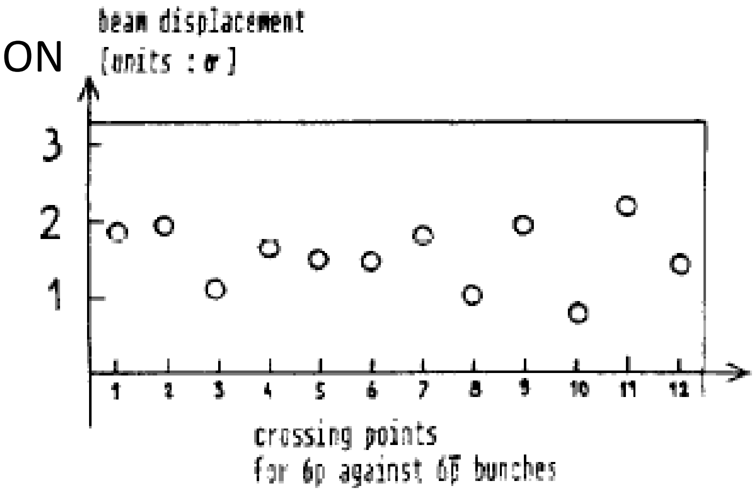


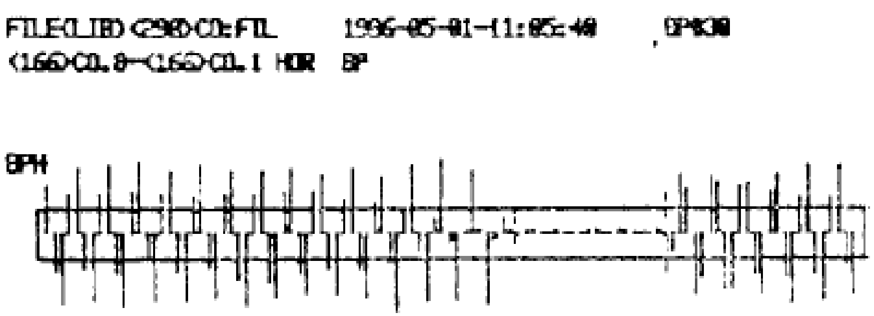

Tune footprint at 26 GeV for 3 on 3 (6 collisions)

# SPS horizontal separation scheme

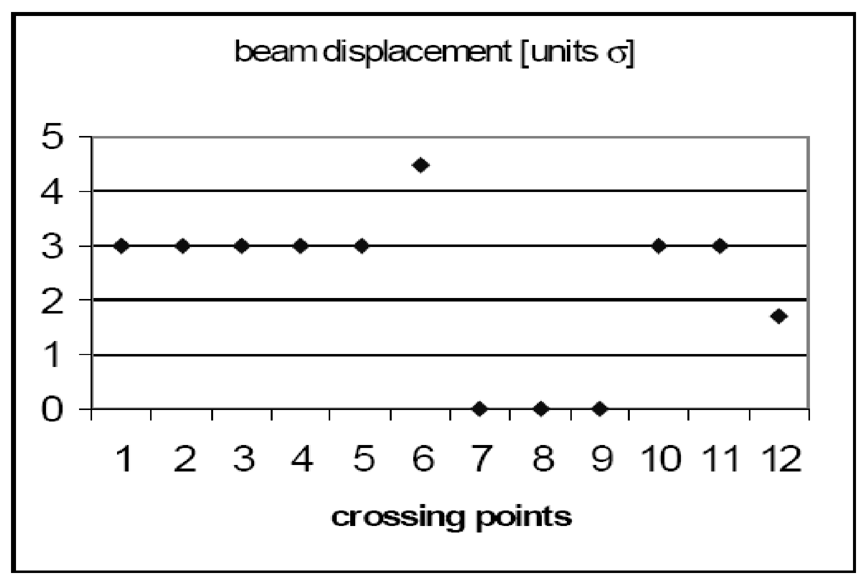



INJECTION



COAST



# Effect of separation at 26GeV

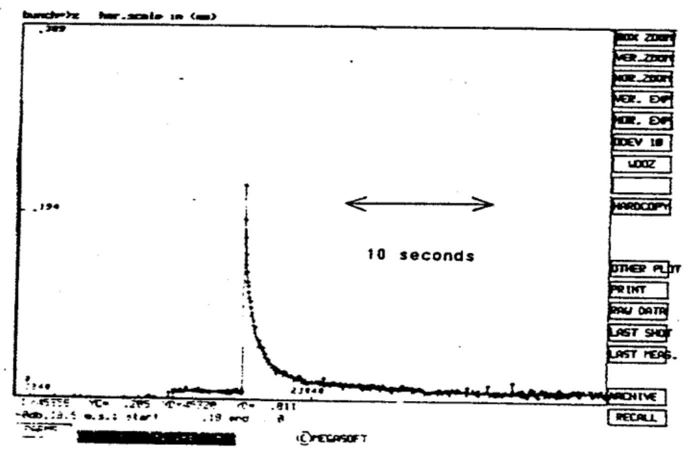



Fig.16 Antiproton intensity as a function of time without injection separation in the presence of 6 proton bunches (Qz slightly raised).

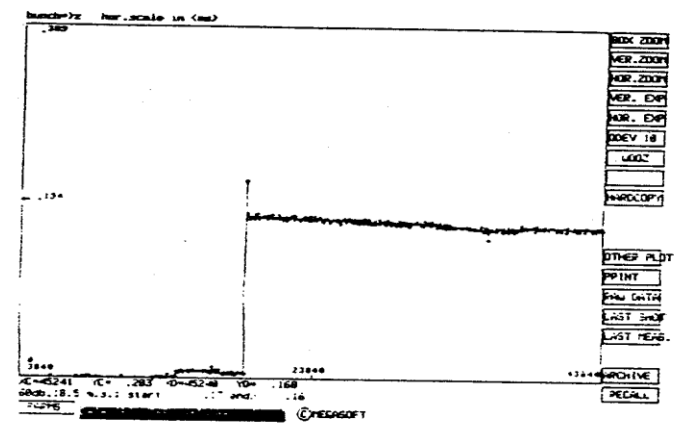
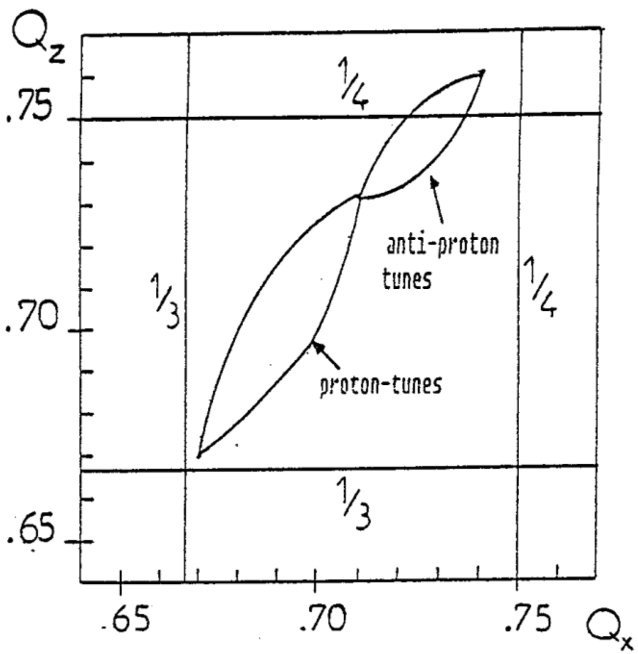


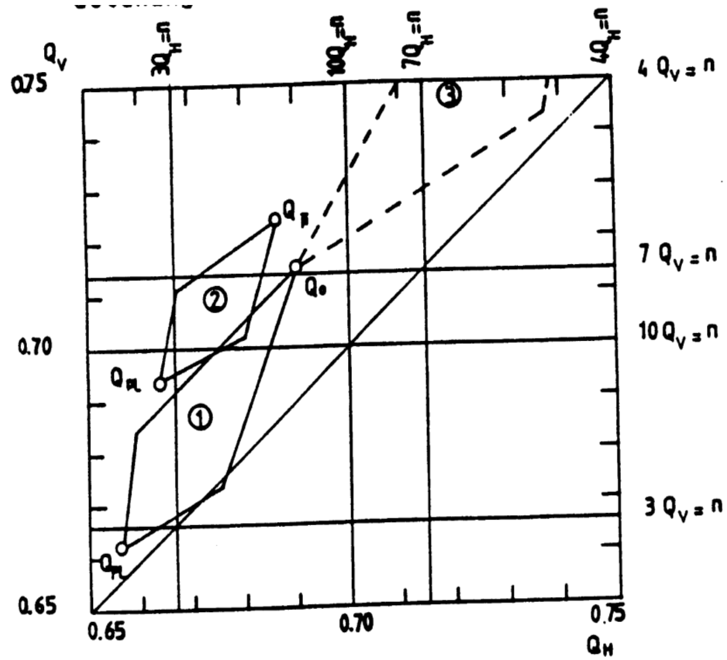

Fig.17 Antiproton intensity as a function of time with injection separation in the presence of 6 proton bunches

Intensity evolution at injection of a anti-proton bunch in the presence of 6 proton bunches with (right) and without separation (left)

# Emittance Conservation




3+3 no separation

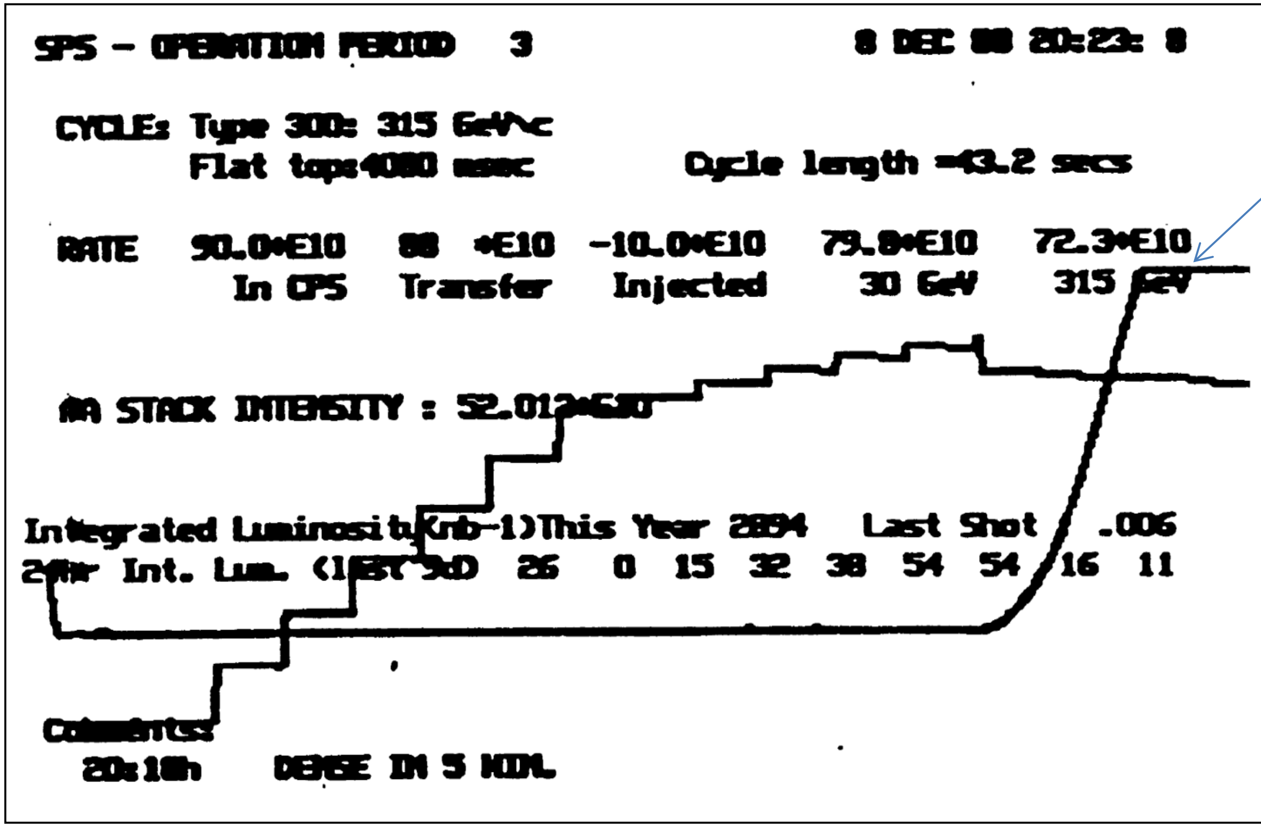



6+6 with separation

The Laslett tune shift at 26 GeV turned out to be the limiting factor for the proton emittance conservation. The PS was asked to send bunches as long as possible to fit in our 200MHz bucket.

Later we added a 100MHz so w could except even longer bunches from PS. As from the we were able to get very bright protons in collisions : 12 $\pi$ mm mrad. i.e. 3 $\mu$m In LHC language.

# Emittance conservation



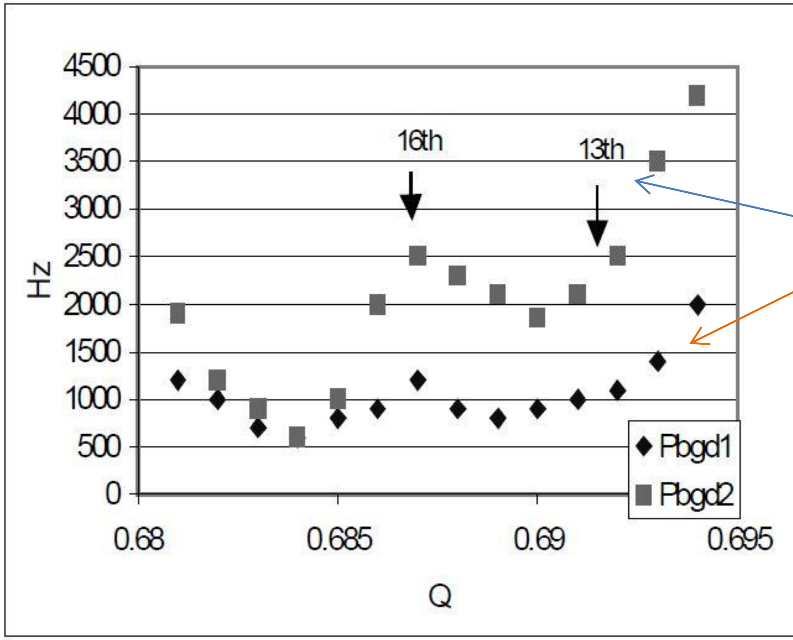

The squeeze was a critical phase were it was not so easy to keep the tunes correct.

The temperature of the insertion quadrupoles played an important role.

# The effect of small emittance

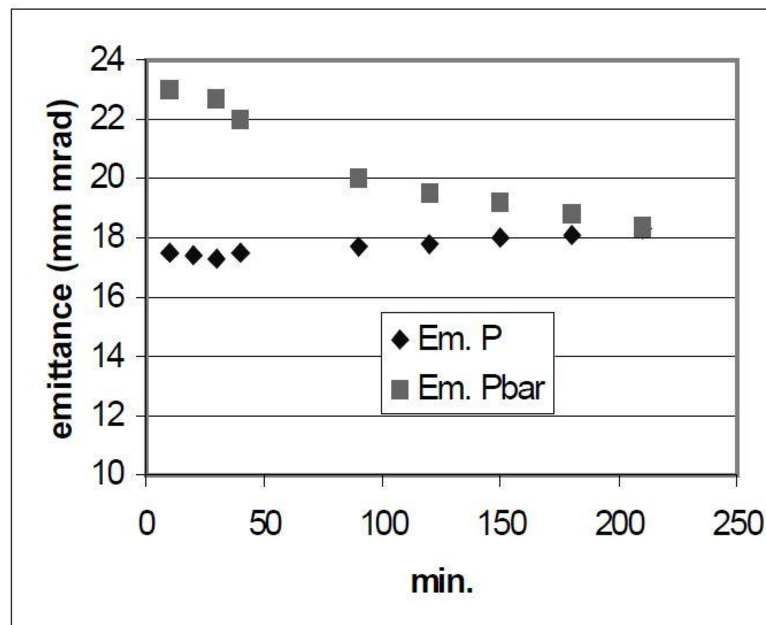
- The first fill with separation (still 3 on 3) we managed to keep the anti-proton emittance very small 12 (μm/4) with protons still at 25 (μm/4).
- Although the intensity of the anti-protons was almost 10 times less than the proton intensity, the protons were literarily blown out of the machine.
- At this point we realised that the particles outside the other beam are dynamically scraped, even for small beam-beam tune shifts.

# The effect of the emittance



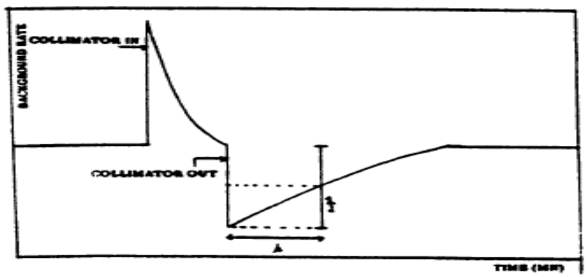

Tune scan with equal beams and on where the intensity of anti-protons was reduced by scraping, reducing the emittance as well.

Emittance evolution of proton and anti-protons during an operational fill.



# Beam-Beam studies : diffusion speeds

tions 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.



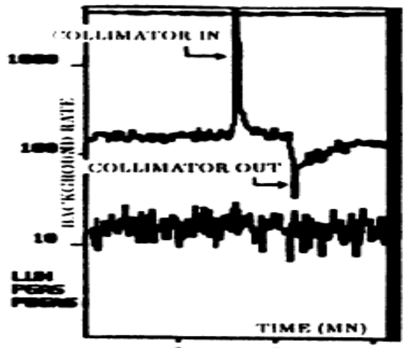
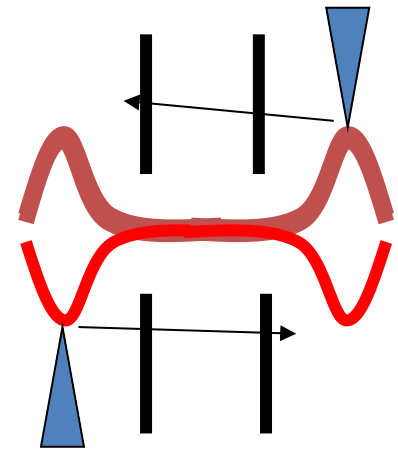




Fig.5: schematic drawing of the proton backgr function of time and the observed proton backg function of time.



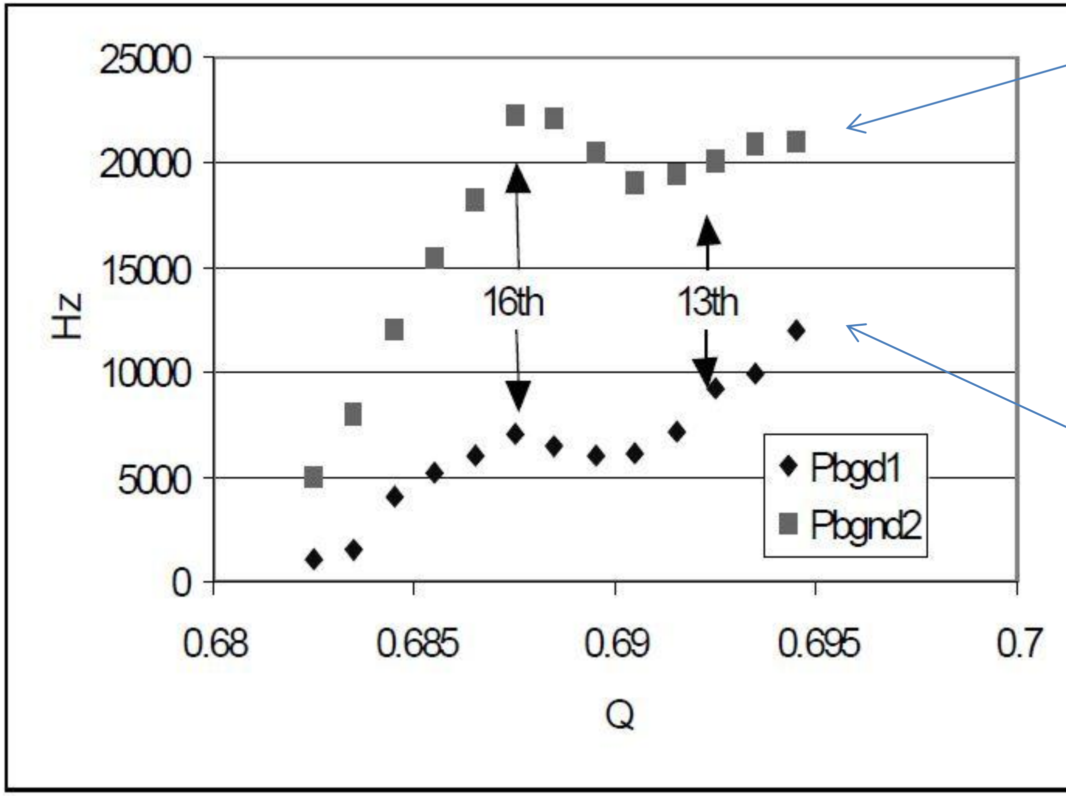
- Measurement consist of moving the collimator closer to the beam centre and then retract a fixed amount. Then measure the time it takes for particles to be scattered on the collimator again.

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 amplitude of the protons. From Fig.3 it is clear t

# Beam- Beam studies: effect of separation




- Separation reduced by 50%
- Nominal separation

# Beam-Beam studies : effect of crossing angle

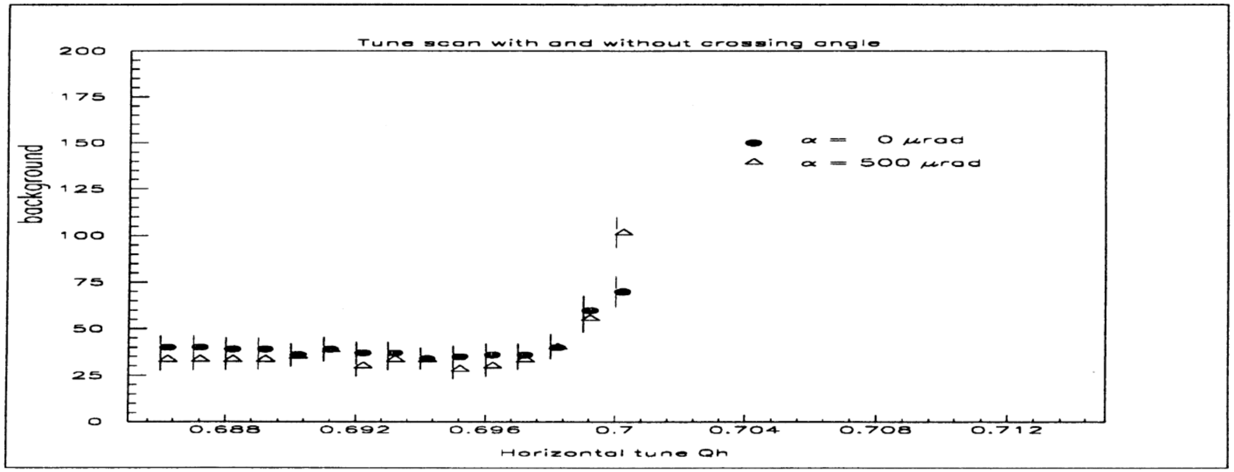



Figure 2: Tune scan with $\alpha = 500\ \mu rad$

$\alpha\sigma_s/2\sigma_{x,z} = 0.45$

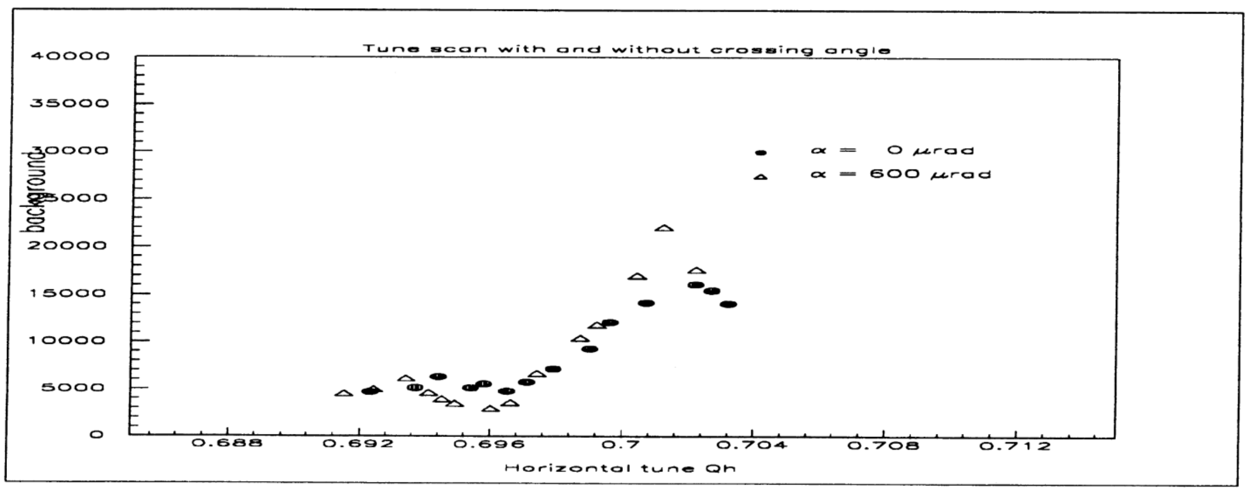



Figure 4: Tune scan with $\alpha = 600\ \mu rad$

$\alpha\sigma_s/2\sigma_{x,z} = 0.7$

# Noise and tune modulation

- High order resonances become more harmful in presence of noise or tune modulation
- Special care had to be taken of  the noise on the main magnets. During the collider run special capacitors were put on the main magnets to get rid of higher harmonics of the 50 Hz lines.
- In order to keep a good life time and low background  we had to run with very low chromaticity : 0.005 (dQ/Q/dp/P).

# Effect of tune modulation

(simulation)

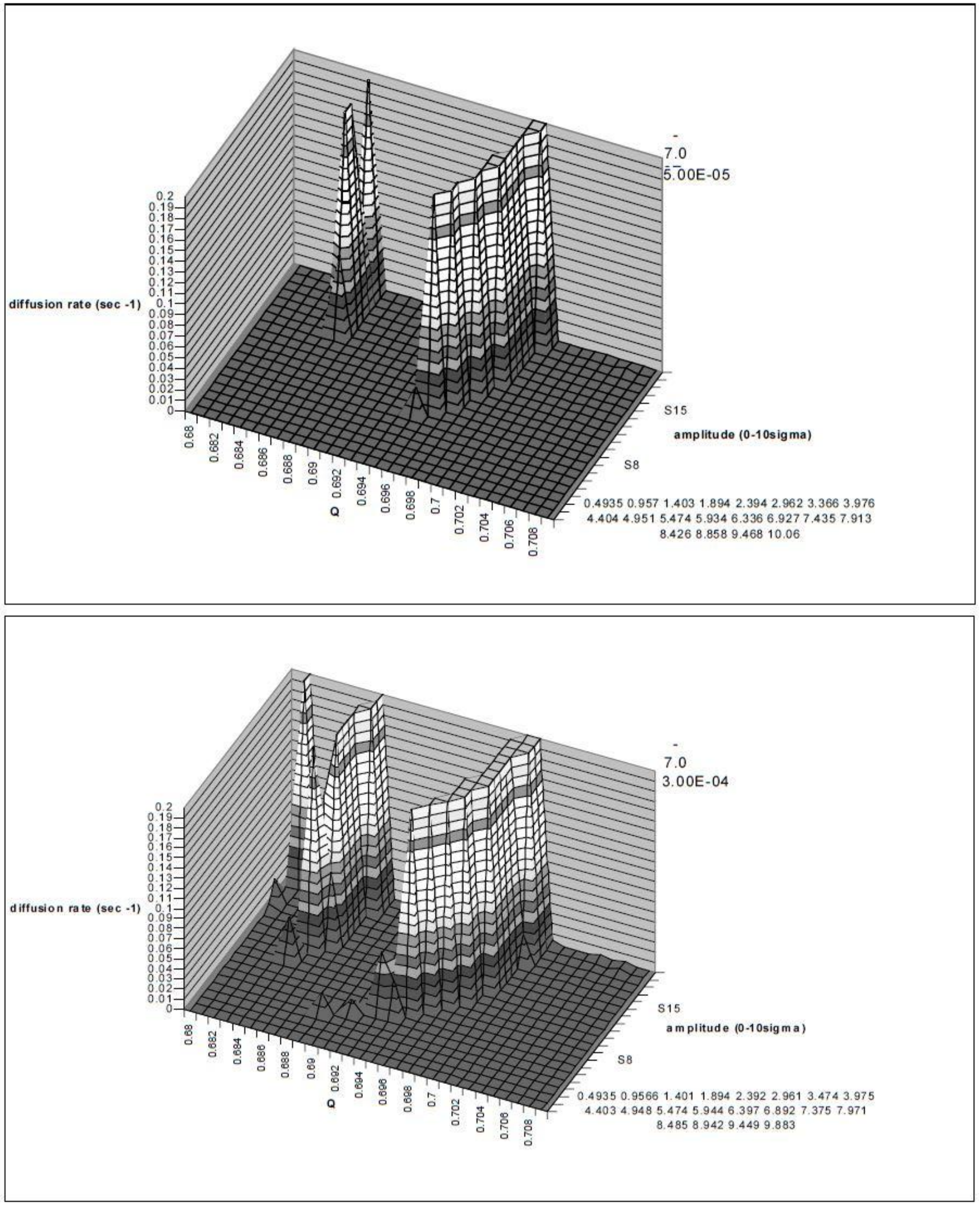
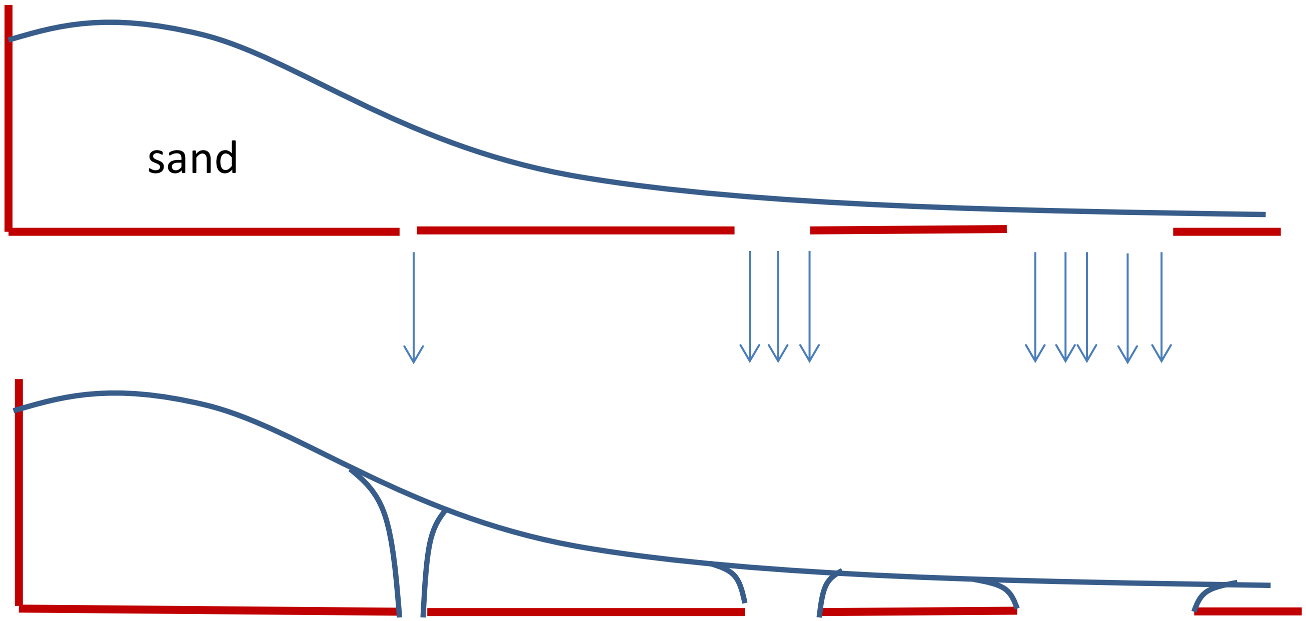
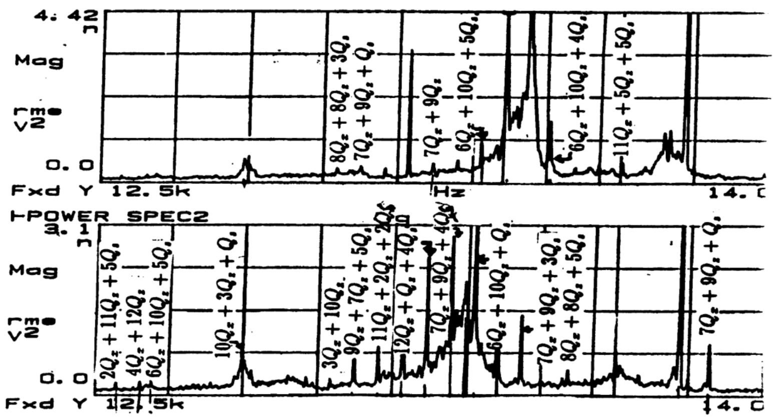



Fig 8 : diffusion rates (z) as function of tune(x) and initial amplitude (y : 0 to 10 σ). Total tune shift 0.012. Tune modulation 200 Hz, modulation amplitude 0.00005 (above) and 0.0003 (below).

# The sieve picture



# Working point



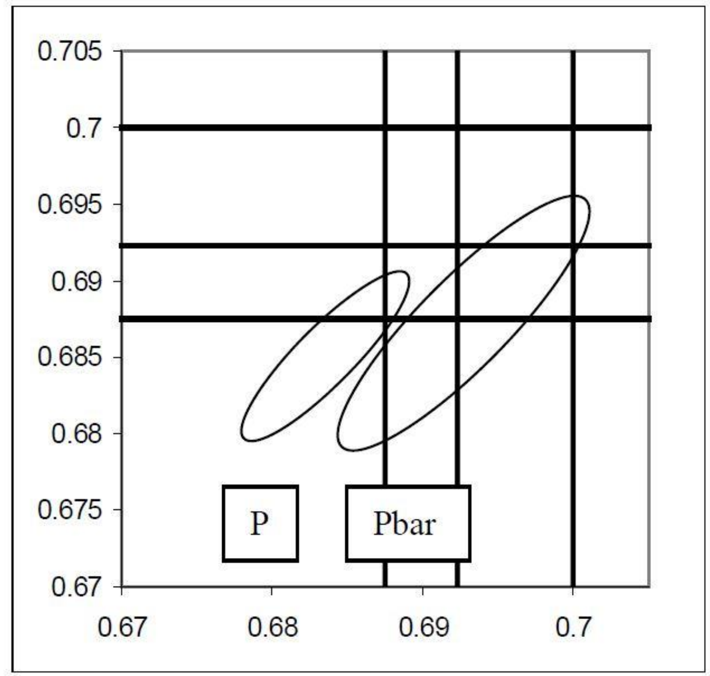




Fig 3 : Working point during physics. The horizontal and vertical lines represent respectively the 16th (.6875), the 13th (.6923) and the 10th (.700) order resonance.

# Conclusions

- Higher brightness could be achieved by beam separation, and reducing the space charge effect with longer bunches, with the help of 100 MHz cavities.
- A good luminosity life-time needs: an optimum working point, low chromaticity and matched beam sizes.
- During ~10 very interesting years of proton-anti-proton collisions in the SPS, we learned a lot on the behaviour of colliding hadron beams. This knowledge and experience was a major input for the LHC design.