# THE LOW-BETA INSERTIONS OF THE SPS PROTON-ANTIPROTON COLLIDER

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## Summary

Low-beta insertions have been installed around each of the two experimental zones of the SPS collider. They are currently used during p-pbar physics runs and provide actually a gain in luminosity of a factor around 53 without any detrimental effect on the stored beams. After a short description of the insertion layout and hardware, and of the setting-up procedure, this paper gives the main results obtained with the double FDDF optics which allowed to reach $\beta^*_x$=1.3 m, $\beta^*_y$=0.65 m at both crossing points simultaneously. Thanks to flexbility of the insertion layout, one has also tested and used other optical configurations, as for instance a "high" beta insertion for small angle scattering experiments. Finally, possible improvements for running the insertions at higher energies and/or for reaching lower $\beta^*$ values are briefly described.

## Introduction

Because of the relatively low beam currents one can ever expect in the SPS proton-antiproton collider, low-beta insertions are essential for obtaining useful luminosities. Such insertions had to be installed in an existing machine which implied severe constraints on their layout. It was requested, in particular, that the SPS could run either as a collider with the insertions in service or as an accelerator for fixed target physics, without having to displace any machine element during the changeover. Moreover the ratio between the horizontal and vertical beam emittances was expected to vary between 1 and 2 in the p-pbar collider[1]. If one wants to arrive at equal beam-beam tune shifts in the two transverse planes, one must aim at a similar ratio for the amplitude functions $\beta^*_x$ and $\beta^*_y$ at the crossing point: this is somewhat different to what is usual for $e^+e^-$ storage rings and poses difficult problems for the correction of the chromatic aberrations.

A flexible insertion layout could nevertheless be found[2] and since its implementation it has worked successfully, allowing to run the SPS collider with different optical configurations.

## Insertion hardware and operation

### Insertion layout

The insertions are installed in the two adjacent long straight sections LSS4 and LSS5 and make use of exactly the same layout. The crossing point is not at the center of the long straight section, but exactly midway between the lattice quadrupoles 18 and 19, which leaves more than 28 m free for the experiments. As shown on Fig. 1, the two insertion doublets are constructed with these quadrupoles and with six more quadrupoles installed outside this space reserved for the experiments.

Matching of the betatron and dispersion functions from the crossing point to the regular SPS lattice is done separately for the upstream and for the downstream parts of the insertions and requires the independent adjustment of the strength of five lattice quadrupoles on either side of the crossing point, in addition to the doublet strengths. None of these lattice quadrupoles need be displaced for putting the insertions into service: simple by-pass switches are used to disconnect them from the normal busbar feeding system and to have them powered by individual supplies.

Calculations with the AGS computer program[3] have also shown that several optical configurations, which can be characterized by the doublets' polarities, can be implemented with this layout: FDDF, DFFD, or even the antisymmetric FDFD+DFDF. Consequently, invertor switches for all doublets and for some insertion quadrupoles have been installed in order to be able to find experimentally the best configuration.

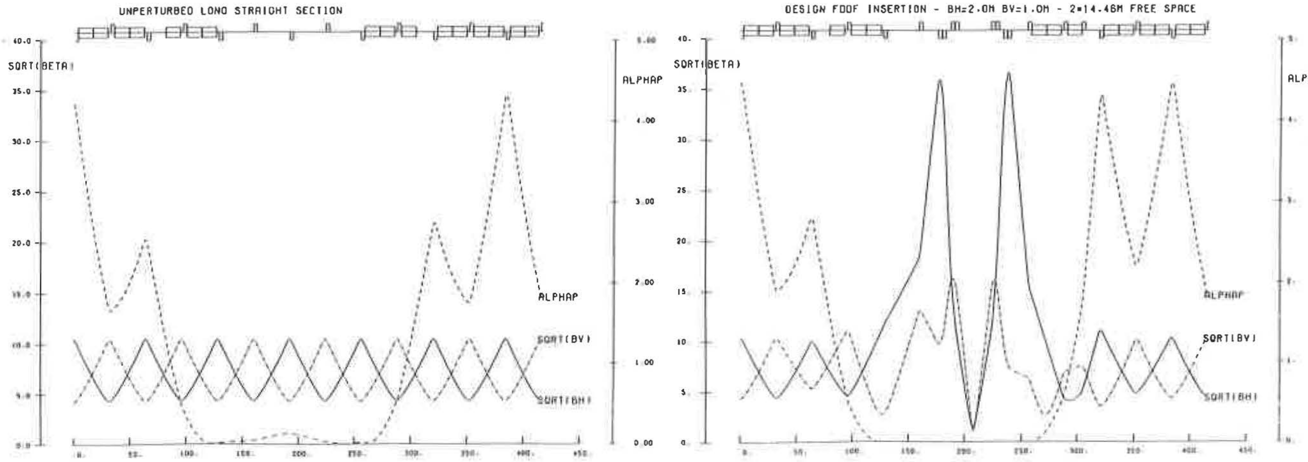

Fig. 1 The standard SPS lattice and the design FDDF insertion.

## $\beta^*$ squeezing

Owing to the desired aspect ratio $\beta^*_x/\beta^*_y$ at the crossing points, the betatron functions exhibit high maxima at the doublet quadrupoles. One must then detune the insertions, when injecting the beams at 26 GeV, in order to increase the machine acceptance and to reduce the chromatic aberrations induced by the insertions. For the double FDDF insertion of Fig. 1 for instance, the AGS program has allowed to find a continuous path from $\beta^*_x$=7.0 m, $\beta^*_y$=3.5m to $\beta^*_x$=1.3m, $\beta^*_y$=0.65m (tuning range of 5.4), but this necessitates the use of 15 independent parameters per insertion, see Fig. 2. The aspect ratio $\beta^*_x/\beta^*_y$ is kept constant during the whole detuning.

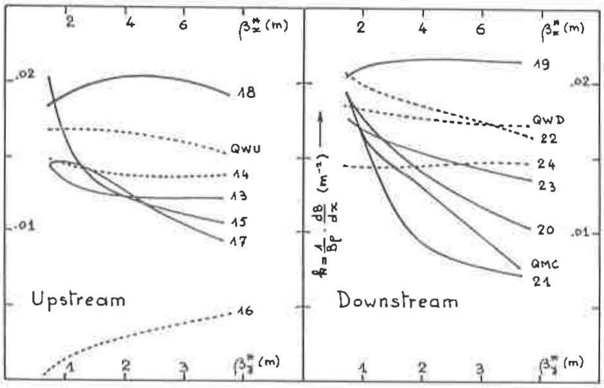

Fig. 2 Detuning of the FDDF insertion

The proton and antiproton beams are then injected and accelerated with both insertions switched on but detuned to their maximum. At 270 GeV, just before storage, when the beam emittances are smaller, the $\beta^*$'s are "squeezed" to the desired values. For a suitable variation of $\beta^*$s with time, a computer dedicated to each insertion calculates the 15 current waveforms corresponding to the detuning curves of Fig. 2 and using the magnetizing characteristics of the different quadrupoles. At the same time the lattice quadrupoles are also automatically adjusted so as to keep both machine tunes constant. This process normally takes 1.2 seconds and is achieved without any beam loss.

## The double FDDF insertion

This type of insertion allows an aspect ratio $\beta^*_x/\beta^*_y$=2 and hence equal beam-beam tune shifts for the nominal emittances. It was then tested first and has now become the standard configuration with $\beta^*_x$=1.3 m, $\beta^*_y$=0.65 m at both crossing points during storage, but further $\beta^*$s reduction down to 1.0x0.5 m$^2$ has been shown to be feasible.

## Insertion matching

To verify the insertion matching, i.e. the absence of modulation of the $\beta$-functions in the unperturbed part of the lattice, one has first measured the local $\beta$'s inside each insertion by varying deliberately the insertion quadrupoles one after another and by measuring the resulting tune shifts. $\beta$-functions outside the insertions could also be measured at 26 GeV by exciting small quadrupoles formely used as stop band correctors for 10 GeV injection which led to a correction of the magnetizing curves of the F-lenses of the doublets$^{4)}$. During beam storage at 270 GeV, one has looked at the variations of the $\beta$-functions at a specific point outside the insertions, which can be deduced from the beam profiles measured by a scanning wire$^{5)}$, when one varies one insertion quadrupole. Good agreement was always found between these measurements and the $\beta$-values calculated by the AGS program for the same conditions. No insertion mismatch could then be found, for all $\beta^*$s used within the measurement accuracy.

Finally beam profiles at the LSS5 crossing point were observed with another wire scanner: Fig. 3 clearly demonstrates the effect of the $\beta^*$-squeezing at 270 GeV, but the accuracy on the $\beta^*$-values one can deduce from these profiles is limited as there were some irregularities in the wire motion.

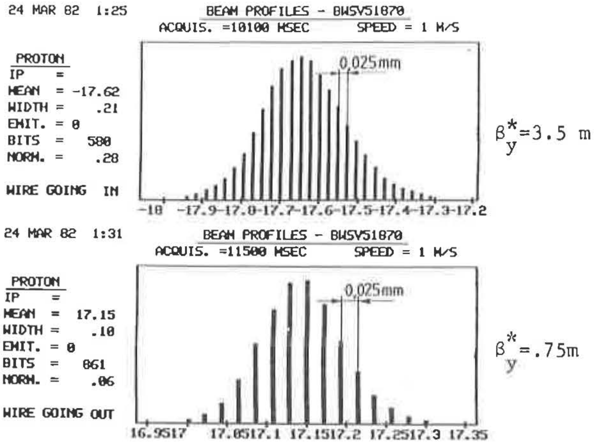

Fig. 3 Vertical beam profile at crossing point.

## Chromaticity and other corrections

Earlier studies$^{2)}$ have shown the necessity of using four independent sextupole families in the SPS for adjusting the linear chromaticities to the desired values while minimizing the higher order terms of the tune variations with the momentum deviation. Further calculations and experiments$^{6)}$ have led to the conclusion that the four sextupole currents can be deduced from the desired amount of chromatic corrections $\Delta\xi_x$, $\Delta\xi_y$ with a matrix relationship in which the matrix coefficients are fixed and determined only by the type of optics used but do not depend in practice on $\Delta\xi_x$, $\Delta\xi_y$, nor on the actual $\beta^*$'s during squeezing and storage.

Fig. 4 shows the resulting variations of the machine tunes with the momentum deviation measured during storage at 270 GeV for different $\beta^*$-values. (Note that $\xi_x \simeq \xi_y \simeq .06$ for stabilizing the beams.) For the detuned insertions, i.e. without $\beta^*$-squeezing, the non-linear variations of the tunes $Q_H$ and $Q_V$ with $\Delta p/p$ are almost negligible. When the $\beta^*$ are reduced, $Q_H$ exhibits a cubic dependence on $\Delta p/p$, which is stronger, the lower the $\beta^*$s are, but one does not observe a residual quadratic term, as it was anticipated by simulation studies$^{2)}$. Nevertheless, the chromaticity correction scheme has proven to be efficient and provides a sufficient momentum acceptance, even for the lowest $\beta^*$s of 1.0x0.5 m$^2$.

The horizontal-vertical betatron coupling increases when reducing the $\beta^*$s: almost a factor 2 was observed when going from 1.3x0.65 m$^2$ to 1.0x0.5 m$^2$. This is however easily compensated$^{7)}$ by two skew quadrupoles installed in each insertion.

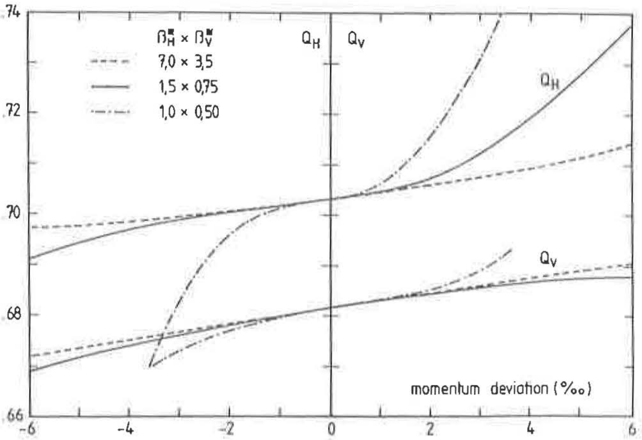

Fig. 4 Chromaticity correction of the double FDDF insertions.

As the betatron phases exhibit jumps in the insertions, third-integer stop bands induced by the sextupoles cannot be avoided: their width increases when lowering the $\beta^*$, but local compensation is being investigated.

## Other insertions

For increasing the acceptance in the LSS5 experiment, one has set up the hybrid configuration, in which the LSS4 insertion makes use of the FDDF optics with $\beta^*_x=2\beta^*_y$ as above, but with the LSS5 insertion inverted, i.e. DFFD, thus giving $\beta^*_y=2\beta^*_x$ at that crossing point. Another advantage is that the chromatic aberrations are more equally shared between the horizontal and vertical planes. The $\beta^*$-squeezing allowed to reach 1.0x.5m$^2$ in LSS4 and 0.5x1.0 m$^2$ in LSS5, but this configuration was abandoned as it led to very strong coupling which could not be corrected because of the non-availability of the skew quadrupoles at that time.

By drastically reducing the doublet strengths, it is possible to increase the $\beta^*$s in one or both insertions up to $\beta^*_x=\beta^*_y=100$ m (see Fig. 5). In this case there is no need to change the machine optics between injection and storage (no $\beta^*$ "blowing"). This high beta insertion was successfully used for elastic cross-section measurements (UA4) and has allowed to reach a minimum scattering angle of 0.4 mrad.

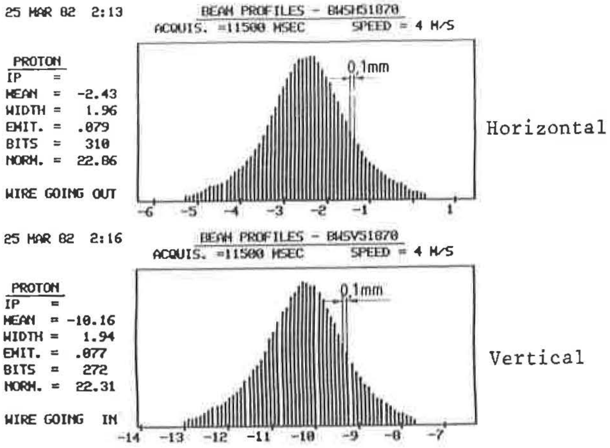

Fig. 5 Beam profiles for $\beta^*_x=\beta^*_y=100$ m at crossing point.

Other insertion configurations are possible with this layout, as for instance the antisymmetric FDFD in one LSS and DFDF in the other, leading to $\beta^*_x=\beta^*_y$ at both crossings. They were not tested however because of the good results obtained with the double FDDF and because of lack of time.

## Future improvements

Almost all p-pbar physics runs were made with the double FDDF insertions. Each time the $\beta^*$s during storage could be reduced, the luminosity increased accordingly, reaching a record of $1.6\times10^{29}$ cm$^{-2}$ s$^{-1}$ for $\beta^*_x=1.3$ m, $\beta^*_y=0.65$ m. This was achieved without any evident reduction of the luminosity lifetime, which is presently around 18 hrs. Similarly the background in the two experiments did not increase when lowering $\beta^*$.

It is therefore planned to continue running the collider with this configuration, but with some improvements. The addition of two quadrupoles, 0.7 m long, in each insertion will allow to reach $\beta^*_x=1.0$ m, $\beta^*_y=0.5$ m at 310 GeV.

This will almost double the $W^+/W^-$ and Z° production rate, but can be considered as the limit of the present layout, because of the maximum achievable gradient of the insertion quadrupoles and also of the chromatic aberrations which can be accepted by the beams.

A further luminosity gain of 25% or a higher storage energy around 350 GeV could be obtained by reducing to 21 m the free space for the experiments and by using stronger quadrupoles, but this will reduce the machine acceptance. Mini-beta schemes have also been studied[8]: the potential gain is a factor 3 to 4 in luminosity at 270 GeV, but this necessitates the use of 3.5 m long superconducting quadrupoles. The free space would also be reduced to 14 m and such schemes do not appear very attratcitve for the years to come.

## Acknowledgements

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