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AND THEIR CHROMATICITY CORRECTION

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ABSTRACT

Two low beta insertions are foreseen for the $p\bar{p}$ collider in the SPS. With the addition of some quadrupoles in the regular machine lattice several insertion configurations are possible, thus allowing a wide range of beta values at either one or both interaction points. This scheme requires a chromaticity correction by four independent families of sextupoles, whose strengths are calculated by minimizing the second order variations of the tunes with the momentum deviation. Experiments simulating the large betatron perturbations induced by the insertions have shown the feasibility of the proposed scheme which should provide a gain in luminosity by a factor greater than 35.

1. INTRODUCTION

For the proton-antiproton project in the SPS machine, low beta insertions around the interaction points are necessary to reach the design luminosity of $10^{30} \text{ cm}^{-2} \text{ s}^{-1}$. These insertions must nevertheless be compatible with the normal running of the SPS as an accelerator for fixed target physics. It was therefore decided early on that all machine quadrupoles must remain in place and that the collision points will be midway between two lattice quadrupoles, the space in between being left for experimental apparatus¹⁾. Also the two experimental areas will be located in the adjacent long straight sections 4 and 5. In spite of these constraints which suppress any symmetry and reduce the machine superperiodicity to one, one could find a flexible insertion layout whose feasibility has been demonstrated experimentally.

2. INSERTION DESIGN AND PERFORMANCES

One SPS insertion is basically made of a classical doublet on both sides of the crossing point, but each doublet component is split in two identical quadrupoles powered in series in order to get the required focussing strength at the design energy of 270 GeV (Fig. 1). Matching of the betatron and dispersion function into the regular lattice is done with the AGS computer programme²⁾ and necessitates six more quadrupoles on either side, of which five are lattice quadrupoles but with an independent power supply. This arrangement which leaves all machine quadrupoles in place is quite flexible: by simply changing the doublets' polarities and retuning the other quadrupoles, several insertion configurations with different beta values are obtained, as summarized in Table 1.

The insertion 1 gives linear beam-beam tune shifts equal in both planes and a large momentum window, whereas insertion 2 has a larger operating energy and a greater detuning factor. Note that the momentum window is defined as the variation in momentum over which both tunes vary by less than $\pm .01$ after correction of the chromaticity (see chapter 3). The maximum operating energy is limited by the maximum achievable quadrupole gradient of 21 T/m. Both insertions 1 and 2 can be squeezed down to $\beta_H^* \cdot \beta_V^* = .5 \times 1.0$ and $1.0 \times .5$ respectively, which

Table 1

Design insertions

Insertion type	1	2	3	4
Doublet configuration	FD-DF	DF-FD	FD-DF	FD-FD+DF-DF
Nominal $\beta_H^* \beta_V^*$ at crossing (mm)	2.0x1.0	1.0x2.0	70.x70.	1.0x1.0
Momentum window (‰)	± 9	± 6	± 10	± 6.5
Maximum energy (GeV)	295	315	> 340	290
Tuning range with $\beta_H^*/\beta_V^* = \text{cte}$	0.5-3.0	0.5-4.5	-	0.7-4.0

are the lowest betas compatible with the full bunch length of the beams, but this is at the expense of the momentum window and operating energy. Insertion 3 is intended for small angle scattering experiments and allows moderate "high" betas of up to 150 m, with a symmetry in beam optics extending outside the insertion doublets. If it appears impossible to keep the design emittance ratio $\epsilon_H/\epsilon_V = 2$ during beam storage³⁾, insertion 4 which is fully antisymmetric will become attractive as it allows $\beta_H^* = \beta_V^*$, and this at both crossings.

Any combination of these insertions at either one or the other or both interaction points is possible and can be tuned over a large range of Q-values. Nevertheless, Q_V must be greater than Q_H by one or two integers in order to keep the betatron phase advance in both planes close to 90° per period in the unperturbed part of the machine: the phase jump, when passing through the insertion, is larger in the vertical than in the horizontal plane. Finally, to avoid the difficult transition from the unperturbed machine to the final insertion configuration, the beams will be injected and accelerated with the insertions already on but sufficiently detuned, squeezing to the desired beta values being done at high energy, just before storage.

3. CHROMATICITY AND OTHER CORRECTIONS

Owing to the free space of ± 14.4 m left for the experiments on either side of the crossing point, the beta functions are fairly high in the doublet region: $\beta_H \approx 1320$ m in the case of Fig. 1. This induces a large chromaticity increase, whose correction poses a delicate problem, especially when they are two insertions in service, with the lowest possible β^* at the crossings.

Actually the SPS chromaticity sextupoles are grouped into one SF and one SD family, with 36 sextupoles each, regularly distributed around the ring. Apart from a lack of sextupole strength at 270 GeV, this arrangement is not suitable, as it leads to a strong quadratic dependance of the horizontal tune Q_H with the momentum deviation, as well as to steep variations of β_H^* at both interaction points: see curves a) of Figs. 2 and 3, which correspond to the insertion No. 1 of Table 1. Moreover the machine is unstable for $|\Delta p/p| \geq 2.5$ ‰ which is totally unacceptable.

This situation can only be improved by adding more 13B and 18B sextupoles and by rearranging all sextupoles into 2 SF and 2 SD families, which is the maximum possible in the SPS, because of the 90° phase advance per period. The strengths of the four families are then calculated by cancelling the horizontal and vertical chromaticities and by minimizing the following function:

$$\lambda_H \sum_n \left| \frac{a_{nH}^2}{n^2 - 4Q_H^2} \right| + \lambda_V \sum_m \left| \frac{a_{mV}^2}{m^2 - 4Q_V^2} \right| \quad (1)$$

where λ_H and λ_V are two weighting factors, a_{nH} and a_{mV} are the Fourier components of the horizontal and vertical chromatic function:

$$a_H(\phi_H) = \beta_H^2 (S\alpha_p - K) = \sum_n a_{nH} e^{in\phi_H}, \quad d\phi_H = ds/Q_H \beta_H \quad (2)$$

and similarly for a_{mV} . Each sum in (1) is related to the quadratic term of the tune variation with momentum⁴⁾, but also to the linear part of the beta variation at a given location⁵⁾. The Fourier analysis of (2) and the minimization of (1) are done by a computer programme using the AGS output. The results for the insertion No. 1 are shown by the curves b) of Figs. 2 and 3. As each insertion behaves like a delta function, it creates many spatial harmonics which cannot all be suppressed. This explains why there is some curvature left for Q_H , but it can practically be suppressed by a small current in the SPS octupoles (curve c) of Fig. 2), leading to a comfortable momentum window. The vertical plane gives no problem and although not shown, Q_V is constant to within $\pm .001$.

The relatively higher β_H^* variation in LSS4 as compared to LSS5 can be explained by tracking through the machine the mismatch of the insertions for an off-momentum particle⁶⁾. One can then show⁷⁾ that this can be partially cured by splitting the 4 sextupole families into 2 sets, one with the sextupoles in between the two interaction points, the other with the outer elements. When calculating the strengths as above but for each arc independently, one obtains the curves c) of Fig. 3. Although there is an improvement in LSS4, this scheme does not suppress the residual Q_H curvature obtained with four complete families. It will then only be used if it becomes necessary to correct third integer stop bands driven by the sextupole themselves. Because of the large jump of the vertical betatron phase when passing through insertions, the $Q_H + 2Q_V$ stop band could be worrying for the squeezed insertions, whereas the $3Q_H$ are always negligible.

4. SIMULATION EXPERIMENTS

In order to assess the sensitivity of the SPS machine to strong and localized betatron perturbations as implied by the above insertions, experiments were carried out in which the perturbations were created by two quadrupoles of equal strength and opposite polarity, placed on either side of a long straight section, near normal F quadrupoles, but at exactly one betatron wavelength distance. In this way, the β_H function exhibits peaks $\lambda/4$ and $3\lambda/4$ downstream of the first perturbing quadrupole, but remains practically unperturbed on the rest of the machine⁸⁾. To the contrary of the final insertions, this arrangement also perturbs the

dispersion function in between the two quadrupoles, but not elsewhere in the machine.

Measurement of the obtained β_H was done first by using a small additional quadrupole located near the maximum of β_H , which induces a horizontal tune shift proportional to its strength and to the β_H value at its location. The results are plotted on fig. 4 and agree very well with what can be calculated with the AGS programme ²⁾, when taking into account that the local β_H seen by the measuring quadrupole is 85% of β_H max. Note that 1000 A in the perturbing quadrupoles gives about the same β_H max as insertion 1 and that 1500 A correspond to nearly the strength of the normal lattice quadrupoles at 270 GeV. For these high currents, compensation of the local closed orbit defects in the two perturbing quadrupoles was necessary to avoid large orbit perturbations elsewhere, and hence coupling and resonances.

Storage of a bunched beam at 26 GeV was then tried with the aim of finding the highest β_H max with which one can keep the p and $\bar{p}$ bunches during the one minute injection flat bottom ³⁾, without losses. The observed limit of β_H max $\approx$ 600 m is well within the detuning range of the insertions, but in fact was due to the large dispersion at the locations of β_H max, associated with the high momentum spread of the SPS beam at 26 GeV. This restriction due to the perturbed dispersion will not exist for the final insertions.

Finally one has measured the lifetime of a beam coasting at 270 GeV as a function of the quadrupole current (fig. 4). The results agree well with the formula for multiple scattering on the residual gas ⁹⁾ and show that the aperture limitation is not in the horizontal plane where β_H is maximum, but in the vertical plane at the entrance of some bending magnets: while β_H is changed only in between the two quadrupoles, β_V is perturbed all around the machine, reaching maxima of 570 m for 1500 A at 270 GeV. Here again this effect will be suppressed for properly matched insertions.

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Fig. 1 - FD-DF INSERTION IN LSS4 AND LSS5 - BH=2.M BV=1.M

Fig. 2 - Q_H variations with momentum

- a) actual sextupoles. b) 4 families
- c) 4 families + octupoles.

Fig. 3 Relative variations of β_H (—) and β_V (---) with momentum
a) actual sextupoles. b) 4 families. c) 2 sets of 4 families

Fig4 Measurement of horizontal beta (—) and of beam lifetime (---) at 270 GeV versus the perturbing quadrupole current