THE OPTICS OF THE FAST EJECTIONS OF THE CERN PS

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Abstract

The horizontal dispersion of the PS ring is squeezed in each of the proton and pbar ejection regions simultaneously by means of two pairs of quadrupoles in order to allow the entire beam to pass through the limited aperture of the ejection channels to the SPS collider.

The resulting non-local modifications of the beta values and phase advances make this configuration very sensitive to the closed orbit distortion and the betatron tune. Non-zero chromaticities and orbit distortions introduce considerable dispersion variations across the large momentum spread of the short bunches required by the collider. This results in incoherent horizontal betatron oscillations upon their injection in the SPS ring.

A recent upgrade of the poleface winding system and the introduction of two closed orbit correction dipoles allow the correction of both the closed orbit and the chromaticity in the PS ring. These corrections increase the stability of the dispersion function, thus improving the ejection efficiency and suppressing the emittance blow-up.

1. Introduction

In the first few years (1981-1985) of the SPS collider operation the bunches were ejected from the PS using a conventional orbit and optics configuration, which limited the pbar ejection efficiencies to 85-90 % due to the large radial beam size in the small aperture of the first beam transfer quadrupole.

In 1985 a double low-dispersion scheme[1] was introduced, consisting of 4 quadrupoles in straight sections 5, 25, 49 and 69, which are pulsed at 1400 A during the ejection, producing an integrated normalized gradient of 0.024/m. The defocussing quadrupoles 5 and 69 amplify the effect of the ejection kicker. The scheme reduces the horizontal dispersion simultaneously in the proton and pbar ejection regions, thus increasing the ejection efficiencies to around 100 %. Although the horizontal beta values are equally reduced, the effect is small on the pbar ejection trajectory. The vertical betas remain unchanged (see Table I and figure 1).

Disadvantages of this configuration were the deterioration of the chromaticities (Q'_x = -15.0), which could at that time not be corrected with the existing poleface windings and power supplies) and the closed orbit distortion (50 mm peak-to-peak). A previous paper [2] proposed a number of improvements which were implemented before the start of the 1988-1989 collider run. The present report describes these improvements and more particularly their beneficial effect on the transverse emittance blow-up.

2. The present (1988) scheme

In 1988 the following improvements were applied to the optics of the PS and its ejection channels towards the SPS collider:

1. The horizontal chromaticity Q'_x at ejection was reduced to zero with 1260 A in the new figure-of-eight poleface winding[4], while keeping Q_x at 6.205.
2. the closed orbit distortion at ejection was reduced from 50 mm to 12 mm peak-to-peak, using 2 dipoles in straight sections 15 and 73.
3. after the final tests of the ring optics the TT2 and TT70 quadrupoles were adjusted to make the PS SPS dispersion matching perfect.

The evolution between 1982 and 1988 of the principal optics parameters of the PS ring central orbit and the proton and pbar ejection trajectories is presented in table I.

			1982	1985	1988
orbit distortion		[mm]	15.	50.	12.
chromaticity Q'_x			-7.0	-15.0	0.0
proton ejection septum	D_x	[m]	3.5	1.2	1.6
	β_x	[m]	17.9	8.3	9.3
	β_y	[m]	17.1	18.3	17.9
first proton transfer line quadrupole	D_x	[m]	5.6	3.4	3.6
	β_x	[m]	43.5	22.5	25.6
	β_y	[m]	7.9	6.0	6.0
pbar ejection septum	D_x	[m]	2.7	1.5	1.1
	β_x	[m]	16.9	15.2	14.4
	β_y	[m]	18.8	15.8	16.1
first pbar transfer line quadrupole	D_x	[m]	7.7	5.5	4.5
	β_x	[m]	95.3	89.7	87.4
	β_y	[m]	1.0	0.7	0.7

Table I. Evolution of the PS ejection parameters

The subsequent 1988 collider run has shown the beneficial effects of these corrections. For the first time conservation of the transverse emittances from PS ejection orbit to SPS injection orbit has been possible, which may be explained by the following considerations.

Firstly, the dispersion functions are less sensitive to operational variations around the reference situation like adjustments of tunes or bump amplitudes, and hence the transfer line matching remained valid without any adjustments during a period of several months. It is essential in this respect that the Q_x value should be above 6.20.

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Secondly, a consequence of the first 2 corrections is the fact that all orbits in the large $\Delta p/p$ range (from - 0.003 to + 0.003) of the short bunches now have the same dispersion values, which allows a correct injection into the SPS of the entire beam. As will be shown below, the 1985 - 1987 working point is estimated to have increased the normalized horizontal proton and pbar emittances by about 5 π mm.mrad, which means an initial luminosity loss of about 25 %.

3. Higher order orbit dispersion

3.1 Effect of the closed orbit distortion on the dispersion

During beam transfers from one machine to another the horizontal emittances can only be conserved if the dispersion functions of the two machines are matched to any order in $\Delta p/p$. This implies that a particle circulating without betatron oscillation on any closed orbit in the first machine is injected without oscillations in the second machine onto the closed orbit corresponding to the momentum of the particle.

In the following only the dispersion aberrations of the PS are studied, and for simplicity the SPS is assumed to be a linear machine. The $\Delta p/p$ dependence of the horizontal dispersion D_x in the PS ring and in the PS-SPS transfer lines has been studied with MAD [3] by calculating the ring dispersion function for different $\Delta p/p$ values and propagating these dispersion functions along the ejection trajectory into the transfer channel.

The PS bending magnet field is described for this purpose by a polynomial fit to recent magnetic measurements. Circulating beam ($-50 < x < +50$ mm) is calculated with multipoles up to 12-pole. The model agrees well with tune measurements. On the ejection trajectory (x up to 100 mm) multipoles up to 20-pole have to be used. The closed orbit is the sum of a nominal dispersion term $x_n(\delta)$ and a distortion term which is mainly a function of the tune Q_x and the N error strengths k_i. With

δ = $\Delta p/p$
x_n = the orbit in the absence of distortion
D_n = the dispersion in the absence of distortion
k_i = the strength of the i-th of N orbit kicks
f_i = the effect of 1 mrad at kick i on the orbit
f'_i = its derivative with respect to Q_x

the modified orbit and dispersion may be written:

$$x(\delta) = x_n(\delta) + \Sigma\, k_i \,.\, f_i(Q_x) \qquad i = 1, N$$

$$D(\delta) = D_n(\delta) + \Sigma\, k_i \,.\, Q'_x \,.\, f'_i(Q_x) + \ldots$$

The $\Delta p/p$ derivative of the dispersion contains terms which are quadratic in Q'_x:

$$k_i \,.\, (Q'_x)^2 \,.\, f''_i(Q_x)$$

which shows the importance of the chromaticity correction in the presence of a large orbit distortion, as was the case at the PS. The main consequences of these aberrations are an apparent loss of aperture at ejection and a transverse emittance blow-up at injection in the SPS. The 1988 corrections in the PS ring reduced the k_i values and cancelled Q'_x, resulting in a considerable decrease of the higher order effects.

3.2 Emittance blow-up due to higher order dispersion

The horizontal blow-up at injection in the SPS caused by the multipolar orbit mismatch between the PS and the SPS may be used as a measure of the higher order aberrations. The two-sigma emittance of a particle oscillating around a reference trajectory is given by 2 π times the Courant-Snyder invariant:

$$2\pi \,.\, (x^2 + z^2) \,/\, \beta$$

where $z = \alpha.x + \beta.x'$, and x and x' are the position and angle of the oscillation (particle trajectory - reference trajectory).
If evaluated in the PS-SPS proton or pbar transfer line downstream of all non-linearities, and assuming the SPS to be a linear machine, this quantity is equal to the radial emittance of the particle after injection in the SPS onto an orbit which is matched to the above mentioned reference trajectory. In the following x denotes the difference between a trajectory matched to a PS closed orbit and the trajectory matched to the SPS closed orbit with the same $\Delta p/p$ value. The emittance increase of a beam having a non-zero initial emittance in the PS is equal to the above expression averaged over all particles.

The effect of an injection damper or injection steering will be to replace x and x' by respectively $x - \langle x\rangle$ and $x' - \langle x'\rangle$, and hence the emittance increase becomes:

$$\Delta E = 2\pi.(\langle x^2\rangle+\langle z^2\rangle-\langle x\rangle^2-\langle z\rangle^2)/\beta$$

Two sets of polynomial coefficients a_0, a_1, ... and b_0, b_1, ... describe the $\Delta p/p$ dependence of x and z. Their values were obtained by least square fits to orbit coordinates calculated by the MAD program. They are conveniently used to express the emittance increase in terms of the momenta of the $\Delta p/p$ distribution:

$$x = \Sigma\, a_n \,.\, \delta^n \qquad n = 0, 1, 2, \ldots$$
$$z = \Sigma\, b_n \,.\, \delta^n$$

$$\langle x^2\rangle = \Sigma\, a_k \,.\, a_l \,.\, \langle\delta^{k+l}\rangle \qquad k,l = 0, 1, 2, \ldots$$
$$\langle z^2\rangle = \Sigma\, b_k \,.\, b_l \,.\, \langle\delta^{k+l}\rangle$$

$$\langle x\rangle^2 = \Sigma\, a_k \,.\, a_l \,.\, \langle\delta^k\rangle \,.\, \langle\delta^l\rangle$$
$$\langle z\rangle^2 = \Sigma\, b_k \,.\, b_l \,.\, \langle\delta^k\rangle \,.\, \langle\delta^l\rangle$$

$$\Delta E.\beta/(2\pi) = \Sigma(a_k.a_l + b_k.b_l).(\langle\delta^{k+l}\rangle - \langle\delta^k\rangle.\langle\delta^l\rangle)$$

Since $\langle\delta^n\rangle = 1$ for $n = 0$ there is no contribution from terms with $k = 0$ or $l = 0$. This reflects the action of the injection damper: the position of the beam in the transfer line has no effect on the final result.

If the linear dispersion matching is perfect, the trajectory matched to the PS and the corresponding trajectory matched to the SPS closed orbit have the same linear $\Delta p/p$ dependence, and hence the coefficients a_1 and b_1 are zero. In this case the summation may therefore start at $k = l = 2$. In the same way a_2 and b_2 might be cancelled by installing matching sextupoles in the transfer lines.

This emittance blow-up has been computed for gaussian, parabolic and rectangular $\Delta p/p$ distributions. The exact distribution is not precisely known, but it is believed to be intermediate between rectangular and parabolic. As the blow-up values for these 2 cases are rather similar, a rectangular $\Delta p/p$ distribution between - 0.003 and + 0.003 will be assumed in the following.

3.3 Results of the blow-up calculation

Six cases were studied (labeled A to F): 3 values of Q' with both corrected and uncorrected orbits. Only 2 of these working points have been in operation: working point C was used from 1985 to 1987, and F has been in use since September 1988. The corresponding results will be presented as 2 by 3 matrices.

Table II shows for each of these cases the estimated increase of the normalized horizontal emittances in units of π mm.mrad (the nominal horizontal proton and pbar emittances in the PS are 9 π). The PS ring box considers only the ring non-linearities, the transfer line boxes take into account the non-linearities of both the ring field and the stray field at ejection.

uncorrected orbit 50 mm p-to-p	A	C	E
corrected orbit 12 mm p-to-p	B	D	F
Q'_x :	-30.	-15.	0.

PS ring

16.4	4.4	0.1
4.3	1.7	0.1

proton transfer line			pbar transfer line		
18.1	5.8	0.1	17.9	4.2	0.2
3.2	1.8	0.2	6.5	2.5	0.1

Table II. Horizontal emittance increase [π mm.mrad] due to higher order dispersion mismatch

4. Conclusions

The quadrupole scheme used since 1985 for fast proton and pbar ejection from the PS reduces the dispersion in the ejection channels by about 40 % and to a smaller extent the beta values, which results in an apparent aperture gain of about 20 mm. The losses in the first transfer line quadrupoles, which were the main bottleneck during the first few years of the SPS collider operation, have disappeared. The large chromaticity and orbit distortion introduced by the scheme were corrected in 1988.

The 1988 corrections linearize the ring dispersion, which makes it possible to conserve the horizontal emittance during the transfer from PS to SPS. Table II shows that, starting from the 1985 working point C, both the closed orbit correction and the chromaticity correction decrease the blow-up. Correcting only the chromaticity would produce an optical configuration (E) which is still sensitive to variations of the chromaticity, a parameter which is difficult to monitor continuously. On the other hand, correction of the closed orbit only would leave the optics (D) sensitive to the inevitable day to day adjustments of ejection bumps etc.

The blow up values presented in the PS ring box of table II are close to the values in the transfer line boxes. This suggests that the PS ring is the main source of non-linearities, and not the stray fields at ejection as was previously thought.

The PS ejection optics configuration now satisfies the most important requirements:

- no beam loss at ejection from the PS
- no transverse emittance blow-up in the PS-SPS transfer process
- the quality of the matching does not depend critically on PS machine settings

The 1988 configuration is in operation on the proton and pbar cycles used for the SPS collider, and on the high intensity proton cycles used for antiproton production.

5. References

[1] J. Boillot, T. Risselada, "Réduction de α_p et β_x et effet de kick enhancement", PS/OP/PSR/Note 84-5

[2] T. Risselada, "Analysis of the optics of the fast proton and pbar ejections from ss 16 and 58 at the CERN PS and proposed improvements", CERN/PS/87-71.

[3] F.C. Iselin, "The MAD program", CERN/LEP-TH/88-38.

[4] Y. Baconnier, "Proposal for a new figure-of-eight loop", PS/PSR/Note 84-6.

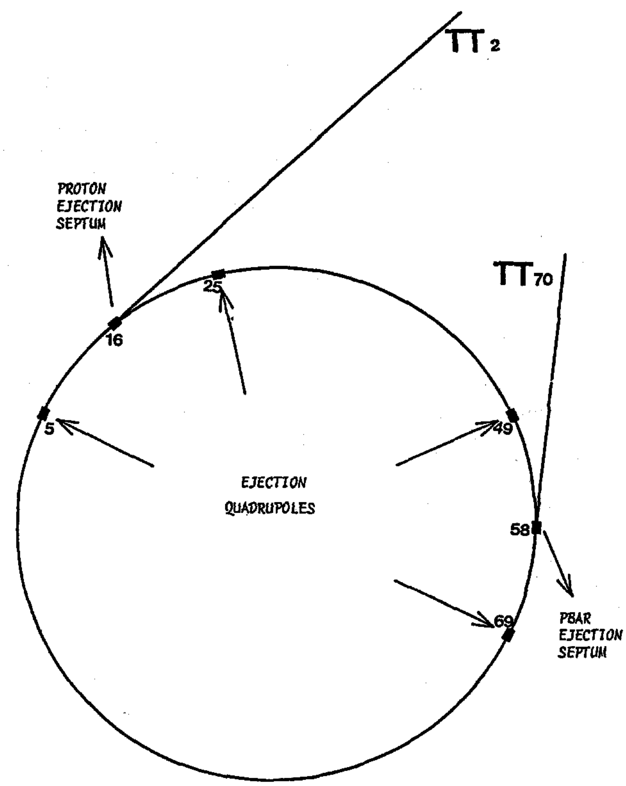

FIGURE 1

LAYOUT OF THE PS RING AND THE TRANSFER LINES TO THE SPS COLLIDER