MISMATCH MEASUREMENTS

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Abstract

The tight emittance budget imposed to the injector chain in the LHC era and the increasing request for high intensity beams for fixed-target physics demand for a careful monitoring of the emittance and of the mismatch at injection during setting-up and on-line during operation. The methods applied to measure emittance and injection mismatch are discussed with particular emphasis to those applied in the SPS.

1 MISMATCH: CAUSES AND EFFECTS

Mismatch is every deviation of the optics, as seen by the beam, with respect to the model. Mismatch in the Twiss parameters (α and β) as well as in dispersion and its derivative (D and D') might occur. This can be represented in the normalised phase space (X_{norm}, X'_{norm}) where:

$$X_{norm} = \frac{x}{\sqrt{\beta}}$$

$$X'_{norm} = \frac{\alpha}{\sqrt{\beta}} x + \sqrt{\beta}\, x'$$

$$x' = \frac{dx}{ds} \quad \text{(s = longitudinal coordinate)}$$

$$X'_{norm} = \frac{dX_{norm}}{d\phi} \quad (\phi = \text{phase})$$

In Fig. 1 a momentum slice of a beam corresponding to a momentum deviation $\Delta p/p$ with respect to the reference momentum p is considered. Equi-density contours for a matched beam are circles. The equi-density contours of an unmatched beam with betatron mismatch are ellipses. The areas of the circular and elliptical contours are the same for the matched or the unmatched beam if the same density level is considered. Dispersion mismatch introduces an offset ($\Delta D_{norm}\ \Delta p/p$, $\Delta D'_{norm}\ \Delta p/p$) at injection.

Mismatch might originate from hardware faults (e.g. an inter-turn short circuit in a quadrupole coil) or hardware tolerances (e.g. accuracy of the alignment, of the excitation current, of the calibration curves, etc.). This kind of errors can be detected by measuring the elements of the transfer matrix between a reference point, upstream of the location of the hardware error, and any other beam position monitor downstream. Another important source of error is due to the uncertainties on the initial conditions (α, β, D and D') at the beginning of the transfer line and their dependence on the extraction parameters. This is the case of the injection transfer line from PS to the SPS. The presence of important stray fields from the PS combined magnets makes the modelling of the extraction and the determination of the initial conditions quite complex [1]. Any difference between the momentum of the beam and the momentum control value for which the settings of the elements of the line are calculated might also induce a non-negligible mismatch at injection.

Mismatch results in emittance blow-up after injection in the ring in fact the 'quadrupolar' oscillations that it induces cannot be handled by the transverse feedback. This can only damp injection oscillations occurring as a result of dispersion mismatch in the presence of momentum fluctuations. This has the effect of reducing the margin available for injection errors due to other sources. Mismatch implies a different evolution of the beam size as compared to that provided by the expected optical model. That might determine aperture problems in the line and in the ring. The latter can be considered as a continuation of the transfer line as far as the behaviour of the beam is concerned, at least for the first few turns.

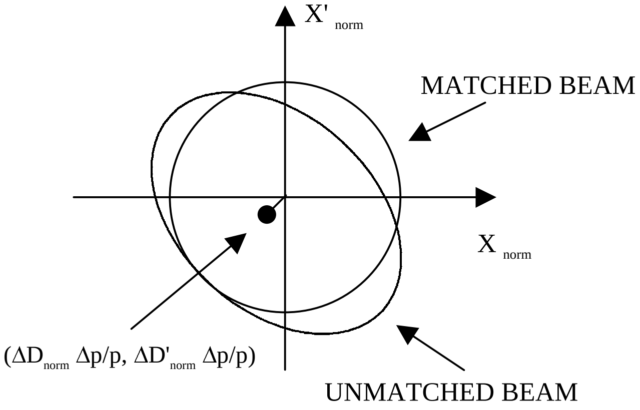


Figure 1: Equi-density contours for a matched and an unmatched beam (betatron and dispersion mismatch) in normalised phase space.

2 GEOMETRIC BLOW-UP VS. BLOW-UP AFTER FILAMENTATION

2.1 Betatron mismatch

The unmatched beam rotates in phase space and after several turns the rotational symmetry will be recovered (filamentation) due to the presence of non-linear fields (space-charge, non-linear magnetic elements, stray fields, etc.) and to second order effects. These introduce non-linear terms in the equation of motion and therefore a dependence of the betatron frequency on the amplitude of the betatron oscillations. In a transfer line or in the first turns in a circular machine filamentation is negligible and geometrical blow-up must be considered for aperture considerations. The geometrical blow-up is given by the ratio A_{gb}/A_0 where A_{gb} is the area of the circle of minimum radius including the ellipse of the mismatched beam and A_0 is the area of the circle enclosing the matched beam (see Fig. 2).

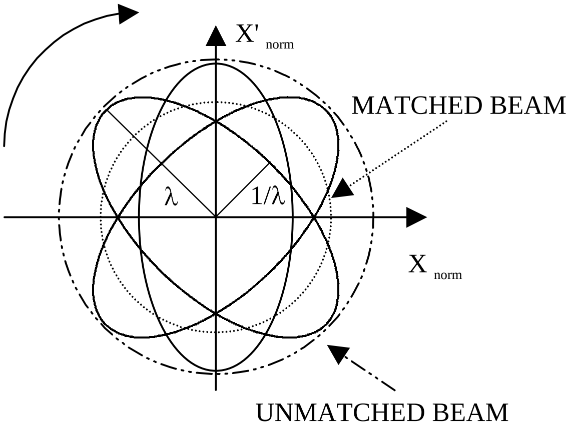


Figure 2: Equi-density contours for a matched and an unmatched beam (betatron mismatch) in normalised phase space.

If the equi-density circle representing the matched beam has unitary radius the corresponding unmatched ellipse will have a major axis of length λ and a minor axis of length 1/λ. The geometrical blow-up is [2]:

$$\text{Geometrical blow-up} = \lambda^2 = H + \sqrt{H^2 - 1} \tag{1}$$

$$H = \frac{1}{2}\left[\frac{\beta_0}{\beta_m} + \left(\alpha_0 - \alpha_m \frac{\beta_0}{\beta_m}\right)^2 \frac{\beta_m}{\beta_0} + \frac{\beta_m}{\beta_0}\right]$$

where (α_0,β_0) are the expected Twiss parameters and (α_m,β_m) are the measured Twiss parameters.

Filamentation occurring after injection in a ring smears out the azimuthal dependence of the distribution of the unmatched beam. A complete randomisation of the phase can be assumed after several turns with a consequent reduction of the r.m.s. beam size [3]. The blow-up after filamentation is therefore always smaller then the geometrical blow-up and is given by [2]:

$$\text{Blow-up after filamentation} = H = \frac{1}{2}\left(\lambda^2 + \frac{1}{\lambda^2}\right)$$

where H has been defined in Eq. 1.

2.2 *Dispersion mismatch*

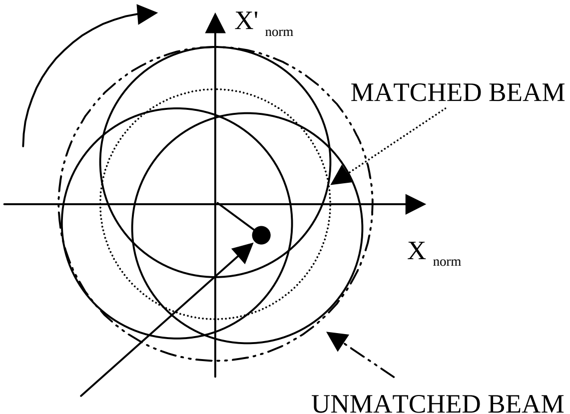
In the presence of dispersion mismatch every momentum slice of the beam will have an offset (ΔD_{norm} $\Delta p/p$, $\Delta D'_{norm}$ $\Delta p/p$) with respect to the beam with nominal momentum (see Fig. 3). ΔD_{norm} and $\Delta D'_{norm}$ are the errors in the normalised dispersion and its derivative and $\Delta p/p$ is the deviation from the nominal momentum. D_{norm} and D'_{norm} are defined as follows:

$$D_{norm} = \frac{D}{\sqrt{\beta}}$$

$$D'_{norm} = \frac{\alpha}{\sqrt{\beta}} D + \sqrt{\beta}\, D'$$

$$D' = \frac{dD}{ds} \quad \text{(s = longitudinal coordinate)}$$

$$D'_{norm} = \frac{dD_{norm}}{d\phi} \quad (\phi = \text{phase})$$



INJECTION OFFSET
($\Delta D_{norm}\Delta p/p$, $\Delta D_{norm}\Delta p/p$)

Figure 3: Equi-density contours for a matched beam and a momentum slice of an unmatched beam (dispersion mismatch) in normalised phase space.

The geometrical blow-up will be given by the ratio A_{gb}/A_0 (A_{gb} and A_0 have been defined previously) that can be expressed in terms of the errors in the dispersion and its derivative [4]:

$$\text{Geometrical blow-up} = \left(1 + \sqrt{2(J-1)}\right)^2$$

$$J = 1 + \frac{\Delta D_{norm}^2 + \Delta D'^2_{norm}}{2\varepsilon_{r.m.s.}}\left(\frac{\Delta p}{p}\right)^2_{r.m.s.} = \tag{2}$$

$$= 1 + \frac{\Delta D^2 + \left(\Delta D'\beta_0 + \Delta D\alpha_0\right)^2}{2\varepsilon_{r.m.s.}\beta_0}\left(\frac{\Delta p}{p}\right)^2_{r.m.s.}$$

The blow-up after filamentation is smaller than the geometrical blow-up because of the phase randomisation generated by filamentation and it is given by [2][4]:

$$\text{Blow-up after filamentation} = J$$

where J has been defined in Eq. 2.

It is important to observe the quadratic dependence of the blow-up on the momentum spread of the beam and the inverse dependence on the transverse emittance. This is unfavourable for the LHC type beam due to its small transverse emittance and large momentum spread.

The unmatched beam will keep its initial distribution for several turns in phase space, therefore, as can be inferred from Fig. 3, the geometrical blow-up should be quoted for considerations related to the physical aperture of the elements of the transfer lines and of the machine. On the other hand blow-up after filamentation, that takes into account the modifications to the beam distribution due to filamentation after injection, should be quoted for performance considerations related to emittance preservation.

3 HOW DO WE MEASURE MISMATCH?

A qualitative method to determine the mismatch at injection in a ring consists in measuring the emittance of the circulating beam after injection (e.g. with a wire scanner) and in comparing it with that measured in the transfer line (e.g. with 3 beam profile monitors). This method does not provide any information about the source (dispersion or betatron mismatch) of the blow-up and lacks of precision because of the systematic errors inevitably introduced when comparing measurements performed with different devices. Furthermore the two measurements must be performed in different cycles because of the semi-destructive nature of the profile measurements in the line.

3.1 Dispersion mismatch

It can be determined by measuring the dispersion in the injection line and in the first turn in the SPS ring, considered as a continuation of the transfer line. The measurement of the dispersion is performed by varying the momentum of the beam extracted from PS in steps and by recording the transverse displacement at each available beam position monitor (see Fig. 4).

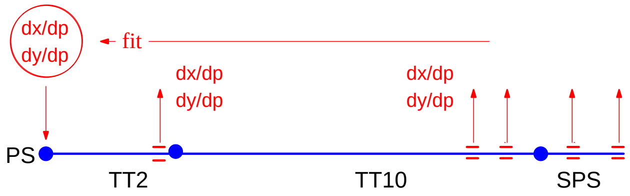


Figure 4. Schematic representation of the dispersion measurement.

The momentum offset Δp with respect to the reference momentum p is calculated by measuring the change in radial position ΔR of the beam in its first turn and by applying the relation:

$$\frac{\Delta p}{p} = \frac{1}{\alpha_p}\frac{\Delta R}{R}$$

That requires the knowledge of the radius R of the SPS machine and its momentum compaction factor α_p [5].

The measurements of the beam displacement as a function of the momentum offset are fitted to a straight line for each beam position monitor and the slope dx/dp is obtained. A three-parameter ($(dx/dp)_m$, $(dx'/dp)_m$, δ) least-squares fit of the calculated $(dx/dp)_i$ by the function

$$C_i\left(\frac{dx}{dp}\right)_m + S_i\left(\frac{dx'}{dp}\right)_m + \xi_i\,\delta$$

is performed. C_i, S_i, ξ_i are the elements of the transfer matrix:

$$\begin{bmatrix} C & S & \xi \\ C' & S' & \xi' \\ 0 & 0 & 1 \end{bmatrix} \qquad (3)$$

from the measurement point m to the i^th^ beam position monitor (ξ and ξ' are the dispersion and its derivative for null dispersion and dispersion derivative at the beginning of the line) and δ is a calibration factor to correct for possible scaling errors in the measurement of the momentum offset.

As a result of the fit we get:

$$D_m^{fit} = \frac{(dx/dp)_m^{fit}}{\delta^{fit}} \qquad D'^{fit}_m = \frac{(dx'/dp)_m^{fit}}{\delta^{fit}}$$

at any point in the line if the transfer matrix (3) from the measurement point to any beam position monitor is known. Normally this is the case for the injection transfer line and the SPS ring with the exception of the beginning of the line that is affected by the stray fields of the combined function magnets of the PS ring.

The presented method takes advantage of the large number of beam position monitors in the SPS ring and provides an immediate picture of the mismatch with respect to the dispersion in the ring.

3.2 Betatron mismatch

Betatron mismatch can be determined by measuring the beam size at three or more beam profile monitors per plane if the momentum spread of the beam, the dispersion at the monitors and the transfer matrices between any pair of monitors are known [2][6]. The typical phase advance between two consecutive beam profile monitors is about 60^0. From this measurement the emittance ε of the beam and the Twiss parameters α and β at any of the beam profile monitors can be derived. The Twiss parameters can be inferred at any other point in the line if the transfer matrix to any of the monitors is known.

This method is generally applied to transfer lines, once the dispersion has been measured, but it is also valid for circular machines at injection. It is sufficient to have a beam profile monitor integrating over less than one turn for few turns (at least three) after injection. The Twiss parameters and the beam emittance can be calculated if the dispersion is known at the monitor. In the SPS such a beam profile monitor (based on optical transition radiation -OTR- emitted by the beam traversing a thin Titanium screen) is installed, the integration is performed in less than 1 turn every 8 turns [7][8]. Dispersion in a ring is normally well known due to the periodicity of the solution and the precise knowledge of the strength of the dipoles and quadrupoles. Furthermore it can be easily measured by changing the momentum of the captured beam by changing the RF capture frequency.

3.3 Dispersion and Betatron mismatch

The availability of a larger number of beam profile monitors gives the possibility to measure additional parameters. With 5 beam profile monitors per plane it is possible to measure ε, α β, the dispersion D and its derivative D' at one of the monitors if the momentum spread $\Delta p/p$ of the beam and the transfer matrices between any pair of monitors are known. In that case [9]:

$$D = \Sigma'_4 \Big/ \left(\frac{\Delta p}{p}\right)^2 \qquad D' = \Sigma'_5 \Big/ \left(\frac{\Delta p}{p}\right)^2$$

$$\alpha = \frac{B}{\sqrt{AC - B^2}} \qquad \beta = \frac{A}{\sqrt{AC - B^2}} \qquad \varepsilon = \sqrt{AC - B^2}$$

where

$$A = \Sigma'_1 - \Sigma'^2_4 \Big/ \left(\frac{\Delta p}{p}\right)^2 \qquad B = \Sigma'_2 + \Sigma'_4 \, \Sigma'_5 \Big/ \left(\frac{\Delta p}{p}\right)^2$$

$$C = \Sigma'_3 - \Sigma'^2_5 \Big/ \left(\frac{\Delta p}{p}\right)^2 \qquad \underline{\Sigma}' = \underline{M}^{-1} \underline{\Sigma}$$

$$\underline{M} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ C_2^2 & -2C_2S_2 & S_2^2 & 2C_2\xi_2 & 2S_2\xi_2 \\ C_3^2 & -2C_3S_3 & S_3^2 & 2C_3\xi_3 & 2S_3\xi_3 \\ C_4^2 & -2C_4S_4 & S_4^2 & 2C_4\xi_4 & 2S_4\xi_4 \\ C_5^2 & -2C_5S_5 & S_5^2 & 2C_5\xi_5 & 2S_5\xi_5 \end{bmatrix}$$

$$\underline{\Sigma} = \begin{bmatrix} \sigma_1^2 \\ \sigma_2^2 - \xi_2^2 \left(\frac{\Delta p}{p}\right)^2 \\ \sigma_3^2 - \xi_3^2 \left(\frac{\Delta p}{p}\right)^2 \\ \sigma_4^2 - \xi_4^2 \left(\frac{\Delta p}{p}\right)^2 \\ \sigma_5^2 - \xi_5^2 \left(\frac{\Delta p}{p}\right)^2 \end{bmatrix}$$

where C_i, S_i, ξ_i are the elements of the transfer matrix (3) from the first to the i^{th} monitor.

In order to invert the matrix $\underline{M}$ at least two of the beam profiles monitors must be located in a dispersive region. This method is applicable to transfer lines once the momentum spread has been measured. Under the same condition it can also be used for a circular machine at injection if a beam profile monitor integrating over less than one turn and for at least five turns is available. In the case of a circular machine only the horizontal dispersion and its derivative can be measured because no significant vertical dispersion is normally present.

The momentum spread of the beam can also be measured with the multi-profile analysis method whenever 6 beam profile monitors are available. A redundancy in the number of beam profile measurements with respect to the number of unknown is desirable in order to minimise the errors in the measurement by considering an average of the results obtained with different combinations of monitors.

4 PRECISION OF THE MEAUSREMENTS AND (PRESENT) LIMITATIONS

The measurements of the optical parameters of the injection transfer line TT2-TT10 performed in the last 2 years [10] show that a precision of the order of 10 % can be achieved in the determination of α β, D and D' by applying the methods described in 3.1 and 3.2 and using SEM grids as beam profile monitors.

Based on this assumption the error in the geometric blow-up and on the blow-up after filamentation have been estimated considering the mismatch originating from the discrepancy between the beam momentum and its control variable (see Section 1). The results of this extrapolation for the LHC beam (r.m.s. normalised emittance $\varepsilon_{x,y}$=3 μm, $\Delta p/p$ (r.m.s.) $=10^{-3}$) for the optics presently installed in the injection line [10] are shown in Fig. 5 for the betatron mismatch and Fig. 6 for the dispersion mismatch.

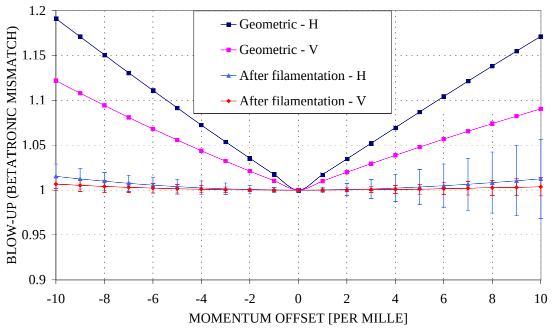


Figure 5. Geometrical blow-up and blow-up after filamentation as a function of the relative difference between the beam momentum and its control value (betatron mismatch). The errors in the blow-up after filamentation have been estimated for a relative error of 10% in the measured values of the Twiss parameters α and β. The error bars for the geometrical blow-up are not shown because they are very large and would make the plot difficult to read.

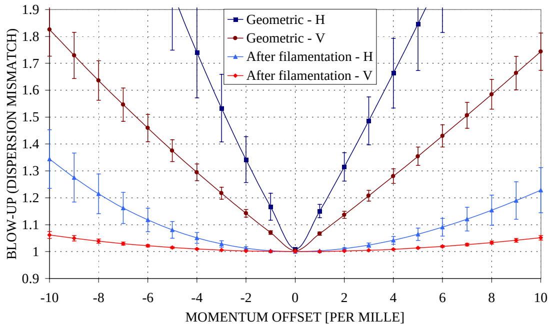


Figure 6. Geometrical blow-up and blow-up after filamentation as a function of the relative difference between the beam momentum and its control value. The errors have been estimated for a relative error of 10% in the measured values of the dispersion and its derivative.

The evolution of α β, D and D' as a function of the relative difference between the beam momentum and its control value have been calculated with MAD [11] by assuming that only the quadrupoles are set to the 'wrong' momentum. The momentum offset in the dipoles is corrected for when the beam is steered through the line.

The following considerations can be drawn from Figures 5 and 6:

- Geometric blow-up is much larger than the corresponding value after filamentation as already anticipated in Section 2.
- For the LHC beam the contribution to blow-up due to dispersion mismatch dominates the contribution originating from betatron mismatch.
- A precision of about 5% in the measurement of the blow-up originating from betatron and dispersion mismatch seems to be feasible. Better precision seems to be difficult to achieve, particularly for the dispersion mismatch.
- The mismatch originating from errors in the momentum control value for the transfer line provide a significant contribution to emittance blow-up at injection. This is particularly important for the lead ion beam for fixed-target physics and for LHC. Here the control of the beam momentum before and after the stripper is important in order to minimise blow-up. The energy loss in the stripper might in fact originate coupling between the longitudinal and transverse plane if the dispersion and its derivative are not zero at that position.

From the present experience it seems convenient to allocate an emittance blow-up at injection not smaller than 5%. All the above measurements and in particular the measurement of the betatron mismatch rely on the absence of badly kicked bunches that could distort the overall profile of the beam. *Any scheme aiming at minimising position or angle offsets between the bunches of the injected beam is highly desirable* [12].

A gain in precision in the measurement of the blow-up resulting by betatron mismatch might be achieved by the systematic use of OTR screens read by CCD camera for which more experience is needed. The OTR matching monitor installed in the SPS [7][8] allows to distinguish oscillations in size of the injected beam with a precision of a few percents. Nevertheless this does not allow to disentangle between the contributions originating by betatron and dispersion mismatch which, for opportune combinations, might only induce small beam size oscillations due to the fact that both generate beam-size oscillations with the same frequency. The method described in Section 3.1 is for the moment the only one allowing to measure dispersion mismatch with good precision and it is defining the baseline for the precision of the measurement of the mismatch and its effect (blow-up). Dispersion measurement via the multi-profile method, though very simple, has not yet achieved reasonable precision, this was of the order of 30-50% in the first tests performed in the SPS injection line [9].

The present limitation to the extensive use of OTR monitors for beam profile measurement in the injection line is the insufficient acceptance of the optics system. This has the effect of 'cutting' the tails of the beam profiles. SL/BI has planned to improve the situation during the present shut-down.

The OTR matching monitor installed in the SPS provides an acquisition of the average (over all bunches) beam profile of the circulating batch every 8 turns due to intrinsic hardware limitations (image intensifier). At least 17 turns are required to provide a measurement of the betatron mismatch (see Section 3.2) therefore the blow-up due to the multiple passage of the beam through the thin Ti screen is not negligible and affect the precision of the measurement of the beam size oscillation. A method consisting in combining measurements performed in different cycles and displaced by 1 turn has been tested but its precision is strongly dependent on the stability of the emittance of the beam extracted from PS. The measurements performed up to date were conducted with low intensity beams, the higher intensity of the nominal LHC beam might provide enough signal for the beam profile measurement without the need of image intensification, in that case the minimum time between two consecutive readings might be significantly reduced.

The measurement of all the optical parameters of the injection line by means of multi-profile analysis was not possible in the vertical plane due to the location of all the beam profile monitors in non-dispersive regions. The availability in 1999 of an additional OTR screen in a dispersive region in TT10 should eliminate the above constraint. The increasing number of beam profile monitors and their increasing resolution should help in reducing the errors in the measurements performed with this method.

All the methods discussed for the measurement of the betatron mismatch are destructive or semi-destructive. At present no experience has been gained with other non - destructive devices such as: gas scintillation beam profile monitor, rest-gas beam-profile monitor, quadrupolar pick-up.

5 POSSIBLE MEASUREMENT PROCEDURES FOR THE SPS

For the LHC beam, but in general for all the fixed-target beams, it will be very important to measure and (if necessary) correct the mismatch at injection in the SPS. Based on the experience gained in the last 2 years procedures for the measurement of the betatron and dispersion mismatch are proposed below. Normally the stability of the extraction conditions is good and the observed fluctuations in the mismatch parameters are comparable with the precision of the measurement. It is therefore reasonable to assume that a precise measurement of the mismatch will be necessary during setting-up and only parasitic and less precise monitoring of the injection conditions will be required regularly during normal running.

5.1 Procedure for the setting-up phase (or in case of problems)

The proposed procedure for the setting-up phase includes the following steps:

- Measurement of the momentum and momentum spread of the beam.
- Adjustment of the momentum control value for the calculation of the currents of the power converters of the injection transfer line.
- Measurement of the dispersion mismatch by changing the momentum of the beam.
- Measurement of the betatron mismatch in the ring or in the transfer line.
- Correction (if necessary) and reiteration of the measurement.
- Comparison of the emittance in the injection line with that of the circulating beam for reference.

5.2 Procedure for monitoring during running

- Comparison of the emittance in the injection line with that of the circulating beam. The measured blow-up should be compared with that measured during setting-up for optimum matching (see last point of Section 5.1).
- Measurement of the momentum spread of the beam.
- Measurement of the dispersion and betatron mismatch with the multi-profile method.
- If a blow-up or mismatch is observed the procedure for the start-up should be applied.

6 CONCLUSIONS

Mismatch between the injection transfer line and the SPS ring might originate from hardware errors, modifications of the extraction conditions from the PS or from errors in the momentum control value for the transfer line. Mismatch might generate aperture problems in the injection line and in the SPS ring, in that respect the geometrical blow-up must be considered to evaluate the impact on the required physical aperture. Mismatch also induces emittance blow-up at injection due to filamentation, this phenomenon affects machine performances and is quantified by the blow-up after filamentation. Dispersion mismatch is the most critical source of blow-up due to injection mismatch for the LHC beam because of its small emittance and its relatively large momentum spread. The accuracy in the correction of the mismatch will depend on the precision of its measurement (in particular for the dispersion mismatch. The measurements performed extensively in 1997 and 1998 for different optics indicate that a precision of about 10% should be achievable in the mismatch measurement with the present techniques. This corresponds to a precision of about 5% in the measurement of the blow-up after filamentation. It seems therefore advisable to allow for emittance blow-up of the order of 5% for injection mismatch (betatron and dispersion). The achievement of this precision is conditioned to the absence of parasitic bunches having non-nominal positions, therefore any scheme aiming at their suppression or at the minimisation of their perturbation is highly desired. Easiness, reliability and precision of the measurements of the mismatch might be enhanced by the extensive use of optical transition radiation beam profile monitors and by the development of non-destructive techniques to measure beam profiles (gas scintillation monitor, rest-gas monitor, quadrupolar pick-up) on a turn-by-turn basis in the SPS. Experience in that direction is therefore mandatory. Based on the present experience possible procedures for betatron and dispersion measurement and monitoring have been proposed.

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