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PRESERVATION OF THE TRANSVERSE EMITTANCE OF THE LHC BEAM IN THE SPS

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Preserving the emittance during the injection process in an ideal accelerator and transfer line is trivial for beams which are transversely stable (eventually with feedback). To approach as much as possible the ideal state with a real machine it is sufficient, but not trivial, to measure the deviations from that state and correct them. The survey of the SPS and its injection line in view of transverse emittance conservation leads essentially to a demand for efficient instrumentation and implementation of specific measuring strategies.

Keywords: Emittance growth; Injection

1. INTRODUCTION

The LHC imposes a very tight transverse emittance blow-up budget. The SPS has to deliver a beam with at most a normalised transverse emittance of 3.5 μrad m with a 3 μrad m beam ejected from the PS. The maximum blow-up of 0.5 μrad m is split between static (0.15 μrad m) and dynamic effects (0.35 μrad m).

The SPS was designed and constructed more than 20 years ago to provide high energy high intensity proton beams for fixed target physics. The machine and its injection line were well adapted to handle low energy beams with small momentum spread, important transverse emittance and moderate bunch intensity. Keeping beam losses

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to a low level was the main issue of the emittance preservation of fixed target beams. The LHC beam will have *small* transverse emittance, *large* momentum spread and *high* bunch intensity. The following sections will discuss the ways and means to satisfy the emittance requirements with these beam properties.

2. TRAJECTORY STEERING IN THE BEAM TRANSFER AND MATCHING OF TRAJECTORY TO CLOSED ORBIT IN SPS

2.1. Transfer PS to SPS

The transfer line TT10 that joins the PS with the SPS was designed for a low momentum (10 GeV/c) beam with small relative momentum spread (rms $\delta p/p = 0.00025$)[1]. The betatronic functions in the line are comparable with those in the SPS machine with maxima in the order of 120 m. Two types of optics are available. First the typical fixed target optics in which a transverse phase oscillation exchange takes place to put the smallest emittance (horizontal due to beam slicing in continuous extraction) in the vertical plane where the SPS aperture is most restrictive. Second there is the fast ejection optics where this phase gymnastics is simply suppressed. Steering and beam position monitoring is adequate near the beginning and the end of the line where the main trajectory changes take place. The nominal trajectory is straight in between. The mechanical half-aperture is 60 mm, largely sufficient for the fixed target beam for which this installation was intended. The LHC type of beam, however, will have higher momentum (26 GeV/c) which is good, but also much higher relative momentum spread ($\delta p/p = 0.001$). This may not pass without problem. Indeed, the dispersion in TT10 reaches repeatedly values of 5 m vertically and 6 m horizontally in both the well instrumented zone and in the halfway straight section. The combination of large dispersion and large momentum spread demands accurate beam positioning in the aperture. To achieve this it will be necessary to equip the straight section with additional monitoring and beam steering elements. Also some high dispersion places near the SPS need to be equipped as well.

2.2. Injection Optimisation

The transverse feedback will damp injection oscillations. However it will only be able to handle this up to a maximum amplitude. If the injection amplitude is larger then the emittance blow-up will be out of tolerance. The task of the static injection oscillation is to minimise the errors to within the acceptance of the transverse feedback. This operation only needs to be done occasionally. However it will be necessary to check the state of the injection errors at each injection. This check can either be done in the wide band observation branch of the transverse feedback, either via one or several orbit monitors where the betatron oscillation is obtained by subtraction of trajectory and orbit (available in that form in the feedback). If the second solution is chosen then it may be interesting to make this observation station wide band as well. This allows the surveillance of single bunches which is a precious diagnostic tool in case of fast timing errors in the ejection/injection process.

3. BEAM SIZE MATCHING

The optics of circular machines and transfer lines can be computed rather exactly since the magnetic elements are well known and of high harmonic purity. The PS, SPS and TT10 are no exception to this. This situation changes when the beam is forced into extreme trajectories for extraction of the PS. Stray fields then become important. Model calculations[2,3] are done which approach reality as good as possible, but some uncertainties may persist. Therefore, it is proposed to increase the observation power in order to check beam optics matching experimentally and lift this uncertainty.

3.1. Dispersion Matching

If the trajectory of the beam is well adjusted such that the injection oscillations are minimal it is further necessary that the dispersion is matched as well at the injection point of the SPS. If this were not the case then the off-momentum particles would blow up their transverse emittance since their injection error is not zero. This cannot be corrected by the feedback that only treats rigid bunches.

For a beam with a Gaussian longitudinal profile and rms relative momentum spread $\delta p/p$ it is easy to see that a momentum mismatch $\Delta\alpha$ causes a transverse emittance blow-up of

$$\Delta\varepsilon = \frac{\beta\gamma}{2\beta_y}\left(\Delta\alpha\frac{\delta p}{p}\right)^2,$$

where β and γ are the usual relativistic factors and β_y the betatronic function at the place where $\Delta\alpha$ is defined.

The longitudinal profile of the dense proton bunches is only roughly Gaussian and is limited to about twice the rms bunch length. Truncating the Gaussian profile to $2\delta p/p$ reduces the emittance blow up to ~3/4 of the calculated one. It turns out that this blow up in the SPS is less than 0.04 µrad m if the mismatch is kept smaller than 0.25 m at the injection point.

The way to check the dispersion mismatch is to measure trajectories for several momenta. A small momentum spread probe beam is necessary to ensure sufficient resolution. As a consequence the bunches will be much longer than nominal. This can be obtained easily in the PS by disabling the bunch compression prior to ejection. Every position monitor will need to be equipped with a low frequency (40 MHz for example) system on top of the standard 200 MHz system to measure these long bunches. The dispersion measurements are intended for setting-up periods of the accelerator. It is not expected that the matching varies once it is statically adjusted, barring hardware failures.

3.2. Betatron Matching

The effect of a betatron mismatch on the emittance is well known[4]. It is a multiplicative effect contrary to dipole injection errors. The mismatch λ is defined as the ratio of the injected beam ellipse and the acceptance ellipse which is conveniently represented by a circle in Figure 1.

The emittance blow-up is given by

$$\varepsilon = \frac{1}{2}(\lambda^2 + \lambda^{-2})\varepsilon_0,$$

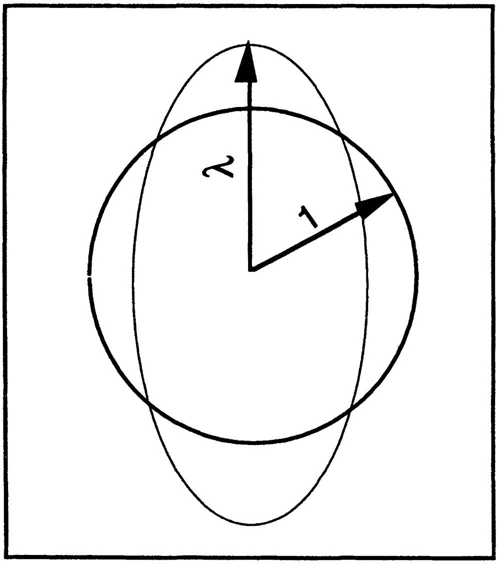

FIGURE 1 Definition of mismatch λ.

where ε_0 is the input emittance and ε the emittance after mismatch and filamentation. The emittance blow-up for the LHC type beam is shown in Figure 2. To keep the emittance increase below 0.15 μrad m (5%) it is necessary to ensure $\lambda < 0.15$.

Betatron mismatch in the transfer line can be measured with three successive emittance monitors. They exist but were intended for large emittances. Their resolution must be improved considerably in order to measure the mismatch with sufficient accuracy. Increasing their number from 3 to 4 units is considered a useful improvement of their performance.

The final word of the mismatch will have to be said in the receiving machine, the SPS. It is planned to use a new emittance monitor that will store the beam profiles for many successive turns[5]. This allows a very accurate check. However this cannot be done on every injection. Therefore it is also planned to develop a non-interactive quadrupole oscillation monitor[6] that will play the role of a less sensitive watch dog that may trigger a measurement session with the accurate and sensitive turn by turn emittance monitor. The presence of a

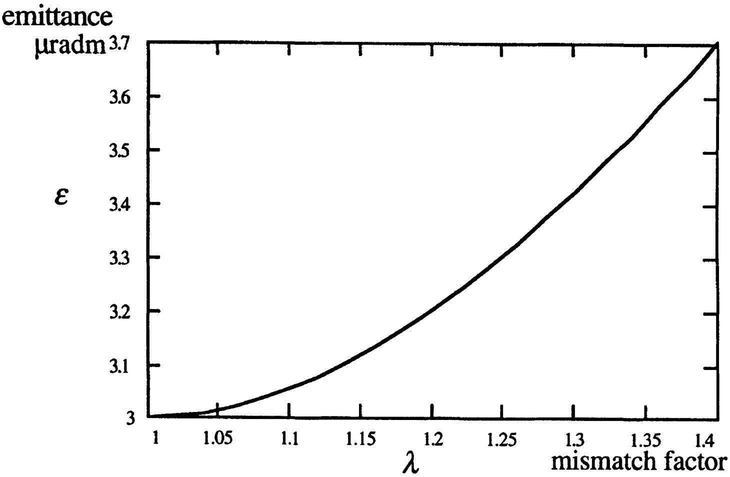

FIGURE 2 Emittance blow-up due to betatron mismatch.

powerful injection feedback system will alleviate considerably the pollution of the coherent quadrupole signal by the dipole signal both at twice the betatron frequency.

4. MULTIPOLE ERRORS

The multipole errors in a machine manifest themselves through high order resonances. They cause blow-up and beam loss for particles that get trapped in them. The SPS builders were very careful about this subject and the multipole content of the machine is small but not zero. The number-one remedy is to avoid putting beam on resonances. In principle their number is infinite but fortunately the strength of a resonance decreases rapidly with its order. The choice of the working point is very important. The high intensity bunches occupy a large area in the tune diagram since the rms space charge tune spreads are $\delta Q = 0.0035$ and 0.016 in the horizontal and vertical plane respectively. Already the $p - \bar{p}$ beam was confronted with this problem. The chosen working point was above the third order at $q = 0.7$ leaving sufficient room for the tune spreads. The same working point is proposed.

Choosing a good working point and maintain the beam on it during operation are different issues. The available tune space is sufficient but not ample. Therefore bunch intensities should be reasonably equal along the beam to avoid too large differences in direct space tune shift and coherent tune shifts by the inductive wall impedance. This requirement is already issued by the LHC. A good intensity profile measurement along the circumference with sufficient time resolution is required.

Tune measurements should be precise and frequent during the acceleration cycle. Past experience has shown that the SPS is very reproducible. This is fortunate since active kicked beam measurements can be made in the form of spot checks on cycles that are not used for luminosity running. The beam will be continuously excited by the resistive wall instability up to the observation limit of the transverse feedback system. A high resolution observation of this beam may provide a passive control of the tune.

The coupling of betatron oscillations in itself is harmless. However, if the coupling is too large it will restrict the available tune space since it will forbid a band around the diagonal equal to the coupling strength. Since that is the zone where the clean tune room is maximal it is necessary to correct for coupling especially at injection momentum. The tools to do this do exist. The situation is much simpler than for the $Sp\bar{p}S$ (one observable and four correctors) since only the zero order (one observable and one correction) is at play in the absence of a tune split.

5. CONCLUSION

Preserving the emittance during the injection process in an ideal accelerator and transfer line is trivial for beams which are transversely stable. To approach as much as possible the ideal state with a real machine it is sufficient, but not trivial, to measure the deviations from that state and correct them. The survey of the SPS and its injection line in view of transverse emittance conservation leads essentially to a demand for efficient instrumentation and implementation of specific measuring strategies.

References

[1] The 300 GeV Programme, CERN/1050 (1972).

[2] T. Risselada, The optics of the fast ejections of the CERN PS (1989).

[3] I. Kirsten, D. Manglunki and M. Martini, Trajectory and optical parameters in non-linear stray field, CERN/PS 96-24 (PA) (1996).

[4] P.M. Hanney and E. Keil, How does betatron mismatching affect beam size and beam density? CERN-ISR-TH/69-32 (1969).

[5] C. Bovet and R. Jung, A new diagnostic for betatron phase space matching at injection into a circular accelerator, LHC Project Report 3 (1996).

[6] G. Carron, D. Möhl, Y. Orlov, F. Pedersen, A. Poncet, S. van der Meer, D.J. Williams and P. Krejcik, Observation of transverse quadrupole mode instabilities in intense cooled antiproton beams in the AA, CERN/PS/89-18 (AR) (1989).