A New Diagnostic for Betatron Phase Space Matching at Injection into a Circular Accelerator

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ABSTRACT

For proton and ion accelerators, betatron matching at injection is a delicate procedure, vital to preserve phase space density. A new diagnostic is proposed in which a single detector in a circular machine measures the beam size for a dozen successive turns. Applications to SPS and LHC are exemplified. The method is so robust and accurate that it should allow to reduce the emittance blow-up to below 1 % in each plane. Experimentation is ready to start in the SPS.

1 INTRODUCTION

During the many transfers needed in the injector chain for the LHC it is vital to preserve the highest possible phase space density, avoiding emittance blow-up due to mismatch of beam optics. With bunch to bucket transfer from one circular machine to the next, the loss of phase space density results from filamentation of bunches which are not perfectly well placed and shaped in the 6-dimensional phase space, to fit Courant & Snyder invariant ellipses.

Filamentation, which is responsible for the emittance blow-up, does not happen in transfer lines where the chromaticity is too small to bring significant phase shifts in a single passage. Provided the transfer line aperture is large enough, no blow-up nor beam loss should happen and therefore matching becomes a real issue only when the beam reaches the next circular machine.

Twelve parameters are needed to adjust the centre and the shape of beam ellipses in the three phase planes. Adjusting to theoretical values is a good first approximation and is, of course, done to start with and get a circulating beam. But a final transfer optimisation can best be achieved with a fine tuning of some elements in the transfer line, as a function of observations made on the beam circulating after injection.

i) The injection trajectory in 6-dimensions (x, x', y, y', z, Dp/p) is optimised by minimisation of coherent oscillations measured with beam position monitors;

ii) In longitudinal phase plane, ellipse matching is obtained by minimising quadrupolar oscillations that can be observed with a wide-band pick-up;

iii) Transverse phase plane matching is traditionally done by observing the beam size with three detectors in the transfer line, separated by known optical conditions and relying on the optical matching of the transfer line to the downstream circular machine. But values obtained from MAD for the Courant & Snyder invariants cannot be trusted, since those invariants are, in reality, sensitive to all magnet imperfections which are not known to the optics modelling program. LEP has shown beta beating of up to 40% !

In this paper a new diagnostic method is proposed for performing the third step mentioned above, in a way which does not rely on a precise knowledge of machine optics. The new idea is to observe the beam for many turns, after its injection in the considered circular machine, with the help of a single detector.

A detailed simulation of the process is described in Ref.[1] where the cases of SPS and LHC are exemplified with realistic machine optics, beam properties and existing detector characteristics, and the effect of multiple scattering in the detector is rigorously taken into account. Thin screens observed with a CCD camera working in a fast acquisition mode, are proposed as a practical solution for the detector. It is an inexpensive and extremely powerful solution. After the number of turns necessary for data taking, the beam has to be dumped to save the detector from overheating and to reduce the flux of secondaries produced in nuclear interactions. The beam energy loss due to dE/dx is less than one per mil even after 80 turns and can be taken into account in the data analysis.

2 A NEW DIAGNOSTIC

Betatron matching at injection is traditionally done using the knowledge of the beam emittance measured either in the previous machine or in the transfer line and the knowledge of the optics of the machine where the injection takes place. Whatever the care put in the process, this methodology has a weak point with large accelerators where beta-beating can alter completely the invariants of motion obtained from a computation of the machine optics with ideal quadrupoles. The resulting emittance blow-up cannot be avoided and will, in most cases, be measured only after filamentation, with beam profile equipments like wire scanners, ionisation scanners or synchrotron radiation telescopes.

In order to detect any potential blow-up due to betatron mismatch, all one needs is to measure the beam size during a few turns, after injection. This is a very sensitive means since 10% modulation of the r.m.s. beam size would result, after filamentation, in an emittance blow-up of only 1 % because this effect adds in quadrature to the r.m.s. betatron amplitude distribution. When there is no beam size modulation, the matching is perfect. Of course, with hadrons, non intercepting detectors are not capable of doing this measurement turn by turn, but thin detectors that existed for twenty years like SEM grids and luminescent screens could have been used with the only prerequisite of dumping the beam soon after the measurement, in order to save the detector. One difficulty is due to multiple scattering induced on the beam at each passage through the detector but this effect can be taken into account and does not prevent, on paper, a precise optimisation of betatron matching as shown in Ref.[1].

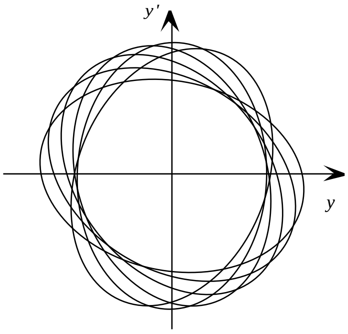

Fig. 1. Phase plane ellipse seen at 6 successive turns with a fractional tune q=0.06.

The real power of this method comes from the fact that it requires the knowledge of only one machine optics parameter, i.e. the betatron phase advance per turn, q_x or q_y (fractional part of $Q_{x,y}$) which can, in all machines, be adjusted and measured with great accuracy. And the perfect matching is achieved when the r.m.s. beam sizes measured on successive turns are constant (corrected for multiple scattering) what does not even require for the monitor to be calibrated, nor for machine physicists to agree on a definition of emittance !

As seen in Fig. 1, the beam size will show a modulation at twice the betatron frequency : 2q or 2(1–q). Therefore with q=0 or q=0.5 this method does not work.

Another more subtle trap is q=0.25 or q=0.75 which also would hide the size modulation for a mismatched beam injected with a phase of 45^o, see Fig. 2.

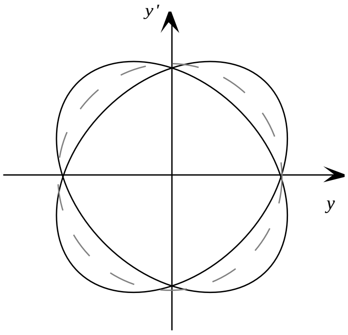

Fig. 2. Phase plane ellipses traced at successive turns with a fractional tune q=±0.25.

Hence for a clear observation of betatron mismatch any q value can be used, provided it is different from q = 0, 0.25, 0.5 or 0.75, by more than 1/2n, where n is the number of turns for which the beam size is measured.

In principle these techniques can be applied to any machine, but of course will be more easy to use with large machines where the injection energy is high (small multiple scattering) and the revolution frequency is low (which eases the readout). In Ref.[1] the cases of SPS and LHC are studied in details. The effect of multiple scattering in the detector is calculated and simulations are shown of the amplitude modulation that can be expected for a mismatch of 20%. Beam size measurements with an accuracy of 1% can be achieved, turn by turn, with the help of only about 20 channels as it has been demonstrated with the synchrotron light telescopes [2] and the hard X-ray detectors [3] in LEP.

Therefore one can expect to detect mismatches of the order of 0.1%, using these techniques and since the phase of the mismatch can be determined, systematic corrections can be applied to optimise the matching. It should also be noted that the injection steering (in the 6-dimensional phase space) which should have been done prior to betatron matching, will also be checked during the present optimisation.

3 THE USE OF THIN DETECTORS

The beam profiles can be measured with SEM grids or screens. Experience in the SPS transfer lines has shown that screens recorded by CCD cameras have now many advantages over SEM grids for profile measurements [4]. Screens of various types have been used in the SPS and LEP transfer lines: Al_2O_3(Cr), CsI(Tl), Li glass(Ce) and quartz. Activated alumina sheets are too slow for this application; CsI(Tl) screens are fast enough, but not really compatible with ultra-high vacuum; quartz and lithium glass are good candidates and can both be thinned below 1 mm.

Another possibility is to use optical transition radiation (OTR) screens. Recent tests in the SPS transfer lines have shown that they are suitable for 450 GeV protons, and marginal with 14 GeV ones. The big advantage of OTR screens is that their light production is due to a change of the dielectric constant at the vacuum-screen interface, and hence the light production is independent of screen thickness. The only disadvantage is the narrow light emission cone which may set a limitation on the space resolution, via diffraction. Screens made of 12 µm titanium and of 20 µm Mylar coated with aluminium have been tested with good results.

4 CCDS FOR IMAGE RECORDING

CCDs now on the market have a fantastic analytic power. Their spatial resolution is enormous : lets take as an example the Thomson TH7863 chip : it contains 2×384×288 i.e. $2 \cdot 10^5$ pixels, each 23 µm × 23 µm. The sensitivity is also high since each pixel has a quantum efficiency of more than 20% in the useful spectrum.

For each pixel the charge saturation is reached at about 8×10^5 electrons and the thermal noise accounts for about 100 charges per 20 ms, which means that a dynamic range of several 10^3 is available for data readout at the normal

TV pace, when the CCD chip is kept below room temperature, for instance with a Peltier cell.

For turn by turn measurements a fast time resolution can be achieved with a Micro Channel Plate used as a shutter to select the wanted images, and with the help of a dedicated readout process in order to speed-up the CCD image acquisition [5].

5 SIMULATION RESULTS

A computer code has been developed which allows to simulate the observation over n turns of a newly injected beam, with a two-dimensional Gaussian distribution. The r.m.s. beam size measured at the detector is obtained, taking into account the optical mismatch and the multiple scattering suffered by the beam at each passage through the detector. Numerical applications have been run for the LHC beam at injection into the SPS and the LHC, see Ref. [1]. An example is given in Fig. 3 which shows a beam injected into the LHC with a nominal emittance: ε=7.8×4π nm and the machine optics characterised by α=5.0, β=200 m, q=0.06; the mismatch is of 20% and the scattering angle θ_0=1.60 µrad corresponds to a titanium screen of 250 µm thickness. The solid line is for a perfectly matched beam which shows a steady blow-up and some undulation due to multiple scattering, and dots are for a 20% mismatched beam which can be easily witnessed. At 26 GeV (injection into the SPS), simulations show excellent results even with a detector made of 20 µm of titanium, which means that this method will be useful in the two large machines of the LHC complex.

The simulations made so far show that it will be possible, once the beam size modulation has been observed, to implement a deterministic feedback on correcting elements in the transfer line, in order to optimise the matching, and this procedure can be done independently for both x- and y-planes.

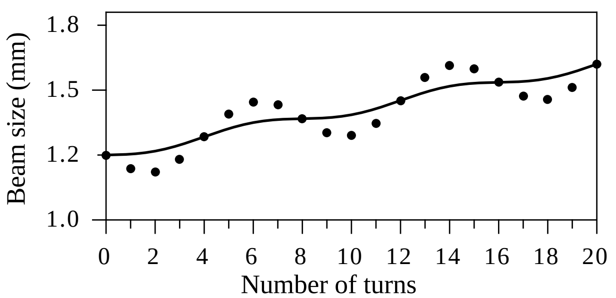

Fig. 3. Perfectly matched (solid line) and 20% mismatched beam after injection into the LHC.

6 CONCLUSIONS

The optimisation of beam emittance matching at transfer from an injector into a circular machine is a crucial ingredient to keep the highest possible phase space density. It has been shown that this goal will be achieved in the future with a much higher efficiency when the injected beam is observed with the same detector, for many revolutions. Thin screens can easily stand multiple traversals of a pilot beam and the beam blow-up due to multiple scattering can be taken into account in the matching optimisation. This new procedure will be particularly robust since it is not affected by the modelling of machine optics. It does not require a perfect knowledge of the transfer line optics nor an absolute calibration of the detector. With the use of these techniques one can hope to reduce the blow-up due to betatron mismatch at injection to below 1% what has never been possible in the past. Experimentation will start in 1996 when newly installed screens will allow the observation of beams injected into the SPS.

7 REFERENCES

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