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THE OTR SCREEN BETATRON MATCHING MONITOR OF THE CERN SPS

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CERN – Geneva - CH

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In order to satisfy the stringent emittance requirements of LHC, betatron matching monitors, based on multiturn beam profile measurements, have been proposed for the SPS and LHC. A test monitor has been installed for evaluation in the CERN SPS first in 1996 and improved in 1997. It is based on an OTR screen and a fast beam profile acquisition system. It has been used with proton beams to assess the quality of the betatron matching from the PS to the SPS in 1998. Experience and results are presented.

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Abstract

In order to satisfy the stringent emittance requirements of LHC, betatron matching monitors, based on multiturn beam profile measurements, have been proposed for the SPS and LHC. A test monitor has been installed for evaluation in the CERN SPS first in 1996 and improved in 1997. It is based on an OTR screen and a fast beam profile acquisition system. It has been used with proton beams to assess the quality of the betatron matching from the PS to the SPS in 1998. Experience and results are presented.

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 by 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 well placed and shaped in the 6-dimensional phase space.

Filamentation which is responsible for the emittance blow-up, does not occur in transfer lines where the chromaticity is too small to give significant phase shifts in a single passage. If the transfer line aperture is large enough, no blow-up or 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, implemented at the beginning to get a circulating beam. But a final transfer optimisation can best be achieved by the 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% !

The diagnostic method proposed for performing the third step mentioned above, does not rely on a precise knowledge of machine optics. The 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 is dumped to protect 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. DIAGNOSTIC PRINCIPLE

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. Regardless of the care put into 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 monitors like wire 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 certain number of 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, present non-intercepting detectors have not been capable of doing this measurement turn by turn, but thin detectors like SEM grids and screens can be used with the only prerequisite of dumping the beam soon after the measurement, in order to protect 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 a precise optimisation of betatron matching as shown in Ref. [1].

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 Qx or Qy) which can be adjusted and measured with great accuracy. The perfect matching is achieved when the r.m.s. beam sizes measured on successive turns are constant (corrected for multiple scattering) which does not even require that the monitor be calibrated, nor that machine physicists agree on a definition of emittance !

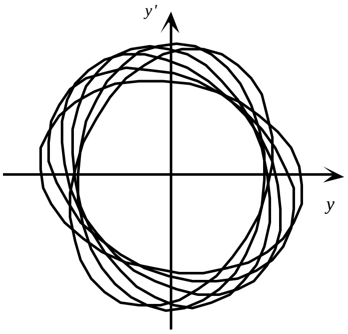

Figure 1: Phase plane ellipse seen at 6 successive turns with a fractional tune q = 0.06.

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 will not work.

Another more subtle trap is when q = 0.25 or q = 0.75 which would also hide the size modulation for a mismatched beam injected with a phase of 45^{o}, see Fig. 2. For a clear observation of betatron mismatch any q value will be adequate, 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.

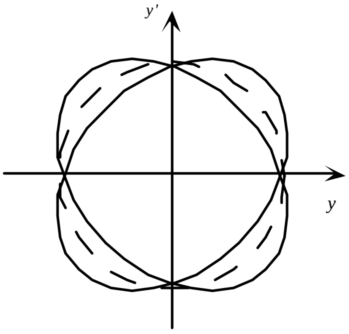

Figure 2: Phase plane ellipses traced at successive turns with a fractional tune q = ±0.25.

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 have been studied in detail. 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%. Turn by turn beam size measurements can be achieved with an accuracy of 1% with the help of only about 20 channels (lines or columns).

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 analysis described above.

3. THE OTR SCREEN MATCHING MONITOR IN THE SPS

A 12 μm thin Titanium screen was installed in 1996 in a Luminescent Screen tank in the SPS for preliminary tests, which were encouraging. The foil was placed at 45° with respect to the beam trajectory and used as an Optical Transition Radiation (OTR) generator in the reflective mode. It was noted that the beam could be left circulating with the foil in place for at least 300 turns without damaging the Titanium foil.

For the 1997 run, a dedicated monitor was installed with optimised OTR light collection at the low injection energy, i.e. low γ. It provides the visualisation of the proton beam injected into the SPS at 26 GeV for about 100 turns, after which the beam starts to show appreciable blow-up.

It also uses the OTR from a thin 12 μm Titanium screen located in LSS4 of the SPS, through which the injected beam passes for 130 revolutions before being dumped. The set-up is represented schematically in Fig. 3.

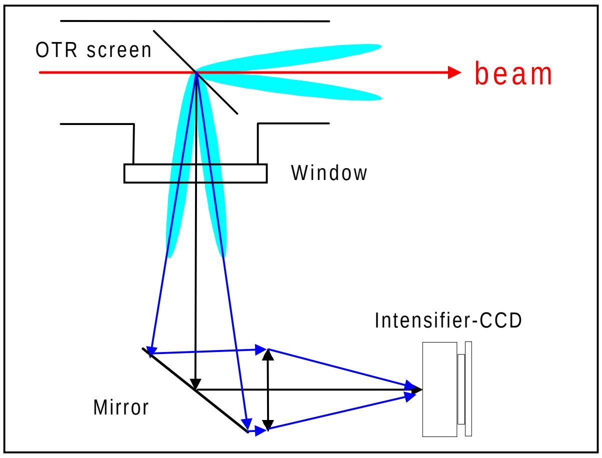

Figure 3: Matching monitor set-up in the SPS

The beam light is sampled by a pulsed intensifier and acquired on a CCD used as a fast buffer memory to acquire successive turns of the beam as described in Ref. [2]. A measurement result is given in Fig. 4. It shows a very clean signal, with only a few noise peaks on the whole CCD surface and a slope of thermal origin which can be subtracted during the processing. Due to the large emittance of the beams delivered by the PS at the time of the test, only one out of two images was acquired to have well separated projections. So only four instead of the normal nine profiles per injection have been acquired.

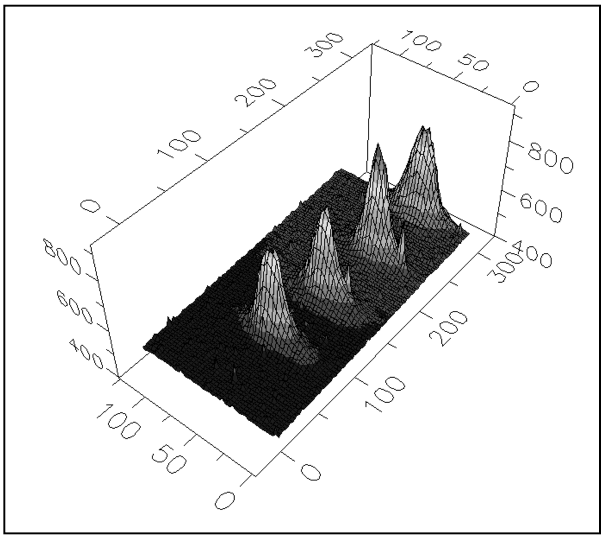

Figure 4: Result of the digitisation of four beam profiles from different SPS turns memorised on the CCD. The beam dimensions are given in pixels [500µm/px] and the amplitudes in counts of the 12 bit ADC.

At the beginning of the measurement sequence, a reference image is taken before the first injection. This reference image will be subtracted from the following measurements, suppressing the thermal slope as well as dark current noise inhomogeneities.

The Horizontal and Vertical projections are obtained from the individual beam images, from which the beam sizes are calculated with a gaussian fit using a χ^2 minimisation routine, see Fig.5.

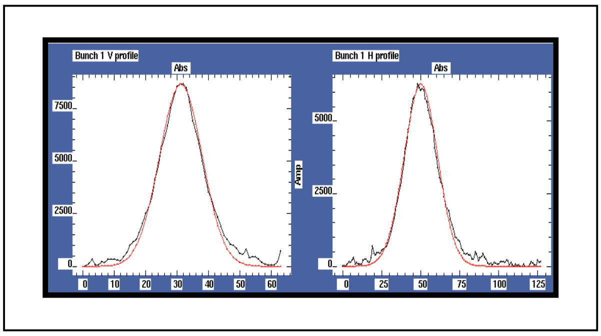

Figure 5: Horizontal and vertical projections of a selected revolution together with their gaussian fits.

The main limitation in the image acquisition rate was found to be the acceptable repetition rate of the intensifier. The rate, and hence the image acquisition, could be increased to 10 kHz only by using a high strip current MCP intensifier [3]. To have some safety margin, the acquisition rate was decreased in 1998 to one every eight SPS turns, i.e. 5.62 kHz, still much higher than the usual 25 Hz rate of normal frame grabbers.

To fill in the data of the missing turns, a timing sequencer was developed to automatically scan the missing turns by displacing the first acquired turn for subsequent injections. A typical measurement result is given in Fig. 6. A full profile history over 32 revolutions reconstructed with 8 successive injected pulses takes less than three minutes. It has to be verified that during this duration, the whole process from PS to SPS is stable. It was found during a Machine Development (MD) run in 1998 that this assumption is valid in the vertical plane, but may be questioned in the horizontal plane for various reasons, one of them being a radial displacement of the first bunch of the batch at the time of the MD [4].

The tune values measured with the Q-meter were $q_h = 0.6294$ and $q_v = 0.5825$. The 8 turn sampling was a compromise between the MCP frequency limit and the vertical tune. It is clear that it was not favourable for the horizontal plane for a given single measurement sequence since the eight turn phase advance is so close to integer ! The curves in figures 6 and 8 have been obtained with a fit of an amplitude oscillation with the known tune value. The phase, the amplitude and the slope representing the emittance blow-up have been obtained by a Monte-Carlo selection of parameters. The beam has suffered multiple scattering due to many foil traversals and the average vertical beam size increase is clearly visible and amounts to about 9% for

32 turns which is perfectly acceptable and does not affect the mismatch observation.

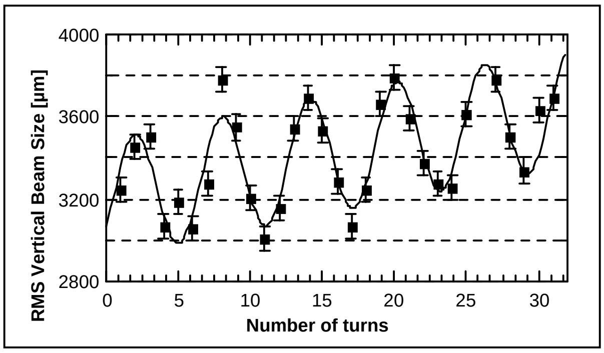

Figure 6: R.m.s. vertical beam size modulation measured over 32 turns in the SPS for a mismatched beam.

During the same MD, the vertical matching optics were changed [5] and the resulting beam size oscillations measured by the monitor, see Fig. 7.

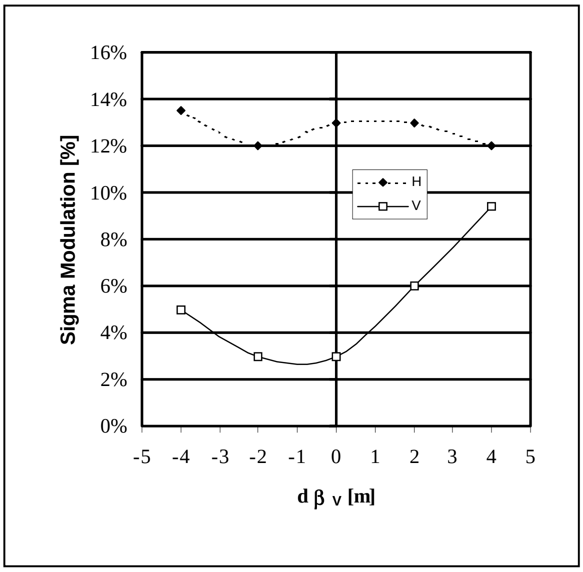

Figure 7: Evolution of the Vertical (Full line) and Horizontal (dashed line) beam size oscillations measured when changing the vertical matching optics.

In Fig. 7 it is quite clear that the vertical matching goes through a minimum, reaching a modulation of only 3 % which is a remarkably small value (see Fig. 8) leading to a filamentation blow-up of about 0.1 %. On the other hand the horizontal mismatch was virtually unaffected by changing the vertical optics.

From these results it seems possible to close a control loop for achieving in a semi-automatic way an optimum matching by searching for a minimum beam size oscillation. It is planned to test this facility during 1999 MDs.

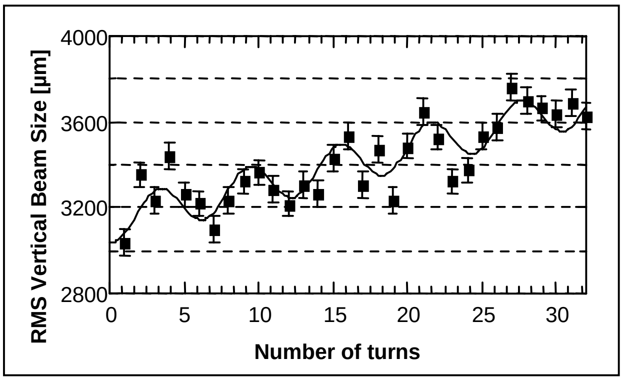

Figure 8: R.m.s. vertical beam size modulation measured over 32 turns in the SPS for a matched beam.

On the other hand it will be important to check that the matching does not change during the filling of LHC. This check can obviously not be performed by the described monitor. Non-intercepting monitors will be needed such as the Ion Profile Monitor [6] or a Luminescence Monitor [7], both working in the single turn mode described previously. They will probably not achieve the same precision, but must be able to detect turn-by-turn beam size changes at nominal intensity.

4. CONCLUSION

The SPS matching monitor is able to detect beam size oscillations over at least 30 revolutions with an OTR screen observed with a CCD read in a fast mode. Beam size oscillations of a few percent have been measured, which give confidence to limit the resulting beam blow-up through filamentation to less than 1%.

The screen has survived 300 consecutive traversals, which is far more than needed. The beam blow-up due to the present screen is acceptable. In the future it is envisaged to reduce the screen thickness to 5 µm of Titanium or to 2 µm of aluminised mylar which will reduce the beam blow-up even further.

The complete measurement is presently made with a number of injections (8) because of the limitation in acquisition rate of present MCPs. This number can probably be decreased by a factor of two. This situation will be difficult to improve, but is not felt to be a serious limitation. Since LHC has a revolution period of 89 µs, turn-by-turn measurements will be possible in LHC with the OTR detector.

It is hoped to test in 1999 a closed loop matching control to go towards an automated matching procedure.

With some software improvement, the monitor will be ready for use by non-specialists in SPS to fulfil the required check on emittance preservation. The same system will be available for use in the LHC and special efforts will be devoted to develop non-intercepting beam size monitors to check on-line the conservation of the betatron matching during the filling of LHC.

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It is a pleasure to acknowledge their contributions to the success of the monitor.

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