TURN BY TURN PROFILE MONITORS FOR THE CERN SPS AND LHC

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Abstract

In order to preserve the transverse beam emittance along the acceleration chain it is important that the optics of the transfer lines is perfectly matched to the optics of the rings. Special monitors capable of measuring the beam profiles with a turn by turn resolution are very helpful in this respect. A new type of matching monitor has been developed at CERN for the SPS and LHC machines. This monitor relies on imaging OTR light by means of a fast line scan CMOS and an asymmetric optical system based on cylindrical lenses. This contribution describes the design of this monitor, presents the results obtained during the 2012-13 run and outlines the plans for further improving the design.

OVERVIEW OF THE SYSTEM

The new SPS and LHC matching monitors allow the acquisition of several hundred consecutive profiles on a turn by turn basis. During the design phase of the LHC it was planned to perform this rapid acquisition by means of high speed cameras observing the optical transition radiation (OTR) emitted by a thin radiator. Unfortunately it turned out that the sensitivity of the camera selected [1] was not sufficient and that the frequency of single event upsets (SEU), induced by radiation and requiring to power-cycle the camera, was very high. After some unsuccessful effort to couple the camera to an image intensifier and battling with the SEUs it was finally decided to give up on this method.

A new method was then considered that, although it only allows the acquisition of beam profiles and not of beam images, has the advantage of requiring very little electronics in the machine tunnel. This method consists of an asymmetric imaging optics and a linear CMOS image sensor [2]. The magnification of the two orthogonal directions has to be very different since the almost round beams have to be squeezed into a rectangular sensor of 6.4 mm x 250 μm. Cylindrical lenses are used to obtain this result.

In principle it is possible to split the OTR light and have two orthogonal systems operating in parallel allowing the simultaneous acquisition of the horizontal and vertical profiles. However, after the first tests in 2011, it was clear that even for this sensor the sensitivity is at the limit. It was therefore chosen not to split the light and use a movable mirror to select one plane at a time.

The maximum number of profiles that can be acquired is limited by the fact that the injected beam has to be dumped before it damages the OTR radiator.

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Table 1: Beam and Monitor Parameters

		SPS	LHC
OTR Radiator		Al	Ti
OTR cone	[deg]	4.5	0.25
Opt. Line Length	[mm]	1300	900
Resolution	[μm / pix]	64	64
Beam Size HxV	[mm]	3 x 2	2 x 1
Beam Energy	[GeV]	26	450
Bunch Intensity	[10^{10} p^+]	0.5 - 33	0.5 - 5
Revolution frequency	[kHz]	44.8	11.2

DESIGN PARAMETERS

The main parameters for the beam and the detector are summarized in Table 1. It should be noted that in the LHC the OTR radiator is made of titanium while in the SPS it is made of aluminium, both 12 μm thick. Aluminium has the advantage of a higher specular reflectivity, yielding 20% to 40% more light.

The maximum bunch intensity that can be injected into the empty LHC (and thus for matching measurements) is quite low and is dictated by machine protection issues. In order to inject high intensity bunches in the LHC it is necessary to already have a circulating beam (at least a single pilot bunch), but with the OTR screen inserted this is clearly not possible. For the SPS the maximum intensity is given by the largest bunch that the injectors can produce.
The injection energy of the LHC is much larger than for the SPS meaning smaller beam sizes, more OTR and a narrower OTR cone, all of them favourable for the LHC matching monitor.

OPTICAL SETUP

In order to improve the system tested in 2010-2011 [3], the optical line was completely redesigned using larger, achromatic lenses as can be seen in Fig. 1 (from 1" to 2"). This modification has increased the numerical aperture and reduced the aberrations. By adding a spherical field lens in the virtual image plane the vignetting effect has also been reduced increasing the usable sensor area.

The alignment of the optical system is very important since the final image must be formed on the 250 μm high CMOS sensor. In reality this tight constraint is only needed between the sensor and the camera lens, but misalignment in the optics reduces the aperture and increases the vignetting as well as aberrations. All optical components have been mounted on precision adjustable supports, see Fig. 2, and

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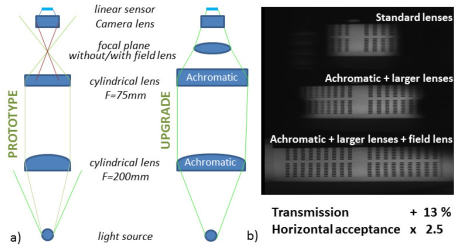

Figure 1: Initial design of the optical line for the LHC monitors (left), upgrade (center) and relative performance (right).

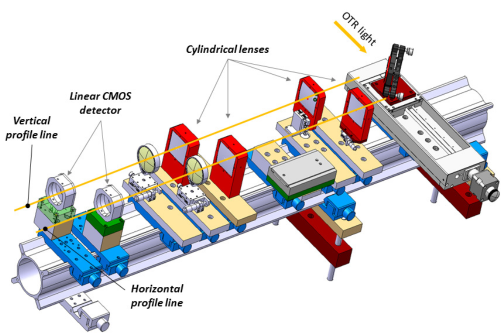

Figure 2: Rendering of the new optical setup.

pre-aligned in the laboratory using a laser beam. For the SPS monitor the layout is slightly different since the mechanics of the OTR station is different and the OTR cone angle has to be taken into account. In fact the optical bench with the matching monitor optics can only be installed about one meter away from the viewport. As shown in Fig. 3, in this case the optical line includes two more spherical lenses (of 500 mm and 250 mm focal length) that create an additional virtual image just before the cylindrical lens system. Moreover the optical axis of the system is no longer centred on the OTR axis, but at an angle of about 2 degrees in order to maximize the fraction of OTR captured by the optics (OTR having a null in its centre).

RESULTS WITH THE NEW SYSTEM

The new matching monitors have been validated for both LHC and SPS, during dedicated machine developing sessions in 2012.

As mentioned above, for the LHC the highest bunch intensity is limited by machine protection constraints to a rather low value and for both the LHC and the SPS the injected

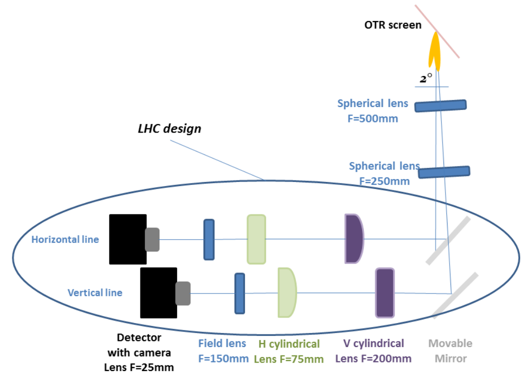

Figure 3: Layout of the optical line used in the SPS monitor.

beam has to be dumped after a few hundreds turns in order to avoid damaging the OTR radiator. The limit, defined by the bunch intensitiy and screen material, is about 300 in the SPS and 1000 in the LHC).

Data Treatment

As can be observed in the top plot of Fig. 4, the raw profile acquired by the CMOS sensor is not very clean. In particular there is a fixed pattern electronics noise and a non uniform offset. The high frequency component of the fixed pattern (at half the pixel frequency) is probably due to a non perfectly matched parallel read-out inside the sensor. An algorithm has been developed to remove both noise/background components leaving relatively clean Gaussian profiles as can be seen in the bottom plot of Fig. 4. Since the offset and noise pattern change from one image to the next it is not possible to just subtract a common pedestal and the suppression algorithm has to be applied to each profile independently.

A variation in the total light intensity from profile to profile has also been observed by plotting the integral of the profiles vs. turn number, as can be seen in Fig. 5 (black dots). An explanation for this effect has not been found yet but it may be caused by beam oscillation in the other plane. We assume that the beam size measurement is not be affected by this modulation (we are however still looking for the cause) and have included in the data analysis the normalization of the profile amplitude. This normalization forces the integral of each profile to follow the decay of the beam current estimated from the linear fit (red line in the figure).

Results in the LHC

In 2012 a complete system has been installed on one of the two LHC beams (allowing horizontal and vertical measurements). Unfortunately only one read-out electronics was available and therefore only the horizontal monitor has been tested. The test was started by injecting bunches

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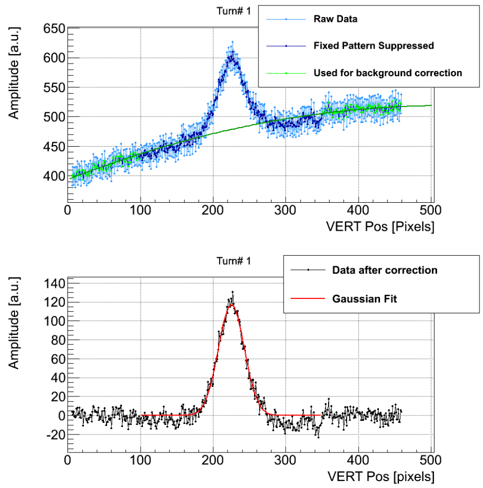

Figure 4: Example profile: raw profile, fix pattern suppression and background fitting (top). Post-processed data and Gaussian fit (bottom).

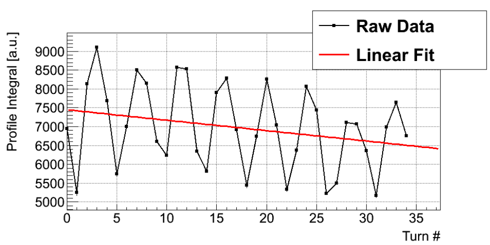

Figure 5: Integral of the profiles vs. turn number (black dots) and linear fit (red line).

of increasing intensities to study the system response and sensitivity. The profiles relative to the first turn for three beam intensities are shown in Fig. 6. The ratio of the profile amplitudes follows very well the ratio in beam intensities indicating a linear response of the detector (the amplitude of the profiles was first normalized using the method described above in order to eliminate the effect of the oscillations).

The turn-by-turn beam size evolution for the same set of measurements is shown in Fig. 7. The initial beam size is very similar for the three intensities, and in all cases it doubles after about 300 turns. The absolute increase is not surprising since the transverse dampers are set-up for physics beams and do not act on these small intensities. It is well known that in the LHC the injected beams experience relatively large oscillations at injection mainly due to the ripple in the SPS extraction kickers.

The difference in beam size increase (higher for higher bunch intensities) and beam size beating (higher for lower bunch intensities) has to be studied further in order to understand if it is real or just an artefact of the S/N of the pixels which decreases with the increase of the beam width. The levelling out of the sigma evolution at different levels for different intensities points toward this hypothesis.

The monitor also allows the turn-by-turn beam position oscillation to be measured as shown in Fig. 8, with the injection oscillations clearly visible. An energy mismatch is probably the cause for the position drift over hundreds of turns. In fact since this test was used to test the monitor no particular care was taken in optimizing the injection. The beam size and beam position evolution (for the case of $4.3\ 10^{10}$ protons) can also be inferred by the color plot in Fig. 9.

In order to estimate the effect of the OTR radiator on the

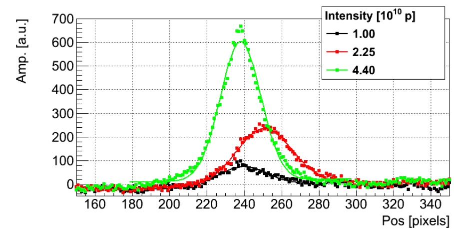

Figure 6: Horizontal profiles relative to the first turn for three beam intensities.

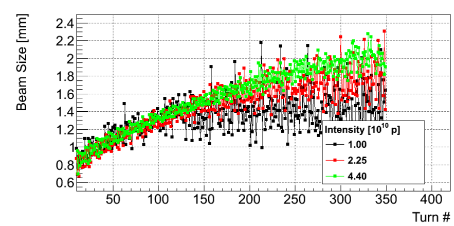

Figure 7: Horizontal beam size vs. turn number for three different bunch intensities.

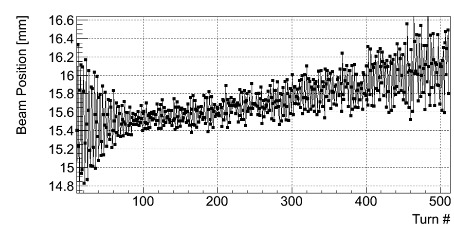

Figure 8: Horizontal beam position vs. turn number for a bunch of $4.3\ 10^{10}$ protons.

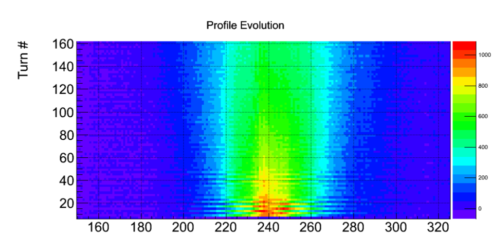

Figure 9: Horizontal profile vs. turn number for a bunch of $4.3\ 10^{10}$ protons.

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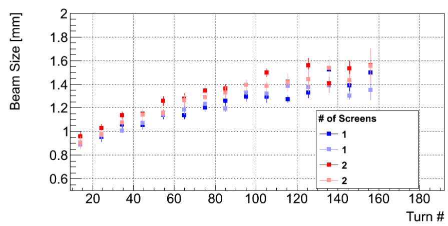

Figure 10: Horizontal beam size evolution for 1 and 2 OTR radiators inserted. Each data point is the average over 10 turns.

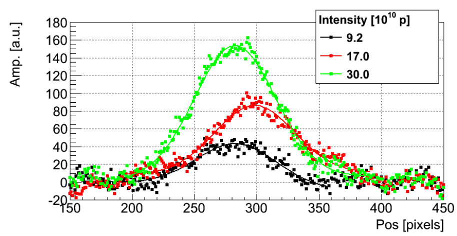

Figure 11: Horizontal profiles measured at the first turn after injection in the SPS, for different bunch intensities.

beam blow-up turn after turn, a test was done by inserting a second OTR screen and comparing the blow-up in the two cases. The effect of the multiple Coulomb scattering of the protons traversing the 12 μm titanium screens can be calculated, but the model is only valid for thicker materials (e.g. 30 μm carbon wires as discussed in [4]). The results are shown in Fig. 10. A systematic difference between the two measurements exists, but the increase due to the presence of the second screen is hardly measurable.

Results in the SPS

Due to a problem in the acquisition system, which was still in the development phase, it has only been possible to acquire profiles every second turn (this was not a problem in LHC because of the four times lower revolution frequency). In the SPS both systems, horizontal and vertical, were operational. As for the LHC the bunch intensity was varied in order to study the detector response and sensitivity. The results of this scan are presented in Fig. 11, 12 and 13. Also in this case the detector response is linear with beam intensity, however the signal amplitudes remain smaller than those observed in the LHC even with the maximum intensity of 3.0 10^{11} protons. This poses a problem for the beam size measurement as the S/N is small, especially in the horizontal plane where the beam was larger.

OVERVIEW AND CONCLUSIONS

In 2012, the upgraded fast profile monitor based on cylindrical lenses and a linear CMOS sensor was tested in the LHC and the SPS. Even though the accuracy required

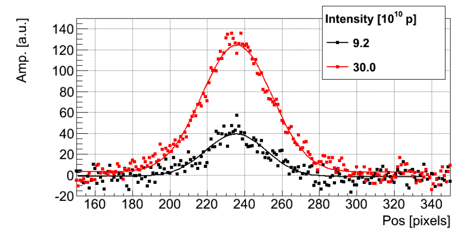

Figure 12: Vertical profiles measured at the first turn after injection in the SPS, for two different bunch intensities.

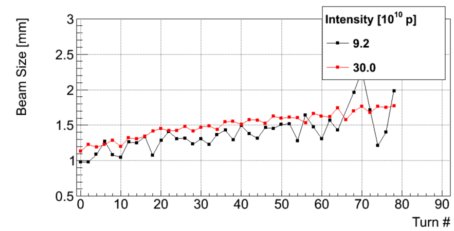

Figure 13: Vertical turn-by-turn beam size evolution for two different bunch intensities.

for using it as *matching monitor* has not been demonstrated yet, both tests gave consistent turn-by-turn profile measurements. The LHC measurement (horizontal plane) showed sufficient sensitivity for bunch intensities above 2 10^{10} protons while below this value the S/N is too small. In the SPS the monitor is usable only above 3 10^{11} protons which is well above the typical LHC intensities (1.7 10^{11}).

A number of issues with the CMOS sensor have been discovered requiring the development of correction algorithms, like an unexpected beating in the signal amplitude pixel by pixel.

The next step consists of improving the sensitivity of the sensor or improving the light collection efficiency. Seeing the sensitivity of the monitor to the alignment and the difficulty in aligning the optical bench vs. the OTR axis a remote control of some elements of the system could help improve the light collection efficiency. The magnification factor should also be recalculated so that the minimum number of pixels is used to increase the S/N.

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