PRELIMINARY TEST OF A LUMINESCENCE PROFILE MONITOR IN THE CERN SPS

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Abstract

In order to satisfy the tight emittance requirements of LHC, a non-intercepting beam profile monitor is needed in the SPS to follow the beam emittance evolution during the acceleration cycle from 26 to 450 GeV. Beyond 300 GeV, the synchrotron light monitor can be used. To cover the energy range from injection at 26 GeV to 300 GeV, a monitor based on the luminescence of gas injected in the vacuum chamber has been tested and has given interesting results. This monitor could also be used in LHC, where the same problem arises. Design and results are presented for the SPS monitor.

1. INTRODUCTION

For the LHC project, there is a severe constraint on the transverse emittance preservation from PS ejection to LHC. The allowable beam blow-up will be from 3µm to 3.4 µm for the normalised one sigma emittances in both transverse directions. As presented in other papers [1,2], the emittances will be measured in the transfer channel TT10 and the matching from PS to SPS checked on dedicated injections by means of an OTR screen in the SPS ring where the injected beam will be dumped after 100 revolutions. A specific beam monitor is then needed to check the emittance preservation in the SPS up to the extraction towards the LHC.

Wire Scanners are available for precision reference measurements, but they are beam perturbing and of low repetition rate, allowing a maximum rate of only two measurements per SPS cycle.

A non-intercepting beam profile monitor with a high sampling rate of at least 25 Hz is essential to identify beam blow-ups and their causes.

From 300 GeV to the extraction at 450 GeV, a Synchrotron Radiation (SR) monitor is available, but from injection at 26 GeV up to 300 GeV, no monitor is yet available. If this monitor is fast and sensitive enough, it could also be used to check on-line the matching preservation which has been established with the OTR screen monitor.

Two types of monitors are being considered for this task: the Ionisation Profile Monitor (IPM) of which a monitor from DESY has been installed in the SPS and is being tested [3] and a Luminescence monitor which will be discussed in this paper. In the Luminescence monitor, the information is transported by photons and will not be influenced by the beam space charge as is the case for the IPM. This is very interesting and makes the effort to test the usefulness of such a device as a beam profile monitor worthwhile.

2. THE LUMINESCENCE MONITOR

This type of monitor has been used at Los Alamos in the late seventies where it gave interesting results with low energy and high intensity proton beams passing in Nitrogen [4]. It seems that this type of monitor has never been used in high energy accelerators. This is probably because it was felt that the light production is too low at higher energies, above several tens of MeV [5], despite a study made for HERA [6].

The luminescence monitor makes use of the excitation of gas molecules by the particle beam to generate light. This light production is proportional to the particle density and to the gas pressure [7]. Several types of gas can be considered. Nitrogen has been studied for many years in the context of the aurorae borealis. It is a good candidate, because it emits light close to the lower limit of the visible spectrum, within the sensitivity region of normal intensifiers. The light production cross section of nitrogen is high and is well known at low energies [7]. An additional advantage of Nitrogen is that it is easily pumped by the vacuum system.

As the available data is given for energies below 1 MeV, the light production at SPS energies was estimated by using the Bethe-Bloch equation: Fig. 1.

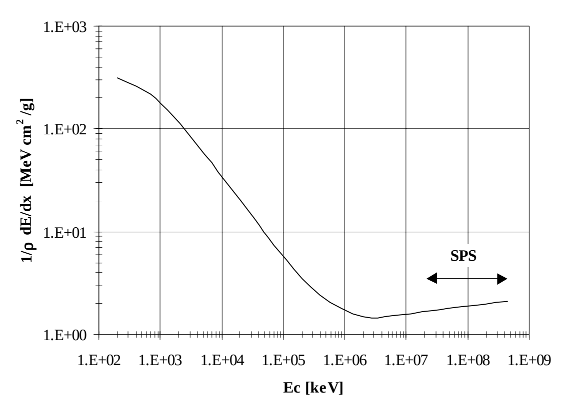

Figure 1: Energy dependence of the normalised proton energy loss to Nitrogen molecules as a function of proton energy as given by the Bethe-Bloch equation.

If the light production is only proportional to the energy loss of the charged particle, then there is a reduction factor of nearly 200 at the SPS energies with respect to the available 200 keV data. Nevertheless, it appeared that enough photons should be available from a reasonable Nitrogen pressure bump to make beam profile measurements possible with the usual intensified detectors: see Appendix.

3. BEAM TESTS WITH PROTONS

To assess rapidly the possibilities of such a monitor, preliminary tests were performed in early 1998 [8] by making use of a standard “quatro” vacuum vessel installed in the SPS for another purpose. One of the free horizontal ports was fitted with a window and a leak valve was installed to introduce the gas under study in a controlled way in this vacuum tank. In this set-up, the vertical size of the beam is observed along the visible part of the trajectory. The light emission was observed with a standard SPS intensified CCD camera, using a lens-coupled single stage MCP intensifier. The images were acquired by the usual VME 8 bit frame grabber and the data processed by the standard software, producing 2-dimensional images (Fig.2), projections (Fig.3), and 3-dimensional images, where the third dimension represents the pixel light level, which visualises clearly light inhomogeneities.

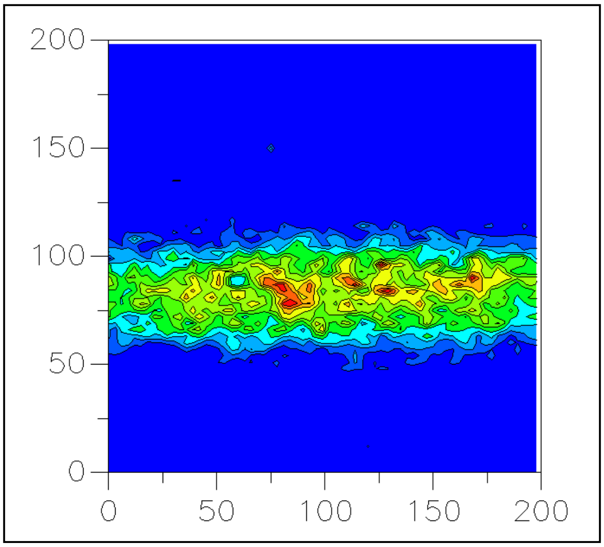

Figure 2: Side view of the beam (vertical dimension) as seen by the camera: the units are in pixels [156 μm/px]. The beam length seen in the 200 pixels window is 31 mm.

The tests were performed with Nitrogen pressures of between 10^{-5} and 10^{-6} T, which were felt to be close to the highest acceptable limit. Even so, no detrimental effect on the beam was observed by the Control Room team.

From these tests it was confirmed that the light was scarce and that the efforts had to be directed in priority towards an improvement in the light collection set-up. It was also clear that the light had to be taken over the longest trajectory length possible and used to perform the projection of the detector data along this direction thus decreasing the effect of the statistical photon fluctuations. There is no hope, nor reason, to consider single beam cross-sections.

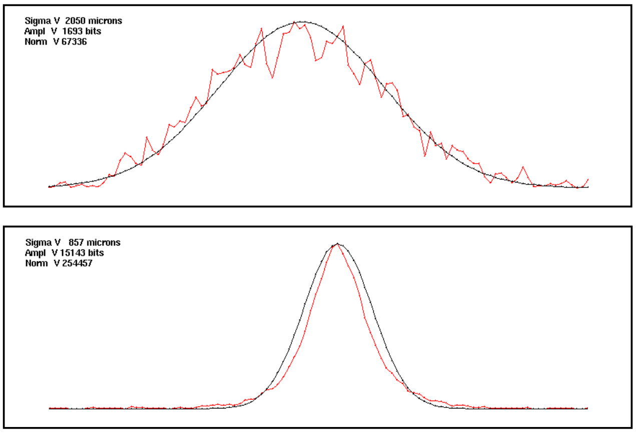

Figure 3: Vertical Beam Profiles (summed over the observation window) measured at 14 GeV (top) and 450 GeV (bottom) together with their gaussian fits.

A crosscheck of the measured beam sizes, to assess the precision of the device, was made with a Wire Scanner, which was located at 1.5 m from this monitor. Both instruments agreed within 6%, at a beam sigma of 860 μm at 450 GeV.

A complete vertical beam size history over a full SPS cycle was also taken: Fig. 4.

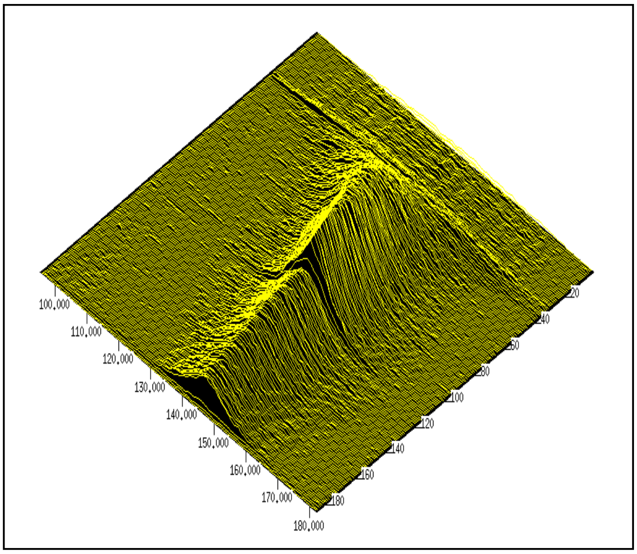

Figure 4: Mountain range view of 182 profiles of the vertical beam dimension [156 μm/px] for a full SPS cycle: from right to left: Injection at 14 GeV, Ramp to 450 GeV, and Extractions: 1st Fast, Slow and 2nd Fast extractions.

The movement of the nitrogen molecules between the time they have been excited and the time they emit the photons can be a source of beam size broadening. To evaluate this possibility, the intensified camera was replaced by a photomultiplier in single photon counting mode with a 200 ns gate length. The light pulse length of a single batch circulating in the SPS together with the length of the batch measured with a SEM foil in the transfer line is given in Fig. 5.

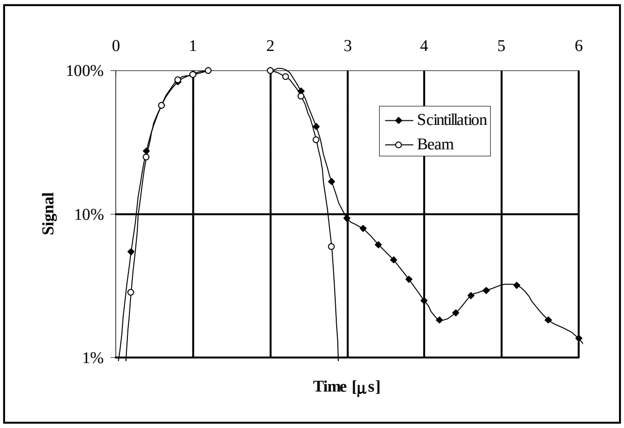

Figure 5: Comparison of beam and scintillation signal lengths. There is a long afterglow tail below the 10% level with respect to the maximum light signal.

At the 10% level, the light signal is trailing behind the beam signal by approximately 200 ns, compatible with a lifetime of N_2^{+}* around 60 ns. As the beam size is calculated with a gaussian fit above the 30% limit of the maximum signal, the time to be considered is of the order of 50 ns. It seems that in the luminescence signal there are at least two other components with longer time constants, which are most probably due to different spectral lines, from different molecules in the rest gas, having longer afterglow characteristics. This low intensity structure was also present in tests made with Argon, which indicates that it is not exclusively related to Nitrogen. If the excited molecule is ionised, which is most likely the case, the ion will move during this time under the influence of the electric field generated by the beam, which will then result in a broadening of the light envelope. The molecules close to the core of the beam will see the smallest integral field and move very little, whereas the ones at the periphery will see the largest field and move more. Hence the beam tails rather than the beam core will be enlarged. Even these peripheral molecules will move only a few tens of micrometers. This has been confirmed by comparison with the beam size measured by the wire scanner which gives a beam broadening of only 50 µm.

4. BEAM TESTS WITH LEAD IONS

Between the proton and the Lead ion run of the SPS, the set-up was modified to improve its sensitivity, i.e. decrease the pressure for a given Signal-to-Noise ratio. The major modifications were the use of a two lens optical system for increasing the light collection efficiency and the use of a two-stage MCP, fibre-optically coupled to a Peltier-cooled CCD in order to increase the light “amplification” and decrease the thermal noise generated in the CCD. The corresponding mechanical set-up is depicted in Fig. 6. The light collecting lens is a F = 500 mm achromat of 80 mm diameter placed at 350 mm from the beam centre, the objective has a 50 mm focal length and an aperture of 71 mm.

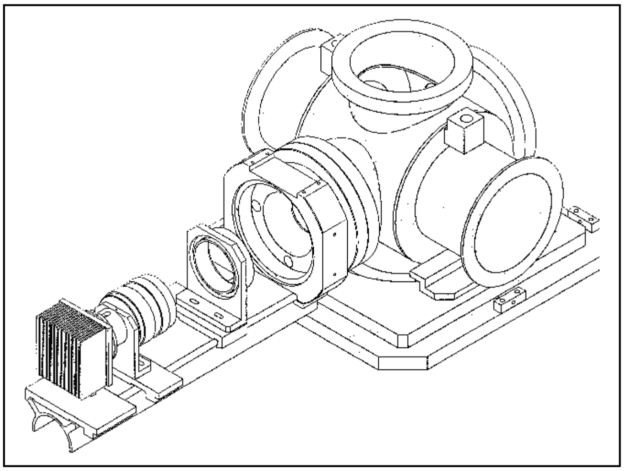

Figure 6: The test monitor set-up: Right: the “quatro” tank with the left horizontal port fitted with a glass window. Left: the optics set-up with a 500 mm achromat followed by a 50 mm lens, a double stage MCP and the Peltier-cooled CCD with radiator.

As there is ample resolution, the magnification was decreased to 177µm/px, which increases the number of photons collected per pixel by 30%.

Tests were performed with Lead ions at pressures of 5 10^{-6} to 1 10^{-7} T with beams of 8 10^{8} Pb^{82} ions. It could be verified that the light signal is proportional to the Nitrogen pressure, see Fig. 7, and increases about as predicted by the Bethe-Bloch equation, i.e. an increase by Z^2 =6724 of the sensitivity. The lack of precision is due to the change of set-up between the proton and the Lead run.

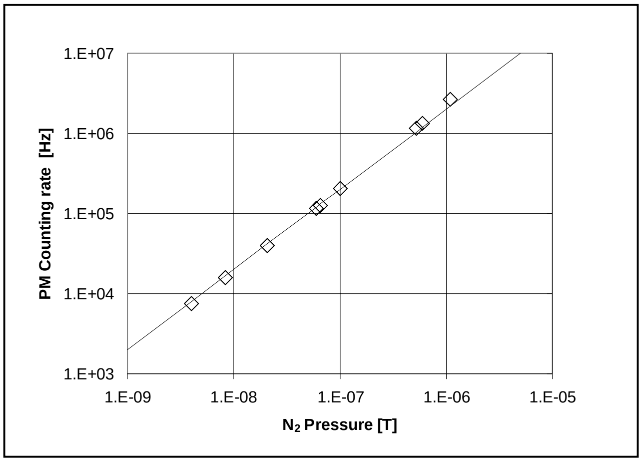

Figure 7: Light signal as a function of the N_2 pressure measured with a photomultiplier in counting mode.

A typical set of measurements is given in Fig.8, where the beam image (vertical side view) which is the same as that seen on a TV monitor, the 3-dimensional view and the projection on the vertical axis of the 200 x 200 pixels window are given.

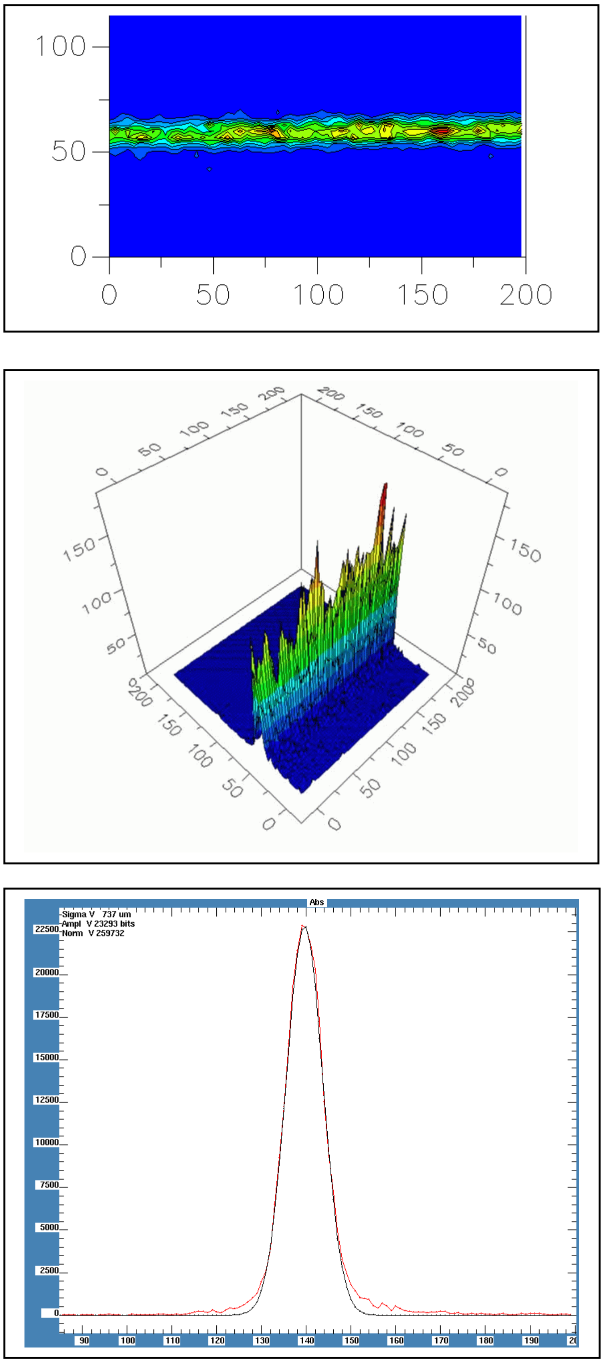

Figure 8: From top to bottom: Side view (vertical), 3-D view and Projection (vertical) with gaussian fit, of a 8 10^8 Lead ion beam at 150 GeV/nucleon with an N_2 pressure of 5 10^{-6} T. The dimensions are in pixels, with 177µm/px.

The 3-dimensional view demonstrates most clearly the statistical nature of the luminescence signal, with wild variations of the individual pixel signals; they smooth out remarkably well when summed for producing the vertical projection. In this case, the signal is integrated over 35 mm along the beam trajectory.

The beam projection is given together with the gaussian fit calculated with the data above 30% of the signal maximum. The excess beam tails are clearly visible. It seems that they are less pronounced on the Wire Scanner measurements, i.e. they may be due to an instrumental effect produced by the afterglow considered earlier. This will have to be checked more precisely.

The lowest useable signal was obtained at a pressure of 1 10^{-7} T: Fig. 9. The same signal should be obtained at a pressure of 3 x 10^{-8} T for a proton beam of 2 10^{13} particles. This would result in an average pressure increase in the SPS of 1%, which is negligible. The profile is noisy, but should still be suitable for beam size comparisons.

The monitor could not profit from the maximum MCP gain available. Only gains up to 10^3 could be used. Above this gain, the 3-D picture showed many random high level spikes which gave even more noisy profiles than the one in Fig. 9. One of the reasons could be that the detector set-up was located in the machine plane, and that stray particles were hitting the detector.

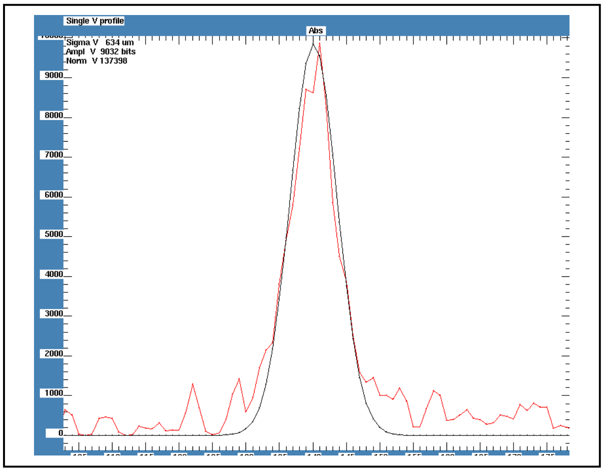

Figure 9: Beam projection obtained at 1 10^{-7} T with 8 10^8 Lead ions.

5. PLANS FOR THE FUTURE

For the 1999 run, a dedicated monitor has been installed on the SPS ring. It comprises of a dedicated “quatro” tank and has two ports equipped with quartz windows, for best transmission down to the UV and little risk of browning due to radiation.

For the start-up, only the vertical port, giving the horizontal profile this time, has been instrumented. The detector is at 750 mm below the medium plane of the SPS, protected from stray particles by its distance to the beam level and by the addition of iron shielding blocks. This should enable the MCP gain to be increased and to compensate any loss in light collection.

The magnification has been reduced to a value giving a scaling factor of 565µm/px to favour the measurements at injection energy where the beams are largest.

The CCD will be digitised over 12 bits and the whole CCD height of 288 pixels will be acquired. If necessary, the CCD can be rotated by 90° to increase the length to 384 pixels. The integration will either be done numerically or directly on the CCD by the “fast projection” mode [9]. The integration time will be adjustable from 1 revolution to 100 ms, depending on the desired time resolution and the acceptable local pressure bump. The MCP voltage will be adjustable during the SPS cycle to compensate for the change in beam size, i.e. light density, see Fig. 3 for instance.

Measurements on the beam tails and light production by the rest gas will have to be remade with better precision.

A collaboration with the Vacuum group has been initiated to improve the vacuum part of the monitor design. If the length of the pressure bump can be reduced, bearing in mind that only 15 cm beam trajectory are used for light collection, then the pressure can be increased while still staying within a 5% limit of the average SPS pressure increase.

Other issues on hand are the test of different gases and gas mixtures, which may be more efficient in light production [10], but have to be checked for decay times and compatibility with the vacuum system.

ACKNOWLEDGEMENTS

Thanks are due to J. Bosser and R. Maccaferri for allowing us to use a port of the “quatro” tank which we had installed for them in the SPS for testing their Ion Beam Scanner under development for LHC, as well as for their interest for the preliminary tests.

The collaboration and help of the LHC Vacuum Group was important and is appreciated.

REFERENCES

1. G. Ferioli et al.: “Beam Profile measurements at 40MHz in the PS to SPS transfer channels”, these Proceedings.
2. C. Bovet et al.: “The OTR screen betatron matching monitor of the CERN SPS”, these Proceedings.
3. C. Fischer, J. Koopman: “Ionization Profile Monitor tests in SPS”, these Proceedings.
4. D.D. Chamberlin et al.: “Noninterceptive transverse beam diagnostics”, IEEE Trans. on Nucl. Sc., Vol. NS-28, no. 3, June 1981.
5. J.S. Fraser: “Development in non-destructive beam diagnostics”, IEEE Trans. on Nucl. Sc., Vol. NS-28, no. 3, June 1981.
6. F. Hornstra: ”A beam induced gas scintillation (BIGS) profile monitor for HERA”, DESY HERA 89-04, January 1989.
7. R.H. Hugues, J.L. Philpot: “Spectra induced by 200 keV proton impact on Nitrogen”, Phys. Rev., Vol. 123, Nb 6, September 15, 1961, p. 2084-2086.
8. J. Camas et al.: “First test in the SPS of a gas scintillation beam profile monitor”, SL-Note-98-037 MD SPS, June 1998.
9. R.J. Colchester et al.: “Towards the limits of frame Transfer CCDs in Beam Observation”, BIW96, Argonne, May 1996, AIP Conf. Proc.390, 1996 and CERN-SL-96-10 (BI), 1996.
10. F. Sauli: private communication.

APPENDIX

Given below is an evaluation of the CCD signal at injection in the SPS for the major spectral line of N_2 [7]. This calculation has to be made for each spectral line and the results have to be summed for estimating the total signal level at the detector.

	Spectral Line	
Major line: λ	391.4	nm
Cross section [7]	3.3 10^{-7}	cm^2 at 200 keV
N_2 pressure	5 10^{-7}	T
	SPS beam	
Np	2 10^{13}	Protons
Frev	44 10^3	Hz
Energy	26	GeV
σv	3000	µm
	Optics & Detector	
Magnification	0.04	
Transmission	41	%
MCP gain	4000	
Acceptance	0.33	%
CCD pixel	23	µm H & V
CCD saturation	0.18	µJ/cm^2
	Signal	
Bethe-Bloch	1/185	attenuation
photons	4 10^{10}	s^{-1}
CCD signal	40	% of Vsat