

# FIRST BEAM MEASUREMENTS WITH THE LHC SYNCHROTRON LIGHT MONITORS\*

T. Lefevre, G. Burtin, E. Bravin, A. Goldblatt, A. Guerrero, A. Jeff and F. Roncarolo (CERN)  
A.S. Fisher (SLAC)

## Abstract

The continuous monitoring of the transverse sizes of the beams in the Large Hadron Collider (LHC) relies on the use of synchrotron radiation and intensified video cameras. Depending on the beam energy, different synchrotron light sources must be used. A dedicated superconducting undulator has been built for low beam energies (450 GeV to 1.5 TeV), while edge and centre radiation from a beam-separation dipole magnet are used respectively for intermediate and high energies (up to 7 TeV). The emitted visible photons are collected using a retractable mirror, which sends the light into an optical system adapted for acquisition using intensified CCD cameras. This paper presents the design of the imaging system, and compares the expected light intensity with measurements and the calculated spatial resolution with a cross calibration performed with the wire scanners. Upgrades and future plans are also discussed.

## INTRODUCTION

Different beam instruments have been developed and installed on LHC to monitor the transverse profiles of the proton beams. Imaging systems using intercepting screens are currently used in the transfer lines from SPS, in the LHC injection regions and in the LHC dump lines. In the ring, wire scanners provide high-resolution profile measurements from injection to top beam energies, but they cannot handle the full beam intensity.

For continuous beam imaging, one synchrotron light monitor (BSRT) per beam was developed [1] and installed in the IR-4 straight section. Protons are injected at 450 GeV, then ramped up to 7 TeV and brought into collision. Above 1.5 TeV, the light emitted in superconducting dipoles is sufficient to image the beam. The BSRT uses D3, one of four dipoles that widen the separation of the beams at the RF cavities. D3, just after the cavities, bends the orbit by 1.57 mrad and is followed by a 62-m warm drift. After 26 m, the light has diverged sufficiently from the particles to be extracted by a mirror. The light goes downward through a fused-silica vacuum viewport to an optical table below the beamline. The field in D3 reaches 3.88 T at 7 TeV, and the critical wavelength  $\lambda_c$  goes from 0.23 mm to 61 nm during the ramp.

At injection, visible emission from the dipole is very low; therefore, a short superconducting undulator [2] with  $N_u=2$  periods,  $B_u=5$  T, and  $\lambda_u=28$  cm is installed 937 mm upstream of D3. The centre of the undulator spectrum at 450 GeV is 610 nm. A detailed analysis of the light emission can be found in [3] and [4]. Fig. 1 shows that the calculated intensity varies by more than 4 orders of magnitude as the beam is accelerated to top energy.

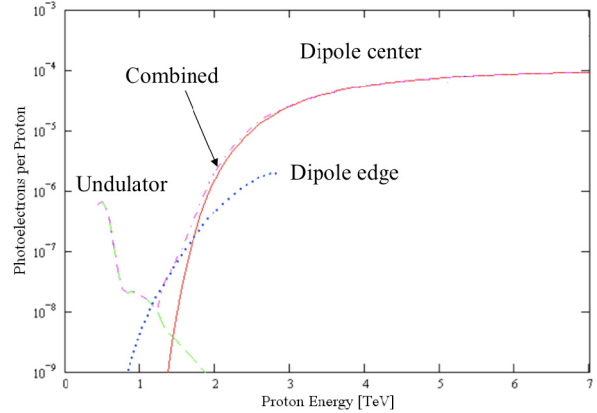


Figure 1: Light intensity as a function of beam energy.

## OPTICAL SYSTEM

The telescope is installed below the beam pipe on a vibration-damped optical table, visible in Figure 2. The first mirror on the table, M1, is remotely controlled to correct for mechanical misalignments. A 3-m adjustable “optical-trombone” delay line is used to focus on the desired light source: undulator, edge of D3 or interior of D3. Two spherical mirrors provide the required focusing; one focal length from the first, a horizontal slit with independent, remotely adjustable jaws delimits the light source and optimizes image quality. Intensity is controlled using two neutral-density filter wheels, each providing an attenuation of up to  $10^4$ . An additional 30-m optical line on the table is used for calibration and troubleshooting with the luminous target of Fig. 2. It also characterizes the telescope’s magnification and point spread function.

The optical system characteristics have been simulated using ZEMAX [5] and are summarized in Table 1. The calculated point-spread function has an RMS radius of 9.5  $\mu\text{m}$ . The images show a small horizontal elongation to one side because the light is offset from normal incidence on both spherical mirrors by a tilt of  $1^\circ$  horizontally. For undulator light, this asymmetry can be compensated by optimisation of the slit. In addition, because this light is

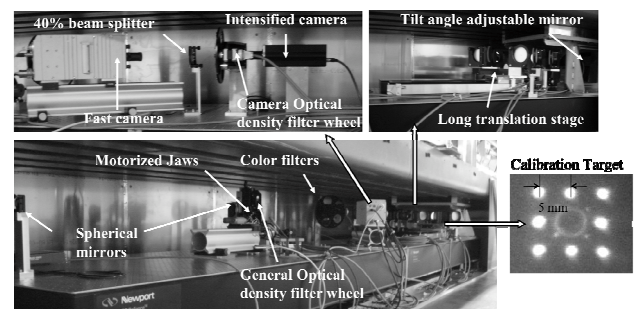


Figure 2: The LHC Synchrotron radiation telescope

emitted along the full 560-mm length, some blurring from depth of field is expected.

At higher energies, the light comes from the curved orbit in interior of D3, introducing an additional horizontal asymmetry. After the slit is adjusted, an asymmetric Gaussian fit to the image, using a common peak but different widths to either side, gives a good measure of beam size using the smaller width.

To study the blurring in the undulator, a series of simulations were performed with ZEMAX trying to simulate an extended source by considering a moving object with a size of 1mm over a distance of 56cm. The results are plotted in Figure 3. Assuming a Gaussian bunch distribution and integrating over the length of the undulator, the expected increase in beam size is found to be very small, of the order of few percents.

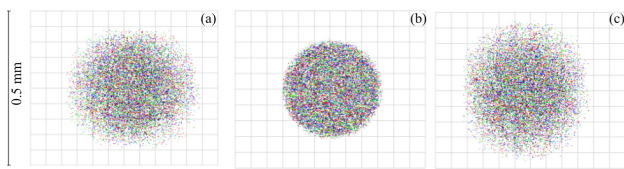


Figure 3: Evolution of the measured spot size as the source moved along the undulator: beginning (a), centre (b) and end (c). The image is at focus in the central part of the undulator.

As the beam energy increases, the transverse beam size shrinks. The expected beam sizes are summarized in Table 2. Based on our calculations [3, 4], the accuracy of the beam size measurement should be of the order of few percent at injection energy and not better than 20% at top energy due mostly to diffraction effects.

Table 2: Nominal beam sizes for different beam energies

Beam Energy	Beam size ( $\mu\text{m}$ )	
	Horizontal	Vertical
450GeV	1302	1244
3.5TeV	473	447
7TeV	334	315

## AUTOMATIC SETTINGS

During the operation of the accelerator, the telescope should be adjusted automatically following the variations in beam intensity, beam energy and beam sizes. As the LHC will experience the various commissioning and operation phases, the beam intensity will increase from a single “pilot” bunch of  $5 \times 10^9$  protons up to 2808 nominal bunches of  $1.1 \times 10^{11}$  protons. Consequently, the light intensity on the cameras must be tuned to cope with a 5 orders of magnitude beam intensity variation. During the energy ramp, several components need to be adjusted as well. The delay line provides the switching among sources (undulator, D3 edge and D3 core) and the optical density filters the attenuation of the increasing light

emission as shown in Fig. 1. In order to obtain optimized performances the slits and the colour filters should also be adjusted as the beam energy evolves. During periods with beams circulating at constant intensity and energy, beam losses and emittance growth also induce light intensity and density variations. Adjusting the gain of the intensified camera refines the coarse adjustment of the light intensity obtained with the neutral filters.

A first version of the automatic control of the synchrotron light monitors has been implemented. It is already compensating for light intensity changes during the fill and during the ramp. For high beam energies, a blue colour filter is inserted to limit the spot size growth due to diffraction. The adjustment of the delay line is still done manually for the moment at injection and at the end of the ramp. The main limitation comes from a small misalignment of the trombone, which induces a beam position offset that must be corrected by M1. A feedback on the position will be implemented soon to overcome this limitation. The slits jaws are also positioned manually for the time being as we determine their optimal settings.

## BEAM MEASUREMENTS

The synchrotron light monitors have provided a continuous stream of beam images since the start-up of LHC. Fig. 4 shows a sample of typical beams images and profiles. At injection energy, the intensified CCD camera, provides an amplification of up to 2000, sufficient to image a pilot bunch circulating for few turns. The evolution of the light intensity as a function of the beam energy has been measured and is shown in [6].

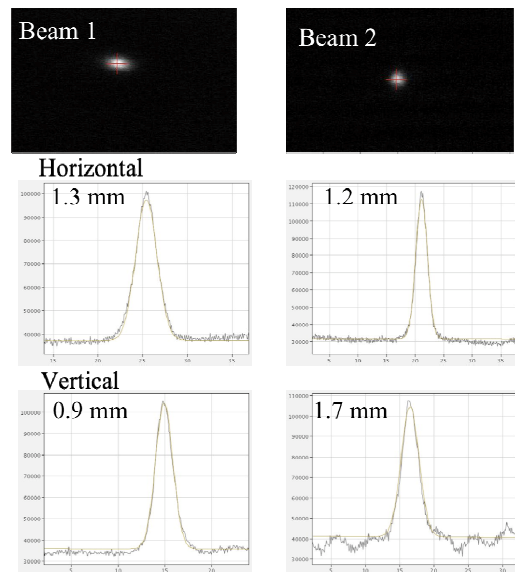


Figure 4: Beam images and profiles at 450GeV

As a first cross-calibration, the centroid of the beam spot measured with the synchrotron light camera has been compared to the beam position measured with the beam position monitors. The comparison was performed during beam orbit adjustments in the horizontal plane and the result is shown in Fig. 5. The difference is below 5% and

validates the calibration of the telescope's magnification performed using the calibration target.

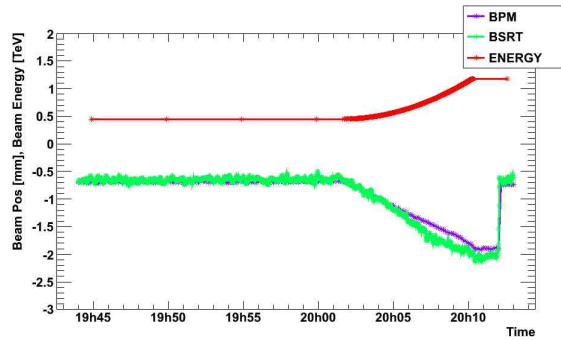


Figure 5: Beam positions vs. time measured with the beam position monitors and the BSRT

Figure 6 presents the beam intensity measured with the Beam Current Transformer (BCT) and the intensity calculated from the BSRT images and vertical beam profiles. The beam intensity is calculated from the Gaussian fit of the profiles as the product of the amplitude and sigma. The agreement in terms of relative intensity change is very good. The plot also shows an increase in beam size over time. The source of this growth in the vertical emittance is not yet understood.

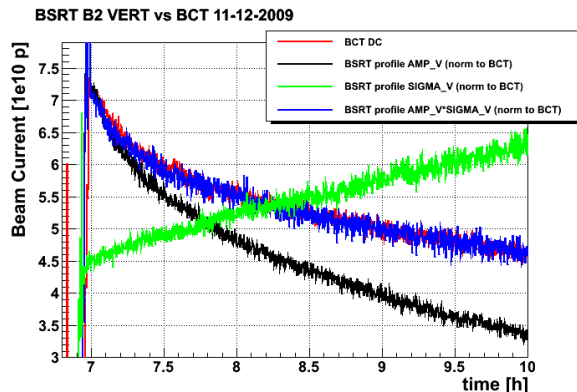


Figure 6: Comparison between the DC beam current transformer and the synchrotron light monitors

For another cross-correlation, profile measurements were also acquired at low intensity using the wire scanners at different times during the machine cycle. Comparisons between the two instruments are displayed in Figure 7. The beam emittances have been calculated using the measured profiles and the betatron function values at the positions of the SR monitor and the wire scanners. The absolute values agree within 20% and the relative variations are in much closer agreement.

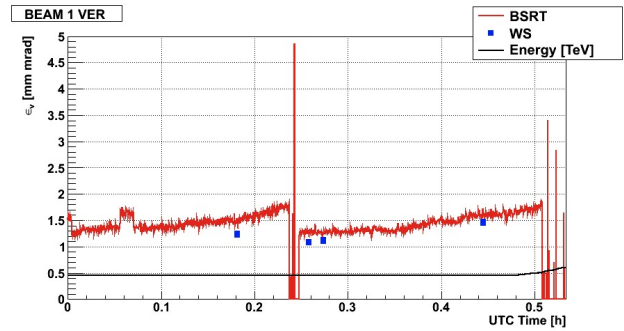


Figure 7: Emittance evolution with the BSRT and the wire scanner

## CONCLUSION

The LHC synchrotron light monitors have been commissioned successfully. As expected, the superconducting undulator is required at injection energy in order to obtain sufficient light. The telescopes are now routinely used over the full energy range to provide continuous monitoring of the beam sizes.

Systematic comparisons between the synchrotron light monitors and other beam instruments have been done and have shown reasonable agreement. At injection and top energies, the telescope has been commissioned extensively, and beam profiles measured by the BSRT and the wire scanners agree within 10-20%. Nevertheless the system still needs to be improved in order to provide the best accuracy during the whole energy ramp.

A turn-by-turn and bunch-by-bunch imaging system is also currently being developed as an additional synchrotron light monitor. This device uses a gated image intensifier coupled to the 'Redlake HG-100k' camera, capable of acquiring images at 100kHz. A minimum gate of 5 ns can select one bunch and follow it turn by turn.

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