DESIGN AND PERFORMANCE OF THE UPGRADED LHC SYNCHROTRON LIGHT MONITOR

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Abstract

The LHC is equipped with two synchrotron radiation systems, one per beam, used to measure the transverse bunch distributions. The light emitted by a superconducting undulator and/or by a dipole magnet (depending on beam energy) is intercepted by an extraction mirror in vacuum and sent through a viewport to the imaging Beam Synchrotron Radiation Telescope (BSRT). The first version of the telescope, used from 2009 to mid 2012, was based on spherical focusing mirrors in order to minimize chromatic aberrations. However, this required a very complicated delay line in order to switch the focus between the two different light sources as a function of beam energy. A new system based on optical lenses was designed and installed in mid 2012 in order to simplify the optical line and thus reduce misalignment and focusing errors. The first results with LHC beam using this new system showed a significant reduction in the correction factor required to match the emittance as measured by wire scanners. This contribution discusses the performance of the new optical system, presenting the LHC results and comparing simulations with measurement performed in the laboratory using a BSRT replica.

OVERVIEW OF THE SYSTEM

Light Sources

The BSRT monitor images the synchrotron light generated by beam particles traversing two supeconducting magnets (an undulator and a dipole) located one after the other. From the LHC injection energy (450 GeV) to about 1.5 TeV, the radiation generated by the undulator is in the visible range, and shifts to the X-rays for the top energy. Particles traversing the dipole emit light in the visible range from 1.2 TeV onwards [1].

The BSRT extraction mirror located 27 m downstream of the magnets collects the light coming from the undulator and the dipole, as sketched in Fig. 1 . Therefore, the imaging system must focus objects at different distances depending on the beam energy. A non proper focusing results in a blurring of the image.

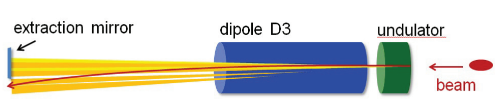

Figure 1: Sketch of the BSRT light sources.

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Optics

The BSRT light extraction system is based on a retractable mirror in vacuum, that re-directs the intercepted light through a view port to an optical table located below the beam pipe. The first mirror on this table is motorized and is used to adjust the light steering for the following elements, in order to cope with beam position drifts and any fluctuation/vibration of the table. The table is also equipped with the optics for reconstructing the transverse beam profiles. Those are acquired by an intensified CCD camera whichallows the measurement of a single pilot bunch of 5x109 charges at LHC injection energy in a single turn.

Given the large distance needed between the light sources and the extraction mirror to separate the photons from the beam, a two-focusing element system is necessary to achieve the imaging on a reasonably short table and with the desired magnification (CCD acceptance). At the LHC top energy, the resolution of the system is limited by optical diffraction, and as this is proportional to the wavelength, a 400 nm bandpass filter is placed in front of the camera.

At two different stage, the light is splitted in order to send part of the radiation to two other detectors for longitudinal diagnostics (the abort gap and the longitudinal density monitors).

A laser beam following the same path as the synchroton light in the beam pipe allows the optical elements, including the extraction mirror, to be precisely aligned. In addition, a calibration line on the table, based on an optical target placed at a distance from the camera equal to the undulator distance (via folding mirrors sending the light back and forth on the table multiple times) is used to verify the focusing and optical magnification of the system.

COMPARISON OF MIRRORS VS LENSES

Spherical Mirror Optics

From the beginning of the LHC operation until the end of 2012, the imaging was done with two spherical mirrors of 4000 mm and 750 mm focal lengths, labeled as F1 and F2 respectively in Fig 2. The choice of spherical mirrors was motivated by the need of ensuring high image quality from 250 to 800 nm. Theoretically, the performance of spherical mirrors is better than glass lenses, since they produce no chromatic aberrations.

The optics focused the light coming from the center of the undulator. In order to keep the focalization at higher beam energies while the SR light source shifted from the undulator to the dipole, a motorized delay line composed of eight mirrors on translation stages was used. This permitted the path length between the source and F1 mirror to be extended by 3 m, which corresponds to the distance between the undulator center and the last point in the dipole where emitted SR is collected by the extraction mirror. The final image had an optical de-magnification of 0.3.

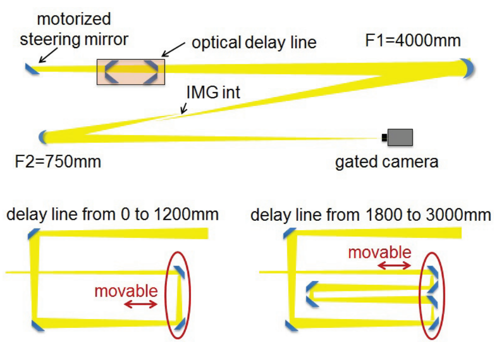

Figure 2: Sketch of the optical line with spherical mirrors.

Lens Optics

The operation of the BSRT with spherical mirrors posed some problems that will be discussed later in this document. It was consequently decided to change the telescope layout and replace the focusing mirrors by lenses. This allowed removing the delay line and installing the second lens on a movable stage in order to change the focusing according to the beam energy. The resulting optical variations with beam energy was considered a negligible drawback with respect to the previous system and is well counterbalanced by a much simpler optical line. The difference between the two optical line layouts can be seen in Fig. 3 and 4. It also freed space on the optical table for testing alternative imaging techniques (e.g. interferometry).

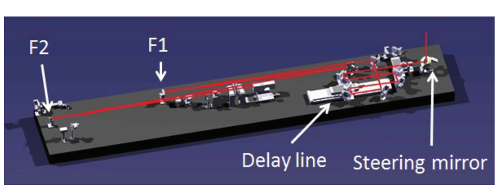

Figure 3: Optical line based on focusing mirrors.

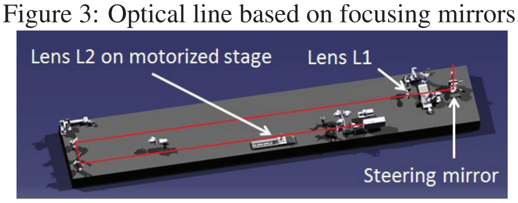

Figure 4: Optical line based on focusing lenses.

The two lenses (labeled L1 and L2 in Fig. 4, with 4810 mm and 300 mm focal length respectively), are

Table 1: Comparison of the Mirror Based and Lenses Based Optics in Terms of Magnification and PSF (Raytracing, no Diffraction and Extended Source Effects)

E [GeV]	Mag		PSF [um]	
	Mirrors	Lenses	Mirrors	Lenses
450	0.3	0.6	18	25
4000	0.3	0.55	3.5	5

custom designed achromat lenses optmised for 400 nm. The optical magnification, which was constant and equal to 0.3 with the spherical mirror optics, is now 0.6 at injection energy (focusing on the undulator) and 0.5 at higher energy (focusing on the D3 dipole).

Simulation of the Two Systems

The point spread function (PSF) at the image plane for injection and top energy were simulated with Zemax [2] for both systems, without taking into account the effect of diffraction and extended source (ray tracing mode). Table 1 summarizes the results of these simulations. In order to understand as precisely as possible the expected performance of the system and the contribution of diffraction, simulations were also done with the Zemax *Physical Optics Propagation* (POP) mode. With this method, the synchrotron radiation electromagnetic field is propagated through each surface of the system (mirrors, lenses) and scored at the image plane, allowing the effect of the extended light source and diffraction to be taken into account. Such effects are not resolved by the conventional Zemax sequential (i.e. ray tracing) mode.

The electromagnetic field used as input to Zemax, was generated with SRW [3], at a single wavelength of 400 nm. The image (and the corresponding horizontal profile) reconstructed at the camera location with such a method, considering a single proton at 4 TeV traveling through the D3 dipole, is shown in Fig. 5.

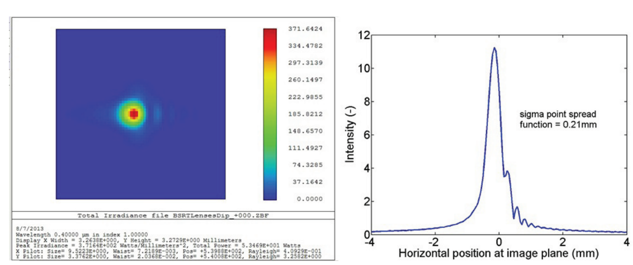

Figure 5: Image and horizontal profile as scored by Zemax (POP mode) at the image plane, for a single proton traveling through the D3 dipole.

Table 2 shows the horizontal and vertical PSF values, after applying the proper magnifications (i.e. transported to the object plane), for both spherical mirror and lens optics, when focussing on the undulator and on the dipole.

ISBN 978-3-95450-127-4

Table 2: Point Spread Function at the Object Plane, as Calculated by Zemax POP

Energy [GeV]	Plane	PSF [mm]	
		Mirrors	Lenses
450	H	0.273	0.268
	V	0.197	0.191
4000	H	0.414	0.445
	V	0.399	0.363

Considering a beam size of 1 mm at low energy, when the BSRT is focused on the undulator, the calcultaed PSF is about 20% of the beam size. At high energy, when the beam size is about 0.34 mm, the PSF is about 100% of the beam size. Given the small difference in the PSF values for the two optical layouts and the results from Zemax ray tracing, it can be concluded that the chromatic aberrations introduced by the lenses are negligible compared to the contribution of diffraction.

LABORATORY TESTS

Before installing the new telescope based on lenses in the LHC, the optics was tested in the laboratory on an optical table that is an exact replica of the tunnel system. An extended light source cannot be easily implemented in the laboratory, and the tests were based on illuminating optical targets and imaging them with a camera at a distance equal to the undulator (or dipole) distance using a folding mirror calibration line. At first (via a target with alphanumeric characters) it was possible to verify the focal length of the lenses, found to be within 2 % the theoretical ones.
Then, the same target was used to find the lens and camera positions for the proper focusing at injection and top beam energies. Finally, the alphanumeric target was substituted by a circular iris and its image acquired for different camera positions. As expected in the BSRT case, the imaged iris size follows a parabola (see Fig. 6), where the minimum determines the best image plane (the geometrical aberrations are minimized with negligible influence of the magnification). The positions of the lenses and camera found with these methods were in accordance with Zemax simulations.

The same experiment was repeated in the tunnel, where the measurement result was more noisy and it was not possible to reproduce a parabola. This was attributed to air flows stronger than in the laboratory. Nevertheless, the imaging of the alphanumeric target positioned at the undulator distance resulted in a proper focusing when installing the optical elements (L1, L2 and camera) according to the laboratory test results.
The laboratory setup was also beneficial for testing the alignment procedures, the mechanics (e.g. custom made supports) and controls (e.g. motors), before the installation in the LHC tunnel, which had to be done in a limited time.

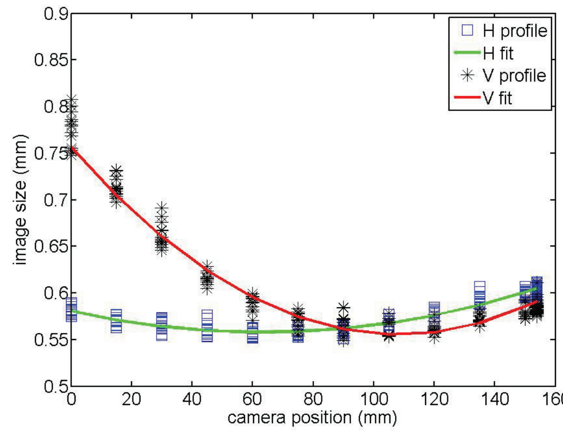

Figure 6: Example of lab measurements: image size of a circular iris for different camera positions. The points are fitted with a parabola, whose minimum corresponds to the image plane.

MEASUREMENTS WITH BEAM

The Operation of the BSRT from 2009 to 2012 comprised dedicated time for the commisionning of the instrument and its calibration. The LHC Wire Scanner (WS) detectors are the reference beam size monitors and have been used to cross-calibrate the BSRT transverse profile measurements. At constant beam energy, the expected beam sizes at the BSRT location $\sigma_{x,y}^{BSRT}$ are simply given by:

$$\sigma_{x,y}^{BSRT} = \sigma_{x,y}^{WS} \sqrt{\frac{\beta_{x,y}^{BSRT}}{\beta_{x,y}^{WS}}} \quad (1)$$

where $\sigma_{x,y}^{WS}$ are the beam sizes measured by the WS and $\beta_{x,y}^{BSRT}, \beta_{x,y}^{WS}$ the betatron functions at the two monitors. Such a cross-calibration has been used to calculate correction factors to be applied to the BSRT measurements. This factor includes the geometrical aberrations and the diffraction PSFs, and since these are considered gaussian, they are subtracted in quadrature from the measurement according to:

$$\sigma_{x,y}^{BSRT} = M\sqrt{{\sigma_{m\ x,y}^{BSRT}}^2 - {\sigma_{c\ x,y}}^2} \quad (2)$$

Where M is the magnification of the optical system in mm per pixel (of the camera), $\sigma_{m\ x,y}^{BSRT}$ the BSRT measurement results (in pixels), and $\sigma_{c\ x,y}$ the correction factor (in pixels).
The BSRT-WS cross-calibration was performed periodically. In particular, during dedicated LHC machine development periods the beam emittance was changed on purpose (either bunch per bunch or fill per fill) in order to verify the cross-calibration for different beam size values.

With the mirror based optics, such studies resulted in correction factors $\sigma_{c\ x,y}$ larger than expected (see table

3). In addition, the correction factors changed from one calibration session to the other [4], [5]. A major source of error and calibration stability was identified in the system alignment, strongly affected by the eight movable mirrors of the delay line. The misalignment often resulted in a variation of the optical aperture during the steering of the light spot on the camera and/or moving the delay line. With the lens based system, measurements showed a significant reduction of the calculated correction factors, as shown in Table 3.

When compared to the PSF calculated by Zemax (Table 2), the correction factors are in good agreement at 4 TeV, but are 4 times larger at injection energy. A factor 2 can be explained by the fact that the bandpass filter of 400 nm (included in the simulations) cannot be used during measurements at low energy. Since the undulator radiation is maximum at around 800 nm, diffraction is doubled. Time was missing to investigate the other sources of errors, and this will be continued after the restart of the LHC.

Table 3: Correction Factors and Expected Beam Size for 3 um Emittance [mm]

Energy	Plane	Corr. Factor σ_c Mirrors	Lenses	beam size
450 GeV	H	0.9	0.85	1.05
	V	1.1	0.87	1.09
4 TeV	H	0.6	0.35	0.35
	V	0.7	0.33	0.37

The comparison between BSRT and WS in terms of horizontal normalized emittance is shown in Fig. 7. During this set of measurements (at injection energy) the emittance was increased on purpose to perform the cross-calibration for different absolute beam sizes, while applying a constant correction factor to the BSRT (0.85 mm). After correction, the agreement between the two monitors is excellent.

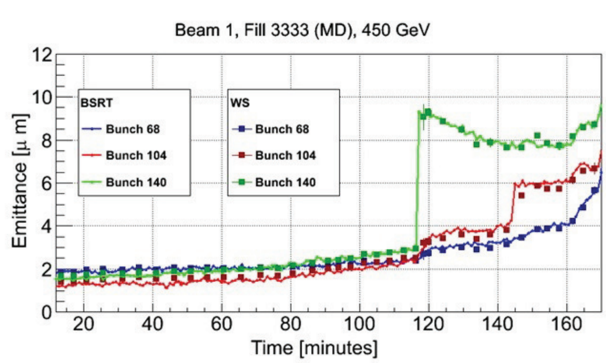

Figure 7: Comparison between BSRT and Wire Scanner.

Even though the correction factor stability in time improved after the optics upgrade, they were still found to drift. Indeed, a drift of the light spot on the camera has been observed as soon as the LHC total intensity and intensity per bunch were increased. This was later also correlated to the beam spectrum (shorter bunch lengths enhanced the effect). Following such observations, a simulation and laboratory campaign were launched in order to characterize the electromagnetic coupling and a new design aiming at minimizing the coupling (i.e. the heating) is in progress [6].

CONCLUSION AND PERSPECTIVES

The replacement of the spherical mirrors by lenses significantly improved the quality of the measurement. It also simplified the operation of the instrument itself, by reducing the misalignement and thus the steering corrections that had to be applied, and saved space on the optical table.

During the LHC long shut down which is now in progress, it is planned to make important upgrades to the BSRT. Achromat lenses optimized around 250 nm will be installed and will be used for high energy beam in order to reduce diffraction. Also, a double slit interferometry system will be installed in parallel to standard imaging. This method is expected to give better resolution, since the diffraction is not a limitation. A replacement of the extraction mirror assembly will be also performed in order to minimize RF coupling.

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ISBN 978-3-95450-127-4