PERFORMANCE OF THE UPGRADED SYNCHROTRON RADIATION DIAGNOSTICS AT THE LHC

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Abstract

During the LHC long shut down in 2014, the transverse beam size diagnostics based on synchrotron radiation was upgraded in order to cope with the increase of the LHC beam energy to 6.5 TeV. The wavelength used for imaging was shifted to near ultra-violet to reduce the contribution of diffraction to the system resolution, while in parallel, a new diagnostic system based on double slit interferometry was installed to measure the beam size by studying the spatial coherence of the emitted synchrotron radiation. This method has never been implemented before in a proton machine. A Hartmann mask was also installed to identify possible wavefront distortions that could affect the system accuracy. This paper will focus on the comparison of visible and the near ultra-violet imaging and on the first experience with interferometry.

INTRODUCTION

The synchrotron light monitors, being the only instruments continuously measuring the beam emittance bunch-by-bunch, play an important role in the performance optimisation of the LHC. A big effort took place during the CERN Long Shutdown in 2014 (LS1) to upgrade this diagnostic tool to cope with the increase of the beam energy to 6.5 TeV. This paper summarizes the challenges the system faced in Run I (2009-2013), the improvements it underwent in LS1 and its performance at the start of Run II in 2015. This will concentrate on the SR imaging system but will also also offer a first glance at results from the first ever proton SR interferometry prototype. In addition, the future upgrades currently under study will be briefly discussed.

MONITORS IN RUN I

The Beam Synchrotron Radiation Telescopes (BSRT) in the LHC have been continuously evolving since their installation in 2009.

The original imaging system was a two stages focusing system based on two fixed focusing mirrors [1]. It featured a sophisticated variable light delay path, known as the "trombone", consisting of 8 mirrors used to cope with the shift of the longitudinal position of the SR source from an undulator to an adjacent bending magnet during the beam energy ramp. With this system the calibration factors obtained by simultaneously measuring the beam size with the BSRT and the Wire Scanners (WS) were not stable over time. It was subsequently demonstrated that the system's performance suffered from misalignment [2] with the expected benefits of chromatic aberrations reduction using reflective optics compromised by the increase of diffraction phenomena caused by SR incident on the edges of the mirrors.

The first upgrade consisted of replacing the reflective optics with refractive optics and eliminating the complex delay line. The shift of the SR source from the undulator to the dipole was instead compensated by automatically moving one of the lenses in the optical system. Studies showed that, despite the theoretical worsening of aberrations, the overall system accuracy and stability would be improved thanks to its reduced complexity (i.e. less optical elements) and ease of alignment [3]. This was confirmed with beam measurements where both the measured resolution and stability was found to be drastically improved. However, the new system had an intrinsic resolution limit due to diffraction for the small beam sizes (200-300 μm) expected at the LHC design beam energy of 7 TeV.

During the last year of Run I operation, the stability and the optical resolution was seen to worsen with time. This was traced to heating of the light extraction system caused by electromagnetic coupling with the beam as the total and bunch intensities increased. This produced a deterioration of the mirror coating and ultimately led to a failure in the mirror support mechanism [4]. The CERN Long Shutdown 1 (LS1) was the best opportunity to tackle all these limitations with a refurbishment of the entire system to cope with the planned energy increase to 6.5 TeV in Run II.

BSRT REFURBISHMENT IN LS1

The urgent issue to tackle in LS1 was the reliability of the SR extraction system. A new holder for the in-vacuum extraction mirror, featuring smoother transitions in the beam pipe, was designed with a much lower longitudinal impedance. The silicon bulk mirror was also replaced by a dielectric coated glass bulk mirror to reduce the absorbed heat and consequently deformation of the coating. The new system was validated both via simulations and experimentally using the stretched wire technique for impedance measurement [2].

To monitor and measure any deformation and irregularities on the mirror surface (resulting from the coating process or caused by heating due to the EM coupling), a Hartmann Mask [5] was installed. This allows any wavefront distortion caused by the mirror to be measured by sampling the extracted SR with an opaque screen filled with a pattern of holes, as shown in Fig. 2. The spacing between the light spots observed on a camera at a certain distance from the mask is directly related to the surface flatness of the optical

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components transporting the light, in this case mainly the in-vacuum mirror.

At high energies the radiation emitted by the dipole is broadband and the effects of diffraction can be reduced by using short wavelength SR. A Near Ultra-Violet (NUV) imaging system, with lenses optimized for operation at 250 nm, was implemented alongside the existing system which was optimized for 600 nm. As predicted by simulations [6], changing the imaging wavelength to the NUV region improved the resolution but still requires important corrections dominated by diffraction for very small beam sizes. For this reason, alternative methods for beam size measurement have been investigated.

SR Interferometry

The interferometry technique, described in [7], was found to be the best alternative to direct imaging for beam size measurement with visible SR. It consists of determining the size of a spatially incoherent source by probing the spatial distribution of the degree of coherence after propagation, with an achievable resolution of a few microns. Based on the findings in [2], where the instrument was fully characterized, a prototype was installed for measuring the vertical beam size on one of the LHC beams. The system consists of a set of simple double slits, an apochromat lens and an eyepiece. The line is also equipped with a linear polarizer (Glan Laser Cube), a bandwidth filter and a digital sCMOS camera optically coupled to a gated intensifier.

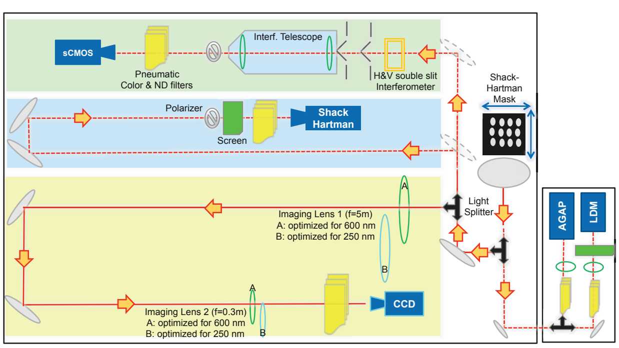

Figure 1: Layout of the LHC SR optical table for Run II.

The layout of the optical table at the end of LS1 is sketched in Fig. 1, where the integration of the imaging lines, the Hartmann monitoring line, the interferometry line and the complex splitting mechanism between the various systems is shown.

PERFORMANCE IN RUN II

Status of the SR Extraction System

During the intensity ramp up in the LHC beam commissioning at the start of Run II, the temperature of the extraction mirror was closely monitored via in-vacuum probes installed on the mirror holder. No significant heating was observed, confirming the results of the simulations and laboratory test. The flatness of the extraction mirror was also checked using

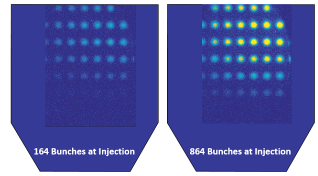

Figure 2: Hartmann Mask pattern captured for a different total intensity circulating in the LHC (left 144 bunches, right 864 bunches)to study any extraction mirror deformation.

the Hartmann line, investigating effects of beam intensity. Figure 2 shows snapshots of the Hartmann patterns sampling the extraction mirror when the machine was filled with 144 and 864 nominal bunches. The maximum deformation observed to be around 130 μm at the detector plane, corresponding to a mirror deformation of $\lambda/5$ at 650 nm and considered acceptable being in the shadow of the original coated mirror flatness of $\sim\lambda/4$.

Beam Size Calibration

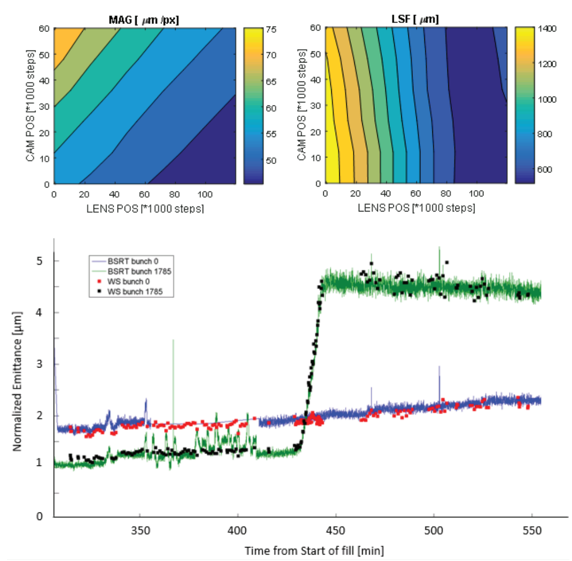

Figure 3: Top: BSRT Optical magnification and resolution for various combinations of lens and camera. Bottom: Emittance evolution as measured by the WS and a calibrated BSRT.

The beam size σ_{Beam} is extracted from the BSRT measurements ($\sigma_{BSRT_{meas}}$) by applying a correction in quadrature, assuming a Gaussian Line Spread Function (σ_{LSF}) as the resolution of the optical system:

$$\sigma_{Beam} = \sqrt{\sigma_{BSRT_{meas}}{}^2 - \sigma_{LSF}{}^2} \quad (1)$$

The correction is the result of the convolution of the broadening caused by diffraction, the depth of field in the dipole and any eventual aberrations. This is calculated through calibration with the WS measurements. A new calibration technique studied in [2] was used, allowing both the magnification K and resolution (σ_{LSF}) of the optics to be extracted

ISBN 978-3-95450-147-2

from the cross-calibration with the WS. The former is derived from the slope and latter from the offset of a linear regression in terms of ${\sigma_{BSRT_{meas[px]}}}^2$ and ${\sigma_{WS[mm]}}^2$:

$$ {\sigma_{BSRT_{meas\,[px]}}}^2 = \left(\frac{\frac{\beta_{BSRT}}{\beta_{WS}}}{K} \right) {\sigma_{WS\,[mm]}}^2 + {\sigma_{LSF\,[px]}}^2 \quad (2) $$

with β_{BSRT} and β_{WS} being the beta functions at the SR source and the WS respectively. The full calibration process includes scanning both the focusing lens and the camera searching for the combination featuring the lowest σ_{LSF}. A typical result map is shown in Fig. 3 (top right) where the focus can easily be found. Figure 3 shows also the evolution of the normalized emittances for two bunches over a large range as measured by the WS and the BSRT indicating the validity of this calibration procedure. With respect to the visible optical system in Run I where the resolution was found to be 395 µm and 350 µm for the horizontal and vertical plane respectively, the RUN II NUV system improved the resolution by 15-20% (H:345 µm, V:280 µm).

This calibration technique, that does not need slow closed orbit beam bumps to calculate the optical magnification, allows a calibration "on the fly" during the energy ramp, producing an energy dependent correction curve that can be used to measure the beam size from 2 TeV, once the visible SR is emitted exclusively by the bend.

Interferometry

The interferometer is a wavefront-division-type two-beam SR interferometer using polarized, quasi-monochromatic light. It probes the spatial coherence of the SR, in particular measuring the first order degree of mutual spatial coherence Γ. The double slit samples the incoming wavefront to obtain the one-dimensional interference pattern along the vertical or horizontal axis. The intensity of the interference pattern measured on the detector plane depends on: Γ, the single slit width, the separation between the two slits, the wavelength of observation and the focal length of the optical system.

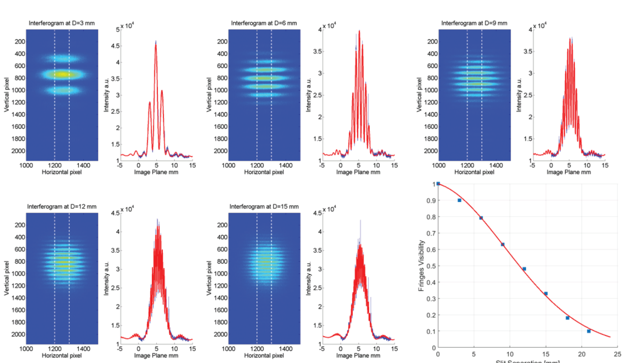

Figure 4: Interferograms and fringe visibility obtained at various double slit separation.

The visibility of the interferogram fringes, using the intensities I_{max} at the peak of the interference fringe and I_{min} at its valley, is defined as:

$$ V = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} = \frac{2\sqrt{I_1 \cdot I_2}}{I_1 + I_2} |\Gamma| \quad (3) $$

where I_1 and I_2 are the light passing through the first and the second slit respectively. Figure 4 shows the results of a beam size measurement where the intensity pattern is recorded for varying slit separation D. Accounting for the intensity imbalance factor leads to the curve |Γ(D)| that allows the reconstruction of the vertical beam distribution according to the Van Cittert-Zernike theorem [7].

Preliminary measurements show a discrepancy with the WS measurements of almost 30-35%, where the beam size inferred by interferometry results in an underestimation. Beam size overestimation can normally be attributed to source movement, air turbulence, noisy optical system, chromatic aberration or incoherent depth of field effects, but it is harder to explain this underestimation. An additional de-focusing deformation in the SR path before the slits, detector non linearity, bad background subtraction and different linear coupling values at the SR source and the WS are all being investigated to explain this underestimated beam size.

The installation of the finalized setup of the interferometer for the 2016 run will allow this issues to be studied in detail with the aim of providing a reliable calibration free beam size measurement by interferometry.

FUTURE DEVELOPMENTS

Seeing the encouraging interferograms obtained with the prototype interferometry system of the BSRT, it is foreseen to install fully motorized slits that will allow both horizontal and vertical beam size measurement. It was also reassuring that no radiation issues nor particular aging was observed with the operation of the digital camera installed for the interferometry measurements. Given the extremely low image noise compared to the analog cameras used for standard imaging, it is now planned to replace all the fiber-coupled, intensified, analog cameras by digital optically-coupled intensified sCMOS sensors. This would greatly reduce the time needed to scan speed reducing the time needed to scan a full ring of 2808 bunches from some 10 minutes to less than a minute.

CONCLUSIONS

The LHC Synchrotron radiation monitors have undergone several overhauls since their initial installation. The redesign of the in-vacuum light extraction mirror and its holder played a key role in improving the stability and reliability of the system in Run II. Additionally the refurbishment of the optical system, mainly shifting the imaging wavelength to NUV for top energy improved the optical resolution leading to higher accuracy measurements. Finally, the first ever proton SR interferograms show very promising results with a systematic qualification of this technique expected in 2016 once the finalized setup is installed.

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ISBN 978-3-95450-147-2