# WHAT YOU GET? TRANSVERSE AND LONGITUDINAL DISTRIBUTIONS

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*Abstract*

The transverse beam emittances of the LHC proton and ion beams can be inferred by measuring the beam sizes with Wire Scanner (WS), Synchrotron Radiation (BSRT) and Beam Gas Ionization (BGI) monitors. The Abort Gap Monitor (AGM) and the Longitudinal Density Monitor (LDM) are used to characterize the longitudinal distributions. This paper covers at first all aspects related to the use of such devices in 2012. Achieved performances, reliability and operational limitations, like system failures due to high intensity beams or ageing are covered. A particular emphasis is given to the planned system upgrades for improving accuracy and robustness, while coping with both the operational limits and the LHC energy and intensity upgrades after LS1. This includes the impact of the 25 ns bunch spacing on the bunch per bunch measurements and the need for resolving smaller beam sizes at 7 TeV.

## TRANSVERSE DISTRIBUTION MEASUREMENTS

### *Wire Scanners (WS)*

The LHC is equipped with eight WS systems. Four are kept operational (one per plane per beam) while four spares can be connected remotely without interventions in the machine. They act as a reference (cross-calibration) for other devices, but can be used only below a threshold intensity that depends on energy (see Table 1). Above the threshold, wire damage and/or dumping the beam due to downstream BLM interlocks can occur, as verified through simulations and experiments. The corresponding BLM thresholds are set to minimize to possibility of a superconducting magnet quench. Failures/issues during 2012 were related to bellow vacuum leaks, wire breaking and beam dumps due to downstream BLMs.

The WS bellows are designed to withstand about 10000 scans. Indeed, in 2012 there was only one system failure, after about 10200 scans. Since each system's history is logged, the probability of such a failure is predictable and switching to the spare scanner should be the baseline when the number of executed scans approaches the design limit.

| Beam Energy $[TeV]$ | Intensity Threshold $[protons]$ | Dominant Reason |
|---|---|---|
| 0.450 | $2.7 \cdot 10^{13}$ | Wire damage |
| 4 | $3.6 \cdot 10^{12}$ | BLM threshold |
| 6.5 | $1 \cdot 10^{12}$ | BLM threshold |

Table 1: Beam intensity thresholds above which WS measurements are software interlocked.

Concerning wire damages, in 2012 there was no evidence of wire breakage due to beam induced effects (RF coupling or direct energy deposition) during normal operation. However, there was evidence of wire diameter reduction (34 $\mu m$ Carbon wires are used for the LHC WS) due to sublimation, as shown in Fig. 1.

On two occasions (Nov 14, 2012 and Jan 20, 2013), while the operator requested scans on both beams at the same time, the WS systems failed, the wires remained stuck in the IN position with circulating beam and consequently broke. In both cases the FESA server crashed after the IN movement. In the first occasion, the sever crash followed a failure of the WS actuator power supply, while for the second occasion the crash reason is not yet understood despite several attempts to simulate the behaviour without beam in the machine.

Concerning the dumps due to BLMs detecting the losses downstream the WS systems, it must be noted that during the year the intensity thresholds mentioned above were tuned to allow the scan of the maximum possible intensity in a safe way with respect to quench probability. The BLM thresholds were adjusted by measuring losses induced by a scan. In some cases, it turned out that the losses depend on the wire ageing, i.e. to the wire actual diameter. As evidenced in the examples of Table 2, this led to beam dumps after replacing a broken wire, since the new wire induced higher losses than the previous (aged) one.

During 2012 it was possible, especially during MD

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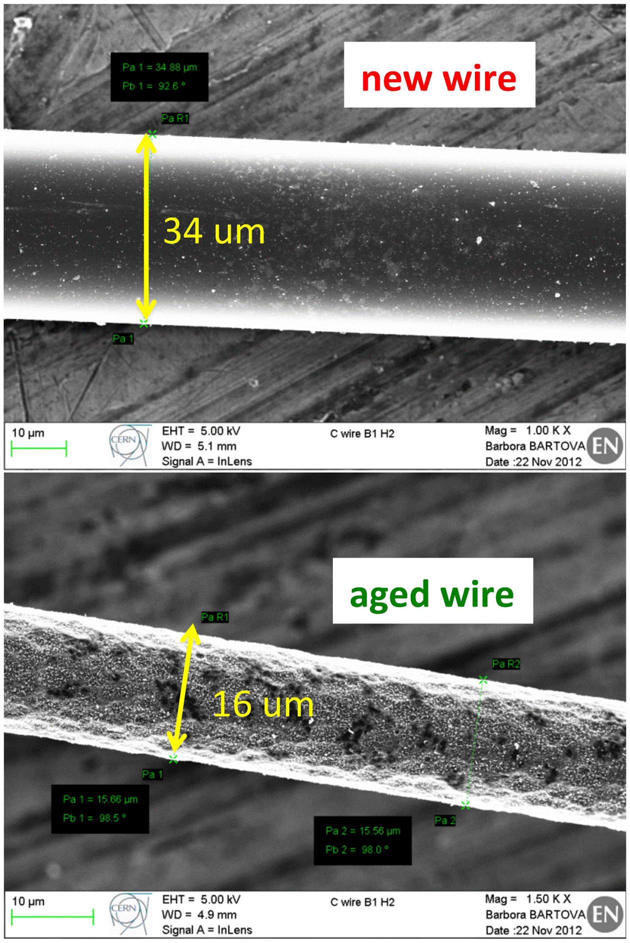



Figure 1: Microscopic inspection of a new (top) and a used (bottom) carbon wire, evidencing the wire diameter reduction due to sublimation.

| | 22-Aug | 12-Oct | 22-Nov |
|---|---|---|---|
| System | B1 H | B1 H | B1 V |
| Wire age | aged | new | new |
| Beam Intensity | $4.3 \cdot 10^{12}$ | $4.2 \cdot 10^{12}$ | $3.5 \cdot 10^{12}$ |
| BLM [Gy/s] | 0.0091 | 0.0218 | 0.0335 |
| Losses [Gy/p] | $5.4 \cdot 10^{-19}$ | $2.7 \cdot 10^{-17}$ | $2.4 \cdot 10^{-17}$ |
| Dump | NO | YES | YES |

Table 2: Effect of a WS measurement on the BLM signals in three different occasions, with aged and new wire

periods, to study the effect the detectors' working point (determined by the photo-multiplier voltage and the optical filter settings) on the beam size determination accuracy. This is discussed in another paper included in these proceedings [1].

In general, as an outcome of the LHC Run 1 experience, the WS application is judged inefficient by OP: the bunch selection is sometimes tricky, the results display difficult to handle and interpret and the request for automatic scans at given times is pending.

Concerning WS upgrades/improvements, the situation at the moment of writing is the following:

- During the 2012 TS#4 a 7 $\mu m$ carbon wire was installed on one system. The tests foreseen in February 2013 could not take place and will be done after LS1. They aim at characterizing the wire robustness, the signal and the induced losses with respect to the 34 $\mu m$ wires. This will be compared to literature [2] predicting the thinner wire's higher robustness (even though smaller diameter means less material to sublimate before breaking) and faster cooling due to the higher surface/volume ratio.
- During LS1 it is foreseen to
  - investigate the possibility of slightly increasing the scan speed (of a maximum 10 % with respect to the nominal 1 m/s)
  - change the bellows, with the aim of gaining a factor 5 in lifetime
  - deploy a new, more efficient, operational GUI
- During LS2 it is foreseen to:
  - possibly install faster devices (20 m/s), following the SPS prototype tests after LS1. This would allow increasing the energy/intensity limits
  - possibly install new detectors (e.g. diamonds) at the place of the scintillator - photo-multiplier chain, in order to increase the detectors linearity range.

## *Beam Gas Ionization Monitor (BGI)*

The BGI systems provide continuous beam size measurements averaging over all bunches circulating in the machine. The principle is based on imaging the residual gas electrons following the beam induced gas ionization (after their collection on an MCP intensifier glued to a phosphor that converts them into visible photons).

During early 2012 both the horizontal and vertical BGI MCPs on Beam 1 (exchanged during the winter technical stop) were damaged due to operational/technical failures (wrong high-voltage settings). This was the consequence of two different issues:

1. too large signal on the MCP because of electron cloud, for an extended period of time
2. abrupt shutdown of high voltage due to a hardware reading error.

Following the second issue, the automatic high-voltage shut-down procedure was improved to provide a smoother ramp down rate. To avoid the first problem, To avoid the first problem, an automatic feedback should be put in place. During the year, several problems with the camera remote control occurred, which compromised the continuous recording of the beam size measurement and the consequent understanding of the whole system.
Considering the above issues, in addition to the lack of suitable beam intensity overlap between WS and BGI during p-p runs, it can be concluded that the BGI results interpretation and its calibration remains difficult.
An example of BGI measurements compared to WS is shown in Fig. 2. This refers to the ion beam during a p-Pb MD period [5] with only 13 ion bunches and $7 \cdot 10^9$ charges per bunch. Despite the low BGI signal, it was possible to find a good calibration w.r.t. WS at both 450 GeV and 4 TeV. As mentioned above, calibration was much more difficult with protons, for which there was also evidence of BGI beam size measurement dependence on the beam space charge
During LS1, it is foreseen to

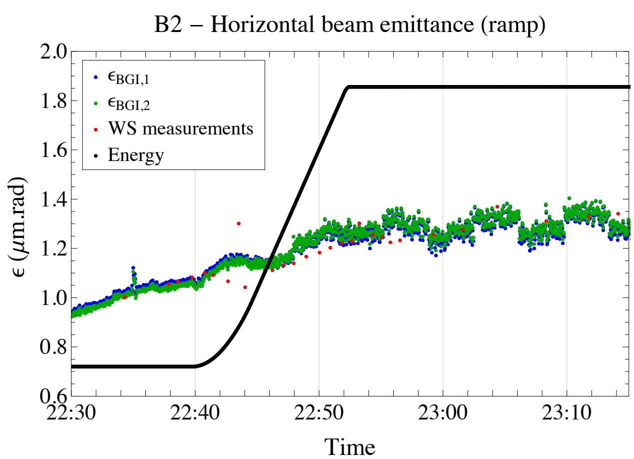



Figure 2: Horizontal BEAM2 emittance as measured by BGI and WS during a whole p-Pb fill.

- Review the low level software, taking into account the lessons learned during 2012
- Dismantle the BGI tanks and re-machine the vacuum sealing surfaces to minimize the risk of leaks
- The cameras' MCP will be repaired. In addition, the imaging optical system will be adapted to
- Ensure the optics compatibility with the smaller beam sizes at 7 TeV
- Upgrade the HV system to ensure a more stable detector operation
- Launch discussions concerning the allowable gas budget (i.e. investigate the possibility to run continuously with gas injection)

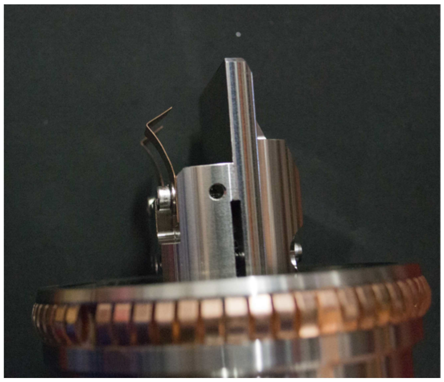
## *Synchrotron Light Monitor (BSRT)*

The BSRT systems provide continuous bunch per bunch beam size measurements by imaging the synchrotron radiation emitted by a superconductor undulator (for beam energies below 1.5 TeV) or the D3 dipole (above 1.5 TeV). The 2012 BSRT performances were heavily affected by heating of the extraction mirror and mirror support due to electro-magnetic coupling with the circulating beam. This effect was enhanced in 2012 by the beam total intensity and intensity per bunch. The thermal cycles caused a permanent deformation of the clamps holding the mirror and a blistering of the mirror reflective coating, as can be seen in the pictures of Fig. 3, taken after the B2 system removal during TS#3. The B1 mirror was found in a very similar state after its removal in TS#4. More information about the BSRT heating effects can be found in the LHC Machine Committee minutes [3, 4].

Both systems were originally equipped with silicon bulk mirrors with dielectric coating. TS#3 and TS#4 were used to test other mirror types for investigating the best option to minimize the heating effects with the present tank design, while ensuring enough reflectivity. The outcome can be summarized as follows:

1. A silicon bulk, uncoated mirror showed a reduced heating (as measured with temperature probes outside the BSRT tank), but resulted to be unusable for imaging, given the distorted recorded images.
2. A glass bulk, metallic coated mirror resulted in a reduced heating effect at low beam intensities, but suffered coating deformation (evidenced by the beam spot image deformation) at high intensities
3. A glass bulk, dielectric coated mirror resulted in a reduced heating (w.r.t. the original silicon bulk, dielectric coated mirror) and did not show any coating deformation according to the recorded images, also at high intensity.

The extraction mirror coating damages compromised considerably the BSRT accuracy in the beam size determination. Not only did the blistering caused the image smearing, but the calibration with respect to the WS had to be



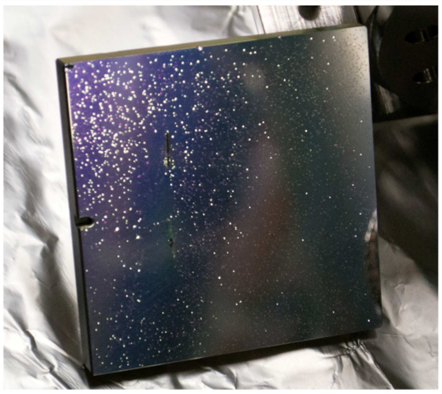


Figure 3: BSRT mirror holder clamps deformation and coating blistering, as evident after the B2 system removal in September 2012.

changed continuously following the coating ageing. Nevertheless it was possible during the year to recalibrate the system regularly and log useful data.
The analysis of the 2010 and 2011 data showed a higher than expected point spread function of the imaging system. As an improvement, towards the end of the 2012 run, the BSRT optics was changed from a layout based on focusing mirrors to focusing lenses. Due to the different focal lengths, this allowed simplifying meaningfully the optical line, by reducing the number of components and thus the image smearing due to vibrations and air flows.
A BSRT-WS comparison (B1, vertical) after the telescope upgrade is shown in Fig. 4. The example refers to a 450 GeV fill during which different bunches were blown-up with the ADT system and then scraped. Considering the BSRT calibration according to

$$\sigma = \sqrt{\sigma_{meas}^2 - \sigma_{psf}^2} \ , \quad (1)$$

in the shown example a unique $\sigma_{psf} \approx 0.8\,mm$ correction was applied to all BSRT data, for a measured $\sigma_{meas} \approx 1.3\,mm$. This is still higher than expected from simulations, but is 20-25 % smaller than what normally found

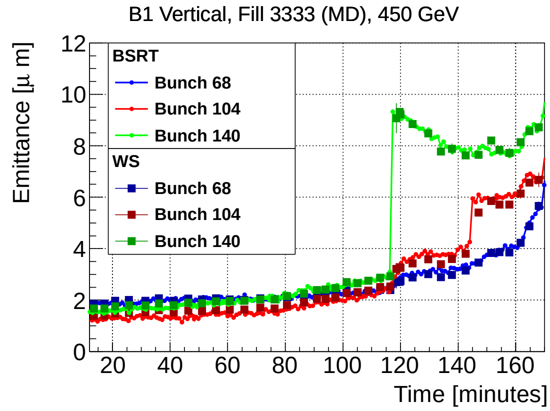



Figure 4: Example of emittance measurements with WS and BSRT at 450 GeV (B1 Vertical), while having bunches with different beam sizes and applying a single calibration factor to the BSRT.

with the old telescope. Preliminary results at 4 TeV also confirm the point spread function reduction after changing to the new optics.
A new control server, managing the BSRT system's gain and light steering as well as the bunch per bunch scans, was deployed at the end of 2012 and validated during the ion-proton run in 2013. This improved the system reliability and availability (previously BI-expert interventions were often needed to recover the proper light steering or control settings) and increased the bunch scan speed from 1 to about 10 Hz.
Concerning the BSRT upgrades foreseen for LS1, a first step was to install during TS#4 temperature probes in vacuum (B2 system only) in strategic locations (close to the mirror holder clamps, to the ferrite tiles and the bellow at the outer edge of the mechanism shaft. The temperature data recorded during a high intensity test in February 2013 are being analyzed and are meant to complement electro-magnetic and thermo-mechanical simulations in order to characterize the amount of power transferred from the beam to the equipment and the heat propagation mechanisms.
For after LS1 it is foreseen to start with:

- mirror and mirror holders minimizing RF coupling while maintaing reflectivity in the appropriate spectral range. This may imply modifying the BSRT tank, at first according to the outcome of the RF and thermo-mechanical studies.
- a telescope optics (including the extraction mirror coating and the camera sensor) suitable for a low wavelength imaging system to reduce diffraction effects at 7 TeV.

In addition, the telescopes will be equipped with a new light shielding designed to minimize parasitic light and air flows. This was motivated to diminish the Longitudinal Density Monitor and the Abort Gap Monitor background, but will be beneficial for the BSRT as well.

## LONGITUDINAL DISTRIBUTION MEASUREMENTS

### *Abort Gap Monitor (AGM)*

The AGM has been designed to monitor the particles population inside the 3 $\mu s$ abort gap, needed almost empty by the dump kickers to perform clean beam dumps. The system is based on the detection of synchrotron light by a gated photomultipier and shares with the BSRT the light extraction and part of the focusing system.

During 2012 the system reliability was affected by the problems with the BSRT extraction mirror heating described above (no BSRT spot on the cameras always meant no proper AGM signal). Software issues (both on the BSRT and BSRA) also caused some AGM unavailability periods requiring the intervention of an expert, especially in the first part of the run.

The AGM accuracy relies on the energy dependent protons per photon calibration and the overall error on the abort gap population is about 50 %. The uncertainty is dominated by:

- Alignment and steering, affecting the light collection efficiency
- Attenuation of light in optical components, that can change due to dust, radiation etc.
- PMT gain versus voltage stability and HV control
- PMT Photocathode ageing
- Electromagnetic noise in the signal

For these reasons, in 2012 the AGM monitors needed frequent re-calibration by gating the PMT on a filled RF bucket and cross-calibrating with respect to the Fast Current Transformers.

The new BSRT telescope optics (after TS#3 for B1 and after TS#4 for B2) resulted in a simplified optical line to the AGM and no movable elements before the PMT. This improved the AGM calibration stability, at first by eliminating the need to compensate for light losses at the moment of inserting the old optics delay line.

During LS1, it is foreseen to improve the AGM reliability by introducing software self-checks and self-calibration procedures that should be performed systematically with circulating beam. During the self-calibration the abort gap population cannot be monitored, but this represents less than 1% of a fill. The exact details should be discussed with the MPP committee.

### *Longitudinal Density Monitor (LDM)*

In addition to the camera for transverse beam size measurements and to the PMT for the abort gap monitoring, the BSRT telescope delivers the extracted synchrotron radiation to an avalanche photo-diode for the Longitudinal Density Monitor (LDM). At the cost of a relatively long integration time, the LDM allows measuring the intensity of satellite and ghost bunches down to about $10^{-4}$ of the main bunches. Despite its 50 ps resolution, it is not designed to verify the bunch shape at a fine level.

During 2012, the LDM remained an expert tool and the related operational software was still under development. Artifacts linked to the detector behavior still required a BI expert to properly setup the system during normal LHC operation. This had no impact during the Van Der Meer scans, for which the LDM proved to be an important tool to determine the absolute luminosity calibration.

Issues were related to the detector dead time and after pulse dependence on the filling pattern, for which the correction algorithms were not always effective. In addition, the measurement accuracy and interpretation was affected by internal light reflections in the telescope.

After LS1, the LDM will still start in a development mode, at first to study the filling pattern dependence and to deploy operational software. The new telescope optics (already tested in 2012) and a new light shielding will certainly diminish the internal reflections.

An example of LDM measurements during a Van Der Meer scan fill is shown in Fig. 5.

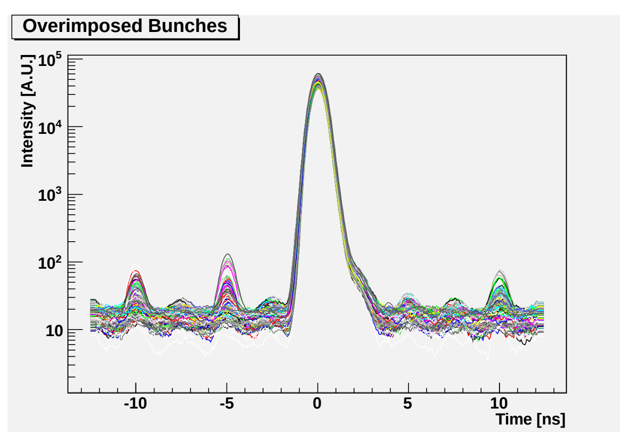



Figure 5: 25 ns slot population as measured by the LDM during a Van Der Meer scan with ions at 1.38 TeV (Fill 3540). Different colors correspond to different (superimposed) slots.

## FROM 4 TO 7 TEV

Moving from 4 to 6.5 or 7 TeV, given the present beam optics (with almost constant betatron functions in IR4 as function of energy), will imply having smaller beam sizes at the transverse profile monitors.
For the WS, this will result in fewer data points per sigma. Since it is not convenient to reduce the wire speed and consequently the intensity thresholds, to increase the resolution it could be necessary to use the overlap of several data sets:

- either multiple scans on the same bunch (with different acquisition delays w.r.t. to the bunch passage through the wire)
- or the profiles from multiple bunches during a single scan (for which at each turn, the acquisition is slightly delayed from bunch to bunch according to the bunch spacing)

This second technique is already successfully used for the SPS WS at 450 GeV.
At higher energy the WS operation will be limited up to about $10^{12}$ circulating protons (see Table 1) in order to cope with lower BLM thresholds for protecting superconductor magnets.
For both the BGI and the BSRT, it is foreseen to adapt the optical imaging system in order to have about the same mm/pixel resolution as at 4 TeV.
The BSRT will also suffer of a higher relative contribution of diffraction to the point spread function. This is due to both the smaller beam size and the reduced synchrotron light emission cone angle. Since quantifying the absolute value of diffraction (in order to exactly correct for it) has been difficult until now, as already mentioned above, it is foreseen to design a new telescope optics working in the low wavelengths (i.e. $\leq 300\,nm$) in order to anyhow reduce the effect.

At higher energy, both the AGM and the LDM signals will result in higher photon rates. This will be easily managed by properly dimensioning the optical filters attenuations in front of the detectors.

## FROM 50 TO 25 NS

The LHC WS are equipped with 40 MHz acquisition electronics allowing bunch per bunch acquisition with 25 ns sampling resolution. However, tests with 25 ns spaced bunches showed a cross-talk between consecutive bunches of about 10 %. This will be studied during LS1.
Concerning intensity thresholds, the possibility of scanning 288 bunch trains at injection will depend on the decision for going to smaller diameter wires (i.e. lower losses downstream, decision not taken yet) and of course on the actual bunch population for 25 ns beams.
For the BGI, presently averaging over multi-bunches, there is no evident difference between 50 and 25 ns beams.
Concerning the BSRT, the camera intensifiers can be gated to 25 ns and the only impact will be longer periods to scan over all bunches.
For the AGM and the LDM there is no evident impact.

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