CAN WE GET A RELIABLE ON-LINE MEASUREMENT OF THE TRANSVERSE BEAM SIZE?

F. Roncarolo, S. Bart Pedersen, E. Bravin, A. Boccardi, J. Emery, A. Guerrero, T. Lefevre, A. Jeff, A. Rabiller, M. Sapinski, CERN BE-BI

A.S. Fisher, SLAC

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. This presentation covers all aspects related to the operation of such devices in 2010. The absolute and relative accuracy of the emittance measurement is discussed, including cross calibration among the three instruments and with the luminous region estimation during collisions at the LHC experiments. This allows reviewing the reliability of the on-line data and of the values published in the logging database. In addition, an overview of the programmed hardware and software upgrades is given.

WIRE SCANNER MONITORS (WS)

WS monitors consist in a 30 um diameter carbon wire flying through the beam at a maximum speed of 1 m/s. The accuracy of LHC-type WS monitors has been studied in the SPS [1]. Assuming proper monitor settings and the knowledge of the beam optics, the absolute accuracy on the measured emittance is of the order of 1%. The measurement is 'on-demand' and the operator can switch between two types of electronics: at every turn the signal is sampled either i) on a single time window of about 10 us (TURN mode) or ii) a number of selectable time windows 25 ns wide (BUNCH-to-BUNCH mode). The maximum number of selectable bunches is at the moment limited to 75 by the front-end memory and firmware. A software interlock forbids the WS operation for beam intensities above $2{\cdot}10^{13}$ p at any energy. This is compatible with the intensity limits established at the WS design stage [1]: $5{\cdot}10^{13}$ p at 450 GeV to avoid the wire damage and $1.5{\cdot}10^{13}$ p at 3.5 TeV to avoid quenching the SC downstream elements. The software interlock has been set after some 'quench test' experiments in 2010 during which the wire speed was on purpose diminished in order to enhance the secondary shower and induce a quench. In 2011 the software interlock will be reviewed (likely allowing scans at higher intensities, after checking BLM thresholds downstream the WS).

SYNCHROTRON RADIATION MONITORS (BSRT)

The two BSRT detectors [3,4] are installed about 30 m downstream the D3 cryostats hosting the D3 dipole and a SC undulator. The latter has been built to provide enough synchrotron radiation (SR) at low beam energies. As the beam energy reaches 2.5-3 TeV, most of the useful SR power starts to be generated first by the D3 edge and then by the D3 centre. A retractable extraction mirror deviates the light below the beam pipe where an optical system performs the imaging of the beam spot on CCD cameras. The optical system is shown in Fig. 2 and is equipped with remote control in order to focus on the different SR sources.

The total SR power is shared between the Abort Gap monitor (PMT in Fig. 2) and the two cameras dedicated to transverse profiles. In 2010 only the Proxitronic cameras [4] (one per system, indicated as 'slow' in the figure) have been commissioned. Such cameras provide acquisitions at 1 Hz and have two operation modes:

- continuous (DC mode): each acquisition corresponds to the integration for 20 ms of all circulating bunches;

- gated (PULSED mode, available from September 2010): each acquisition corresponds to the integration over all the time windows (gates) programmed in 20ms.

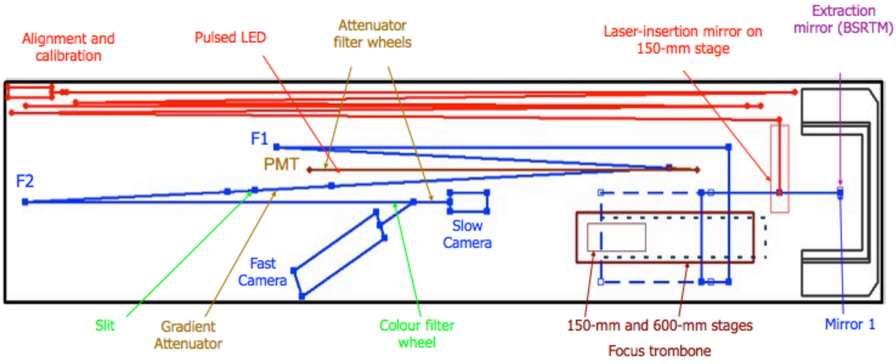

Figure 2: Schematic drawing of the BSRT telescope system sitting below the LHC beam pipe.

When the camera is in PULSED mode, the minimum gate length is 25 ns and the maximum gate repetition rate is 200 Hz. This means that it is possible to measure a single LHC bunch for a single turn, sampled every 55 turns.

The SR power generated by protons and the system efficiency is such that there are no intensity limitations for proton beams: a single pilot gives a signal well above background. A minimum of about 30 lead ion bunches averaged for 20 ms (DC mode) are necessary to have enough light at injection energy. This is due to the shift in frequency of the undulator light generated by ions.

The BSRT absolute accuracy relies at first on the imaging at a calibration target illuminated by a lamp, installed on the same optical table at the beginning of the calibration line displayed in red on Fig. 2. The optical path is such that the target distance from the first focusing mirror is 32 m, the same as the distance between the same mirror and the centre of the undulator. This calibration allows determining the system magnification and optimizing the focusing, by tuning the camera position while imaging the target. The ultimate absolute accuracy and resolution depend on several effects affecting the imaging of an extended light source, which, in addition, is changing with energy. This includes aberration, diffraction and depth of field [5,6].

BSRT expected and measured signals

In 2010 it was possible to start comparing the measured SR power to what expected from the simulations. An example is shown in Fig. 4, where the number of photons per charge measured by the Abort Gap monitor as function of energy is compared to what simulated, both for protons and Pb ions.

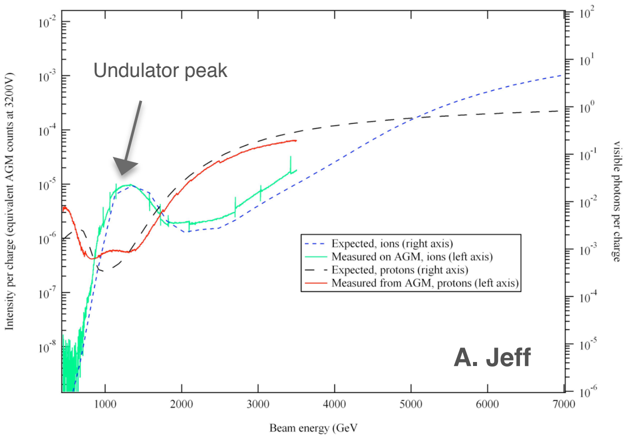

Figure 4: Number of photons per charge, as measured by the Abort Gap monitor as function of energy, compared to simulations, both for protons and Pb ions.

The agreement is rather good, even though the low energy region for protons and the 2-3.5 TeV regions for ions have to be studied in more detail. The plot shows that at 450 GeV the signal given by ions is at least a factor 10^4 lower than the one for protons.

BSRT bunch per bunch measurements

As explained above, during the second part of the 2010 run the BSRT cameras could be used in PULSED mode and monitor single bunches. Even though only a BI expert could enable this functionality, it was extensively used during the last part of the proton run and the entire ion run. The bunch per bunch emittances as measured along 12 trains of 48 proton bunches on Nov 8th, 2010 are shown in Fig. 5. Each measurement point is the average emittance over 2 or 3 periods (5 seconds long) separated by about 50 minutes. Therefore, the error bars represent the emittance variation from the beginning to the end of the measurement period.

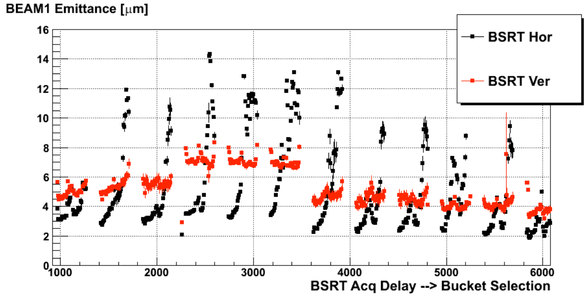

Figure 5: Bunch per bunch emittance as measured by the BSRT along 12 trains of 48 proton bunches each.

The measurement clearly showed the difference between bunch trains and between bunches inside a train.

Another example can be seen in Fig. 6, where the measured horizontal emittance of 17 lead ion bunches is shown as function of time. Since the filling from the SPS consisted in a single bunch followed by 4 trains of 4 bunches each, the plot evidences the larger emittance increase of the first bunch of each train.

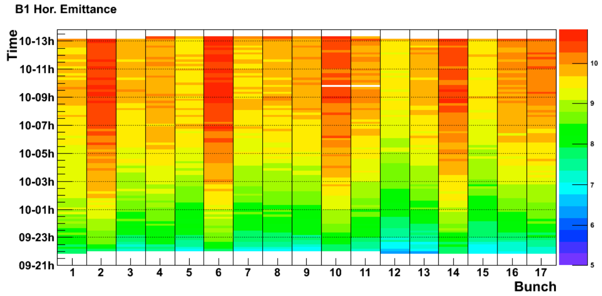

Figure 6: Horizontal emittance evolution during a fill with 17 lead ion bunches.

BSRT – WS comparison

The BSRT system are equipped with movable stages, optical density filters and chromatic band pass filters that, together with the adjustment of the video camera gain, allow optimizing the system resolution and accuracy for the different beam intensities and energies.

Despite the several degrees of freedom for optimization, the BSRT measured beam sizes are still biased by intrinsic limitations, like diffraction, and possible inaccuracies in the system installation in the tunnel (alignment, focusing etc…). Therefore the BSRT calibration is complemented with the comparison to WS measurements, which are considered as the reference.

An example of BSRT – WS comparison is shown in Fig. 7, where the BSRT emittances already include correction factors on the measured beam sizes intended to maximize the agreement with the WS. For the moment, a correction in quadrature on the beam size, according to

$$\sigma = \sqrt{\sigma_{meas}^2 - \sigma_{corr}^2} \qquad (1)$$

is considered the best approximation.

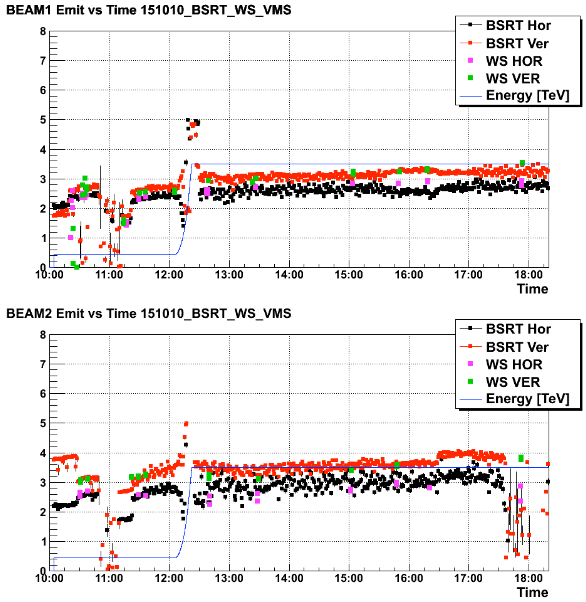

Figure 7: Normalized emittances for Beam 1

(top) and Beam 2 (bottom) as measured by WS and BSRT. These kind of measurements allowed calculating the BSRT correction factors.

Such correction factors are different for each beam and for each plane and changed during the 2010 run, mainly following interventions in the tunnel aimed at improving the overall system. As shown in Table 1, at least three sets of correction factors can be considered for the data logged in 2010.

Table 1: Correction σ_{corr} $[mm]$ to be applied to BSRT measured beam size (see Eq. 1) for the 2010 data.

Protons until 22 Oct		**450 GeV**	**3500 GeV**
B1	H	0.70	0.57
	V	0.63	0.50
B2	H	0.60	0.59
	V	0.50	0.77
Protons after 22 Oct		**450 GeV**	**3500 GeV**
B1	H	0.60	0.50
	V	0.95	0.55
B2	H	0.60	0.52
	V	0.65	0.42
Ions		**450 GeV**	**3500 GeV**
B1	H	0.60	0.40
	V	0.99	0.65
B2	H	0.60	0.55
	V	0.50	0.40

BEAM GAS IONIZATION MONITORS (BGI)

Collecting the electrons generated by the rest gas ionization induced by the beam is used to reconstruct the beam transverse profiles [7]. The electrons are accelerated by high voltage electrodes towards an electron amplification stage (MCP). The beam profile is reconstructed by imaging a phosphor that is placed at the MCP exit. Two orthogonal systems equipped with two video cameras provide the horizontal and vertical profiles.

The cameras can be gated to select bunches, but in 2010 were not remotely controllable and were only used in automatic mode. This meant that the camera gain was fixed at maximum and the gate length automatically adjusted depending on the amount of signal reaching the camera. The data are logged a 1 Hz.

The proton / rest gas ionization cross sections are such that gas injection is needed for proton beam intensities below 400 nominal bunches. In 2010, with about 2e-8 mbar gas pressure (10 times lower than the interlock limit) it was possible to measure a single bunch. This was verified before the scrubbing run and must be rechecked in 2011.

On the other hand, 2 lead ion nominal bunches were enough to image the beam without any gas injection.

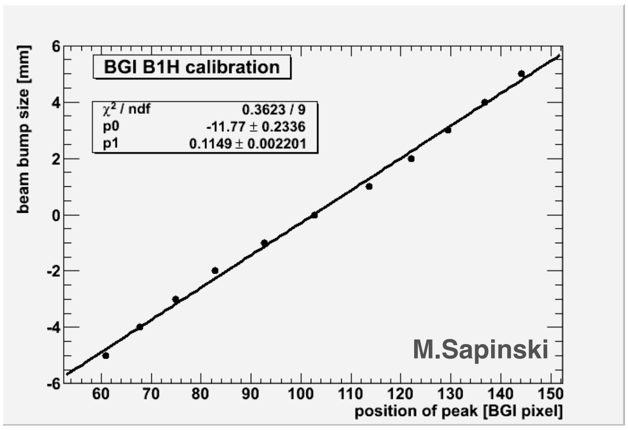

Figure 8: BGI calibration by comparing to BPMs while applying closed orbit bumps.

The BGI absolute accuracy relies on a reference Electron Generation Plate (EGP) calibration. In addition, a correction factor was calculating by comparing BGI and beam position monitors (BPM) while introducing local orbit bumps with different amplitude (see Fig. 8). This yielded to a correction of a factor 1.4 to be applied on the measured (and logged in 2010) beam size. As for the BSRT, the BGI absolute calibration is also being studied by cross calibration with WS. In general, the BGI data logged in 2010 should be treated carefully. Since the system is in a commissioning phase, the data quality, including the profiles fit, is sometimes affected by the specific conditions, namely the gas pressure and the camera gating (that was automatically changing depending on the signal). In 2011 the remote controls for both the gas pressure and the BGI detector will be improved.

BGI – WS – BSRT comparison

In addition to the calibration with respect to BPMs, the BGI can be compared to WS and BSRT. This has not been studied systematically yet, but two examples are shown in Fig. 9. Both examples refer to ion beams (Beam 2) and BGI and BSRT data have been already corrected according to the calibration factors discussed above (computed after calibration with respect to BPM and WS respectively).

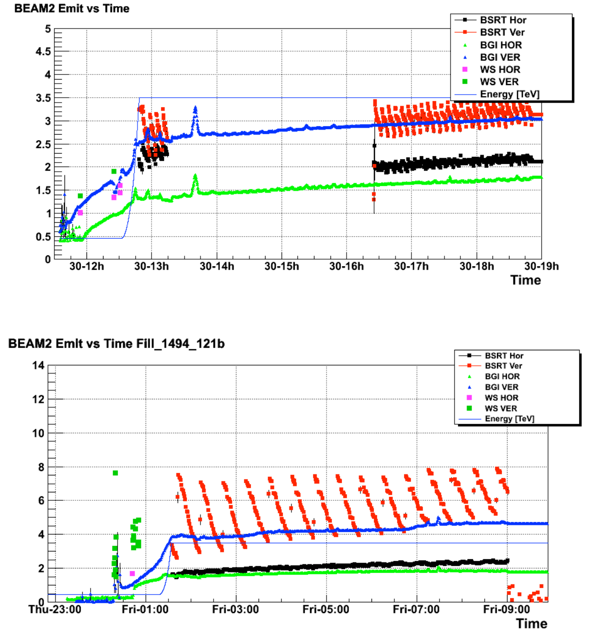

Figure 9: Examples of comparison between BGI, WS and BSRT while measuring the same ion beam during the VMS scans on Nov 30th, 2010 (top) and during the physics fill 1494 (bottom).

From these preliminary tests (to be repeated and improved in 2011) it can be assessed that:

- BGI H and V reproduce the emittance blow-up measured by WS at 450 GeV (top plot);
- BGI V is in good agreement with BSRT
- BGI H gives a smaller emittance than WS (at 450 GeV, top plot) and BSRT (at 3500 GeV, bottom plot).

In general, the emittance evolution monitored by the BGI during the energy ramp can be considered accurate, even though for the moment one should always check with off-line analysis the data fit quality and the absence of saturation effects (e.g. due to beam size shrinking during the ramp).

CONCLUSIONS AND OUTLOOK

The WS monitors act as a reference and are routinely used by OP. Bunch per bunch mode will become operational in 2011. In addition, it is foreseen to perform systematic studies on saturation levels (as done at the PSB in 2010).

The BSRT monitors provide a continuous relative emittance variation (at constant beam energy) that can be considered accurate at the 10% level. Even though calibration factors can be used to analyse the 2010 data, the BSRT absolute calibration and the ultimate resolution need to be studied in more detail.

The BSRT automatic settings of gain/attenuation following beam intensity and energy variations were considered reliable during the last months in 2010. Additional automatic settings, like ‘auto-focusing’ versus beam energy will be tested in 2011. At the moment the BSRT bunch-to-bunch mode takes at least 3 seconds per bunch and requires BI experts to perform the measurements. The implementation of OP software dealing with the bunch-to-bunch mode will be discussed. At least one ‘fast’ camera [8] will be installed before the 2011 run and will allow the test of bunch-per-bunch, turn-by-turn acquisitions.

The BGI monitors were in a commissioning phase for the whole 2010 run. The relative accuracy can be considered better than 10 % once the beam profile quality has been checked. The absolute calibration has to be studied in detail, to complement cross-calibration with respect to BPMs. In 2011 the remote controlling of both gas injection and video cameras will be improved.

As additional information, the logging DB is already equipped with virtual variables containing normalized transverse emittances. In 2011 the values with which they will be filled should become trustable, after applying the best estimated calibration factors to BSRT and BGI.

REFERENCES

[1] F. Roncarolo, B. Dehning, C. Fischer and J.Koopmann, "Accuracy of the SPS transverse emittance measurements", CERN-AB-2005-081

[2] M. Sapinski, Tom Kroyer, "Operational limits of wire scanners on LHC beam", Proceeding of the Beam Instrumentation Workshop, Lake Tahoe, California, (2008), pp383

[3] T. Lefevre et al., "First Beam Measurements with the LHC Synchrotron Light Monitors", Proceeding of the IPAC Conference, Kyoto, Japan, (2010), pp.1104 and CERN-ATS-2010-108

[4] http://www.proxitronic.com, Model: HF4 S 25N NIR

[5] A.Hofmann and F. Meot, "Optical resolution of beam cross-section measurements by means of synchrotron radiation", *Nucl. Instrum. Methods Phys. Res.* 203 (1982) 483-493

[6] A.S. Fisher, "Expected Performance of the LHC Synchrotron-Light Telescope (BSRT) and Abort-Gap Monitor (BSRA)", LHC-Performance-Note-014

[7] J. Koopman et al., "Design and Tests of a New Rest Gas Ionisation Profile Monitor Installed in the SPS as a Prototype for the LHC", *AIP Conf. Proc.* 732 (2004) pp.133-140.

[8] http://www.redlake.com/, Model: HG-100k.