FIRST LHC EMITTANCE MEASUREMENTS AT 6.5 TeV

M. Kuhn[1,2], F. Antoniou[1], E. Bravin[1], B. Dehning[1], J. Emery[1], V. Kain[1],
A. Langner[1,2], Y. Papaphilippou[1], E. Piselli[1], G. Trad[1]
[1]CERN, Geneva, Switzerland [2]University of Hamburg, Germany

Abstract

During LHC Run 1 significant transverse emittance growth through the LHC cycle was observed. Measurements indicated most of the blow-up to occur during the injection plateau and the ramp. Intra beam scattering was one of the main drivers of emittance growth. However, finding a good wire scanner working point was difficult. Photomultiplier saturation added uncertainty on all measurements. A large discrepancy between emittances from wire scanners and luminosity was discovered but not solved. During Long Shutdown 1 the wire scanner system was upgraded with new photomultipliers. In April 2015 the LHC re-started with collision energy of 6.5 TeV per beam. This paper presents the first transverse emittance measurements through the LHC Run 2 cycle with low beam intensity. Comparisons with data from the synchrotron light monitors and the LHC experiments will be discussed and results summarized. In addition, a thorough study of wire scanner photomultiplier saturation will be presented. Finally, the emittance growth results will be compared to intra beam scattering simulations.

INTRODUCTION

In 2012 the LHC was operated with high brightness beams with beam parameters pushed to their limits for outstanding luminosity production. With a bunch spacing of 50 ns the LHC was filled for physics with 1374 bunches per ring, containing up to $1.7{\times}10^{11}$ protons per bunch (ppb) with transverse emittances as small as 1.5 µm at injection. However, the high brightness could not be preserved during the LHC cycle. Measurements in 2012 revealed a transverse emittance blow-up of about 0.4 to 0.9 µm from injection into the LHC to the start of collisions [1].

At the start of Run 2 in 2015 the LHC is operated with beams of reduced brightness. The beam parameters of the 2015 early physics beams as well as the nominal parameters are listed in Table 1. During the first phase of commissioning and intensity ramp-up measurements indicate less total blow-up than in 2015. This paper summarizes the results of beam size measurement accuracy with the LHC wire scanners and emittance growth through the LHC cycle.

LHC Wire Scanner Intensity Limitations

The LHC wire scanners are equipped with a 36 µm thick carbon wire attached to a linearly moving fork [2]. The wire crosses the beam at a constant speed of 1 m/s. For each measurement the beam profile is scanned twice as the wire passes through the beam with in and out scan. In this paper only the average beam size obtained from in and out scan is used and the error from averaging is included in the results.

Table 1: LHC Design and Early 2015 Run Configurations

	Design	Early 2015
Total number bunches per beam	2808	3 – 458
Bunch spacing [ns]	25	25 and 50
Mean bunch length [ns]	1.3	1.2
Bunch intensity [10^{11} protons]	1.15	1.0 – 1.2
Injection energy [GeV]	450	450
Emittance at injection [µm]	3.5	1.5 – 3.0
Collision energy per beam [TeV]	7	6.5
Emittance at collision [µm]	3.75	1.5 – 4.0
β^* at ATLAS/CMS [m]	0.55	0.8

The LHC wire scanners can only be used with a small fraction of the total nominal intensity per ring due to wire heating. The carbon wire should be able to take 2–3×10^{13} charges/mm before sublimating. The close-by LHC superconducting magnets limit the maximum scan intensity further, to 5×10^{12} charges/mm [2], because the particle showers produced by the wire passing through the beam can quench the magnets. This limit corresponds to about 240 bunches per beam ($2.7\times10^{13}p$), less than one injected nominal batch (288 bunches). At 6.5 TeV flattop energy scans were possible with up to two nominal bunches ($2.3\times10^{11}p$). The flattop limit has recently been redefined to $1.6\times10^{12}p$ after the first experience at 6.5 TeV.

The emittance evolution of high intensity physics fills cannot be measured with the LHC wire scanners. The synchrotron light telescope (BSRT) is used for that purpose. The BSRT absolute beam size measurement is obtained from a cross-calibration with wire scanners. Also, the wire scanner is currently the only operational device that can accurately measure beam sizes through the LHC energy ramp. Low intensity test fills during the commissioning phase are used for the calibration of the emittance measuring instruments and emittance preservation studies.

RUN 2 LHC WIRE SCANNER ACCURACY

The obtainable emittance measurement accuracy for a wire scanner at location with no dispersion depends on the accuracy of the optics knowledge (β) and measurement error ($\Delta\beta$) as well as on the beam size measurement accuracy ($\Delta\sigma$) of the given device:

$$\frac{\Delta\varepsilon}{\varepsilon} = \sqrt{\left(2\frac{\Delta\sigma}{\sigma}\right)^2 + \left(\frac{\Delta\beta}{\beta}\right)^2} \qquad (1)$$

A large contribution to the wire scanner beam size accuracy derives from the wire position measurement precision and the position measurement calibration. The precision

ISBN 978-3-95450-176-2

of the position measurement potentiometer is estimated to be 50 µm. The position measurement calibration was verified with beam by an orbit bump scan at the wire scanner location.

The wire scanner shower product is amplified by a photomultiplier (PM). The amplification settings (gain and filter) can alter the obtained beam profile. During LHC Run 1 a strong dependence of PM settings on the measured beam size was observed [1]. Therefore the optimum PM working point has to be established.

Wire Position Measurement Calibration

While the centre of the beam was shifted locally at the scanners, wire scans were triggered to determine the accuracy of the position measurement of the wire scanners. The orbit at the wire scanner is extrapolated from beam position measurements with the LHC orbit system and compared to the mean position obtained from a Gaussian fit to the measured wire scanner beam profile. Measurements at 450 GeV and 6.5 TeV are consistent. As an example the calibration results of scanner B2V1 are shown in Fig. 1. The slope of the linear fit shows a 3.3 % calibration error for this wire scanner. The results in terms of emittance for all operational wire scanners are listed in Table 2. Another set of orbit bump scans is foreseen for the near future to check reproducibility. For the time being measurement results in this paper do not include a calibration error.

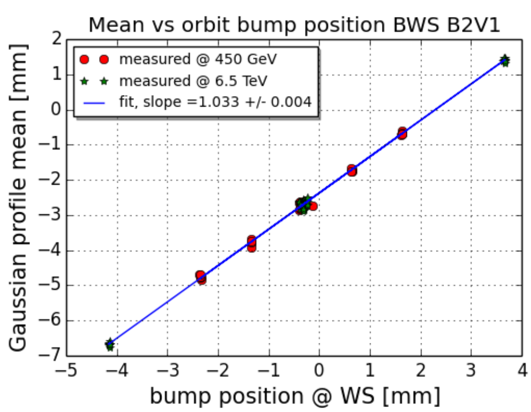

Figure 1: Gaussian profile mean of beam 2 vertical measured with wire scanner at different orbit bumps at 450 GeV (red) and 6.5 TeV (green), Fill 3644 (April 24, 2015). A linear fit (blue) is applied.

All wire scanner measurements show a large beam size measurement spread from scan to scan which depends on the scanner and the energy, see Fig. 2 and Fig. 3. Table 2 summarizes the emittance measurement precision with the different wire scanners according to the current knowledge. The LHC Run 2 optics at the transverse profile monitors have been measured with the k-modulation method at 450 GeV injection energy [3] and with the turn-by-turn BPM phase advance method at 6.5 TeV flattop energy, before and after the 80 cm β^* squeeze. The β function accuracy at the wire scanners is better than 3 %.

Photomultiplier Working Point Investigations

To find the optimum working point of the wire scanners, measurements with all available PM gain and filter setting combinations were performed. Figure 2 shows the measurement results for scanner B2V1 at 450 GeV. Bunches with different beam sizes were injected into the LHC. The beam size evolution is plotted over time with the applied gain and filter settings. To remove the natural emittance growth at the injection plateau, scans with a fixed reference settings were done after each settings change and fitted assuming an exponential function. Figure 4 then shows measured beam sizes minus the fitted growth. In addition, the results of measurements with same gain and filter settings are averaged to one data point. At 450 GeV no sign of PM saturation could be detected. Moreover, all combinations of settings below ADC saturation result in reasonable profiles. Similar results were obtained for the other wire scanners.

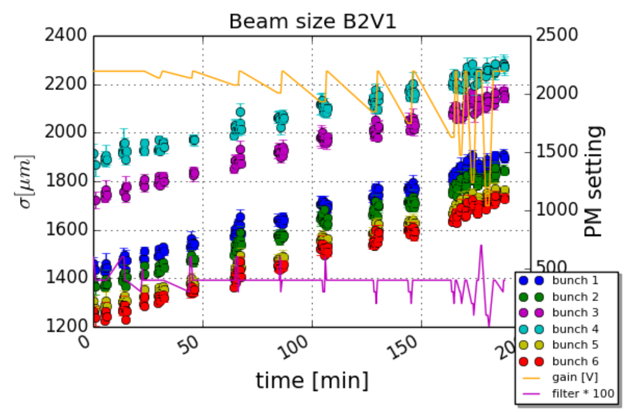

Figure 2: Beam 2 vertical beam size of six single bunches from wire scans at 450 GeV, Fill 3808 (May 31, 2015). The PM voltage (orange) and filter (purple) are displayed.

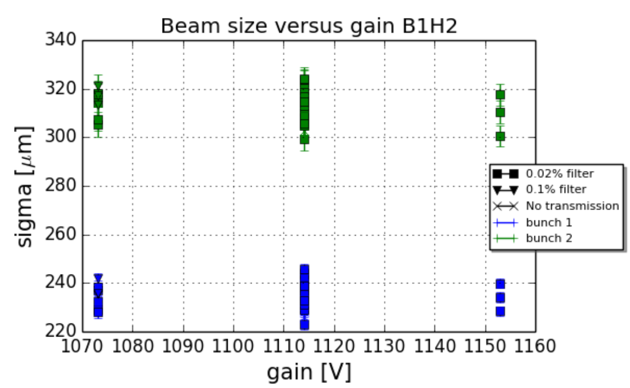

Figure 3: Beam 1 horizontal beam size of two single bunches from wire scans at 6.5 TeV, Fill 3809 (June 1, 2015), as a function of the applied PM voltage. The different PM filters are marked.

Measurements at 6.5 TeV were more difficult because the possible range of PM settings is much smaller than at 450 GeV. Nevertheless, also at flattop energy no PM saturation can be seen, see Fig. 3.

Investigations during Run 1 showed significant dependency of measured beam size on PM settings. The upgrade

ISBN 978-3-95450-176-2

Table 2: LHC Run 2 wire scanner emittance calibration error ($\Delta\varepsilon_{cal}$), typical emittance measurement spread of four consecutive measurements at 450 GeV ($\Delta\varepsilon_{inj}$) and 6.5 TeV ($\Delta\varepsilon_{top}$), and β function measurement results.

Scanner	$\Delta\varepsilon_{cal}$ [%]	$\Delta\varepsilon_{inj}$ [%]	$\Delta\varepsilon_{top}$ [%]	β_{inj} [m]	β_{top} [m]	$\beta_{squeeze}$ [m]
B1H2	+7.2	25	20	194.0 ± 0.8	196.8 ± 1.4	209.0 ± 5.0
B1V2	-5.2	20	10	363.3 ± 1.8	369.0 ± 3.0	366.0 ± 4.0
B2H1	+9.0	25	15	192.0 ± 0.7	193.8 ± 1.1	196.0 ± 3.0
B2V1	+6.6	15	10	410.7 ± 2.3	396.0 ± 3.0	404.0 ± 5.0

of the LHC wire scanners during Long Shutdown 1 could explain the improved situation. One broken PM has been replaced (beam 2) and power supply schematics have been upgraded. Also the PM gain dependency on light intensity has been reduced.

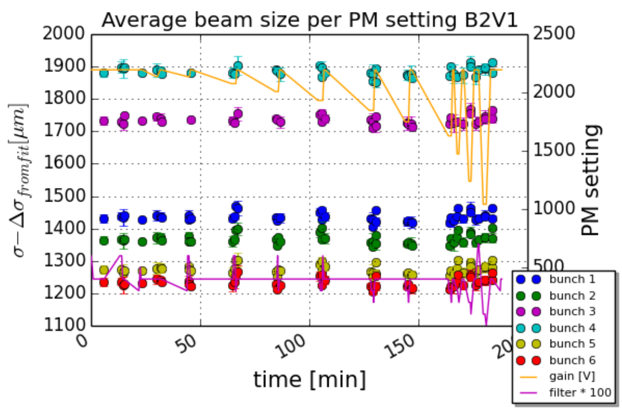

Figure 4: Average beam 2 vertical beam size per PM setting minus growth from exponential fit of six single bunches from wire scans at 450 GeV, Fill 3808 (May 31, 2015). The PM voltage (orange) and filter (purple) are displayed.

FIRST EMITTANCE MEASUREMENTS

The emittance evolution through the different parts of the LHC cycle has been studied during the LHC commissioning phase for 30 low intensity fills. As an example Fill 4287 was analysed in detail through the cycle with the following phases:

- Injection process from SPS to LHC
- 450 GeV injection plateau (~ 30 min)
- Ramp from 450 GeV to 6.5 TeV (20.2 min)
- Change to collision tunes and β^* squeeze from 11 m to 80 cm in ATLAS/CMS (12.5 min)

During Fill 4284 three bunches were injected into the LHC with different initial emittances, intensities ($0.6 - 1.1 \times 10^{11} ppb$) and bunch lengths (1.0 – 1.25 ns). An overview of the measured emittances through the cycle can be found in Fig. 5.

The total measured and simulated emittance growth through the LHC cycle of bunch 3 is enumerated in Table 3. The emittance at SPS extraction of bunch 3 measured with wire scanners was 1.9 µm in the horizontal plane and 1.5 µm in the vertical plane. The procedure was repeated during many fills. No emittance growth could be observed during the transfer from SPS to LHC within measurement accuracy.

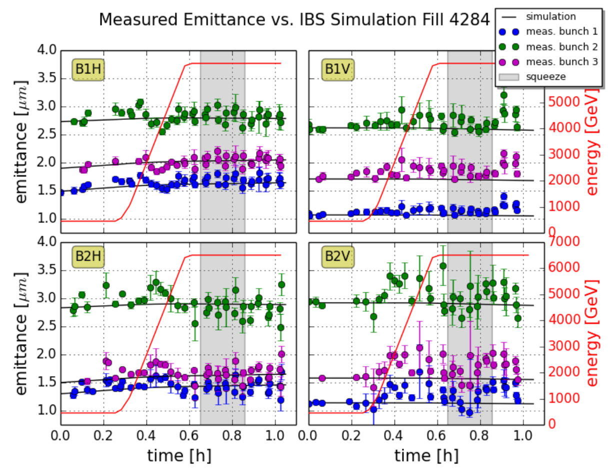

Figure 5: Emittance from wire scans of three single bunches during the LHC cycle, Fill 4284 (August 28, 2015), with IBS simulations (black). The energy (red) and β^* squeeze (grey) are displayed.

Table 3: Emittance Blow-up from Injection (0) to End of Squeeze (1), Fill 4284 Bunch 3, and Simulated Growth (sim)

	ε_0 [µm]	ε_1 [µm]	$\Delta\varepsilon$ [µm]	$\Delta\varepsilon/\varepsilon$	$\Delta\varepsilon/\varepsilon_{sim}$
B1H	1.90	2.08	0.18	0.09	0.08
B1V	1.71	2.04	0.33	0.19	−0.02
B2H	1.50	1.65	0.15	0.10	0.10
B2V	1.58	1.95	0.37	0.23	−0.02

IBS at the Injection Plateau

The emittance growth during the injection plateau depends on the initial beam parameters. Intra beam scattering (IBS) is the major cause for horizontal emittance blow-up at low energies. An IBS simulation with MADX [4] is shown in Fig. 5. The simulated growth is compared to the measured emittances. For all planes the growth at 450 GeV is fairly well predicted. Despite the large emittance spread, the mean measured horizontal growth matches the simulated values.

Emittance Growth during the LHC Ramp

Measured β functions for the 2015 energy ramp are not yet available. Non-physically growing and shrinking emittances in all planes can be observed, see Fig. 6, as was

ISBN 978-3-95450-176-2

already the case during LHC Run 1. This was due to the non-monotonically changing β functions during the ramp. IBS simulations with these parameters suggest less than 0.05 µm (3 %) horizontal emittance blow-up during the ramp, which is within the measurement accuracy and consistent with measurements. Vertical emittances experience an emittance blow-up of about 0.1 – 0.3 µm (10 – 20 %), which cannot be reproduced with IBS simulations.

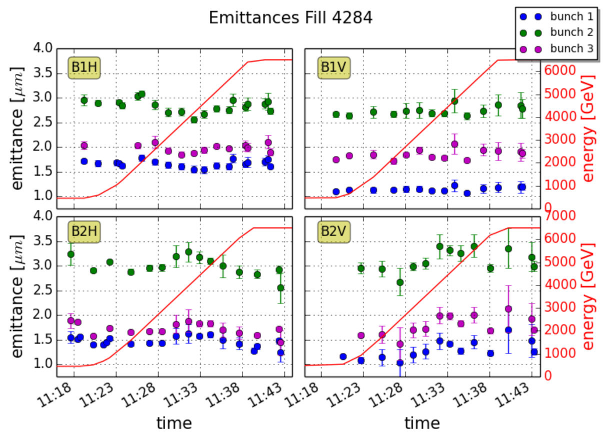

Figure 6: Emittance from wire scans of three bunches during the energy ramp to 6.5 TeV for Fill 4284. The energy (red) is displayed.

Emittance Preservation during the Squeeze

Within measurement accuracy the emittances are conserved during the β^* squeeze, see BSRT measurements in Fig. 7. This result is reproducible and has also been confirmed with wire scanner measurements. BSRT emittances are averaged over several hundred measurements. Beam 1 horizontal always shows large statistical fluctuations from measurement to measurement.

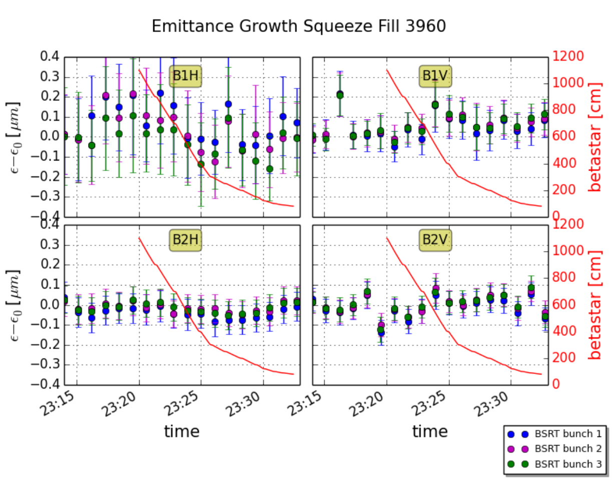

Figure 7: Emittance from BSRT measurements of three single bunches during the tune change at 6.5 TeV and the β^* squeeze to 80 cm in ATLAS/CMS, Fill 3960 (July 4, 2015). The β^* value (red) is displayed.

Emittance at the Start of Collisions

During head-on collisions it is possible to derive emittance from luminosity and directly compare it to the convoluted emittance from simultaneous wire scans during low intensity fills. The method assumes identical Gaussian shaped and perfectly aligned beams. During collisions of Fill 3954 the convoluted emittance from wire scans is compared to emittance from ATLAS and CMS luminosity, see Table 4. The values are taken after the interaction points have been optimized. ATLAS and wire scan emittances at collision agree within measurement uncertainties. However, the luminosity is not yet calibrated. According to experts the luminosity in both experiments is currently low by 10 % with an uncertainty of ± 10 %. The measured β^* values are used. They have been measured with k-modulation with 1 % uncertainty [3]. The crossing angle is known within an uncertainty of ±5 %. Due to a controlled longitudinal RF blow-up of the bunches at 6.5 TeV the longitudinal bunch shape becomes non Gaussian. However, the LHC Beam Quality Monitor (BQM) publishes a 4σ bunch length value based on the Full-Width-Half-Maximum algorithm assuming Gaussian bunch profiles. This results in an estimated bunch length error of ±1 cm [5]. If the measured bunch length is for instance 0.09 m (= 1.2 ns), the real bunch length is rather 1.1 ns. This would result in a 0.1 µm larger emittance.

The large discrepancy between emittance from luminosity and wire scanner as found during Run 1 is not apparent any more during Run 2. A possible explanation is the better understanding of the wire scanners. The total convoluted emittance blow-up through the cycle is 10 % from wire scanners and 20 % from luminosity for single bunches.

Table 4: Comparison Convoluted Emittance from Wire Scans and Luminosity for Fill 3954

	Wire Scan	**ATLAS**
$\varepsilon_{injection}$ [µm]	2.51 ± 0.10	No measurement.
$\varepsilon_{collision}$ [µm]	2.75 ± 0.20	2.97 ± 0.36
$\Delta\varepsilon$ [µm]	0.24 ± 0.22 (10 %)	0.46 ± 0.37 (19 %)

Radiation Damping at 6.5 TeV

At high energies protons circulating in the LHC emit enough synchrotron radiation to modify the beam parameters. This effect counteracts IBS and could be observed for the first time during LHC Run 2. Synchrotron radiation damping slowly reduces the vertical emittance at 6.5 TeV, see Fig. 8. The LHC emittance damping time is about 32 hours at 6.5 TeV. The emittance evolution due to radiation damping was simulated with the MADX IBS module and also displayed in Fig. 8. The simulation predicts slightly faster vertical emittance decrease than measured due to emittance growth from proton collisions and other beam-beam effects not included in the simulation.

ISBN 978-3-95450-176-2

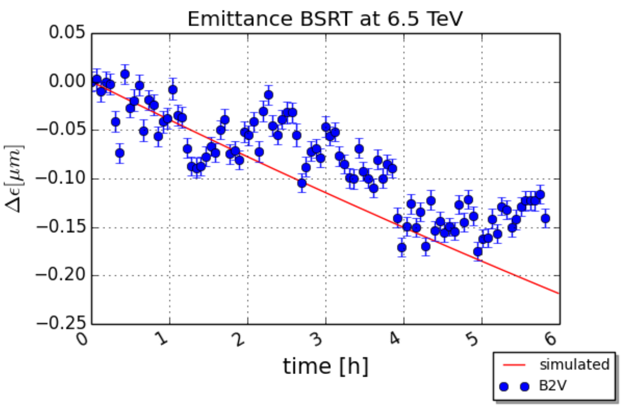

Figure 8: BSRT measurements of beam 2 vertical emittance during collisions of Fill 3988 (July 12, 2015) compared to simulations.

PERFORMANCE OF THE LHC

Wire scanner measurements of low intensity fills can only give an indication of emittance blow-up during the various phases of the LHC cycle. High intensity effects have to be added. To understand the emittance evolution for LHC physics fills, the transverse emittance at the end of the cycle is derived from ATLAS and CMS luminosity. The emittance of the first injected batch at the start of the cycle can be measured at SPS extraction and LHC injection with wire scanners. For the intensity ramp-up in 2015 with 50 ns beams an overview of all physics fills can be seen in Fig. 9. Overall, the emittance blow-up is much smaller than during Run 1 (10 % average growth). Emittances of the 25 ns physics beams during the intensity ramp-up in 2015 show a large blow-up from injection to start of collisions, see Fig. 10, but improving over time (25 % for the most recent fills). Possible sources are electron cloud effects and beam instabilities.

Emittance measurements with the BSRT are unfortunately not useful for a short time frame and many bunches due to a long integration time. Only three to four bunch profiles per second can be obtained.

CONCLUSION

Good progress was made in understanding the wire scanner (and BSRT) emittance measurements for LHC Run 2. In general, the profile monitors are in a better shape than during Run 1. The wire scanner calibration could be verified and no PM saturation effects could be detected. Horizontal emittance growth during the entire LHC cycle can be matched with IBS simulations. Small growth in the vertical planes was measured and is not yet understood. For the first time, synchrotron radiation damping of protons at 6.5 TeV was observed. With the still not fully calibrated luminosity data, emittances from wire scans and ATLAS luminosity agree within measurement uncertainties. ATLAS luminosity measurements of 50 ns beams in 2015 indicate small growth through the cycle. However, large emittance blow-up

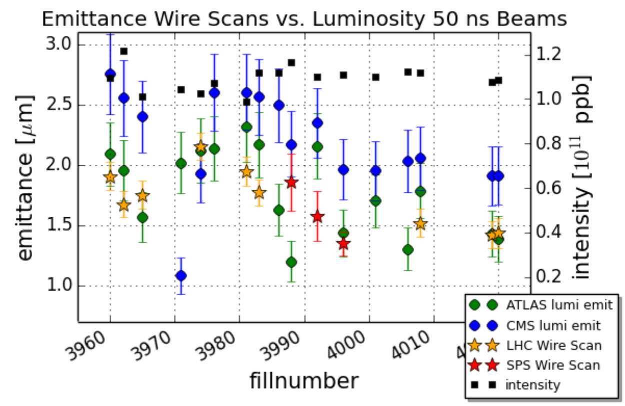

Figure 9: Emittance of 50 ns beams from ATLAS (green) and CMS (blue) luminosity at the start of collisions compared to the convoluted emittance at LHC injection (orange) or SPS extraction (red) measured with wire scanners.

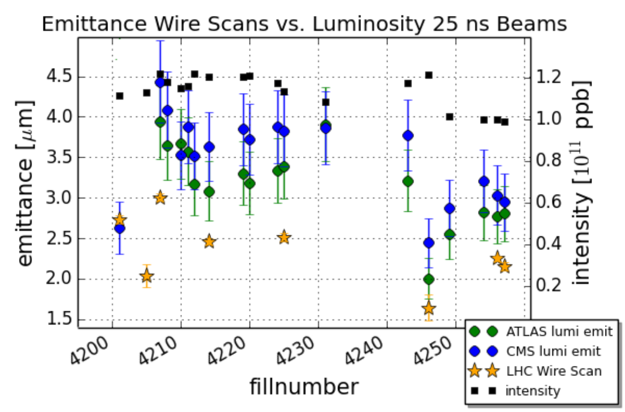

Figure 10: Emittance of 25 ns beams from ATLAS (green) and CMS (blue) luminosity at the start of collisions compared to the convoluted emittance at LHC injection measured with wire scanners (orange).

of 25 ns beams during the cycle could be measured. The electron cloud effect is not fully under control and beam instabilities degrade beam quality.

REFERENCES

[1] M. Kuhn, "Emittance Preservation at the LHC," Master Thesis, University of Hamburg/CERN, Geneva, Switzerland 2013.

[2] M. Sapinski, "Beam Interaction with Thin Materials: Heat Deposition, Cooling Phenomena and Damage Limits," BIW2012, Newport News, Virginia, USA, April 2012.

[3] M. Kuhn, "First K-Modulation Measurements in the LHC during Run 2," presented at IBIC'15, Melbourne, Australia, Sep 2015, paper MOPB046, these proceedings.

[4] http://mad.web.cern.ch/mad/

[5] M. Hostettler, "Observations from OP extended luminosity scans," LBOC Meeting No 44, CERN, Geneva, Switzerland, July 28, 2015.

ISBN 978-3-95450-176-2