BEAM QUALITY AND AVAILABILITY FROM THE INJECTORS

G. Papotti, CERN, Geneva, Switzerland

Abstract

The success of the first year of operation of the LHC would not have been possible without the hard work from the whole injector chain. Beams with different intensity, emittance and bunch spacing have been produced and tuned according to the often varying needs of the LHC. A review of the produced beam parameters is given, as for example transverse and longitudinal emittances, equality between bunches, presence of satellites. Additionally a critical view on how time could have been saved and which tools could be improved for the future is also given.

INTRODUCTION

This paper presents an overview of many aspects of the operation of the LHC injector chain as seen from the point of view of LHC operations. A list of the produced beam types is given, highlighting the flexibility of the injector chain. Some considerations on the transverse plain are presented, as the techniques used to perform emittance blow up, a short overview on the SPS scraper and on transverse size measurements. The subject of intensity measurements and bunch-to-bunch equality are treated next, followed by a short introduction on the SPS Beam Quality Monitor (BQMSPS) and lists of improvements foreseen for the SPS and PS RF. Some considerations on satellite bunches are also included. All along, possible improvements are highlighted when needed, as for example equipment which needs to become Pulse-to-Pulse Modulated (PPM).

BEAM PARAMETERS IN 2010

The progress of the LHC machine during the year 2010 has been impressive, and one of the factors that contributed to that is the flexibility of the injector chain in delivering different beam parameters according to the changing needs.

The PSB determines the transverse emittance of the beam and thus its intensity through the number of turns injected from Linac2 (multi-turn injection). At the PS the longitudinal structure of the beam is fixed as the RF splittings define the bunch spacing. Additionally transverse blow up can be performed. At the SPS more transverse blow up can be performed, longitudinal blow up is also available and PS batches are packed together so to minimize the number of injections at the LHC.

On March 30th 2010 the first stable beams at 3.5 TeV/c were declared, beams consisting of 2 pilot bunches per beam. Low intensity single bunches were injected until May, when the LHC started taking single nominal bunches. In July a campaign of injection studies allowed the first multi-bunch injections, with four bunches extracted from the SPS at a time. Time was allocated in September for bunch train setting up where the bunch spacing was 150 ns and 8-16-24-32 bunches were injected at a time. In November lead ions were injected at the LHC as single, then four and eigth bunches per injection, interleaved by a couple of short runs with both 75 and 50 ns proton beams. This meant that the LHC took 1 to 3 PSB rings, in 1 to 4 PS batches, different batch spacing at the SPS and different bunch spacing at the LHC (50, 75, 150, 500, 1000, 1250, 2500 ns). This while increasing the bunch intensity, decreasing the transverse emittance, and playing around with longitudinal emittance.

The possible multibunch types of beam are listed in Table 1 along with their intensities and transverse emittances [1]. The last two columns in the table indicate which beams were taken at the LHC in 2010 and which were used during Machine Developments (MDs) at the injectors up to the SPS.

Table 1: LHC multibunch beams characteristics in the injectors (◇ for single batch production, ∘ for double batch production). The emittances are given at PSB extraction (1 σ normalized).

Type of beam	ppb@SPS [$\times 10^{11}$]	$\epsilon_x + \epsilon_y$ (μm)	to LHC	to SPS
150 ns (◇)	1.1×10^{11}	2.5	√	√
75 ns (◇)	1.1×10^{11}	3.5	√	√
50 ns (◇)	1.1×10^{11}	5	√	√
25 ns (∘)	1.1×10^{11}	5		√
ultim. 50 ns (◇)	1.6×10^{11}	7		√
ultim. 25 ns (∘)	1.7×10^{11}	8		√
50 ns (∘)	1.1×10^{11}	3		

It has to be noted that the 75 ns and 150 ns beams are produced with emittances that are much smaller than nominal and require tranverse blow up at the downstream machines. The 50 ns beams are now operationally produced with single batch injections from the PSB; the double batch version that was operational until 2008 allows smaller transverse emittances. Ultimate intensity beams consist of $1.6/1.7\times10^{11}$ ppb and were first studied during MDs up to the SPS in 2010 in 25 ns and 50 ns configurations. To be noted that for these MDs the losses at the SPS were still significant and the emittances were not optimized.

TRANSVERSE SIZE

Transverse blow up

In the LHC Design Report the nominal values for the transverse emittances are 3.5 μm rad at the LHC injection, but many types of beams are produced with smaller values (see Table 1). While at the PSB controlled emittance blow up cannot be performed in a reproducible fashion, reliable techniques were found and used at both the PS and SPS.

At the PS [2] transverse blow up was performed by changing the tune and coupling the two planes. This method consists of one knob only, is inherently PPM and gives very reproducible results. Additional controlled blow up at the SPS was needed as the PS transverse blow up was not sufficient to reach nominal emittances.

Also other techniques were experimented at the PS, namely mis-steering of injection trajectories and injection optics, but in both cases the amount of obtained blow up was not sufficient. To be noted that the transverse damper in combination with powering the octupoles is used in the case of multi-turn extraction cycles, but could not be used for LHC-type beams as its controls are not PPM.

At the SPS the transverse damper is used to apply the excitation and perform the controlled blow up [3]. Powering the octupoles provides a large and defined tune spread that tends to minimize the creation of tails. The controls for this method are unfortunately not PPM and not integrated into the SPS control system, and this complicates the procedures the SPS shift crews have to follow in order to use the blow up.

An upgrade of the system is on the list of BE-RF-CS projects and is based on the use of a CVORG board (developed by BE-CO), also foreseen to be used for the longitudinal blow up. It has to be noted that the current verifications on orbit, tune and chromaticity will still be required after the hardware improvements as this technique will still need reproducible tunes, tune spread and chromaticity.

Scraping

In [4] it was foreseen to “clean the tails of the beam distribution down to 3-3.5σ by means of fast scrapers” at the SPS.

In 2010 only one scraper was available, installed in sextant 5 [5]. The main showstopper was that the cables which hold the counterweight broke four times over the run, requiring each time an access to fix them. In order to increase the mean time between failures, the scraper was later in the run turned on only when filling the LHC, effectively reducing the time it was on, but also delaying shortly the start of the filling process to allow the final and fine tune of beam parameters. Additionally the scraper rest position is too close to the beam and this often caused the scraping to happen already at injection rather than only at the flat top.

One additional scraper is planned to be installed in sextant 1 in 2011, followed later in the year by one spare. The fragile cables will be substituted with springs, and it is planned to move the scraper in as late as possible in the cycle in order to avoid scraping at injection. Beam Loss Monitors will also be added in the long term for scraper protection.

It has to be noted that throughout the year extra transverse blow up was needed due to the fact that the scraper often scraped 5% of the beam, rather than the tails only.

Transverse size measurement

Concerning transverse measurements, none of the injectors has a continuous, online, non-destructive measurement of transverse size during acceleration, nor bunch-by-bunch measurements are possible. The only measurement system consists of the wire scanners, which require a manual action (the operator decides to “fly the wire”).

Concerning the PSB wire scanners, measurements were carried out from operations and benchmarked against SEM grids. The result [6] is that they are now considered to work reliably and can be used more easily thanks to the new saturation detection algorithm. Concerning the PS wires, one outstanding issue which still remains is the mechanical fatigue of the bellows, which does not allow for repeated multiple measurements, impacting heavily on the acquisition of statistics.

Due to the small emittance and low intensity of the LHC beams, the linear wire scanners (517) are required at the SPS to get precise/accurate measurements. Unfortunately this system is currently unavailable. A full system upgrade is planned, which involves the use of LHC electronics and a software upgrade that includes the saturation detection algorithm from the PSB developments. It would be important to also include the correction for the known systematic errors between “in” and “out” measurements, which can be tackled by either the hardware or software side. A list of SPS wire scanner systems, with statuses and foreseen upgrades is shown in Table 2 [7].

Table 2: List of SPS wire scanner systems, status and foreseen upgrades.

Device	Scanner Type	Electr.	Status	2011 run
414 h	rot.long	90’s	motion card issue	
414 v	rot. long	90’s	OK	
416 h,v	rot.short	LHC	OK	sw upgrade 40 MHz test
517 h,v	linear	90’s	not avail.	hw+sw upgr. 40 MHz test
519 h,v	rot.long	90’s	OK	
521 h,v	linear	90’s	OK	

INTENSITY

In 2010 the LHC shift crew would decide which intensity they wanted, pass the request onto the SPS crew that then would ask the PSB to regulate the number of turns injected from LINAC2 such that, including the losses along the chain, the required value per bunch would be found at extraction from the SPS.

The workhorse for intensity measurements is the DC-BCT (Beam Current Transformer), for which the agreement between the SPS-ring and PS-ring intensity is very good. Minor flaw is that for now the threshold on DC noise level is only an expert setting and can be found to be not perfectly regulated, resulting in an offset in the BCT measurement which for example still gives a reading even after the beam has been dumped.

The intensity per bunch was manually derived from the total intensity at extraction by dividing by the number of bunches. That is because unfortunately the reading of the fast-BCT is often not well calibrated and cannot be trusted in absolute value, but only in relative terms for an indication of bunch to bunch equality.

Concerning the PS measurements, more sensitive electronics for low-intensity beams is to be commissioned, and a follow-up from BI was agreed on which implies removing the auto-calibration feature (which should improve cross calibration between ring and TT2 transformers).

BUNCH-TO-BUNCH EQUALITY

From [8], "fluctuations inside the bunch train in intensity, bunch length and transverse emittances are within 10%" for 25 ns spacing beams. The main reason for bunch-to-bunch differences is the transient beam loading at the PS splittings.

As already mentioned earlier in the section concerning transverse emittance measurement, nothing is available at the injectors that allows assessing bunch-to-bunch transverse emittance differences, so that possible discrepancies are found only with LHC measurements.

The bunch length is monitored before SPS extraction by the BQMSPS. Every bunch is measured and if any is too long, the beam is not extracted to the LHC. More concerning the BQMSPS is discussed later in the section on Longitudinal Parameters.

Intensity

As already quickly mentioned in the intensity section, the SPS fast-BCT is the measurement system that should allow bunch-by-bunch intensity measurements, but unfortunately is was so far used only in relative terms. Its absolute calibration with respect to the DC-BCT is not obvious as the sampling phase (at 40 MHz) needs to be scanned to make sure to integrate the whole signal from each bunch. A calibration of the 40 MHz phase was suggested with bucket 1 as reference as any LHC beam will be injected from bucket 1 on with a 25 ns (or multiples) spacing.

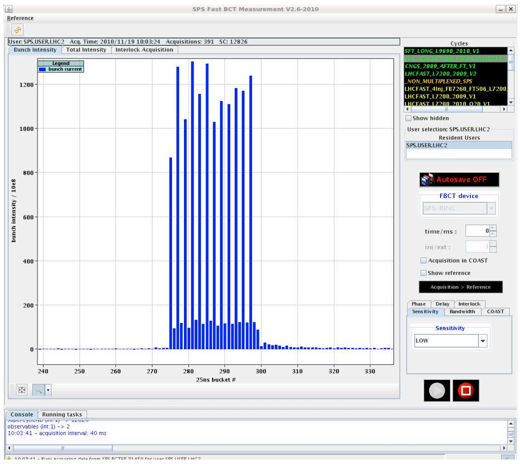

Figure 1: Example of bunch-by-bunch intensity acquisition with the SPS fast-BCT, 12 50 ns spaced bunches in the machine. The tails after the last bunch are clearly visible and are not due to real charge captured in the following buckets.

Additionally there are long tails for each bunch signal which can be up to 10% of the main bunch and are present up to two 25 ns slots. These tails are due to a lack of bandwidth, possibly from the long cables that bring the signal to the surface, but make it impossible to use the fast-BCT for satellite bunch detection. An example acquisition for the fast-BCT is shown in Figure 1.

An interlock signal derived from fast-BCT data has been developed as part of the LHC Software Interlock System (SIS) tree, but has not been made operational yet due to the above mentioned problems. When intensity fluctuations happened repeatedly due to some known temporary problem at the injectors, a "human" interlock was used, that is manually flipping the LHC injection inhibit (OP switch) in case of need for the ongoing SPS cycle.

The possibility of adding further checks in the BQMSPS will be investigated during the shutdown: limits on the calculated standard deviation on measured bunch lengths or peak values will be rather straightforward, while reasonable values for interlocking thresholds will be dictated by operational experience.

LONGITUDINAL PARAMETERS

SPS Beam Quality Monitor

The BQMSPS is a tool that performs an automated analysis of the longitudinal beam profile at the SPS with the aim of avoiding injection at the LHC of beams which are measured not to be good. It is based on an acquisition of a Wall Current Monitor (WCM) profile. This is digitized by an Acquiris DC211 ADC controlled by a FESA class and synchronized to the SPS RF and revolution frequencies by VME Trigger Units (VTUs). The analysis routines are written in C++ and are part of the same FESA class: they perform various checks on beam parameters. If these beam parameters are found not to be compliant with the expected values, then the result of the analysis is negative and the beam is dumped already at the SPS in order to avoid stressing Machine Portection components at the LHC and in order to save time (as losing one SPS supercyle is much shorter than dumping a fill at the LHC).

The BQMSPS performs three sets of acquisitions. The first acquisition is performed at each injection to verify the injected beam parameters from the PS: it calculates the bunch lengths and verifies that the first bunch is injected into the SPS bucket 1. The second acquisition is performed during the ramp and verifies the presence of satellite bunches and that the bunch pattern corresponds to what is requested by the LHC. The third acquisition is performed just before extraction and verifies the beam stability, the bunch lengths and re-checks the first bunch position. As the flat top acquisition is synchronized to the LHC-SPS fiducial frequency, the bunch position verification is equivalent to checking whether the LHC-SPS rephasing has performed correctly. The thresholds that determine acceptance or rejection are set through the Graphical User Interface (GUI) so that a certain degree of freedom is allowed for daily operation.

During the 2010 run, the BQMSPS blocked extraction for many different causes, among which: very bad injection phase or bad PS splittings, fully debunched beam, missing PS LHC-cavities, not enough or too much SPS longitudinal blow up, injections in the wrong bucket, missing injections.

Statistics concerning the 2010 run were acquired from the logging database and analysed, extracting information for the LHC beam modes Injection Probe and Injection Physics Beam, for most fills between 1000 and 1535. Notably about 20% of the LHC beams were dumped at the SPS due to the BQMSPS and a breakdown of the causes is shown in Figure 2. The main cause for dumps is a failure of the LHC-SPS rephasing, which was particularly painful in the case of overinjection. The missing extraction due to the BQMSPS in fact does not prevent the LHC Injection Kicker (LHC MKI) to fire, and this resulted in the pilot being kicked out while no new beam was injected, effectively emptying the machine and obliging the shift crew to start over with the filling process. It can also be noted that the presence of satellite bunches was not a limiting factor, and the fill pattern check prevented quite often the injection of beams that did not match the request.

SPS RF improvements

A number of improvements are needed and foreseen in the SPS RF systems [9].

Concerning the BQMSPS, the system so far required dull maintenance that consisted in filling in by hand a text file containing all possible SPS beam patterns in the form of a Look-Up-Table (LUT). In 2011 there will be no need for a LUT as the patterns will be set directly through the LHC Injection Sequencer (or the SPS GUI in case of SPS mastership). The hardware currently in use imposes the satellite sensitivity to be limited to about 2-3%, while more

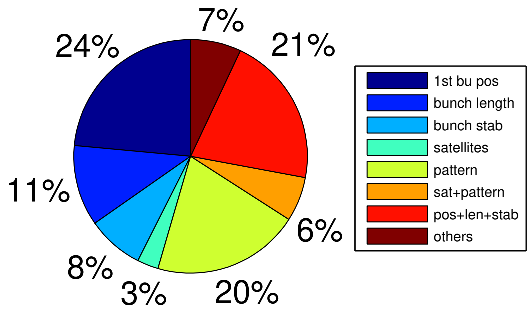

Figure 2: BQMSPS 2010 statistics: main reasons that prevented extraction.

recent hardware is being ordered or installed (fibre optic link, new front end CPU) and should allow better results to be reached after a full campaign of studies.

Concerning the LHC-SPS rephasing, for 2011 it is foreseen to use the same settings for the "training" of ring 1 and 2, as the LHC RF frequencies for beam 1 and 2 are foreseen to stay locked. This could not be done in 2010 and requires a small software upgrade. Additionally, in order to reduce the number of pilots kicked out at overinjection, two options are available. First and most simple, fill patterns that leave the pilot in can be designed (this can be used until the pattern is not too packed, e.g. not for the nominal 2808 bunch scheme). Second, the idea of a "late" pilot injection, which consists of using a pilot injected, rather than in bucket 1, later in the LHC, somewhere where it is not affected by a MKI pulse targeted for bucket 1, and where it is fully kicked out with a later MKI pulse.

The SPS longitudinal blow up was thoroughly tested in many SPS Machine Developments in the past years and became operational in 2010. Still many software improvements are needed to ease the job of the shift crews, as for the moment it is not Pulse-to-Pulse Modulated (PPM), hardware settings are not readable, the interface is non standard. A FESA version was being tested towards the end of the 2010 ion run and is foreseen to become operational sometime in 2011. It will communicate with LSA to retrieve settings as the synchrotron frequency, the noise amplitude, the spectrum shape. It will also allow the development, and later use, of a standard Java GUI.

The 800 MHz RF system currently presents the difficulty of not allowing any diagnostics directly from the CCC. In fact it requires an expert intervention e.g. to verify whether it is locked on the wrong harmonic frequency, or whether it is not locked at all. An alarm is foreseen for 2010 to inform the shift crews if the free running frequency is too far from the target, with measurements at the flat bottom and at the flat top. For sometime in the future the amplifiers are foreseen to be upgraded also, and this will come with a full low level upgrade also.

Finally in the list of improvements, the SPS frequency program playback is planned to be made PPM (to be tested later in 2011).

PS RF improvements

Concerning the PS RF system, the 80 MHz cavities were the most noticeable weak point seen from LHC operation point of view. Presently there are three cavities, two of which are operational and one a spare. The spare had to be re-tuned to a different frequency for ion operation, and this is a problem during parallel operation with ions and protons in case that one cavity has problems: this year it meant a one-hour stop between ion and proton fills. For 2011, the mechanical tuner control is foreseen to become automatic, and this will compensate for pressure and temperature changes. Two streams of thought were encountered by the author while discussing about this subject with various PS colleagues: some thought one extra 80 MHz cavity would not be bad, while others believed it to be better to improve reliability of the existing system, while not increasing the impedance in the machine.

Additionally, ideas for a "PS Beam Quality Monitor" are starting to circulate, as means to have an online monitoring of longitudinal beam parameters. Some of the information could even be fedforward to the LHC SIS to prevent injection in the LHC in case of bad cycles.

Satellite bunches

In the LHC nominal pattern, at most one 2.5 ns bucket is filled every ten, corresponding to one bunch every 25 ns. In early filling schemes, the bunch density is even lower, e.g. 150 ns and 50 ns spacings were used for physics in 2010. If any non-negligible quantity of beam is present in the buckets which are designed to be empty, these bunches are called "ghost" or "satellite" bunches. They can be created for example from not well tuned bunch splittings at the PS or by not well corrected injection phase at any of the transfers between machines.

An agreement between machine and experiments was found at the LEADE meeting [10] indicating a limit of a "few percent" as acceptable for the satellite bunches. Down to the level of 2-3% they are checked with the BQM-SPS with two different algorithms, one based on the mid-bucket bunch height and one based on signal intregration per bucket. It has to be pointed out how more precise measurements will be possible only after the BQMSPS hardware upgrade, which includes the use of a fibre optic link for the WCM signal, and a recent CPU for allowing more computation capability in the same amount of time.

Measurements of satellite bunch population were performed at the LHC by J.J. Gras (BE/BI) with the LHC Longitudinal Density Monitor [11]. For the LHC lead ion fill 1515, a beam 2 measurement integrated over 50 min during stable beams revealed that many 2.5 ns buckets had been populated due to the newly introduced RF gymnastics at the flat bottom (total voltage dip at every injection). Some of the satellites though were noticeably higher than the neighbouring ones, indicating that they were already present on the injected beam, rather than created at the LHC. Additionally, they showed a 5 ns structure which is another clear indication that they came from the injectors. The intensity of these ghost bunches was a few per mille of the main bunches.

Additional measurements came from the experiments for Van der Meer scan fills, and were presented in [12]. Measurements from the ATLAS and Alice Collaborations gave indications of contributions of about 1 per mille to 1 per cent of the main bunch peaks, with longitudinal spacing pointing to the injectors as sources of the satellites.

OTHERS

A number of various other possible improvements was foreseen. Something which was highly desired by the LHC Performance Coordinator is the automatization of the selection of the number of Booster rings in use. This would allow an increased flexibility in the creation of LHC fill patterns, but would also allow the filling to be faster in case of enforced reduced number of bunches for the first high intensity injection (limited to 8 or 12 bunches). The main issue is the PS RF settings which require a very fine tuning (mostly for 50 and 75 ns spaced beams), so that the automation of the number of Booster rings boils down to either storing the settings in different users, or to make use of "double" or even "triple" PPM settings.

At the SPS, the batch spacing cannot be remotely programmed, but requires a setting through the Man-Machine Interface (MMI) software. An improvement of this has long been promised, and is foreseen for sometime in the future.

It has also to be noted that the SPS supercycle composition and the supercycle change affect the LHC efficiency. Concerning supercycle changes, e.g. for pilot and nominal intensity users, it was noticed that the change was faster when the sequences were ready. But this would be most optimized for standard sequences, that is in the absence of MDs, which highlights a tradeoff between LHC efficiency and injectors schedule flexibility.

Last but not least, it has to be noted how in 2010 the injectors never went into dedicated LHC filling, which by the way led to greater than expected performance for non-LHC beams, like CERN Neutrinos to Gran Sasso and Fixed Target beams. This is due to the fact that anyway the LHC could not have taken beams from contiguous SPS cycles as extra time was needed for the Injection Quality Check analysis and to send the next request down the injector chain. For example, in order to request beam on the LHCION2 user (ion cycle, up to 4 PS injections), a padding with 12 extra basic periods would allow LHC injection every SPS supercycle; while 10 extra basic periods would not be sufficient. This delay could be avoided if the request handling was "per ring" in the injection sequencer, rather than purely serial as it is at the moment (a verification for ring 1 is awaited before sending a request for beam2, and viceversa). An upgrade of the LHC Injection Sequencer in this direction is foreseen for the 2011 run.

Communication

A few words have to be spent for noting how the whole CCC learnt along the first year of LHC operation how to handle LHC requests. At the shift crew level, the shift crews learnt the tricks: for example, back in the beginning of the run many first injections failed simply because the PS shift crew was not informed to turn on their cavities, which were still off when the LHC was requesting beam. Or for example when first trying the overinjections, many pilots were kicked out simply because the SPS extraction kickers were forgotten disabled.

At the level of coordination between the different machines, often it was noted from the injectors how not enough time was allowed for them to set up the users and beams properly. But also this improved as time passed by and steps will be taken from 2011 to try and improve the communication even further.

STATISTICS AND CONCLUSIONS

In the 2010 statistics presented in these proceedings [13], it is shown how 2.3% of the LHC downtime is due to the beam not being available at the injectors. A further breakdown per machine, according to the LHC logbook, points to the PSB for 14.5% of the time, to the PS for 17.5% and to the SPS for the remaining 68%. It is not clear whether the SPS was really the major cause, or whether the faults were not fairly assigned from the shift crews.

Anyway, regardless which of the injectors caused most faults, the injector chain provided a very high availability over the run and made 2010 a remarkable year. It has to be remembered also how this was helped by the fact that plenty of problems were kept in the shade, as for example fixes were held until the next LHC access or until filling was finished. One example for all, when the vacuum at the SPS was a problem, then the LHC had the record fill length of about 30 hours.

Despite the great success, this paper provided a list of improvements and upgrades which will make operations even easier and the performance even better in the future.

ACKNOWLEDGEMENTS

The author would like to underline how the discussion with many colleagues was essential and made this summary possible. G. Arduini, T. Bohl, A. Butterworth, H. Damerau, J. Emery, S. Hancock, W. Hofle, L. Jensen, E. Veyrunes, J. Wenninger are warmly acknowledged as very important sources of information, and in particular G. Rumolo and S. Gilardoni. Additionally, the author would like to acknowledge the work of A. Apollonio and G. Trad, who shortly after joining the operations group, quickly extracted the 2010 BQMSPS statistics from the logging database.

REFERENCES

[1] Rumolo G., private communication.

[2] Gilardoni S., private communication.

[3] Höfle W., “Transverse blowup in SPS going ppm”, Machine Study Working Group (MSWG) 03-12-2010.

[4] AA.VV. “LHC Design Report”, Vol.III Chapter 12, CERN 2004-003.

[5] Veyrunes E., Donze M., private communication.

[6] Mikulec B., “PSB Wire Scanner Measurements with new Photomultipliers”, MSWG 19-11-2010.

[7] Emery J., private communication.

[8] AA.VV. “LHC Design Report”, Vol.III Chapter 10, CERN 2004-003.

[9] Butterworth A., Bohl T., private communication.

[10] Wenninger J., “Satellite bunches in the LHC” and minutes, LHC Experiment-Accelerator Data Exchange Working Group, 18-08-2003 .

[11] Lefevre T., “Bunch by bunch beam instrumentation”, these proceedings.

[12] Bunch Current Normalisation Working Group Meeting, 29-11-2010

[13] Venturini Delsolaro W., “Operational efficiency”, these proceedings.