STATUS OF THE BEAM INSTRUMENTATION AFTER LS1

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Abstract

During LS1 a number of upgrades were applied to the LHC beam instrumentation, partially to cope with the increase of the beam energy and partially to solve issues observed during RUN 1 or to add new functionalities. This presentation will give an overview of the changes made during LS1 and report on the results obtained for most of the BI systems, in particular BPM, QFB, OFB, BCT, BBQ, BTV, BRAN, BQS, BSRL. Finally an outlook of changes foreseen for the upcoming YETS will be presented.

INTRODUCTION

Beam instrumentation is a key system for all accelerators as it provides information to the operators about the status and quality of the particle beams in the machine.

In the case of the LHC this information is used in two ways: to optimise the beams and maximise the collider performances and to ensure that the beams are under control and pose no safety issue to the components of the accelerator.

The LHC beam instrumentation performed rather well during run 1, nevertheless few problems and limitations were discovered and a lot of work was carried out during the first long shutdown (LS1) to correct the issues and improve the performance.

The operation of the LHC during 2015 was devoted to recommission all the machine systems after the LS1 upgrades, the increase of the beam energy from 4 TeV to 6.5 TeV and the change of the bunching structure from 50 ns spacing to 25 ns spacing.

This contribution describes the changes in the LHC beam instrumentation w.r.t. run 1, the performance demonstrated during 2015, the issues encountered and the plans for the future.

This paper does not cover all the beam instrumentation systems as some aspects are covered in other contributions at this workshop. Namely the wire scanners (BWS), the synchrotron light emittance monitor (BSRT), the beam loss monitors (BLM), tha abort gap monitors (BSRA), the tune and orbit feedbacks (QFB and OFB) and the head-tail monitor (BQHT) are not included in this analysis.

The system handled in this presentation are: the beam position monitors (BPM), the DC and fast beam current transformers (BCTDC and BCTFR), the tune monitor (BBQ), the TV observation screens (BTV), the luminosity monitors (BRAN), the Schottky monitors (BQS) and the longitudinal density monitor (BSRL).

BEAM POSITION MONITORS

During LS1 several changes were applied to the BPM system, the most relevant are:

- Replacement of all the electronics racks hosting the VME crates with temperature controlled versions
- Replacement of all the VME controllers, based on PowerPC microprocessors, by new boards based on Intel chips
- Replacement of the VME controllers operating system from LynxOS to Linux SLC5
- Removal, cleaning and re-installation of all front end DAB boards and of the relative optical fibres
- Upgrade of the BPM FESA classes to FESA3
- Addition of one monitor in IR4 and the renaming of few existing monitors
- Implementation of the non-linearity-cross-term correction in the front end firmware
- Installation of the new DOROS acquisition electronics for the new tertiary collimators (TCT) which are equipped with button pick-ups
- installation of the new DOROS acquisition electronics in parallel to the existing electronics (normaliser) for the BPMs around the Q1 quadrupoles in IR1 and IR5.

The implementation of these changes inevitably introduced new issues, most were identified and corrected during the hardware commissioning, some could however only be identified with beam, like few cable inversions promptly corrected. On few pick-ups, a not fully understood problem was observed resembling to a bad connection inside the cryostat. Further investigations will take place during the upcoming year-end-technical-stop (YETS) to see if a fix can be found for this issue.

At the end of the year 48 channels were not correctly functioning, and thus masked by the operation crew, out of 2160. This corresponds to 98% of the BPM channels being available.

The new thermalised racks have shown to perform well, with temperature variations inside $0.5\,^{\circ}C$, corresponding to orbit drifts of less than $20\,\mu$m RMS during a physics fill as shown in Fig. 1. The thermal orbit drift is directly proportional to the BPM aperture and teh figure refers to a large aperture IR strip-line BPM. In a few cases the high summer temperatures required changing the set-point of the regulation (to avoid condensation) and/or re-tuning the

PID controller, Figure 2 shows the example of a regulation instability. The temperature of the racks is linked to the LASER alarm system so that misbehaviours can be immediately identified and corrected.

In order to improve the efficiency of the vacuum chamber scrubbing with beam a new filling scheme has been proposed and tested in 2015[2]. This requires the use of so called doublets, i.e. couples of bunches separated by merely 5 ns. Due to the inherent way the present BPM system works, based on the normaliser cards[1], it can not cope with bunch spacing of less than 20 ns. This implies that the orbit of the doublet beams could not be measured. A work-around to this limitation was found and consisted in injecting a single bunch alongside with the doublet trains and using the synchronous orbit mode gated on the single bunch. Clearly this work-around poses the problem that the real orbit of the doublets is not measured posing a potential machine safety issue.

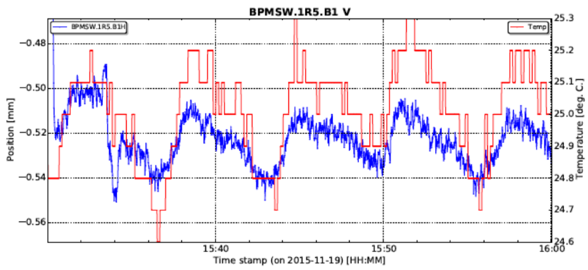

Figure 1: Remaining temperature variations (red) and corresponding drifts in the orbit reading (blue) for an large aperture strip-line BPM.

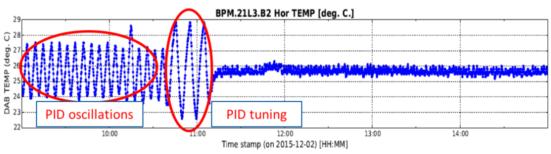

Figure 2: Temperature stability of the new thermalised racks. On the left an unstable behaviour is evident that was cured by retuning the PID controller.

DOROS

DOROS consists of a new scheme for the acquisition of the pick-up signals. It is largely based on the BBQ technology used for the tune measurement in use in most machines at CERN. The DOROS acquisition system provides the orbit information as well as an oscillation information. The orbit is the time-averaged position of all the bunches in the machine while the oscillation provides the evolution turn per turn of the position of the bunches.

DOROS provides a better signal-to-noise ratio compared to the normaliser with a resolution of around 1 μm as can be seen in Fig. 3.

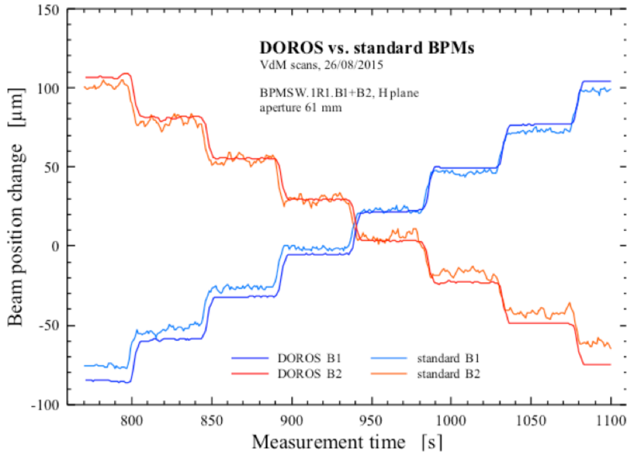

Figure 3: Comparison between the DOROS and normaliser orbit measurement. DOROS show much less noise than the normaliser. A difference in scale is also visible which has not been understood yet.

Figure 4 shows the beam spectrum obtained with the capture mode of the normaliser and with the oscillations channel of DOROS. The noise floor of the DOROS system is clearly much lower allowing precise measurements. This functionality has been added in particular for betatron coupling[3] and phase advance measurements.

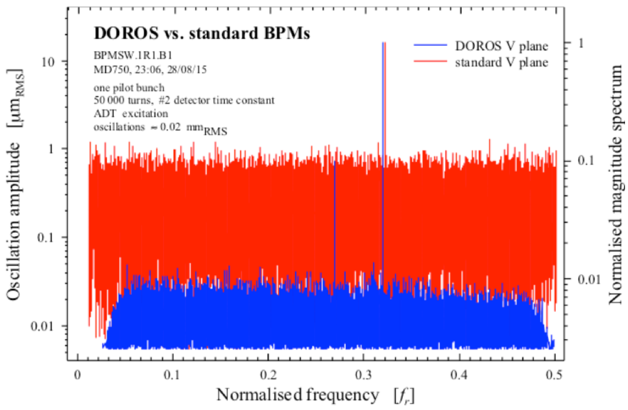

Figure 4: Comparison between the DOROS and normaliser beam spectrum. The DOROS system shows a much lower noise floor compared to the normaliser.

Another case in which the DOROS electronics performs better than the normaliser is around the interaction regions were the two beams pass through the same BPM monitor. In this case a particular type of BPM is used called directional couplers, consisting of strip lines read out at either ends. Ideally the signal of each beam can be independently read out on the side where it enters the monitor, in practice reflections due to imperfect matching of the different parts create delayed cross talks between beams. The normaliser can only make accurate position measurements if the bunches of the two beams arrive at the monitor with more than 6 ns delay while for the DOROS electronics 2 ns separation are sufficient. Figure 5 shows the read position versus the beams separation for the two electronics during an RF phase scan (cogging)[4].

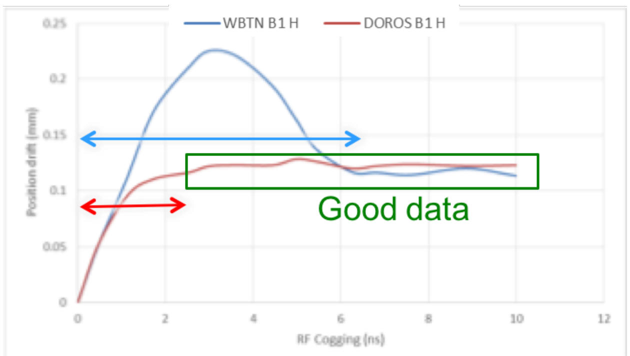

Figure 5: Comparison between the DOROS and normaliser for the directional couplers used on the common vacuum chambers around the IPs. DOROS requires only a few ns separation between beams for a correct measurement.

A total of 16 DOROS front-ends were installed in 2015: 10 for the acquisition of the button pick-ups on the new TCT collimators and 6 for normal BPMs, these systems are installed mainly around the luminous regions of the LHC. Each DOROS front-end provides 8 input channels (not all always used) and is read out via an Ethernet link.

Possible Improvements and Plans for YETS 2015

Although the BPM system worked reliably during 2015 there are still a few issues to be addressed and aspects that can be improved.

With the knowledge gained in the first year of operation of the new thermalised racks it is possible to improve further the temperature control and reduce even more the excursions by optimising the PID tuning. It is also possible to (re)introduce software corrections for the remaining drifts.

During the year it was necessary to re-phase several times the acquisition chain, this is to align the acquisition clock with the machine RF. Work is ongoing to try to understand why this operation needs to be repeated, as in principle a phasing at the start of the year should be sufficient. Also new improved tools for the automatic phase adjustment are being prepared.

Another issue observed this year is probably related to the change of operating system. If the capture mode is used alongside the orbit mode this causes data corruption in the capture data. Although the phenomenon is not fully understood it looks like being induced by the way VME interrupts are handled and was never observed with the old PowerPC CPUs. In 2016 a new firmware will be used in the DAB cards and this problem will be addressed. For 2015 the solution was to disable the orbit mode when the capture mode was needed, e.g. during optics measurements.

There is also still some uncertainty about the overall BPM scales and non-linearity corrections (cross terms). In particular the optics measurements seem to indicate inconsistencies in the data. The scales and the corrections will be verified with simulations and laboratory measurements. This includes the investigation of the scale difference between the normaliser and the DOROS systems.

The problem with the mismatch inside the cryostat for some BPM is being studied and a fix being tested, the cryostats can clearly not be opened for the proper repair. If the proposed fix can be validated in the lab it will be deployed on the faulty channels.

Concerning the DOROS system, it still requires some fine tuning of the digital processing parameters to cope with beams with large intensity variations between bunches. In fact a new firmware will be finalised and deployed during YETS to improve further the performance of the DOROS system. Furthermore additional DOROS systems will be added for the readout of the Q1 BPMs around IP2 and IP8. It is worth considering if there are other places where DOROS could be useful, e.g. extending further into the LSS.

There will be a change also for the control of the sensitivity of the BPMs, this will allow to select independently the sensitivity of the normal BPMs and of the interlocked BPMs around the dump channels in IR6. This modification will give more options and freedom in the operation of the machine, where large bunch intensity differences, e.g. due to few bunches becoming unstable, often lead to the beams being dumped by the interlocked BPMs system.

DC BEAM CURRENT TRANSFORMERS

During LS1 the control crates of the DC beam current transformers were upgraded. The powerPC VME controllers were replaced by the new Intel based version and the operating system replaced by SLC5. The FESA classes were also ported to FESA3 so that the renovation of the crates is now completed. On the acquisition side there were also few changes, the most important being the replacement of the 12 bits MPV908 ADC VME modules with the more modern 16 bits VD80. Due to the large dynamic range of the beam current in the LHC even 16 bits are not sufficient to cover the whole interval, therefore the 4 ranges system used before LS1 remained unchanged. In parallel to the system mentioned above a new acquisition chain based on a single 24 bits ADC has been tested during 2015 and will become the default in 2016, with the 4 ranges 16 bits ADC system remaining as the backup.

During the year the BCTDC performed very well and all the changes/upgrades have been fully validated.

A few problems however affected the setup-beam-flag (SBF) signal provided by the BCTDC system. First of all the threshold for the SBF at 6.5 TeV is close to the noise floor of the transformer at $1.2\,10^{10}$ protons. This caused flickering of the flag with safe beams, leading, in a few cases, to the firing of masked interlocks. The averaging time of the BCTDC readings was increased for energies above injection thus reducing the noise and solving the problem. Once left the injection plateau there is anyway no possibility of increasing the beam intensity.

Another problem observed in a couple of occasions was the SBF remaining stuck to FALSE after a sequencer driven calibration of the device (not posing any safety issue). The flag can be easily unblocked by repeating the calibration. Being the event very rare it is difficult to understand what causes it and work is still ongoing.

FAST BEAM CURRENT TRANSFORMERS

For the fast beam current transformers the main change w.r.t. run 1 has been the rewriting using FESA version 3 of the acquisition and calibration servers. Some modification have taken place also in the acquisition firmware, mainly to correct issues observed in the past.

The most substantial work concerning the fast transformers during LS1 has been however the development of new sensors. During run 1 the system has shown performance limitations due to large sensitivity of the measured bunch current on the transverse position of the beam. This problem has been studied extensively and tracked to an inherent problem of the design of the transformer. In order to overcome this limitation an R&D project has been carried out over several years and led to the development of two alternative sensors. One is entirely developed by CERN and is based on the CTF3 BPMs design, the so called wall current transformer (WCT), the other developed by BERGOZ called integrating current transformers (ICT)[6].

Another limitation of the operational systems originates from the long tails of the response pulses, that extends past the 25 ns of a bunch slot, and introduces crosstalk between neighbouring bunches. This problem was not important in run 1 as then the LHC was not operated with 25 ns bunch spacing, apart from few MDs. In run 2 however 25 ns is the default mode and the crosstalk becomes a problem.

During 2015 one of each design was installed in the LHC in parallel with the operational monitors for testing (system B), the ICT being installed on beam 1 and the WCT on beam 2. Both designs demonstrated to be much less sensitive to the beam position, to have shorter response tails, to have comparable noise levels and to be at least as precise as the operational devices in the measurement of the beam current. The results of a dedicated MD[5] can be seen in figures 6 and 7. Although both designs performed well the WCT maintained a little edge over the ICT.

The WCT results are slightly better also in terms of pulse shape. In fact the ICT response pulse is still a bit longer than 25 ns while the leak into the next bunch slot is practically zero in case of the WCT.

Based on the good results obtained in the dedicated beam studies in 2015 it has been decided to replace the sensors of the operational BCTFR with WCTs for both beams during the YETS 2015. The old sensors will be shifted into the parking position as their removal would require the opening of the vacuum pipe.

At the moment the signals of the fast transformers are acquired using fast interleaved integrators. Some quirks and limitations in the integrators require a delicate and frequent phasing and calibration. Some artefacts introduced by the integrators is also impossible to completely correct.

Figure 6: Comparison between the operational BCTFR and the new ICT during a dedicated MD where beam offsets were intentionally introduced at the monitors location. The improvement of the ICT is evident, but a little sensitivity remains.

Figure 7: Comparison between the operational BCTFR and the new WCT during a dedicated MD where beam offsets were intentionally introduced at the monitors location. The improvement of the WCT is striking.

For this reason a study is ongoing for the replacement of the analogue integrators with fast digitizers and digital integration. This development is however not yet ready and will thus not be deployed for the 2016 start-up. Depending on the progress the roll-out may happen during a technical stop or at the end of the year.

TUNE MONITORS

Few interventions were done on the LHC tune monitors during LS1 and they operated reliably during 2015. The main changes w.r.t. run 1 are:

- Installation of two new pick-ups (BPLX)
- Acquisition of the different devices split among two VME front-end crates (single crate before)

- System integration of the gated system
- Addition of the beam transfer function (BTF) functionality
- Consolidation of the code, correction of few bugs, improvement of the filtering algorithms
- Correction of the post mortem data delivery

Figure 8 shows the topology of the BBQ system that was implemented for the 2015 start-up.

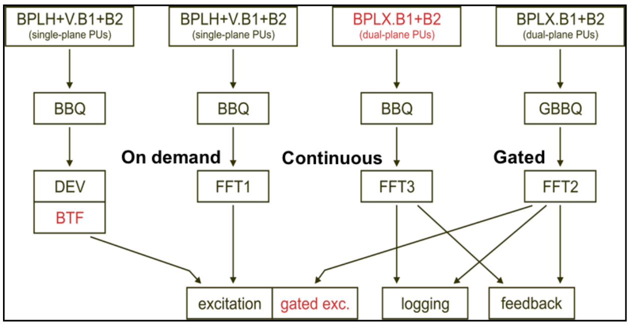

Figure 8: Layout of the BBQ systems as deployed in 2015.

For next year a few more changes will be made, in particular a new version of the DAB firmware will be deployed which will solve the problem of lost VME interrupts. It is also planned to port the FESA classes to version 3, the date for the deployment is however not yet set. This will offer the opportunity to clean up the code and improve stability further.

BEAM TV OBSERVATION SYSTEM

The main work on the BTVs during LS1 consisted in fixing the problem with the damaged RF fingers. This was a serious issue that led to the lock-out of several devices during run 1. The reason was understood, leaky copper depositions leading to cold-welds, and corrected, but required removing, repairing and reinstalling the vacuum tanks.

In addition, based on radiation monitoring during run 1, several radiation hard cameras were replaced by standard CCD models as these produce better quality images and are more sensitive. In the case of the BTVDD it was preferred to maintain the existing radiation hard camera and add in parallel a standard CCD by mean of a light splitter optical set-up. On top of improving the image quality this has the advantage of adding redundancy in that delicate device.

The only change foreseen for 2016 is the porting of the BTV FESA class to version 3. Probably a separated class will be developed for the BTVDD as the present one-cover-all solution lead to some issues in integrating the BTVDD in XPOC, not yet fully solved.

LUMINOSITY MONITORS

Two types of luminosity monitors were used in LHC in run 1: the BRAN-A based on ionisation chambers installed in the TANs around IP1 and IP5 and the BRAN-B based on Cadmium-Telluride (CdTe) detectors installed around IP2 and IP8. At the end of run 1 the performance of the CdTe detectors installed in point 8 had been seriously degraded by radiation damage to the point that they were barely usable. This came as a bitter surprise as the technology had been radiation tested before the construction of the LHC and was expected to last at least ten years at nominal beam parameters.

A new BRAN design (BRAN-C) was developed during LS1 based on Cherenkov radiation in fused silica rods and photomultipliers. Four monitors have been built and installed around IP2 and IP8. The performance of the new monitors in 2015 has been excellent also surpassing the results of new CdTe monitors in terms of sensitivity and linearity. The deployment of the BRAN-C went smoothly as the acquisition chain remained unchanged.

For the BRAN-A system the only intervention consisted of porting the FESA class to version 3 and removing/reinstalling the monitors several times due to bake-out of the TANs.

Seen the good results obtained with the BRAN-C systems and the ageing of the BRAN-A systems, fused silica rods of different grades will be installed inside one TAN in IP1 to investigate the radiation hardness. In case of a positive outcome Cherenkov based detectors could eventually be deployed around IP1 and IP5 as well.

The porting of the BRAN-C FESA class to FESA3 is in the pipeline, but will probably not be ready for the 2016 start-up.

SCHOTTKY MONITORS

The Schottky monitors underwent a substantial overhaul during LS1 with modifications both in the pick-ups hardware and read out circuitry. For one of the monitors the front end electronics has been completely rebuilt and the new design tested during 2015.

A lot of extra diagnostics has also been added like oscilloscopes and spectrum analysers to facilitate the debugging and tuning of the system. On the software side there have been improvement as well with the creation of numerous expert tools, again aimed at facilitating the development of the monitors.

The modifications paid off nicely and the Schottky monitors behaved rather well during the ion run. With protons the large coherent signal still poses strong limitations as it requires continuous fine corrections of any beam position offset. Figure 9 shows the signals obtained both with ions and protons[7] in 2015, the tune and chromaticity measurements obtained along the cycle look very promising.

The results obtained with the new front-end design are very positive and this new scheme will now be deployed on the other devices as well.

The added diagnostics capability allowed to identify a new issue, a long ringing of the pick-up signal after the bunch passage. The ringing has a decay constant of hundreds of microseconds. This effect has been explained by unavoidable small matching errors in the pick-up hardware. Measures to reduce the impact on the measurements are being studied, in particular fast gating of the input signal itself.

The Schottky team is presently trying to deliver an on-line chromaticity measurement for the normal proton operation and bunch by bunch tune measurement mainly for MDs. The test and deployment plan is however still fluid.

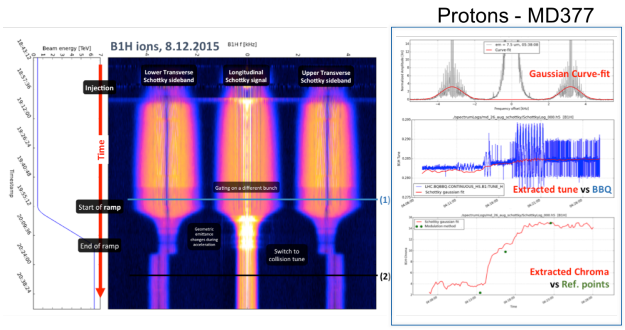

Figure 9: Examples of Schottky signals with ions (left) and protons (right) during 2015.

LONGITUDINAL DENSITY MONITOR

Two major changes were applied on the longitudinal density monitor (BSRL a.k.a. LDM): the optical set-up and the integration inside the BSRT was completely revised and a new type of sensor was tested (hybrid photomultiplier).

The change in the optics set-up allows a better decoupling between the different systems sharing the synchrotron light extraction, it also reduces the sensitivity on the light steering and the fraction of parasitic optical reflections.

The hybrid photomultiplier (HYBPMT) was chosen among various single photon timing detectors after extensive tests in the laboratory. Compared to the previously used avalanche photo-diodes (APD) the HYBPMT is far superior in terms of: reduced dark counts, negligible after-glow and very short dead time.

The characteristics of the HYBPMT allow to extend the dynamic range of the LDM almost two orders of magnitude and do not require complex post-processing of the data as for the APDs. At the start of run 2 one HYBPMT was installed on beam 1 for testing it in real conditions, while the main systems were still based on APDs, seen the positive results, soon after the beam 2 APD was replaced by an HYBPMT.

A new GUI written in PYTHON was also written allowing the acquisition and analysis of the BSRL data on-line (FESA) and off-line (extracting from LDB). This new interface, allows the visualisation of many parameters on top of the standard longitudinal beam density histogram. In particular it contains:

- Particles population with 50 ps resolution and 5 orders of magnitude
- Bunch current,
- Bunch length
- Bunched/unbunched fraction
- Comparison w.r.t. BCTFR or BQM

Figure 10 shows the large dynamic range obtained with the BSRL in 2015. In the same picture it is also possible to see how the background signal is very small allowing a direct measurement of the abort gap population. This measurement was not possible with the APDs as the afterglow created a large background difficult to correct for.

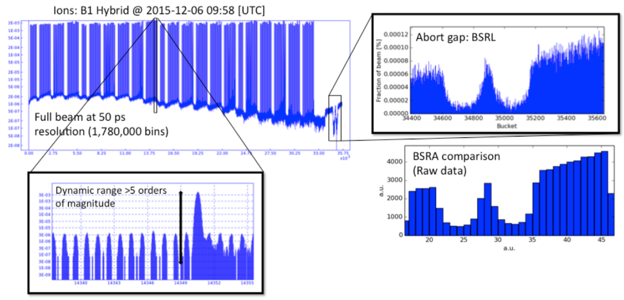

Figure 10: Longitudinal beam density measurement in the LHC with the BSRL.

GENERAL REMARKS

Software, at different levels, is now a major component of all devices. All levels of software, front-end, back-end, GUI applications etc. depend more and more on packages provided by other groups (e.g. BE-CO) or commercial companies. During LS1 there have been numerous important changes in this infrastructure and software developers have been forced to write code using unfinished/unstable packages. Apart from frustration and additional work this also meant that most code required modifications until the last minute (and after...) introducing instabilities and/or unpredicted behaviour of certain systems.

Moreover tools and documentation were not ready until after restarting the machines, in particular concerning FESA3 and RDA3.

The BE-BI group is particularly sensitive to this point as it has a very large number of different FESA classes with few instances each. This implies a large amount of work every time a framework change requires retrofitting the existing code.

In fact software engineers were still busy fixing code on the injector complex at the time the LHC restarted inducing big delay on the LHC developments.

At present the main request from BE-BI is to concentrate on consolidating the present infrastructure and to (re)introduce specialised tools.

CONCLUSIONS

2015 has been a very successful year for the LHC beam instrumentation. Several teething problems appeared at the restart of the accelerator as a consequence of the many changes in the systems and in the infrastructure. The BE-BI group reacted promptly in all occasions and almost all issues were solved by the end of the year. More consolidation work will take place during this YETS and the beam instrumentation will be in a good shape for the upcoming production period.

All the important LHC BI systems are now mature and working reliably, allowing the various engineers to shift focus from LHC R&D to HL-LHC R&Ds.

ACKNOWLEDGMENT

This contribution sumarizes the work of a large number of people inside and outside the BE-BI group. I would like to thank them all for the precious help in preparing this talk.

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