LHC TRANSVERSE FEEDBACK

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Abstract

The LHC Transverse Feedback System [1], habitually called *ADT* has undergone considerable modifications in LS1 aimed at improving performance and flexibility. The new features added are summarised along with the major LS1 maintenance works. The major causes of faults of the 2015 run as well as pending issues and possible mitigations for the 2016 run are discussed. Operation with doublets and an outlook to the 2016 production run with 25 ns bunch spacing is given.

SUMMARY OF ADT LS1 ACTIVITIES

As part of the maintenance work for all power amplifiers the high voltage dividers inside the amplifiers and the related electronics in UX45 were calibrated and re-commissioned in the amplifier testing facility. The tetrode amplifier upgrades also included new powerful air cooling units for the tube sockets, as well as a rework of the water cooling infrastructure in the tunnel. The loads for the drive signal, located inside the power amplifiers were exchanged for a new model with a power rating of 200 W.

Additional vacuum gauges on each side of the IP were added to increase availability by an appropriate voting logic.

A modernised digital signal processing unit *mDSPU* was developed during LS1 and deployed for the 2015 run. This new unit comfortably integrates all added features requested during LHC Run 1 [2, 3] with individual output DACs and gain control for the different functionalities, namely feedback, abortgap and injection cleaning as well as blow-up for loss maps. Goals and changes from Run 1 to Run 2 comprise the possibility to combine data streams from four pick-ups in total.

The substantial modifications deployed in LS1 required to follow the full setting-up procedure to newly adjust all parameters of the feedback.

RUN 2: IMPROVEMENTS

Cabling

During LS1 all pick-up cables linking the tunnel to the service building SR4 were successfully replaced [2]. A thorough quality control performed during cabling ensured a top quality of installation which payed off during LHC Run 2 by resulting in an unprecedented signal purity available for beam position processing. Key to a high-performance closed loop feedback response is to measure the bunch position with high precision and low noise and without interference from signals leaking from adjacent bunches which can be caused by reflections on an improperly installed cable.

Figure 1: New clamping mechanism (in blue) connecting the RF contacts between the amplifier and the ADT kicker.

As part of the full setting-up procedure the length matching carried out for each pair of cables connected to a pick-up achieved a length balancing of better than 25 ps, corresponding to ± 5 mm (at lengths of up to 800 m of the coaxial transmission line).

Power System

A new clamping mechanism developed and installed by BE/RF/PM now interconnects the RF contacts to the kicker feedthroughs with the power amplifiers right below the structure in the tunnel with a robust and easy to operate novel bracket (see Fig. 1). This new mechanism allows easier exchange of an amplifier and ensures that a proper RF contact is maintained during operation.

Transfer functions of the power system were measured between the surface installation in point 4 and the tunnel equipment. Digital correction of the frequency response has been optimised within the new digital signal processing units for best phase linearity, essential to cure coupled bunch instabilities between the lowest betatron frequency and 20 MHz (25 ns bunch spacing).

New signal processing unit: mDSPU

As the successor of the former DSPU (digital signal processing unit) the new VME module allows for implementation of all added features during LHC Run 1 and additional features, thanks to an Artix VII FPGA. This board is also used in the SPS damper and has been the result of synergies between the LHC damper upgrade and the LIU SPS Damper upgrade. All hardware tests were successfully passed in the SPS in 2014, with the digital hardware further adapted for the LHC ADT startup in 2015.

Four high speed (up to 2.5 GBit/s) optical digital serial links receive data streams from up to four pick-ups (illustrated in Fig. 2). The further data processing is done digitally, with the received beam positions combined for generating

the feedback correction signals for each ADT power module. For the operation of ADT in 2015 the same pick-ups as in Run 1 were used (Q7 and Q9) with the additional set of two pick-ups per plane expected to be gradually coming online when the required analog pre-processing hardware will have been completed.

The new design of the DSPU features four dedicated high resolution DACs for separate control of all features (loop gain, cleaning and excitation). The new VME boards are located in four new VME crates equiped with the latest CPUs, RF specific crate management module, two CTRV cards for timing and a timing distribution module. All software commissioned for these crates in 2015 has been developed for FESA3 and is operated using a dedicated application using "Inspector" [4] . Programmable parameters are integrated in LSA and can be managed by the operations team for cycle generation and higher level application development.

Fiber optic links connecting the existing Beam Position VME modules to the new mDSPU VME processing modules are used. At present optical splitters are used to branch off one channel per beam and plane to the ADT observation system (ADT ObsBox).

FGC RF-function generators

The new mDSPU requires more FGC functions to control parameters. To this end the number of function generators deployed were doubled (eight RF FGCs are now operated capable of providing 128 functions) and 96 functions are operationally used:

- 32 functions for the cycle-dependent control of all output gain stages

- 32 phase functions to control changes of the required feedback phase setting during tune changes (at the start of the squeeze)

- 32 functions allocated for implementing a PU mixing/vector sum

ADT Controls

With the move to FESA3 for the 2015 run all new control software classes were supporting RDA3:
- *ALLADTmDSPU* – newly developed class for the new hardware replacing former FESA2.10 class
- *ALLAbortGapClean* – ported from former DSPU, now using FESA3
- *ALLCrateMan* – migrated during 2015 for all damper crates

Former expert ADT LabView panels are still in use for the Beam Position modules (*ALLBeamPosMeas* class running FESA 2.10) and to operate the RF switching matrices for remote monitoring of analog signals. New Inspector UI panels have been created for the expert control and setting-up of all eight mDSPU VME modules.

RUN 2: NEW FEATURES AND USE CASES

Feedback loop control on dedicated signal paths

The new features developed and used in 2015 were the independent loop gain control for the main feedback loop (gain A) and for the witness bunches (gain B). Usually the witness bunches are the first 6 bunches (50 ns spacing) or 12 bunches (25 ns bunch spacing). The feedback gain for these can be separately controlled and lowered to help increase the residual oscillation to provide a cleaner signal for the BBQ tune measurement system. The tune measurement system now also offers the posibility to gate on the witness bunches. The combined measures led to a good cohabitation of the two feedback systems, the transverse feedback system and the one for the tune.

The third independent output gain control (gain C) was used during the 2015 Run in open loop configuration with no active feedback, for cleaning and transverse blow-up (noise) of individual bunches (e.g. loss maps). Figure 2 outlines the structure. a fourth channel was used for developments and MDs in 2015 and will be made operational in 2016 to disentagle the functionalities of cleaning and blow-up. All four available channels offer independent bandwidth control and output filtering.

Injection- and Abort Gap Cleaning

Injection cleaning and abort gap cleaning were fully automated. Integrated into SIS along with measurements of the abort gap population from the abort gap monitor, cleaning is now automatically triggered when this feature is enabled — for example during Physics at top energy.

Pulses were shaped to be bipolar for the abort gap cleaning with increased risetime for the edges for use at 450 GeV. Bipolar pulses are also planned for 2016 for the injection gap cleaning and faster risetimes can be used as well, as long as the lower maximum kick strength is not of concern. At top energy, for abort gap cleaning and blow-up, the bandwidth can remain small, with slower risetime, fully profiting from the maximum kick amplitude of the power system. As in Run 1 injection gap cleaning uses the horizontal plane and corresponding ADT systems and abort gap cleaning is done in the vertical plane.

ADT Observation Box

The *Observation Box* ("ObsBox") is a newly added "proxy" system developed to receive bunch-by-bunch data from the RF VME hardware modules via serial link, to store long records of data and present these to higher level applications. These applications can subscribe to receive data via Ethernet on request or at predefined events, upon injection or instability triggers. In 2015 a first set of these servers was put in operation together with a backbone of the LHC Instability Trigger Network ("LIST") to which in 2016 ADT will be fully connected. The ObsBox system offers new possibilities for continuous online analysis of the transverse motion and fixed displays [5, 6]. Storage of full 40 MHz bunch-by-bunch data for offline analysis is possible [7, 8].
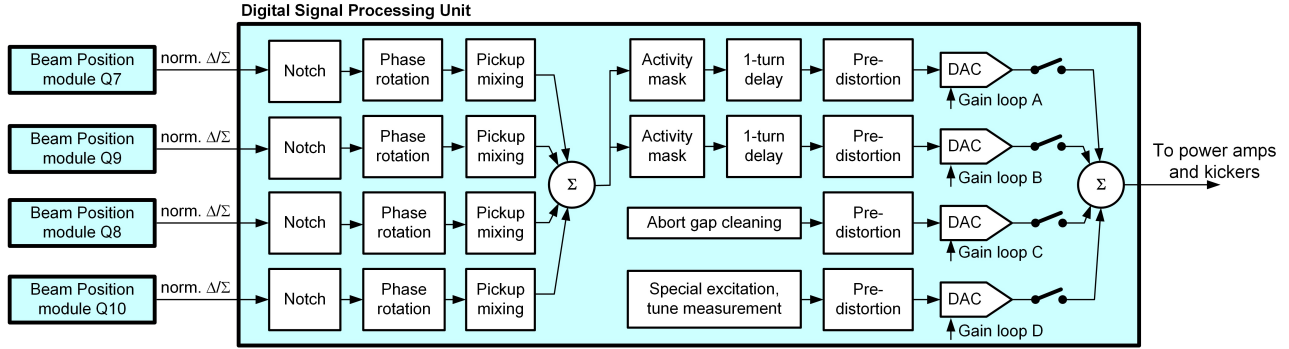
Figure 2: Block diagram of the new digital signal processing unit (mDSPU).

2015 the single server for ADT permitted to access data from one pick-up per plane. For 2016 each plane and beam will have a separate ObsBox server installed increasing the number of channels by a factor of four.

Frontend gain and interlock settings

The purpose of the controllable electronic gain in the ADT front-end analog processing is the adaptation of the signal levels to the mixers and the ADC input according to bunch intensity. As the bunch intensity varies over a large range from pilot beam intensity (5×10^9 charges) to close to 4×10^{11} for MD purposes, the gain needs to be switched between different modes of operation. Gain values were loaded manually by new tasks in the LHC sequencer, commissioned for

- Pilot Intensity (& Ions) 2×10^{10}

- Nominal intensity (1.3×10^{11} ppb)

- Doublets (2.0×10^{11} ppb)

- MD (4.0×10^{11} ppb)

A software state machine is in preparation that will permit automatic switching from pilot intensity to nominal for the standard operational cycle. Interlocks have been prepared (SIS) to prevent injecting beam when the set intensity range is too low for the measured intensity in the SPS, prior to injection. This new automatic switching is planned to become operational in 2016 and will permit systematic monitoring of the undamped injection oscillations of the pilot bunches.

ADT PERFORMANCE

Injection damping

Average low frequency damping times for coupled bunch modes were better than 10 turns. Studies were also carried out on the damping times of a single bunch of every injected train [9] and these damping times can be extrapolated to bunch trains.

The ADT system itself can also be used to excite a coherent oscillation and from the decoherence and damping extract feedback and characteristic beam parameters. It has
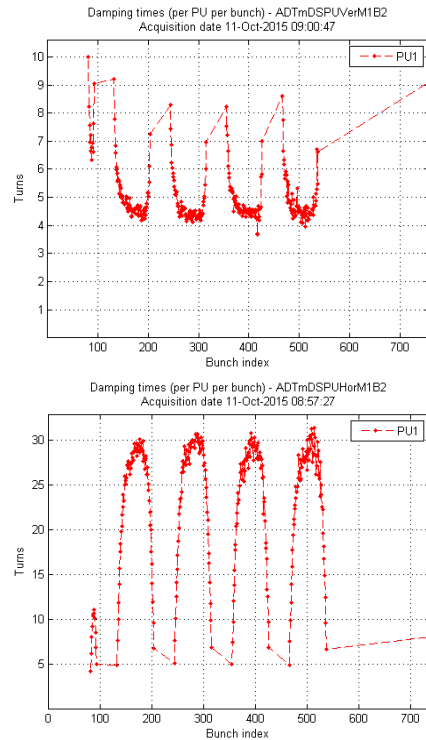

Figure 3: Damping times of four batches of 144 bunches and one batch of 12 bunches. The top plot shows data for beam 2 in the vertical plane (normal situation). The bottom plot shows analyzed data for beam 2 in the horizontal plane with too high gain.

been shown that a single turn kick with the ADT is sufficient [5] to do this. By this method overdamping was discovered for example on beam 2 in the horizontal plane on one occasion. Fig. 3 compares a normal situation (damping time in center of batch equal to half the damping at the edges of the batch) with the situation with too high gain at the edge of instability: The damping time is now high in the center of the batch and still low at the edges.

Machine tunes were changed by operations on several occasions in order to improve losses. The feedback phase was adjusted accordingly using the equation

$$\Delta\varphi = 4.5 \times 360° \times \Delta Q \,, \tag{1}$$

where the factor 4.5 accounts for the group delay of the digital signal processing.

For example, following the tune change by the fraction $\Delta Q = -0.005$ the feedback phase setting for pick-ups Q7H and Q9H where updated by $-8.1°$.

MD studies on emittance growth by Damper

During the last MD block the effect of the abort gap cleaning, injection slot cleaning, and transverse damper action itself on emittance growth was investigated using single bunches at 450 GeV. Abort gap cleaning had no visible effect on the emittance while injection slot cleaning blows up close-by bunches in the horizontal plane. Note that this can be attributed to the fact that the bipolar pulse had not yet been implemented for the injection slot cleaning and hence a considerable tail was thus present. This should improve by propagating all abort gap cleaning improvements to the injection slot cleaning for the 2016 run. Having the transverse damper active or disabled for the single bunch has no visible effect on vertical emittance blow-up. Note that the observed emittance growth cannot be suppressed by the damper either, pointing to an incoherent effect, also supported by the absence of BBQ activity [10].

Operation with doublets and scrubbing

The ADT hardware has been working reliably with the special doublet beam with pairs of 5 ns spaced bunches every 25 ns, as has been predicted by the simulation studies carried out in 2013 [11]. The fine delay for sampling clocks required a separate set-up.

Scrubbing was carried out at high damper gain, chromaticity and octupole settings. The damper has been essential in keeping the beam under control. The detrimental effect of a too high coupling when running at close tune values has been noticed and is under investigation in simulations. [12].

LHC Ion Run

The ADT system has also operated as in the past with fully stripped lead ions (Pb^{82+}) during the LHC ion run. Frontend gain settings for pilot intensity were used (ion bunch: up to 2×10^{10} charges) with hold cycles enabled to increase the damping rate at the used bunch spacing. With increased intensity available from the SPS a dedicated intensity range was set-up later in the ion run.

AVAILABILITY IN 2015

Fault breakdown

The recorded ADT faults can be attributed to four different subsystems:

- UW45 cooling recovery ADT → 2 faults

- ADT Power → 4 faults

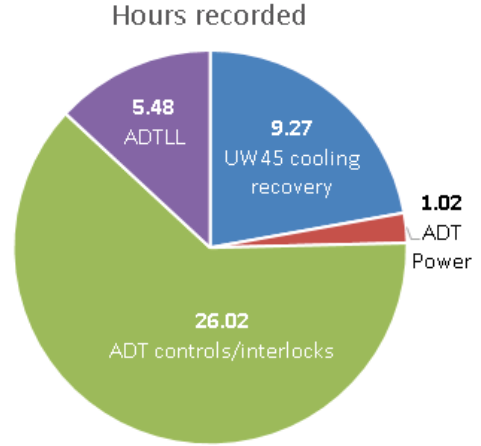- ADT controls/interlocks → 9 faults

Figure 4: ADT downtime in 2015 per hours and subsystem/component.

- ADTLL/configuration → 4 faults

The cooling water recovery followed a major problem with the cooling in point 4 of the LHC and required access to adjust the water pressure during the time period following the initial cooling outage. Power system faults included amplifier faults which can be temporarily mitigated by the Piquet taking an amplifier offline. Controls and interlock problems and LLRF faults included issues with the software configuration of the system, corrupted data on digital links and a faulty auxiliary power supply in an interlock crate in UX45.

Downtime per hours

The three largest faults account for 82 % of the registered fault time:

1. UX45 interlock chassis (22.05 h) → 3 interventions

2. CV water cooling UW45 recovery (9.27 h) → 2 interventions

3. Gigabit Link ADTLL (3.16 h) → 3 interventions

It should be mentioned that the repair work for the interlock chassis included a night shift in which the machine was down for another fault and the ADT experts decided to delay the repair to daytime.

ISSUES AND POSSIBLE MITIGATION

Loop gain saturation

Due to the increased energy at flat top it was not possible to maintain a constant damping rate along the ramp as the electronic gain available for the mDSPU saturated with the digital gain chosen. At injection sufficent gain was available. This is outlined in Fig. 5 which shows that for all but one of the gain functions saturation occured for the operationally used parameters. For the 2016 run gains will be re-scaled in the digital part removing this limitation.
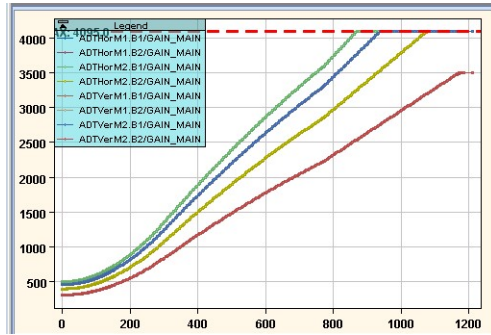
Figure 5: Loop gain evolution as a function of acceleration, shown per module for both beams and planes.

Settings management for loss-maps and excitation

The entanglement of gain settings for the cleaning and blow-up functionalities led to some configuration issues when switching between operational cycles and cycles that were needed to carry out loss maps. The plan for the 2016 run is to use the fourth gain function (gain D) for the blow-up by which the settings become independent from the cleaning settings (gain C). The risk of manual changes to the settings (for loss maps) overwriting the cleaning settings (gain or bandiwdth) is thus removed.

Monitoring damper HW with the IQC

It is planned that the Injection Quality Check (IQC) system will collect data from the ADT system on every injection. A check can be made in the IQC system inhibiting further injections when the data received is zero or shows an abnormal damping. Instabilities right after injection and problems with the digital data links in the ADT system can be captured by this analysis (see also [13] for the ADT data link problem). Data can be collected from both associated mDSPU modules and checked for consistency.

Extended diagnostics of damper performance

Using the data acquired through the ObsBox, extended beam and damper diagnostics is possible. Parameters can be determined from injection oscillations or on demand by giving a small kick to the beam with ADT [5]. The feedback parameters that can be determined are

- loop gain
- open and closed loop feedback phase
- total loop delay

Moreover, per-bunch damping times, per-bunch tune, the LHC injection kicker waveforms, the SPS extraction kicker waveforms, and the quality of injection steering can be monitored provided the resources to develop the software and integrate it with the control system can be made available. A key role is played by the ObsBox [6, 8] that represents the interface to the data as well as the logging system (Timber), and yet to be developed applications for displaying of the data in the CCC.

SUMMARY

Following substantial maintenance work, re-cabling and the deployment of a new digital signal processing unit (mD-SPU) ADT was ready for first beam and has permitted to produce excellent quality beam at low emittances for the first LHC run with 25 ns bunching for Physics production. Both the instability trigger network and the ObsBox were commissioned with a minumum set of functionalities with increased usage foreseen for the 2016 run.

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