"WHAT YOU GET" – TRANSVERSE DAMPER

F. Dubouchet, W. Höfle, G. Kotzian, D. Valuch
CERN, Geneva, Switzerland

Abstract

The transverse damper (ADT) operation in 2012 was very smooth, routinely switching between different modes and operating the feedback during the entire LHC cycle. We present the new features developed and commissioned in 2012, the selective blow-up, gain gating within the turn and increased bandwidth operation. Several methods were proposed and tested concerning the ADT vs. BBQ cohabitation in order to find the best compromise for machine operation. Performance scaling from 4 TeV to 6.5 TeV, potential limitations at high energy as well as the consolidation and upgrade activities for the long shutdown starting in 2013 (LS1) will also be presented.

PEFORMANCE AND SETTINGS MANAGEMENT FROM CCC

Each of the four ADT systems (one per plane and beam) [1] take signals from two pick-ups located at the Q7 and Q9 magnets in LSS4 on that side of IP4 where the betatron functions are high for the respective plane and beam. For reasons of redundancy each of the two pair of kickers with two amplifiers, is driven by a dedicated LLRF module for the signal processing as depicted in Fig. 1.

Settings to adjust for the per bunch intensity are processed by the Beam Position module (Beam Pos) [2] while all other controls of the feedback loop and processing is carried out within the DSPU module [3]. This includes the signal processing for the normalized bunch-by-bunch position as well as all gain control and additional excitation signals such as for abort gap cleaning and transverse blow-up as shown in Fig 1. An analogue input "chirp" permits the addition of an excitation signal provided by the Beam Instrumentation Group Systems in UX45.

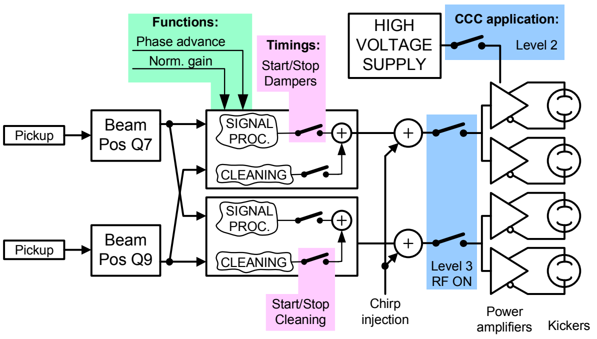


Figure 1: Layout of ADT damper feedback loop.

Operational Performance and Downtime

Thanks to the regular maintenance of the power system during the technical stops the overall downtime in 2012 has been very small. A total of 18 hours downtime affecting machine operation has been recorded. The power system comprises a total of 16 power amplifiers employing 32 tetrodes of 30 kW. During 2012 a total of 20 tetrodes were exchanged, identifying tetrodes at their end-of life by regular checks of the emission curves. The tetrode exchanges were carried out during the technical stops and thanks to the redundancy with four power amplifiers per beam and plane, machine operation could continue once a defective amplifier had been put in stand-by and the cables feeding the high voltage were disconnected.

Faults of the power system in 2012 included:

- tetrodes reaching their end-of life
- PT100 temperature probes defective
- attenuators and HV load defective in amplifiers
- water flow meters indicating insufficient supply of cooling water
- faults in the HV power converter due to damaged cables and a fault on the electronics controlling the thyristors (gate control failure)
- TPG 300 fault (vacuum gauge)

All the power amplifier faults could be quickly fixed by installing one of the two spare amplifiers held available in the LHC tunnel for this purpose. During LS1 the vacuum pumps and gauges and the water flow meters for the damper will be upgraded making these systems more robust against false measurements.

LLRF and controls faults include two FESA server crashes, the exchange of a faulty PLC (Beckhoff) module, a problem with the cabling for a GigaBit data link and a configuration issue following a technical stop which resulted in an invalid sampling clock (40 MHz).

Not counting the tetrode exchanges during the technical stops the average fault time has been 1h20min (18 hours for 13 faults counted). This can be considered small taking into account that the hardware faults required intervention in SR4, UX45 or the LHC tunnel. The short intervention duration is due to an efficient stand-by service team, backed up by experts, as well as the availability of spare material on site. A continuous effort is necessary to replenish spare material, in particular for the power system and consolidate the electronics where required.

A test lowlevel electronics system in SR4 is fed with true beam signals and has been extensively used to validate new firmware and software before deployment on the four operational VME crates. Software errors and teething issues with new features could be kept to a minimum thanks to this test system.

Settings Management

With respect to damper configuration settings and control functions one has to distinguish between beam type or beam parameter dependent settings and functions and operational settings that are permitted for any kind of beam. In order to assure equipment protection some of the settings still required a manual intervention by an expert to load or change and are not fully integrated into the LSA system. In particular this includes the settings for the bunch intensity for which the injection of a high intensity bunch can damage the electronics when configured for low intensity bunches. Interlocking with the SPS bunch intensity interlock was successfully tested in preparation of the automation of the intensity settings management.

The less critical adjustments such as for the bunch spacing and parameters for the new wideband mode and gain modulation within the turn have already been implemented in LSA and were driven by the sequencer using Discrete Beam Processes. For the transverse blow-up a fully integrated application has been used. Further improvements to the control of the damper are planned for after LS1.

NEW FEATURES IN 2012

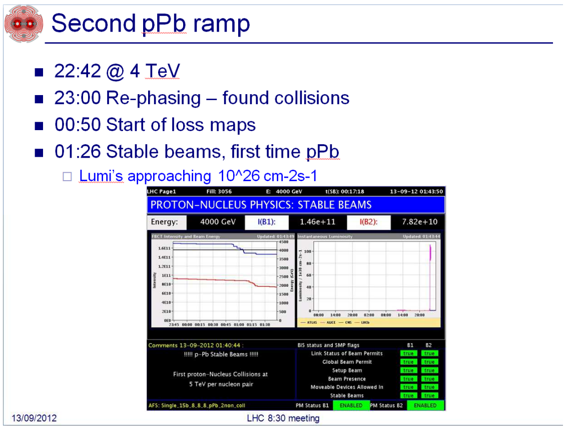
In the following the new features of 2012 are presented:

- selective transverse blow-up
- gain modulation within the turn for improved ADT-BBQ cohabitation
- increased bandwidth operation towards 25 ns bunch spacing
- R&D in the framework of a future tune measurement using the ADT system

Selective transverse blow-up

Following the successful tests of transverse blow-up using the ADT system in 2011 [4], a user application has been developed which is now fully integrated into the CCC control system. It permits to select individual bunches or groups of bunches to which a transverse excitation based on noise internally generated on the FPGA is applied. This facility became the standard way of checking the aperture and validating the collimation system by loss maps in 2012. It has been used at all beam energies from injection through the ramp and squeeze up to 4 TeV. Due to the selectivity of the blow-up (gating on individual trains of bunches) the efficiency of loss maps has been greatly improved.

As an example of efficient collimation system validation Fig. 2 shows the time line for the p-Pb setting-up in September 2012. 12 bunches were accelerated of which two were used for loss maps once collisions were found. A first Physics run could be carried out using the remaining ten bunches which were left untouched thanks to the gated excitation during the loss maps.


Second pPb ramp

- 22:42 @ 4 TeV
- 23:00 Re-phasing – found collisions
- 00:50 Start of loss maps
- 01:26 Stable beams, first time pPb
  - Lumi's approaching 10^26 cm-2s-1

LHC Page1 Fill: 3056 E: 4000 GeV t(SB): 00:17:18 13-09-12 01:43:50

PROTON-NUCLEUS PHYSICS: STABLE BEAMS

Energy: 4000 GeV I(B1): 1.46e+11 I(B2): 7.82e+10

Comments 13-09-2012 01:40:44 :

!!!!! p-Pb Stable Beams !!!!!

First proton-Nucleus Collisions at
5 TeV per nucleon pair

BIS status and SMP flags	B1	B2
Link Status of Beam Permits	true	true
Global Beam Permit	true	true
Setup Beam	true	true
Beam Presence	true	true
Moveable Devices Allowed In	true	true
Stable Beams	true	true

AFS: Single_15b_8_8_8_pPb_2non_coll PM Status B1 ENABLED PM Status B2 ENABLED

13/09/2012 LHC 8:30 meeting

Figure 2: Efficient generation of loss maps (example from the p-Pb set-up).

Gain modulation within the turn

As proposed in 2011 a modulation of the damper gain within the turn was introduced in 2012 and operationally used. It permits to run with high gain during the ramp and the prepare-for-ramp process, while keeping the gain for the leading bunch train, six "witness" bunches at 50 ns spacing for the operational Physics beam, very low. In combination with a gating on these six bunches in the BBQ system the performance of the tune feedback system was improved even with high damper gain on the remaining bunches.

The gain modulation is implemented in the digital part of the feedback loop on the FPGA multiplying the feedback signal by a function that can be programmed to be between 0 and 127 in steps of 1 unit. A sample function accessible via LSA is depicted in Fig. 3. The horizontal axis is the bunch index, the vertical axis the gain modulation function. It should be noted that for small gains the digital multiplication and subsequent conversion to the analogue domain results in a loss of resolution, i.e. the signal-to-noise ratio for the leading bunches with low gain is reduced with respect to the rest of the beam. This loss in resolution and the limitations from having a single function controlling the output gain via the DAC have inspired the planned upgrade whereby multiple DACs are used to convert the individual signals, maintaining independent control and resolution.

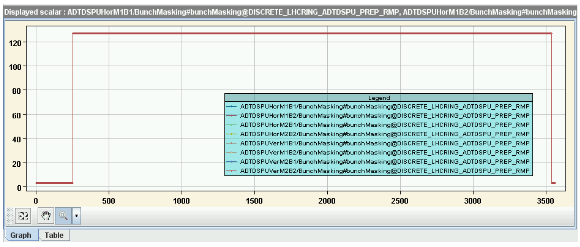


Figure 3: Gain modulation function within the turn.

Increased bandwidth operation

The appearance of instabilities in LHC in particular when running at 25 ns spacing, but also at 50 ns during the squeeze and adjust beam process, has triggered measurements and developments aimed at increasing the bandwidth of the ADT system.

The gain versus frequency characteristics of the ADT system is essentially determined by its power system, which is driving a capacitive load. The ideal low pass characteristics given by the RC time constant of the driving circuit and the kicker capacitance is plotted in Fig. 4. For comparison measured curves are also shown in Fig 4. Up to 10 MHz, the maximum frequency of coupled bunch modes with 50 ns bunch spacing, all curves perfectly agree, while in practice between 10 MHz and 20 MHz more gain is available than predicted by the ideal low pass characteristics. It should be noted that the phase response of the power system is compensated by digitally pre-distorting the signal [3] such that different coupled bunch modes are correctly damped, however with a damping time that depends on frequency.

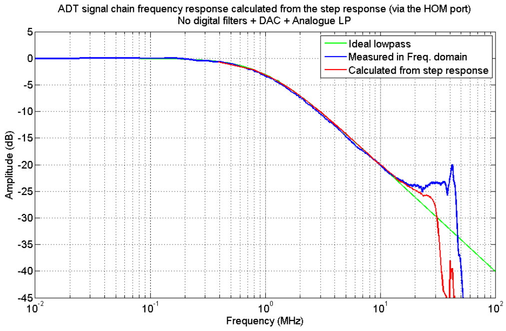


Figure 4: Gain versus frequency characteristics of ADT system without correction.

Viewed in time domain the decrease in gain for higher frequencies will spread out an initial oscillation from one bunch to adjacent bunches: Bunch oscillations appear to be coupled by the damper which may not be the optimum when individual bunches become unstable. Such single bunch instabilities call for a bunch-by-bunch damper with truly independent action on each bunch.

In theory such an independent treatment can be achieved if the transfer function exhibits a certain symmetry of the roll-off at half the bunch repetition frequency: The real part of the amplitude response at half the bunch frequency must be 0.5 and point-symmetric and the imaginary part can be arbitrary as long as it is symmetric with respect to half the bunch frequency. The resulting time domain impulse response then features zeros at adjacent bunch positions. This condition was first formulated by Niquist [5] and is today commonly known as the condition to achieve inter-symbol-interference free transmission in communication theory.

As the phase response of the ADT system had already been successfully compensated in the past it was sufficient to correct the amplitude response. Because drive power is available up to 25 MHz an FIR filter was designed to shape the roll-off of the ADT gain from 15 MHz to 25 MHz to achieve a fast time domain response for bunch-by-bunch operation.

Fig. 5 shows the step-response of the uncorrected system (blue curve), the phase compensated system (green) with its symmetric characteristics and the increased bandwidth response with tapered gain to 25 MHz (black). The responses are measured on an actual system integrating the raw signal from an HOM port with capacitive coupling to the kicker plates. It can clearly be seen how the signal processing has made the response faster (black curve).

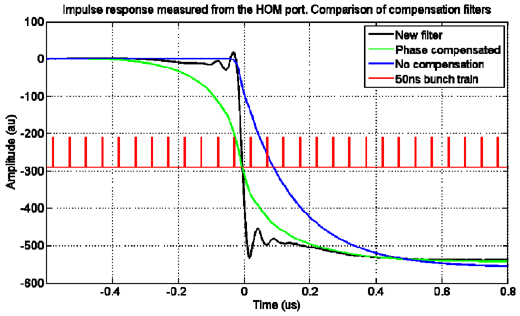


Figure 5: Measured step response of ADT with different pre-distortion filters.

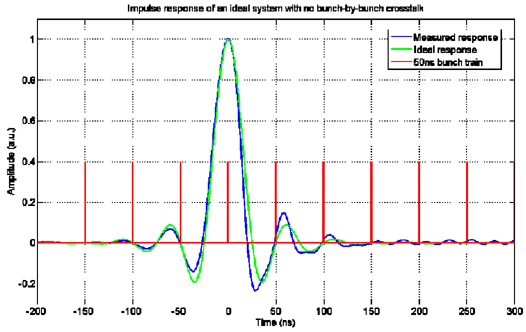


Figure 6: Comparison of measured impulse response and an optimized response for bunch-by-bunch operation at 25 ns bunch spacing.

The bunch-by-bunch properties are best checked by looking at the impulse response shown in Fig. 6. The green curve represents the ideal response with zeros spaced at 25 ns and the blue curve the actually achieved response. This measured response has perfectly spaced zeros at 50 ns spacing, the operational bunch spacing used in 2012. The leading part of the impulse response also has zeros at the intermediate positions of possible bunches for 25 ns bunch spacing but in the trailing part some residual kicks remain for bunches spaced at an odd multiple of 25 ns.

These so called “wide band” or “high bandwidth” settings have been used for the 25 ns tests and for the 50 ns operation in the second part of the 2012 LHC run during the squeeze which was the most critical part of the cycle with respect to the instabilities.

Tests during Physics have indicated that the wideband settings lead to an increased emittance blow-up. This is a result of the large tune spread in collision in combination with the increased noise when the wide band settings are used. The low pass filter characteristics with the standard settings cuts off contributions of the noise spectrum well above 1 MHz, while the wideband settings let these noise spectral components pass through onto the beam. Improvements in the electronics foreseen for the LHC run after LS1, the use of double the number of pick-ups and an improved signal processing are expected to reduce the overall noise of the bunch oscillation detection, so that the effect of the wideband settings on the emittance are reduced.

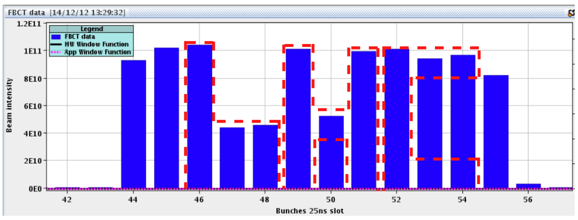


Figure 7: Beam intensity reduction after blow-up of individual bunches within a train with wide band settings.

An additional benefit of the wideband settings can be seen in Fig. 7. Using these settings for the transverse blow-up permits to target individual bunches in a train of 25 ns spaced bunches. The figure shows the bunch intensity after bunches number 47, 48 and 50 have been targeted by the blow-up and lost about half of their intensity while adjacent bunches have not been affected.

For the run after LS1, transfer functions of the damper will again be carefully measured, and the pre-distortion by the signal processing adapted to improve the bunch-by-bunch performance for the 25 ns bunch spacing.

R&D in the framework of a future tune measurement using ADT

R&D work on extracting the tune from the ADT data continued in 2012. It should be noted that the present hardware (VME crates) does not permit to extract all bunch-by-bunch data in a continuous way via the VME bus, due to the limitation of the data transfer speed of the VME bus as heavy data transfer can compromise the LLRF system operation and reliability. After LS1 additional hardware is foreseen that will process the full data available which can be streamed via GBit serial links from the VME boards without interfering with the feedback loop and its control functionalities via the VME bus.

In order to permit machine developments additional internal test buffers of a length of 16384 samples were introduced in 2012. These could be used to quasi continuously record for test purposes the oscillations of six bunches over 2730 turns with only a small interruption after each acquisition as required by the software to fetch the data over the VME bus.

The tests carried out included a passive observation of the bunch oscillations and a synchronized observation following a small excitation with the damper. The excitation kicked the leading six bunches only, for a programmable number of turns, modulated at the nominal tune. Subsequently the free oscillation of these bunches was observed using the special buffer. This way a tune measurement could be developed, however the method also suffered from spurious signals in the FFT which need further study.

An example of a passive observation without excitation is shown in Fig. 8. It shows a spectrum of horizontal oscillations of beam 2 with the data from the leading six bunches averaged. We can see in the top part the effect of cleaning during which a tune measurement seems not possible without active excitation. The dark blue vertical line represents the trench at the location of the tune, which can be used for a tune measurement during high gain operation. During the ramp at lower gain the beam is naturally oscillating and the tune can be picked-up from these oscillations. However, in this low gain regime the beam is again sensitive to external interferences such as multiples of 50 Hz, and in practice it might be difficult to separate the true tune and the spurious lines.

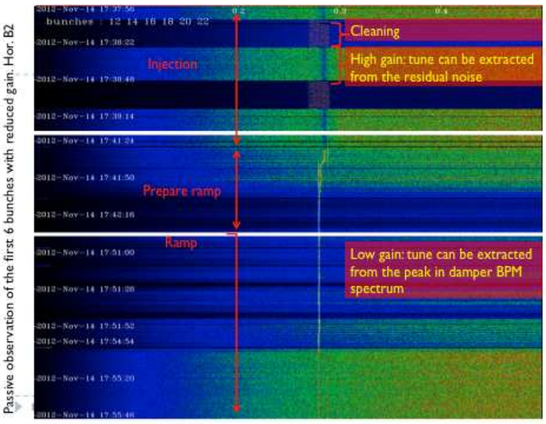


Figure 8: Result of tune observation with ADT on six witness bunches (horizontal plane, beam 2).

OUTLOOK ON OPERATION AT 6.5 TEV AND IMPORVEMENTS FOR LHC RUN 2

Outlook at 6.5 TeV operation

Measures planned to improve the signal-to-noise ratio will permit to maintain performance achieved at 4 TeV at the increased energy of 6.5 TeV planned for the LHC run 2 after LS1. Running at 25 ns with high bandwidth settings will remain a challenge due to the increased level of noise acting on the beam in this mode of operation. The strategy should be to use the wideband settings only when required and adapt the frequency response to what is needed to damp instabilities.

Maintaining a damping time of 50 turns at 6.5 TeV is feasible and the required shuffling of gains within the feedback loop to achieve it, is foreseen for LS1.

Improvements for LHC run 2

More than 25 km of new smooth wall coaxial cable will be installed to connect the existing eight pick-ups and the new set of eight additional pick-ups to the surface. The doubling of the number of pick-ups, the new coaxial cable with reduced reflections, newly built electronics with lower noise properties and improvements to the signal processing are the four measures that are expected to reduce the noise level of the feedback system.

Re-design of the VME DSPU module will permit to better integrate the different operational modes with the control of the gain, by having an independent set of DACs for the different signal contributions (feedback, cleaning, excitation).

Streaming of data via serial link to a separate stand-alone hardware is foreseen in order to fully exploit the potential of the ADT system for beam observation including tune measurement. Tests in 2012 have shown that a variety of methods are possible to extract the tune from the ADT data, with and without excitation. However, separation of the tune from parasitic beam oscillations caused by 50 Hz lines and other spurious lines is a challenge for ADT, too.

As in 2012 a train of witness bunches will be essential for the tune measurement. In addition an instability trigger to efficiently synchronize acquisitions by the damper with other instruments around the accelerator is primordial for an improved diagnostics on instabilities.

ACKNOWLEDGMENT

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