A BEAM-BASED MEASUREMENT OF THE LHC BEAM DUMP KICKER WAVEFORM

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Abstract

The increase of the LHC collision energy to 13 TeV after Long Shutdown 1 has doubled the operational energy range of the LHC beam dump system (LBDS) during Run 2. In preparation for the safe operation of the LHC, the waveform of the LBDS extraction kicker was measured using beam-based measurements for the first time during the machine's re-commissioning period. The measurements provide a reference for a more precise synchronisation of the dump system and abort-gap timing, and provide an independent check of the system's calibration. The precision of the beam-based technique allowed the necessary adjustments to the LBDS trigger delays to ensure the synchronous firing of the LBDS at all beam energies up to 6.5 TeV. In this paper the measurement and simulation campaign is described and the performance of the system reported.

INTRODUCTION

The LBDS [1] is a key component of the LHC Machine Protection System (MPS) and is used to safely dispose of the large stored energy in both circulating beams when a dump request is issued, either at the end of a physics fill or in the event that the MPS detects a failure in the LHC. The LBDS is designed to be failsafe to ensure the beams are still extracted safely and reliably in one turn of the collider, even if a failure of the LBDS is detected. The LBDS is composed of two extraction systems placed symmetrically about the centre of Insertion Region 6 and deflects the counter-rotating circulating beams into magnetic septa before diluting and dumping them safely onto graphite absorber blocks.

The extraction kickers (MKD) are the most critical elements for the reliability of the system as they sit on the circulating beam and erratic triggering, or even non-triggering, could have devastating consequences for the LHC and its equipment. The two MKD systems are each composed of 15 fast-pulsed kicker magnets individually powered by their own high-voltage pulse generators [2] operating up to 30 kV (for a 19 kA current pulse) and designed to switch-on synchronously within the 3 μs particle-free abort-gap in the circulating beam. The MKD magnets are 1.4 m long and composed of a steel yoke with a single-turn high-voltage winding capable of delivering a kick strength of up to 0.428 Tm, which corresponds to a total deflection angle of 0.275 mrad for the ensemble of 15 magnets at all energies in the dynamic range of the collider, i.e. from 450 GeV to 7 TeV. A dedicated Beam Energy Tracking System (BETS) [3] continually surveys the voltage held on the capacitor of the generators to ensure the normalised MKD kick remains constant and within tolerance throughout the LHC operational cycle.

An illustration of the current provided by the MKD generator is shown in Fig. 1. The rise-time is defined by,

$$\tau_{\text{rise-time}} = T_{\text{DELAY}} - T_{\text{THRESHOLD}} \qquad (1)$$

where the magnitude of $I_{\text{THRESHOLD}}$ corresponds to a 0.5σ deflection, i.e. 0.86 % and 0.22 % of $I_{\text{REF100PCT}}$ at 450 GeV and 7 TeV, respectively. The current is specified to remain above $I_{\text{REF100PCT}}$ throughout the 89 μs it takes to empty the LHC in a single turn. The flatness of the pulse, defined by the difference between $I_{\text{REF100PCT}}$ and $I_{\text{OVERSHOOT1}}$ or $I_{\text{OVERSHOOT2}}$, is limited only by the aperture of the extraction beam line. In a simplified manner, the generator is composed

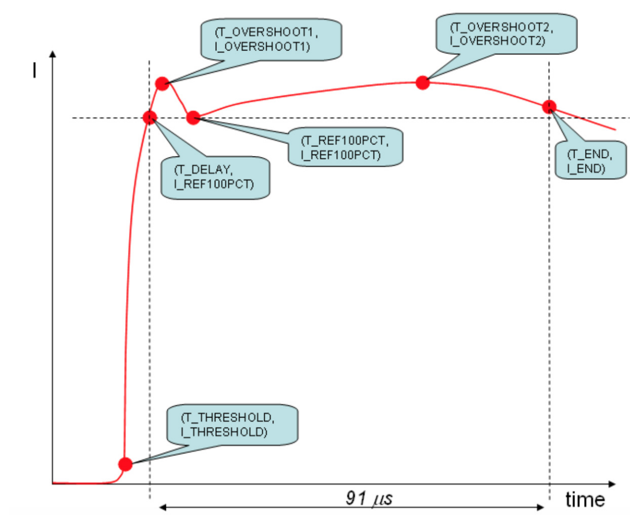

Figure 1: Illustration of MKD characteristic points with their coordinates [4].

of a capacitor connected in series with a solid-state switch. The capacitor initiates the fast rise of current when the switch is triggered and it is discharged into the magnet. As the current in the magnet reaches its peak and the polarity of the generator reverses, the current is conducted by a parallel diode stack that connects another capacitor to the magnet inductance and causes the current to oscillate slowly with a superimposed half sine-wave. The pulse length is then extended towards T_{END}. Each generator is composed of two of the aforementioned circuits for redundancy that normally equally share the discharged current.

To achieve the specified reliability the LBDS performance is analysed after every dump event by the Internal Post-Operational Check (IPOC) system [5] and only after all tests are passed is the beam permit released for the LHC

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to continue operation. An important module of IPOC is the surveillance of the MKD current waveforms. In order to convert the measured current into integrated magnetic field all the magnets, generators and pick-ups were carefully calibrated as a function of energy before installation, along with the effect of the ceramic vacuum chambers [6]. The measured current waveforms are used to calibrate and synchronise the system by adjusting the common voltage of the generators and their individual trigger delays. The scaling of the voltage with energy during operation is linked to the BETS, however, the trigger delays are fixed for all energies and installed as hardware before each run. The variation of the rise-time as a function of energy for all 15 MKDs on Beam 1 is indicated by the values of T_{DELAY} in Fig. 2, to which delays have been computed and added to synchronise the kickers before the 2016 LHC start-up.

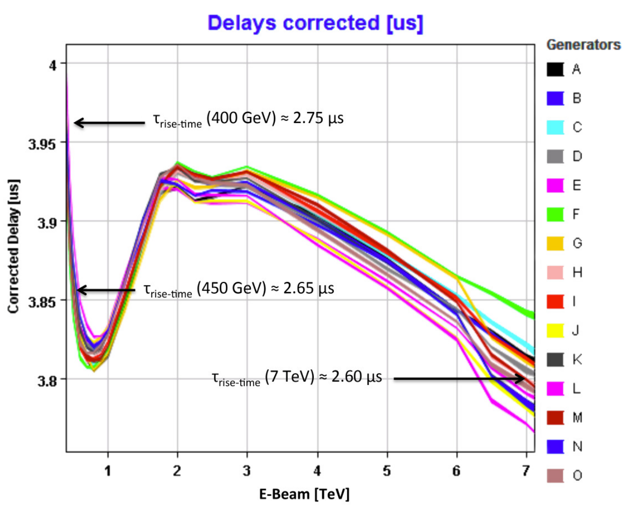


Figure 2: Measured values of T_{DELAY} including computed trigger delay corrections to synchronise the LBDS.

MEASUREMENTS AND SIMULATIONS

During the 2015 re-commissioning period beam-based waveform measurements were carried out on the LHC injection plateau at 450 GeV. The time taken to ramp the LHC makes waveform measurements at higher energies prohibitively lengthy. Nevertheless, the main goal of LBDS synchronisation is achievable with circulating beam at injection energy. The deflection of single pilot bunches containing $\sim 5 \times 10^9$ p^+ was measured on a beam screen (BTVSE) in front of the septum (MSD) and the waveform probed by injecting bunches one at a time into different RF buckets. The chosen BTVSE is shown in Fig. 3, located on the extraction beam line downstream of the MKD and the kick enhancing quadrupole (Q4). It was preferred to dump circulating beams instead of dumping immediately after injection, i.e. after less than one turn, as the shot-to-shot stability of the bunch position was far improved once the injection oscillations had damped. The dump request was made manually by the operator after several seconds of circulating beam. In fact, the stability of the LHC was remarkable; after 3 hours of measurements cycling along the waveform, the bunch returned to the same position within the resolution of the screen and any shot-to-shot variation was difficult to observe. For the measurements made in 2015 the Abort Gap Keeper (AGK) was exceptionally disabled so that it was possible to inject onto the rising edge of of the MKD.

The alumina screen of the BTVSE offered unrivalled resolution ($\sim$ 0.2 mm/pixel) at the low intensities needed to make the measurement and was ideal for the analysis of the top edge of the rising waveform. As indicated by the sweep in Fig. 3, the bottom edge of the waveform can also be measured on the same screen because, for small deflections, the bunch remains in the LHC aperture and is extracted on its second pass of the MKD. For intermediate kicks, the bunch is lost safely on the protection devices of the LBDS (TCDQ and TCDS) or on the LHC collimation system.

The rise-time measurements for the two systems, on Beam 1 and 2, are presented in Fig. 4. The bunch position measured on the screen is plotted as a function of time and centred on T_{DELAY}, which is defined by the level $I_{REF100PCT}$. Approximately 30 shots were taken per beam focusing on the rising edge of the waveform and close to the point ($T_{REF100PCT}$, $I_{REF100PCT}$) needed to ascertain the 100 % level. Normally, the screen position can be calibrated by scaling the voltage and measuring the response on the screen. However, for reliability reasons, it is not possible to trim the LBDS parameters from the control room and this calibration could not be carried out. However, the rise-times could be reliably estimated from the BTVSE data using the simulations to give the screen position values corresponding to $I_{THRESHOLD}$.

On the same plot the measurements are compared to simulations using the calibrated IPOC data. The current waveforms measured by IPOC were incorporated into a particle tracking routine applying thin lens kicks. The same current-to-field calibration factors as used in IPOC were implemented in order to compare the prediction with the beam-based measurements. The one-turn transfer matrix of the LHC was applied in the simulation to compute the position on the BTVSE for the bunches that perform an additional turn.

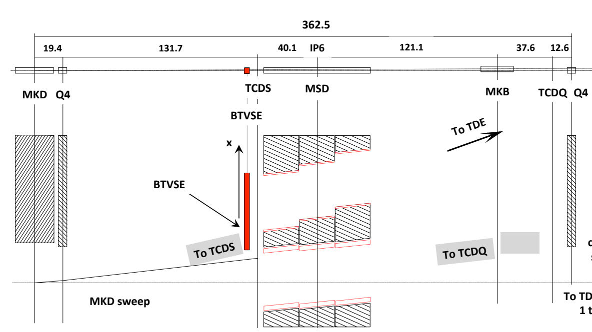
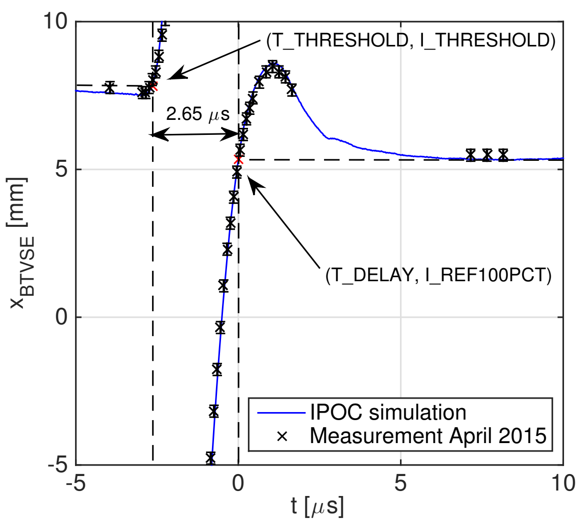
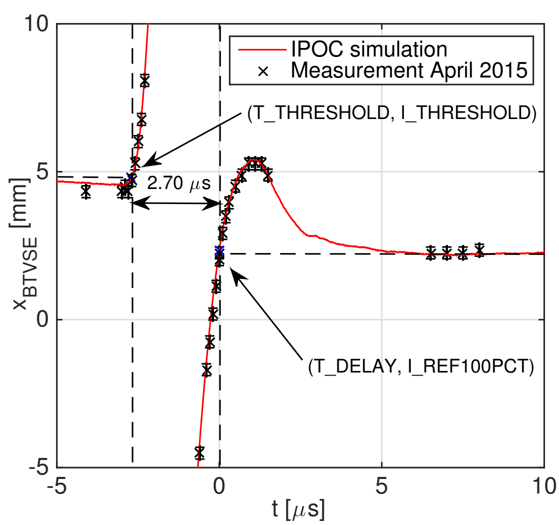


Figure 3: Schematic layout of LBDS extraction channel and position of the BTVSE screen [1].

The asymptotes in the plots of Fig. 4 divide the data in two; to the right bunches make the extraction channel on the first pass of the MKD and to the left they make an extra tour of the LHC before being extracted. The shot-to-shot stability was good enough to avoid having to take more shots for statistics and was preferable in view of the tight commissioning schedule. The data shown represents single-shots with error bars representing the screen resolution. The error bars representing the 10 ns stability of the LBDS trigger are barely noticeable on Fig. 4 and the largest contribution to the error in the measured rise-time of ∼ ±25 ns comes from the screen resolution.



(a) Beam 1: rise-time 2.65 μs: defined 0.86 % (0.5σ) to 100 %.



(b) Beam 2: rise-time 2.70 μs: defined 0.86 % (0.5σ) to 100 %.

Figure 4: MKD waveform measurement at 450 GeV made in 2015.

The agreement between measurement and simulation is impressive and gives measured rise-times, as defined by Equation 1, of $2.65 \pm 0.025\ \mu s$ and $2.70 \pm 0.025\ \mu s$ for Beam 1 and 2, respectively. The measurements in 2015 led to the adjustment of the LBDS trigger synchronisation on Beam 2 by 120 ns and were repeated in 2016 to verify the LBDS synchronisation. The trigger delay includes enough margin to absorb the variation of the rise-time at energies above 450 GeV shown in Fig. 2. It was possible to synchronise the LBDS this year without disabling the AGK using the first overshoot on the waveform as a reference. In addition, the fine synchronisation of the fast beam current monitor in IR6 could be calibrated using the beam-based waveform measurements.

CONCLUSION

The rise-times of the LHC beam dump extraction kicker systems (MKD) of Beam 1 and 2 were measured at 450 GeV as $2.65 \pm 0.025\ \mu s$ and $2.70 \pm 0.025\ \mu s$, respectively. The measurements fall well within the specification of $< 2.80\ \mu s$. The complete calibration procedure of the LBDS, including its synchronisation, was independently validated along with the MKD IPOC module. The LBDS was synchronised to the circulating beam with a resolution of approximately 25 ns. The waveform measurement is now an integral part of the LBDS start-up and re-commissioning procedure.

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