

CONTROLLED TRANSVERSE BLOW-UP OF HIGH-ENERGY PROTON BEAMS FOR APERTURE MEASUREMENTS AND LOSS MAPS

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Abstract

A technique was developed to blow-up transversely in a controlled way high energy proton beams in the LHC. The technique is based on band limited white noise excitation that is injected into the transverse damper feedback loop. The injected signal can be gated to selectively blow-up individual trains of bunches. The speed of transverse blow-up can be precisely controlled. This opens the possibility to perform safely and efficiently aperture measurements and loss maps with high intensity bunch trains well above stored beam energies that are considered to be safe. In particular, lengthy procedures for measurements at top energy, otherwise requiring multiple fills of individual bunches, can be avoided. In this paper, the method is presented and results from beam measurements are discussed and compared with alternative blow-up methods.

INTRODUCTION

The verification of the collimation system is performed by the creation of multi-turn losses (loss-maps). These losses are currently created by crossing the 1/3 integer tune resonance in both transverse planes for both beams [1]. This method excites the entire beam, it requires special fills with a small number of bunches and is time consuming. In addition, there can be some coupling between the two planes because loss maps on one plane are done with a beam already blown up in the other plane. Therefore, it is highly desirable to replace it by a method, which allows a controlled transverse blow-up of only a small number of bunches. This controlled blow-up is also desirable for measuring and verifying the mechanical aperture of the LHC. Here an increase of the transverse emittance of a low intensity bunch up to the mechanical aperture limit is needed [2].

TRANSVERSE DAMPER AND BLOW-UP METHOD

Transverse Damper

In the LHC a powerful transverse feedback system, also referred to as the *transverse damper* has been fully commissioned in 2010 with beam [3]. The system is in use since first commissioning in 2008 also to excite transverse oscillations for the tune measurement system [4]. The damper can deflect the beam transversely by more than 2 μrad at the injection energy of 450 GeV, corresponding to approximately 0.3 σ (σ is the beam size) in a single passage. The system is also used for other applications. It is used for cleaning of the particle free gaps for injection

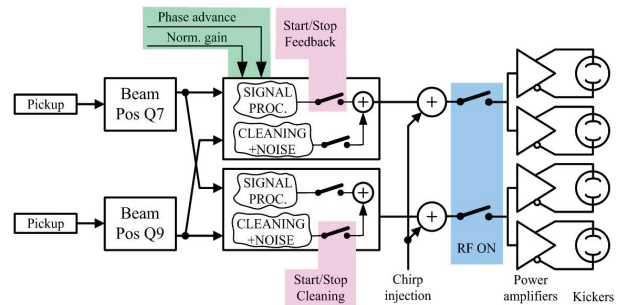


Figure 1: Transverse damper system with inputs for excitation.

and extraction (abort gap) using a gated excitation with coherent modulation at the betatron frequency which became part of the standard operational procedure at injection in 2011 [5, 6].

Fig. 1 shows a sketch of the system components, with pick-ups that detect the beam transverse motion, a digital signal processing running at a bunch synchronous 40 MS/s clock frequency computing the feedback signal, power amplifiers and kickers in the tunnel as well associated controls [4]. With two beams and two transverse planes, the LHC comprises a total of four transverse damper systems, one per transverse plane and beam. Signals to excite the beam can be either internally generated in the digital part of the system on an FPGA, or externally added in the analogue domain. The first method is used for both the abort gap cleaning and the injection of noise for the purpose of blow-up described in this paper, the latter is used to inject a swept frequency signal “chirp” for the tune measurement.

Excitation with Band-Limited White Noise

In order to achieve a reproducible blow-up of the beam a broad-band excitation is preferred. The broadband excitation signal is derived from a pseudo-random number generator which produces a 14 bit word every 25 ns clock cycle. The system runs on an FPGA and uses a 43-bit long linear feedback shift register for every bit of the output word using the feedback polynomial $x^{43} + x^{42} + x^{38} + x^{37} + 1$ [7]. The sequence repeats every 61 hours approximately when run at a 40 MHz clock rate. The output spectrum is sufficiently flat with frequency and represents therefore, converted to analogue, a “white” spectrum below half the sampling frequency (20 MHz).

As the damper power system has its maximum kick strength roll-off beyond 1 MHz, a programmable two section IIR low-pass filter has been foreseen that will limit the frequency of the excitation signal. Faster blow-up can be

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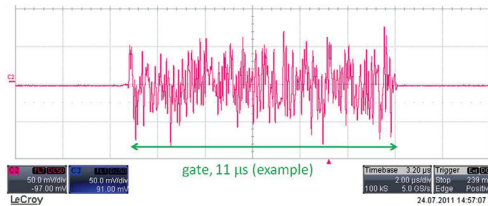


Figure 2: Gating of noise.

achieved by activating the filter and increasing the signal amplitude of the excitation.

Gating of Excitation for Batch Selective Blow-up

As for abort gap cleaning the band limited noise for transverse blow-up can be internally multiplied by a gating function with a maximum length of $11 \mu\text{s}$ covering the maximum batch length of beam that can be injected from the SPS into the LHC.

Fig. 2 shows the gated noise as function of time, with no band limitation by the IIR filters activated. Between batches a gap of 975 ns is required to accommodate for the LHC injection kicker rise time. Due to the rise time of the damper system the excitation can be gated within the same limitations and can hence be targeted to individual *batches*.

EXPERIMENTAL RESULTS

Experimental Set-up and Beams

The full digital implementation described above was developed and deployed for tests in LHC in August 2011. The test system was used on beam 2 only in 2011 with the digitally generated signal being added either to the vertical or the horizontal damper system. Most of the tests were carried out in the horizontal plane at injection energy (450 GeV) with a limited number of bunches and low intensity keeping the feedback loop of the damper system open.

Due to the broadband nature of the signal applied (1 MHz), covering many betatron lines (1 MHz equals approximately 89 times the LHC revolution frequency of 11.245 kHz) the method is not sensitive to the transverse tune. The resulting blow-up is a function of both the excitation used and the machine non-linearities such as provided by the octupoles. In the SPS a similar technique has been used for the blow-up whereby the octupoles have been ramped to higher than normal values in order to enhance the blow-up [8].

Initial tests in LHC reported here were carried out at 450 GeV with low intensity bunches with 1×10^{10} protons per bunch (ppb). After successfully commissioning the excitation signal and the synchronisation of the gating with the bunch 1 position, test fills with nominal bunches and bunch trains with 50 ns spacing followed. The selectivity of the gating was tested using special filling patterns with bunch trains spaced by at least 975 ns, for a summary of the results see [9].

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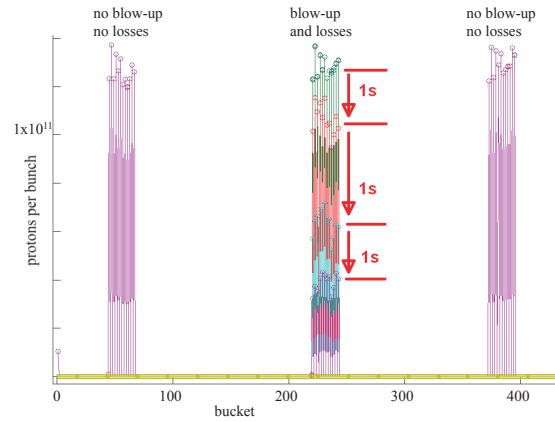


Figure 3: Batch selectivity of blow-up demonstrated by comparing losses.

Batch Selectivity

The batch selectivity was demonstrated by individually blowing up and consequently losing intensity for the targeted batch, while adjacent batches did not lose intensity and their emittance was maintained [9]. Fig. 3 shows the intensity of bunches grouped in three batches with the second batch selected for the blow-up. The blow-up was successively applied three times for a duration of 1 s. Each excitation burst resulted in approximately 20% to 25% of intensity reduction of the second batch.

The selectivity and reproducibility is sufficient to envisage to use the method in end-of-fill studies with 1380 bunches per beam present and only blowing up a small group of bunches.

Loss Maps

The traditional method to qualify the collimation system has been to create multi-turn losses to produce so-called loss maps using a technique by which the tunes are swept across the third order resonance. As this procedure causes a blow-up of the entire beam, it requires special fills with low intensity with a few bunches only, to avoid beam aborts due to losses exceeding the dump thresholds.

It was important to verify that the method using the damper blow-up to create losses and the third order resonance technique give the same result, i.e. the same loss pattern around the ring. Figs. 4 and 5 depict the resulting loss maps. The loss patterns created with both methods are very similar. The variation of the leakage into the cold aperture of the dispersion suppressor downstream of the main cleaning insertion (IR7), is in the order of $\sim 15\%$ in both cases. For the 2012 run loss maps using both techniques are used to further investigate differences that may be present between the two methods.

Blow-up for Aperture Studies

For aperture studies it is desired to create bunches with a large transverse emittance and tails extending up to the

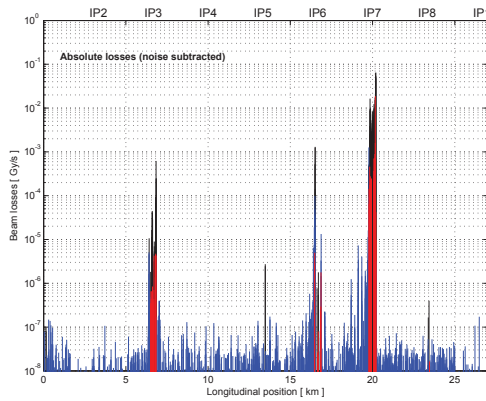


Figure 4: Loss maps obtained with the damper blow-up method with one nominal bunch in the LHC (blue: cold part of LHC, red and black: warm part).

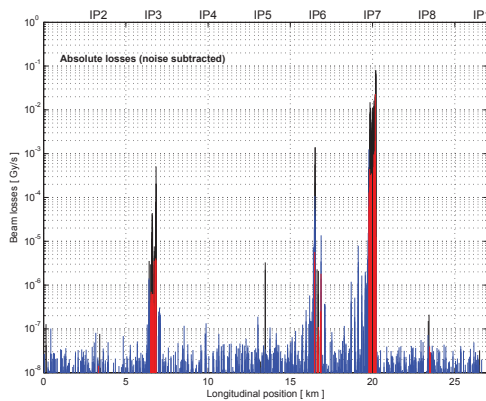


Figure 5: Loss maps obtained by crossing the third-order resonance with one nominal bunch in the LHC (blue: cold part of LHC, red and black: warm part).

aperture limit. Injected bunches have very small emittances, often well below $2 \mu\text{m}$. By slowly applying a transverse blow-up using the damper, the losses around the LHC can be observed and bottle necks in the aperture be identified.

Collimators and beam absorbers can be aligned using the blown up bunches to fulfil their protective functions in an optimized way. Fig. 6 shows how a low intensity bunch could be selectively blown up to the aperture limit (a normalized measured emittance of $18 \mu\text{m}$ could be achieved), while the normalized transverse emittance of a second low intensity bunch was maintained at $2 \mu\text{m}$.

SUMMARY AND OUTLOOK

In 2011 it has been demonstrated that the transverse damper can be used to blow-up the beam transversely up to the mechanical aperture limit of the LHC and to create losses that permit to verify the correct position of the collimators (loss maps). The blow-up is well controlled and can be targeted to a limited group of bunches. During the 2012 start-up the blow-up method was used operationally

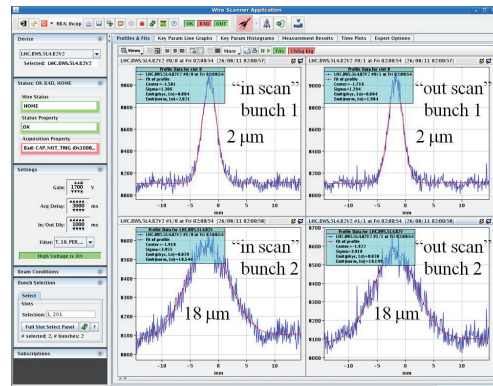


Figure 6: Profiles measured with the wire scanners after a blow-up targeted to bunch 2: blow-up to aperture limit of this bunch; bunch 1 emittance unchanged.

and saved a considerable amount of time during the first global aperture measurements at top energy (4 TeV) and loss maps. Future developments include the automation of the procedure and its use in studies at the end of luminosity fills with 1380 bunches. Machine studies are also foreseen to quantify the collimation efficiency in various conditions, during the ramp, squeeze and for different settings.

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