RECENT DEVELOPMENTS FOR INSTABILITY MONITORING AT THE LHC

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Abstract

A limiting factor on the maximum beam intensity that can be stored in the Large Hadron Collider (LHC) is the growth of transverse beam instabilities. Understanding and mitigating these effects requires a good knowledge of the beam parameters during the instability in order to identify the cause and provide the necessary corrections. This paper presents the suite of beam diagnostics that have been put into operation to monitor these beam instabilities and the development of a trigger system to allow measurements to be made synchronously with multiple instruments as soon as any instability is detected.

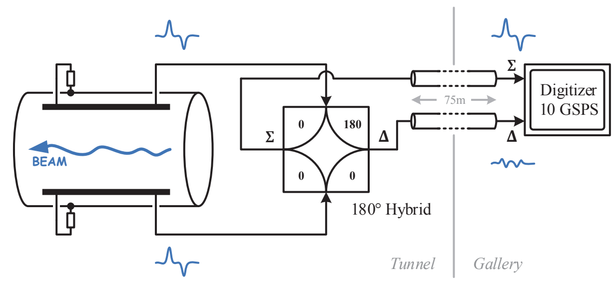

Figure 1: Block diagram of the LHC head-tail monitor.

INTRODUCTION

The first run of the Large Hadron Collider (LHC), from 2009 to 2013, saw transverse beam instabilities at injection and during physics fills while running with 50 ns bunch spacing at an energy of 3.5 TeV [1]. The second physics run, beginning in 2015, has moved to 25 ns bunch spacing, increasing electron cloud and other collective effects [2]. Other changes, such as tighter collimator settings at 40 cm β^* [3] and strict limits on beam loss at the increased operating energy of 6.5 TeV [4], mean that the mitigation of beam instabilities has continued to be an important consideration.

The availability of diagnostics to characterise beam instabilities is important, both for qualifying experimentally the LHC impedance model [5] and for making the correct adjustments to the machine settings if instabilities occur during operation.

The recently deployed LHC Instability Trigger Network [6], based on White Rabbit technology [7], enables bi-directional trigger distribution between instruments capable of detecting and observing beam instabilities. The first major use of the network has been to trigger the LHC head-tail monitor [8] with a trigger algorithm running on the base-band tune (BBQ) system [9].

HEAD-TAIL MONITOR

A workhorse instrument used for characterising beam instabilities is the LHC head-tail monitor. The system, shown in Fig. 1, is based on the high speed acquisition of a long stripline type beam-position monitor (BPM). A commercial wideband 180° hybrid generates the sum and difference of the BPM electrodes and these signals are directly digitised with a 10 GSPS 8 bit digitizer located close to the beam line in a service gallery.

The head-tail monitor was originally installed in the CERN-SPS for chromaticity measurements by the observation of the phase shift between the head and tail of the bunch [8]. Because of the high bandwidth of the BPM and acquisition system, it can also be used for direct time-domain measurements of intra-bunch motion. Although it can provide direct information about the beam stability, the minimum detectable oscillation amplitude is limited by the dynamic range of the acquisition system. A second limitation is the available acquisition memory and data readout speed. The commercial oscilloscopes used in the LHC are limited to 11 turns for all bunches (1 ms of data) and take approximately 10 seconds to read out. These two factors require that the head-tail monitor be precisely triggered once the oscillation amplitude has reached a sufficient level to be visible, but before significant beam loss leads to a beam abort.

New digitizers [10] are being tested that feature much larger acquisition memories, capable of storing up to 1.6 s of data. While easing the trigger requirements, the increased data size of up to 64 GB per acquisition poses serious challenges for data storage and processing.

Data Processing

The raw data from the head-tail monitor requires a number of post processing steps in order to obtain useful information about the bunch stability. During the first LHC run, where the head-tail monitor was primarily used for measurements during machine development sessions, the processing was performed manually. In order to understand instabilities that occur during normal operation, the head-tail monitor is now used on a day-to-day basis generating large quantities of data. To help with extracting useful information from these large data sets, an automatic method for determining if an acquisition contains an instability has been developed.

The first step is to determine which, bunch slots are actually filled with beam. For this, a single turn of data from the sum signal of the head-tail pickup is divided into 25 ns intervals. Each of these “bunch slots” is then further subdivided into five 5 ns segments and the maximum signal amplitude in each of these is calculated. For a slot where no

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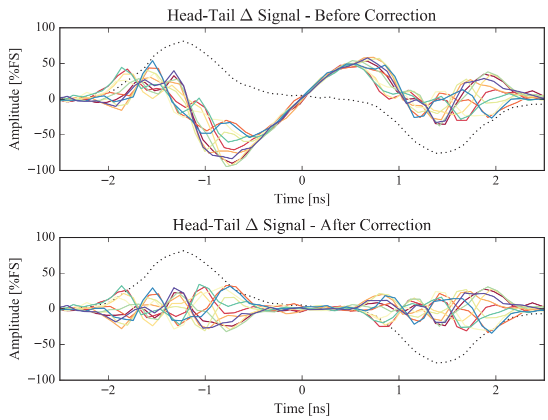

Figure 2: A mode $|m| = 4$ instability, captured by the head-tail monitor, before and after the baseline removal.

bunch is present, all of the 5 ns segments will contain only noise and will therefore be of similar amplitude. For a slot where a bunch is present (LHC bunches are typically 1 ns in length), at least one 5 ns segment will have a data point of much higher amplitude. A simple threshold comparison can therefore be used to determine if a bunch is present or not. The threshold is set such that nominal intensity bunches ($N_b = 1.1 \times 10^{11}$) will be reliably detected while "pilot" bunches ($N_b = 5 \times 10^9$) will be ignored. These threshold settings avoid saving files which only contain low intensity bunches, as the head-tail monitor does not have enough dynamic range to see oscillations of pilot bunches when set up for nominal intensities.

Secondly, the data for each bunch must be aligned over all of the acquired turns. As the sampling rate of the digitizers is constant, the number of samples per turn changes due to variations of the frequency of the LHC RF system. To determine the correct number of samples per turn, the sum signal of a single populated bunch slot is used. An approximate value is taken as a starting point and the overlap of the two turns is changed in steps to search for the best fit. The scan is repeated for both decreasing step sizes and by comparing to more distant turns to obtain the required precision.

Finally, the large, constant, difference signal "baseline", present due to both the beam orbit offset in the head-tail pick-up and non-linearities of the hybrids, needs to be removed. The mean of the corresponding samples in each turn is computed over all turns and this mean is then subtracted from each turn. For example, for a sample a_n in turn t the corrected sample is obtained with:

$$a_n(t) = a_n(t) - \sum_{\tau=1}^{\tau=T} \frac{a_n(\tau)}{T}$$

where T is the number of turns of data acquired. This procedure is complicated by the fact that the number of samples between turns is not an integer number, as the sampling frequency is not linked to the beam's revolution frequency. Before the mean can be calculated, the data from each turn needs to be interpolated, for which a simple linear interpolation is used. The mean value is then re-interpolated to the original sample points of each turn before subtraction.

Finally the amplitude of the instability can be approximated by looking at the ratio of the difference signal amplitude inside and outside the bunch area. The mode number can be determined by searching for the zero-crossing points of the difference signal within the bunch. By automatically processing the head-tail monitor data, "uninteresting" acquisitions, for example those containing no bunches or no visible oscillations, can be removed to limit the amount of data which needs to be evaluated manually.

An example of a mode $|m| = 4$ instability, captured during a 2015 MD session, is shown in Fig. 2, both before and after the baseline removal. The plot overlaps 11 turns of the difference signal from a single bunch such that the stationary nodes within the bunch can be seen. The dotted line shows the corresponding sum signal. Also visible is the characteristic response of the stripline BPM with the first pulse followed by an inverted reflection after twice the length of the stripline. The 40 cm long "BPLX" type BPM, used as the LHC head-tail pickup, is dimensioned to ensure that the two pulses are well separated in time to avoid cancellation.

INSTABILITY TRIGGER

The LHC base-band tune (BBQ) system is based on diode peak detectors that convert the high-frequency signal from the BPM to a low-frequency "oscillation" signal that can be sampled with high resolution audio ADCs [9]. Because of its high dynamic range, the BBQ has the chance to detect the onset of an instability before any other instrument and can serve as a trigger source for less sensitive diagnostics.

Under optimal conditions, a growth in amplitude of the time-domain BBQ signal is a reasonable indication of the appearance of an instability. In this case, the eigenmode of the oscillation becomes the dominant component of the spectrum and gives the biggest contribution to the amplitude of the signal. However, with a high number of bunches and high transverse damper gain, the BBQ signal can be dominated by other noise sources. While still possible to detect, a single bunch becoming unstable then has a much lesser effect on the overall amplitude of the signal.

The first version of an instability trigger algorithm, called the "three-averages" algorithm, was developed in 2013 based on simulated data [11]. For the startup in 2015, the trigger algorithm was deployed on the BBQ to gain experience with its performance under operational beam conditions. Although the algorithm was found to perform well with optimal conditions, during physics fills it proved to be extremely sensitive to small fluctuations resulting in spurious triggers. A second algorithm, called the "increasing-subsequence" algorithm, has been developed using a different principle which attempts to reduce the number of false positives under operational conditions.

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Three-Averages Algorithm

This algorithm computes the average of the standard deviation about the mean of the signal over three different time windows. The window lengths are proportioned so that $W_{short} < W_{med} < W_{long}$. Under stable conditions, it is expected that $\sigma_{short} \approx \sigma_{med} \approx \sigma_{long}$. During an instability, the amplitude of the input signal increases and the averages change with a rate that corresponds to the length of their windows. Then the following inequalities will hold:

$$\sigma_{short} - \alpha\sigma_{med} > 0$$
$$\sigma_{med} - \beta\sigma_{long} > 0$$

where $\alpha, \beta > 1$ are coefficients chosen to reduce the influence of noise. Fulfilling these conditions for many consecutive turns is a clear indicator of a growing instability. To detect this condition a counter (C) is initialised to zero and is incremented on each turn by the normalised difference of each pair of window functions:

$$C = C + w_\alpha \frac{\sigma_{short} - \alpha\sigma_{med}}{\sigma_{short} + \sigma_{med}} + w_\beta \frac{\sigma_{med} - \beta\sigma_{long}}{\sigma_{med} + \sigma_{long}}$$

where w_α, w_β are weighting factors corresponding to the number of turns sufficient to confirm the presence of an instability for this window. Once the counter reaches a threshold value, a trigger is generated and the counter is reset to zero. In order not to generate a large number of consecutive triggers, the counter is held at zero for a short "holdoff" period after each trigger.

Increasing-Subsequence Algorithm

For a given sequence of values (Q) that are oscillating independently around a constant value, for example the steady state amplitude of a stable beam, a subsequence (S) can be defined that consists of the elements that are the maximal ones up to their appearance. In the steady state, it can be shown that the expected length of the subset S is approximately a logarithmic function of the length of Q with a standard deviation lower than the square root of the length [12]. The situation changes dramatically if the values in a sequence correspond to a rapid growth in amplitude, because there is a much higher probability that the current amplitude will be larger than previous one.

A second algorithm for instability detection can then be described by the following procedure. As with the three-averages algorithm, a counter is used to track the instability growth. On each new sample, the maximum value in the last n samples is found. If it is the newest sample, the counter is incremented by one, while if it is the oldest sample, the counter is decremented by a set value. Once the counter reaches a threshold value a trigger is again generated.

In order to reduce the probability of a trigger caused by the large transient seen at beam injection, a further check is made on each sample. If the value is significantly greater than maximum in the last n samples it indicates a transient rather than an instability and can therefore be filtered.

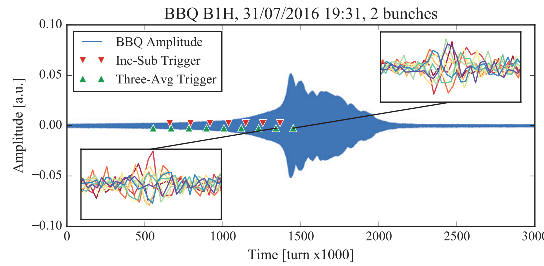

Figure 3: Comparison of the trigger algorithms during an instability with a two nominal bunches with markers indicating the trigger points of each algorithm. The inset plots show the head-tail monitor acquisition for the indicated triggers.

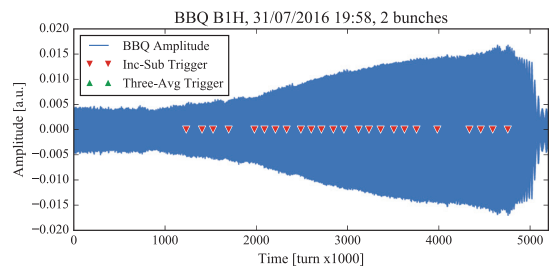

Figure 4: A slower instability, again with two nominal bunches, which is unseen by the three-averages algorithm but is detected by the increasing-subsequence algorithm.

Comparison Between the Algorithms

In order to compare their performance, both algorithms have been simulated during known instability events with various beam conditions where the data from the BBQ and head-tail monitor have been stored.

Figure 3 shows an example of an instability with only two nominal bunches in the machine where both algorithms perform in a similar fashion. However, if the instability rise time is slower, as shown in Fig. 4, the three-averages algorithm does not trigger as all three averages follow the rise in amplitude and their difference is never big enough to generate a trigger. For cases like this, the increasing-subsequence algorithm is a clear improvement as it detects the amplitude increase and generates triggers.

One important requirement for the new algorithm was to avoid triggering on injection transients. The behaviour of the two algorithms to an injection seen by the BBQ is shown in Fig. 5. The three-averages algorithm triggers on the large increase of amplitude caused by the injection event as σ_{short} increases rapidly above σ_{med} and σ_{long} with the counter quickly reaching its threshold. In comparison, the increasing-subsequence algorithm filters the transient and is able to trigger on a subsequent rise in BBQ amplitude which could be indicative of an instability.

For conditions where there are only a small number of bunches in the machine, it is clear that the increasing-subsequence algorithm improves upon the three-averages algorithm, generating triggers for slow instabilities and being

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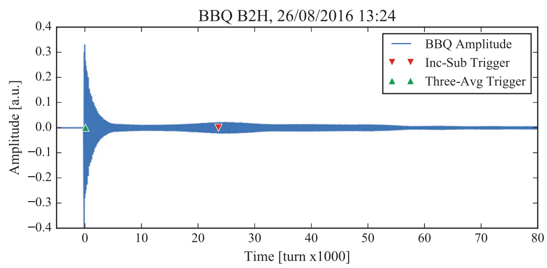

Figure 5: Comparison of the trigger algorithms during the transient caused by an injection.

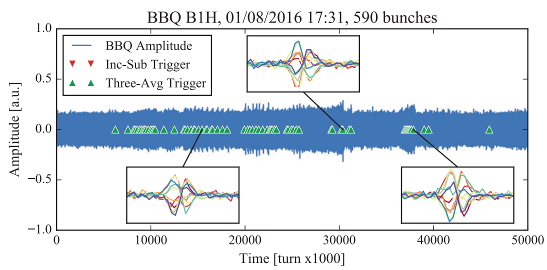

Figure 6: Instabilities with 590 nominal bunches that are seen by the three-averages algorithm but that would not be detected by the increasing-subsequence algorithm.

insensitive to injection transients. However, in cases with a larger number of bunches, the difference in amplitude during the instability can be less prominent on the BBQ if only a small subset of bunches become unstable. A case like this is shown in Fig. 6. As it is very sensitive to changes in amplitude, the three-averages algorithm is able to detect these instabilities while the increasing-subsequence algorithm is not.

FUTURE DEVELOPMENTS

A multi-band instability monitor (MIM) [13] is under development to provide an alternate trigger source and complement the BBQ instability trigger. By looking at the spectral power contained in different frequency bands the MIM can provide information about the instability mode as well as detecting the presence of an instability. The initial version of the MIM splits the signal with a RF filter bank into eight bands from 400 MHz to 3.2 GHz. The acquisition for each band is then performed with diode detectors and high-resolution ADCs, similar to that of the BBQ. Commissioning of the MIM with beam is expected before the end of the 2016.

CONCLUSION

Measurement and mitigation of beam instabilities is an important consideration for the second physics run of the LHC. The head-tail monitor provides a direct measurement of intra-bunch motion and is an important instrument for classifying the type of instability. However, due to the limitations of its high-speed acquisition system, it has to be accurately triggered to catch the oscillation once it reaches a sufficient amplitude. For this, an instability trigger based on the sensitive BBQ system has been developed and two separate algorithms for detection have been tested with various beam conditions. The BBQ is now used to trigger the head-tail monitor regularly during operation for instability analysis. In order to deal with the large amount of data produced by the head-tail monitor, methods to automatically process the data and identify the acquisitions containing unstable bunches have been developed, greatly aiding the subsequent off-line analysis. Finally, to provide additional instability information, a multi-band instability monitor has been installed in the LHC is currently being commissioned.

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