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claudia.gomez.menendez@cern.ch

Automated analysis of turn-by-turn beam trajectories following beam dumps at the LHC

Summer Student Project Report
Claudia Gómez
Supervised by: Cedric Hernalsteens

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Abstract

The Large Hadron Collider (LHC) is a particle accelerator where two counter rotating beams circulate in opposite directions and are brought into collision at different points. The stored beam energy exceeds 400 MJ, so the machine is protected by a large number of interlock channels that provide vital information to understand failures and recover from perturbations. The Post-Mortem System organizes the data recorded during a beam abort and reconstructs the event sequence that led to it. The position of the LHC beams is monitored around the whole ring by a total of 1090 Beam Position Monitors (BPMs). In this project, we study BPMs at the time of dumps in order to detect key features. We look at invalid data and particular phenomena, such as quench heaters or missing beam-beam kick events, trying to develop and algorithm that enhances their detection. We find that the implementation of such an algorithm proves to be useful in a significant number of cases, although the establishment of the threshold values and confidence intervals remains as a subject for further study.

Contents

1 Introduction

The Large Hadron Collider (LHC) is a particle accelerator using superconducting magnets to collide protons and heavy ions[1]. It consists of two differentiated beams, labeled as Beam 1 (B1) and Beam 2 (B2), circulating in opposite directions and brought into collision at four points, where the four main experiments (ATLAS, CMS, ALICE and LHCb) are located. A schematic overview of the accelerator's layout is shown in **Figure 1**.

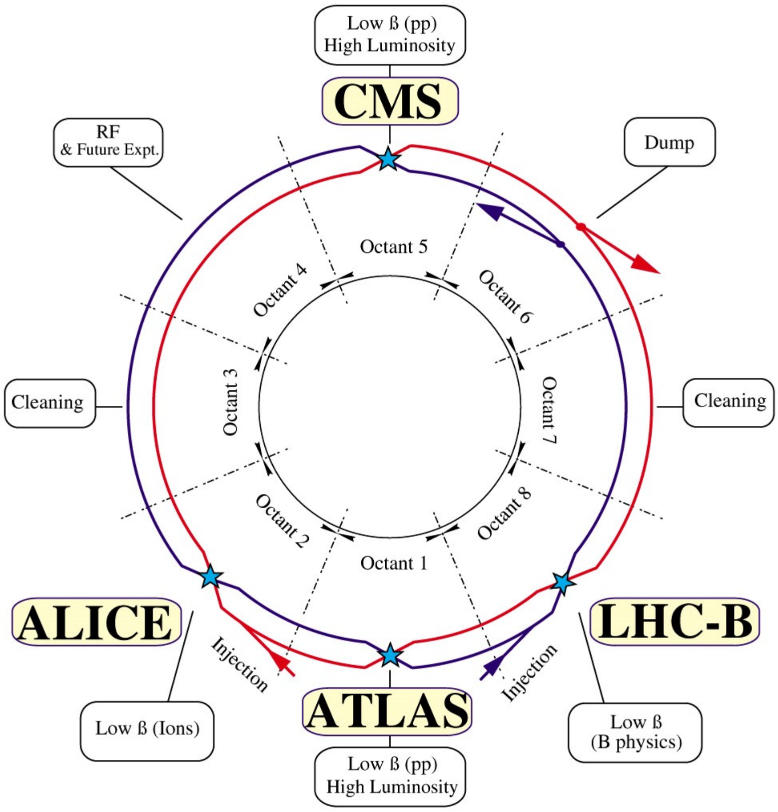

Figure 1: The LHC is housed inside a 27 km circular tunnel and made of eight arcs with a regular lattice structure plus eight insertions dedicated to beam collisions, injection, beam dumping or beam cleaning.

The LHC is filled with 2400 trains of bunches coming from previous accelerators, each of them composed of 1.60×10^{11} protons at 6.8 TeV. As a result, there is a stored beam energy exceeding 400 MJ in the machine. Such a huge amount of energy underlies the need of having a protection system that traces back the origin of beam related problems. In order to accomplish this task, the position of the beam is constantly monitored around the ring by the so-called **Beam Position Monitors (BPMs)**. A total of 516 BPMs are installed in each ring, measuring the position of the beam in both horizontal and vertical planes. When a beam or power abort takes place, all the data is collected and organized by the **Post-Mortem System**[2], whose final goal is to reconstruct the event sequence that led to it.

2 Goal of the project

As part of CERN's Technology Department (TE), the **Machine Protection and Electrical Integrity Group (TE-MPE)**[1] is responsible for the magnet protection system and machine interlocks for the CERN accelerator complex. During my nine week internship, I was integrated in the **Controls and Beam Studies for Protection Section (MPE-CB)**[2], a dynamic group working in machine protection systems and beam related failure case studies, as well as reliability and availability of systems for present and future accelerators. Through the operation of the LHC, events leading to beam or power aborts are stored in the *Post Mortem Database*. I took part in a project whose purpose was to perform an automated analysis of turn-by-turn beam trajectories following beam dumps. The accomplishment of this task involved analyzing several BPMs at the time of dumps and detecting key features: quench heaters or missing beam-beam kick events, as well as invalid data.

3 Previous work: Data acquisition and pre-processing

3.1 Data acquisition

For each beam dump event, the beam positions at the BPMs are stored for the last 1024 turns in *Post Mortem*. The first step of the project, consequently, involved looking at all 2022 and 2023 stable and top energy (> 6.8 TeV) beam dumps to extract some common patterns, as well as repetitive particular behaviours. Belonging to that last group, two specific phenomena were specifically studied: **quench heaters**[3] and **missing beam-beam kick** events[4].

A magnet quench occurs when the superconducting coil becomes normally-conducting, as a consequence of exceeding its critical temperature or field. It translates into a partial or total dissipation of the stored energy, and leads to a melting of the magnet cables. Beam-beam interaction is a result of the electromagnetic forces existing between the particles in each beam. An absence of the beam-beam kick constitutes another source of beam loss. The two phenomena, together with a normal dump, have been plotted in **Figure 2**.

[1]More information can be found on the group website: Machine Protection and Electrical Integrity Group (TE-MPE).

[2]More information can be found on the section website: Controls and Beam Studies for Protection Section (MPE-CB).

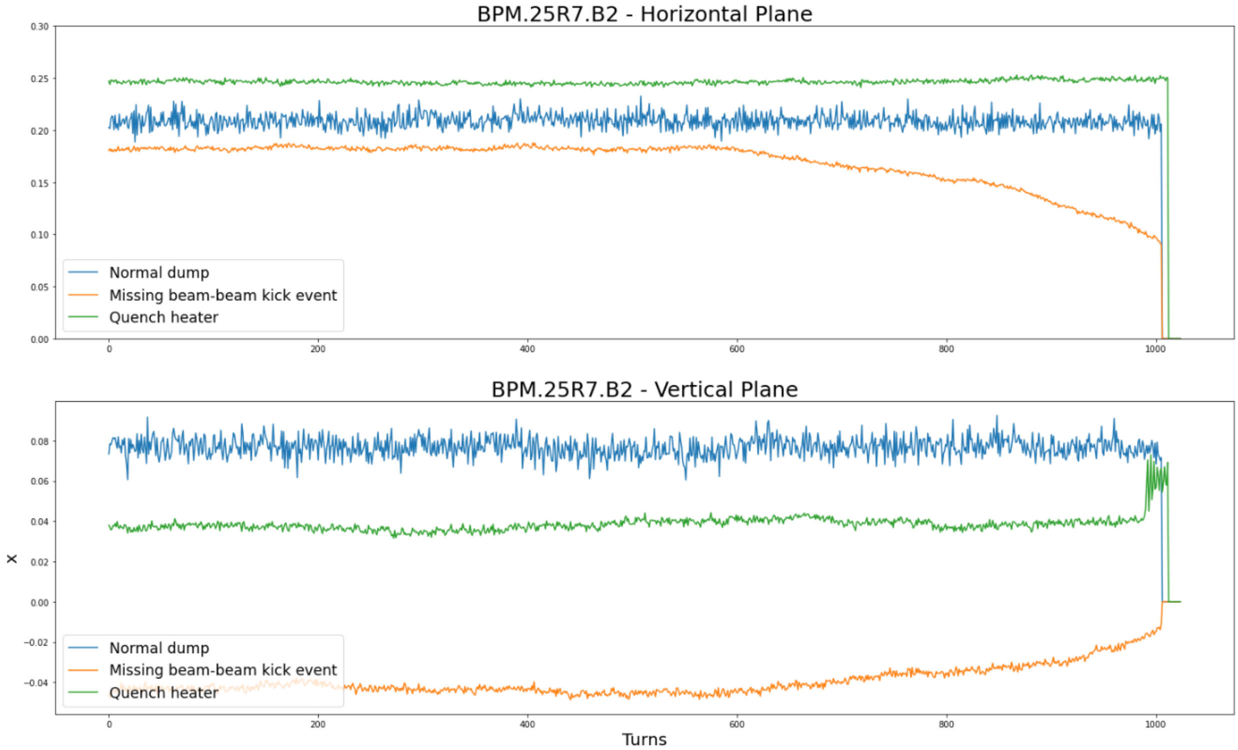

Figure 2: Comparison of a normal dump (blue), a quench heater (green) and a missing beam-beam kick event (orange) in both the horizontal and the vertical plane. While a normal dump is characterized by a final abrupt drop to zero, both quench heaters and missing beam-beam kick events exhibit anomalous behaviours in the last turns. It is important to note that both planes are independent of one another.

3.2 Pre-processing: Removing the offset and the zero values and normalization

As shown in **Figure 2**, a normal dump is characterized, along the horizontal axis, by a constant tendency that suddenly breaks up to zero. For subsequent analyses, removing those final zero turns would provide the bare oscillating signal, allowing us to calculate important parameters of the remaining data. Even though some statistical procedures, such as the **interquartile range (IQR) method**[3] for the detection of outliers were tried, the NumPy *trim_zeros* function proved to be the most efficient method of accomplishing this task.

```
original_signal = data_bpms_w[0, 'horTurnPosition', 0]
modified_signal=np.trim_zeros(original_signal, 'b')
```

[3] In descriptive physics, the IQR is a measure of statistical dispersion, which is the spread of the data.

When executed for a concrete BPM of a given event, the result was the one exhibited in **Figure 3**.

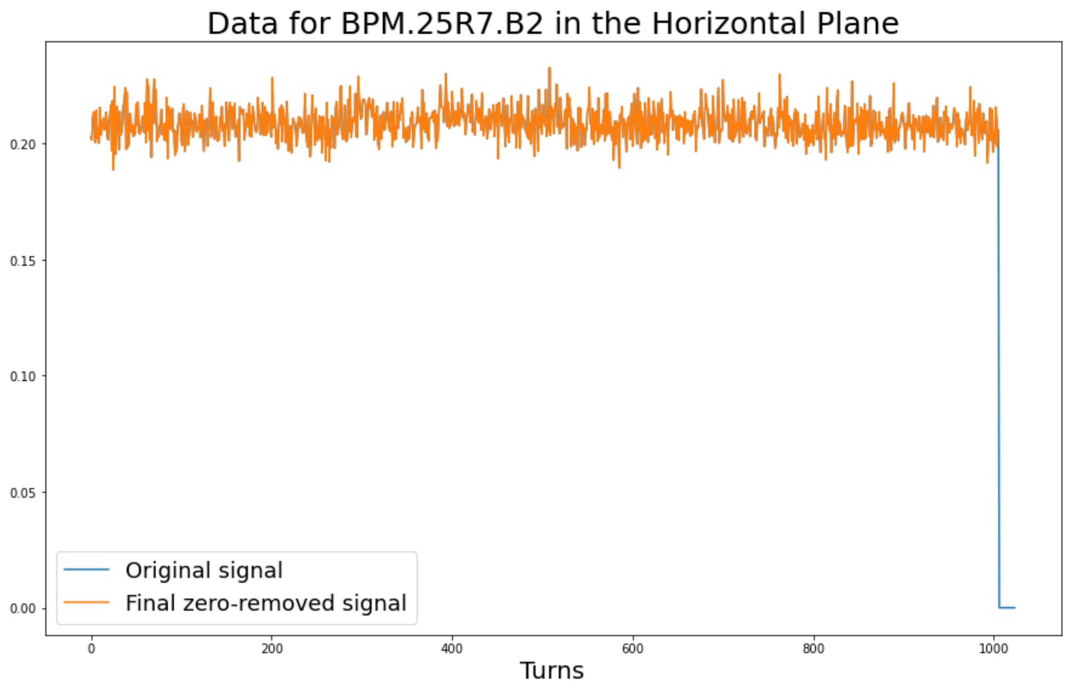

Figure 3: Original (blue) and final zero removed (orange) signal for a given BPM.

In an ideal design orbit, the particles in the beams describe closed trajectories: turn after turn, their paths have no displacement from the nominal position and angle. When a beam enters the machine, though, a bundle of trajectories spread about this ideal orbit: at any instant, particles may be displaced horizontally and vertically, and may also have divergences angles that would cause them to leave the vacuum pipe in case there was not a restoring field bringing them back to the beam centre[5]. The action of this restoring force causes particles to oscillate around the ideal orbit, so a process of normalization must be carried out in both planes in order to mitigate this effect and make analysis accessible:

$$x_n = \frac{(x - x_{co})}{\sigma_{x,y}} \tag{1}$$

where x_{co} corresponds to a closed orbit and $\sigma_{x,y}$ are given by

$$\sigma_{x,y} = \sqrt{\beta_{x,y} \cdot \varepsilon^g} \tag{2}$$

with ε^g the so-called *geometrical emittance* ($\varepsilon^g = \varepsilon_N/\beta\gamma$). The *normalized emittance* ε_N, as well as the relativistic beta β and the Lorentz factor γ, are well-known parameters for the LHC, with corresponding values of $\varepsilon_N = 3.5\,mm\,mrad$, $\beta \approx 1$ and $\gamma = 7249.47$. Moreover, the values of β_x and β_y are available for every single BPM of a particular event in a *.csv file*. Making use of Python's Pandas Library, it is possible to query all the data and obtain a normalized representation of the information exhibited in the previous graph, as shown in **Figure 4**.

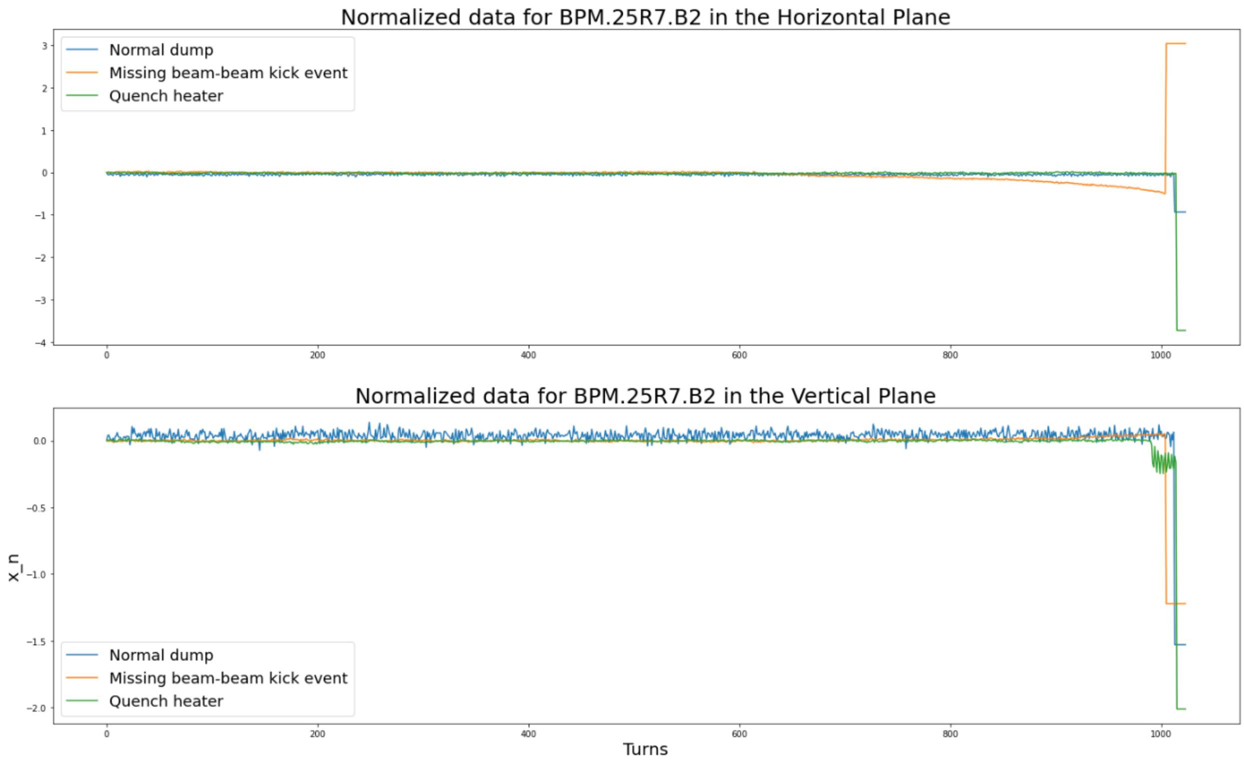

Figure 4: Normalized comparison of a normal dump (blue), a quench heater (green) and a missing beam-beam kick event (orange) in both the horizontal and the vertical plane. As shown in **Figure 1**, the atypical behaviour of quench heaters and missing beam-beam kick events becomes particularly clear for the last turns.

4 Classification

4.1 A first approach to the detection of Quench Heaters

As mentioned in previous sections, the superconducting magnets conforming the LHC structural frame can transition into the normal conducting state during machine operation. Such anomalous transition, known as **quench**[6], provokes an energy release in the form of heat, leading to the melting of the magnet and a consequent malfunctioning of the system. A whole protection system is installed all around the accelerating circumference to protect the magnets from overheating in case of a quench: the magnet coils are equipped with the so-called **quench heaters**[4]. These quench heaters are fired immediately after a quench is detected, driving large fractions of the magnet coils normal and distributing the dissipated energy over the whole magnet. However, they produce an undesired horizontal dipole field to which the beam can be exposed, experimenting a displacement from its nominal orbit. In order to better illustrate it, a particular quench heater has been selected and zoomed in in **Figure 5**. Without prejudice to the generality, it can be considered that all quench heaters show a similar behaviour. This specific case would also serve as an example for the following development of a detection criteria.

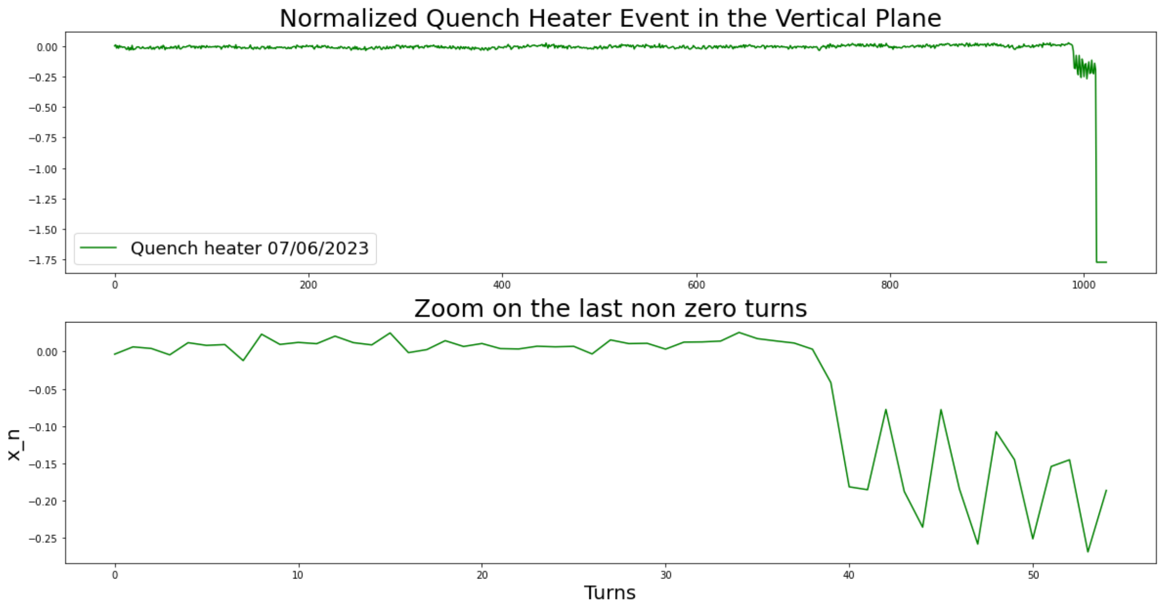

Figure 5: Normalized quench heater BPM signal with particular attention to the last non zero turns. When zoomed in, those final terms reveal a behaviour that breaks with the traditional trend, highlighting the singularity of this physical phenomena.

A quench heater is characterized by the abrupt presence of some final turns disrupting with the previous tendency. Considering our horizontal axis, *turns*, as a measure of time, in the way that it reveals us information of the signal as it moves forward in the accelerator, the following step in our treatment must not be surprising: **Fourier Analysis**.

In signal processing, the Fourier Transform takes a function of continuous or discrete time and maps it into a frequency spectrum. As a result, a decomposition of a function into sinusoids of different frequencies is obtained.

The NumPy function *numpy.fft.rfft* computes the one-dimensional discrete Fourier Transform of a real-valued array. For a given window length and a selected threshold, its implementation reveals to provide a systematic manner of identifying effective peaks.

[4]The LHC is equipped with two 0.025 mm-thick quench heaters made of stainless steel and bonded in between two layers of insulating polyamide.

```python
def compute_oscillation_amplitude(signal):
    WINDOW_LENGTH = 15
    result = []
    result_i = []
    for i in range(0, len(signal) - WINDOW_LENGTH):
        s = signal[i:i+WINDOW_LENGTH]
        result.append([
            i + WINDOW_LENGTH / 2,
            np.max(np.abs(np.fft.rfft(s-np.mean(s))))
        ])
    return np.array(result)

result = compute_oscillation_amplitude(y_n0_qh[0])
np.any(result[:, 1] > 0.1)
```

In the above routine, the *compute_oscillation_amplitude* function computes iteratively the Fast Fourier Transform (FFT) of the data over a moving window of 15 samples, providing 15 frequency components or "peaks" in the FFT for each of the 1008 windows[5]. It returns an array containing the maximum value for the computed number of moving windows. Then, for a given BPM, *np.any* gives back a "True" output if there is, at least, one FFT window whose maximum peak is above the preselected threshold of 0.1. Making use of a loop, it is possible to run the whole process for each single BPM.

To get an overall insight of the situation, the true/false result for each BPM is illustrated in **Figure 6**.

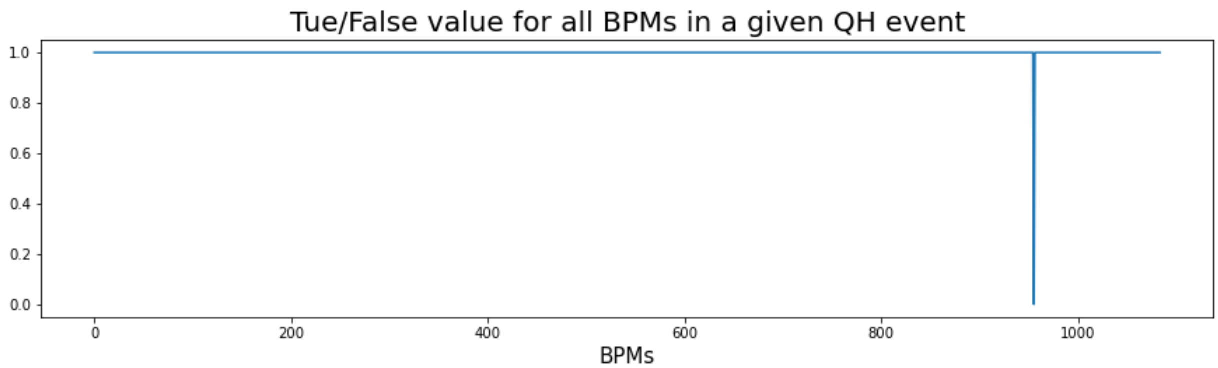

Figure 6: True/false value for all the BPMs involved in a given event. The flat line, corresponding to a "True" output, means that each BPM has detected an oscillation somewhere in its signal. As it can be seen, it is the leading tendency. For a certain BPM, though, there is a "False" detection, meaning that such particular BPM did not have a single window for which the oscillation peak was above the 0.1 threshold.

[5]The total number of window is given by the number of turns (1024-1, considering that the count starts at 0) minus the number of samples (15).

Once it was deeply analyzed, the "False" detection BPM, corresponding to index 955 and BPMSX.7L1.B2, proved to be an invalid BPM, always leading to a flat line. It was consequently classified as invalid data and removed from the database. For the considered window length (15 samples) and threshold (0.1), the *compute_oscillation_amplitude* function confirmed herself as a useful tool for oscillation detection, providing the expected results in all of the five 2022 and 2023 analysed QH events.

4.2 A first approach to the detection of Missing Beam-Beam Kick Events

As a moving collection of charges, a beam represents an electromagnetic potential for other charges. When two beams are brought into collision in a particle accelerator, namely the LHC, the electromagnetic forces between the particles that constitute each beam can cause transverse defections, known as *kicks*, resulting in a distortion of their trajectories. The primary effect of the beam-beam interaction[7] represents a limiting performance factor, since it is intrinsically linked to a reduction of the luminosity. The explanation to this fact lies in the electromagnetic forces, that generate a redistribution of the particle's transverse momentum. Since these forces are very non-linear, there is a wide spectrum of consequences arising from their manifestation, not being their study the purpose of this report. Nevertheless, further information on the subject can be found in [8]. The relevant issue concerning our project is, particularly, the miss of this beam-beam signature due to the dump of one beam. This phenomena is known as **missing beam-beam kick**, and it leads to beam losses in the betatron collimation region (IR7). As done in the case of the quench heater, a particular missing beam-beam kick event has been chosen and plotted with greater detail in **Figure 7**. The LHC layout counts with separate *beam permits* that are linked during high intensity operation. When a protection dump of one of the beams takes place, the other one is also dumped, not immediately, but with a delay of up to three turns. Several studies carried out at the LHC during the past years have proved that the loss of the beam-beam signature due to the dump of one beam can move the other one by more than 1σ[9]. Considering a threshold of 1.5σ, this is particularly relevant, and should be avoided, in the case of round optics in HL-LHC, where an orbit excursion of 1.9σ is reached in the second turn.

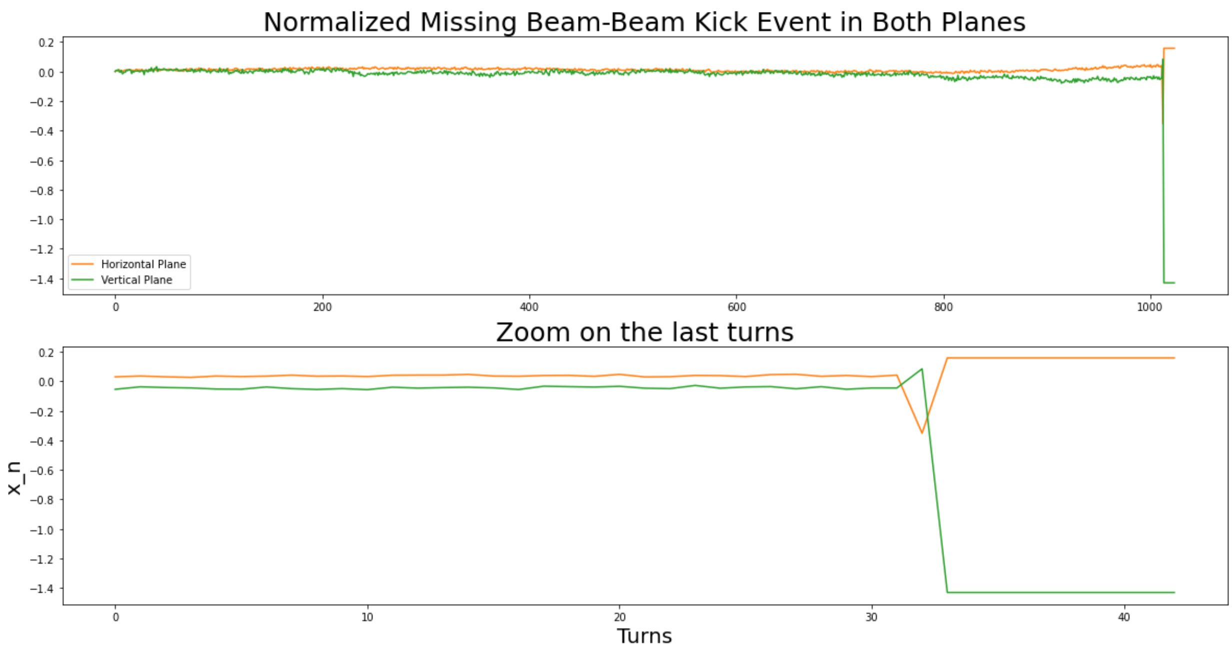

Figure 7: Missing beam-beam kick event in the horizontal and the vertical plane. Apart from the visible oscillations in both H and V, which regularly fall within the interval of a few dozens of um, common effects of this phenomena include slightly asymmetric losses in the betatron collimation region (IR7) and higher tan usual AG losses.

In the case of a missing beam-beam signature event, which is not an oscillation, the *compute_oscillation_amplitude* function implemented to analyze QH serves no useful purpose. Even though some mathematical approaches, such as the **Wavelet transform** method[6] for the detection of peaks, were tried, the establishment of an statistical threshold proved to be the most efficient method of analyzing MBBK events.

```python
import math
def detect_peaks(data, threshold_multiplier):
    peaks = []
    above_threshold = False
    window_size = 15
    moving_means = [0]
    moving_sigmas = [0]

    for i in range(1, len(data)):
        tmp = 0
        actual_window_length = 0
        for j in range(i-window_size,i):
            if j >= 0:
                actual_window_length += 1
```

[6]The most intuitive transformation space for peak identification is a peak width-position space, which is given by the wavelet transform.

```
                tmp += data[j]

        mean_previous = tmp/actual_window_length

        tmp = 0
        actual_window_length = 0
        for j in range(i-window_size,i):
            if j >= 0:
                actual_window_length += 1
                tmp += (data[j]-mean_previous)**2

        variance_previous = tmp/actual_window_length
        sigma = math.sqrt(variance_previous)

        moving_means.append(mean_previous)
        moving_sigmas.append(sigma)
        if i > 1 and abs(data[i]-mean_previous) > threshold_multiplier *
        ↪  sigma:
            peaks.append(i)

    return peaks, np.array(moving_means), np.array(moving_sigmas)

data = x_n0_mbbk[0]
threshold_multiplier = 7

detected_peaks = detect_peaks(data, threshold_multiplier)
```

In the above routine, the *detect_peaks* function compares the value of a given term with the statistical mean of the 15 previous ones. It calculates the standard deviation of the considered sample and gives back a "Detection" output if it detects a peak above a preselected threshold of 7σ. Making use of a loop, it is possible to run the whole process for each single BPM.

To get an overall insight of the situation, the implementation of the function for a given missing beam-beam signature event is illustrated in **Figure 8**.

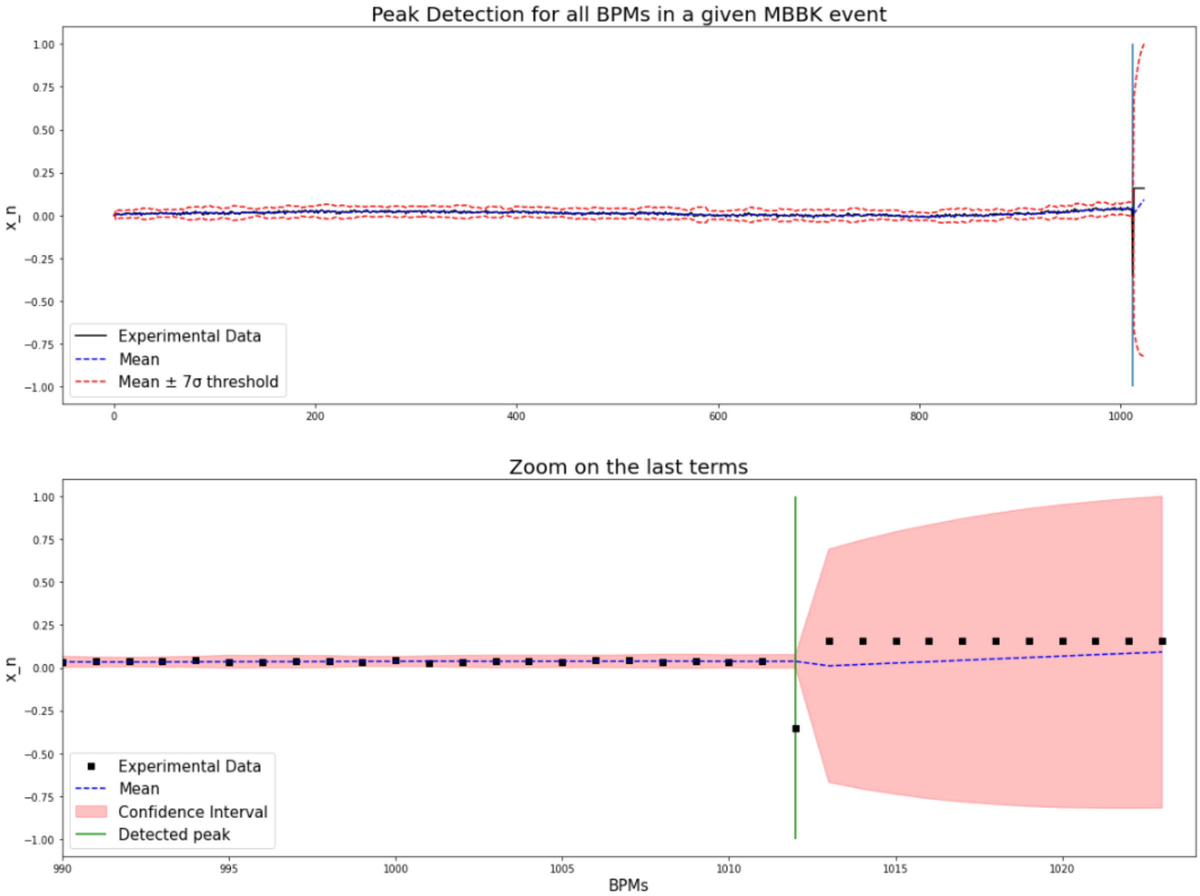

Figure 8: Peak detection for a given MBBK event. For the vast majority of the BPMs, the experimental data (represented by a discontinuous black line) falls inside the 7σ confidence interval, translating into a "non detection" output. A significant exception is shown, though: for a certain value (green vertical line), a positive detection output is exhibited.

The establishment of the threshold was not an arbitrary election. For the five 2022 and 2023 analysed missing beam-beam kick events, a 7σ confidence interval proved to be effective in all of the cases. When becoming more restrictive, i.e., narrowing the interval up to 5 or 6σ, significant information was only provided in two of those events, since minor peaks had been wrongly detected in the three remaining ones. No effective detection was registered under the value of 5σ.

5 Conclusion

The purpose of this project was to analyze several BPMs at the time of dumps in order to improve the detection of quench heaters, missing beam-beam kick events and other key features on the circulating LHC beam. The first step involved looking at all 2022 and 2023 top energy beam dumps. It was followed by a necessary removal of the offset and the final zero values, that allowed us to access the bare oscillating signal that characterises a dump. When the beam enters the machine, a bundle of trajectories spreads about the ideal design orbital. Particles are displaced horizontally and vertically and show divergences angles. Due to the action of a restoring field bringing them back to the center, they start oscillating around this ideal orbit. A consequent normalization process had to be carried out as a final step of the pre-classification approach.

Quench heaters were firstly study in our project. Using Fourier Analysis, we computed the Fast Fourier Transform (FFT) of the available data over a moving window of 15 samples, obtaining the maximum value for each of them. Establishing a threshold of 0.1, we were able to compute a function that gave us back a "True" output when there was a window whose maximum peak surpassed it. A similar approach was accomplished in the study of missing beam-beam kick events. A peak detection function was developed on the basis of statistical procedures. By comparing a certain value with the mean of the 15 previous ones, it calculated the standard deviation of the considered sample and gave back a "Detection" output when the result did not fall within a confidence interval of 7σ.

In both cases, the computed functions were implemented in all the QH and MBBK events of the present and past year. The main results were reassuring: for certain threshold values, a successful detection was achieved in almost all of them. The election of this values, though, could potentially constitute a subject of study, since it was currently carried out manually. As a final word, it is important to outline that all the analysis presented here focuses only on two particular phenomena. Other possible events have not been considered so far, leaving the path often to further investigation.

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