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Study of the BCM1F beam induced background

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Summary

This document contains a detailed summary of my work during the summer student internship at CERN. Throughout this time we conducted study of the effects of collimator positions on beam induced background measured on the BCM1F, designed a simple algorithmic procedure to identify the dominant causes of background throughout the LHC fills, and lastly we analyzed the albedo/afterglow effect, derived the correction for the new μTCA subsystem, and tested whether there exists a temporal component to this effect.

Contents

1 Introduction

The word background is one of those terms that are severely overloaded which meaning can change greatly depending on the context it is placed in. Since it is one of the main focuses of this work we find it opportune to explain in more detail what exactly do we mean by background. To attempt this we first need to explain a bit more on how the Fast Beam Condition Monitor (BCM1F) works.

1.1 Overview of the BCM1F

The BCM1F is one of the core subdetectors of the Compound muon solenoid (CMS) experiment. It consists of four C shapes which are paired to form two rings. On each of these C shapes there are 12 silicon detectors amounting to 24 per ring and 48 detectors (channels) in total. These rings are placed deep within the CMS 1.8 meters to the left and to the right of the interaction point. Figure 1 depicts the CMS as a whole, the positions of the Beam Radiation, Instrumentation and Luminosity (BRIL) groups subdetectors are highlighted.

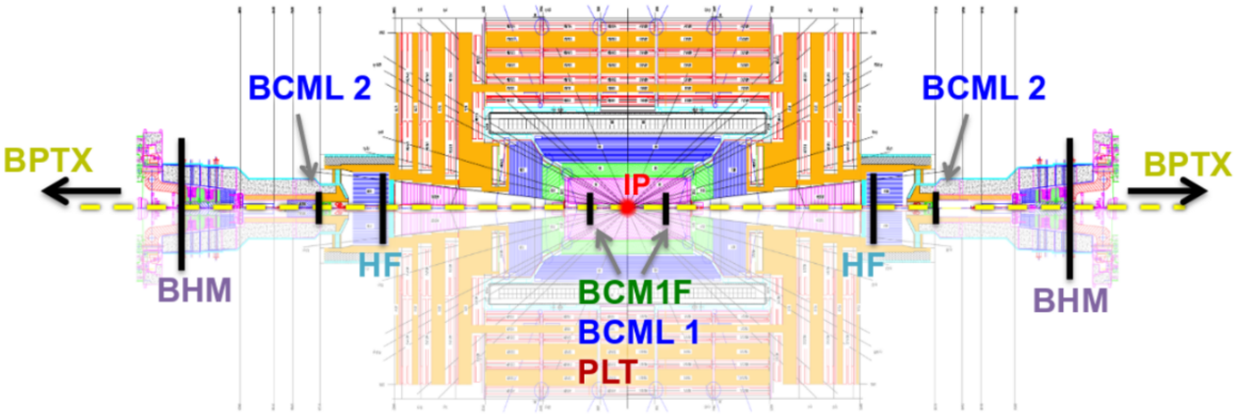

Figure 1: Cross section of the CMS detector showcasing BRIL subdetectors. The BCM1F is one of the detectors closest to the interaction point (IP).[1]

The role of the BCM1F is twofold: it is primarily used to measure the instantaneous luminosity at the CMS, and it can measure the so-called beam-induced background. The way this is conducted is by counting the number of hits the BCM1F channels receive.

The BCM1F is equipped with VME and μTCA counting units, the former has a temporal resolution of 6ns while the latter 4.5ns yielding 4 and 6 counting bins per bunch crossing respectively. Figure 2 shows three important moments for the BCM1F measurement. In the first instant, the beams cross the BCM1F, the hits measured here are produced by the beam halo i.e. the contents of the first bin are used to calculate the beam halo. The beams need another 6ns to get to the interaction point (IP) where collisions occur. Another 6ns are needed for collision products and the remaining beams to reach the BCM1F again, most hits per bunch crossing come from this moment, and are recorded in the third bin. All four bins are aggregated for luminosity measurements[1].

1.2 Types of background to be analysed

This report is divided into three sections each being related to some sort of background effect. In the first section we report on the effects of the collimator system on the BCM1F measurements

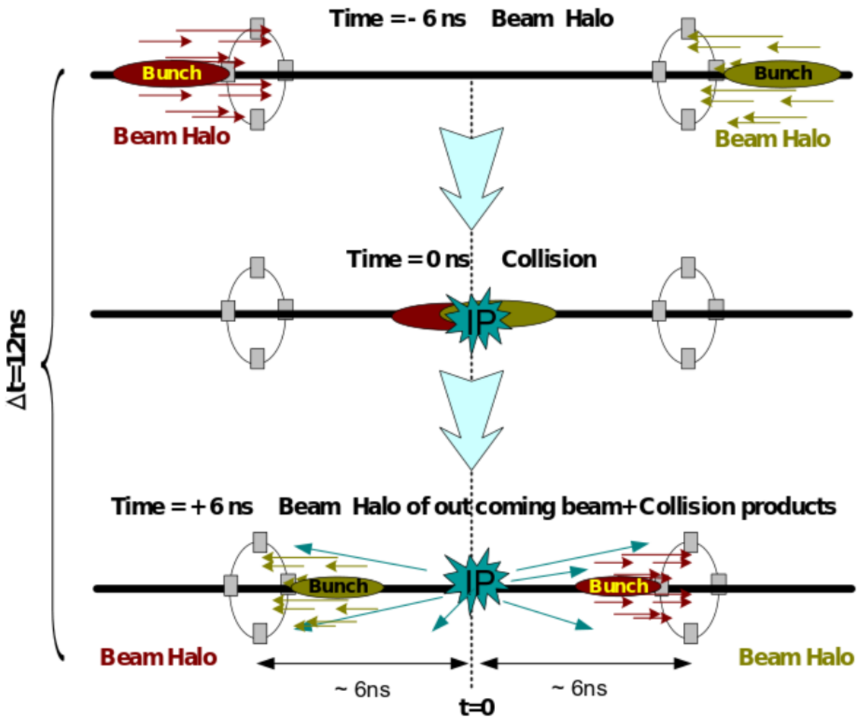

Figure 2: Three phases of the BCM1F measurements.[1]

of the beam induced background. The second part extends beyond the collimator study and explains on a simple procedure on how to identify the most dominant cause of background e.g. poor vacuum or high beam losses on the collimators. In the end we discuss the role of albedo, a completely different but very important source of background.

2 Collimator study

2.1 The Collimator System

When protons are injected into the LHC we assume that they are all placed on the so-called beam axis and that they stay there throughout the fill[1]. In the real world of course things are never so simple, first of all, protons are all positively charged and therefore repel each other, secondly while upon entering the LHC they also differ slightly in momentum which means that the dipole magnets used for changing their trajectory also disperses the beam. These are two of many reasons why protons disperse away from the beam axis.
These stray protons can produce a high beam background or even worse damage the highly sensitive parts of the LHC such as the superconducting magnets used for beam manipulation. To protect this equipment the collimator system was put in place. It consists of vertical and horizontal movable jaws, such that when the beam passes through the collimator the stray protons are absorbed and the equipment is preserved. However, upon interacting with the collimator material protons produce a shower of other particles, the most troublesome of which are muons [2]. The effects of the beam-induced background induced by collimator settings are tested in special fills called Loss maps, where beam excitations are induced to produce large showers at different collimators.

[1]Fill is the time from when the beam is injected into the LHC to the moment when the beam is dumped

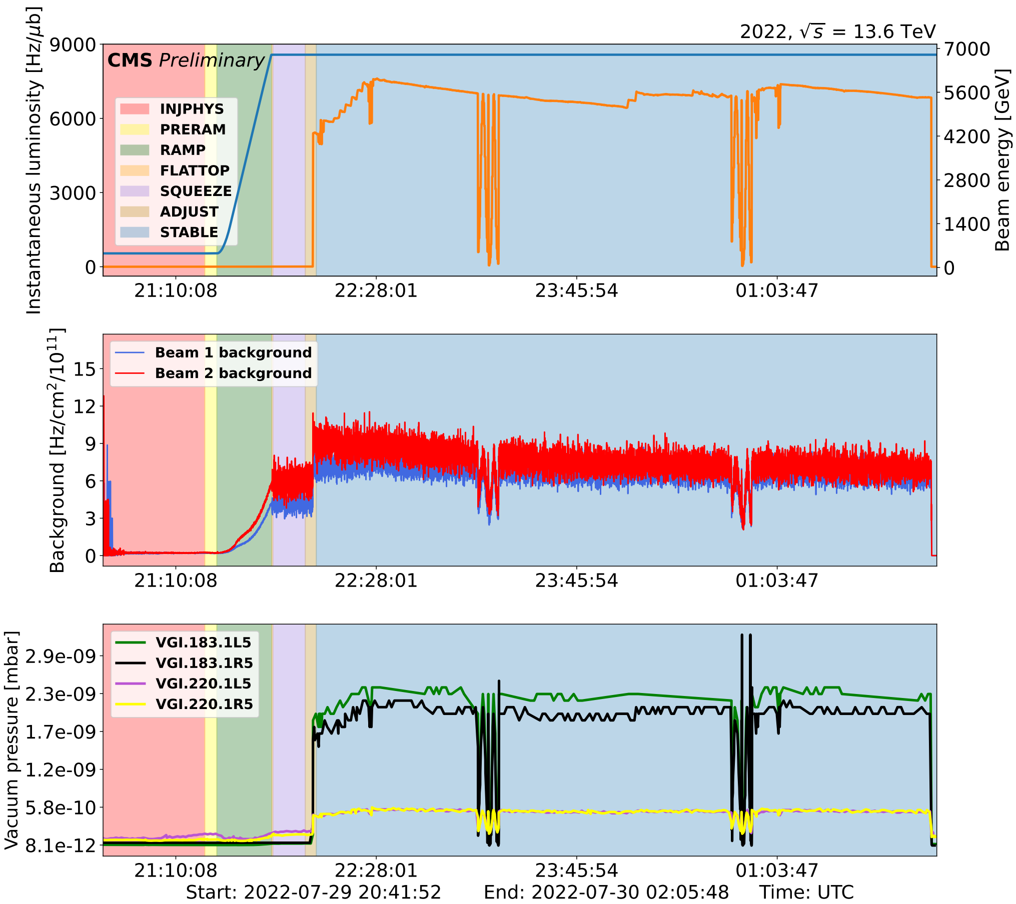

Figure 3: Fill 8068 information. The top graph depicts the BCM1F luminosity in orange and the beam energy in blue. The middle graph shows the beam idnuced background for beam 1 and beam 2 measured by the BCM1F. The bottom graph shows the vacuum measurements at two distinct points left and right from the BCM1F. The LHC beam modes are shown with the background shading.

2.2 Feature selection model

The main problem with loss map studies is that simulating collimator-beam interactions is very difficult. This prompted us to conduct a purely data-driven analysis of this phenomenon. To this end, we constructed a feature selection model that takes into consideration polynomial combinations of collimator settings. The motivation to include polynomial features stems from observing the collimators before the IP for instance TCTPH.4L5 and TCTPV.4L5. They are horizontal and vertical collimators respectively put close together and the number of protons colliding with collimators should be inversely proportional to the area $c_i c_j$ of the slit these collimators form.

Assume we have a set of collimator variables $\{c_i | i = 0...N\}$ where $c_0 = 1$ by convention. Then we form a set of polynomial features $\mathcal{P}$ of order n by creating products that contain n collimator features from the initial set. For example for $n = 2$

$$\mathcal{P} = \{c_i c_j | i, j = 0, ..., N\} = \{p_k | k = 1, ..., M\}$$

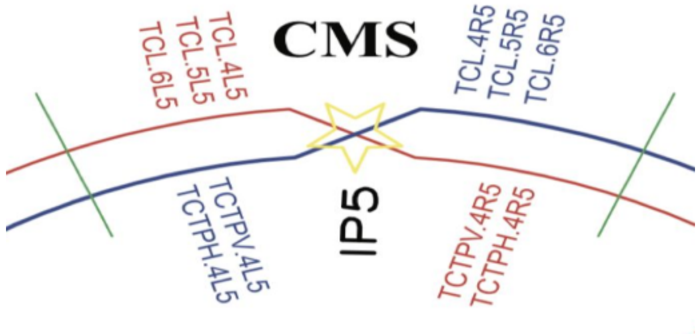

Figure 4: Collimators closest to the CMS. The blue track is the beam 1 trajectory (clockwise), and the read track is the beam 2 trajectory (anticlockwise).

This way we can have linear and quadratic features in this set. Next we define our model as

$$\mathcal{F} = \sum_{k=1}^{M} w_k p_k$$

The goal here is to model the importance of a particular variable p_k with the magnitude of its weight w_k. To this end, we train the model using a specific type of loss function

$$\mathcal{L} = 1 - \frac{\sum_{i=1}^{m} \mathcal{F}_i \mathcal{B}_i}{||\mathcal{F}|| \cdot ||\mathcal{B}||} + \lambda \sum_{k}^{M} |w_k|$$

Here the $\mathcal{B}$ can either be beam 1 or beam 2 background (its logarithm to be more precise) and λ is a hyperparameter that determines how much importance we place on penalising the model for using many variables. The loss is split into two parts the first one that accounts for the model to be as correlated to the background as possible[2], and the second (one multiplied by λ) that forces the model to use a small number of variables. What we extract from this model is a small number of variables that have the largest absolute value of their weight, in that way we can see which collimator combinations cause the highest beam induced background in the BCM1F.

2.3 Training and validation

At our disposal we had several loss map fills during which collimators were moved. Specifically, for training, we used the fill 7825 (21st June 2022) and for validation, we used 7886 (29th June 2022). These two fills exhibit similarities in that there was a lot of collimator movement and the positions of similar collimators were varied. Parts of the fill with no beam excitations were removed from the dataset. Furthermore, only collimators closest to the CMS were used i.e. the one shown in Figure 4. In fills where there is a lot of collimator movement (e.g. fill 7825) the beam-induced background already exhibits a high correlation with single collimator variables, however, using this model we can get a significant improvement in correlation[3]. Two models were trained, one for each beam-induced background, using stochastic gradient descent, with minibatch size of 1024, and regularization parameter $\lambda = 1$. The model performance is shown in Figure 5. Even though the models manage to correlate strongly with the beam-induced

[2] To be more precise we are maximising the cosine similarity of model output and background, however, the cosine similarity is equal to the correlation when the data has zero mean.

[3] All code is available on https://github.com/mirxonius/BRIL_Student_Project/tree/main/Collimator%20analisys

background there are some issues with the model. The first one is the erratic behavior of the beam 2 model towards the end of the fill: the model output is varying yet the background remains more or less constant. The second issue is the presence of spikes in the background that cannot be accounted for by observing collimator positions only and could be a product of random noise, this motivated work is discussed in the third section.

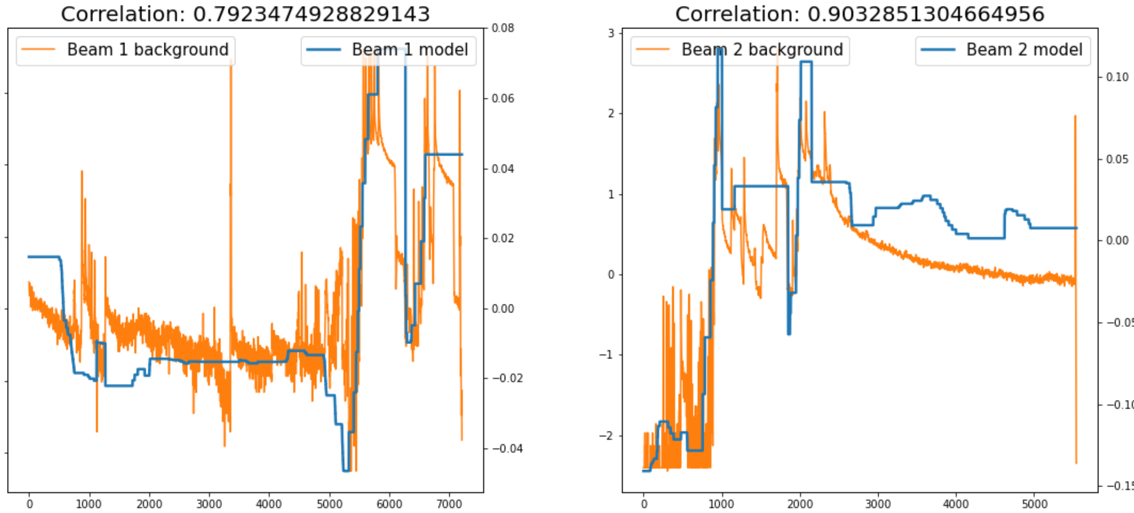

Figure 5: Fill 7825: 21st June 2022. Figures show the beam-induced background on a logarithmic scale for beam 1 and beam 2. Only the part of the fill where beam excitations were performed is shown. The blue lines depict the model prediction on this data set.

Regardless of these issues, the goal of the model was not prediction, rather it was feature selection. And we believe that that task was accomplished successfully. To evaluate that we picked the top three collimator variables with their respective weights and calculated the correlation with the beam-induced background.

Table 1: Most important variables chosen by the model and their weights

Beam 1 variables	Beam 1 weights	Beam 2 variables	Beam 2 weights
TCTPH.4L5^2	0.913980	TCTPV.4L5 $\cdot TCTPH.4R5$	0.586160
TCTPH.4L5.B1$\cdot TCTPV.4R5$	0.320454	TCTPH.4R5^2	0.341356
TCTPH.4L5$\cdot TCL.5L5$	0.099911	TCL.5R5 $\cdot TCTPH.4R5$	0.274231

Figure 6 shows the correlation between the backgrounds from fill 7886 and the combinations of the top three variables chosen by the model trained on fill 7825. The increase of correlation by introducing multiple collimator variables and their products indicated that the entire collimator system contributes to the background, rather than individual collimators.

3 Dominant background search and spike identification

The model described above only takes into account the collimator settings and their combinations. For the most part, this works well for fills with plenty of collimator movement, however, most fills, even ones used for loss map measurements, have very little or no collimator movement. The above-described procedure is incapable of extracting any information from these fills. Apart from that, we have noticed spikes in the beam-induced background that the feature

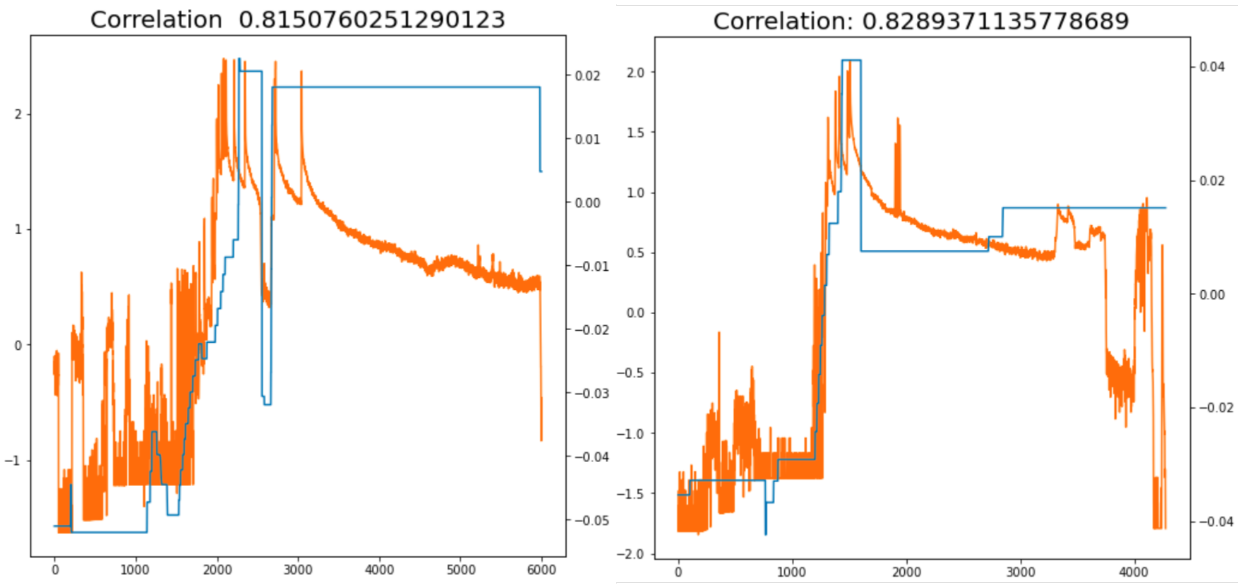

Figure 6: Fill 7886: Combinations of top three most important variables chosen by the models shown in Table 1. Left: Beam 1 Right: Beam 2

selection model cannot account for (see Fig. 5). To mitigate these issues we constructed a simple algorithm that may help us identify the most dominant cause behind the overall beam induced background as well as the source causing the spikes.

3.1 Algorithm description

Instead of observing collimator positions here, we considered the beam losses measured by the beam loss monitors positioned around the collimators shown in Fig 4. their integration time is 1.3s, and the vacuum variables present in Fig 3 as candidate variables. First, we convolve every variable with a gaussian kernel to reduce its noisiness, also, this artificially spreads the width of the spike making it easier to correlate it to other sources. Next, we divide the fill into subsections containing 5-10 % of the entire fill data. On each of these subsections, we compute the mean for the beam-induced background as well as for every candidate variable considered. The mean is subtracted from each variable. Once the mean is subtracted we can compute the cosine similarity of each of the candidate variables to the beam-induced background on every subsection. Here we can justify the convolution: the cosine similarity is essentially the scalar product of the two variables in question and if the two spikes are slightly misplaced (perhaps due to the different integration times of the beam loss monitors and the BCM1F) the algorithm would not notice that the two spikes are correlated. The variable with the highest similarity, which exceeds 0.75, to the background is deemed as the main cause of the spike or the signal shape in general. If none of the variables exceed this threshold the subsection remains unlabeled. A short summary of the algorithm is given below.

1. Select all relevant variables
2. Convolve the variables and the backgrounds with a Gaussian kernel
3. Split data into smaller segments
4. Compute the mean of each variable and background on every segment and subtract it from the data

5. Compute the cosine similarity between backgrounds and variables on each segment.

$$Similarity = \frac{\sum_{i=1}^{n} C_i \mathcal{B}_{\rangle}}{||C|| \cdot ||\mathcal{B}||}$$

6. If the maximum similarity exceeds some threshold (0.75) label the segment with the corresponding variable.

3.2 Results

The above-described procedure seems to correctly identify the main causes of background, furthermore, it works in conjunction with the feature selection model described in Section 2. For most fills, we use this algorithm on[4]it manages to identify the main cause of the spikes in the background, however, the parts of the fill where the background was mainly caused by collimator movement remain unlabeled, note that the collimator positions weren't included in the candidate set. This meant that no other variable exceeded the required threshold on that interval. The advantage of this approach is that we might automatically and efficiently extract the main causes of background in these sorts of measurements. The fact that it can work in conjunction with other correlation models is also a plus.

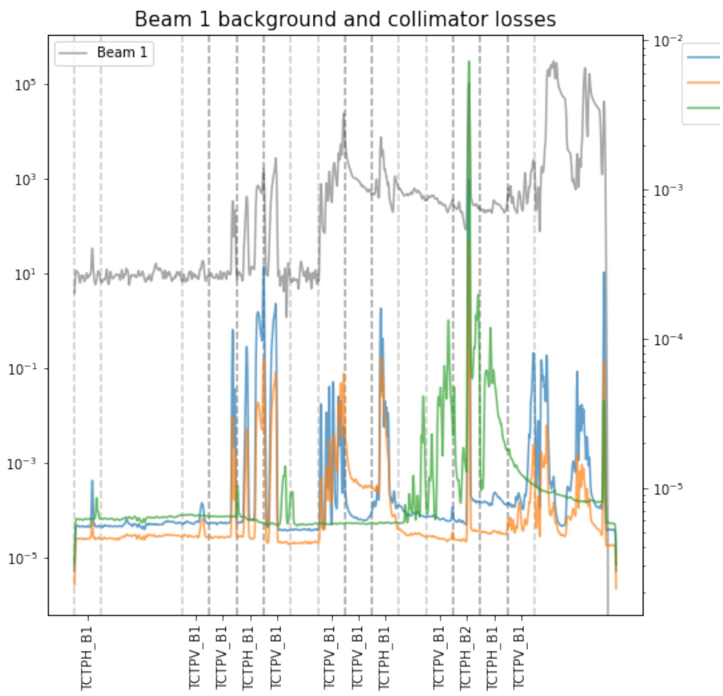

Figure 7: Fill 7825: Beam 1 background is in gray, alongside the two other candidate variables deemed as the cause of background. Aside from the good spike identification note that the last couple of segments remain unlabeled, this is because collimator positions that explain the background were not included among the candidate variables.

Unfortunately, the drawbacks are also apparent. For instance, the same algorithm was used on a loss map fill 7884 and 7882, both of which have almost no collimator movement, yet the algorithm does not manage to find the cause of the spikes in the background, we believe that this is not due to the poor algorithm rather to the fact that the main cause was not included in the candidate set.

[4]The fills we used it on were: 7825, 7882, 7884, 7886, 7889.

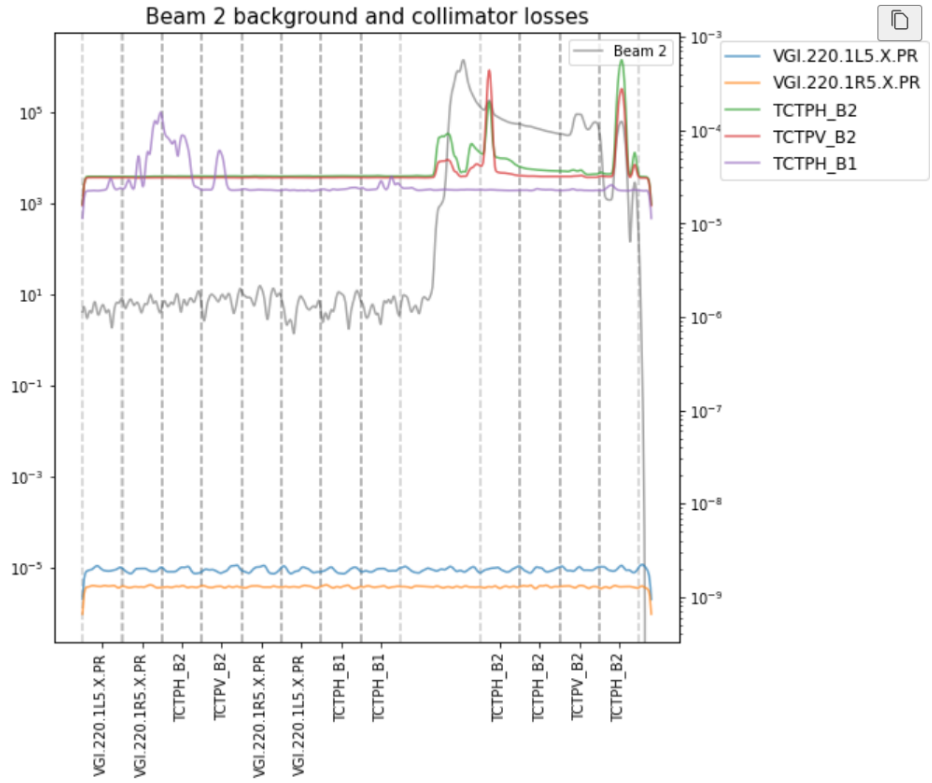

Figure 8: Fill 7886: 29 June 2022. The algorithm manages to identify the background spikes while the section of the fill where the background is dominated by collimator movement remains unlabeled showcasing how this procedure works in conjunction with the feature selection model.

Another drawback is visible in Figure 8 and 9, towards the beginning of the fill. No excitations were induced there and beam losses on collimators weren't significant yet the algorithm labels these as the main cause of background, we would expect these intervals to remain unlabeled. This indicates that the algorithm find spurious correlations as well as important ones. A remedy for this once again might be including more variables for instance the the rate of change of each variable, beam size and intensity, or perhaps a dummy variable that is random in nature to ensure that these false positives are removed, however this was not attempted in practice.

4 Albedo

A subtle cause of background and noise in the LHC is the so-called albedo or afterglow. After two bunches of protons have collided the collision products pass through the CMS and its subdetectors. This inadvertently irradiates the material that the debris passes through, in a sense the surrounding material continues to glow. The radioactive products from the activated material can produce all sorts of false signals and the BCM1F is no exception to this. In this last section, we tested some of the basic assumptions regarding albedo, specifically the fact that it is independent of the total luminosity produced or rather time.

4.1 Temporal component of the Albedo

The effect of albedo is best seen in fills with a few colliding bunches that are well separated in the orbit. In the case of the BCM1F, the clearest visualization of the effect is obtained by summing up the rates in each bunch crossing across the time domain. What remains is a

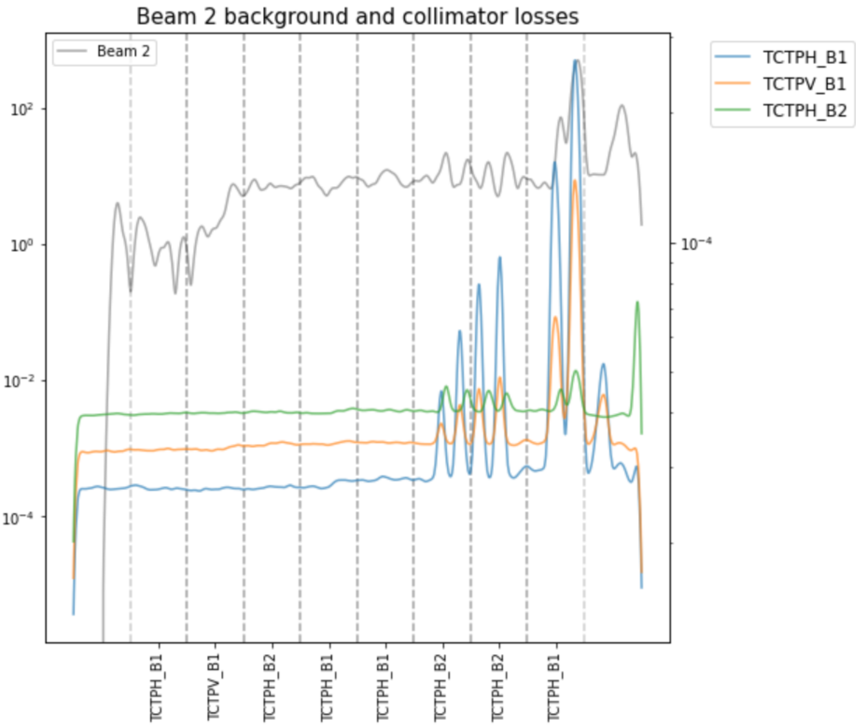

Figure 9: Fill 7889: 29th June 2022. One of the loss map fills with no collimator movement, yet the algorithm manages to identify the cause of spikes. Towards the beginning of the fill, this algorithm finds spurious correlations.

pattern similar to the one shown in Figure 10. This means that in regular fills where bunches arrive in *trains*, that is colliding bunches are grouped close together, the albedo effect can cause aditional hits in neighboring colliding bunches leading to overestimation of luminosity and beam-induced background. To account for this effect an albedo model is constructed that can be used to correct for it. The model is again constructed from data, usually using special fills that have very few colliding bunches, in our case we used fill 7921 with only two colliding bunches.

However, by summing across the entire time domain we lose any information on the possible temporal component of the albedo. To test whether one exists we divided the fill 7921 into smaller segments containing 50 to 250 time points, and performed the summation on these intervals. After the summation, an exponential was fitted to the data in each interval.

$$fit = ae^{-\lambda t} + c \tag{1}$$

The fit parameters a and c were normalized by the rate of the colliding bunch, their interpretation is obtained at $t = 0$ which coincides with the colliding bunch. $a + c$ if the fraction of the rates in the colliding bunch is caused by the albedo.

This procedure was done for VME and μTCA data across channels. The albedo parameters exhibit no temporal dependence and remain consistent across the majority of channels, the exceptions being the erratic channels that are usually masked. For instance, the albedo decay rate λ is shown in Figure 12 for each of the intervals from Figure 11.

4.2 Albedo correction model

Our idea on how to handle albedo was first to observe a fill with a few, well separated, bunches such as 7921. On the data from such a fill fit the exponential to find the albedo parameters shown in equation 1. From the analysis discussed in the previous sections, we were certain that

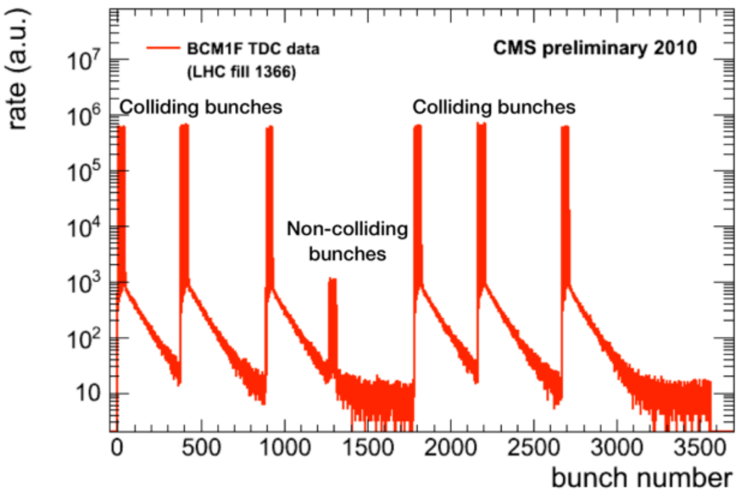

Figure 10: BCM1F rates for Fill 1366. Exponential albedo tails after colliding bunches are visible. [3]

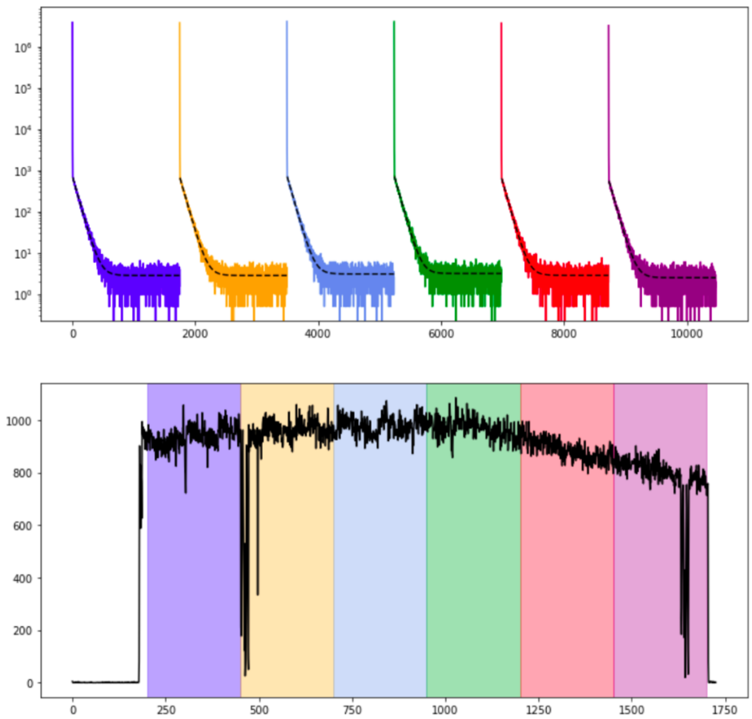

Figure 11: Fill 7921. Top: Albedo exponential tails and their fits calculated on every interval for BCM1F channel 1. Bottom: BCM1F channel 1 rates across time. The colors indicate the interval subdivisions, paired with their albedo exponential that is obtained after summation across time.

	tau	std_dist	lambda	std_lam
0	2.073359	0.028154	0.482309	0.032715
1	2.077788	0.487222	0.481281	0.489245
2	2.078865	0.598904	0.481032	0.600015
3	2.055262	1.847500	0.486556	1.853009
4	2.067674	0.561041	0.483635	0.556086
5	2.085574	1.294261	0.479484	1.287120

Figure 12: Results for VME channel 1. The albedo decay rate and lifetime for each of the intervals in μs^{-1} and μs respectively. For every interval, the distance from the mean in standard deviations is also shown.
$< \tau >= 2.073 \pm 0.009 \mu s$ $\qquad < \lambda >= 0.482 \pm 0.002 \mu s^{-1}$

the same decay rate λ could be used in other fills, the remaining problem was how to store the parameters a and c for them to be applicable in fills with different bunch configurations. Here we performed a simple scaling. Once a and c were found we scaled the with the rate of the colliding bunch.

We then tried to test our correction model on a fill with a dense bunch configuration; 8091. The procedure was the following: for each colliding bunch in the fill, we found the parameters A and C which are the same as a and c but scaled by the rate of the colliding bunch that was being corrected. With A, C, and λ we again constructed the exponential which we reduced from the entire data. This process was repeated for each colliding bunch.

The results showed that this way of correcting the albedo greatly overestimates the effect. The total correction was usually around 98%, meaning this procedure predicted that around 2% of all rates were due to albedo, which is the expected order of magnitude. What troubled us was the fact that in the regions without colliding bunches i.e. the exact places where the albedo tails are visible the albedo overestimation is significant. Due to the overestimation, the rates here become negative, which would not have been a problem if the magnitude of those rates were *small*. Unfortunately, when comparing the regions where the corrected rates were negative before and after corrections we get a ratio of about 33%. Meaning that the over-estimations are significant at least in the regions without bunch crossings. We assume that the problematic step in this procedure is the scaling of a and c, since the model did not overestimate to this extent on the fill it was fitted on. How one would perform this scaling to be stable is not clear to the author.

5 Conclusions

In this report, we have presented the three main points of my summer student project at CERN. In the first part, we have shown an increase in correlation between beam-induced background and collimator positions by considering their combinations and viewing the system as a whole. Nevertheless, some sharp spikes in the background were observed that cannot be accounted for even by considering combinations of collimator variables. To this end, we constructed a simple algorithm that manages to find the main cause of beam-induced background across fill subsections. The algorithm is generally successful, however, we have pointed out its drawbacks and suggestions on how to improve it. We have tested the temporal component of the albedo effect and found that it is indeed time-independent. Lastly we have attempted to use a different albedo correction model and found it to overestimate the amount of aferglow significantly.

6 Acknowledgements

In this last section, I would like to give my thanks to all the members of the BRIL group for giving me the amazing opportunity to work with them. A more sincere thanks to Hamed Bakhshiansohi for taking me in as his summer student. To all the other summer students that gave their invaluable advice on the project. Last but certainly not least. The biggest thanks to Joanna Wanczyk without her dedication, patience, advice, and ingenuity this project would not go beyond page one. It is certainly a good sign when one has the attention of his or her superiors. An equally important, but often overlooked good sign is when one has the respect and gratitude of her or his subordinates. After three months of work, I am fairly certain that Joanna has both. This not only makes her a skilled physicist but a promising teacher and leader in development. I wish her all the best.

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