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MD3263: Beam-Beam Long-Range Compensation using DC Wires in the LHC

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Summary

This note summarizes the experimental results obtained during the 2018 LHC Machine Development program during the measurements campaign of the Beam-Beam Long-Range compensation using DC wires (MD3263). After the promising results obtained with the prototypes installed in IR5 in 2017, two new ones have been installed in IR1 during the EYETS 2017-18. They were commissioned with beam during the two first blocks of 2018 MDs (MD#1 and MD#2). More complex configurations were tested in the second part of the year: (i) compensation while reducing the crossing angle (MD#3) and (ii) compensation with trains in a configuration compatible with operation (MD#4).

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1 Introduction

1.1 Motivations

In the LHC and in its future upgrade the HL-LHC [1, 2], the Beam-Beam Long-Range (BBLR) interactions have a detrimental effect on the beam lifetime and represent a major limitation while going towards higher beam intensities. Those effects are well known and they have been observed and studied during the two first runs of the LHC operation [3, 4, 5]. The compensation of this detrimental effect has been under scrutiny for the last 20 years and one of the promising solutions to counteract this problem is the use of compensating DC wires [6, 7].

This solution is now known as the HL-LHC Plan B [8]. During the EYETS 16-17, two prototypes of those Beam-Beam Wire Compensators (BBCW) have been installed in the LHC on Beam 2 (B2), on both sides of the IP5. Those prototypes have been then tested during the LHC Machine Development Program in 2017. The results are reported in [9]. Through these experiments it has been observed that the proposed DC wires can actually improve the beam lifetime, even compensating only the BBLR encounters located in the IR5. During the EYETS 17-18, two additional prototypes have been installed on both sides of IP1, still on B2 [10].

1.2 Experimental setup

In the LHC, the wire prototypes are embedded in the jaws of the B2 tertiary collimators. Since EYETS 17-18 there are, in total, 8 wires installed. Each of those wire collimators contains one wire in each of its jaw. The four wire collimators are listed here after:

- In IR1:
  - TCLVW.A5L1.B2
  - TCTPV.4R1.B2
- In IR5:
  - TCL.4L5.B2
  - TCTPH.4R5.B2.

The location of the wire collimators in the LHC is presented in Figure 1. The wires are installed in the IP crossing plane: 4 wires therefore sit in the horizontal plane in IR5 while 4 others are installed in the vertical plane in IR1.

The details of the technical implementation of the wires into the collimators is reported in [11]. The presence of a wire in each jaw of the collimators allowed the use of two different configurations during the MD program. The first one - called in the following single wire configuration - consists in powering only the *internal* wires as shown on Figure 2a. The second one - called quadrupolar configuration - consists in re-cabling the two wires of the same collimator in series, as shown on Figure 2b. In this configuration, the strength of the

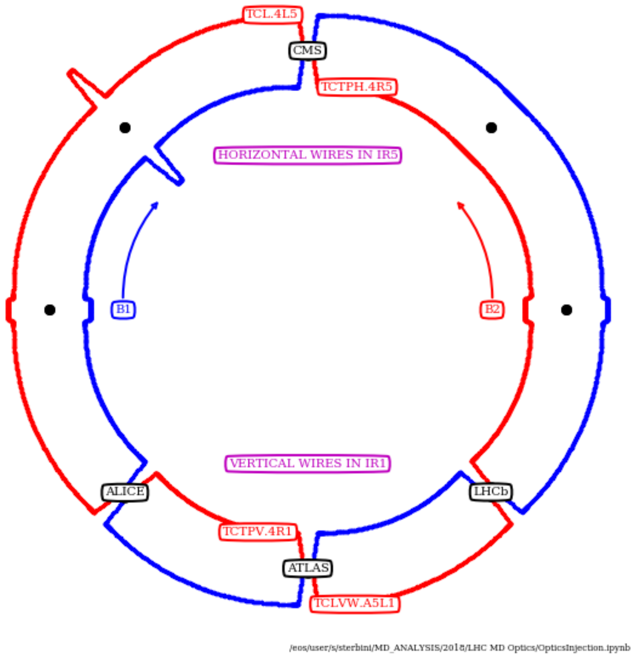
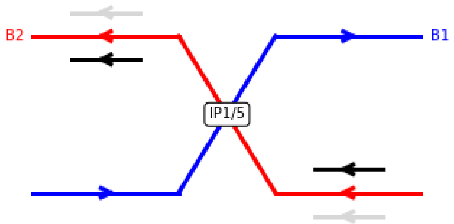


Figure 1: Scheme of the LHC ring with the location of the wire collimators.

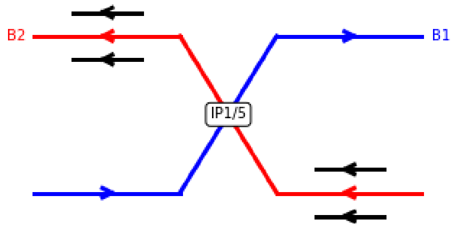
even multipoles (using the European convention, e.g., quadrupolar component) is doubled while the one of the odd multipoles (e.g., dipolar component) vanishes. As shown later, the resonances of interest are mainly the octupolar ones. This configuration has therefore been considered in the last part of the MD program in order to test the wires potential with collimators in their operational settings (half-gap equal to 8.5 σ_{coll}).

1.3 Main objective of the MDs

Despite the fact that different configurations have been tested in the different MD blocks, all the experiments led through the year were purchasing the same goal. In [8], a method for a systematic compensation of the BBLR interaction for HL-LHC is proposed. It is shown that, in a weak-strong approximation, the presence of the strong beam excites some resonances, perturbing the weak beam. As a matter of fact, and since the shape of the kick produced by the strong beam is very similar to a $1/r$ function - given that the beams are separated enough, the resonance driving terms (RDTs) excited by this strong beam are very similar to the ones excited by a wire. In addition in [8] it is therefore shown that there is even an optimal s-position for the wires (corresponding actually to an optimal β aspect ratio) where compensating 2 RDTs (4 by symmetry) leads to the minimization of most of them. This approach is adopted, as starting point, in the constrained context that is the actual



(a) Single wire configuration.



(b) Quadrupolar configuration.

Figure 2: Two different wire configurations were used during the 2018 MD program.

experimental program in the LHC, in order to determine the optimum setting of the wires in order to compensate 2 RDTs, in general the octupolar ones. The locations of the wires in the present LHC do not correspond to the optimal ones to achieve this *optimal* compensation. Moreover, the fact that the wires are embedded in the jaws of collimators adds an extra constraint to the configuration since the transverse position of the wire has to respect the collimation hierarchy. Given those constraints, the goal of the MDs is to power the wires in order to see an improvement of the beam lifetime, in a variety of configurations. The main observable during the experiment is the **effective cross section**, noted σ_{eff}, defined as the proton losses in the unit of time normalized by the luminosity, as written in Equation 1:

$$\sigma_{eff} = -\frac{1}{\sum_{i \in IPs} \mathcal{L}_i} \frac{dN}{dt}, \tag{1}$$

where $\frac{dN}{dt}$ is the loss rate and $\mathcal{L}_i$ is the luminosity at a given IP i .

Starting from a luminosity dominated regime, the idea is to first put the machine in a BBLR dominated regime by blowing up the weak beam, before switching ON the wires to come back to a luminosity dominated regime, as shown on the Figure 3. In terms of figures, when the losses are dominated by the luminosity, the effective cross-section is about 80 mb, corresponding to the total inelastic proton cross-section at an energy of 6.5 TeV. In a BBLR dominated regime, this figure can raise around 160 mb, corresponding to an efficiency of about 50%. The wire compensator is a DC device, therefore the compensation is done in average on the bunch trains, despite the fact that different bunches see different BBLR encounters (BB schedule). The goal is therefore to see an improvement of the effective cross section for a regular bunch (with the highest number of BBLR encounters), without degrading the one of the bunches suffering less BBLR interactions (the so-called PACMAN bunches). To do so, B2 is usually composed by two bunches suffering different number of BBLR interactions. This typical picture, Figure 3, is the one, ideally, to be reproduced during the experiment.

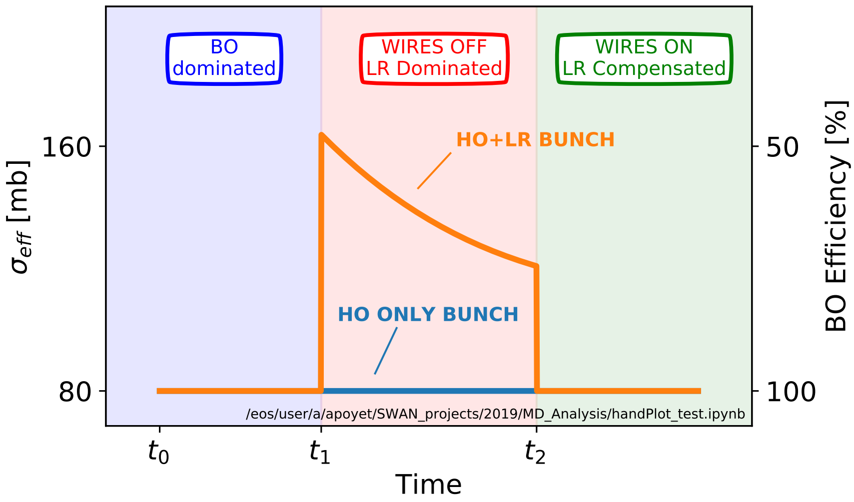


Figure 3: Rationale of the MDs in 2018.

1.4 MD Program 2018

The BBLR experiments took place during the 4 first MD blocks of 2018 [12]. In the following we present the results obtained during those blocks in a chronological way. MD#1 was the first attempt to compensate the BBLR interaction using the recently installed wires in IR1. This MD was jeopardized by stability issues of the Beam 1 during the ramp (unrelated to the wire compensation itself), but allowed the necessary measurements for the collimators alignment. In MD#2, the goal was to reproduce the results of the fourth block of MD 2017 and to explore the potential of the wires in IR1. During MD#3, the goal was to compensate the BBLR interaction while reducing the crossing angle between the beams at the Interaction Point (IP). Finally, before MD#4, the wires were re-cabled in the quadrupolar configuration in order to observe, for the first time, the compensation of the BBLR interaction with trains in a operation-like configuration.

2 MD Preparation

In the following section we will present the details of the necessary commissioning due to the installation of new hardware in the machine, two main points were studied in order to prepare correctly the upcoming MDs.

2.1 Wire settings optimization

As mentioned in the introduction, the beam-wire distance is constrained by the opening of the collimators and therefore depends on the intensity of the beam (at high intensity, $> 3e11$ proton per beam at 6.5 TeV, the collimation hierarchy shall be preserved). On the other hand, one is free to power the four wires independently up to the 350 A, corresponding to the limit imposed by the heating due to the ohmic losses on the wire. Starting from the formalism and the assumptions introduced in [8], it is therefore possible, after having selected the two RDTs to compensate, to compute the needed currents. This is done in the case of the single wire configuration. Figure 4 shows an example of the currents needed in each wires in order to compensate the (4,0) and (0,4) RDTs as a function of the collimators opening (jaw position). The choice of the RDTs to compensate is motivated by the fact that fourth order terms correspond to the first non zero detuning terms that are not self compensated by the alternated crossing angle in the (HL)-LHC. In the case of the quadrupolar configuration, the optimum currents are anyway out of reach by about 30%. Both wires are simply powered up to their maximum current.

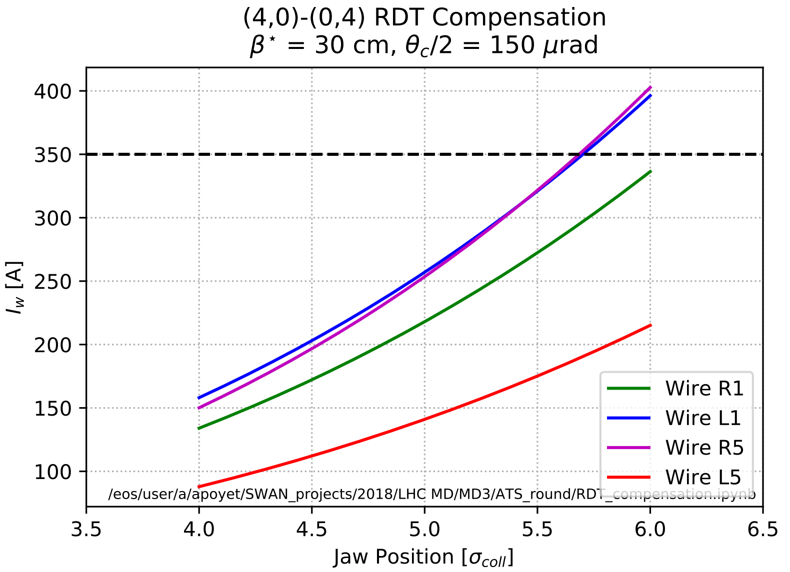


Figure 4: Optimal currents needed in the wires to compensate the (4,0) and (0,4) RDTs as a function of the wire collimators opening.

The mention "coll" refers to the collimation sigma, assuming an emittance of 3.5 μm.

2.2 Feed-forward implementation

For the sake of consistency while powering the wires, it is important to ensure that the machine stays the same from the linear point of view. If the orbit distortion induced by the wires is corrected using the feedback system of the LHC [13], the implementation of a feedforward system is necessary in order to keep the tunes constant. Instead of using the Q-trims as in operation, the quadrupoles Q4 and Q5 are powered with the wires. This provides a local compensation therefore minimizing the induced β-beating.

To do so, one has to provide the strength to apply in the concerned quadrupoles (Q4 and Q5) as a function of the current and the position of the wires. This can be done, for example, using the formula given in [14] giving the tune shift induced by a wire. One can then compute the new strength needed in the two quadrupoles. This strength is proportional to the ratio of the wire current and the square of the beam-wire distance. Following this observations, one can obtain the gradient correction of Q4 and Q5 as a linear function of I_w/d_w^2. Those results were verified using the matching module of MAD-X [15]. During the experiment, the user enters the current and the position of the wire in a graphical application that will control the quadrupoles accordingly.

The implementation of the feed-forward had also to be changed in the case of the quadrupolar configuration: since the strength of this particular multipole is doubled, so is the strength of its compensation. As shown later, this change implied some later experimental validations.

3 MD#1: results jeopardized by the B1 instability after the squeeze

During the night between the 14^{th} and the 15^{th} of June 2018, a block of 12 hours has been dedicated to the BBLR compensation using DC wires. This MD has been composed of 3 different fills, since the two first have been dumped due to instabilities occurring on B1. A fill-by-fill analysis is therefore presently proposed.

3.1 FILL 6797: The first B1 instability

After a pre-cycle, both beams were injected according to an asymmetric filling scheme, as shown on Figure 5. B2 is composed of only three bunches (the pilot is also visible on the plot) in order to be considered as *safe* beam ($< 3e11$ protons at 6.5 TeV). This allows to reduce the wire collimators gap, and therefore, the beam-wire distance. On the other hand, B1 is composed by 3 trains of 48 bunches, a train of 12 bunches and an LHCINDIV bunch.

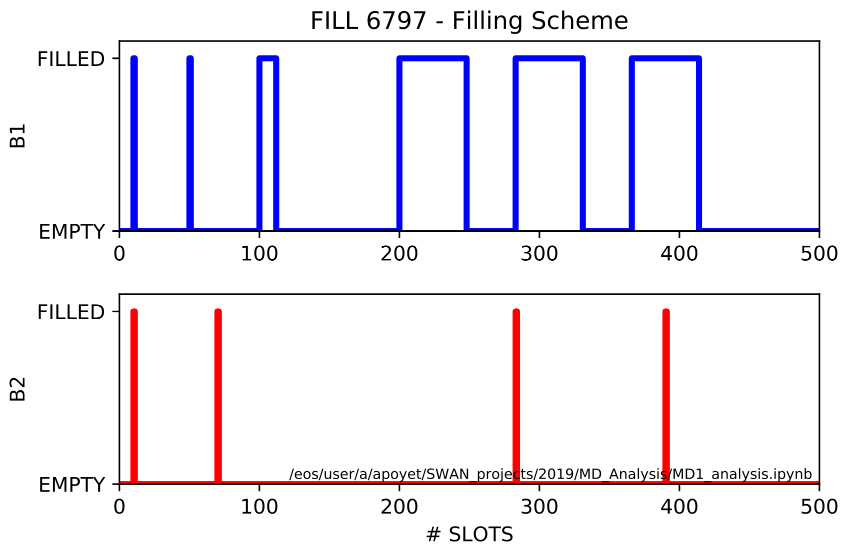


Figure 5: Filling scheme of the Fill 6797.

As seen on the plot, one bunch of B2 is colliding only head-on (HO, bunch 10), one is colliding HO and sees only half the BBLR encounters (PACMAN, bunch 283) and one is colliding HO and sees all the BBLR encounters (regular, bunch 390).

An overview of the fill is given in Figure 6.

As previously mentioned, an instability occurred on B1 right after the squeeze. The octupole currents were increased up to 500 A, but this was not enough to stabilize the beam. The BE-ABP-HSC Instability team concluded that the two tunes approached very close at the end of the collapse, triggering an instability. Given the reduced intensity of B1, it was decided to dump this fill and to re-inject.

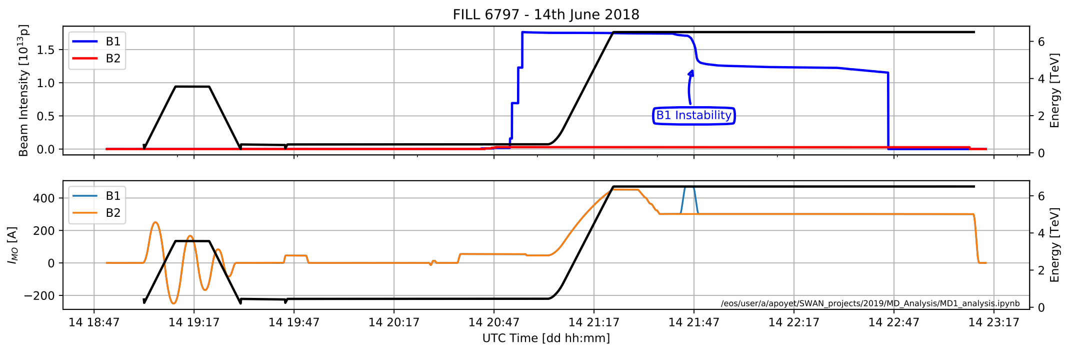


Figure 6: Beam intensities, octupoles and energy during the Fill 6797.

3.2 FILL 6798: The second B1 instability

For the second injection, the chromaticity was increased to 20 and the octupole currents were programmed to reach 500 A at the end of the ramp and to keep this value all along the squeeze. An overview of the fill can be seen on Figure 7.

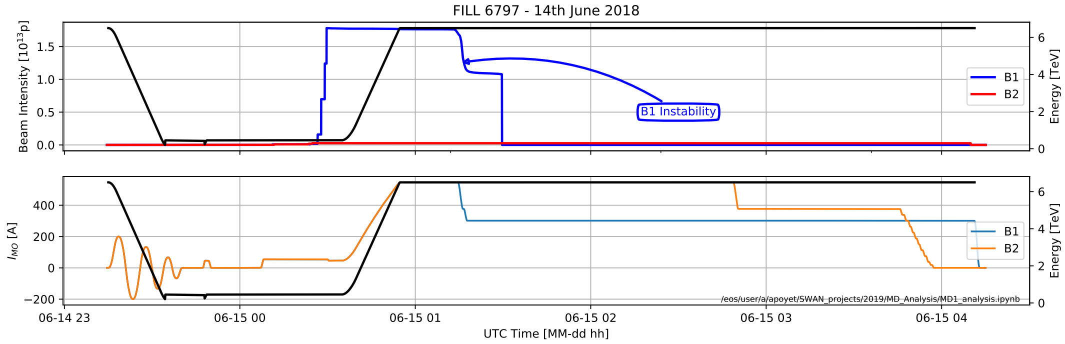


Figure 7: Beam intensities, octupoles and energy during the Fill 6798.

Unfortunately, B1 developed again an instability and was dumped consequently. Nevertheless, the B2 was kept to progress with the compensation preliminary tests. The first one was to measure the misalignment of the recently installed collimator on the right side of the IP1. It was indeed known that the alignment of this particular wire would require an manual intervention in the tunnel after this MD. It was therefore important to measure precisely the wire position (an input for the survey team). To do so, the 5^{th}-axis of the collimator is moved and the BPM reading is plotted as a function of this displacement. Assuming a perfect linear response of the pick-up, this shall give a parabola, whose maximum corresponding to the aligned position of the 5^{th}-axis. Due to the limited range of the 5^{th}-axis movement, a second order fit is necessary to determine the maximum of the parabola. This is shown in Figure 8.

This methods reveals a misalignment of the collimator by almost 2 mm. All the other wire collimators misalignments were measured in order to save time in the next fill during the aligning procedure.

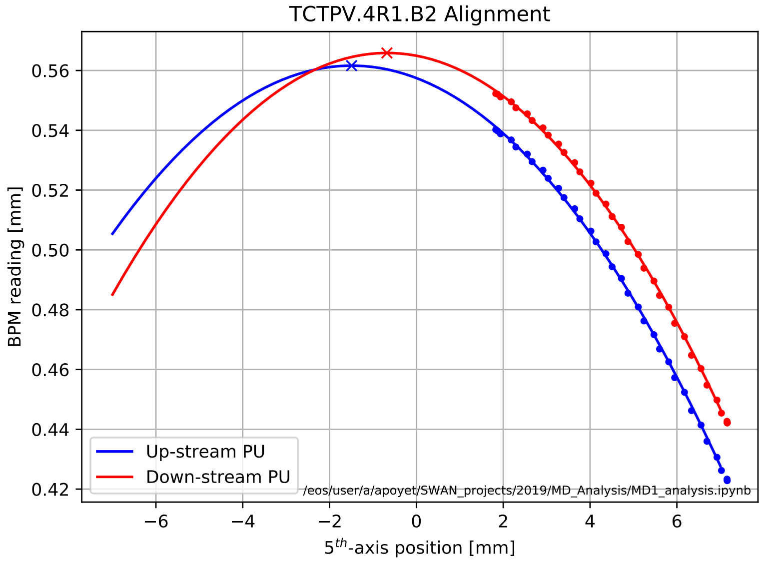


Figure 8: Alignment of the TCTPV.4R1.B2 during the FILL 6798.

3.3 FILL 6799: the B1 was stable

The last fill was the successful one. B1 was indeed kept stable by reducing the bunch intensity of B1 by ∼5-10% and by going back to the filling scheme of the MD#4 2017 (only 2 bunches for B2, see Figure 9).

The last point was probably the reason of the success but the idea was to reproduce exactly the MD#4 of 2017. An overview of this fill is given in Figure 10.

As described in the introduction, before compensating the BBLR interactions, it is necessary to identify their signature. To do so, it is possible to use the transverse damper in order to blow up the bunches of the weak beam. This will modify the distribution of the weak beam, increasing the density of higher amplitude particles. These particles are the ones more affected by the strong beam since during their betatronic oscillation they get closer to the strong beam. Once this was done, and even if a clear BBLR has not been identified, wires have been powered, first separately and then together and the effect on the effective cross-section is reported on Figure 11.

An effect - even unclear - is visible when powering the wires in IR5 or all the wires together. The wires in IR1 appear - as expected, seeing the misalignment of the wire located on the right of IP1 - to be less efficient.

Another interesting observable is the beam lifetime from the Beam Loss Monitors (BLM). Its evolution, for B2, as well as the current in the wires, is plotted in Figure 12.

A slight gain in lifetime is observed using again the wires in IR5 or all the wires together. But, as in the first MDs of 2017, the effect on the lifetime is mostly visible while switching OFF the wires. A drop of lifetime is indeed systematically observed.

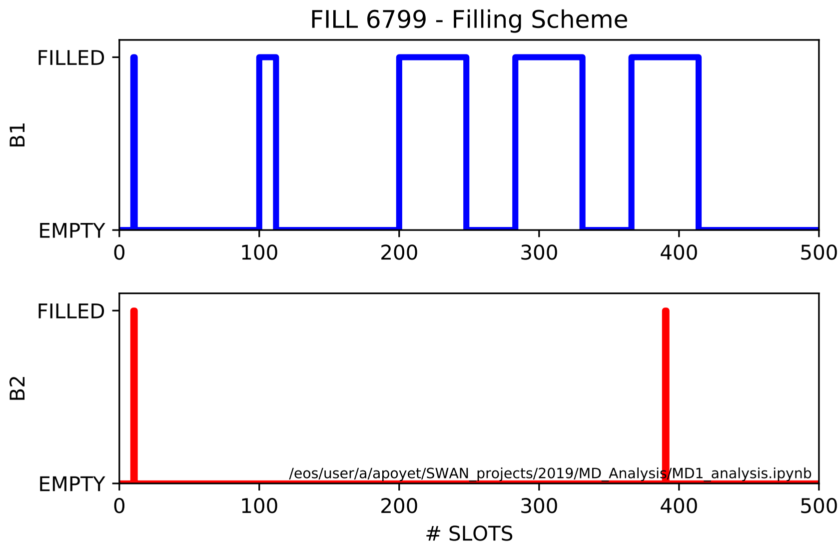


Figure 9: Filling scheme of the Fill 6799.

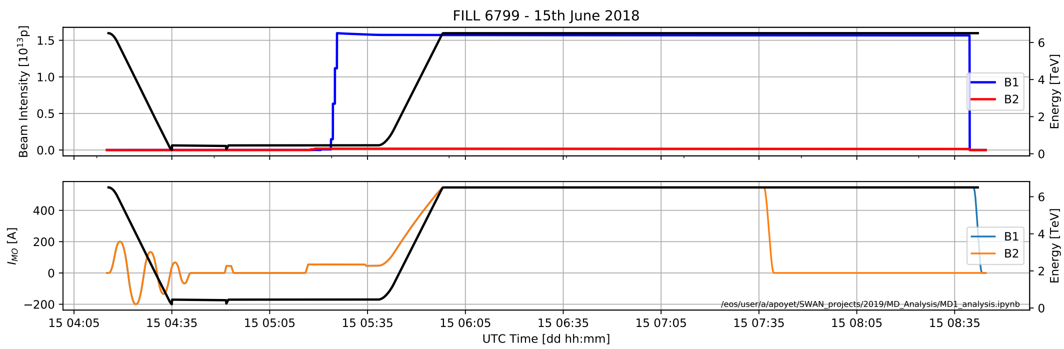


Figure 10: Beam intensities, octupoles and energy during the Fill 6799.

3.4 Conclusions

The first block of the LHC MD program was jeopardized by the instability of B1 after the squeeze. Two fills were dumped as consequence of the B1 instability. During the third fill the B1 was kept stable by reducing its intensity and the wires newly installed in IR1 were powered for the first time at flat top. However, mostly due to the limited time, the beam-beam regime could not be established and therefore the effect of BBLR compensation could not be conclusive.

The second fill allowed to measure the TCTPV.4R1.B2 misalignment, as a preparation for the tunnel intervention that took place during the Technical Stop #1.

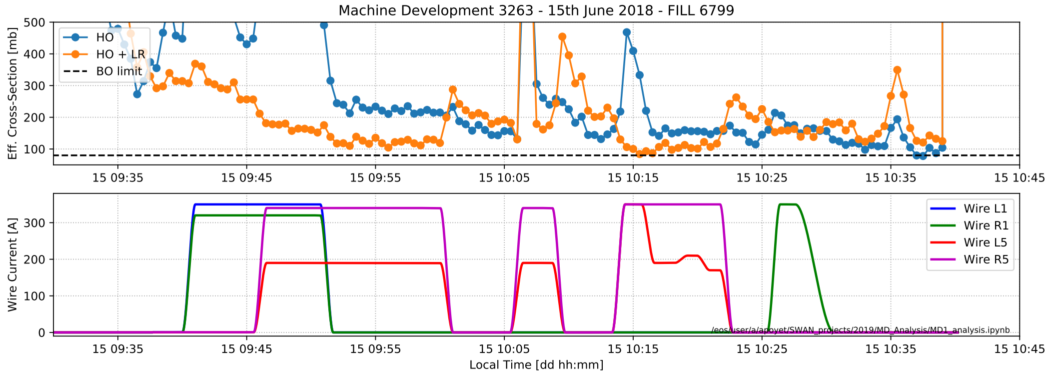


Figure 11: Effect of the wires on the effective cross-section of the two bunches of B2 during the fill 6799.

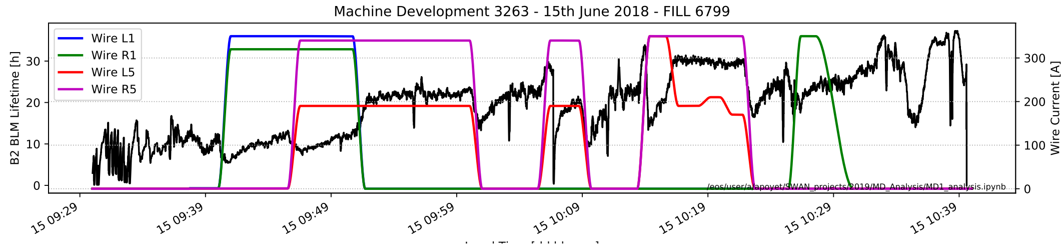


Figure 12: Effect of the wires on the BLM lifetime of B2 during the fill 6799.

4 MD#2: clear compensation result

Following the disappointing absence of results during the MD#1, the adopted strategy for the second block of experiments was to work at reduced intensity, in order to ensure the stability and the success of the experiment. In that context, 8 hours were dedicated to the experiment on the 24^{th} of July 2018. The main concern was to avoid the development of instabilities in B1. For that reason, the bunch intensity of B1 was reduced down to $1.05 \cdot 10^{11}$ p. As during the last fill of the MD#1, the octupole currents were programmed to reach their maximal value at the end of the ramp, and to keep this value during the squeeze and in adjust mode, as shown on Figure 13. For the same motivations, the filling scheme was the one used in the last fill of the MD#1, shown in Figure 9.

with the reduction of intensity of B1, we managed to keep it stable, apart from one single bunch. The vertical emittance of this bunch, located at the end of a train, indeed blew-up after it started to oscillate in the horizontal plane. The bunch-by-bunch intensity evolution for both beams is shown in Figure 14.

Concerning B2, as requested, the intensities were slightly higher than the bunches if B1. However, the first bunch of B2 became unstable during the squeeze even though the octupoles were set to their maximum strength. Its emittance reached $\sim$10 μm and the associated losses are clearly visible on Figure 14. The choice to keep this fill instead of dumping and requesting a fresh beam was motivated by the unavailability of the injectors at that moment. In order to make possible the comparison between the two bunches in

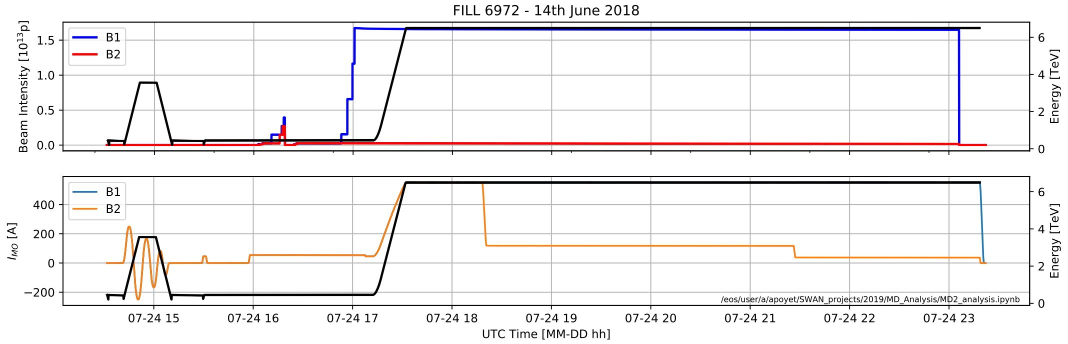


Figure 13: Beam intensities, octupoles and energy during the Fill 6972.

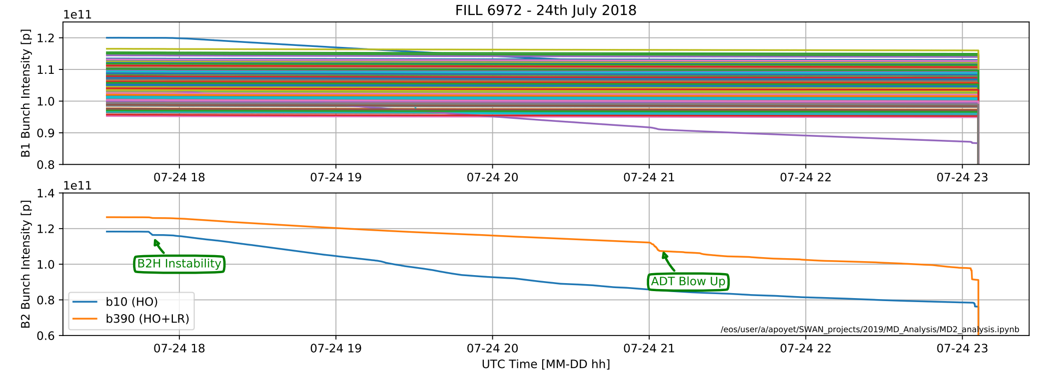


Figure 14: Bunch-by-bunch intensities evolution during the Fill 6972.

terms of luminosity (and therefore, in terms of effective cross-section), the second bunch was blown-up using the transverse damper was as shown on Figure 14.

After the blow-up, the signature of the BBLR interactions could be identified and the compensation using the wires was therefore visible in terms of effective cross-section. In Figure 15, one can indeed observe that the wires worsen the lifetime of the bunch colliding Head-On only while observing a clear improvement of the lifetime of the bunch suffering the BBLR interactions. Moreover, during the MD the contribution of the IR1 and IR5 wires was studied. As already shown during the last MD of 2017, the wires in IR5 are very efficient. Nonetheless, the new wires installed in IR1 are also working, even though they are less effective. The partial alignment performed during the Technical Stop #1 has been beneficial. A residual misalignment of ∼0.8 mm could not be corrected to due mechanical interference between the collimator and the B1 vacuum chamber.

The results obtained during the MD#2 block of experiment confirmed that the LHC was equipped with a set of four functional Beam-Beam Long-Range Wire Compensators. This opened the possibility for exploring new configurations.

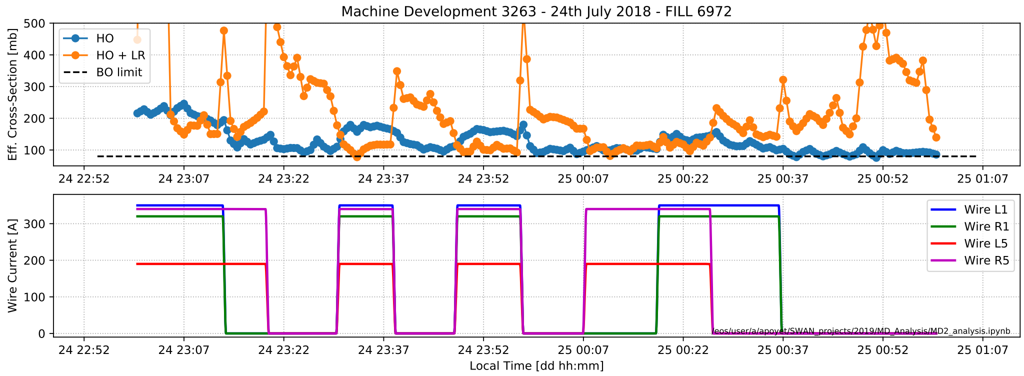


Figure 15: Bunch-by-bunch effective cross-section evolution for B2 during the Fill 6972.

5 MD#3: Compensation versus crossing angle

On the 14th of September 2018, the wire team had the chance to test the compensation in a different configuration. The main goal of the MD#3 experiment was indeed to observe the compensation of the BBLR interaction while reducing the crossing angle. In this process, the wire currents and the beam-wire distance are not dependant on the crossing angle but wire collimators jaws followed the B2 closed orbit, being part of the so-called crossing angle orchestration [16].

Figure 16 gives an overview of the experiment led during the third block of MDs 2018.

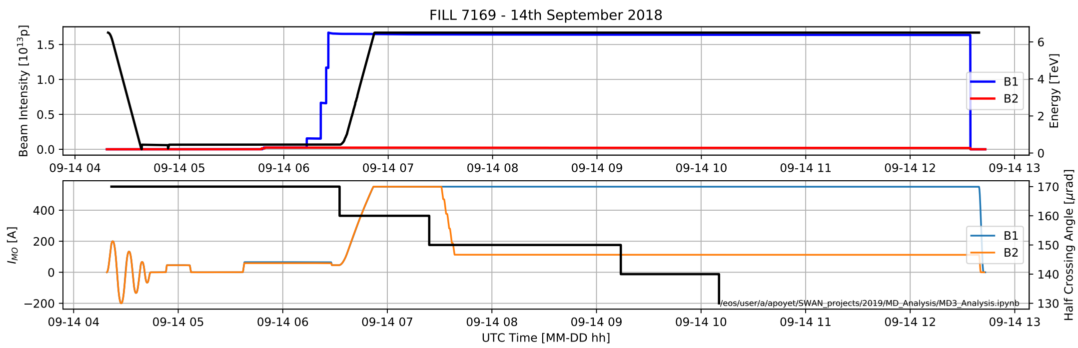


Figure 16: Beam intensities, octupoles and energy during the Fill 7169.

As in the previous MD, the filling scheme was the one presented in Figure 9. Issues with the BPM masking procedure and with the SPS availability, delayed the injection. The two beams were then brought to flat-top energy, squeezed and put in collision. A single bunch of B1 became slightly unstable, with ~0.5 % losses observed. The crossing angle has then been reduced to 150 μrad, defining the starting point of the experiment. After the alignment of the wire collimators was done, the decision was taken to blow-up the two bunches of B2 in order to identify the BBLR signature. In that purpose, the emittances of those bunches were increased up to 3.8 μm in the horizontal plane, and 4 μm in the vertical one. The effect of the wires on the effective cross-section of the two bunches of B2 is then reported in Figure 17.

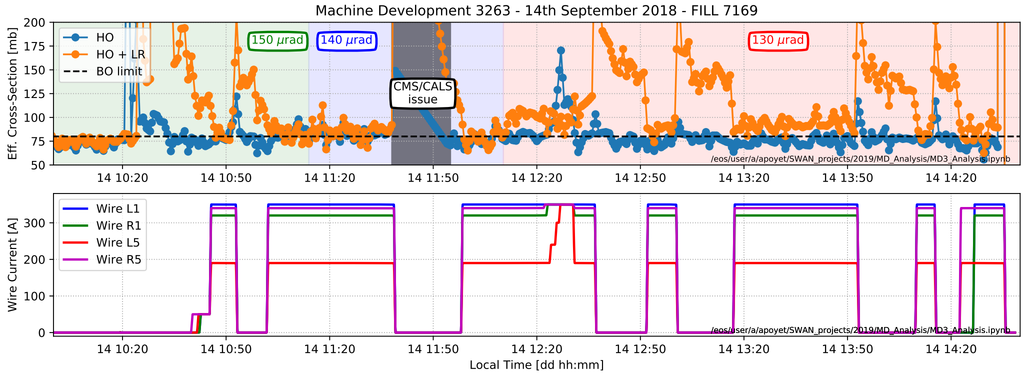


Figure 17: Bunch-by-bunch effective cross-section evolution for B2 during the Fill 7169.

The beneficial effect of the wires is again clear from the first ON/OFF cycle: the effective cross-section of the bunch suffering the BBLR is reduce down to the level of the one of the bunch colliding HO only. After some systematic ON/OFF cycles, the crossing angle was reduced down to 140 μrad with the wires switched ON. Even after optimizing the luminosity no additional losses were observed: the compensation was still efficient. The wires were then switched OFF in order to observe an increase of the losses. Unfortunately an issue in the luminosity data logging prevented for few minutes a correct observation of the effective cross-section. Switching the wires ON again showed back a compensation regime. The crossing angle has then been reduced down to 130 μrad, region where the BBLR interaction induces generally high losses [17] and a DA reduction [18]. A slight increase of the losses is indeed observed, but this increase became much worse when switching OFF the compensation. Switching ON the wires allowed to recover an almost perfect compensation with an effective cross-section observed to be around 90 mb.

As last step of this MD, the goal was to squeeze with the compensation ON down to 25 cm. Unfortunately, the β-squeeze application could not perform the needed trim because of the values in the quadrupoles Q4/Q5 were not the ones of the nominal sequence (due to the tune feedforward). This MD has therefore been completed with additional of ON/OFF cycles with the wire collimators opened at 6 σ_{coll}, still observing a partial compensation.

As a conclusion, the third block of MD was successful for the compensation.

6 MD#4: Getting closer to an operational scenario

As last step of the LHC MD program 2018, MD#4 was dedicated to the study of a possible compensation of the BBLR interactions in an operation-like configuration. The goal of this MD was to power the wires with B2 being composed of trains, adapting therefore the measurement protocol to the machine protection constraints. The main modification concerns the opening of the wire collimators. From the 5.5 σ_{coll} half gap of the previous MDs, the collimators were opened up to 8.5 σ_{coll} (2018 operational configuration). This implies that the currents needed to achieve the compensation of the octupolar RDTs are not reachable anymore using the previous single wire configuration of the wires. As mentioned in the introduction, a re-cabling of the wires took place in between the two last MD blocks (Technical Stop #2). This doubles the strength of the even (e.g., quadrupolar term) multipoles while cancelling the strength of the odd (e.g., dipolar term) ones.

Such a configuration was never tested during the commissioning of the machine and therefore needed a validation fill.

6.1 FILL 7385: Validation at injection energy

The first step of the MD was to test the new setup at injection energy, especially in order to check the good polarity of the wires after the re-cabling. A single LHCINDIV bunch per beam was injected in order to validate the new powering, before injecting a second bunch for B2, and trains for B1 as shown in Figure 18. The filling scheme is given on Figure 19.

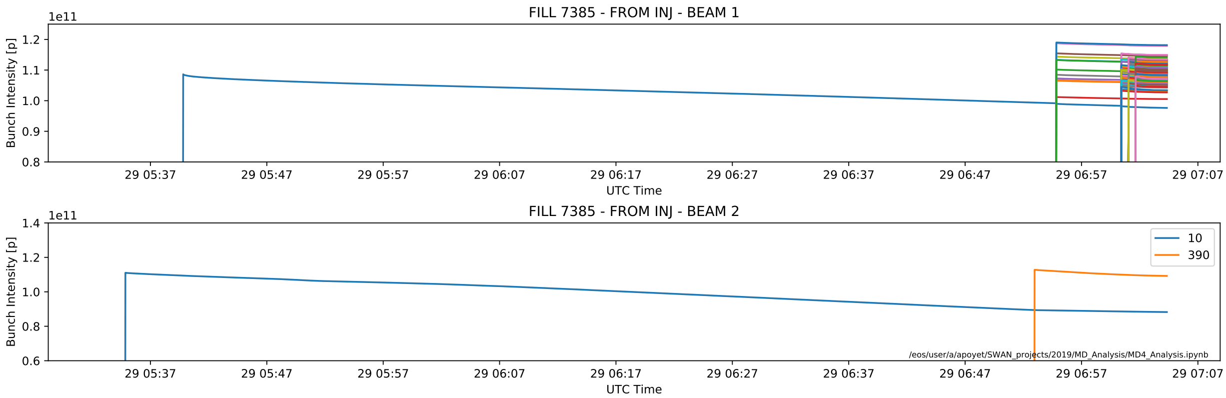


Figure 18: Bunch-by-bunches intensities of the two beams at injection energy during the fill 7385.

The polarity of the wires was validated by monitoring their effect on the tunes. This is summarized in Figure 20.

Even though only the wires located on the right side of the IPs were used during the MD (the left ones being too far), all of the wires were tested since all of them were re-cabled during the technical stop. As expected, the wires in IR5 induce a negative horizontal tune shift when powered with positive current while the ones in IR1 induce a negative vertical tune shift when powered with a positive current.

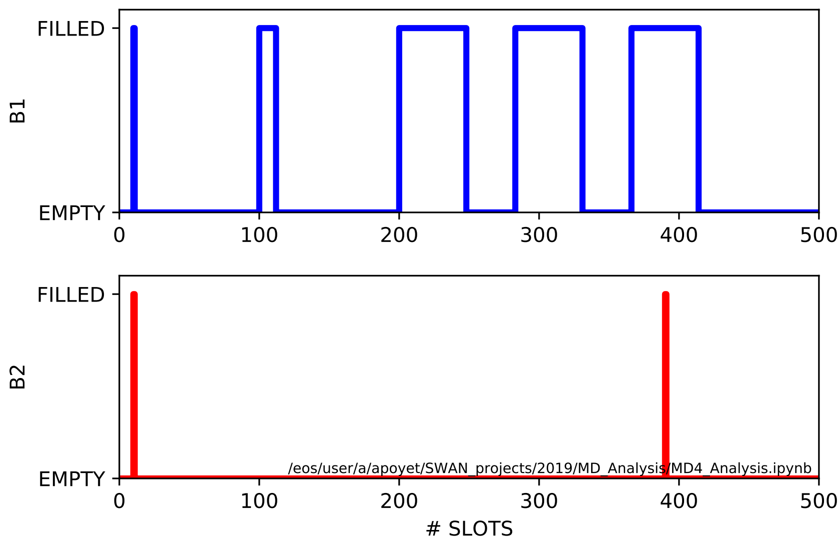


Figure 19: Filling scheme of the Fill 7385.

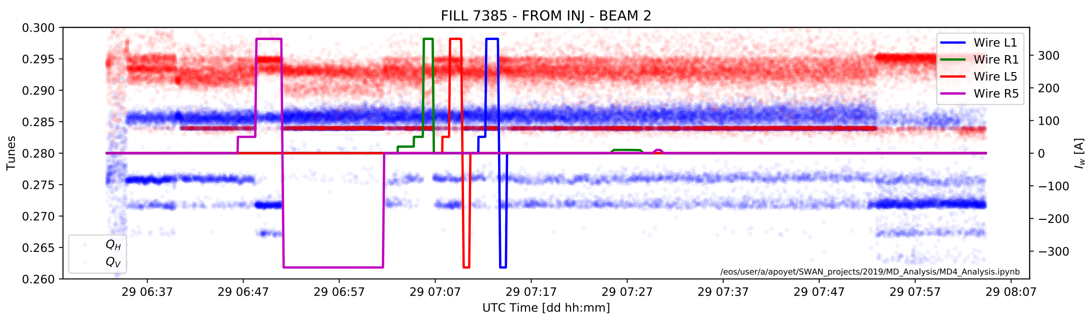


Figure 20: Effect of the wires on the tunes at injection energy during the fill 7385.

6.2 FILL 7385: Validation at flat top energy

Once the usual asymmetric filling scheme was injected (see Figure 19), the machine was ramped-up to flat top energy and the wires on the right side of each IP were powered in order to validate the proper functioning of the feedforward implementation. The feedforward is optics dependant and therefore requires to be tested at flat top energy. The re-cabling indeed implied a modification of how the quadrupolar effect of the wires is compensated using the Q4 and Q5 quadrupoles. Since the strength of the quadrupolar component of the field is doubled, so is its compensation. The current needed in the quadrupoles to reach this strength are higher that the margins allowed in operation. Those margins have therefore been increased before the MD: a check was therefore required to make sure the new margins were effective and that the feed-forwards was working correctly. Figure 21 shows the evolution of the currents in the Q4 and Q5 quadrupoles as a function of the wire currents.

The feedforward system reacted as expected. Once those checks were completed, the beams were dumped and the machine was prepared for a new injection.

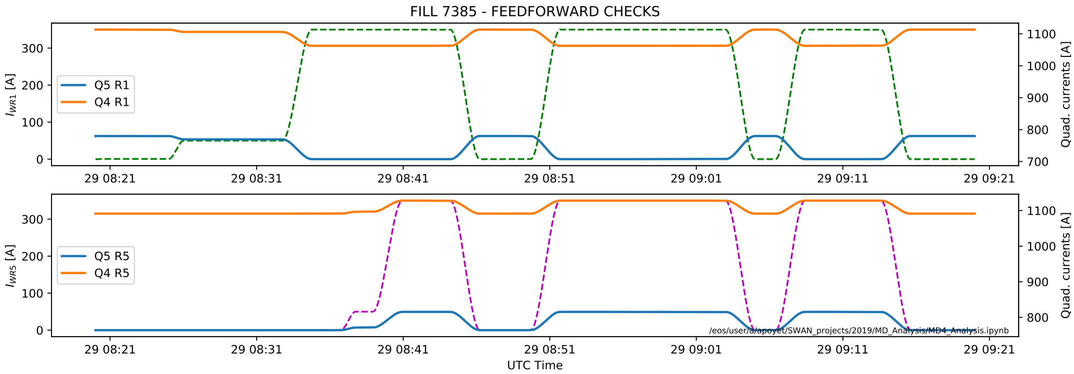


Figure 21: Q5 and Q6 (R1 and R5) currents evolution as a function of the wire currents at flat top energy during the fill 7385.

6.3 FILL 7386: BBLR compensation with trains

For this fill, symmetric beams were injected. As shown in Figure 22, B1 was indeed composed of three trains, as B1. The *safe beam* flag could not be applied anymore and the collimator jaws were therefore set to their operational position (8.5 σ_{coll}). This is the main reason why only two wire collimators were actually used during this experiment. The two sets of wires located on the left side of each IP were too far ($d_{beam-wire} > 15$ mm) from the beam to expect any visible effect.

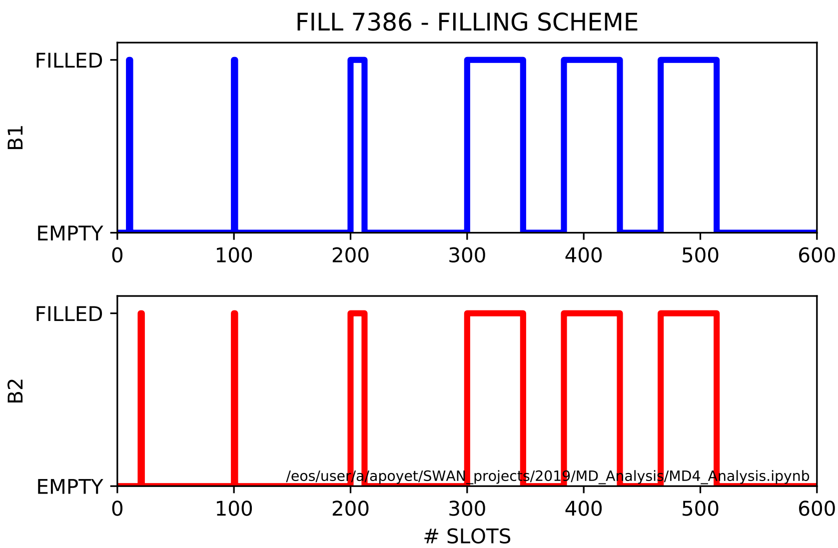


Figure 22: Filling scheme of the Fill 7386.

An overview of the fill is visible in Figure 23. For this fill, the octupoles settings were the one used in operation. The fact of using a symmetric filling scheme was enough to ensure the stability of both beams (as during the standard operation fills).

Once the beams were brought in collisions, the wires were powered, and the effective

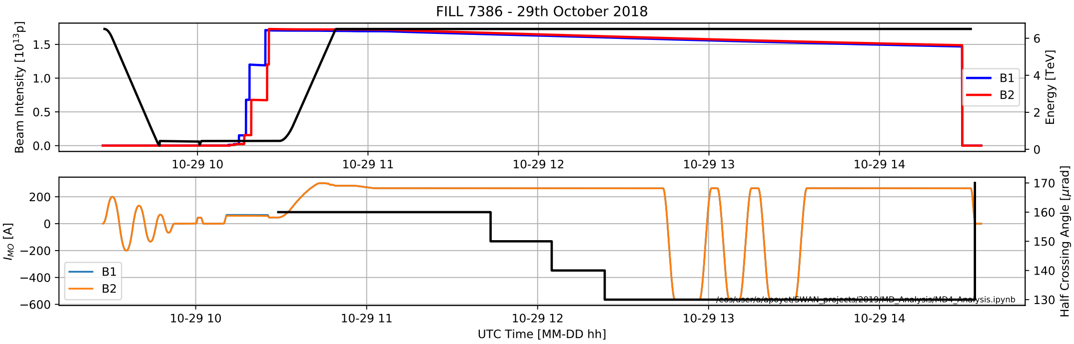


Figure 23: Beam intensities, octupoles, crossing angle and energy during the Fill 7386.

cross section monitored. The evolution of the effective cross-section for the bunches of the first train of B2 is shown in Figure 24.

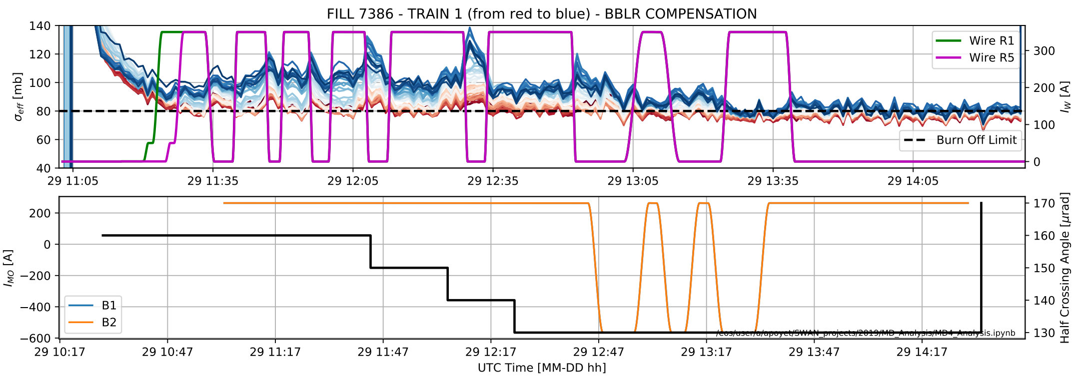


Figure 24: Effect of the wires on the bunch-by-bunch effective cross-section of the first train of B2, in collisions, during the fill 7385. The bunches position in the train is color-coded (reddish bunches are at the head of the train while blueish ones at its tail).

The variation of losses among the train looks typical for an electron cloud dominated regime [19] with the bunch at the tail of the train suffering more than the ones at the head. Moreover the pattern is quite similar for the three trains of B2, as shown on the Figure 25.

The effect of the wire is less visible, as expected, than in the previous experiment but the wires allow a reduction of the crossing angle without any significant increase of losses. Nonetheless the effect of the wire is clearly visible on the BLM losses. Figure 26 shows the evolution of the losses recorded by the Beam Loss Monitors (BLM) for the two beams.

The compensation of the BBLR using wires can provide a reduction of the losses on B2 by $\sim$20%.

Finally, it is also possible to visualize the effect of the wires on the bunch-by-bunch losses using the new devices implemented in the LHC: the so-called diamond BLM (dBLM) [20]. Those devices provide bunch-by-bunch losses data. It is therefore possible to obtain similar plots as in Figure 24 or Figure 25, but visualizing directly the losses instead of computing an

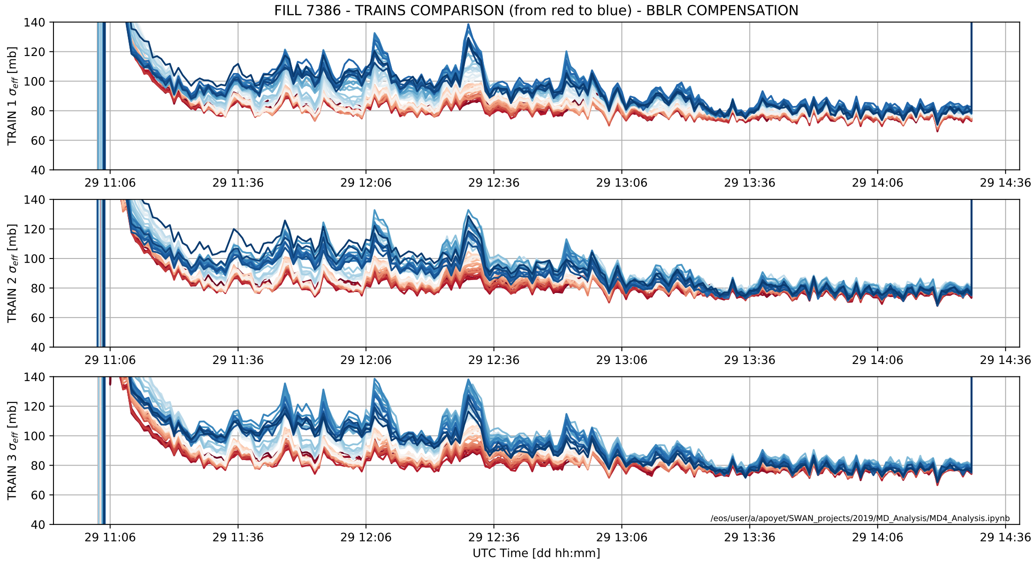


Figure 25: Comparison of the effective cross-section between the three trains of B2 during the fill 7385.The bunches position in the train is color-coded (reddish bunches are at the head of the train while blueish ones at its tail).

observable that depends on several parameters. The evolution of the losses of the bunches among the first train of B2 is given in Figure 27.

The effect of the wires is still slightly visible, with a reduction of the losses observed when the wires are powered. One can again observe the electron cloud pattern among the train, with the bunches located at the end of the train suffering more than the ones located at the beginning. This result is particularly reproducible among the different train of the beams, as shown on the Figure 28.

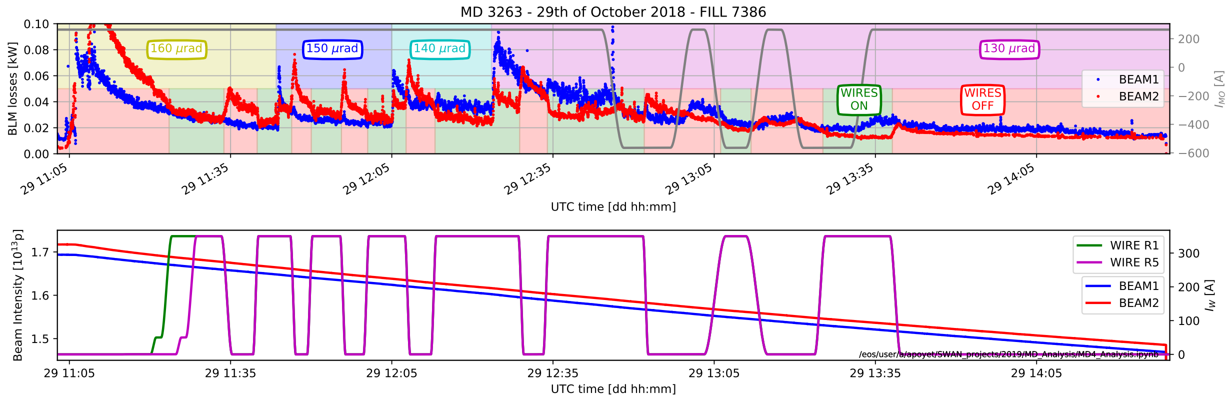


Figure 26: Effect of the wires on the BLM losses for both beams during the fill 7385.

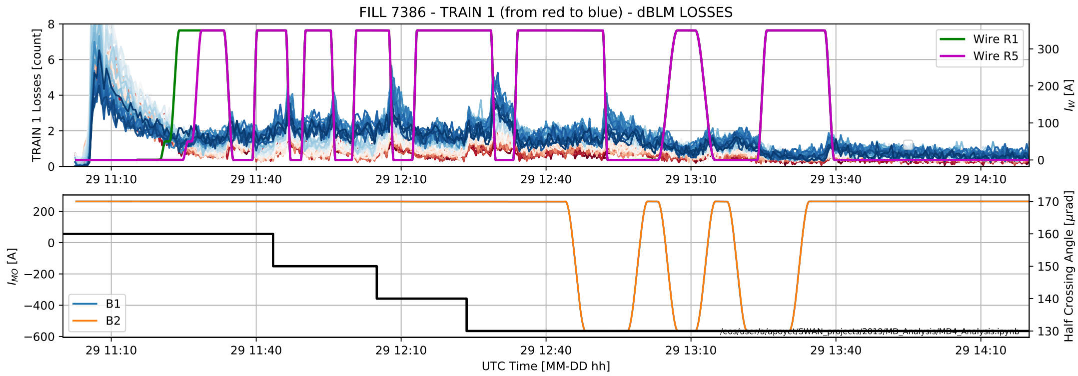


Figure 27: Effect of the wires on the bunch-by-bunch losses of the first train of B2, in collisions, during the fill 7385. The bunches position in the train is color-coded (reddish bunches are at the head of the train while blueish ones at its tail).

7 Conclusions

The LHC MD Program of 2018 has been successful for the Beam-Beam Wire Compensators. After the installation of new prototypes during the EYETS 2017-2018, they have been commissioned and have shown a potential even though less efficient than the wires installed in IR5.

During the first block of MD, the new prototypes were tested for the first time. Unfortunately, instability issues on B1 forced the experiment to be shorter than expected. Nevertheless, the B2 was used to measure the misalignment of the newly installed wire collimator in view of an intervention that took place after the first MD block.

With the re-alignment done, MD#2 was the first observation of the BBLR compensation in the LHC using a set of four functional wires. Despite an instability occurred on B2 (not related to the compensation), the potential of the wires was observed on the bunch-by-bunch effective cross-section.

During the third MD block, the effect of the wire compensation was successfully tested by reducing the crossing angle. With the compensation ON a gain of 10-20 μrad is observed.

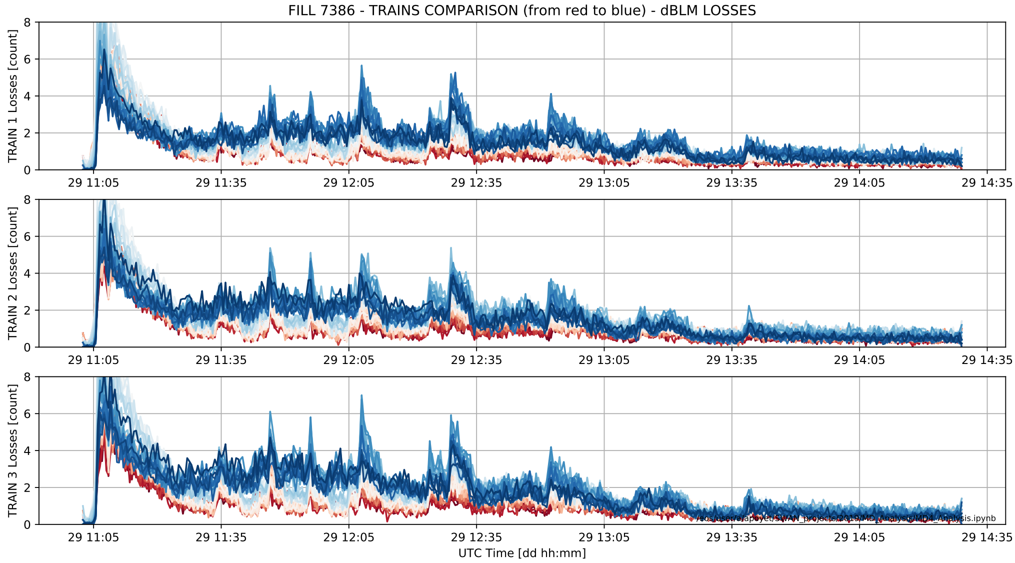


Figure 28: Comparison of the bunch-by-bunch losses between the three trains of B2 during the fill 7385. The bunches position in the train is color-coded (reddish bunches are at the head of the train while blueish ones at its tail).

Eventually in the last MD block, after re-cabling the wires into the so-called quadrupolar configuration, the BBLR compensation has been observed for the first time using trains for B2. This represents a milestone for the wire compensation since it shows that the wires can still be efficient even though they are far from the beam, as in operation with the present wire demonstrators.

Those four experiments, combined with the successful program of MD 2017 open the way to a possible implementation of the wires in operation during the Run III of the LHC. To do so different options are under scrutiny. The idea is to move two of the four wire collimators on B1 and to gain experience in operation in view of the possible implementation of the wires in the HL-LHC.

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