HOW TO OBTAIN CLEAN INJECTIONS

W. Bartmann, F. Burkart*, T. Bohl, C. Bracco, B. Dehning, L. Drosdal, V. Kain,
M. Meddahi, R. Steerenberg, O. Stein, F. Velotti, CERN, Geneva, Switzerland

Abstract

During 2015, injections of 144 bunches into the LHC induced losses of up to 93 % of the dump thresholds on the TDI BLMs. During run 2 these losses were studied in greater detail with diamond based particle detectors. It was found that the main loss contribution is due to ghost bunches, originating from the SPS, swept over the TDI during the rise and fall time of the injection kicker magnet MKI. This contribution will summarize the measurement results (transversal and longitudinal losses) in comparison to run 1. In addition, possible loss mitigations, already applied for a first time during an MD, will be discussed in view of injections of 288 bunches planned for operation in 2016.

LOSSES DURING RUN 2

During 2015, injections of 144 bunches into the LHC induced high losses at the TDI. This has to be compared to run 1, where 288 bunches were injected with a factor 25 smaller loss level at the TDI. In addition, the losses during the injection process of 144 bunches in run 1 were dominated by transfer line showers.
The measured losses reached between 30 and 93 % of the dump threshold for Beam 1 and 10 to 60 % for Beam 2. The difference in loss amplitude is induced by the different rise time of the SPS extraction kickers (MKE) in LSS4 (Beam 2) and LSS6 (Beam 1). The rise time of MKE.6 is ~ 6 μs, whereas MKE.4 has a rise time of ~ 1 μs. The measured loss signals from the BLMs installed at the TDIs for running sum 1 (40 μs) is shown in Figure 1.

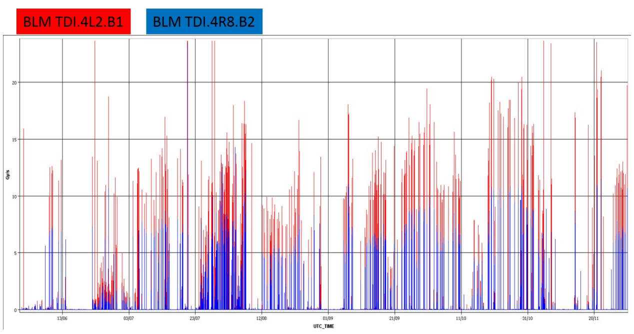

Figure 1: Loss signals during 2015 run measured with the BLMs at the TDIs in IR2 (red) and IR8 (blue). The difference in the signal amplitude can be explained by the different rise times of the extraction kicker magnets MKEs in LSS4 (1 μs) and LSS6 (6 μs).

TRANSVERSAL LOSSES

Orbit drifts and shot-to-shot trajectory variations

During run 1 orbit drifts and shot-to-shot trajectory variations in the transfer lines TI2 and TI8 were observed. Detailed studies using Model Independent Analysis (MIA) revealed that the extraction septas (MSE) in LSS4 and LSS6 are the main source for both lines. End of 2011 work was started to improve the stability of the power converter of MSE.6. During LS1 this work was continued at the MSE.4. The results of the MIA for the transfer lines before (April 2012) and after (November 2014) the investigation is shown in Figure 2 and Figure 3. In TI8 the strength of the normalized eigenvalue for the MSE was reduced from 73 μm to 42 μm, for TI2 it was improved from 86 μm down to 39 μm [1].
The source of orbit instability in the SPS is still under investigation. At the end of 2015 almost 1000 extraction orbits were saved and analyzed. The analysis showed that an orbit drift at the BPCE4 can be observed. The source of the orbit variations was found to be a main bend field variation in the area of MBA.11190 in LSS1. More measurements are needed to study the field variation and a possible correlation between temperature and orbit drift in greater detail [2].

Transfer line collimator settings

The initial settings of the transfer line collimators (TCDIs) were at 4.5 nom. sigma. This was increased in 2011 to 5 sigma due to the available aperture in the LHC. This will be re-measured after the christmas stop YETS 2015/2016.

MKE waveform measurements

During LS1 the waveforms of the SPS extraction kickers in LSS4 and LSS6 were measured. The results are shown in Figure 4 and Figure 5. The flatness of the MKE.4 waveform was improved and the overshot in the first part after the rise was reduced. The delay for the first bunch was optimized to 48.1 μs. The MKE.6 waveform is flat and the delay was set to 38.5 μs. During the YETS 2015/2016 the MKE.4 generators will be modified and a comparable waveform as for MKE.6 is expected. This will be re-measured during the commissioning in 2016.
The transversal losses are well understood, the MSE ripple was reduced, the delay for the first bunch on the MKE waveform was optimized. Nevertheless the losses at the TDIs increased.

LONGITUDINAL LOSSES

It was expected, that the high losses observed in 2015 are caused by longitudinal losses, therefore the injection losses

* florian.burkart@cern.ch

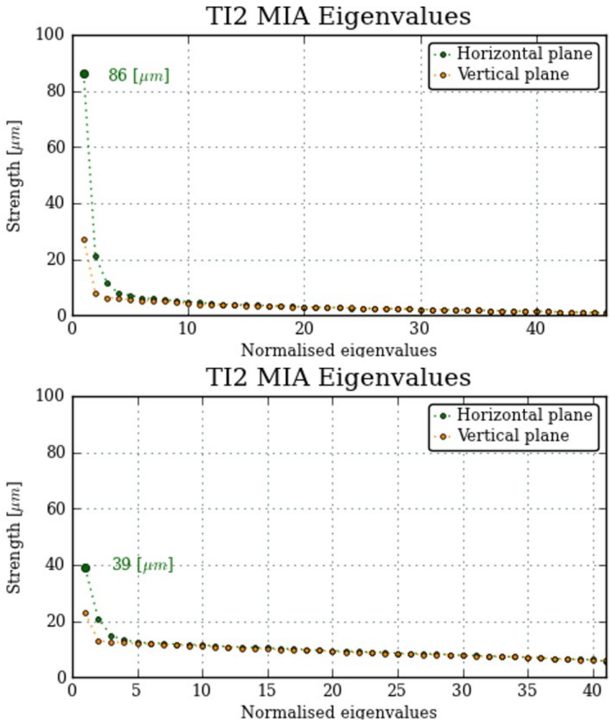

Figure 2: Results of the Model Independent Analysis (MIA) from April 2012 (top) and November 2014 (bottom). The plot shows the normalized eigenvalues for the horizontal and vertical plane and the corresponding strength. The strength of the septa point could be reduced from 86 to 39 μm. This was done in 2011 by improving the stability of the septa power converters.

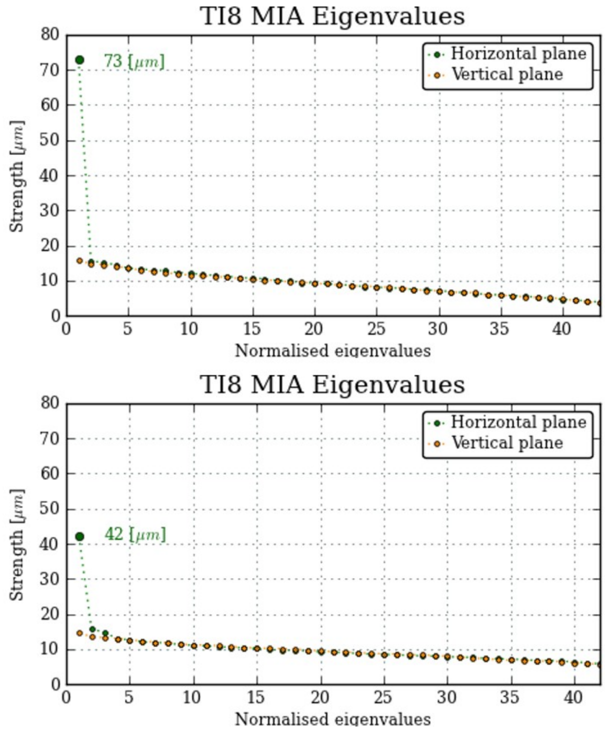

Figure 3: Results of the Model Independent Analysis (MIA) from April 2012 (top) and November 2014 (bottom). The plot shows the normalized eigenvalues for the horizontal and vertical plane and the corresponding strength. The strength of the septa point could be reduced from 73 to 42 μm. This was done during LS1 by improving the stability of the septa power converters.

were measured and studied for the first time with diamond based beam loss monitors (dBLMs).

Diamond based beam loss monitors around LHC

dBLMs with their nanosecond time resolution, radiation hardness and high dynamic range over 8 orders of magnitude in measurable losses can be used to obtain bunch-by-bunch loss data, in addition, they were used to study ghost bunches and RF-recapture during the injection process. 9 dBLMs are already installed along the injector chain. They are used to:

- Measure extraction losses at the PS, installed downstream to septum MU16.
- Measure extraction losses at the SPS, installed at the TPSG TI2 and at the septum TI8.
- Measure injection losses at LHC, installed in IR2 and IR8, downstream of the TDIs.
- Measure global losses and post-mortem event recordings in left and right IR7, downstream of the TCPs.
- Measure extraction losses at LHC installed in IR6, downstream of the TCDQs.

Currently three different read-out systems are used, an OASIS oscilloscope in the PS, oscilloscopes in the SPS and the LHC and a ROSY read-out system from CIVIDEC in IP7.

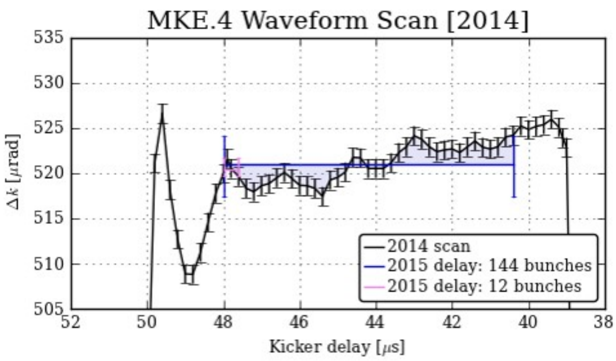

Figure 4: Measured waveform of MKE.4. The waveform was improved during LS1 and a optimized delay for the first bunch of 48.1 μs was set.

Measurement results

During 2015, the beam losses at the TDIs were measured with dBLMs installed downstream of the TDI tank in IR2 and IR8 [3]. The comparison of the measurement results for Beam 1 (blue) and 2 (red) are shown in Figure 6. The amplitude of the signal is not directly comparable as the dBLM are not installed symmetrically around the TDIs. The first part of the loss signal (till ~5800 ns) is produced by particles impacting on the TDI with full impact

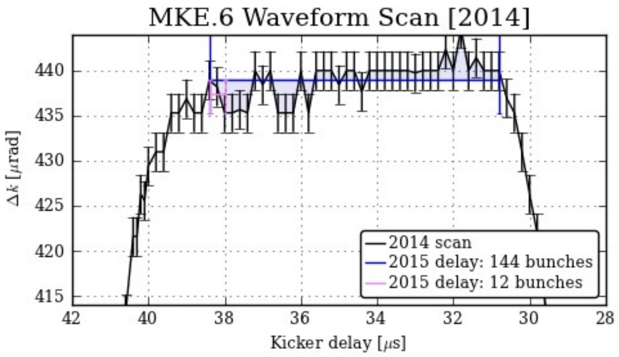

Figure 5: Measured waveform of MKE.6. The waveform is flat and a optimized delay for the first bunch of 38.5 μs was set.

parameter (MKI not yet fired) after passing the shadow of the TCDIs. The effect of the different MKE risetimes in LSS4 (~ 900 ns) and LSS6 (~ 6000 ns) in clearly visible in the length of the loss plateau.
In the second part (~ 5800 ns to ~ 6700 ns) the MKI field rises and moves particles from full impact parameter on the TDI via grazing impact (rising edge in the loss signal) on the TDI jaw to the closed orbit in the LHC (falling edge in the loss signal). This part directly shows the rise time of the MKI with 900 ns. These measurements showed that the losses occurred with a 5 ns structure, directly pointing to particles, also called ghost bunches, re-captured by the 200 MHz RF structure of the SPS. As an example a zoom into the loss pattern is shown in Figure 7.

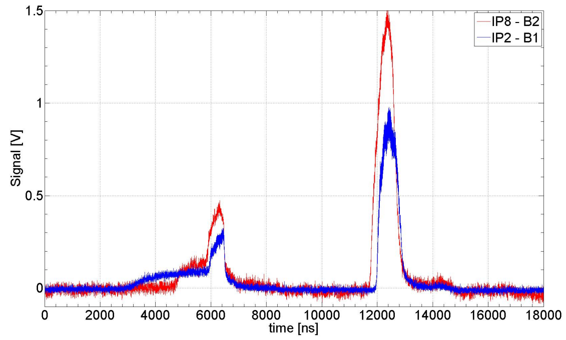

Figure 6: Measured signals of a dBLM for the injection of 144 bunches in Beam 1 (blue) and Beam 2 (red). 4 different parts of the loss signals can be identified, first part till ~ 5800 ns: MKI off, ghost bunches hit the TDI with full impact parameter. Second part till ~ 6700 ns: rise time of the MKI (900 ns), ghost bunches are swept over the TDI. Third part till ~ 12000 ns: MKI flat top, LHC bunches are properly injected. Fourth part till ~ 14000: fall time of the MKI, ghost bunches behind the LHC bunches are swept back over the TDI.

The third part of the loss pattern (till ~ 12000 ns) corresponds to the MKI flat top, in this area the nominal LHC

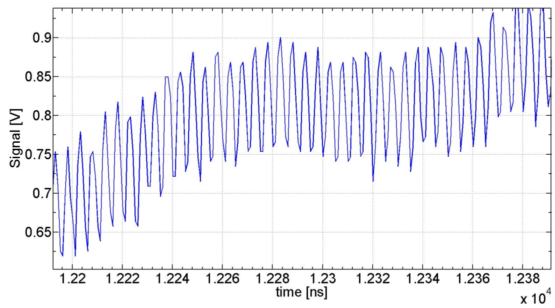

Figure 7: Zoom into the loss signal. The losses occurred with a 5 ns structure, directly pointing to particles re-captured by the 200 MHz RF structure of the SPS.

bunches are injected. A zoom is shown in Figure 8. It shows the losses from the 25 ns spaced bunches. The losses are a factor ~ 50 lower then the losses in part 2.
The fourth part (till ~ 14000 ns) shows a loss peak induced by ghost bunches swept over the TDI during the MKI fall time. The comparison between Beam 1 and Beam 2 shows a 200 ns shorter flat top length in MKI.8. The losses during injection are distributed one third in the first and second part and two thirds in the fourth part of the loss signal. The loss contribution from the injected LHC bunches is negligible.

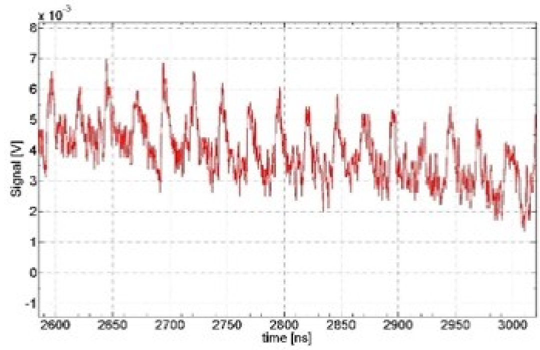

Figure 8: Zoom into the loss signal of the 25 ns spaced, injected LHC bunches.

Shots with pilot bunches impacting on the TDI with full impact parameter were used to calculate a calibration factor, at least for the first part of the loss signal. It shows, that in average 4E9 protons hit the TDI with full impact parameter, which can directly translated to 6.2E5 protons per 5 ns bucket. Calibration factors for the other parts of the loss signal, where particles hit the TDI with grazing impact parameter, are under investigation. For this FLUKA simulations are needed to evaluate the shower behavior for the different TDI materials (hBN, Al, CuBe).
As these measurements show that re-captured beam and ghost bunches are located around the LHC bunches, studies with diamond detectors at SPS extraction were performed. The analysis revealed the locations where the ghost bunches are lost during the extraction process. With the start of the MKE rise time particles get a small kick, not strong enough

to reach the septum protection TPSG. Between ~ 20 and 80 % kick strength of the MKE the particles are lost on the TPSG, before they are moved to the next protection element, which is the horizontal TCDI in the transfer line. When the MKE reaches the maximum kick strength, the particles move through the transfer line and end up on the TDI, assuming that the MKI has not yet started to rise the magnetic field. The loss location is schematically illustrated in Figure 9.

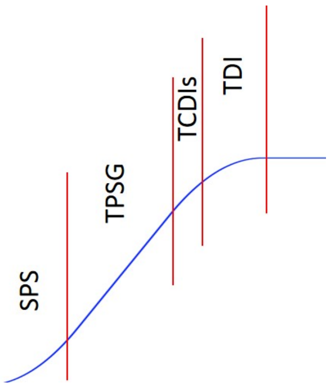

Figure 9: Schematic of the loss locations during the MKE rise time. With small kick strength, the particles get lost in the SPS, with a certain kick strength, particles hit the septum protection (TPSG), with higher kick strength the losses move to the horizontal transfer line collimators (TCDIs).With the MKE at flat top and MKI off, the particles hit the TDI with full impact parameter.

Loss mitigations

During a LHC MD, end of 2015, different loss mitigations were studied [4]. The second loss peak, behind the LHC bunches, is properly injected into the LHC by increasing the MKI flat top length by 1 μs, shown in blue in Figure 10. Two reference measurements (in orange and green) with standard MKI flat top length are shown in comparison to the measurement with increased flat top length. With this method the losses could be reduced down to 18 % dump threshold on the TDI BLM compared to an average of ~ 50 % with standard MKI flat top length.

In addition, the possibility of cleaning the beam around the batches in the SPS was tested. Therefore the tune kicker in the SPS was set-up. The parameters are listed in Table 1. An oscilloscope screen-shot with the batches in the SPS (in green) and the tune kick pulse (in yellow) in between is shown in Figure 11. The tune kicker was set-up to rise at flat bottom after the LHC batches and to fall before the batches arrive one turn later. The measurements showed that the losses could be reduced down to 30 % dump threshold on the TDI BLM compared to an average of ~ 50 % before. Figure 12 and Figure 13 show zooms into the first and second peak of the loss signal. With the tune kicker on the losses in the first part, indicated with the black lines, were reduced by 25 %. In the second peak the falling edge of the loss signal were moved closer to the bunches, which reduced the losses at the TDI. In addition, it shows the possible margin

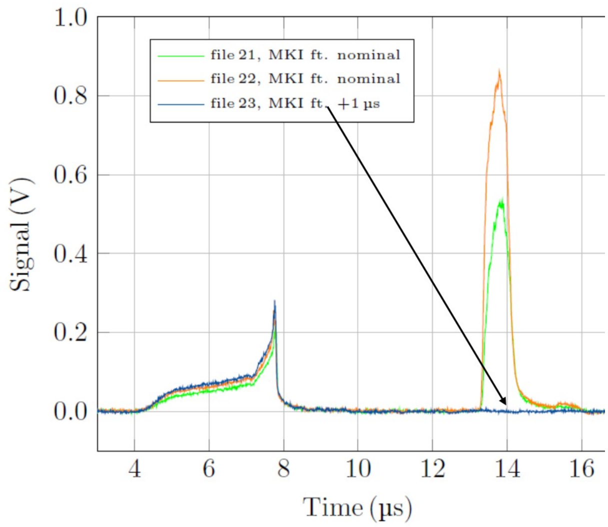

Figure 10: Measured loss pattern with (blue) and without (green and orange) MKI flat top length increase. By increasing the length by 1 μs, the second loss peak disappeared.

to extend the kicker pulse in the SPS without influencing the bunches itself.

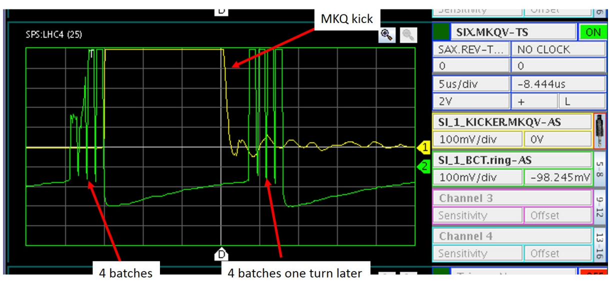

Figure 11: Screen-shot of an oscilloscope. It shows 4 batches each with 36 bunches (green) and the kick of the MKQ (yellow).

Table 1: SPS MKQV parameters used during a MD.

MKQV Parameter	Value
Kick Strength	10.3 kV
Kick Time	10 900 ms
Kick Length	15 us
Kick Delay	30.5 us

During this MD the diamond detectors at the extraction in the SPS measured a reduction of the losses at the TPSG. The measured losses with (red) and without (blue) tune kicker pulse are shown in Figure 14. The losses without MKQ kick are so high, that it induces saturation effects in the read-out electronics, which leads to the negative values in the signal curve.

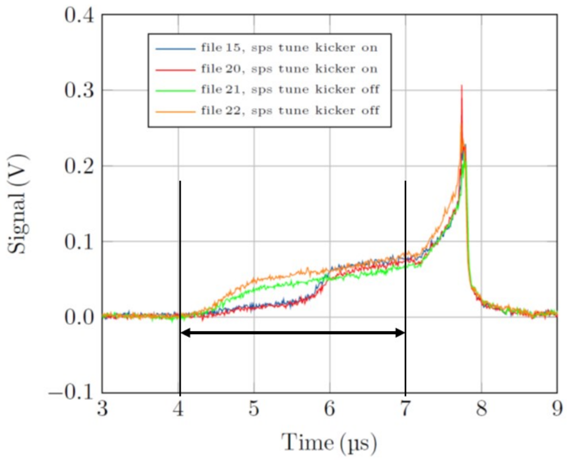

Figure 12: Zoom into the first region of the loss pattern for 144 bunches with (red and blue) and without (green and orange) MKQ kick. In the first part, marked with the black lines, the losses are reduced by 25 %. This directly shows the cleaning effect of the tune kicker.

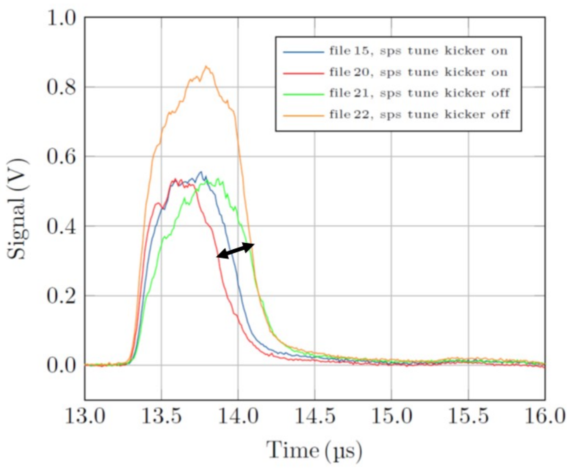

Figure 13: Zoom into the second region of the loss pattern for 144 bunches with (red and blue) and without (green and orange) MKQ kick. The falling edge of the losses is shifted to the left side, indicated with the black arrow.

IQC

The injection quality check (IQC) tool should help to identify the cause of injections with high losses. This OP tool should be maintained with the input of other groups, like BI, RF and ABT. In 2015 the application showed for most of the injections errors and warnings, with the experience from run 2, the thresholds for the color code and warning levels should be reviewed with the input from ABT. As simulations and transfer line loss maps showed that the source of the transfer line losses can be identified, the highlighting of the transfer line collimator name in the application would allow for a faster failure detection and better steering.

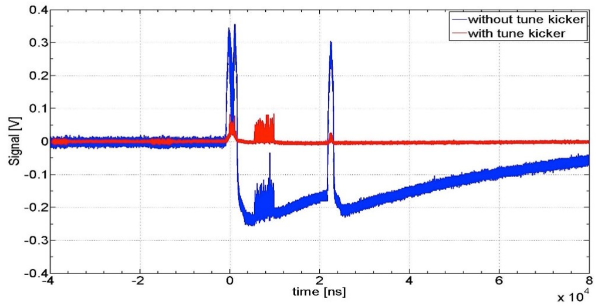

Figure 14: Losses for 144 bunches extraction at the TPSG, measured with the dBLMs. The loss pattern with (red) and without (blue) MKQ kick is shown. High losses induces saturation effects in the dBLM read-out electronics, which lead to the negative values in the plot.

OUTLOOK FOR 2016

Different options to reduce losses in the future were presented. In the SPS the use of the tune kicker can be optimized to clean around the batches, which would lead as a disadvantage to higher losses, distributed in the SPS. In addition, the ramp program can be optimized, but no huge gain is expected for this option.

The MKI pulse length in the LHC can be extend to inject ghost bunches properly into LHC. Options to clean them away afterwards with the injection gap cleaning have to be studied. This possibility is restricted by the limits of the MKI pulse length.

Blind out certain BLMs during injection would hide the problem and does not improve the situation for ALICE and LHCb BCMs [5].

The extraction of ghost bunches after a 288 bunches bunch train from SPS to LHC might overlap with the falling edge of the MKE, which would then shift the losses from the TDI to the TCDIs and the TPSG.

For 2016 it is planned to install dBLMs at the horizontal transfer line collimators, to install them symmetrically at the TDIs in IR2 and IR8 and to revise the read-out electronics.

CONCLUSION

Injections of 144 bunches into the LHC in 2015 reached up to 93 % of the dump threshold on the TDI BLMs. The transversal losses are well understood and under control, further studies are ongoing. The high longitudinal losses occur due to the fact that ghost bunches are located before and after the LHC bunches. These particles are swept over the TDI during the rise and fall time of the MKI. The losses were measured for the first time with nanosecond resolution by diamond based beam loss monitors installed at SPS extraction in LSS4 and LSS6 and downstream of the TDIs in IR2 and IR8 of the LHC. Possible loss mitigations for 2016 operation, like MKQ kick in the SPS and MKI flat top length increase, were presented and will be further tested during injection set-up and intensity ramp-up in 2016.

REFERENCES

[1] L. Drosdal et al., "Analysis of LHC Transfer Line Trajectory Drifts", in proceedings of IPAC 13, Dresden, Germany.

[2] F. Velotti et al., SPS Orbit Stability Analysis

[3] F. Burkart et al., Measurement of injection losses at the LHC and extraction losses at the SPS with diamond beam loss detectors. LIBD on injection losses, September 2015.

[4] F. Burkart, O. Stein, MD 905 note, to be published, 2016.

[5] W. Bartmann et al., Proposals for reduction of LHC injection losses. LIBD on injection losses, September 2015.