INVESTIGATION OF INJECTION LOSSES AT THE LARGE HADRON COLLIDER WITH DIAMOND BASED PARTICLE DETECTORS*

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Abstract

During the operation of the Large Hadron Collider (LHC) in 2015, increased injection losses were observed. To minimize stress on accelerator components in the injection regions of the LHC and to guarantee an efficient operation the origin of these losses needed to be understood and possible mitigation techniques to be studied. Measurements with diamond particle detectors revealed the loss structure with nano-second resolution for the first time. Based on these measurements, recaptured beam from the Super Proton Synchrotron (SPS) surrounding the nominal bunch train was identified as the major contributor to the injection loss signals. Methods to reduce the recaptured beam in the SPS were successfully tested and verified with the diamond particle detectors. In this paper the detection and classification of LHC injection losses are described. The methods to reduce these losses and verification measurements are presented and discussed.

INTRODUCTION

During the beam commissioning of the LHC in 2015 high injection losses were observed at the LHC internal beam absorber blocks for injection losses (TDI) in the injection regions (point 2 and point 8 of the LHC). Theses losses reached up to 90% of the dump threshold of the respective beam loss monitors (BLM). To reduce the stress on accelerator components in the injection regions these losses need to be minimized.

Diamond based particle detectors (dBLM) are installed downstream of the TDIs. Their nano-second time resolution allowed to identify the time structure of the injection losses for the first time.

Figure 1 shows the typical losses during the injection of a train of 72 bunches into the LHC. The schematic in the lower part of the plot shows the kick strengths of the injection kicker in the LHC (MKI) and the extraction kicker in the SPS (MKE). The first bunch is injected into the LHC, when the MKI has reached its maximum kick strength, indicated by a dashed line, at about 2 µs. The rise time of the MKI is 0.9 µs. The losses before the MKI reaches its flat-top are caused by beam coming from the SPS which precedes the nominal bunch train. This signal is modulated by a 200 MHz oscillation which corresponds to the main SPS RF frequency. This shows that these losses come from particles,

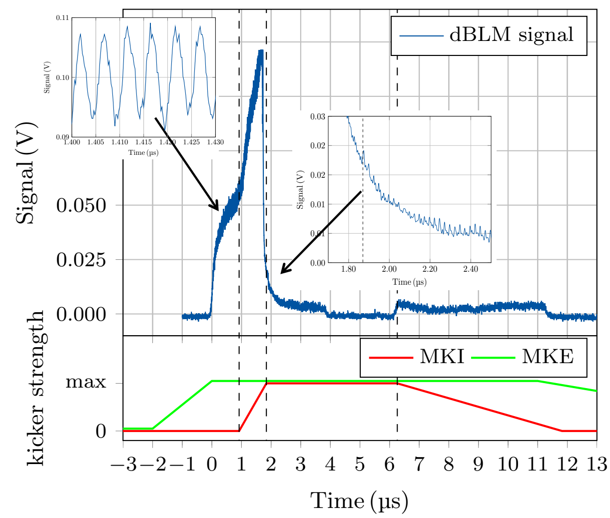

Figure 1: Loss signature of 72 b, beam 2 injection, 20.08.2015, with zooms into the first part of the loss signal (200 MHz SPS RF structure) and the losses from the actually injected 72 bunches.

which are captured in the SPS RF-buckets after the injection from the Proton Synchrotron (PS). Therefore it is called recaptured beam. During the injection process into the LHC the SPS extraction kicker steers the recaptured beam and the nominal bunch-train into the LHC transfer line [1]. As the recaptured beam arrives at the LHC injection region before the LHC injection kicker field starts rising, the particles hit the TDI with full impact parameter (before the first dashed line). When the MKI's magnetic field is rising (between the dashed lines) the incoming recaptured beam is swept over the TDI which causes an increase of the loss signal. When the deflection angle is ≥ 85% of nominal value the beam is properly injected into the LHC. The result is a steep decrease of the loss signals. After the MKI flat-top time (5.05 µs) the field falls, which results in an additional sweep of the still incoming recaptured beam on the TDI. This causes a second loss signature at the end of the signal (after the third dashed line).

DETECTOR SETUP

Polycrystalline diamond detectors (CIVIDEC) are installed about 0.5 m downstream of the TDIs [2]. Their signals are recorded with an oscilloscope. In the direct vicinity a standard LHC ionisation chamber BLM (icBLM) is installed and was used as a reference detector. The icBLMs

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are included in the injection quality monitoring tool (IQC), which analyzes the quality of every injection and potentially interlocks the next injections, in case defined limits have been superseded [3].

CALIBRATION SHOTS ON THE TDI

To calibrate the signal in the dBLM the response of a single pilot bunches (intensities 4×10^9 protons) impacting on the TDI was measured. The bunch intensities were measured in the SPS and retrieved via the IQC.

Three calibration shots were performed.

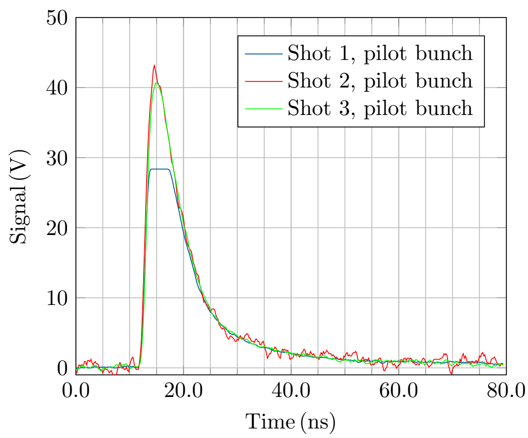


Figure 2: dBLM calibration shot signals.

The first shot was not completely recorded due to resolution limits in the DAQ, which were mitigated by changing the settings of the oscilloscope for the following shots. The measurements of the shots are displayed in figure 2. All three shots had a similar signal shape.

Taking the transferred beam intensity and the integrated dBLM signal into account a conversion factor of 0.10 µVs/10^9 protons was calculated for the last two shots.

INJECTION LOSS MITIGATION

To study different strategies for reducing the loss amplitudes due to beam losses during injection, several trains of 144 bunches (4x36 b) were injected into the LHC. The first approach was exciting the recaptured protons in the SPS at injection energy (26 GeV) by using the SPS tune kicker (MKQ). This led to a cleaning effect of the beam around the nominal bunch train. As an alternative the effect of lengthening the MKI flat-top time was investigated.

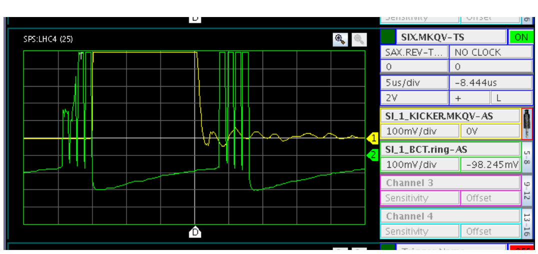
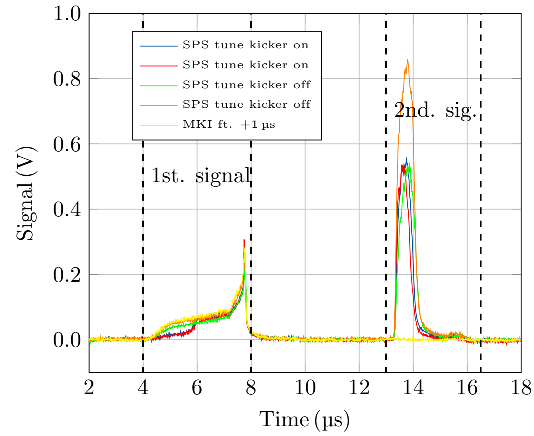
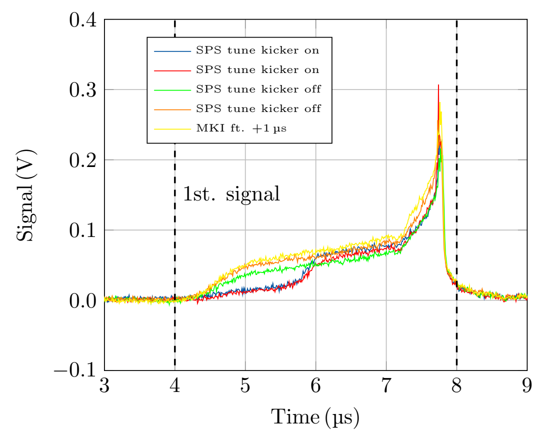


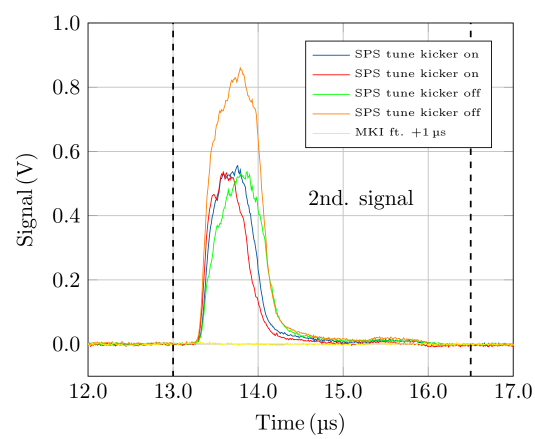
Figure 3: SPS tune kicker waveform (yellow).



a)



b)



c)

Figure 4: Comparison of the losses during the injection of 144 b trains into the LHC with the SPS tune kicker on and off and an increased MKI flat-top time (a). Sub figures b) and c) show zooms into the first and second loss signals.

For the measurements with the SPS MKQ one of the vertical kicker magnets was used. The excitation of the

Table 1: Results of the Loss Mitigation Measurements

	MKQ on	MKQ on	MKQ off	MKQ off	MKI ft.+1 µs
Integrals					
1st. sig.	0.20	0.19	0.22	0.25	0.28
2nd. sig.	0.32	0.28	0.35	0.57	0.0
tot. sig.	0.54	0.47	0.59	0.84	0.29

MKQ is shown in figure 3. The efficiency of these mitigation procedures can be seen in figure 4.

In Table 1 the integrals of the different signal parts are displayed. With the switched on MKQ in the SPS, the signal amplitude is about 17% smaller in the first part of the loss signal than with MKQ off. The measurements show a shortening of the second part of the loss signal if the MKQ is switched on. This leads to a reduction of the loss amplitude in comparison to the measurements without the MKQ cleaning of about 34%.

During the measurements the MKI flat-top time was increased by 1 µs from 5.05 µs to 6.05 µs. The reduction of the losses is significant. No changes are observed in the first part of the losses, see tab. 1. But the second part of the losses vanishes completely. The integrated losses are ~ 60% smaller compared to the standard injections.

Discussion of the Results

The cleaning of the re-captured beam close to the nominal bunch train in the SPS with the MKQ has shown to reduce the losses during injection into the LHC efficiently. To clean these parts of the SPS beam the MKQ timing has to be adjusted carefully to effectively reduce the re-captured beam intensities without affecting the nominal bunches. The efficiency of this method can be optimized in the future to further reduce the injection losses due to re-captured SPS beam.

The lengthening of the MKI flat-top time reduces even more the total integrated injection losses in the LHC than the cleaning with the MKQ, since the second loss signal vanishes. This part of the re-captured beam is then injected into the LHC instead of getting lost on the TDI. This method can cause unwanted recaptured beam in the LHC which probably has to be cleaned with the LHC transverse damper system [4].

Upper Limit of Lost Particle Intensities for LHC Beam Injection

The calculated conversion factor of 0.10 µVs/10^9 protons is only valid for particles fully impacting on the TDI. Particles with a gracing impact on the TDI will likely create a higher signal in the dBLM. Thus, applying the calculated conversion factor to all parts of the injection losses, allows to derive an upper limit for the number of particles lost on the TDI.

Table 2: Loss Intensities Calculated with Conversion Factor for 144 b Injections

	MKQ on	MKQ on	MKQ off	MKQ off	MKI ft.+1 µs
Integrals (µVs)	0.54	0.47	0.59	0.84	0.29
Intensity 10^9 **p**	5.4	4.7	5.9	8.4	2.9
Equiv. of pilots with 4×10^9 p	1.3	1.1	1.4	2.0	0.7

The integrated losses in the TDI during injection are summerized in Table 2 and are equivalent to one to two so-called LHC pilot bunches (signal for a pilot bunch with 9.4×10^9 protons corresponds to 0.41 µVs in the dBLM). To derive a more precise conversion factor FLUKA studies need to be performed for simulating the particle showers for different impact angles on the TDI.

CONCLUSION

The measurements of the injection losses with nanosecond resolution by using diamond based BLMs allowed the identification of recaptured SPS beam as a major contributor to the injection losses at the LHC. By calibrating the diamond based BLMs with LHC pilot bunches a conversion factor was derived. With this factor the upper limit of lost particles per injection can be calculated. Measurements have shown that up to 9×10^9 protons per injection are lost at the TDI. During dedicated beam time at the LHC methods for mitigating these injection losses were successfully demonstrated. By exciting the recaptured beam around the nominal bunch train with a SPS tune kicker magnet a reduction of the loss signal by 34% was achieved. The increase of the injection kicker flat-top time resulted in an even more effective reduction of the injection losses by 60%. To optimize the injection loss mitigation further studies are needed.

ACKNOWLEDGEMENTS

The authors want to thank W. Bartmann, V. Kain and T. Bohl for many fruitful discussions during the preparation of the experiments and the analysis of the results. Furthermore, the authors want to thank the colleagues from the ABT-BTP section for contributing with their expertise in the SPS extraction and LHC injection processes. Special thanks goes to the operators of the SPS and LHC, whose support and ideas were indispensable during the measurements.

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