BUNCH-BY-BUNCH BEAM LOSS DIAGNOSTICS WITH DIAMOND DETECTORS AT THE LHC

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Abstract

A main challenge in the operation with high intensity beams is managing beam losses that imply the risk of quenching superconducting magnets or even damage equipment. There are various sources of beam losses, such as losses related to injection, to beam instabilities and to UFOs (Unidentified Falling Objects). Mostly surprising in the first years of LHC operation was the observation of UFOs. They are believed to be dust particles with a typical size of $1-100\,\mu\mathrm{m}$, which lead to beam losses with a duration of about ten revolutions when they fall into the beam. 3600 BLMs (Beam Loss Monitors) are installed around the LHC ring, allowing to determine the accurate location of UFOs. The time resolution of the BLMs is $40\,\mu\mathrm{s}$ (half a turn revolution). A measurement of the beam losses with a time resolution better than the bunch spacing of $50\,\mathrm{ns}$ is crucial to understand the loss mechanisms. Diamond sensors are able to provide such diagnostics and perform particle counting with ns time resolution.
In this paper, we present measurements of various types of beam losses with diamond detectors. We also compare measurements of UFO induced beam losses around the LHC ring with results from MadX simulations.

INTRODUCTION

The Large Hadron Collider is operated in 2012 with a stored beam energy of $130\,\mathrm{MJ}$. An energy deposition of only a few $\mathrm{mJ/cm^3}$ is sufficient to quench a superconductive magnet. Also damage of material is possible in case of high beam losses. Therefore, it is important to detect and measure all beam losses and dump the beam in case of adverse beam conditions [1]. The focus of this paper is on beam loss measurements during injection, beam dump, beam instabilities and scattering processes with dust particles, so called UFOs. The beam losses are measured with ionization chambers and diamond detectors. The time resolution of ionization chambers is $40\,\mu\mathrm{s}$ (the LHC revolution period is $89\,\mu\mathrm{s}$). If the beam losses measured by an ionization chamber exceeds a predefined threshold, the beams are dumped. A bunch-by-bunch beam loss information with an operational bunch spacing of $50\,\mathrm{ns}$ is not possible with ionization chambers. Diamond detectors have a time resolution of $1\,\mathrm{ns}$ and are therefore capable to distinguish the beam losses of individual bunches [2]. Two diamond detectors are installed in the beam cleaning region (IR7, one of eight regions of the LHC). In this region collimators jaws are positioned to 4-5 sigma from the beam center, the cleaning region is the global aperture limitation of LHC. All major beam losses are detectable there [3]. The diamond detectors are connected to an oscilloscope that allows triggering on certain beam loss events and post mortem analysis. In the following, beam loss measurements with diamond detectors in IR7 are presented.

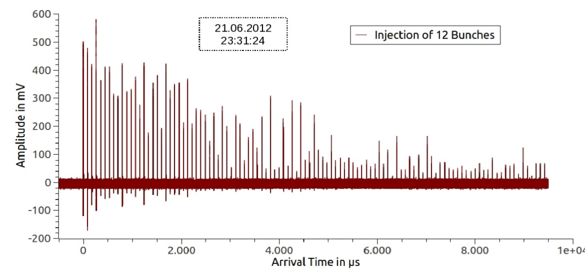

Figure 1a: Measurement of beam losses during injection of 12 bunches for beam 1 into the LHC. Signal amplification: $40\,\mathrm{dB}$. The injection process leads to beam losses during $10\,\mathrm{ms}$ ($\sim$110 turns) and is decreasing after some turns.

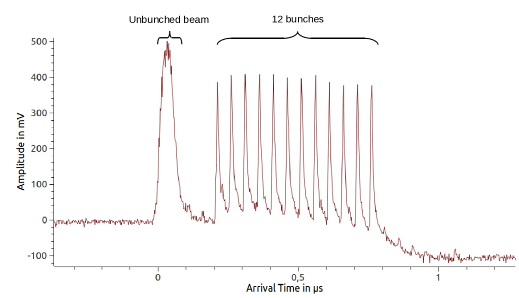

Figure 1b: Zoom into beam losses directly after injection. The measured beam losses are due to unbunched beam and 12 injected bunches with a spacing of $50\,\mathrm{ns}$.

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BEAM LOSSES DURING INJECTION

During the injection process, beam losses are caused by injection oscillations [4]. Figure 1a shows the corresponding signal from an IR7 diamond detector. Injection-induced beam losses are observable over a typical duration of $10\,\mathrm{ms}$. The loss pattern is repeated after $89\,\mu s$, corresponding the LHC revolution period. A closer look to the very first beam loss spike is shown in Fig. 1b. It shows a clear bunch structure of 12 injected bunches that are separated by $50\,\mathrm{ns}$. The first peak, $200\,\mathrm{ns}$ before the 12 injected bunches, is a Gaussian-shape beam loss that is not part of the injected bunches. It is believed that this loss spike is caused by unbunched beam which is lost during the rising edge of the injection kicker waveform but this aspect is still under investigation.

BEAM LOSSES DURING BEAM DUMP

Global beam losses during a normal beam dump are due to the rise time of the beam dump kicker magnets (MKDs) installed in IR6 [5]. Figure 2 shows the rise time of the MKD which starts at $101\,\mu s$ and ends at $104\,\mu s$. The $3\,\mu s$ long risetime is synchronized with the abort gap, which is a normally a beam free region. Unbunched beam can nevertheless propagate into the abort gap and leads to beam losses during the beam dump process [6].

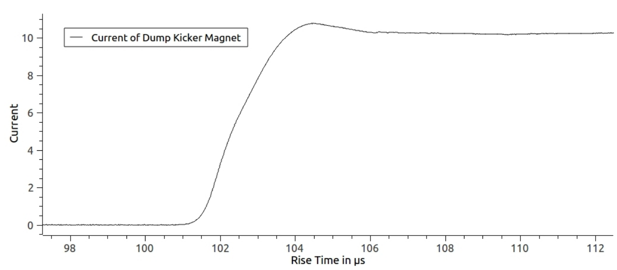

Figure 2: Rise time of a MKD. The rise time of the current during $\sim 101\,\mu s$ and $\sim 104\,\mu s$ is synchronized with the abort gap of the beam. After $\sim 104\,\mu s$ the MKD extracts the protons to the beam dump absorbers via the transfer-lines.

Figure 3 illustrates the trajectories of protons during the increase of the MKD current. The protons are not deflected before the start of the MKD pulse. At the beginning of the pulse, it is possible that the protons are deflected with a small angle and are lost at the collimators in the cleaning region IR7. If the deflection angle is large enough, the protons hit directly the collimators at the beam dumping region. After the rise of the MKD current, the protons go to the beam dump blocks.

All protons with a small deflection angle, not intercepted by the IR6 collimators, are lost in IR7 and can be measured by the IR7 diamond detectors. The beam-dump induced beam losses have approximate a Gaussian profile as shown in Fig. 4. The width of the Gaussian fit is typically $\sigma = 50 - 60\,\mathrm{ns}$. The beam losses appear only at the beginning of the kicker rise time when unbunched particles hit the collimator in IR7.

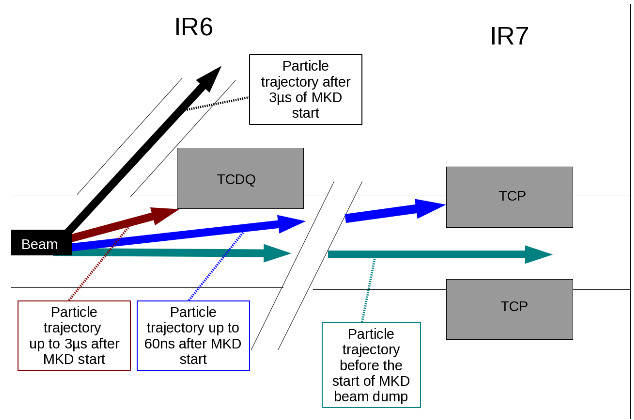

Figure 3: Illustration of particle trajectories during the rise time of the dump kicker. Unbunched protons in the abort gap are deflected and are mainly lost at the collimators in the beam dump (IR6) or cleaning region (IR7) due to the rise time of the kicker magnet.

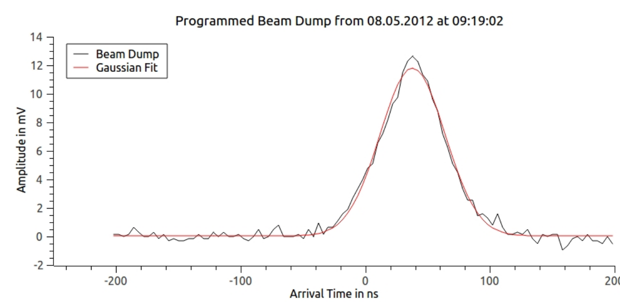

Figure 4: Beam losses due to a beam dump measured with $20\,\mathrm{dB}$ amplification. It is a typically Gaussian loss profile with a standard deviation of $52\,\mathrm{ns}$.

BEAM LOSSES DUE TO INSTABILITIES

Beam instabilities often affect only a few bunches and lead to beam losses over several seconds. The instability can extend to neighboring bunches or collision partner bunches and eventually leads to significant beam losses that can trigger a protection beam dump [7]. Figure 5a shows beam losses as a function of time measured by a IR7 diamond detector due to a beam 1 instability. Only some spikes with beam losses are visible showing that only few bunches become unstable and produce beam losses. One of the spikes appears at an arrival time of $560\,\mu s$ as shown in a zoom, see Fig. 5b. It shows six bunches separated by $50\,\mathrm{ns}$ with large beam losses. After three LHC turns ($\sim 266\,\mu s$), the same bunches with a similar beam loss pattern are observed as illustrated in Fig. 5c. Due to the LHC tune (here it is $Q_x = 64.31$ and $Q_y = 59.32$ with a fractional tune of $\sim$0.3) the loss amplitude is modulated with a periodicity of $\sim$3 turns. The beam losses after the first turn (Fig. 5d) and the second turn (Fig. 5e) are much lower.

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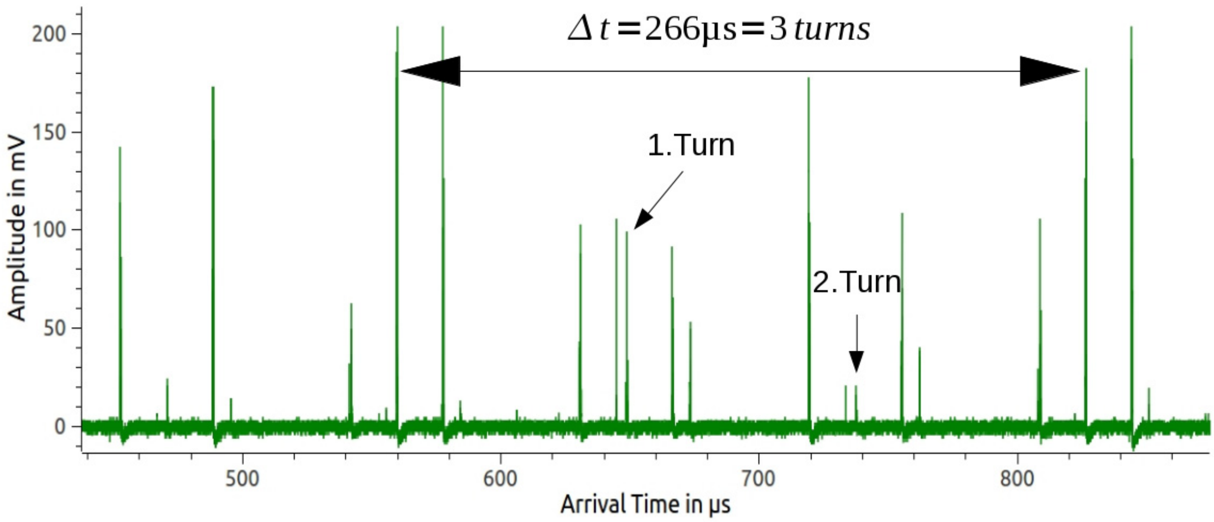

Figure 5a: Measurement from 29.05.2012 at 15:42 of beam losses caused by an instability in beam 1. Due to the fractional tune of ∼0.3, the loss amplitude is modulated with a periodicity of 3 turns. Within 2 s several acquisitions were triggered. Signal amplification: 20 dB.

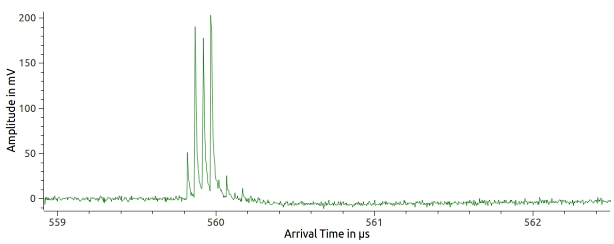

Figure 5b: Zoom of unstable bunches at an arrival time of $\sim 560\,\mu$s. Only six bunches, that are separated by 50 ns, contribute to the beam losses.

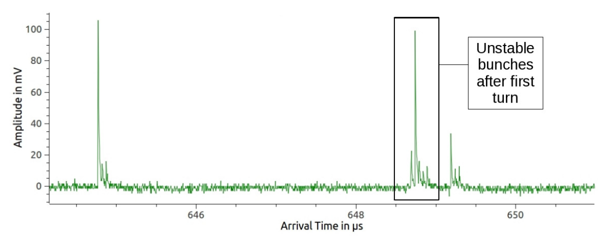

Figure 5d: Zoom of unstable bunches after the first turn. The beam losses are less due to a change of the phase advance.

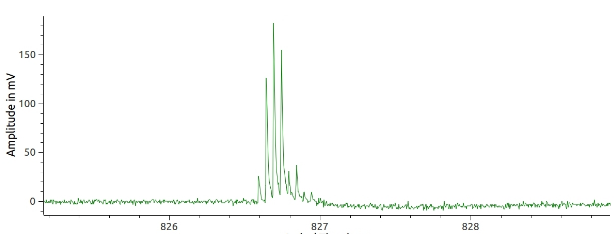

Figure 5c: Zoom of the same six bunches as in Fig. 5b but after the three LHC turns. The loss pattern is still the same.

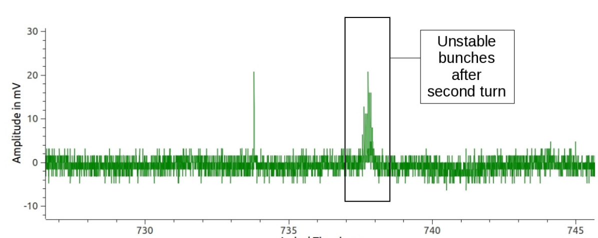

Figure 5e: Zoom of beam losses of unstable bunches after the second turn. The bunches have only small beam losses compared to the third turn.

UFO INDUCED BEAM LOSSES

UFOs are thought to be dust particle of micrometer size. It is believed that they are falling into the beam from above which leads to beam losses with a typically duration of 10 LHC turns. The loss profile of such events have a Gaussian shape and are in general below the beam dump thresholds, only some larger events cause a beam dump [8, 9]. Most of the UFO events occur at the injection kicker in IR2 and IR8. A detailed description of UFO events at the injection kicker is given in [10, 11]. UFO induced beam losses can be measured with diamond detectors in IR7 and a detailed analysis is possible.

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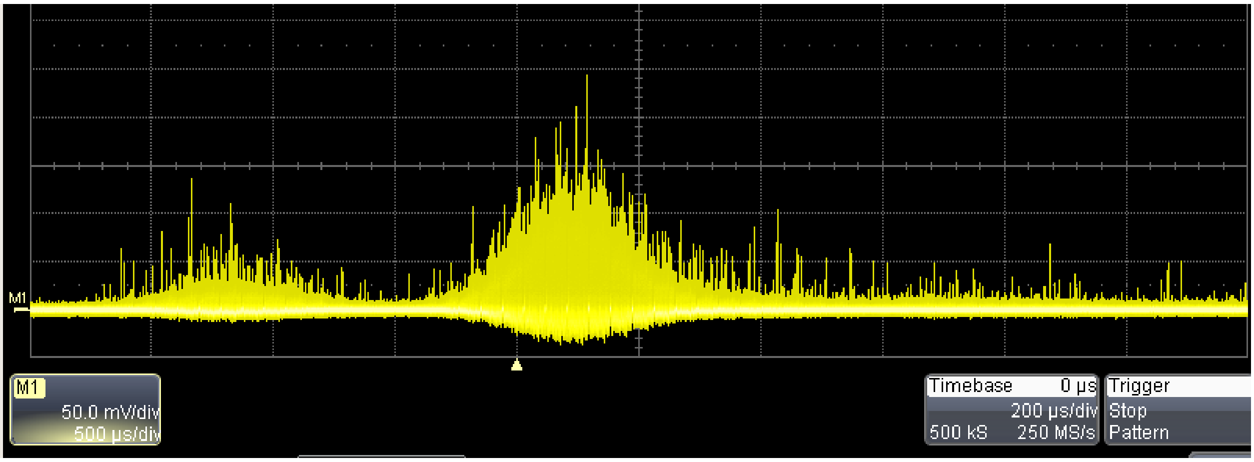

Figure 7: Gaussian beam loss profile as a function of time of two UFO events that occurred at the IR2 injection kicker magnets (beam 1) on the 20.08.2012 at 18:07. The signal of the IR7 diamond BLM is amplified by $40\,\mathrm{dB}$.

MadX Simulations

The interaction processes that lead to UFO induced beam losses can be subdivided into inelastic and elastic interaction. Inelastic scattering produces collision products which lead to very localized beam losses (typically within a few hundred meters). These losses can normally not be detected at the cleaning region. The momentum and angle of elastic scattered protons changes only by a small amount. These protons can stay in the LHC acceptance for several turns and are often lost at the global aperture limitation in IR7. To reconstruct the beam losses in IR7, a simulation with FLUKA was done which is a particle physics Monte Carlo simulation package [12, 13]. Simulations of elastic scattering processes between a proton and aluminum particle at the injection kicker magnet (IR2) were done. Elastic scattered particles were generated by means of a special source routine provided by the CERN FLUKA team. The angular distribution of the elastic scattering process was taken as input for MadX simulations. MadX tracks each elastically scattered proton around the LHC. At the end a beam-loss distribution was provided. The results of the simulations are presented in Fig. 6. Protons are lost at the collimators in IR2, IR3, IR6 and IR7. The horizontal betatron phase advance of 90° between the simulated UFO location and the IR3 collimators, results in significant losses in IR3. Most of the beam losses are in the beam dump (IR6) and cleaning regions (IR7) because of the small opening gap of the collimators. It is therefore reasonable to measure UFOs at IR7.

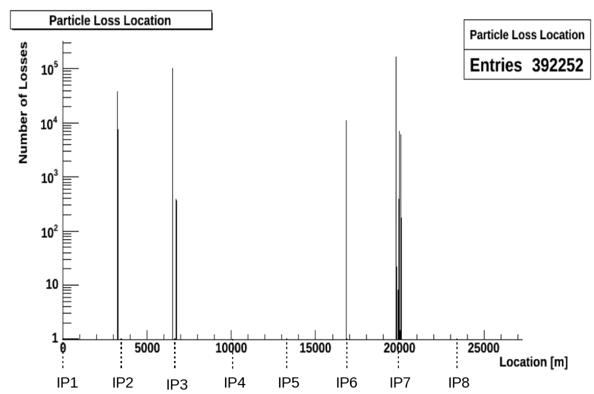

Figure 6: Simulated beam losses due to an UFO event at the injection kicker (IR2). Losses around the LHC ring at the collimators in IR2, IR3, IR6 and IR7 can be observed.

UFO Measurements with Diamond Detectors

The diamond detectors in IR7 were able to detect several smaller as well as larger UFO events. A typical UFO event with a Gaussian loss profile was measured in August 2012 (Fig. 7). The figure shows two different UFO events that occur one after another in the injection kicker magnet. Both events have beam losses below the beam dump threshold but the second UFO event has slightly more beam losses than the first one.

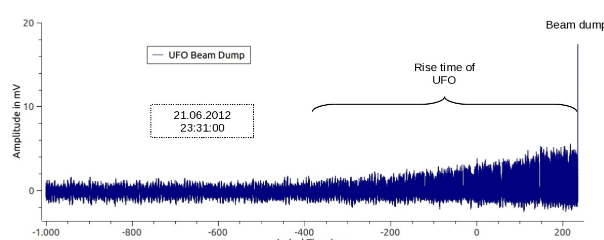

Figure 8a: Diamond measurement of beam losses due to an UFO event from the 21.06.2012 at 23:31. The diamond signal is amplified by 20dB. The UFO has a rise time of $\sim 600\,\mu$s.

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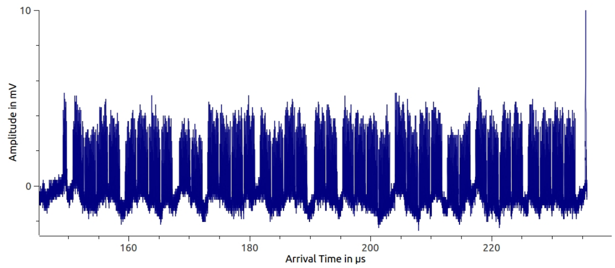

Figure 8b: Zoom into the last beam losses before the beam dump. The injection bunch pattern from the LHC is visible.

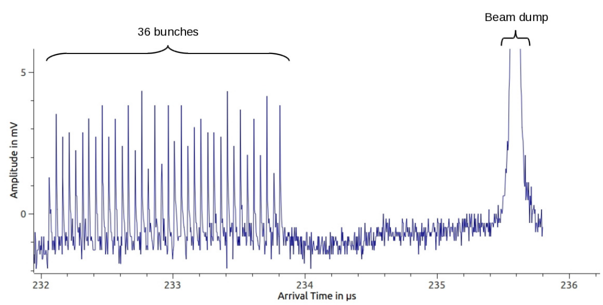

Figure 8c: Zoom into the very last bunches with beam losses right before the beam dump. The bunches are spaced by 50 ns and have different amplitudes due to the time resolution of 2 ns instead of 1 ns.

The beam losses for a large UFO event that dumped the beam is shown in Fig. 8a. The beam was dumped at a rising edge after about 600 μs. Figure 8b shows a zoom of the last part of the beam losses, just before the beam dump. A clear bunch pattern from the LHC injection scheme can be observed and confirms the assumption that all bunches contribute equally to the beam losses. Figure 8c shows the losses right before the beam dump. The last peak is the loss profile of the beam dump.

CONCLUSION

The used diamond detectors have a ns time resolution that allows bunch-by-bunch beam loss observation, which is essential for the understanding of several fast beam loss scenarios. All significant beam losses can be measured by the diamond detectors in the IR7 cleaning region. Different cases of beam losses were measured with these diamond detectors: beam losses due to injection, beam dump, instabilities and UFO events.

The beam loss due to unbunched beam before the injected bunches is the most surprising observation and needs more investigation to develop an appropriate mitigation. The beam losses during beam dump are due to protons in the abort gap which are deflected during the rise time of the beam dump kicker. The beam loss pattern of beam instabilities reveals that only some bunches become unstable and contribute to beam losses. Several observed UFO event have always a Gaussian loss profile and the bunch pattern is clearly visible. The measurements proved for the first time that the beam losses originate almost equally from all bunches. The readout of the diamond detectors is done with an oscilloscope and allows an individual trigger setup for different beam loss scenarios. Due to the good results of the diamond detector measurement it is forseen for the last part of 2012 LHC run to make the diamond measurements more operational and available for the LHC control room. An operational beam loss measurement system based on diamond detectors offer a protection system with better time resolution than ionization chambers and a faster reaction time. Since all significant beam losses are observed in the cleaning region, a system with only a few diamond detectors could complement the current system.

REFERENCES

[1] R. Schmidt et al.,“Protection of the CERN Large Hadron Collider,” New Journal of Physics 8 (2006) 290.

[2] B. Dehning et al., “A&T Sector Note,” ATS/Note/2011/048, Geneva, Switzerland.

[3] R. Assmann et al., “Collimation for the LHC High Intensity Beams,” Proceedings of HB2010, Morschach, Switzerland, MOIB03.

[4] V. Kain, “ Injection Beam Losses and Beam Quality Checks for the LHC,” Proceedings of IPAC 2010, Kyoto, Japan, TUPEB066.

[5] T. Kramer et al., “Apertures in the LHC Beam Dump System and Beam Losses,” Proceedings of EPAC 2008, Genoa, Italy, WEPP064.

[6] M. Meddahi et al., “LHC Abort Gap Monitoring and Cleaning,” Proceedings of IPAC 2010, Kyoto, Japan, MOPEC009.

[7] E. Metral, “Overview of Impedance and Single-Beam Instability Mechanism,”, PAC 2005, Knoxville, USA, CERN-AB-2005-041.

[8] T. Baer et al., “UFOs in the LHC: Observations, Studies and Extrapolations,” Proceedings of IPAC 2012, New Orleans, Louisiana, USA, THPPP086.

[9] E. Nebot del Busto,“Detection of ’unidentified falling objects’ at LHC,” Proceedings of HB2012, Beijing, China, TUO1C04.

[10] T. Baer et al., “UFOs in the LHC after LS1,” Chamonix 2012 Workshop, volume 2, 2012.

[11] B. Goddard et al., “Transient Beam Losses in the LHC Injection Kickers from Micron Scale Dust Particles”, Proceedings of IPAC2012, New Orleans, Louisiana, USA.

[12] G. Battistoni et al., “The FLUKA Code: Description and Benchmarking,” HSS06, 03/2007.

[13] A. Ferrari et al., “FLUKA: a Multi-Particle Transport Code,” CERN-2005-10, 10/2005.

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