ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-WEPTS050

MULTI-SPECIES ELECTRON-ION SIMULATIONS AND THEIR APPLICATION TO THE LHC

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Abstract

During operation in 2017 and 2018, the LHC suffered from recurrent beam aborts associated with beam losses in one of its arc cells in correlation with quickly developing transverse coherent oscillations. The events are thought to have been caused by a localised high gas density resulting from the phase transition of a macroparticle that had entered the beam. In order to model the observed coherent effects caused by the interaction of the beam with the induced pressure bump, novel modelling capabilities have been implemented that allow for the simulation of multiple clouds of different particle species and their interaction with the beam. In this contribution the simulation model and its application are described.

INTRODUCTION

During LHC operation in 2017 unusual fast beam loss events were observed in the 16th half-cell left of Interaction Point 2 (16L2) [1–6]. The loss events were often accompanied by transverse coherent beam motion with extremely fast rise times, and resulted in beam dumps due to losses exceeding the beam abort thresholds either on the collimation system, or directly in the half-cell 16L2. During the 2017 LHC run, in total 68 premature beam dumps with this characteristic signature occurred, significantly impacting the operation.

At the end of the 2017 run it was confirmed that an amount of air had been present in the cryogenic vacuum system in the concerned region, where most of the constituent gases would have been condensed and solidified on the beam screen surface [1]. The loss events are believed to have been initiated by macroparticles of such frozen gases, in particular nitrogen or oxygen, becoming detached and entering the beam. Macroparticle events where a dust particle enters the beam halo, becomes ionized and subsequently repelled by the beam, producing a characteristic loss spike, regularly occur in the LHC [7–9]. While many of the events observed in 2017 initially appeared as regular macroparticle events, they were distinguished by a long tail of losses that is inconsistent with the macroparticle picture [4–6]. However, the macroparticles may have undergone a phase transition to gas, resulting in a local pressure bump of high density, which could explain the observed loss pattern [4]. Beam-induced ionization of the localized gas generated by the macroparticle would in turn produce large numbers of electrons and ions, which are believed to be the cause of the observed strong beam instabilities [2, 3].

In this contribution we describe the on-going efforts to numerically model the beam-induced ionization and the resulting beam-ion-electron system, in order to verify if it can give rise to the observed coherent effects. We will argue why the numerical tools in place at the time of these events, which allowed for the study of beam-electron or beam-ion interactions, but not the three components together, were insufficient for modelling the dynamics of the three-component system. We detail the developments made to this date to enable more accurate studies, show the first results obtained with the new tools, and discuss the needs for possible further extensions to the numerical model.

RELEVANT OBSERVATIONS AND ANALYSES

The observed beam losses provided some of the most important information for identifying the cause of the events leading to the beam dumps. The observed longitudinal pattern in the beam loss monitors allowed estimating the origin of the losses to within a few meters, to the interconnection region between the quadrupole and the neighbouring dipole in the 16L2 half-cell [1, 4]. Furthermore, the atomic densities in this location could be estimated based on the measured loss rates. For a pressure bump extending over the length L, a density range of roughly 10^{19}–10^{21} $L^{-1}\mathrm{m}^{-2}$ can be inferred for the various recorded events, assuming that the nuclei consist of nitrogen gas and that the pressure bump extends transversally over the full beam cross section [4].

Strong transverse coherent beam oscillations were often observed prior to the beam dump of 16L2 events [3]. The pattern of unstable bunches varied between the different events. The rise times of the instabilities were typically between 10 and 100 turns, much faster than any previously known instability mechanism in the LHC. Efforts to damp the instabilities by increasing transverse feedback gain, chromaticity and octupole current were unsuccessful.

For some events it was possible to gain additional information on the characteristics of the instability through further analysis [3]. In cases where frequency analysis of the growing motion could be successfully performed, positive single bunch tune shifts as large as 2×10^{-2} were observed. For a few events it was also possible to detect intra-bunch motion, which displayed a travelling wave pattern along the tail of each bunch. Both positive tune shifts and travelling wave motion at the tail of bunches are typical signatures of electron-induced coherent effects, with the large magnitude of the tune shift implying that unusually high electron densities were present.

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SIMULATION TOOLS AND DEVELOPMENT

The build-up of electron clouds and their impact on the beam dynamics can be modelled numerically with macroparticle tracking simulations using the particle-in-cell (PIC) method. The PyECLOUD macroparticle code models the build-up of electron clouds in 2D using a rigid beam approximation [10, 11]. Among several features, it allows for primary electron production through beam-induced ionization and models the secondary emission of electrons induced by impacts on the chamber wall. The effect of electron clouds on the beam dynamics can be modelled self-consistently through the coupling of the PyECLOUD code and the beam dynamics macroparticle tracking code PyHEADTAIL [11, 12].

The PyECLOUD-PyHEADTAIL simulation setup has previously been generalized to model multi-bunch ion accumulation with electron beams for studies of the fast beam-ion instability [13]. Motivated by the events observed in the LHC, and in particular the hypothesis that high gas densities resulting in significant amounts of electrons and ions could be involved, the PyECLOUD code could quickly be extended to model clouds and beams of arbitrary charge and mass, to study also the dynamics of ion production and motion in the presence of a pressure bump [14]. Unlike for electrons, no ion-induced secondary emission is included in the simulation model, instead, ions reaching the chamber wall are simply absorbed and removed from the simulation.

With these developments, beam-electron and beam-ion interactions could be simulated, but the three components could not be studied together. When studying electron cloud or ion effects involving beam-induced residual gas ionization, the species with the opposite charge is typically ignored, since it is repelled by the beam and therefore does not accumulate. This is a reasonable approximation when the gas density is sufficiently low, such that the amount of ionization products is small compared to the accumulated charge in the electron/ion cloud. However, for high gas densities it may not be the case, and the gas ionization may even be a dominant effect. In this case, one can expect the oppositely charged ionization products to have a significant impact on each other's dynamics through their space charge. Since the observations in the LHC suggested that high gas densities could be involved, the model was extended further to enable also simulations of the full beam-electron-ion system.

To simulate multiple species in PyECLOUD, the possibility to track several *clouds* of macroparticles was introduced. Each cloud has its own set of macroparticles with individual dynamics as well as impact and generation processes, but interact with other clouds through the space charge forces. Although the implementation was facilitated by the modular code structure, significant modifications had to be made to several of the core simulation routines. The multi-cloud implementation has been verified against a standard electron cloud build-up simulation in the LHC [15].

APPLICATION TO THE LHC

Based on the observations of the 16L2 events, simulation studies with a pressure bump located in a field free region in the LHC arcs were set up. The pressure bump is assumed to consist of nitrogen (N_2) gas, with a density that is varied in the simulations. The cross section for beam-gas ionization at injection and collision energy is taken to be 2 Mb. A secondary electron emission yield of 1.75 is assumed, which is well above the multipacting threshold in the considered location.

First simulation studies modelling separately the beam-electron and the beam-ion interactions showed that high densities of either electrons or ions could drive fast instabilities. On the other hand, simulations of electron or ion accumulation with beam-gas ionization showed that for high gas densities (10^{20} N_2/m^3 or above) electron multipacting is no longer the dominant effect, and for both electrons and ions the density in the chamber depends mainly on the gas density. This can be seen in the light blue curve in Fig 1. Consequently, gas densities as high as 10^{23} N_2/Lm^2 and 10^{25} N_2/Lm^2 were needed for the instabilities to occur in simulations with ions and electrons, respectively. The gas densities suggested by these studies are much higher than the 10^{19}–10^{21} $L^{-1}m^{-2}$ range inferred from the losses [4].

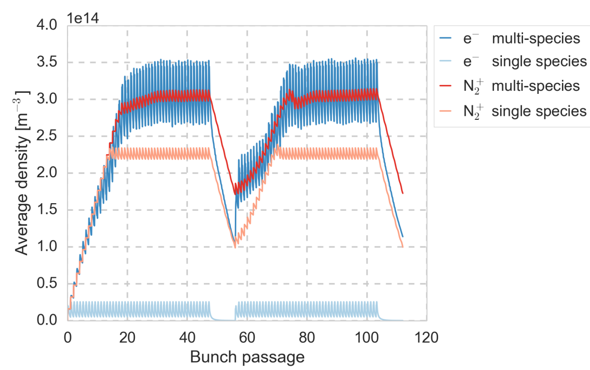

Figure 1: Electron and ion densities during the passage of two bunch trains at LHC injection with a gas density of 10^{21} N_2/m^3, in single-species and multi-species simulations.

With the recent developments outlined above, simulations of the full three-component system could be performed. When electrons and ions are tracked together in the same simulation, the dynamics of both species are altered. In Fig. 1 the electron and ion densities during the passage of two LHC bunch trains in a multi-species simulation are compared to simulations with the individual species in otherwise identical conditions. In particular the electron density in the chamber is significantly increased due to the presence of the ions. This can be understood to be, at least in part, due to the screening by the ions of the self-space charge of the electrons.

Unlike the electrons, the ions produced within the beam take several bunch passages to reach the walls, due to their relatively large mass, and thus stay fairly close to the centre of the beam chamber also after the generating bunch has passed.

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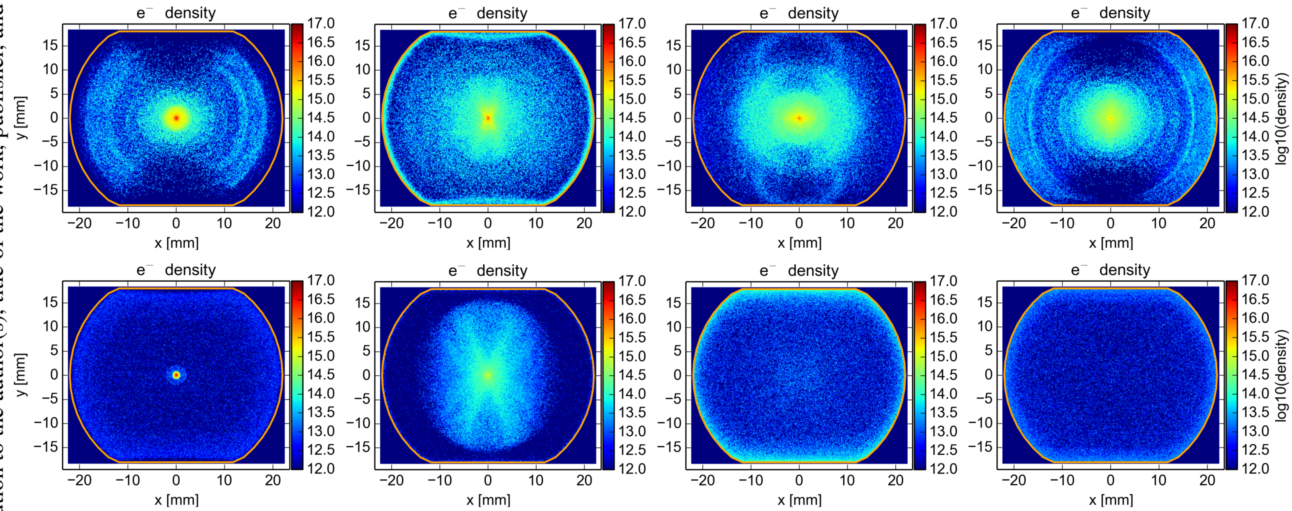

(a) t = 0 (b) t = 1 ns (c) t = 5 ns (d) t = 15 ns

Figure 2: Snapshots of the electron density in the beam chamber during a bunch passage. Images from a multi-species simulation (top), are compared to the equivalent images in a simulation tracking only electrons (bottom). The first image on each row (t = 0) is taken during the passage of the centre of the bunch. The bunch length is 1 ns and the bunch spacing 25 ns.

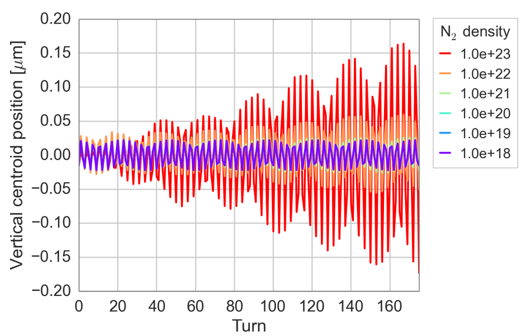

Figure 3: Vertical centroid motion of an LHC bunch at 6.5 TeV in multi-species simulations with gas ionization for varying N_2 gas density extending over $L = 10$ cm.

For sufficiently high gas densities, the ions can accelerate the secondary electrons produced after the bunch passage towards the centre of the beam chamber, and thus reduce the number of secondary electrons that are absorbed by the wall between bunch passages. In addition, further secondary electrons are produced between bunch passages by these accelerated electrons when they hit the chamber wall. This effect can be seen in Fig. 2, where snapshots during and after a bunch passage are shown. In the equivalent snapshots from a simulation without the ion distribution (bottom) this behaviour is not seen. Single-bunch stability simulations with the full multi-species model, Fig. 3, show the onset of fast beam instabilities at gas densities of 10^{22} N_2/m^3, with the gas extending over 10 cm. This is closer to the onset density suggested by observations, which for $L = 10$ cm is around 10^{20} N_2/m^3, but still not fully in agreement.

The cross-section for impact ionization by electrons is larger than the beam-ionization cross-section by at least a factor 50 for electrons in the energy range of 30-850 eV [16]. The electron energies in simulations show a strong dependence on the gas density. With a density of 10^{20} N_2/m^3, the fraction of electrons in this energy range varies between 25-90% during a bunch passage. For densities one to two orders of magnitude higher, more than 50% of electrons lie in this energy range at all times, whereas for lower gas densities the fraction is lower than 10% after the bunch has passed. This suggests that impact ionization by electrons may be an important ingredient, which can increase the electron and ion numbers for a given gas density. Further development to include this effect in the simulation model is on-going.

So far only single-bunch stability studies have been performed. However, the simulation tools have recently been extended to model also multi-bunch stability with electron clouds [17]. In the future, this capability will be used to model multi-species multi-bunch instabilities to attempt to reproduce also the coupled-bunch motion observed during the events [3].

CONCLUSIONS

The multi-species development work presented here was motivated by recent events in the LHC, with a suspected localized transient pressure bump of very high density. Simulation studies with a multi-species tracking tool show a significant effect on the dynamics of the system when ions and electrons are considered together. However, even with this implementation, the instabilities observed in the machine can not be fully reproduced with the gas densities inferred from observations. Studies of the electron energies suggest that impact ionization by electrons, which is currently under implementation in the model, is an important further ingredient that may help reduce this discrepancy.

ACKNOWLEDGEMENTS

The authors would like to thank G. Arduini and E. Métral for their important contribution to this study.

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-WEPTS050

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