Nuclear reactions in the context of LHC operation

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Abstract
Beam losses in accelerator elements of the LHC may pose a limit for machine performance or can give rise to long-term damage of equipment. In this paper, we present a selection of beam-machine interaction simulations with FLUKA, considering different sources of beam losses like collisions in the interaction regions or halo collimation. Relevant nuclear reactions, as well as atomic displacement mechanisms that lead to long-term radiation damage, are briefly reviewed. The impact on the machine is illustrated by means of a few examples, like the radiation damage induced in collimators and magnets or the risk of magnet quenches due to secondary ions emerging from lead-lead collisions.

1. Introduction
The Large Hadron Collider (LHC) [1] has a circumference of about 27 km. A chain of accelerators, as shown in [1], delivers beams of 450 GeV into the LHC. At top energy (7 TeV) and nominal beam intensities (2808 bunches with a bunch intensity of $1.15 \times 10^{11}$ protons), each of the two counter-rotating LHC beams carries an energy of 362 MJ. Owing to this unprecedented stored energy, it is important to analyse the consequences of beam losses considering that already a small fraction of the energy can provoke a magnet quench if being released in the coils of one of the thousands of superconducting magnets. Besides posing a risk for quenches, beam losses can also affect the accelerator performance.
and equipment in other ways, for example they give rise to long-term radiation damage and ageing of magnets and other components. In order to estimate the consequences of beam losses and to derive relevant quantities such as dose, fluences or displacement damage, a detailed description of hadronic and electromagnetic particle showers is required. This in turn requires adequate nuclear reaction models, which allow to predict the production of secondary particles. Monte Carlo codes like FLUKA [4, 5], embedding such models, represent a powerful tool for simulating cascades initiated by high-energy particles in accelerators. FLUKA is regularly used at CERN to study particle-matter interactions in the LHC environment, for example to analyse the energy deposition in magnets, to estimate the radiation to electronics, or to design new equipment for accelerator upgrades. This article illustrates typical beam-machine interaction calculations by means of a few examples.

2. Magnet quench tests

Magnet quenches adversely affect the machine availability as a significant amount of time is lost in recovering from a quench. In order to detect beam losses which can potentially quench a magnet or even induce damage, more than 3000 Beam Loss Monitors (BLMs) are placed around the LHC rings. The monitors are ionization chambers filled with pressurized Nitrogen gas, which record the dose deposition by secondary showers initiated by beam particles interacting with accelerator equipment. Most of these ionization chambers are mounted on cryostats hosting the superconducting magnets. If the dose measured by BLMs exceeds a predefined abort threshold, the beams are extracted onto the beam dump block. In order to define adequate abort thresholds, one requires a good knowledge of magnet quench levels, i.e., of the minimum amount of energy deposition required to provoke the transition from superconducting to normal-conducting state.

In 2013, a test campaign was carried out to probe the quench level of magnets for different time regimes and loss scenarios [2]. In one of the tests, 4 TeV protons were deliberately disposed on the aperture of a quadrupole (MQ) located in the LHC arcs. The magnet quenched when some $10^8$ protons were lost within a few milliseconds. The superconducting coils of LHC magnets are separated from the beam vacuum by a mm thick stainless steel vacuum chamber, which further accommodates a mm thick beam screen for absorbing the beam-generated heat load. When impacting on the beam screen,
protons typically have very grazing angles and hence they undergo an inelastic nuclear collision before reaching the coils. As the energy deposition inside magnets cannot be measured directly, FLUKA simulations were carried out for the above described test to estimate the energy density in the coils and to provide a correlation with BLM signals (see Fig. 2). The shower simulations were based on proton loss distributions derived with the MAD-X code (taken from Ref. [3]). As can be seen in Fig. 2, simulated and measured BLM signals generally agree better than 20%. The results further illustrate that, due to the shielding of showers in the magnet yoke, the energy density in the coils is more than one order of magnitude higher than at the location of BLMs.

3. Secondary particle production in the experiments

The LHC accommodates four experimental insertions where large-scale detectors (ATLAS, CMS, LHCb and ALICE) are installed. A fraction of secondary particles produced in the collision of LHC beams in the interaction points leaks from the experimental caverns to neighbouring accelerator regions, leading to a non-negligible power deposition in magnets. In the following subsections, we compare simulated and measured BLM signals induced by secondary particles from proton-proton and Pb-Pb collisions in the ATLAS and CMS experiments. Such comparative studies are important for understanding the complex radiation environment, but they also strengthen the confidence in the simulation model.

3.1 Proton-Proton Collisions

Fig. 3 presents a comparison of simulated and measured BLM signals induced by the debris from proton-proton collisions at a center-of-mass energy of 8 TeV in the ATLAS experiment. The BLMs shown in the figure are located along the inner triplet quadrupoles which are used to squeeze the beams at the interaction point. Measured signals were recorded during different physics fills in 2012. All signals are expressed per inelastics collision, assuming an inelastic cross section of 74.7 mb [6].
production of secondary particles in the interaction point was simulated using the DPMJET-III event generator [9, 8] (which has been interfaced to FLUKA), followed by FLUKA shower simulations in machine elements. The simulated signals generally agree well with the measured ones (better than 50%), with a few exceptions which are probably due to some approximations in the accelerator model used in the simulation setup.

### 3.2 Lead-Lead Collisions

During dedicated run periods, the LHC operates as a heavy ion collider ($^{208}$Pb$^{82+}$). Electromagnetic processes in ultra-peripheral Pb-Pb collisions give rise to secondary ion species, which are lost at certain locations inside the accelerator owing to their magnetic rigidity which differs from the beam rigidity [10, 11]. The process with the largest cross-section is bound-free pair production (BFPP), where one of the outgoing Pb ions is no longer fully stripped, but has a charge of 81+:

$$^{208}\text{Pb}^{82+} + ^{208}\text{Pb}^{82+} \rightarrow ^{208}\text{Pb}^{82+} + ^{208}\text{Pb}^{81+} + e^+ \quad (1)$$

The secondary ions produced in BFPP remain inside the vacuum chamber for more than 400 m until they impact on the magnet aperture in the dispersion suppressor. Fig. 4 compares simulated and measured BLM signals due to BFPP ions from the collision point in the CMS experiment. The shower simulations were based on ion impact distributions derived in Ref. [7]. In general, simulation and measurement are found to be in good agreement, in particular downstream of the loss location.

### 4. Radiation damage in collimators

The LHC accommodates a multi-stage collimation system for cleaning the beam halo such that losses in superconducting magnets are reduced to acceptable values. It is estimated that about $10^{16}$ protons are lost in the collimation system for every $30 - 40 fb^{-1}$ of integrated luminosity achieved in the experiments. Owing to the high radiation loads, long term radiation damage is a concern for the absorber materials of collimators and requires careful study. This applies in particular to the 60 cm long primary collimators (TCPs), made of carbon-reinforced carbon. The primary collimators represent a global aperture bottleneck and can be impacted by protons multiple times until the particles are subject to
A useful quantity to measure long term radiation damage in non organic materials is Displacements Per Atom (DPA). DPA is related to the total number of defects (Frenkel pairs of interstitial and vacancies) generated in a material after irradiation, which could affect some macroscopic properties of the material (e.g. electrical resistivity). Displacement damage in collimators can be induced directly by primary protons but also indirectly by charged particles, neutrons or ions produced in hadronic cascades, as well as by particles produced in electromagnetic cascades. As most protons typically impact close to the collimator edge (some \( \mu \text{m} \) impact parameter), the induced damage is mainly concentrated within a superficial layer on the collimator surface, but steeply drops inside the bulk material. Figure 5 shows the simulated peak DPA, for 7 TeV protons, over the length of the most impacted jaw of the horizontal TCP along with the individual contribution of the different particle families. The maximum damage of about \( 9 \times 10^{-3} \) DPA is observed at the beginning of the collimator dropping to \( 4 \times 10^{-3} \) DPA by the end the longitudinal length. The peak observed at the start is in a surface layer of a few \( \mu \text{m} \) and can be mainly attributed to recoils produced in elastic encounters of primary protons.

5. Conclusion

In this paper, the importance of nuclear reaction modelling for high-energy accelerator applications has been highlighted by means typical beam-machine interaction calculations carried out at CERN. The shown examples demonstrate the capabilities of Monte Carlo codes like FLUKA for predicting relevant quantities related to complex radiation environments like at the LHC.

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References