Machine and radiation protection challenges of high energy/intensity accelerators: the role of Monte Carlo calculations

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Abstract. The role of Monte Carlo calculations in addressing machine protection and radiation protection challenges regarding accelerator design and operation is discussed, through an overview of different applications and validation examples especially referring to recent LHC measurements.

1 Introduction

The interaction between particle beams and accelerator components is at the origin of a wealth of effects requiring a careful evaluation at the stages of machine design, operation, and dismantling. These include for instance heating, thermomechanical stress of beam intercepting devices (BID), gas production and material damage, superconducting magnet quenching, single event effects in electronic devices, and activation.

Such an interaction is triggered by different scenarios, i.e. either regular or accidental beam losses on BID (targets, collimators, dumps, stoppers, stripping foils, etc.), dust fall into circulating beam, particle debris generation inside the detectors of a collider, nuclear reactions on the residual gas in the vacuum chamber, synchrotron radiation, gas bremsstrahlung.

In order to quantify the above effects starting from the listed loss terms, multipurpose Monte Carlo codes like FLUKA [1, 2] represent an essential tool, allowing to evaluate macroscopic quantities through the microscopic description of particle transport and interaction in matter. This implies tracking in magnetic field as well as the account of all relevant electromagnetic and nuclear processes over an extremely wide energy range. The code reliability is verified through individual benchmarking of physics models against exclusive data. Moreover, a profitable calculation demands to implement to a challenging degree of accuracy the machine geometry, including material information.

This paper presents an overview of FLUKA studies instrumental in CERN accelerator design and operation, with special emphasis on the validation opportunities already offered by the first Large Hadron Collider (LHC) runs.

2 Energy deposition in sensitive components and monitor signals

At CERN, FLUKA is the reference tool to address machine protection aspects as well as the complementary radiation protection scope. It is regularly and extensively used for the whole accelerator

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chain, from the beam dump design of low energy injectors as Linac4 [3] up to LHC collimation [4] and High Luminosity upgrade of the LHC experimental insertions [5]. Also in the context of the Future Circular Collider (FCC) perspective, it plays a crucial role since the early stage of the project, both for accelerator and detector design and both for the hadron and lepton machines. This means that simulations have to deal with protons of some million TeV (the equivalent energy with target at rest of 100 TeV center-of-mass collisions) down to the lowest transport limit of 100 eV photons (for the study of the lepton ring synchrotron radiation). Such a task calls for a continuous improvement of different interaction models, having in mind that, despite the very high energy of beams of interest, several quantities, like for instance those related to radionuclide inventory, are extremely sensitive to low energy nuclear physics ingredients ruling the reaction fragment de-excitation. Together with this physics oriented effort, significant technical developments made possible to automatize the construction of consistent geometry models of several hundred meter accelerator portions [6, 7].

The LHC operation during Run-I (2010-2013) and Run-II (started in 2015) gave as intriguing byproduct a significant amount of data allowing to test the degree of reliability of simulations performed in the long course of the LHC design phase [8]. In particular, the Beam Loss Monitor (BLM) system, consisting of a few thousand ionization chambers all along the 27 km beam line, provides on-line measurement of the energy released by the particle shower originated by beam particle interactions, and triggers beam aborting if the detected values exceed pre-defined thresholds. Particle shower calculations permit to predict BLM signals for the relevant loss scenarios, correlating them at the same time with the energy deposition levels in the most exposed or sensitive elements. A quantity typically investigated is the power density in the superconducting coils of LHC magnets [9]. Its distribution is used to calculate the quench limit, and its absolute value, compared to the latter, indicates the likelihood of a quench event, implying accelerator downtime. While occasional quenches are to some extent natural in a cold machine, despite the BLM protection system in place to prevent them, steady heating from regular collisions in the experiment locations, scaling with the target instantaneous luminosity, has to be maintained at acceptable levels.

Among the various examples that will be included in the full contribution, the following subsection focuses on a very recent case referring to ion operation, enlarging instructively the picture with respect to more usual proton beams.

2.1 BFPP losses in LHC ion operation

Bound Free Pair Production (BFPP) was indicated since long ago [10] as a threatening electromagnetic process occurring in lead-lead collisions at the interaction points and causing specific losses hundreds of meters downstream, in the Dispersion Suppressor (DS) magnets. In fact, the creation of an electron-positron pair, followed by electron binding to one of the two fully stripped lead ions, has a considerable cross section and alters critically the ion magnetic rigidity due to the charge state change to 81+. This secondary beam travels on a peculiar orbit, making it impact the beam screen delimiting the mechanical aperture in the DS.

Using as input the impact distribution determined by independent tracking studies [11], a FLUKA calculation yielded the expected BLM pattern, which turned out to be in excellent agreement with late 2015 measurements, as shown in Fig. 1. As discussed above, the same simulation estimates the peak power density in the magnets coils.

A subsequent test pushing the luminosity to more than twice the design value led the impacted dipole to quench [12], demonstrating that the planned luminosity upgrade requires the already envisaged mitigation measures, that are the displacement of BFPP losses outside the magnet or, where this is not possible, the installation of a dedicated collimator upstream [13].

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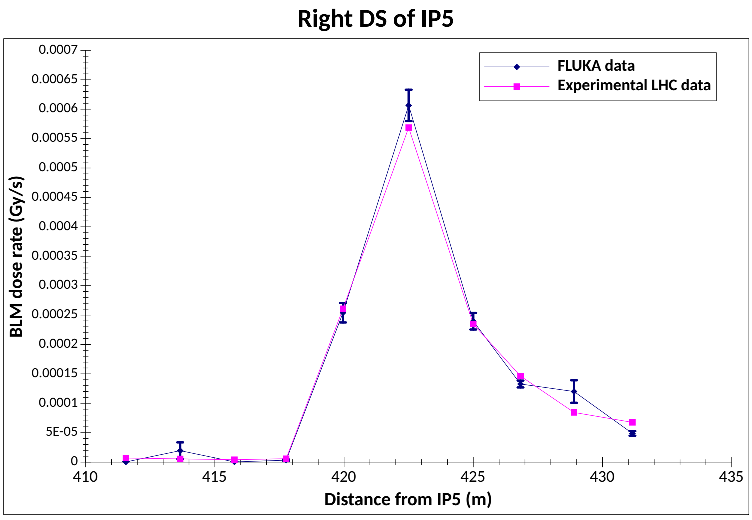

Figure 1. BLM pattern in the DS right of CMS for lead-lead collisions at 10^{27} cm^{-2} s^{-1}. For each monitor in the considered 20 m region, reported values are the absolute dose rate as measured (pink) and calculated by FLUKA (blue). In the latter case, statistical errors are also indicated.

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