ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOPAB022

FailSim: A NUMERICAL TOOLBOX FOR THE STUDY OF FAST FAILURES AND THEIR IMPACT ON MACHINE PROTECTION AT THE CERN LARGE HADRON COLLIDER*

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Abstract

The High Luminosity LHC (HL-LHC) foresees to reach a nominal, levelled luminosity of $5\times10^{34}\,\mathrm{cm^{-2}\,s^{-1}}$ through a higher beam brightness and by using new equipment, such as larger aperture final focusing quadrupole magnets. The HL-LHC upgrade has critical impacts on the machine protection strategy, as the stored beam energy reaches 700 MJ for each of the two beams. Some failure modes of the novel active superconducting magnet protection system of the inner triplet magnets, namely the Coupling-Loss Induced Quench (CLIQ) systems, have been identified as critical. This paper reports on FailSim, a Python-language framework developed to study the machine protection impact of failure cases and their proposed mitigation. It provides seamless integration of the successive phases required by the simulation studies, i.e., verifying the optics, preparing and running a MAD-X instance for multiple particle tracking, processing and analysing the simulation results and summarising them with the relevant plots to provide a solid estimate of the beam losses, their location and time evolution. The paper also presents and discusses the result of its application on the spurious discharge of a CLIQ unit.

INTRODUCTION

The High Luminosity upgrade will increase the levelled luminosity of the CERN Large Hadron Collider (LHC) to $5\times10^{34}\,\mathrm{cm^{-2}\,s^{-1}}$ [1] by means of a higher beam brightness and using new equipment to reduce the value of the β-function at the interaction points (the so-called β^*) for the ATLAS and CMS experiments. The increased beam brightness is achieved by reducing the beam emittance from 3.75 mm mrad to 2.5 mm mrad and by increasing the nominal bunch intensity from 1.15×10^{11} protons per bunch to 2.2×10^{11} protons. The intensity increase means that the total stored beam energy will increase from 362 MJ to reach 677 MJ for the nominal parameters for each of the two circulating beams [1]. This has a critical impact on machine protection. The machine protection systems of the LHC allow for the beam to be extracted safely before uncontrolled beam losses could lead to equipment damage. For fast failures, defined as failures creating beam losses which can lead to equipment damage within 10 ms from their onset, a generic damage level threshold is set at 1 MJ being lost in the collimation region [2]. These failures are critical as it must be ensured that the LHC Beam Dumping System (LBDS) will safely dump the beam before reaching the damage level, which could occur as fast as a few turns after the failure onset.

For HL-LHC, the three-stage collimation system will be upgraded as well and will include a Hollow-Electron Lens (HEL) to reduce the beam halo population [3] by increasing the diffusion speed within the beam halo. The depleted halo also has a direct impact on the machine protection system: in case of failures that are detected *via* their effect on the beam, through the monitoring of beam losses, the detection of the failure will occur later if the beam tails are depleted. It must, thus, be ensured that also in these conditions there is a sufficient margin between the failure detection and reaching the damage limit.

The new equipment allowing to reduce the β^* down to 15 cm include the large aperture superconducting final focusing quadrupole triplets. The active magnet protection of the triplets features the novel Coupling Loss Induced Quench (CLIQ) system [4]. In addition, the new machine optics that will be put in place to reach the target β^* value increases the β-function at the location of critical elements, including the focusing triplets, which in turn increases the sensitivity to failures. Other fast failures are also crucial for the machine protection of HL-LHC, either related to novel equipment such as the crab cavities [5] or linked directly to the beam dynamics, *e.g.* in case of loss of beam-beam kick. These have been considered in [2] and will be studied further with detailed tracking simulations.

To support detailed studies of the impact of fast failures at the HL-LHC, the “FailSim” framework has been developed and this paper presents it for the first time. FailSim provides a set of tools to simulate a variety of failure cases in a flexible Python-based computing environment. The the major features of FailSim are described and the fast failure induced by the spurious firing of the CLIQ units at the triplet quadrupole magnets is used as an example to highlight the main capabilities on a realistic use case of a fast failure study.

THE FAILSIM FRAMEWORK

FailSim [6] is a Python library whose core builds a model of the HL-LHC in successive steps, prepares and adjusts the machine optics, describes the time-dependent multipolar magnetic model of the failure case, and provides a complete simulation input for tracking software. Although semi-analytical models or single-particle tracking are used to investigate and assess fast failures [2], the detailed study of complex cases, such as those featuring beams with depleted halo, require numerical simulation with multi-particle track-

* Research supported by the HL-LHC project.

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ing. FailSim has been developed to streamline that effort, with the following objectives as main requirements.

Reproducibility

To provide reproducible results, FailSim ensures that the HL-LHC lattice sequence and optics are built and configured following the versioned baseline repository data. In addition, the machine parameters are described in text files, and MAD-X is used to fine-tune the sequence to these exact requirements (*e.g.* the tune, chromaticity, etc.). Standardized CERN tools are used for that purpose, particularly the LHC mask files [7]. The resulting model is then "frozen" before being used or converted for the tracking code. Additionally, the analysis tools for the simulation results are included in FailSim, ensuring reproducible analyses for the key results (orbit excursion, β-beating, phase advance between key elements, normalized openings of collimators, collimation hierarchy, beam losses, etc.).

Flexibility

FailSim provides a pipeline to describe a complete simulation study, from lattice preparation all the way to analysis and plotting. While the different steps are built-in, the user can attach specific code at each step. FailSim ensures that all steps are kept distinct, and that previous steps can be reused. This allows to describe the computational workflow from a graph of the simulation steps. This allows simulating different failure cases while ensuring that the exact same model will be used and processing the results using the same user-contributed code. The description of the failures can be included generically, making the whole process independent of the failure being studied, providing a more robust workflow.

Evolutivity

FailSim has been designed from the beginning to be evolutive and modular. Additional modules have already been included, such as for the support of Beam Delivery Simulation, a Geant4-based particle tracking code [8]. The analysis and plotting modules consist of user-contributed code to perform data analyses from a stable, versioned code base.

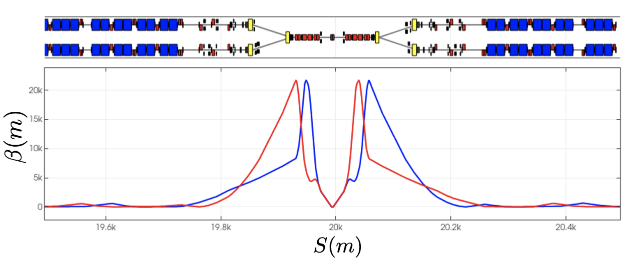

Figure 1: β-functions for the β^*=15 cm round beam optics at IR1 (ATLAS). The horizontal (resp. vertical) β-function is shown in red (resp. blue).

FailSim Architecture

FailSim uses MAD-X [9] *via* the `cpymad` [10] library to prepare the lattice model, to fine-tune and verify the machine optics and to compute the baseline and time-dependent Twiss parameters. Figure 1 illustrates the lattice and optics preparation stage. FailSim is used to load the HL-LHC sequence in MAD-X, the round collision optics is loaded, the values of the β^* at the IPs are verified with respect to the values present in the configuration file, and the optics tools are used to produce the plot in IR1. FailSim can use different plotting libraries; in particular, one can produce interactive graphs that can be manipulated and used to search for the names of elements in the sequence. The FailSim optics plots also provide interactive schematics of the machine layout for both beams, as shown in Fig. 1 (top). The main dipole magnets are shown in blue, the quadrupoles in red, with the special large aperture inner triplet magnets shown on either side of the IP (center). The very large value of the β-functions at the triplets are visible (above 5 km, with maxima above 20 km).

Once the model is prepared and validated, the dynamics of the failure are included. The failures, for example, the spurious discharge of a CLIQ unit or the firing of a quench heater circuit, are described through the time-dependence of their magnetic field, expressed through the multipolar normal and skew components. The resulting, final simulation model is then used for particle tracking. To that end, FailSim can use two tracking codes: MAD-X and BDSIM [8]. This paper focuses on the MAD-X workflow and we do not describe BDSIM tracking in more details in this work. Due to the limited number of turns that need to be simulated, which are typically up to 50 turns for fast failures, the MAD-X tracking routines are sufficient, and the simulations are fast enough so that other, more performant tracking codes, such as SixTrack [11], are not required. FailSim can launch the tracking and parallelize the computation using multiple MAD-X instances.

STUDY OF A CLIQ FAST-FAILURE WITH FAILSIM

The CLIQ magnet protection scheme will be used in the electrical circuit of the final focusing triplet quadrupoles around ATLAS (IP1) and CMS (IP5). The fast heating mechanism uses the coupling losses and is composed of a capacitor bank C, a floating voltage supply S, two resistive current leads CL1 and CL2 connecting the system to the magnet, and a Bidirectional Controlled Thyristor (BCT) package, indicated as TH in Fig. 2. Upon quench detection, the thyristors are activated resulting in a current I_C discharging through CL2 causing an over-current in magnet poles P2-P4 and an under-current in magnet poles P1-P3 as compared to the nominal current in the magnet as shown in Fig. 2. A complete description of the failure mechanisms is discussed in [2].

In the case of a spurious discharge of a CLIQ unit, the beam will be perturbed by the resulting multipolar magnetic

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field. A new connection scheme has been implemented in the HL-LHC baseline to reduce the criticality of this failure. FailSim has been used to further validate the new scheme with multi-particle tracking.

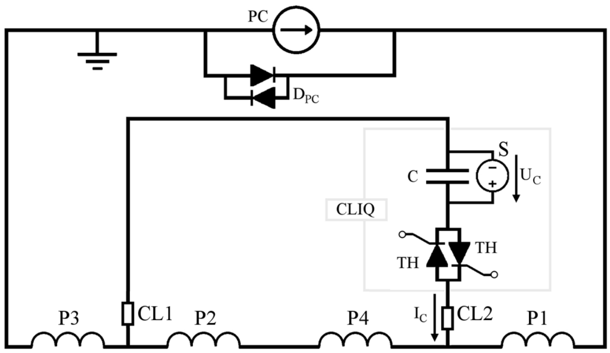

Figure 2: Schematics of a CLIQ system connected to protect a superconducting quadrupole magnet [4].

Figure 3 shows the beam orbit and envelope five turns after the spurious CLIQ discharge in the Q1 magnet left of IP1, using the new connection scheme. The beam envelope is shown at 1, 4.7 and 6.7 beam sigmas, with 4.7 and 6.7 σ corresponding to the transverse location of the hollow electron beam. One can observe that the orbit and envelope remain close to nominal (the crossing angle is visible), while the orbit would drift by up to 5 σ for the old connection scheme. It also shows the plotting capabilities integrated with FailSim: the magnet apertures are shown in the interactive plot.

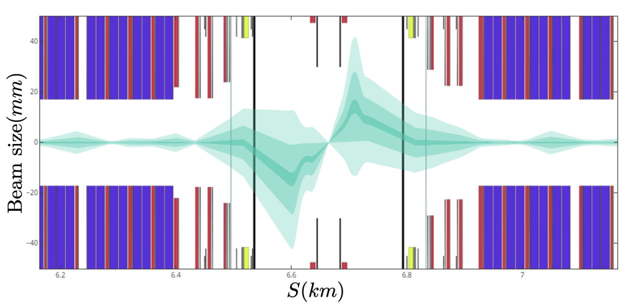

Figure 3: Vertical beam orbit and envelope, expressed in term of beam sigma, shown for 1, 4.7 and 6.7 sigma, at IR1 for the β^*=15 cm round collision optics, 5 turns after the onset of the CLIQ discharge in the Q2 magnet.

Multi-particle tracking can also be performed to estimate the global and local losses in the machine. Although MAD-X treats the apertures of the magnets and collimators as perfect absorbers, it still provides valid beam loss estimates for a first order approach to the problem. In addition to the quantitative estimate, FailSim also automatically processes the losses recorded by the different elements and collimator groups.

The tracking simulations have been validated against the simplified model used in [2]. In that model, the orbit excursion is computed with MAD-X, following the dynamics of the failure, and is used to compute the beam losses based on the integration over the transverse beam distribution. The model takes into account that the fractional parts of transverse tunes of the LHC are close to 1/3: the losses originating from a given orbit excursion are spread over three consecutive turns. This is shown in blue in Fig. 4. Tracking simulations performed with FailSim are shown in orange on the same figure. The agreement is excellent, while the tracking simulations indicate that the simplified model slightly underestimates the beam losses. An even more simplified model which would not take into account the fractional part of the tunes would overestimate the beam losses compared to tracking results. This sparks further interest in performing detailed simulation studies of the HL-LHC failure cases using the FailSim framework with MAD-X as a simple tracking code and with BDSIM to refine the analysis.

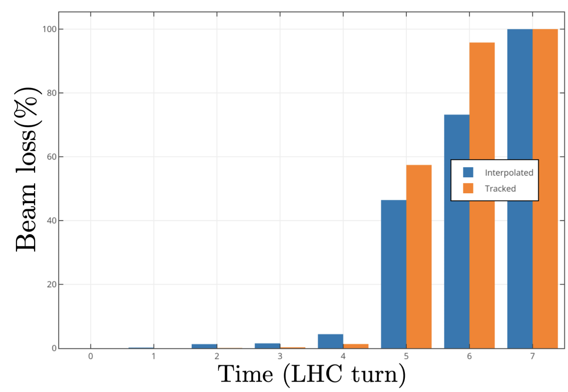

Figure 4: Total recorded losses on a turn-by-turn basis for the spurious discharge of a CLIQ unit at one inner triplet quadrupole. A simplified orbit-excursion model (blue) is compared with a detailed multi-particle simulation (orange).

CONCLUSION AND OUTLOOK

FailSim has been developed to provide a complete framework for the simulation study of fast failures at the HL-LHC, using MAD-X for beam optics and beam tracking simulations, in addition to BDSIM for detailed beam loss studies. It has been validated for the case of failures of the CLIQ units at the inner triplet quadrupoles. The objectives set during the code development have been reached and the first simulations have shown the capabilities of the code and its validity compared to prior work. Further developments foresee the full inclusion of BDSIM within the framework to provide detailed particle tracking and particle-matter interaction simulations.

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