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FIRIA – FDS MODELLING OF A LARGE UNDERGROUND CAVERN OF CERN's LHC ACCELERATOR COMPLEX

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On January 2018, CERN, the European organization for nuclear research, launched the FIRIA project (Fire-Induced Radiological Integrated Assessment). It aims at developing an integrated methodology that allows to assess the fire-induced radiological risk in particle physics laboratories and guarantee a suitable level of safety with respect to life, environment and property. In this context, one of the largest underground caverns of CERN's LHC accelerator complex (which add up to a total of 60 000 m³ at almost 100 m depth, and hosts one of the four particle detectors present at CERN) has been analyzed with FDS, exploiting at its maximum both the software and the High Performance Computing (HPC) resources available. A series of ignition sources positioned in different locations of the experimental cavern have been treated. In addition, the facility was investigated under several configurations varying the layout and ventilation conditions to evaluate not only the impact in terms of consequences, (thanks to the soot deposition sub-model), but also to determine cost-effectively which mitigation measures might be implemented. This case study demonstrates the importance of properly adapting the model to the resources available to obtain timely results, while keeping high its level of details.

INTRODUCTION

The European organization for nuclear research, CERN, is a particle physics laboratory that houses the largest accelerator complex (LHC – Large Hadron Collider) ever built worldwide (Figure 1). Its campus is composed of more than 700 surface buildings and 300 underground structures, for a total footprint of 435000 m² and 59 km of underground tunnels.

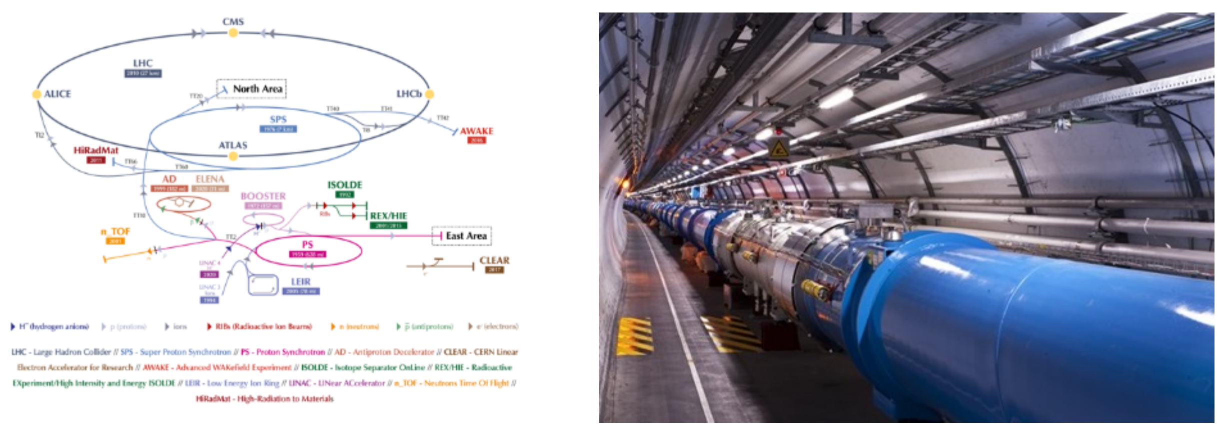

Figure 1. CERN Accelerator complex (left); a section of the LHC tunnel (right). © CERN

When the LHC is in operation (also referred to as RUN mode), a radiological hazard is present. Therefore, this aspect has to be considered when carrying out a fire risk assessment since activated smoke could potentially be released to the environment. In particular, according to the safety policy of the organization, CERN must:

- ensure the best possible protection in health and safety matters of all individuals (independently of their status), participating in the organization's activities or present on its site, as well as of the population living in the vicinity of its installations;
- limit the impact of the organization's activities on the environment, and
- guarantee the use of best practice in matters of safety.

Since most of these so-called experimental facilities lay out of the scope of prescriptive fire regulations, a performance-based approach to verify life safety conditions and design the fire safety concept is required. Hence, there is a need of a CERN-specific framework able to address simultaneously radiological and fire hazards. Such a framework can provide a realistic picture of the consequences in case of a fire during the service life of an experimental facility and which preventive and protective measures can be put in place to mitigate the risk.

THE FIRIA PROJECT

In order to address the above-mentioned issues, the CERN HSE (Occupational Health & Safety and Environmental Protection) Unit launched in early 2018 a project called FIRIA, which stands for Fire-Induced Radiological Integrated Assessment (Gai, 2019). In a nutshell, the 6 key milestones of the project can be summarized as follows:

- to establish a CERN-tailored methodology (in line with international standards such as ISO 16732-1) to assess fire risk and fire-induced radiological releases for typical research facilities (underground caverns, tunnels, experimental halls, etc.);
- to clarify the way soot agglomeration, transport and deposition can be modelled in FDS with respect to its fuel-based aerosol composition;
- to conduct a small-scale testing campaign with samples of items that are widely used at CERN;
- to account for the pertinent radiation protection aspects in the overall fire risk assessment framework (which includes defining the activation level and radionuclides content of the combustible items as well as carrying out a dose assessment to the relevant population groups);
- to implement this framework on existing facilities at CERN in the form of case studies (which allows to analyse, among other aspects, the computational effort required to deliver timely results);
- to develop a series of computing tools to ease the interaction among the project activities (input, and output exchange between fire and radiation protection models), to monitor the usage of the High Performance Computing (HPC) cluster in which all related simulations are run, etcetera.

When implementing this framework on existing facilities, there are several aspects worth highlighting with respect to the FDS simulations that are carried out as part of the analysis. For each facility a series of ignition sources are studied: on the one hand, the location and nature of these sources is chosen based on several aspects such as the radiological hazard associated, the likelihood to hamper evacuation means, or their potential to cause significant damage to the property housed inside the infrastructure. On the other, a testing campaign allowed to characterize the smoke production of the items in terms of soot and CO/CO2 yields as well as the size distribution of the particles produced. All these aspects are used as input data on the FDS simulations in order to feed the deposition sub-model. In these studies, the results of the FDS simulations not only provide the data needed to perform the evacuation simulations, and property protection analysis, but they subsequently feed the input of the environmental dispersion simulations that are key to carry out the dose assessment to the population groups identified. For this reason, in addition to measuring the visibility, temperature, and pressure, special attention will be put to the mass of soot produced, released, and deposited in the equipment. Additionally, these results provide valuable information to the in-house fire brigade to help building up the intervention plan.

CASE STUDY

In this context, the study presented in this paper focuses on the FDS modelling process of one of the largest underground caverns of CERN's LHC accelerator complex. A facility of this nature was chosen as one of the key case studies for the methodology developed due to its complex nature and strategical importance for the organization. Moreover, in terms of resources, it was expected to push to its limits the computational resources available and benchmark the dedicated computing tools developed to pre-process and post-process the data.

Description of the facility

The underground caverns of the accelerator complex are key elements of CERN's LHC infrastructure that contain unique, state of the art technology that can be highly sensitive to small changes in ambient pressure and temperature. In particular, a good example of the challenges that poses this environment, are the so-called experimental caverns located 100 meters below the surface and inside which a particle detector is housed (Figure 2).

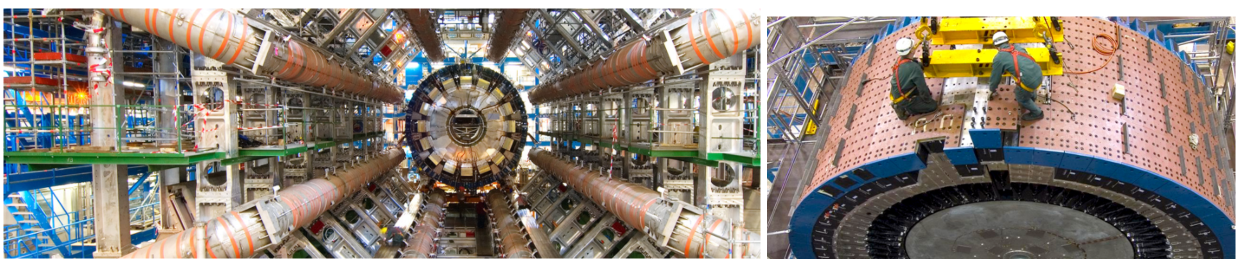

Figure 2. A particle detector (left); two workers (right) performing maintenance activities on the detector © CERN

Each experimental cavern (e.g.: Cavern A on Figure 3) is a fire compartment, connected through fire doors to the adjacent service caverns (caverns B and C), tunnels, and surface buildings surrounding it. Even if the analysis was mainly focused in caverns A and B, prior to carrying out a detailed analysis, it was fundamental to determine whether the smoke could potentially spread from one cavern to another due to leakages (mainly for cabling) and have a significant effect on the fire dynamics. The total volume of the full complex put together adds up to more than 200 000 m^3, which means, that if an adequate level of grid resolution wants to be used, (e.g. 0.25 m^3) at least 14 000 000 cells would be needed. Moreover, due to the radiological specificities of this underground complex, a pressure cascade is established among the caverns to avoid air release from radiological areas when the LHC is in operation. An in-depth investigation of the order of magnitude of the possible leakages with respect to the total volume of each cavern, allowed to discard the possibility of smoke spreading from adjacent caverns, since they are deemed to be properly compartmentalized, and hence the caverns have been analyzed independently. Additionally, the forced ventilation conditions inside each cavern differ depending if the facility is in run or shut down mode as further explained in the section that follows. For the sake of simplicity, the procedure followed (and the results obtained) will be illustrated using cavern A as example due to its more complex and interesting nature.

FDS Model

When building an FDS model, it is of outmost importance to choose an adequate set of boundary conditions (McGrattan et al., 2020). This aspect is especially relevant in this particular case since, depending on the status of the LHC infrastructure: cavern A is connected with surface building 2 through shafts 1 and 2 when the facility is in shut down (no radiological concerns), whereas when the LHC is in operation, the shafts are closed with a shielding screen for environmental protection reasons . Moreover, if the two volumes are linked, then the ventilation conditions of both will impact the fire dynamics of the overall volume (Figure 4).

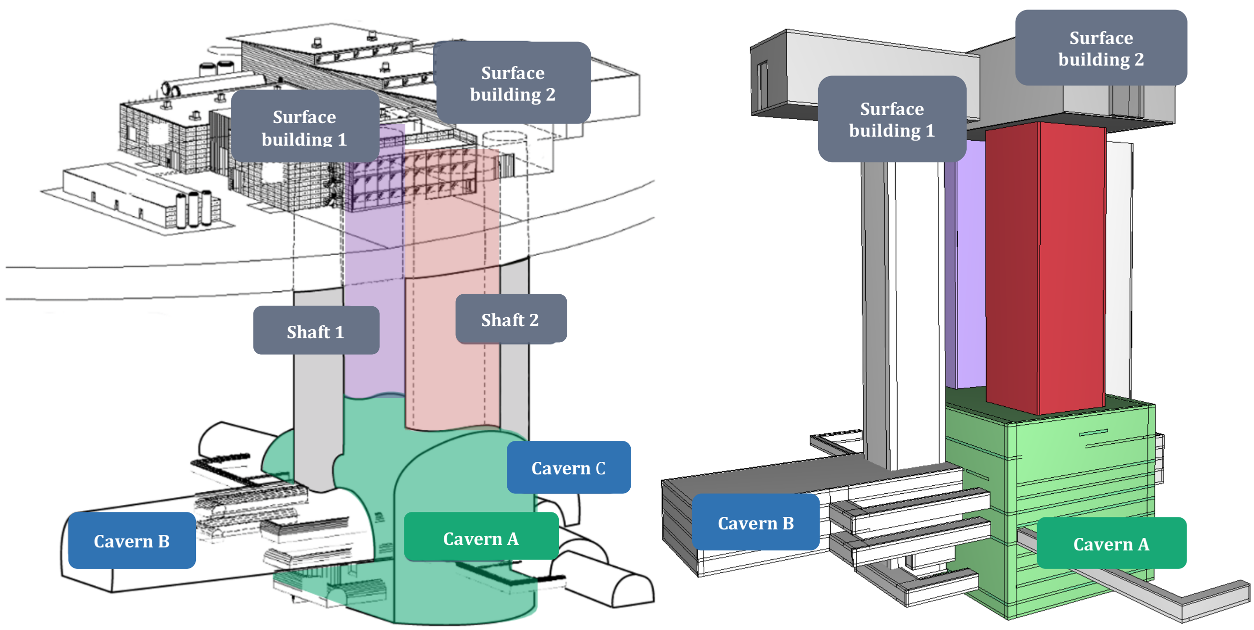

Figure 3. Example of a complex set of underground caverns, tunnels, and surface buildings part of the LHC accelerator: sketch (left), FDS model (right).

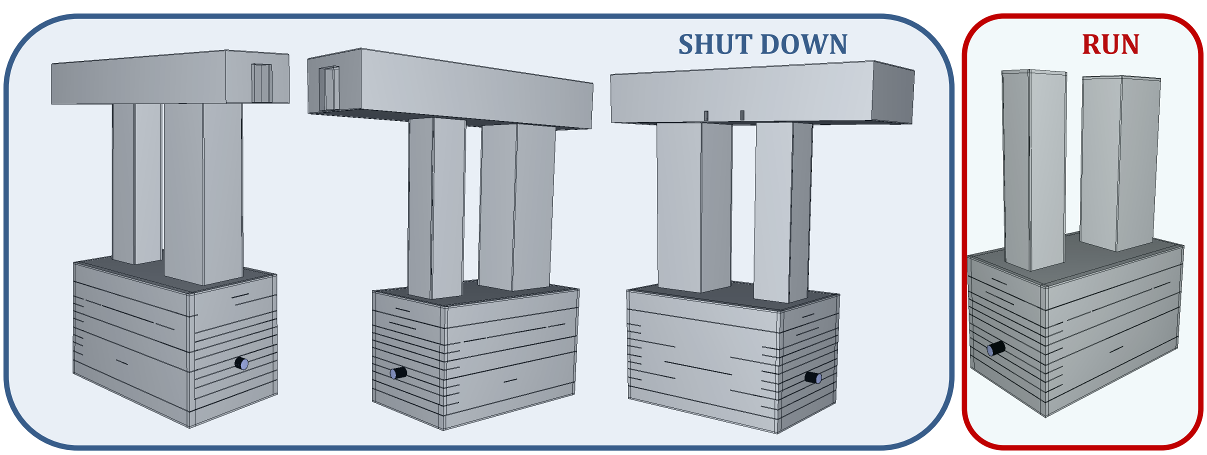

Figure 4. Overview of some of the possible natural ventilation conditions when cavern A is connected to the surface building (LHC in shut down mode), and when they are not (LHC in run mode).

Several FDS simulations were run for a series of fire scenarios, and it was corroborated that the ventilation conditions of surface building 2 (whether those were natural or forced), did not have a relevant impact on the fire dynamics of the facility when in shut down. This phenomenon can be attributed to the fact, that in between them, there are two shafts of 50 meters of length, and circa 15 meters of diameter. This allowed to simplify significantly the number of simulations to be run for each fire design: if in shut down mode, the set-up of surface building 2 was unique regardless of the configuration of cavern A. Since the ventilation set up on the surface building also has a significant effect on the environmental dispersion simulations, and dose assessment, a conservative choice was made with respect to environmental protection concerns. Finally, to ensure that the boundary conditions of the domain itself would not tamper the results, the layout shown in Figure 5 was used.

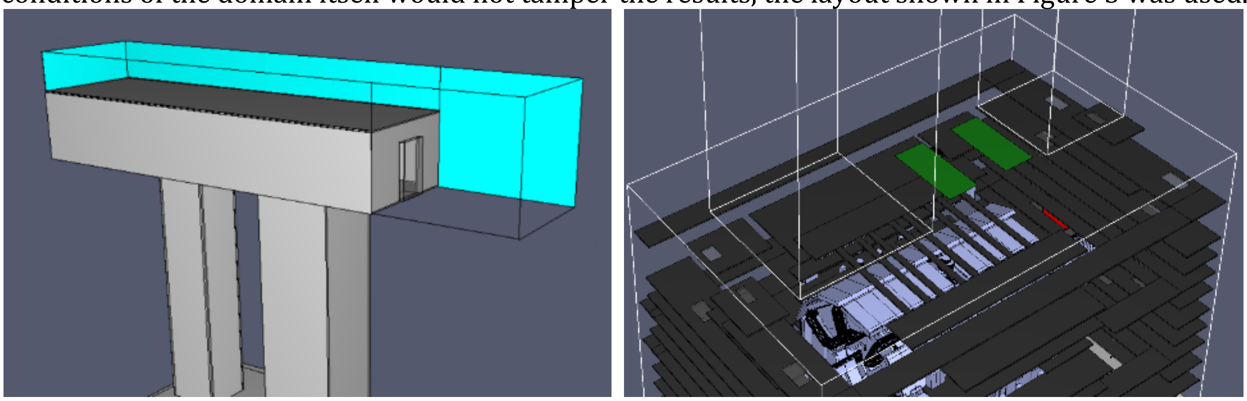

Figure 5. Domain boundary conditions when the LHC is shut down (left). The green rectangles represent the extraction grids that are active when the LHC is in run (right).

When the LHC is in run, the challenge regarding the FDS modelling of an experimental cavern lies on the fact that the computational domain is sealed (because so is the cavern), and the exchange of air with the environment is performed by activating the extraction grids located on its ceiling (Figure 5). In order to deal with this configuration, a pressure zone was defined, and the volume flows of the forced ventilation conditions were set to resemble the reality as closely as possible (Li et al., 2020). To achieve this goal, the extraction grids present in the lower end of the cavern in charge of maintaining the pressure cascade with respect to the adjacent caverns were also modelled (Figure 6). A control on the absolute pressure inside cavern A allowed to activate these outlets, only when the pressure exceeded a certain threshold value.

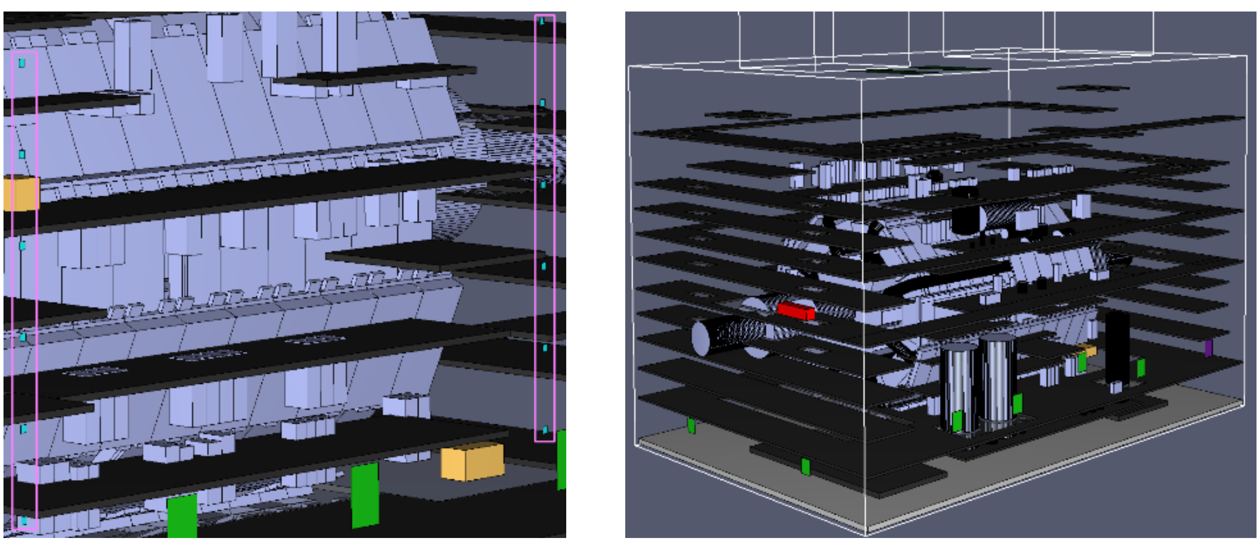

Figure 6. On the right, the blue emerald squares which are part of one of the extraction systems present in the cavern. On the left, the purple rectangle represents another outlet which corresponds to the third extraction system present in cavern A.

Regardless of the status of the LHC machine (run or shut down), the forced ventilation scheme entrains a constant volume flow of fresh air on the lower end of the cavern through the inlets represented as green rectangles in Figure 6.

Concerning the modelling of the structure and machines inside the cavern itself (i.e. the particle detector), a high level of detail is required given the specific goals of a FIRIA assessment, as detailed in the previous section. With this idea in mind, a pre-existing CAD model of the particle detector was imported into PyroSim (Figure 7). The remaining structures present in the cavern are the gangways distributed along the cavern height and were manually introduced as obstructions in the FDS model. These gangways, however, are perforated steel plates full of holes and using a porous media representation might have led to a more accurate representation of the infrastructure. An initial probing of this alternative, yielded almost twice the time to finish the computations for the same configuration and ignition source, and hence, it was deemed sufficient to treat the gangways as obstructions for the purpose at hand, since it is expected to be more penalizing in terms of soot deposition.

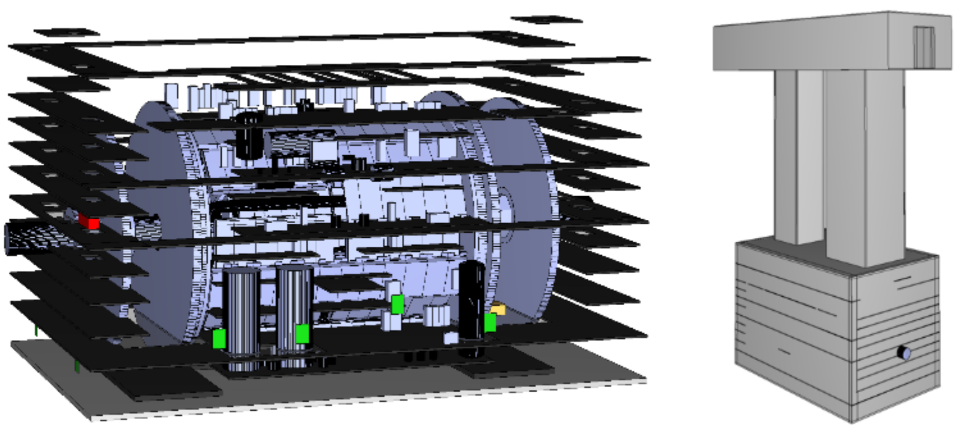

Figure 7. On the left, detail of the final FDS model of cavern A including the particle detector model. On the right, final configuration of the complex when the LHC is in shut down.

Finally, it is worth highlighting that in terms of volume, the largest models run for this study were those characterizing the facility when the LHC is in run comprising cavern A and surface building 2; which was meshed using an 11.5 million cell grid, subdivided into 337 meshes that were run in parallel in a total of 760 CPUs taking circa 2 days to complete for 4000 seconds of simulation time. This model used standard FDS rectilinear obstructions, but in future work it might be worth to investigate the applicability of the immersed boundary method (Vanella et al., 2016). To optimize the computational resources used, the mesh subdivision was not performed evenly along the domain: several iterations were executed and by analysing the CPU time results of each simulation, and in the regions that required more computational effort, the cell to mesh ratio was lowered.

Results

A total of 25 different FDS simulations were run with the aim of analysing different design fires, facility configurations and ventilation conditions. For each of those, a thorough quality check was performed, to validate that the simulation conditions were aligned with the associated input and expected output. In particular, due to the specific nature of this study, and the relevance that the amount of soot released implies, a mass balance check was carried out allowing to ensure that the soot deposited, exiting the mesh, and inside the domain added up to the total amount of soot produced. Moreover, this type of evaluation is critical to determine the effect of different ventilation strategies (upon fire detection) on the total amount of soot released, and the impact this will have on the environmental and dose assessments. Figure 8 shows a comparison of the results obtained when turning on and off the ventilation in cavern A when the LHC is in run mode.

Besides checking the impact of the ventilation on the environmental consequences of a fire inside an experimental cavern, the pressure, visibility, and temperature inside the facility were also analysed to determine the conditions for evacuation, fire brigade intervention, and business continuity. It is also worth noting, that in order to set-up and postprocess all the simulations, inhouse Python scripts were developed to facilitate the tasks and speed up the process of treating the data (in average, the results of each simulation added up to 80Gb of files).

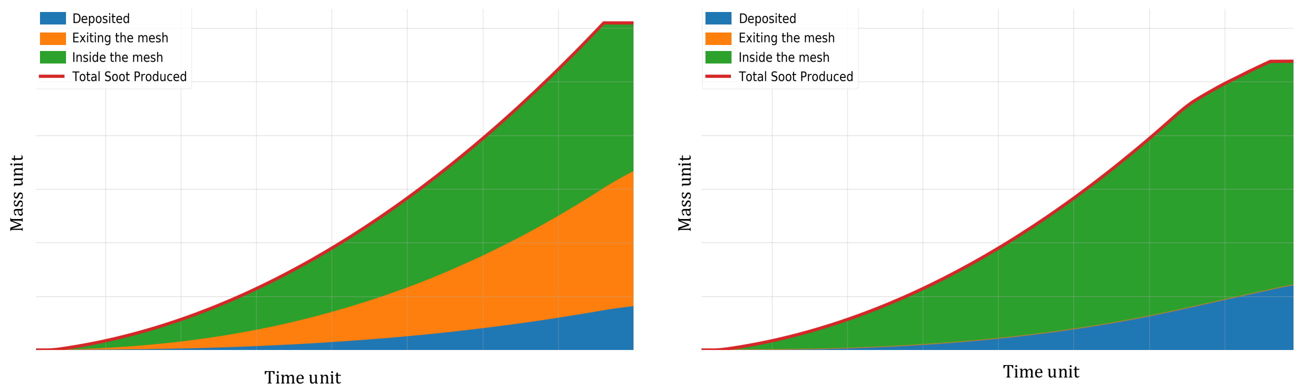

Figure 8. Example of the mass balance check carried out on the soot distribution on the domain for every simulation run. For the LHC in run conditions: on the left, distribution when the ventilation is turned on, and on the right, when the ventilation is turned off.

CONCLUSIONS

In the context of the FIRIA project, one of the largest caverns of CERN's LHC accelerator complex was modelled in FDS allowing to exploit to its limits both the FDS software and the HPC resources used to run the simulations. This pilot case highlights the need of choosing wisely the scope and conditions of the assessment prior to the running the model with different ignition sources and/or ventilation conditions. Developing specific tools and validation tests to ensure the quality of the results proved to be key, especially when the analysis relies on results requiring high resolution. The aerosol modelling of FDS, and the importing capabilities of PyroSim rounded up the model allowing to reach a level of detail in line with the requirements of CERN's FIRIA project.

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