INTERVENTION MODELLING AT HIGH-ENERGY PARTICLE ACCELERATORS

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Abstract

An important aspect in the design and operation of high-energy particle accelerators is the planning of maintenance interventions. In the planning of these interventions, optimizing the exposure of the maintenance workers to ionizing radiation is a core issue. In this context, we have addressed the need for an interactive visual software tool. The intervention planning has been modeled mathematically. A proof-of-concept software tool has been implemented using this model, providing interactive visualization of facilities and radiation levels, tools for trajectory planning and automatic calculation of the expected integrated equivalent radiation dose. We explore the use of the software using a large experimental hall at CERN as a case study. Interactive visualization of the facilities and radiation levels, tools for interactive trajectory planning as well as automatic calculation of the expected integrated equivalent dose contracted during an intervention are explored. The obtained results prove the relevance of the developed methodology and software tool and demonstrate, among others, a better exploitation of the simulation data, leading to a potential accuracy gain.

INTRODUCTION

The presence of ionizing radiation makes certain particle accelerator environments an undesirable working environment. In these facilities, during operation, accelerator components will indeed be activated by the beam itself and by the secondary radiation field. Some strategies to mitigate the risk of irradiation of maintenance workers in this respect are, amongst others, optimization of the design of the equipment for easier maintenance and handling, implementation of telerobotics solutions, and the implementation of tools for optimized planning of interventions. This last strategy is the subject of this paper.

INTERVENTION PLANNING METHODOLOGY

It is possible to model interventions in high-energy particle accelerators environments with ionizing radiation using a sound but accessible mathematical model. Therefore, we model an intervention $\mathcal{I}$ as a set of tasks T_k, each with a specific description and duration τ_k. The first task T_0 hereby corresponds to entering the particle accelerator facility, while T_K corresponds to exiting the facility.

A second set of parameters of the intervention is the trajectory $\mathcal{T}$, consisting of a series of locations m_i, $i = 0, 1, \ldots, N$.

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A time t_i can be associated with each location m_i. From this trajectory $\mathcal{T}$, it is furthermore possible to construct paths between all pairs of consecutive locations m_i and m_{i+1}, denoted by S_i, $i = 0, 1, \ldots, N-1$. With each path, a velocity v_i can be associated.

Finally, a mapping of the trajectory $\mathcal{T}$ and the intervention $\mathcal{I}$ is a last integral part of the intervention, given the fact that the trajectory models the physical locations of the intervention. This leads to:

$$\forall\, T_k \in \mathcal{I} : \quad T_k \text{ is assigned to a location } m_i \text{ and } t_i = \tau_k,$$
$$\forall\, m_i \in \mathcal{T} \text{ and } \nexists\, T_k \text{ assigned to location } m_i : \quad t_i = 0,$$

with $K \leq N$.

This intervention planning model can now trivially be used to compute various radiation protection quantities. Probably the most relevant quantity in this respect is the effective dose equivalent H_{eff} ([Sv]), the radiation protection quantity used for quantifying the stochastic health risk of radiation, taking into account the nature of the organs irradiated and the type of radiation. If measures or simulations of this effective dose rate equivalent are available on the trajectory report, the above-described model can be used to computed the effective dose equivalent associated with the intervention as follows:

$$H_{\text{eff}}(\mathcal{I},\mathcal{T}) = \sum_{i=0}^{N} t_i \dot{H}_{\text{eff}}(m_i) + \sum_{i=0}^{N-1} \int_{m_i}^{m_{i+1}} v_i^{-1} \dot{H}_{\text{eff}}(s)\,\mathrm{d}s. \tag{1}$$

This equation lends itself very well to implementation in software. Using the trapezoidal rule, equation (1) can be calculated as:

$$H_{\text{eff}} = \sum_{i=0}^{N} t_i \dot{H}_{\text{eff}}(m_i) + \sum_{l=0}^{q} \frac{1}{v_i} \frac{\dot{H}_{\text{eff}}(s_l) + \dot{H}_{\text{eff}}(s_{l+1})}{2} \|s_l s_{l+1}\|, \tag{2}$$

A SOFTWARE IMPLEMENTATION

A proof-of-concept software tool for computer-aided intervention planning, implementing this model has been conceived [1], and tested [2, 3] in the context of CERN. The software allows for intervention planning in a visual, interactive way in a three-dimensional virtual environment. This intervention planning specifically includes interactive visualization and data fusion of the facility geometry and radiation simulation data, for which it makes use of input and output data of FLUKA [4,5] simulation data. It provides visual interactivity for the input of a trajectory in this virtual environment, giving the user of the software the ability to interactively alter and eventually optimize the trajectory. It

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furthermore includes three-dimensional data processing in the implementation of equation (2), and includes reporting facilities to make a paper or electronic document summarizing the intervention from a radiological point of view.

A CASE STUDY: THE TCC2 AREA AT CERN

In this section, we present a case study for the use of the developed proof-of-concept software tool in the context of the TCC2 facility at CERN.

Description of the Facility

The TCC2 area is a target area, where primary particle beams interact with metallic targets to generate secondary beams which are then shuttled to physics experiments. It is located in a zone called the North Target Area, a location that is one of the most radioactive at CERN.

As can be seen on Figure 1, the TCC2 area consists of three targets named T2, T4 and T6 followed by their respective beamline. Each of them can then be either dumped or collimated by a device named TAX (standing for "Target Attenuator in eXperimental areas"). These elements are metal plates (copper and iron) mounted in such a way that they can be set up to either block or accept a particle beam through small holes (sometimes filled with beryllium for attenuation). This is done using electrical motors located at the downside of the devices.

Since the targets directly receive the beams and the TAXes can be used as beam dumps, for instance to block any beam circulation to enable human access to the facility, they are the most activated parts of the area.

Purposes of the Simulations

Simulations using the Monte Carlo code FLUKA were performed in order to plan corrective maintenance and consolidation interventions scheduled during the first long shutdown of the LHC (from 2013 to late 2014), and estimate in advance the radiation doses to be expected for the workers involved.

During those interventions, a large number of tasks were anticipated, both on the assets present in the facility (vacuum systems, beamlines and magnets, TAXes, collimators and targets) and the infrastructures (civil engineering to ensure water tightness, improve draining, cooling and ventilation systems, overhead crane and electrical installations including lighting).

The radiation protection Monte Carlo simulations were used to estimate anticipated individual and collective doses received by the personnel taking part in these interventions (about 160 people). These estimated doses were to be confirmed by manual surveys shortly before the beginning of the operations.

Output of the Simulations

A FLUKA simulation is based on a single file containing all the necessary information about the conditions encountered in a facility of interest, such as the energy, density and positions of the particle beams, and the irradiation pattern associated with delays needed for radiation decay if necessary. But more importantly, it contains also the whole geometry of the area under focus, which must be as accurate as possible to get realistic results.

FLUKA is a generalist calculation code which enables the simulation of a large number of physical quantities like particle fluence, deposited energy in the matter and, in our case, ambient dose equivalent rate. Using dedicated software [6], the results can be displayed in two dimension projections of the geometry as illustrated on Figure 1. Using the model presented previously, it is then possible to estimate a received equivalent dose for a given task by creating a trajectory in the projection plan. This can be done using the developed proof-of-concept software, which can also visualize the simulations of interest in a fully three-dimensional way, as discussed in the next section.

The dose estimates based on such trajectories can be optimized or refined using different scenarios and trajectories for each task to be performed. In the case of the TCC2 consolidation works, this enabled to estimate collectives doses for each system-related intervention, for instance the repairs of the TAX tables (11505 μSv split over 20 people) or the repairs on the vacuum systems (1267 μSv for 8 people) [7].

Use of the 3D Interactive Planner

In the case of highly radioactive areas such as TCC2, the use of a 3D interactive planner can prove to be more efficient than 2D projections. While also allowing to superimpose the geometry and radiation protection data, it allows for a finer tuning of the trajectory without having to worry about where the projection will be made (for instance at beamline-level where the tasks are performed, or at chest level where the dosimeters are worn).

A 3D planner also enables technicians who will perform the tasks and are not familiar with FLUKA or radiation protection data to compare trajectories and courses of action, which is a necessary part of the ALARA procedures developed at CERN for such interventions. This is also a major asset for interventions in highly activated zones such as TCC2 were a change of trajectory can produce fairly distinct received doses.

DISCUSSION AND CONCLUSION

In the context of the design and operation of high-energy particle accelerators, we have proposed an intervention planning method for environments with ionizing radiation. A proof-of-concept software tool has been implemented using the developed model, providing interactive visualization of facilities and radiation levels, tools for trajectory planning and automatic calculation of the expected integrated equivalent radiation dose. We have here discussed a new case study for a large experimental hall at CERN.

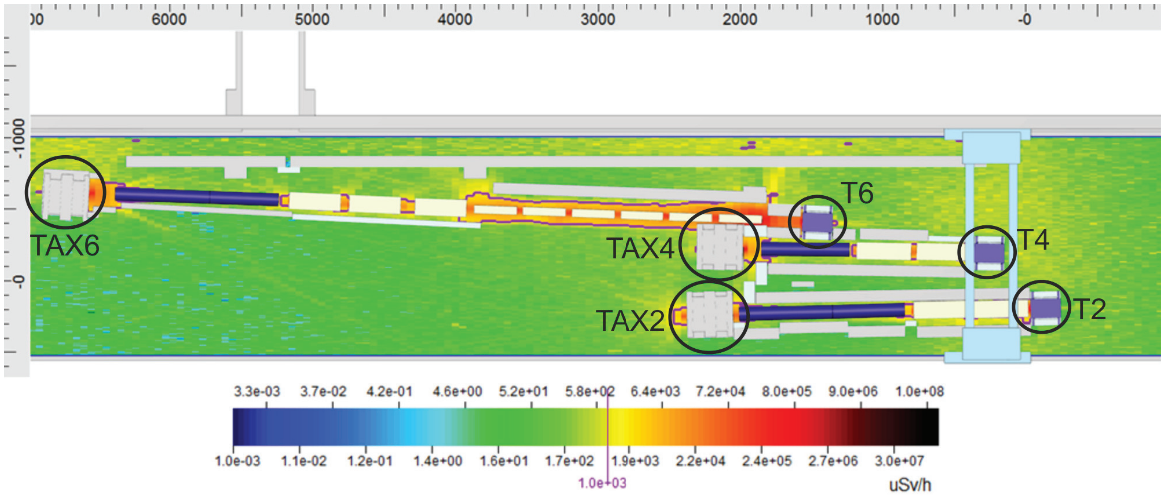

Figure 1: Ambient dose equivalent rates in $\frac{\mu Sv}{h}$ calculated in the TCC2 area.

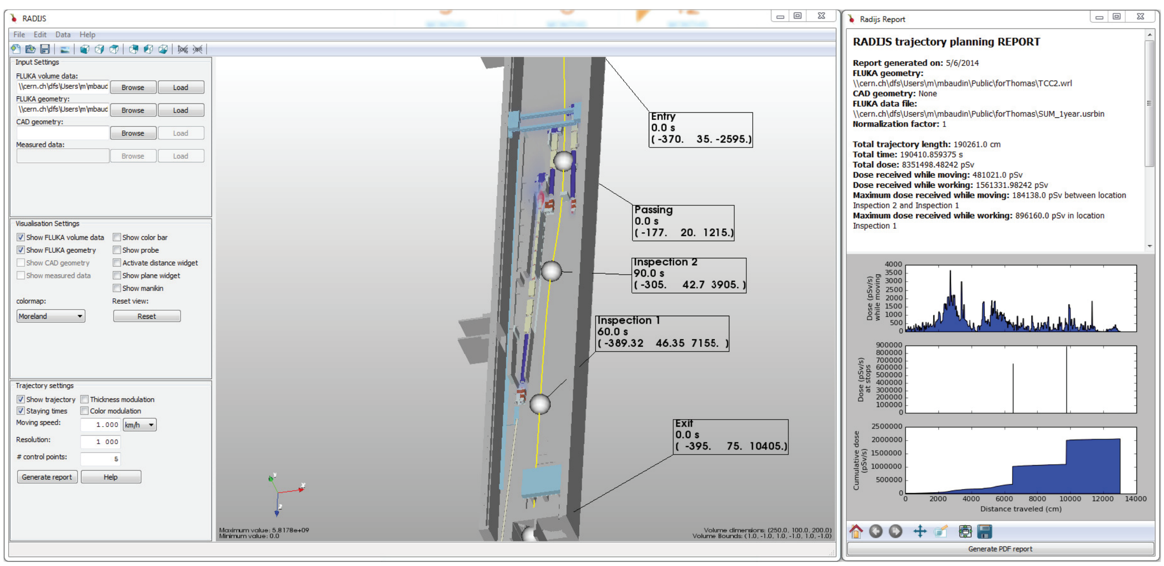

Figure 2: Interactive visual intervention planning of an imaginary intervention using the proof-of-concept implementation of a tool for computer-aided intervention planning.

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