Nuclear Instruments and Methods in Physics Research A 743 (2014) 14–21

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

The practical use of an interactive visualization and planning tool for intervention planning in particle accelerator environments with ionizing radiation

Thomas Fabry [a,*], Jan Blaha [a], Liesbeth Vanherpe [a,1], Christian Braesch [b], Laurent Tabourot [b], Bruno Feral [a]

[a] European Organization for Nuclear Research, CERN, CH-1211 Genève 23, Switzerland
[b] SYMME, Université de Savoie, Polytech Annecy-Chambéry, 5 Chemin de Bellevue, 74944 Annecy le Vieux, France

ARTICLE INFO

Article history:
Received 18 November 2013
Received in revised form
16 December 2013
Accepted 21 December 2013
Available online 16 January 2014

Keywords:
Ionizing radiation
Intervention planning
Radiation dose minimization
Interactive data visualization
FLUKA

ABSTRACT

A core issue during the planning of a maintenance intervention in a facility with ionizing radiation is the minimization of the integrated equivalent dose contracted by the maintenance workers during the intervention. In this work, we explore the use of a technical-scientific software program facilitating the intervention planning in irradiated environments using sound mathematical concepts. We show how the software can be used in planning future operations using a case studies: the decommissioning of a beam dump for a linear 160 MeV H^- accelerator. Interactive visualization of the facilities and radiation levels, as well as tools for interactive trajectory planning are explored, as well as automatic calculation of the expected integrated individual dose contracted during an intervention.

1. Introduction

Particle physics or High Energy Physics (HEP) is a branch of modern physics that studies the smallest known constituents of matter. The instruments for studying these miniscule particles, used at particle physics laboratories, are particle accelerators and detectors. Accelerators boost beams of particles to high energies before they are made to collide with each other or with stationary targets. Detectors observe and record the results of these collisions, aiming to prove or disprove physics theories [1]. The circulation and collisions of high energy beams in the accelerators and detectors have an undesirable consequence, namely the radiological activation of some of the components of the accelerator and detectors, and surrounding equipment in these facilities [2].

CERN, the European Laboratory for Particle Physics, was founded in 1954 in Geneva (Switzerland) as a joint European project to provide a major scientific facility for nuclear physicist [3]. Over the years nuclear physics gave birth to particle physics, which is now the main interest of CERN. For the purpose of particle physics research, CERN operates an accelerator chain, going from two linear injectors at low energy (50 MeV for protons, 4.2 MeV/u for heavy ions) to the Large Hadron Collider, a machine of circa 27 km in circumference, designed to accelerate two counter-rotating beams of protons to an energy of 7 TeV, or to fully stripped lead ions (Pb^{82+}) to 2.76 TeV per nucleon [4,5].

At CERN, as in other HEP laboratories, the so-called ALARP or ALARA approach (As Low As Reasonably Possible or Achievable [6,7]) is implemented to protect maintenance personnel from ionizing radiation during interventions in particle accelerators and detectors. This approach consists of justifying, optimizing and limiting the dose received by all those who need to work on activated components (e.g. [8]). In a more narrow sense, ALARA is the implementation of the optimization procedure in radiation protection. Optimizing alone can still lead to high doses, in which case the principle of limitation guarantees that radiation workers will not receive excessively high doses.

A core issue during the planning of a maintenance intervention in a facility with ionizing radiation is the minimization of the dose contracted by the maintenance workers during the intervention. This optimization cannot fully be automated, since the practical feasibility of intervention tasks requires human assessment based on experience. However, a software tool could potentially greatly enhance the planning of an intervention. The visual conditions in which the intervention planner can perform the optimization are important, and the several layers of data involved in the planning

* Corresponding author.
E-mail address: thomas.fabry@cern.ch (T. Fabry).
[1] Current address: Blue Brain Project, EPFL, CH-1015 Lausanne, Switzerland.

http://dx.doi.org/10.1016/j.nima.2013.12.051
0168-9002/

process, i.e. the facility geometry, the radiation levels and the intervention trajectory, therefore need to be appropriately visualized.

In this context, an important research question is how today's state-of-the-art visualization techniques, for instance those found in the domain of medical imaging, can be applied or adapted to optimize the human interventions in infrastructures emitting ionizing radiation.

Existing solutions, tailored for nuclear power plants and as such providing point-kernel methods to calculate gamma dose-rates based on source terms encountered typically in such facilities [9], cannot be applied directly to radiation environments encountered at high energy accelerators [10]. The composition of the prompt radiation field and, as a consequence, also the source term of the produced radionuclides is different in HEP facilities than in nuclear power plants. In addition, the spatial distribution of the residual radiation source term cannot be left to the user due to the complexity of the beam interaction with the accelerator infrastructure. A beam loss in a high energy accelerator triggers the evolution of secondary particle showers which in turn induce the production of radioisotopes. These showers depend on a multitude of parameters like material composition, the actual geometry of the accelerator infrastructure, particle types and energies. As a consequence they can only be described with the help of explicit Monte Carlo particle transport simulations, and it is not possible to approximate the radiation pattern with point-kernel methods, and the like [2].

It is therefore necessary to split the task of planning an intervention at high energy proton accelerators in two steps. In the first step the nuclide inventory and the associated residual radiation field has to be calculated by using a Monte Carlo code like FLUKA [11,12] which includes dedicated high energy nuclear models and is capable of treating the full build-up and decay chain of the radionuclide-production based on a user-defined irradiation pattern and customizable material compositions. In contrast to the simulations conducted with a software package for use in nuclear power plants, these calculations are based solely on the beam loss of the primary beam, followed by an explicit treatment of all subsequent particle showers leading to the production and spatial distribution of the radioisotopes and the resulting residual radiation fields which include not only gamma radiation but also electrons and positrons. In a second step these results can be used to plan and optimize interventions, which is the topic of this paper.

2. Planning of an intervention in an environment with ionizing radiation

In order to deal with intervention planning in an environment with ionizing radiation, a proof-of-concept of a software tool for interactive visual planning in an environment with ionizing radiation was developed. The software tool has been developed to be able to used in a collaborative fashion and unites features for multiple stakeholders with different requirements, as this is the way HEP big science projects are usually organized [13]. In the same spirit, the software tool has also been developed to be intuitive, and as easy to use as possible.

As part of the software development, the possible benefits of a user study, with the goal of enhancing the visual conditions in which the intervention planner using the software tool is minimizing the radiation dose have already been explored [14,15], and the software development methodology itself has been documented in Ref. [15].

The implementation of the software tool relies on a sound mathematical model [10], summarized in Fig. 1.

An *intervention* $\mathcal{I}$ is a set of *tasks* T_k that need to be completed by the maintenance worker, each with a specific description and

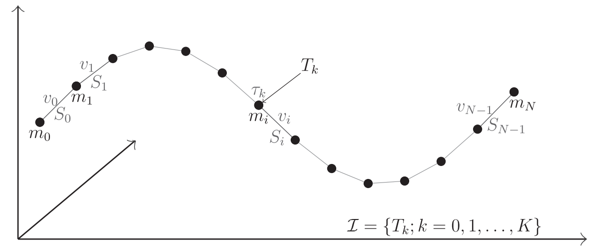

Fig. 1. Schema of the mathematical model for intervention planning.

an estimated duration τ_k:

$$\mathcal{I} = \{T_k; \quad k = 0, 1, \ldots, K\}. \tag{1}$$

Task T_0 corresponds to the entrance of the facility by the worker; task T_K corresponds to the exit of the facility.

A *trajectory* $\mathcal{T}$ consists of a series of *locations* m_i, with $i = 0, 1, \ldots, N$. At each location m_i, a maintenance worker will spend an amount of time denoted by t_i. The *path* between two consecutive locations m_i and m_{i+1} is denoted by S_i, with $i = 0, 1, \ldots, N-1$. Each path S_i is taken by the maintenance worker at a velocity v_i. In the current software implementation, $\forall v_i : v_i = v$.

The planner of an intervention will decide on a trajectory $\mathcal{T}$ with an intervention $\mathcal{I}$ in mind, thus constructing a map between $\mathcal{I}$ and $\mathcal{T}$. As a result

$$\forall T_k \in \mathcal{I} : \quad T_k \text{ is assigned to a location } m_i \text{ and } t_i = \tau_k, \tag{2}$$

$$\forall m_i \in \mathcal{T} \text{ and } \nexists T_k \text{ assigned to location } m_i : \quad t_i = 0, \tag{3}$$

with $K \le N$.

Workers that perform maintenance in an environment with ionizing radiation contract a *radiation dose D* (Gy = J/kg), leading to an *equivalent dose H* (Sv) [16,7].

The equivalent dose H contracted by the maintenance worker performing an intervention $\mathcal{I}$ mapped on a trajectory $\mathcal{T}$ is calculated as the sum of the radiation received at the locations m_i and the radiation received over the paths S_i between the locations:

$$H(\mathcal{I}, \mathcal{T}) = \sum_{i=0}^{N} t_i \dot{H}(m_i) + \sum_{i=0}^{N-1} \int_{m_i}^{m_{i+1}} v_i^{-1} \dot{H}(s)\, ds, \tag{4}$$

where s is a point on the path S_i. The radiation rates $\dot{H}$ are available from simulations of the activation of the facility equipment or from manual measurements performed previously in the irradiated facility. Similar equations hold for the many other related concepts in radiation protection, such as the *effective dose E* (Sv), and for the many related units, such as the *ambient dose equivalent* $H^*(10)$.

3. Practical visual interactive intervention planning in particle accelerator environments with ionizing radiation

3.1. A software tool for visual interactive intervention planning in particle accelerator environments with ionizing radiation

For what concerns traditional intervention planning, we can discern two main scenarios: intervention planning as part of the study of a new (accelerator) facility, for estimating the individual and collective doses due to a maintenance or handling activity that is foreseen to be undertaken, or might be needed, in the future; and work dose planning as part of the preparation an intervention that is scheduled. The first form of intervention planning can be used as part of the design process of a new facility, to optimize future interventions in terms of work dose, by optimizing the design of the facility. An example of this form of intervention planning will be treated further in this article.

In both of these cases, the start of the intervention planning exercise is the explicitation of the maintenance scenario and listing of the different steps associated with the maintenance activity, and their attributes. These attributes are mainly the location of the workers during the different steps of the intervention, and the duration of each activity in the intervention. To come to collective dose, also the number of workers involved should be stated.

This explicitation of the maintenance scenario is a rather encumbered process, in which many collaborators (radiation protection experts, work planners, equipment owners, maintenance personnel, etc.) are involved. The tools used for this process are mostly 2D maps of a facility, on which locations are approximately indicated (for an example, see Fig. 2), and big Excel tables to perform the (mostly manual) dose calculations.

The software tool we developed can enhance this intervention planning process and turn the current work dose planning into software-supported interactive visual intervention planning: the different steps associated with the maintenance can be inputted in the program and can be visually and interactively be positioned in 3D in the facility, with immediate visual feedback of the radiation doses, and can be associated with staying times. From this input, the software can then immediately construct a report, including a dose table and visualizations of the dose rates, for example.

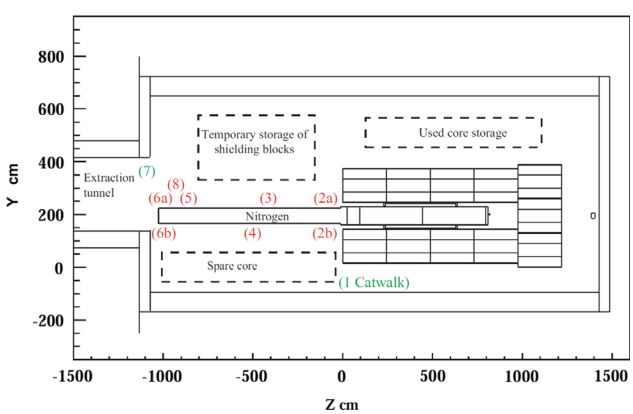

Fig. 2. Areas where workers will be situated during a beam dump core replacement intervention [17].

3.2. Visual interactive intervention planning as part of the design process of a new accelerator facility

Linac4 [18] is a new linear accelerator at CERN, designed to provide a pulsed 160 MeV H^- beam. Linac4 will replace the present 50 MeV proton accelerator LINAC2 as injector to the CERN accelerator chain [19]. Linac4 will as such become an essential component of the whole CERN accelerator complex, especially considering the future increase of the LHC luminosity [20]. A transfer line will connect Linac4 to the rest of the accelerator complex, as illustrated in Fig. 3.

Linac4 is terminated by a dump collecting the beam during the accelerator commissioning phase, during the measurements, and in case of degraded situations of the beam. The material of the beam dump can as such become highly activated. Therefore, an effective shielding surrounding the dump was established in order to limit activation of the structures placed in dump proximity and to protect personnel accessing the machine, for instance during maintenance operations of, or near this beam dump.

As part of the design effort of the beam dump, a detailed Monte Carlo calculation, using the FLUKA particle physics simulation package [11,21], has been performed in order to optimize the choice of shielding material and its design in accordance with the ALARA principle (Fig. 3) [22,23], and to prepare for possible future maintenance operations. Estimations of individual and collective doses for the Linac4 dump replacement and decommissioning are thus used to optimize the design of the dump. Fig. 4 shows dose rate maps resulting of this study, in their conventional visualization. A result of this optimization exercise is the report [24].

3.2.1. Preprocessing of the FLUKA data

One way of preprocessing the FLUKA [11,12] output data for use in intervention planning is integrating the values of a scored quantity over a vertical interval of 60 cm, representing the torso of a human being. This way, the representative values of effective dose rate or ambient dose equivalent rate due to induced radioactivity is obtained for a horizontal plane.

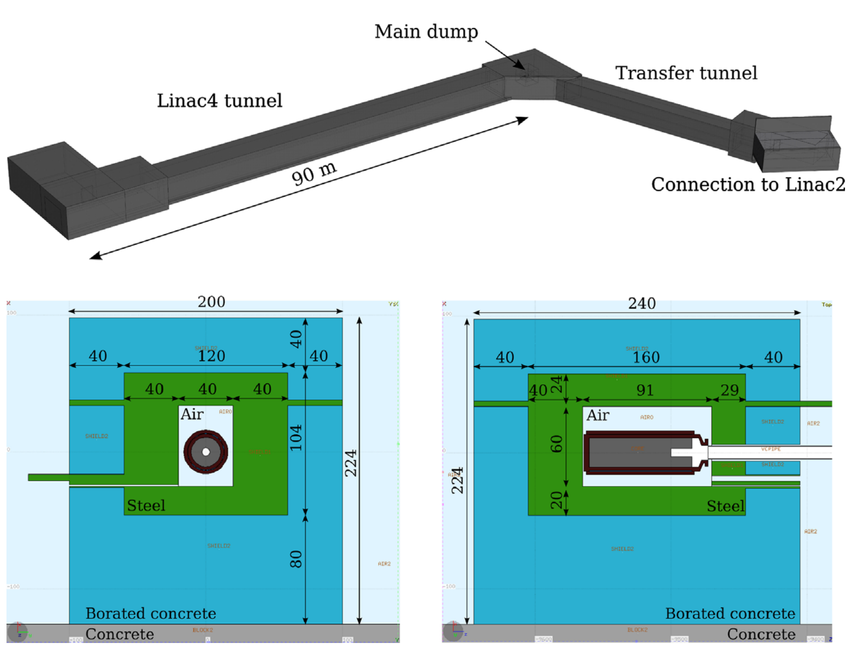

Fig. 3. Fluka geometry of the Linac4 civil engineering (top) and the beam dump shielding (side view (bottom left) and front view (bottom right)) [22,23].

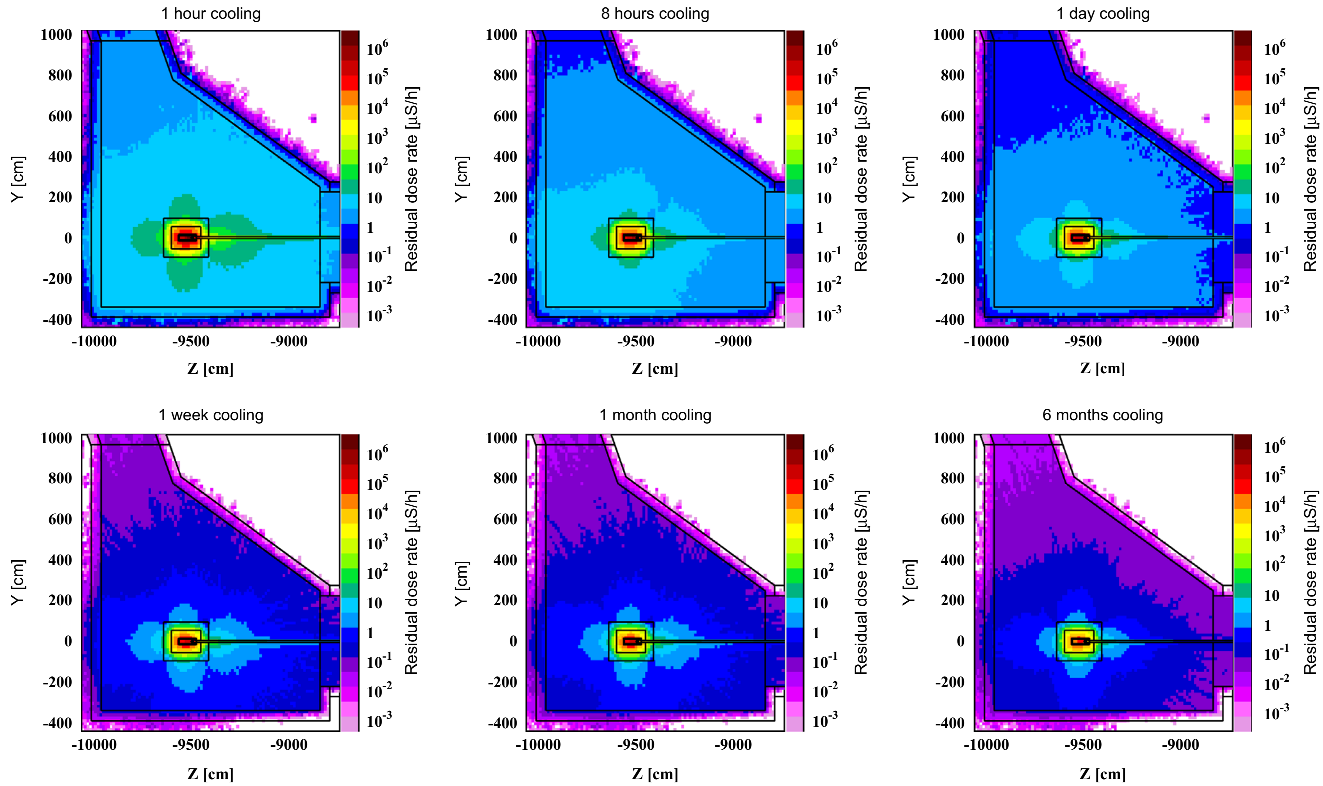

Fig. 4. Ambient dose equivalent rate after 1 month of irradiation with 160 MeV proton beam (2.84 kW beam power) for different cooling times [22,23].

This preprocessing operation leads to a reduction in dimensionality: in the vertical direction, only one bin/voxel of 60 cm high is retained. This makes the data easier to handle with the traditional work dose planning approach. It however also makes that our software tool's abilities are not leveraged fully: instead of a full three-dimensional tool, the tool is factually used as to a two-dimensional planning tool, although the visualization is still three-dimensional and it stays possible to navigate through the facility in 3D.

Although with this kind of data it is not possible to fully leverage all features of our software tool, this case study is performed with this data, because this is the data currently available and it also allows us to benchmark the performance of our data processing. It has become clear that also in this scenario, the software tool can be useful.

3.2.2. *Trajectory planning around the Linac4 beam dump*

Fig. 5(a) shows a volume rendered visualization of a FLUKA simulation of the Linac4 beam dump area. Using our software tool, radiation data can be visualized together with the facility geometry, and the simulation can be probed. In this way, the position of the worker for a certain activity can be optimized interactively and visually, allowing all stakeholders involvement at once.

Fig. 5(b) shows a volume rendered visualization of a FLUKA simulation of the Linac4 beam dump area, together with an interactively positioned trajectory that a maintenance worker could be walking. The trajectory can also be easily updated by just grabbing and moving the control point location interactively. Trajectory points can also interactively be added or deleted. In this figure, the trajectory path's thickness and color is also modulated according to the underlying simulation data, so that the user of the software can easily spot where on the trajectory the maintenance worker will receive the most dose.

Once this is done, or even in during the making of the trajectory, also staying times can be attached to the various activity locations. This can be seen in Fig. 5(c), where three attributes of every control point are shown: a name that can be associated with every control point, the inputted staying time, and the 3D coordinates of the control point. These 3D coordinates can be changed by interactively moving the control point, as described before, but can also be inputted as numbers.

3.2.3. *Benchmarking of the trajectory planning around the Linac4 beam dump*

For benchmarking and quantitative testing of the software tool, we reproduced part of one of the scenario's that are discussed in Ref. [24]. This scenario concerns the preparation of the beam dump equipment for remote opening, following a failure during the reliability run leading to the need for replacement. The steps for this operation are summarized in Table 1.

This operation has been implemented in the tool, as visualized in Fig. 6(a), for a simulation with a cooling time of 1 h[2]. The control point annotations indicated in Fig. 6(a) map the control points to the identification numbers in Table 1.

In Fig. 6(b), an impression of the report that is automatically generated by the software, in PDF format, is visualized. In the current implementation, this report shows the relevant input values of the software (input files and normalization values) and relevant dose planning quantities, as there are the total trajectory length, the total time and total dose, the maximum dose received while working and moving respectively, and the maximum dose received while moving with the relevant trajectory sector. While these quantities have been defined in cooperation with many stakeholders, most notably radiation protection experts, the format of this report is not fixed and will evolve over time until the

[2] For real situations, because of practical consideration, 1 h is a very short cooling time, and generally it is recommended to wait longer so that short-lived radionuclides that might be present can decay. For the purpose of this study, we use 1 h as a test case because planning for this data set better illustrates the power of our tool.

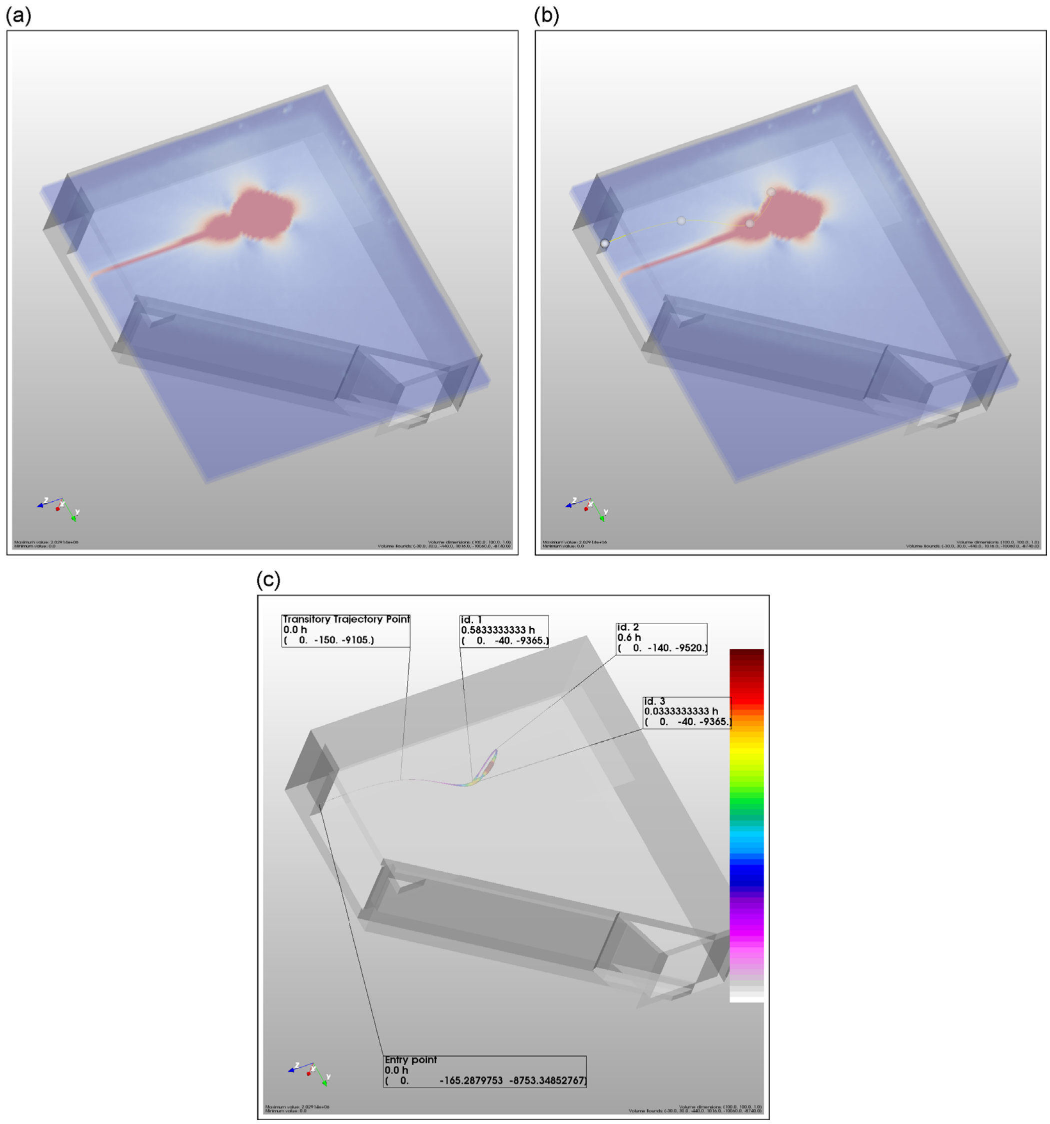

Fig. 5. Intervention planning of the Linac4 beam dump replacement. (a) The geometry of the Linac4 beam dump facility, transparently overlayed on the volume rendered simulation data. (b) The geometry, volume rendered simulation data and the interactively planned trajectory. (c) The planned trajectory, with staying times and other control point attributes. The trajectory thickness and color is modulated according to the dose the maintenance worker will get while passing. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

Table 1
Preparation of the beam dump equipment for remote opening if a failure occurs during the reliability run.

Id.	Action	Position	Time (min)
1	Disconnect water, jackets, vacuum chamber	2	15
	Mounting the engine on shielding	2	10
2	Hang the hoist, lifter	1	15
	Set-up the movable carriage	1	10
	Place the shielded trolley	1	10
	Fix the carriage to shielding	1	1
3	Unlock the movable shielding	2	2

final acceptance of the software. Furthermore, the reports include an overview image of the planned trajectory, a table with the various control points that were interactively indicated, with their *staying times* and resulting dose, and various graphs mapping the dose over the trajectory (see Fig. 6(c)).

The values of the doses are exactly the values that were computed "manually" and written down in Ref. [24]. We can see that time for the worker to be able to move between the different work locations accounts for a dose that makes up ca. 0.3% of the total received dose, as illustrated in Fig. 6(c). This portion of the total dose is neglected in the traditional dose planning procedure. While in this particular case study this seems indeed justifiable, there are certainly situations in which our software can, by not neglecting the *dose while moving*, add to the radiological safety of the worker. Cases where this is potentially the case are being identified and will form further test cases for our software.

4. Accuracy of the dose planning

In line with the previously proposed mathematical model for planning of interventions in an environment with ionizing radiation [14], the software computes the equivalent dose H contracted by the maintenance worker as

$$\hat{H} = \underbrace{\sum_{i=0}^{N} t_i \dot{H}(m_i)}_{\text{stationary dose}} + \underbrace{\frac{1}{v} \sum_{j=0}^{n} \frac{\dot{H}(s_j)+\dot{H}(s_{j+1})}{2} \| s_j s_{j+1} \|}_{\text{dose while moving}}, \quad (5)$$

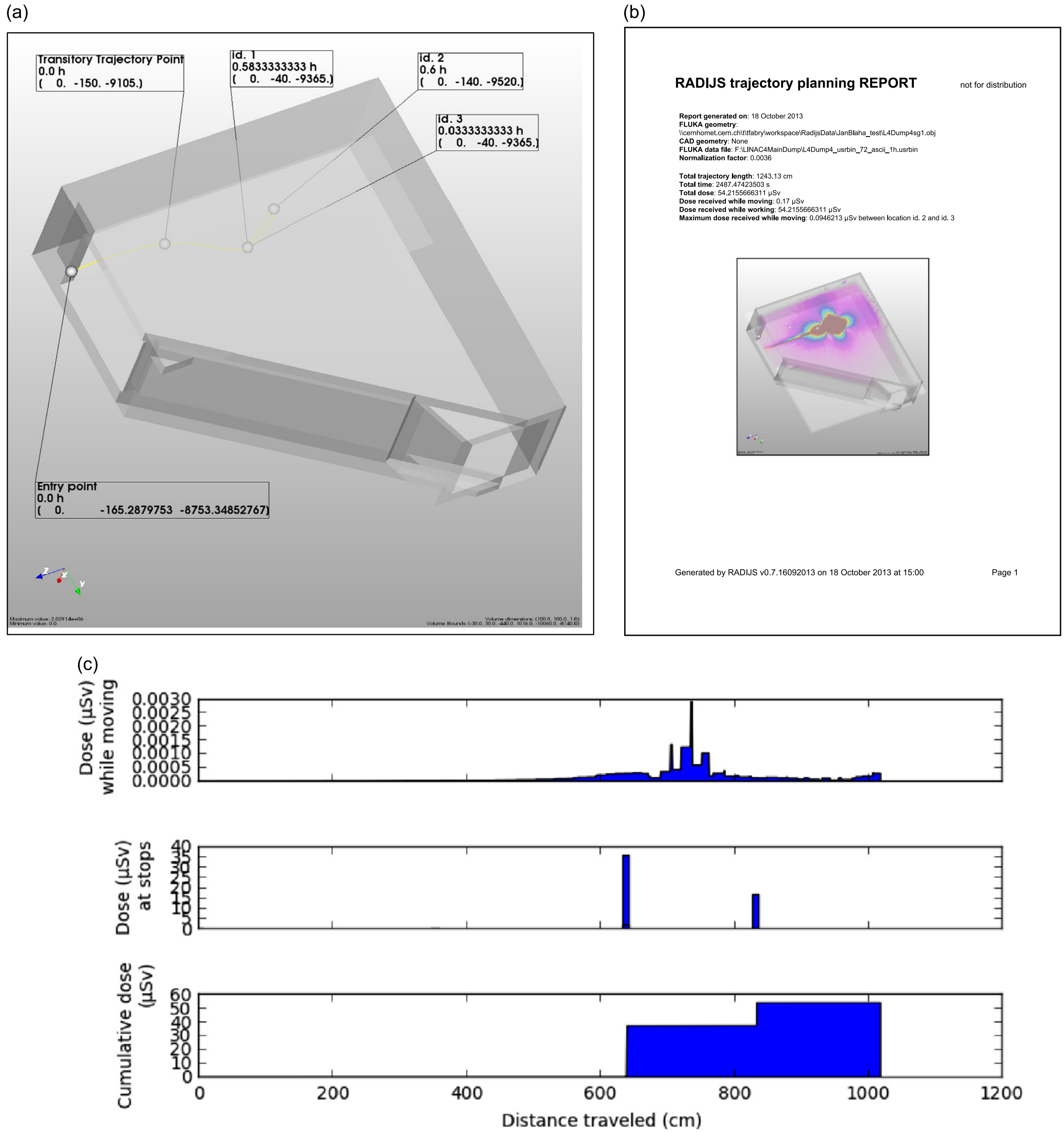

Fig. 6. Intervention planning of the Linac4 beam dump replacement. (a) The trajectory for the preparation of the beam dump equipment for remote opening if a failure occurs during the reliability run. (b) The resulting report, following the software-assisted trajectory planning of the preparation of the beam dump equipment for remote opening if a failure occurs during the reliability run. (c) Graphs of the resulting doses, following the software-assisted trajectory planning of the preparation of the beam dump equipment for remote opening if a failure occurs during the reliability run. These graphs are also part of the resulting report.

which is a discretization of Eq. (4) for a maintenance worker performing an intervention $\mathcal{I}$ mapped on a trajectory $\mathcal{T}$, as defined in Section 2.

Compared to the traditional work dose planning procedure, accuracy is gained in at least three ways:

- In traditional work dose planning, only "stationary dose" term in Eq. (5) is taken into account. The second term, which stands for the dose received during movement, is considered negligible. While this can be justified in many intervention scenarios, sometimes it cannot be justified. An example of the latter is the preparation of a maintenance activity in a highly radioactive area, where a person first goes on a 'scouting' mission to take pictures of the state of the equipment, for planning of the intervention.
- The visually interactive features of the software permit a more accurate positioning of the points of interest in the facility.
- The easiness with which one can add control points of the spline and as such activity locations as part of the trajectory planning will allow for a more fine-grained planning, which will lead to a gain in accuracy.

The effect of the discretization can be considered negligible, as the descretization steps are typically much smaller than the simulation resolution, i.e. the voxel/bin size. To allow maximum flexibility, the software tool currently implements a setting so that the user can very easily choose a value for the number of discretizations for the trajectory. This number is by default set to a value that has empirically been shown to be more than sufficient, so that no user friendliness is lost because the user typically does not need to care about this setting.

The accuracy of the results of the software tool for intervention and dose planning that we developed can also be influenced negatively by at least three issues. These issues are not specific to the software-supported trajectory planning, but are also present in the traditional trajectory/work dose planning procedure.

The first source of possible inaccuracies is the inherent uncertainty of the Monte Carlo simulations. Monte Carlo algorithms rely on repeated random sampling to obtain numerical results. They are a great tool when it is not feasible to apply a deterministic algorithm, as is the case in the simulations that are of interest here, but as they are a statistical approximation to the physical results, there is an inherent limit to their accuracy. This limit is also influenced by the accuracy in mimicking the real world of the Monte Carlo algorithm itself.

FLUKA has been extensively benchmarked for radiation protection purposes [25–29], and has been proven to be sufficient for this purpose. In Ref. [29], it is confirmed that "FLUKA is the most suitable particle interaction and transport code for calculating induced radioactivity at high-energy hadron accelerators", and mentions that "FLUKA reproduces measured specific activities to within 20–30% for most isotopes".

The second and third source of inaccuracy lies in the fact that Eq. (4) is in fact a simplification of [30]

$$E = \sum_{i=0}^{N} \int_{t_{s_k}}^{t_{e_k}} \sum_{p} \left(\iiint_{V_p(t)} \rho_p(x,y,z,t) \dot{H}(x,y,z,t)\, \mathrm{d}x\, \mathrm{d}y\, \mathrm{d}z \right) \mathrm{d}t + \sum_{i=0}^{N-1} \int_{s=m_i}^{m_{i+1}} v_i^{-1} \int_{t=t_{s_i}}^{t_{e_i}} \sum_{p} \left(\iiint_{V_p(t)} \rho_p(x,y,z,t) \dot{H}(x,y,z,t)\, \mathrm{d}x\, \mathrm{d}y\, \mathrm{d}z \right) \mathrm{d}t\, \mathrm{d}s \tag{6}$$

with:

- N the number of locations m_i.
- $t_k = [t_{s_i}, t_{e_i}]$ the estimated time spent at location m_i, which may correspond to a task duration, in case a task is to be executed at m_i, with start time t_{s_i} and end time t_{e_i}.
- p an index to indicate the different organs of the maintenance worker.
- $V_p(t)$ the volume of organ p, which is time-dependent because of the movements of the maintenance worker.
- $\rho_p(x,y,z,t)$ the density of organ p of the maintenance worker, which is time-dependent because of the movements of the maintenance worker.
- $\dot{H}(x,y,z,t)$ the dose rate at point (x,y,z) in 3D space, at time t.

The difference between Eqs. (6) and (1) lies in two separate approximations that have been made. The first one is the time-dependency of the radiation field that has been neglected. Indeed, as we currently work with one set of FLUKA simulation data per trajectory planning instance, the radioactive decay over the time of the intervention is not accounted for. As the simulation for an intervention that is used is always one at a time point at the start of the intervention, this can only leads to an overestimate of the resulting dose, thus not negatively impacting the radiological safety. Because of the particularity of the radiation field around high-energy accelerators, the time dependance of the radiation field should be calculated with a Monte Carlo simulation such as FLUKA, which would result in a big number of 3D simulation results which should then be appropriately processed by the proposed software. Technically, this is certainly possible, as the toolbox that is used for the visualization is capable of handling time-dependent volumetric data [31–33]. Computing the time dependence would however make the FLUKA simulations even more computing and time intensive.

The second approximation that is visible when comparing Eqs. (6) and (1) lies in the fact that the human phantom used in Eq. (1) is reduced to one single 3D location. Given the fact that the dose are in real-life also measured at one point in 3D space using a personal dosimeter, this is a natural approximation. If it would be possible to make very detailed Monte Carlo simulations, leading to very low uncertainties with regard to all of the aforementioned aspects, it might become instrumental to have detailed human phantom be implemented in software. It would take a considerable research and development effort to integrate an existing human phantom [34] into any visualization software. Another open question is how to decouple the human phantom from the simulations, if possible at all, with a satisfactory accuracy, in order to be able to load the simulation data and the phantom independently into the planning software.

5. Discussion

The software tool for the support of planning interventions in environments with ionizing radiation, that has been discussed theoretically and for which an implementation has been presented in this article has been proven to be relevant using the case study of the replacement of the beam dump core of a new linear accelerated. This case study, which has also been used for benchmarking, has lead to the following insights into the technical-scientific benefits that the software tool may lead to. It has also allowed us to identify some challenges the software will have to face.

5.1. *Benefits of the software*

From the text above, it may be clear that the prototype software has many benefits, of which we list the most important here:

- The trajectory and work dose planning becomes more approachable. This not only has benefits for the usual planning personnel, but also unlocks the trajectory and dose planning results to a wider range of stakeholders in the intervention.
- The trajectory and work dose planning becomes more apt to be used in a collaborative fashion, uniting multiple stakeholders with different requirements, better suited for the current HEP big science project organization.
- The proposed software exploits the simulation data that is already available in a more visual, accessible way.
- Accuracy is potentially gained in at least two ways, as discussed in Section 4.

5.2. *Challenges for the software*

In its current form, the developed software can only deal with mono-simulation scenarios, meaning that only situations where the activated equipment (or other sources of radiation) are static. In the case of the Linac4 beam dump replacement and decommissioning scenarios that were described before, this means that the trajectory planning has to be done in multiple steps, according to the number of simulations that have to be used. It is currently under consideration to implement support for multiple simulation scenarios, where care will have to be taken to not diminish the user-friendliness of the application by adding the necessary extra features for this update.

The interactiveness of the software is a big asset, but at the same time it can also be a burden to process a big number of datasets. While it is entirely possible to use a maintenance planning session, and keep all the (visually and interactively) inputted arguments of the planning while changing the underlying simulation data, it can still be is still tiresome to do this with a large number of simulations (for instance for different cool-down times). It is currently under investigation if a 'batch mode' can be integrated in the software while not loosing out of sight the original idea of a collaborative, easy-to-use visual and interactive intervention planner.

6. Conclusion and outlook

The particle accelerators and HEP detectors, as used at CERN, for instance, are subjected to ionizing radiation and their components can become activated. To protect the maintenance personnel from ionizing radiation during interventions, the radiation dose received by the workers during an intervention has to be minimized. Our goal is to provide software to plan an intervention which enables minimization of the contracted radiation dose, taking practical conditions concerning maintenance tasks into account. This optimization cannot easily be automated and therefore requires human assessment. The visualization of the several layers of data involved in the planning process, i.e. the facility geometry, the radiation levels and the trajectory, therefore needs to be clear, intuitive and interactive.

In this work, we first discuss the fundamental principles of a software tool for the support of planning interventions in environments with ionizing radiation. Second, the proof-of-concept software that was implemented has been situated and given a place into the current intervention and dose planning procedures, supported with a case study involving the replacement of the beam dump core of a new linear accelerated that is being constructed at CERN. Next, the software was benchmarked against an existing dose planning. Finally, we have discussed and illustrated how the accuracy of the trajectory and intervention planning in the software is influenced by a variety of parameters and circumstances. In the future, the intervention planning software could be tested with more elaborate case studies, and its settings could be studied using a users study. In addition, in order to mature, the practical understanding the software and the maturity of the code has to be developed further using alpha testing.

Acknowledgements

This research project has been supported by a Marie Curie Fellowship of the European Community's Seventh Framework Programme under Contract number (PITN-GA-2010-264336-PURESAFE).

References

[1] CERN, About CERN. ⟨http://home.web.cern.ch/about⟩, 2013.
[2] H. Vincke, C. Theis, S. Roesler, Radiation Protection Dosimetry 146 (2011) 434.
[3] Convention for the Establishment of a European Organization for Nuclear Research, 1953. As amended, 1971.
[4] A. Breskin, R. Voss (Eds.), The CERN Large Hadron Collider: Accelerator and Experiments, LHC Machine, Alice, and Atlas, CERN, vol. 1, 2008.
[5] A. Breskin, R. Voss (Eds.), The CERN Large Hadron Collider: Accelerator and Experiments, CMS, LHCb, LHCf, and Totem, CERN, vol. 2, 2008.
[6] UK Health and Safety at Work etc. Act, 1974.
[7] C. Grupen, Introduction to Radiation Protection—Practical Knowledge for Handling Radioactive Sources, Graduate Texts in Physics, Springer-Verlag, Berlin, Heidelberg, 2010.
[8] CERN Safety Code F/Rev. on Radiation Protection, 2006.
[9] F. Vermeersch, C. Van Bosstraeten, Development of the VISIPLAN ALARA planning tool, in: Proceeding of the International Conference on Topical Issues in Nuclear Radiation and Radioactive Waste Safety, 1998.
[10] T. Fabry, L. Vanherpe, M. Baudin, C. Theis, C. Braesch, B. Feral, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors, and Associated Equipment 708 (2013) 32.
[11] G. Battistoni, F. Cerutti, A. Fassò, A. Ferrari, S. Muraro, J. Ranft, S. Roesler, P.R. Sala, The FLUKA code: description and benchmarking, in: AIP Conference Proceedings, vol. 896, 2007, pp. 31–49.
[12] A. Ferrari, P.R. Sala, A. Fassò, J. Ranft, FLUKA: A Multi-particle Transport Code, Technical Report CERN-2005-10, INFN/TC_05/11, SLAC-R-773, CERN, INFN, SLAC, 2005.
[13] J. Engelen, Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 370 (2012) 978.
[14] T. Fabry, C. Braesch, B. Feral, Interactive visual intervention planning – interactive visualization for intervention planning in particle accelerator environments with ionizing radiation, in: Proceedings of the 8th International Conference on Information Visualization Theory and Applications (IVAPP), 2013. http://dx.doi.org/10.5220/0004212505850592.
[15] T. Fabry, L. Vanherpe, B. Feral, C. Braesch, International Journal of Advanced Robotic Systems 10 (2013) 1–8.
[16] J. Cossairt, Radiation Physics for Personnel and Environmental Protection, Technical Report FERMILAB-TM-1834 Revision 4, Fermi National Accelerator Laboratory, Batavia, IL (US), 1999.
[17] J. Vollaire, D. Forkel-Wirth, S. Roesler, Estimation of the Individual and Collective Dose Due to the Replacement and Transport of One of the LHC Beam Dump Cores, Technical Report CERN-SC-2007-060-RP-TN, CERN, 2007. EDMS Document Number: 866062.
[18] L. Arnaudon, P. Baudrenghien, M. Baylac, G. Bellodi, Y. Body, J. Borburgh, P. Bourquin, J. Broere, O. Brunner, L. Bruno, C. Carli, F. Caspers, S.M. Cousineau, Y. Cuvet, C. De Almeida Martins, T. Dobers, T. Fowler, R. Garoby, F. Gerigk, B. Goddard, K. Hanke, M. Hori, M. Jones, K. Kahle, W. Kalbreier, T. Kroyer, D. Küchler, A.M. Lombardi, L.A. López-Hernandez, M. Magistris, M. Martini, S. Maury, E. Page, M. Paoluzzi, M. Pasini, U. Raich, C. Rossi, J.P. Royer, E. Sargsyan, J. Serrano, R. Scrivens, M. Silari, M. Timmins, W. Venturini-Delsolaro, M. Vretenar, R. Wegner, W. Weterings, T. Zickler, Linac4 Technical Design Report, Technical Report CERN-AB-2006-084, CARE-Note-2006-022-HIPPI, CERN, Geneva, 2006. (Revised version submitted on 2006-12-14 09:00:40).
[19] R. Garoby, H. Damerau, S. Gilardoni, B. Goddard, K. Hanke, A. Lombardi, D. Manglunki, M. Meddahi, B. Mikulec, L. Ponce, E. Shaposhnikova, R. Steerenberg, M. Vretenar, Status and plans for the upgrade of the LHC injectors, in: Proceedings of the Fourth International Particle Accelerator Conference, IPAC'13, 2013.
[20] HL-LHC: High Luminosity Large Hadron Collider. ⟨http://hilumilhc.web.cern.ch⟩, 2013.
[21] A. Fassó, A. Ferrari, S. Roesler, P. Sala, G. Battistoni, F. Cerutti, E. Gadioli, M. Garzelli, F. Ballarini, A. Ottolenghi, A. Empl, J. Ranft, The physics models of FLUKA: status and recent developments, in: Computing in High Energy and Nuclear Physics 2003 Conference (CHEP2003), La Jolla, CA, USA. (Paper MOMT005) eConf C0303241, 2003, arXiv:hep-ph/0306267.
[22] J. Blaha, F.P.L. Torre, M. Silari, J. Vollaire, Long-term residual radioactivity in intermediate-energy proton linac, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment (2014), submitted for publication.
[23] J. Blaha, J. Vollaire, Radiation protection study for the shielding design of the LINAC4 beam dump, in: Proceedings of the Fourth International Particle Accelerator Conference, IPAC13, 2013.
[24] J. Blaha, J. Vollaire, Radiation Protection Study for the Linac4 Main Beam Dump, Technical Note CERN-DGS-2013-001-RP-TN, CERN, CH-1211 Geneva 23, Switzerland, 2013.
[25] J. Vollaire, M. Brugger, D. Forkel-Wirth, S. Roesler, P. Vojtyla, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 562 (2006) 976 (Proceedings of the 7th International Conference on Accelerator Applications—AccApp05).
[26] M. Brugger, D. Forkel-Wirth, S. Roesler, J. Vollaire, Studies of induced radioactivity and residual dose rates around beam absorbers of different materials, in: Proceedings of HB2010, Morschach, Switzerland.
[27] G. Dissertori, P. Lecomte, D. Luckey, F. Nessi-Tedaldi, F. Pauss, T. Otto, S. Roesler, C. Urscheler, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 622 (2010) 41.
[28] M. Brugger, H. Khater, S. Mayer, A. Prinz, S. Roesler, L. Ulrici, H. Vincke, Radiation Protection Dosimetry 116 (2005) 6.
[29] M. Brugger, A. Ferrari, S. Roesler, L. Ulrici, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 562 (2006) 814 (Proceedings of the 7th International Conference on Accelerator Applications—AccApp05).
[30] 2007 Recommendations of the International Commission on Radiological Protection, ICRP Publication 103 in Annals of the ICRP, Elsevier, 2008.
[31] W. Schroeder, K. Martin, B. Lorensen, The Visualization Toolkit—An Object-Oriented Approach to 3D Graphics, 4th edition, Kitware, 2006.
[32] The VTK User's Guide, Kitware, Inc, 11th edition, 2010.
[33] VTK—The Visualization Toolkit, ⟨http://www.vtk.org⟩, 2013.
[34] X.G. Xu, K.F. Eckerman (Eds.), Handbook of Anatomical Models for Radiation Dosimetry, Taylor and Francis Group LLC, Boca Raton, Fl, USA, 2010.