COMPARATIVE STUDIES INTO 3D BEAM LOSS SIMULATIONS*

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Abstract

A detailed understanding and monitoring of potential beam loss mechanisms is crucial for every particle accelerator. The main motivation in low energy facilities, such as the Ultra-low energy Storage Ring (USR) at the future Facility of Low energy Antiproton and Ion Research (FLAIR), comes from the very low number of particles available which in such machine ought to be conserved. In high energy accelerators it is the concern about activation or even physical damage of machine parts which has to be taken into serious account. The CLIC Test Facility (CTF3) at CERN provides an ideal testing ground for studies into novel BLM systems and is well suited for benchmarking the results from numerical simulations in experiments. This contribution summarizes the three-dimensional beam loss pattern as found with the commonly used codes FLUKA and Géant4. The results from these codes are compared and analyzed in detail and used for the identification of optimum beam loss monitor locations.

INTRODUCTION

Simulations play a crucial role in all fields where one is interested in the behaviour and response of a device even before it is physically realized. Among all numerical methods that rely on N-point evaluations in M-dimensional space to produce an approximate solution, the Monte Carlo method has an absolute estimation error that decreases with $N^{-1/2}$.I In the absence of exploitable special structures or other boundary conditions, all other methods have errors that decrease with $N^{-1/M}$ at best. This feature is crucial when it comes to the decision when and how to apply this method. Its full potential can only be exploited in problems involving more than two dimensions.

In the here-described study the Fluka *("Fluktuierende Kaskade")* [1,2] software and the Geant4 [3] toolkit (G4) were used to create models capable to represent the interactions of beam particles with surrounding materials in a section of the CLIC accelerator Test Facility (CTF3) at CERN and to characterize the beam losses. An Optical Transition Radiation (OTR) screen was chosen for benchmarking purposes as it represents a well defined loss source.

BEAM LOSS CHARACTERIZATION

Fluka is a general purpose software programmed in FORTRAN77 for calculating particle interactions with matter and their transport. The code is being used extensively in the field of accelerator science and technology, as well as in astrophysics and medical applications.

Fluka can simulate the interaction and propagation in matter of about 60 different particle types, including photons and electrons from 1 keV to thousands of TeV, neutrinos, muons of any energy, hadrons of energies up to 20 TeV, as well as all corresponding antiparticles and neutrons down to thermal energies. The available energy range classifies this software as a high energy physics events simulator and this limitation can be crucial for example in cases where it is important to screen the complete energy spectrum of an event, such as in detector modeling.

Fluka can handle even very complex geometries, using an improved version of the well-known Combinatorial Geometry (CG) package, complemented by various visualization and debugging tools.

For most applications, no programming skills are required from the user, which make this software very user friendly. Furthermore, some software developed by different groups, such as for example FLAIR [4] and SimpleGeo (SG) [5] make Fluka more similar to commonly used CAD and EM simulation software, with strong advantages for the users. In addition, a number of special user routines are available for more expert users.

G4 [6] *("Geometry and tracking")* is a set of C++ libraries, structured as an object-oriented code. Geant4 includes a broad set of physical models to describe interactions between particles and matter. The program has the capability to manage a wide energy range, essentially from 0 eV to thousands of TeV.

G4 has an exhaustive build-in library of precompiled particles and the possibility to easily build new ones, if required. Even if the software was originally developed for high energy physics experiments, these features enable a wide area of applications such as for example medical studies, radiation shielding simulations, biology and astroparticle physics.

G4 is capable to allow real time modification by the user during the simulation, acting either before (pre-step) or after (post-step) an interaction. The program requires some average skills in object oriented programming from its user, even for starting a very simply G4 project. Furthermore, G4 includes a wide variety of support tools to manage each simulation aspect such as the visual representation of the geometry and particle tracking, the management of the response of detectors or to display plots for data analysis.

The G4 solid modeler is STEP compliant. STEP is the ISO standard defining the protocol for exchanging geometrical data between CAD systems and is of critical

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importance for more complex geometries. It supports the Constructive Solid Geometry (easy to use with superior performances) as well as Boundary Represented Solids (to reproduce the most complex structures).

Figure 1 shows an OTR screen commonly used for beam profile measurements, designed by using SimpleGeo. When the beam hits the Silicon screen centrally, significant beam losses occur that can be used for benchmarking the results from the two different codes.

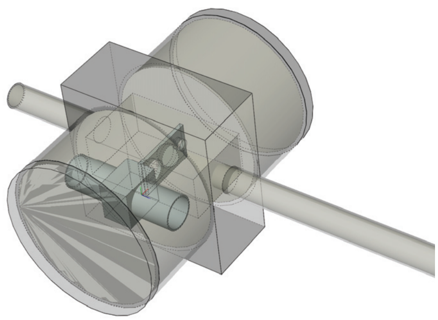

Figure 1: Model of the OTR screen. The external surfaces are made transparent to show the internal structure.

In order to characterize the event and to evaluate the loss level in the surroundings of the device, both Fluka and G4 were used to analyze the shower generated by a 180 MeV electron beam, as found in CTF3. The results of the two codes were then compared to check their level of agreement. A secondary focus was set on the performance of the code with the final goal to be able to determine the optimum code choice for specific problem geometries.

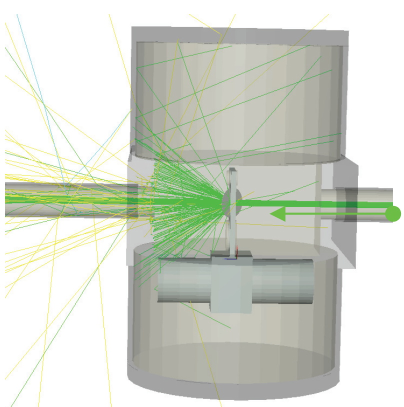

Figure 2: FLUKA representation of a particle shower induced by the silicon screen. Green: electrons, blue: positrons, yellow: photons.

Figures 2 and 3 show the OTR screen and its surrounding vacuum chamber, as well as the shower generated by the beam. The shower shape is conical with full cylinder symmetry. Table 1 summarizes the most important parameters and shower characteristics as found in both codes for direct comparison. A general error of 10% was assumed for each numerical quantity, justified by several simulation and fluctuation studies. As shown in the table, all fundamental parameters taken into account show a good general agreement. Table 2 shows the used memory resources and also the time required to reach convergence. All simulations were done on the same computer, a Pentium core duo 2 GHz PC. It can be seen that for this particular geometry and beam, G4 makes more efficient use of the resources and is faster by almost 40%. This can be a very important point for very complex models and time consuming simulation studies.

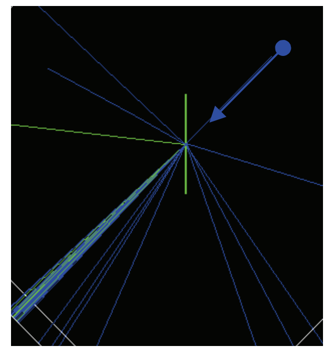

Figure 3: G4 event representation by means of the OpenGL visual driver. To allow a good picture reading, only a few electrons (blue tracks) and positrons (green) are shown.

Table 1: Shower Comparison

Parameter	**Fluka**	**Geant4**
Shower shape	conical	conical
Shower composition	Photons 82%; Electrons 16%; Positrons 2%.	Photons 79%; Electrons 18%; Positrons 3%.
Deposited energy (avg)	$1.3e^{-10}$ GeV/cm^3 (50 cm downstream)	$1.5e^{-10}$ GeV/cm^3 (50 cm downstream)

Table 2: Software Performance Comparison

Characteristic	**Fluka**	**Geant4**
Memory usage	380 MB	240 MB
Time elapsed	90 minutes	55 minutes

CHERENKOV FIBERS

The beam loss monitor tests at CTF3 provide valuable input to identify the best technology choice for the CLIC BLM system. This has demanding requirements in its dynamic range, spatial and time resolution. One possible option is to exploit the Cherenkov Effect (CE) generated by the loss particles in an optical fiber, installed in the vicinity of the beam pipe. The produced photons are then trapped and transported by the fiber. This light is detected by a photomultiplier and the data used to calculate the loss characteristics.

The CE can be activated by the user in either G4 or Fluka. A good representation of this phenomenon is mandatory to be able to carry out a full study into the system beam loss-detector.

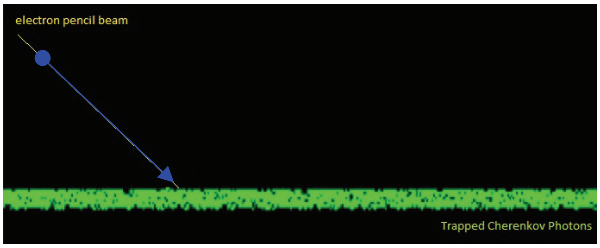

Figure 4: G4 representation of Cherenkov photons production and transport. Photons escaping the cladding are dumped by the buffer.

Cherenkov photons production and transport are related to several parameters of both the fiber and the incident particle: Fiber thickness, aperture and its refraction index on the one hand and incidence angle of the charged particle, its type and energy on the other. All these characteristics, correlated by formal equations [6], must be represented correctly by the simulations. Figures 4 and 5 show two examples of CE induced in a common silica optical fiber, calculated with G4 and Fluka, respectively.

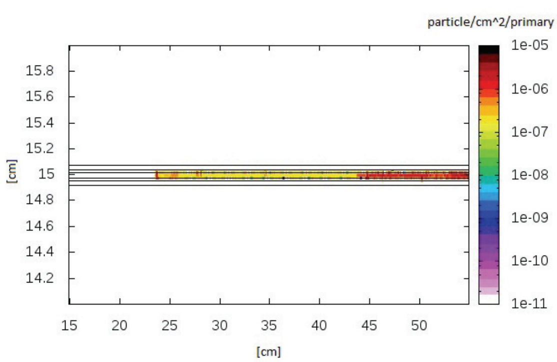

Figure 5: Fluka representation of Cherenkov light production. The photons are produced in the core of the fiber.

In Fig. 5 the loss source was placed on the axis origin (0;0). Thereby, it is possible to ascertain that the minimum angle with respect to the fiber axis and below which no photons are produced corresponds to the angle in which the shower is generated. For electrons the threshold energy to emit Cherenkov light is about 175 keV, and the incident angle where the maximum amount of light is generated is about 46° for a fiber with a refraction index of around 1.5. Figure 6 shows a comparison between theory and simulations of the produced photons as a function of wavelength. The agreement between the codes and theory is good enough to allow the independent use of either of the codes and to thus gain a maximum advantage from both simulators.

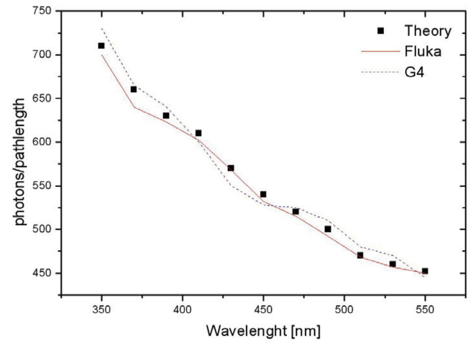

Figure 6: Number of photons produced by single electrons crossing an optical fiber. The results are normalized to the path of the electrons inside the fiber.

CONCLUSION

A detailed study into the 3D beam loss pattern of a 180 MeV electron beam on a specific geometry has been carried out and the results were summarized in this paper. It was found that the results of the two codes were in good agreement with each other. This makes it possible to use either Fluka or G4, for both, beam loss characterization and modeling of a detector based on Cherenkov radiation. Whilst G4 showed superior performance in the simulated cases, Fluka turned out to be more user-friendly and easier to learn. Further studies into light transport are needed to investigate into the level of agreement between the two codes.

REFERENCES

[1] G. Battistoni et al., “The FLUKA code: Description and benchmarking”, AIP Conf. Proc. 896, 31-49, (2007).
[2] A. Fasso`, A. Ferrari, J. Ranft, and P.R. Sala, “FLUKA: a multi-particle transport code”, CERN-2005-10 (2005), INFN/TC_05/11, SLAC-R-773.
[3] S. Agostinelli et al., “Geant4 - A Simulation Toolkit”, Nucl. Instr. Meth. A 506 (2003) 250-303.
[4] V. Vlachoudis, “FLAIR: A Powerful But User Friendly Graphical Interface For FLUKA”, Proc. Int. Conf. on Mathematics, Computational Methods & Reactor Physics (M&C 2009), Saratoga Springs, New York, 2009.
[5] C. Theis et al., “Interactive Three Dimensional Visualization and Creation of Geometries for Monte Carlo Calculations”, Nucl. Instr. Meth. A 562 (2006) 827-829.
[6] J. V. Jelley, “Cerenkov Effect and Its Applications”, British J. of Appl. Phys. 6 (1955), 227-232.