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A new process simulator for the optimization of electron beam crosslinking processes of polymers isolations in electrical cables

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ABSTRACT

A new simulator to calculate the dose deposited in electron beam crosslinking processes of cables is presented, which implements original models to simulate accurately complex irradiation schemes like racetrack, figure of eight, and rotation. The package relies on the Monte Carlo simulation and includes tools to account for the three-dimensional geometry of the accelerators and of the conveyors, a unit to optimize the beam energy for a given process configuration, as well as an editor to visualize and quantify the dose distribution within the irradiated objects. The capabilities and the accuracy of the novel simulator are discussed on the basis of two realistic examples.

1. Introduction

The ability to predict the final dose distribution in electron beam processing of cables and wires has been always a main issue for the optimization of crosslinking uniformity, throughput of accelerators, energy efficiency, and design of new products.

The empirical analytical formulas used in the past (ASTM, 2003); Tabata et al., 1996; Lisanti, 2004) were not sufficient to account for the peculiarities of each accelerator, irradiation scheme, and cable geometry such that they could only roughly be adapted to the solution of two-dimensional (2D) and three-dimensional (3D) problems. The Monte Carlo techniques have been used already starting from the 1990s to calculate the dose distribution in basic shapes and under less realistic irradiation geometries (Weiss et al., 1997; Zhou et al., 2002; Kaluska et al., 2007). EBXLINK3D represents the natural evolution of these tools, which has been made possible in particular by the recent advances in the computational sciences. It is a 3D process simulator that handles cables and accelerator geometries of whatever complexity, under consideration of the full irradiation process. As an example, EBXLINK3D implements very realistic and real size models for racetrack, figure of eight, and rotation. In order to provide sufficient accuracy, relevant parameters like beam energy, beam shape, and local fluence can be easily calibrated based on experimental data acquired for each accelerator. Simulation times on a typical workstation range from few minutes for the simplest cases up to 5 h for the most accurate and complex configurations.

In Section 2 this paper presents the basic simulation model assumed in this simulator. In Section 3 all models for rotation, racetrack and figure of eight processing are discussed together with the solutions adopted to reduce the simulation time without affecting the results. In Section 4, two examples are presented, where beam energy and the geometry of radiation processing are optimized under consideration of a variety of process parameters.

2. Simulation model

The simulation model developed for this simulator assumes that:

- the irradiation field is time-independent,
- the cable is much longer than that of the irradiation field (usually 1–2 m), and
- the cable is moving along its axis (at least piecewise).

Under these assumptions, it is evident that the total dose distribution acquired by each thin orthogonal slice of the cable is the same along the whole cable and that it results from the sum of the distributions at the different locations along the trajectory. This approach enables a time-dependent problem as it is in the real world to be easily transformed into a time-independent

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model as it can be easily solved by the Monte Carlo simulation techniques.

During the simulation, the cable volume is divided in 1 million voxels, where the local dose is calculated. Once the Monte Carlo simulation is concluded, all 2D dose slices along the cable axis are added up to calculate the total absorbed dose. This approach is used in particular for the single exposure, racetrack, and figure of eight modes.

For all other simulation problems, which cannot be described by a static picture, the solution adopted in EBXLINK3D is to discretize the simulation in the time domain. This applies for instance to the case of non-axially symmetrical cables irradiated in the rotation mode.

Since the size of the simulation model is quite large (typically 2–4 m^3), special care has to be paid to the definition of the number of electron showers to be simulated. The number of electrons may range from 1 million up to 50 million and strongly depends on the required level of accuracy and on the simulated irradiation mode (e.g. number of passes in the racetrack mode).

All simulation times reported in this paper refer to a machine equipped with 32 bit Windows XP, 2.6 GHz dual core AMD Opteron and 3.25 GB RAM.

EBXLINK3D is designed to support either static irradiations, either moving objects. This must be taken into account when converting the specific dose per electron obtained by the Monte Carlo simulation unit into an absolute dose. In fact, in the former case all directions in the 3D dose matrix are spatial, thus only the average is feasible. While in the latter case (cable) voxels along the cable axis must be added up because they represent different frames of the dose collected by the same 2D slice. The equations used in the two cases are the following:

$$D\,(kGy) = e \times 10^{-3} It \sum_{k}^{n} \frac{D_e(k)}{n} \tag{1}$$

$$D\,(kGy) = e \times 10^{-3} I \sum_{\lambda_k}^{\lambda_n} D_e(\lambda) \frac{(\lambda_n - \lambda_k)}{v} \tag{2}$$

where e is the electron charge (C), D_e is the absorbed dose per electron (eV/g), I is the beam current (mA), t is the irradiation time (s), v is the conveyor speed (cm/s), k is the voxel index chosen for the dose calculation and λ_k (cm) is the voxel length corresponding to the index k.

An example of complex racetrack geometry, which can be simulated with EBXLINK3D is shown in Fig. 1. After crossing the thin titanium window, the electron beam diameter increases along its path due to the initial divergence and to the scattering with the air molecules. When reaching the lower plane of the cables placed 40 cm below the titanium window, the beam diameter is about 20 times its initial value. In this case, the simulator also accounts for the shadows projected by the upper on to the lower cable plane, as well as for the influence of electron scattering at adjacent cables and at reflecting surfaces. All these effects are relevant when calculating the real irradiation field and cannot be properly predicted by analytical approaches (Ciappa et al., 2009; Mangiacapra et al., 2010).

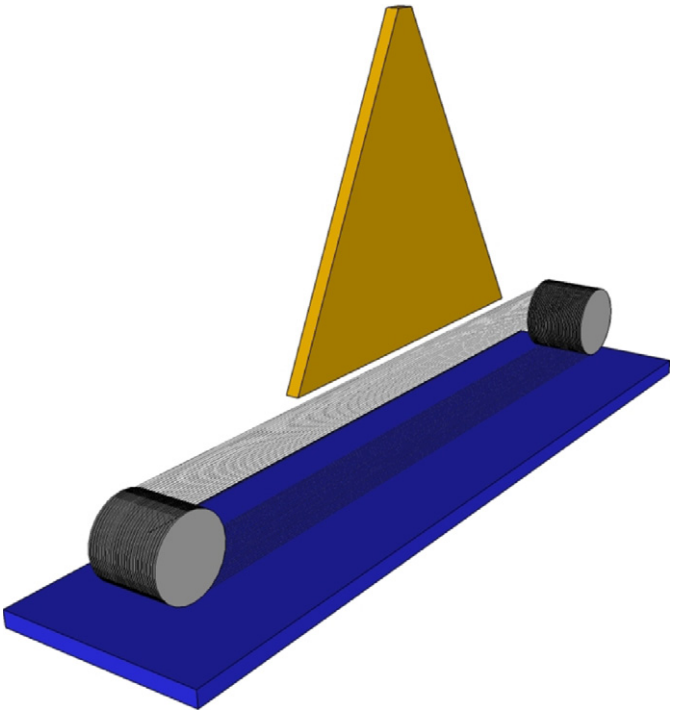

Fig. 1. A typical racetrack model which can be simulated with EBXLINK3D.

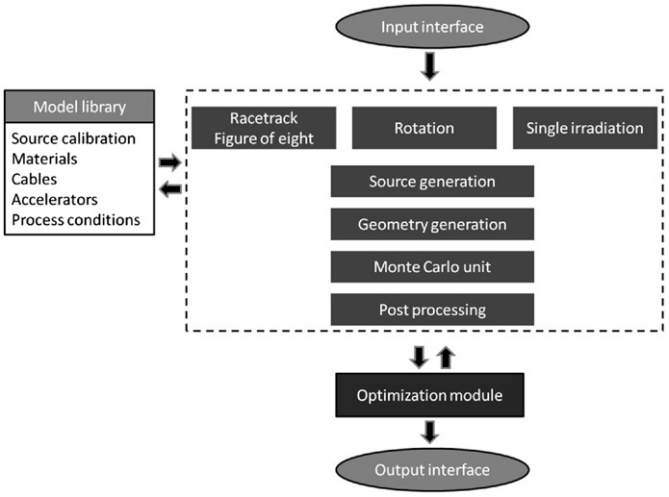

Fig. 2. Scheme of EBXLINK3D. An input interface and a model library help the operator to run the simulation. The modules in charge for racetrack, figure of eight and single irradiation control beam source generation, geometry generation and the Monte Carlo unit. The output interface provides results visualization and a summary of all main process parameters.

3. Description of the simulator

3.1. Software overview

EBXLINK3D has been developed under the MATLAB environment. Fig. 2 shows the main modules composing the software. An input interface lets the user calibrate a new beam source with experimental data, create new materials, define new geometries of cables, accelerators, drums and reels (which determine the cable positions) or load all of them if already present in the library of the simulator.

The three modules in charge for the simulation of cable radiation processing in racetrack/figure of eight, rotation and single irradiation constitute the core of EBXLINK3D. They generate electron source and geometry drawing on different models of different complexities, then perform the simulation controlling a Monte Carlo unit. The optimization module, when activated, keeps the simulator in a loop until a specified condition is reached. An output interface is available to easily visualize 3D dose distributions and all relevant data.

The software supports multicore parallelization, which though implies to split simulations into several parts and then to join the