Geant4 simulations for multidisciplinary and medical applications of laser-driven ion beams

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Charged particle acceleration using ultra-intense and ultra-short laser pulses has gathered a strong interest in the scientific community in the last few decades. Indeed, it could represent the future of particle acceleration and open new scenarios in multidisciplinary fields as, in particular, the medical one. Recently, high interest of the scientific community is driven from the fact that more compact laser-based therapy units could dramatically increase the availability of high-energy proton and carbon ion beams, and provide particle therapy to a broader range of patients [1, 2].

Several international collaborations and experiments have been launched in the last years and many research centers are currently involved in the investigation of laser driven therapy and applications. In this framework, the ELIMED (MEDical and multidisciplinary application at ELI-Beamlines) beamline is being developed with the aim of transport and select in energy proton and ion beams accelerated by laser-matter interaction at ELI-Beamlines (Extreme Light Infrastructure) user facility in the Czech Republic [3]. The beamline will be a key part of the ELIMAIA (ELI Multidisciplinary Application of laser-Ion Acceleration) user beamline, where experiments will be carried out with the purpose of investigating the feasibility of using laser-driven beams for multidisciplinary applications, including medical ones [4].

A Monte Carlo simulation of the ELIMED beamline has been developed for the following purposes: to support the design of the beamline in terms of particle transport efficiency, to optimize the beam parameters at the irradiation point in air and, finally, to predict the transport elements parameters to deliver dose distributions of possible clinical relevance [5]. Indeed, laser-driven beams are typically characterized by broad energy (up to 100% compared to 0.1-1%) and angular distributions and substantial intensity (charge) fluctuations from pulse to pulse. Thus, an application able to realistically reproduce the relevant transport parameters is of crucial importance in the perspective of optimizing the beam for multidisciplinary activities.

The application has been developed with the Geant4 Monte Carlo toolkit. It has been designed in a modular way in order to easily switch on/off geometrical components according to different experimental setups. The application has been preliminary validated comparing particle tracks to results obtained with reference codes for transport of particles in magnetic fields, with a good agreement. Specifically, energy distributions, lateral beam profiles and longitudinal dose distributions in the in-air final section were simulated for proton beams with energies ranging between 5 and 60 MeV. A transmission efficiency of more than 10% was calculated at 60 MeV, which implies the delivery of up to tens of cGy per pulse at the sample irradiation point. Assuming a repetition rate of 1 Hz, between 1 and 10 Gy/min can be potentially achieved in such conditions.

These studies are of great importance to assess the possibility of carrying out in-vitro and in-vivo radiobiology experiments aiming to demonstrate the possible future use of optically accelerated beams for therapeutic purposes. On this regard, the possibility of implementing, in a future perspective, also radiobiological models able to take into account the spatio-temporal correlations is of great interest, as well. Indeed, laser-driven beams are characterized by very intense (10^8 – 10^{12} particles per bunch) ultra-short (~ ps) particle pulses and ultra-high pulse dose rate (up to 10^{12} Gy/min) compared to conventional clinical proton beams (10^7-10^{10} particles/s and dose-rate up to 10-50 Gy/min). Therefore, the possibility to have a comprehensive tool, developed with Geant4, able to first transport the particles with accuracy and then to predict also radiobiological effects for these peculiar temporal structures will be investigated.

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