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Toward high-efficiency and detailed Monte Carlo simulation study of the granular flow spallation target

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ABSTRACT

The dense granular flow spallation target is a new target concept chosen for the Accelerator-Driven Subcritical (ADS) project in China. For the R&D of this kind of target concept, a dedicated Monte Carlo (MC) program named GMT was developed to perform the simulation study of the beam-target interaction. Owing to the complexities of the target geometry, the computational cost of the MC simulation of particle tracks is highly expensive. Thus, improvement of computational efficiency will be essential for the detailed MC simulation studies of the dense granular target. Here we present the special design of the GMT program and its high efficiency performance. In addition, the speedup potential of the GPU-accelerated spallation models is discussed.

1. Introduction

As an innovative facility proposed for energy generation and the transmutation of the long live time nuclear waste [1,2], the Accelerator-Driven Subcritical (ADS) system has aroused worldwide R&D interests in last two decades. In China, after five years intensive R&D on the ADS prototype as well as its key techniques [3,4], a project of building an experimental facility, i.e. the Chinese Initial ADS (CIADS), driven by a 400 ∼ 500 MeV & 10 mA superconducting linac (SCL) has been launched [5].

During the intensive R&D phase started in 2011, one of the significant breakthroughs is proposing the gravity-driven dense granular target concept [6–8] for the long-term China ADS (C-ADS) project. As shown in Fig. 1, by adopting solid granular flow to serve as target body as well as heat carrier, offline heat removal and maintain/renewal can be realized, which is essential for a solid-state target to operate with a beam power as high as tens of MW demanded by an industrial-scale ADS facility. The advantages of this kind of target configuration such as higher power density, corrosion free, long operational life and high dissipating ability for shock wave induced by beam trip have been demonstrated in detail [5,6].

For the feasibility verification of the granular flow target, a half scale bench is under construction to test in operation stability, electromagnetic granular lift, granule wear rate, dusk handling and cooling component. As for the study of the target physics, including the neutronics performance, the particle fluxes, the heat deposition and temperature rising change of the granular flow in helium environment under the bombardment of high-power beam, the radiation damage of the beam tube and the vessel wall come from high particle fluxes, the radioactivity and its shielding in the granular flow loop system and so on, a reliable and detailed MC simulation is more realizable and essential. In this work, we present the algorithm designs for the MC simulation studies of a granular target.

2. Brief description of the development of GMT program

For some research on granular matter, the granular system can be modeled as a whole block as long as the distribution of the granular is homogeneous. For the simulation studies of the beam-target interaction, however, this kind of simplification in geometry should not be performed. For charged particles, their tracks will be curved due to multiple scattering. Thus, the tracking of a charged particle is accurate only if detailed transport is carried out in granules and the space among them step by step.

Besides, for a stable granular hopper flow, there is bound to be density gradient in both axial and radial directions, especially in the area around the beam tube [9]. Moreover, the situation would become more complex when a granular target is working in a gas environment. All of these considerations lead to the conclusion that the detailed simulation is necessary for a granular target.

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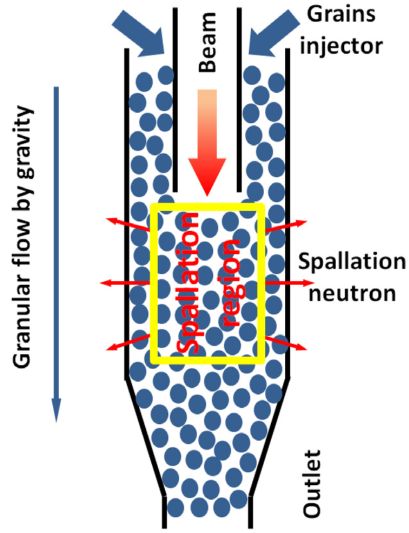

Fig. 1. Schematic outline of a gravity-driven dense granular flow target.

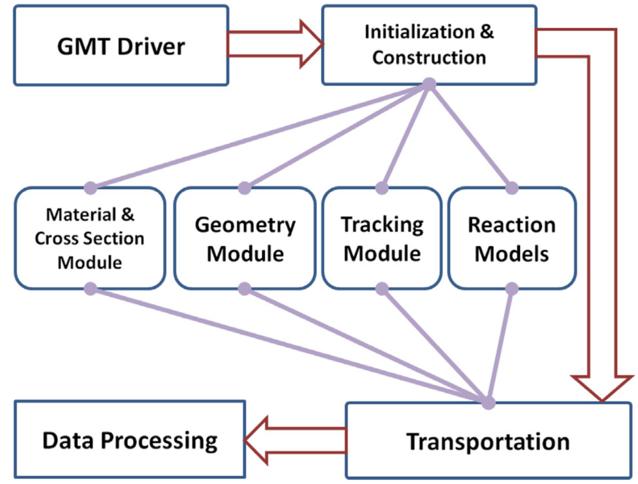

Fig. 3. Structure and main components of the GMT program.

In Fig. 2, the axial-radial distributions of the proton beam flux from the simulation adopting a granular geometry as well as a homogeneous block are shown. The target material is tungsten. The beam energy is 1.5 GeV while the diameter of the beam spot is 15 cm. The target diameter is 35 cm and the target length is 160 cm. The beam tube length is 50 cm. Fig. 2 shows the proton fluxes distributed below the beam tube. In the simulation, the granular diameter is 5 mm and the distribution information of the granules is obtained from the simulation of the dense granular flow using GPU-based discrete element method (DEM) program [10,11]. Considering the fact that there is a free surface below the beam tube for the granular flow target, a spherical surface is used for the modeling of the homogeneous block geometry. The density fraction of the block target is 0.6 [9].

It is can be seen from Fig. 2 that the proton flux map from the detailed simulation using granular geometry is quite different with that from the simulation with the simplified geometry. For the granular geometry, the incident depth of the beam is larger and the radial diffusion is more significant. The deviation of the proton track results in the difference of the neutronics performance [9]. In a word, the simulation of the beam-target interaction using a simplified geometry can hardly reproduce the results from the detailed simulation with a granular geometry.

For the detailed MC simulation study of the beam-target interaction, a dedicated program named as GMT (Granular geometry Monte Carlo Transport program) was developed. As shown in Fig. 3, the program mainly consists of a material and cross section, geometry, tracking and reaction models. In the program, the constructive solid geometry (CSG) representations are used for geometry construction. The cross-section module is based on the combination of experimental data and parameterized formula. For the simulation of spallation reactions, the Intra-nuclear Cascade of Liege (INCL4) model [12] is used for INC process while the ABLA evaporation/fission model [13] is available for the de-excitation of residual nucleus. The evaluated data library ENDF/B-VII is adopted for the simulation of the (n, xn) reactions for neutrons below 20 MeV. To process the outputs of the simulation

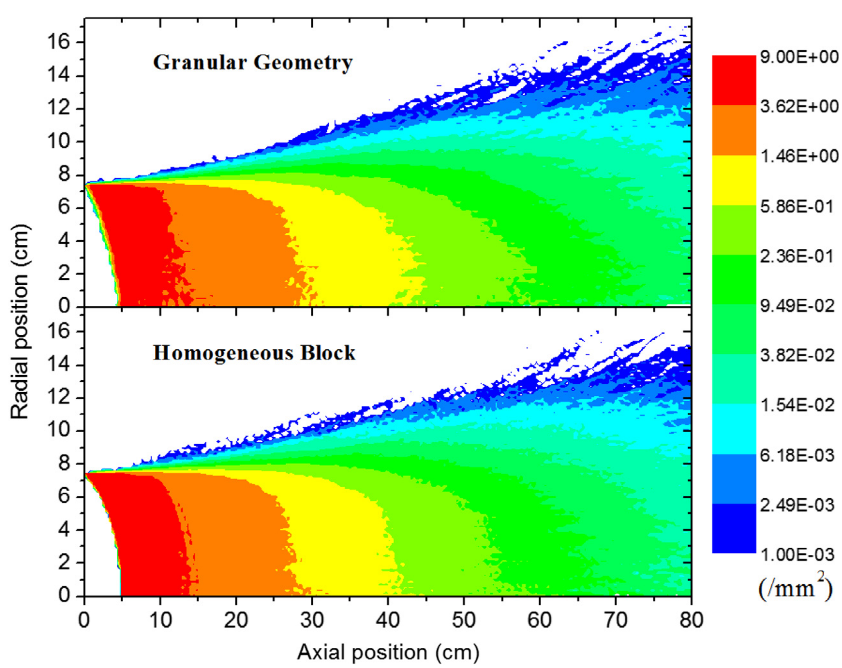

Fig. 2. Axial-radial distribution of the proton beam fluxes across the target for both granular geometry (top) and homogeneous block (bottom).