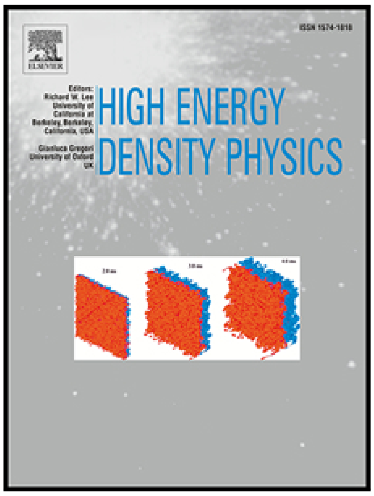

High Energy Density Physics Effects Predicted in Simulations of the CERN HiRadMAR Beam–Target Interaction Experiments

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Abstract–Experiments have been done at the CERN HiRadMat (High Radiation to Materials) facility in which large cylindrical copper targets were irradiated with 440 GeV proton beam generated by the Super Proton Synchrotron (SPS). The primary purpose of these experiments was to confirm the existence of hydrodynamic tunneling of ultra–relativistic protons and their hadronic shower in solid materials, that was predicted by previous numerical simulations. The experimental measurements have shown very good agreement with the simulation results. This provides confidence in our simulations of the interaction of the 7 TeV LHC (Large Hadron Collider) protons and the 50 TeV Future Circular Collider (FCC) protons with solid materials, respectively. This work is important from the machine protection point of view.

The numerical simulations have also shown that in the HiRadMat experiments, a significant part of the target material is be converted into different phases of High Energy Density (HED) matter, including two–phase solid–liquid mixture, expanded as well as compressed hot liquid phases, two–phase liquid–gas mixture and gaseous state. The HiRadMat facility is therefore a unique ion beam facility worldwide that is currently available for studying the thermophysical properties of HED matter. In the present paper we discuss the numerical simulation results and present a comparison with the experimental measurements.

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1. INTRODUCTION

The 440 GeV proton beam generated by the Super Proton Synchrotron (SPS) at CERN, is used at the HiRadMat (High Radiation to Materials) facility, for beam–matter interaction experiments using fixed targets. At present, HiRadMat is a unique ion beam facility worldwide that is available for such interesting scientific investigations. In July 2012, a number of experiments were performed at this facility in which large copper cylinders were irradiated with protons to study the problem of beam–target heating and the results of these studies are documented in [1–3]. The main purpose of these experiments was to confirm the existence of "hydrodynamic tunneling" of ultra–relativistic protons and their hadronic shower in solid targets, as previous numerical simulations predicted a significant range lengthening of the projectile particles due to this phenomenon [4]. This effect is very pronounced in the case of 7 TeV Large Hadron Collider (LHC) protons [4–7]. For example, according to our simulations, the static range of a single 7 TeV proton and the shower it produces in solid copper is about 1 m, whereas, the full LHC beam will penetrate around 35 m in the target due to the hydrodynamic tunneling. This phenomenon, therefore, has important implications on the machine protection design. It is to be noted that experimental verification of the existence of the hydrodynamic tunneling in case of the LHC protons is not possible, which in fact, is a necessary requirement for the validation of the simulations. The success of the HiRadMat experiments and the excellent agreement between the experimental measurements and the simulation results confirmed the existence of hydrodynamic tunneling and established the accuracy of the corresponding simulations [2]. This provides confidence in the validity of the LHC beam related simulations [4] as one may extrapolate the SPS results to the LHC case.

Previously, we published simulation results of selected HiRadMat experiments [2] that were available at that time. We have now completed simulations of the remaining experiment and the results are presented in this paper, emphasizing the HED physics aspect of these experiments. Extensive theoretical work has previously been done to explore the potential of intense heavy ion beams to study HED physics [8–17]. However, the experiments proposed in these papers can not be realized soon because the Facility for Antiprotons and Ion Research (FAIR) at Darmstadt [18], is not yet ready. Ion beams have also been proposed as driver for inertial fusion [19–22]. Another important application of ion beams is the production of radioactive beams [23–26].

In Sec. 2, we present the experimental setup and the beam and the target parameters used in the simulations. The simulation results are presented in Sec. 3 while a brief comparison between the experimental measurements and the simulations is given in Sec. 4. Conclusions drawn from this work are noted in Sec. 5.