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Intense heavy ion beam-induced material evaporation and the resulting dynamic vacuum deterioration of the beam line

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ABSTRACT

We studied the explosive evaporation of high energy density matter generated by irradiation of intense heavy ion beams and the resulting effect on the dynamic vacuum of the accelerator beamlines. High Energy Density Physics (HEDP) experiments are proposed at the plasma physics terminal at the Facility of Antiproton and Ion Research (FAIR), which is currently under construction. The target response to irradiation by intense beam was simulated by HEIGHTS (High Energy Interaction with General Heterogeneous Target Systems) simulation package. The vacuum deterioration resulting from the target evaporation was simulated with the Molflow+ Monte-Carlo simulator. Experimentally we measured the pressure wave propagation at the HTD beamline at GSI in order to benchmark the simulation. The pressure wave was generated through ohmic heating of a cold surface.

1. Introduction

High energy density physics is one of the major research topics at FAIR and HIAF (High-intensity Ion Accelerator Facility), which are currently under construction in Darmstadt, Germany and Huizhou, China [1–8] respectively. The fundamental study of HED matter will be carried out, such as the equation of state, emission and transport properties [9–10]. The proposed experiments such as HIHEX (Heavy Ion Heating and Expansion) and LAPLAS (Laboratory Planetary Sciences) will allow to access wide and unexplored region of the phase diagram, such as warm dense matter, strongly coupled plasmas, hydrogen in metallic state and iron in super earth [3,11–17]. FAIR and HIAF will provide particle beams with unprecedented intensity and quality for these experimental study. The available intensity is usually limited by space charge effects, while for high atomic number Z elements, it is limited by the dynamic vacuum effect and corresponding charge exchange process as well [18]. The consequence of dynamic vacuum effects is an enhanced interaction of heavy ions in the accelerator with residual gas atoms at UHV (Ultra High Vacuum). Due to the ionization or electron capture process in the interaction, the charge state of the ions is changed and consequently the trajectory will deviate from the reference beam trajectory and finally the ions will be lost at the walls of the beam line. The energy deposition of the deviated ions to the wall generates particle desorption into the UHV system and this in turn increases the charge exchange processes. In this way, an avalanche process occurs, which results in significant loss of beam. In the experiment carried out by Peter Spiller [18] at SIS 18 (GSI) the synchrotron was filled with intensities from approximately 1×10^9 particles U^{28+} up to about 8×10^9 particles and the lifetime of the beam was measured. After 1 s only approximately 50% of the beam survived when the synchrotron was filled with 1×10^9 particles. When the synchrotron was filled with more than 7×10^9 particles the beam was almost totally lost after 0.5 s. Since the space charge limit for U^{28+} was calculated to be about 10^{11} particles, the total beam loss happened considerably below the space charge limit due to the dynamic vacuum effect.

To limit the dynamic vacuum effect, on one hand, ion-catchers were installed to reduce the particle desorption from the point of ion incidence on the beam pipe wall. The detailed information can be found in [19–22]. On the other hand, it is mandatory to reduce the residual gas amount, namely preserve a stable ultra low vacuum pressure in the SIS100 accelerator, which is meters-away from the Plasma Physics cave. Special effort has to be taken to suppress any pressure wave propagation from the plasma physics experiments to the SIS100.

In the HEDP experiments to be conducted at the plasma physics cave, targets are irradiated with an intense ion beam containing

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10^{11}–10^{12} heavy ions per pulse. The pulse length is on the order of 100 ns. On the irradiation region of the target, high energy density states of matter will be generated. The target temperature will be up to 10 eV with pressure in the Mbar (100 GPa) regime [3,11–17].

In this way, the target material will undergo a series of phase transitions from solid, to liquid, to gas and finally to dense plasma. During this process, a macroscopic amount of material will be vaporized, resulting in an abrupt increase of the pressure in the target chamber. A pressure rise up to several mbar is expected. Consequently, the vacuum conditions in the whole beam line will be influenced by this process, even the adjacent section in the terminal such as atomic physics or eventually SIS100. Currently at GSI, HEDP experiments with intense ion beams delivered by SIS-18 heavy ion synchrotron are conducted at the experimental area of HHT (High energy, High Temperature), which is located behind SIS18. With a strong Final Focus System, a 100 ns beam bunch containing 1×10^{10} ions can be focused to 1 mm diameter or below. Concerning the dynamic vacuum problem, currently a thin foil window is used to separate the HHT from the general beam line system of the accelerator. Since the expected high intensity beams at FAIR will destroy such a foil with each beam bunch transported to the target area, the use of such a foil window is not possible.

Therefore, we had to have the knowledge about how such HEDP experiments at the plasma physics terminal will influence the vacuum system at the junction of the plasma physics terminal to the other terminals. The pressure must be guaranteed to stay below 10^{-8} mbar, since the heavy ion synchrotron has to be operated under ultra-high vacuum conditions.

In the present paper, the amount of target evaporation under the deposition of heavy ion beams proposed by the FAIR project was estimated with the HEIGHTS simulation package [23–26], which is developed initially at Argonne National Laboratory and now continued at Purdue University. The resulting dynamic vacuum was simulated with a Monte-Carlo Simulator package Molflow + [27] developed at CERN. To check the reliability of the simulation, experimental measurements were done at the HTD beamline of GSI.

2. Hydrodynamic simulation results

HEIGHTS is a powerful tool for comprehensive simulation of the interaction process at very high energy deposition of plasma, laser and particle beams on target materials. During the interaction of heavy ion beams with the target, generally, the incoming ion beam is heating up the target and forming a plasma cloud near the surface. In the following moments, the ion beam deposits part of its energy into the plasma and the remainder into the condensed phase of the surface material. At the same time, the radiation transport and conduction in the plasma is also affecting the whole system. Therefore, to perform a complete evaluation of the material behavior under high energy deposition, three major areas must be taken into consideration, such as material hydrodynamic response, plasma cloud hydrodynamics and the radiation transport.

In HEIGHTS, to make a more realistic prediction of the target behavior, full 2D comprehensive radiation magnetohydrodynamic (MHD) models with Particle-in-Cell numerical techniques and Ray Tracing methods are coupled to target thermodynamics and liquid layer hydrodynamics. The detailed particle transport and energy deposition are depicted with the Monte-Carlo ITMC code, and the atomic radiation data were obtained from the SUPERATOM code in HEIGHTS package. More details about the physical model can be found in [26].

Here the hydrodynamic simulation of solid target heated by intense heavy ion beam was done with HEIGHTS package. We considered a solid target with the size of 60 mm * 60 mm perpendicular to the beam direction. The beam parameters we used in the simulation were taken from the FAIR-design parameters booklets. Assumed is a beam of 1 GeV/u ^{238}U ions with intensity of 4×10^{11} ions per pulse and a pulse duration of 50 ns. The beam has a Gaussian distribution in space with Full Width at Half Maximum (FWHM) of 1 mm. The time structure of the beam was assumed to have a square temporal distribution from 1 to 50 ns. The temperature distribution in the target at 50 ns (the end of the beam pulse) is shown in Fig. 1. The calculation indicates that the temperature in the irradiated region could reach to a magnitude of 2 eV. The heated zone near the surface is fragmented into particles. When the particles expand into the vacuum, plasma plume is formed. The evaporated mass as a function of time, which is calculated with HEIGHTS, is shown in Fig. 2. It can be seen that at around 23 ns, the target begins to evaporate and at the end of the beam pulse, about 43 mg carbon is evaporated. Although it is not shown here, the evaporation will stop after the end of beam pulse according to our experience. Therefore, it can be concluded that about 43 mg of the carbon bulk target will evaporate under heating by the ion pulse beam proposed at FAIR.

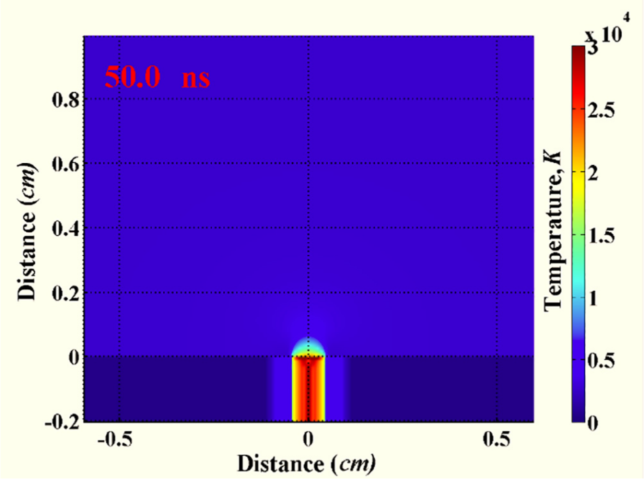

Fig. 1. Temperature distribution of solid carbon target under FAIR-proposed pulsed beam heating at 50 ns.

3. Dynamic vacuum simulation results

Molflow + is a test particle Monte Carlo simulator developed at CERN for ultra high vacuum. It allows to simulate the dynamic gas behavior in a complicated geometry. It is hard to simulate all the particles in the vacuum system, so in Molflow +, virtual test particles are used to represent the real ones. The algorithm of Molflow + is mainly as follows: 1) A test particle is generated at the desorption facet. The velocity of the particle is determined by the Maxwell distribution and the

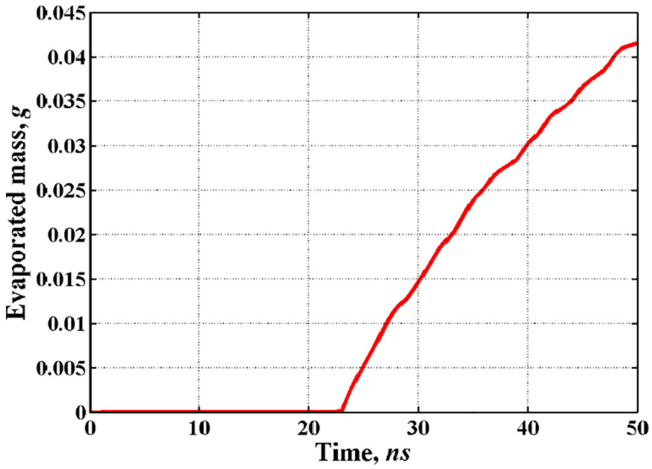

Fig. 2. Evaporated mass of the solid carbon target as a function of time using FAIR beam parameter.