Plasma physics experiments at GSI

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Abstract. Experiments using high-energy/high-power lasers have being pursued for almost a decade at GSI. In the regime of ultra-intense lasers, the PHELIX (Petawatt High-Energy Laser for heavy-Ion eXperiments) system has reached the 20 TW level and first successful experiments have been done. In addition to the experiments on heavy-ion energy loss in laser produced plasmas, our research will focus on laser-assisted particle acceleration and the use of high-energy petawatt lasers (HEPW) for the diagnostics of dense plasmas which has raised great interest in the international community. The plasma physics group at GSI, based on experiments in France, the UK and the U.S., has contributed significantly to this field of research in recent years. Now, with the upcoming commissioning of different power levels of PHELIX our experimental activities can be performed at GSI. Due to the funding of a virtual institute by the Helmholtz Association, the opportunities for new experiments at GSI have grown significantly. The paper will give an overview of recent experimental results, show the link to the future GSI experimental program (including FAIR) and present the experiments that will be done at GSI for the years to come.

1. Overview

Presently, GSI (Gesellschaft für Schwerionenforschung mbH) is the only facility worldwide where a long-pulse high-energy laser system, a short-pulse high-intensity laser system and a heavy-ion accelerator are available at the same site. The plasma physics group of GSI uses this unique combination of ion and laser beams at the experimental area Z6 at the UNILAC accelerator for experiments investigating the properties of dense ionized matter, especially the interaction of heavy ions with laser-heated dense plasmas [1]. To date the group uses the nhelix (Nanosecond High-Energy Laser for heavy-Ion beam eXperiments), that delivers 4-15 ns pulses with up to 100 J ($1\,\omega$) [3] to heat thin carbon foils or hohlraums. The latter are produced by our group at the Darmstadt University of Technology (TUD) in the target laboratory at the Nuclear Physics Institute [2]. The next level of experiments with higher densities demands a more powerful laser driver. The PHELIX (Petawatt High-Energy Laser for heavy-Ion eXperiments) [4] has made significant progress towards first experiments at Z6. The PHELIX will not only drive hot, dense, macroscopic plasmas for heavy-ion interaction experiments, but is also intended to act as a backlighter source for ion-beam driven warm dense matter. As a petawatt facility, it is also an excellent tool to alter the physical properties of ion-beam driven targets and to explore the physics in the regime of relativistic plasmas. For these tasks the PHELIX beam will be sent to three different experimental areas. PHELIX can additionally deliver stretched pulses from the fs-front end of the system to the Z6 area. In order to obtain a power level of 100-200 TW, the "Virtual Institute for the generation of intense Particle Beams by Ultra-intense Lasers" VIPBUL [5] was funded by the Helmholtz association to enable short-pulse laser-matter interaction experiments at Z6. In addition to this, not only the ion beam from the UNILAC, but also the two nhelix beams are available at the same target chamber. They will all be synchronized to each other. This combination of two laser beams (100 J@10 ns and 10 J@0.5 ns, both at 1 ω) together with the PHELIX (40-100 J@0.5 ps or 1 kJ@1 ns, both at 1 ω) and the ion beam (3-20 MeV/u) allows for a large number of experiments that cannot be performed at any other place in the world, e.g. high-precision heavy-ion beam interaction experiments with dense plasmas.

2. Energy loss measurements of heavy ions in dense plasmas

Presently, the energy loss measurement of heavy ions in hot dense plasma is performed by irradiating thin foils with nhelix. The heavy-ion beam is focused through a 500-μm diameter pinhole in front of the foil for collimation. Since the ion-beam focus is large, the laser spot size is 1 mm to achieve a homogeneous plasma in the interaction zone. This large laser focus is obtained with a random phase plate to get a top-hat-like focus. For every laser shot the energy, pulse shape and beam profile at the focus can be monitored. The plasma is probed by a 500 ps, frequency-tripled (355 nm) pulse of the second beamline of nhelix for a spatially resolved free-electron density measurement by Wollaston-interferometry.

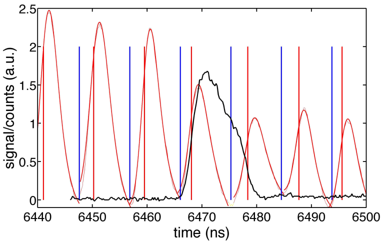
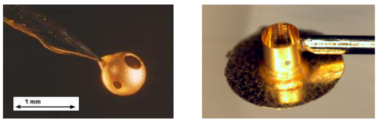


Figure 1. Energy loss of 4 MeV/u Ar in laser-generated plasma, see text for details.

The varying energy loss of the ion beam in the target (solid–plasma–vacuum) is determined by a TOF-technique in which temporal shifts (of the UNILAC micro-bunch period of 9.224 ns) between individual micro-bunches are recorded. The expected energy loss difference between the solid and plasma state is in the order of 30 % - 50 %, that corresponds to a TOF difference of the order of 1-2 ns. Due to this restriction and with respect to future experiments with indirectly heated targets, an ion stop detector made of polycrystalline CVD diamond was developed to match the high requirements as to repetition rate, time resolution, high-ion & low-light sensitivity, and radiation hardness. The time resolution is better than 40 ps which corresponds to an energy resolution of $\Delta E/E = 2 \times 10^{-4}$ for the ion beams used in the experiments. Details can be found in [6]. An example of the energy loss data of 4 MeV/u Ar in a 100 μg/cm^2 carbon foil is shown in Fig. 1. The red curves are the ion bunch structure with a nominal distance of 9.224 ns. The red vertical lines show the arrival time of the bunch center after deconvolution with the detector response function. The energy loss in the cold foil is constant (1.8 MeV) and agrees well with calculations from the SRIM code package [7]. The foil was heated by the nhelix laser with $E = 46$ J, $\tau_p = 10$ ns, 1 ω. When the laser pulse (black curve) hits the foil, the arrival time shifts and slowly approaches the vacuum level (blue vertical lines). The shift in arrival time allows to deduce the energy loss of the ions in the dense plasma. The experiments show that the energy loss is influenced by the time difference between the impact of the laser pulse and ion bunch as well as the foil thickness. We conclude that the plasma effect on the energy loss of heavy ions was clearly observed. Further experiments and theoretical work to understand the details are now in progress.

3. Experiments with Hohlraum targets

The experimental geometry as described above suffers from gradients in density and in temperature within the plasma that change considerably between two micro-bunches. Therefore a precise, time-resolved characterization of the key plasma parameters, like the free-electron density, is necessary in order to compare experimental data with theoretical models. A possible set-up to minimize these detrimental effects utilizes an indirectly heated hohlraum target. Two types of hohlraums are needed: a cylindrical cavity containing the interaction target and a spherical cavity attached to this, serving as radiation converter. The laser will heat the converter and generate thermal radiation in the soft x-ray regime, that in turn will produce the plasma in the cylindrical hohlraum. Simulations have shown homogeneous plasma parameters during the interaction time of an ion bunch [8]. We are manufacturing the hohlraum targets at the TUD target facility; two examples are shown in fig. 2. The sizes of the openings are 160 μm for the diagnostic port and 330 μm for the laser entrance hole. First experiments were focused on a time- and spectrally resolved measurement of the thermal radiation released by the spherical Hohlraum. For a better coupling into the hohlraum, the nhelix main beam was frequency-doubled (λ=532 nm) and delivered 15 J@2 ω on target. The determination of the hohlraum temperature was done with an XUV-spectrometer and photo-diode detectors with sub-ns temporal resolution by measuring the spectral emittance of the hohlraum radiation at several wavelengths in absolute units. The spectral range was $(120 - 320)$ nm. The absolute calibration was performed with a deuterium lamp, that was calibrated by the Physikalisch-Technische Bundesanstalt in Braunschweig/Germany. The temporal profile of the temperature followed the shape of the laser pulse until all laser energy was coupled into the hohlraum. Measurements with a streak-camera in the visible range of the spectrum reveal that the laser-irradiated wall starts to disintegrate before the entire hohlraum explodes. Details will follow in a separate publication [9]. The conversion efficiency into soft x-ray thermal radiation is very promising with regard to the heating of a secondary cavity and future energy loss experiments with indirectly heated targets.



(a) (b)

Figure 2. (a) Spherical (∅= 760 μm) and (b) cylindrical hohlraum (∅=1 mm).

4. Laser-accelerated ions

Almost a decade ago it was found that foils irradiated with ultra-intense short laser pulses generate MeV ion beams from their rear side. These ions form a collimated beam with an exponential spectrum, falling to high energies and exhibiting a sharp cut-off at a maximum energy that depends on the laser and target parameters. The beam is directed normal to the target surface with superior emittance compared to conventional accelerators [10, 11]. In the framework of VIPBUL, we want to investigate this acceleration mechanism with respect to its potential application as a new ion source in conventional accelerators. Since PHELIX is still in the commissioning phase, the first experiments on ion acceleration were restricted to the short-pulse exiting the pre-amplifier section. This low-energy version delivered up to 5 J in 500 fs (= 10 TW) on target and was focused to $I > 10^{19}$ W/cm^2. The targets, produced at the TUD, were (10-50) μm thick Au foils micro-structured at their rear side [12]. During this first experimental campaign, we observed proton emission clearly related to the TNSA process; the results are published in [13]. Up to now, predictions of the ion beam properties like emittance,

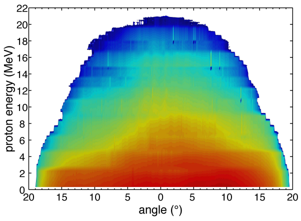


Figure 3. Laser-accelerated proton beam reconstruction.

divergence or spectrum are mainly based on simulations and rather simple estimates. For R&D towards a new ion source, a better modeling and understanding is indispensable. On the experimental side, we developed a Thomson parabola with an electromagnet and MCP for the online analysis of the multiple ion species and charge states accelerated in each shot [14]. Especially for the protons, we use a combination of radiochromic film stacks for an energy-resolved measurement of the spatial beam profile and a 3D weighted subtraction algorithm [12] to get the space and energy resolved proton distribution. An example for a proton beam profile, accelerated at the TRIDENT laser facility at LANL, is shown in fig. 3. The beam profile is parabola-like and smooth; the ion number (color coding) decreases exponentially with energy. Furthermore, we have developed an effective flow model that is based on experimental data and 3D-PIC simulations to fully reconstruct the beam expansion. Details will be published elsewhere [16]; an example can be found in [15]. The knowledge of the exact beam parameters is essential for further developments with the goal of an ion source. Additionally, our group at GSI has started to apply the relativistic 3D-PIC code PSC developed by H. Ruhl, not only as a support for the experiments, but also for investigations of the beam parameters that are to be expected with the next power levels of PHELIX.

5. Program for the very next years

Since the PHELIX beam line to Z6 is getting close to completion, we prepare first experiments on heavy-ion energy loss in plasmas driven by hohlraum radiation. At the same time, we will finish the experimental set-up to compress the PHELIX short-pulse beam at Z6. Once PHELIX is ready, we can start to apply new plasma diagnostics, like laser-driven proton radiography, high-energy x-ray radiography or x-ray Thomson scattering. The expertise gained in these experiments will help to apply these diagnostic capabilities at the HHT experimental area, where the PW-option of PHELIX will be available together with the shortest and most intense ion beam pulses from the SIS-18 synchrotron. The ion beam will be used for the production of high energy-density (HED) matter; the high-energy PW laser (HEPW) will be used as a driver for the diagnostics. Even further in the future at the new FAIR (Facility for Antiproton and Ion Research), the knowledge gained in these experiments is indispensable for a success of the GSI HED physics program [17], that is organized in the HEDgeHOB collaboration [18]. The goal is to study thermophysical, transport, and radiation properties of HED matter generated by the impact of intense heavy ion beams on dense targets and diagnosed by radiation or ion beams generated by a HEPW laser.

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