A novel experimental setup for energy loss and charge state measurements in dense moderately coupled plasma using laser-heated hohlraum targets

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Abstract. We report on a new experimental setup for ion energy loss measurements in dense moderately coupled plasma which has recently been developed and tested at GSI Darmstadt. A partially ionized, moderately coupled carbon plasma ($n_e \leq 0.8 \cdot 10^{22} \text{ cm}^{-3}$, $T_e = 15 \text{ eV}$, $z = 2.5$, $\Gamma = 0.5$) is generated by volumetrical heating of two thin carbon foils with soft X-rays. This plasma is then probed by a bunched heavy ion beam. For that purpose, a special double gold hohlraum target of sub-millimeter size has been developed which efficiently converts intense laser light into thermal radiation and guarantees a gold-free interaction path for the ion beam traversing the carbon plasma. This setup allows to do precise energy loss measurements in non-ideal plasma at the level of 10 percent solid-state density.

1. Introduction

The energy deposition of an ion beam in plasmas is a key question for inertial confinement fusion research (ICF), particularly for simulations of $\alpha$-particle heating, for the assessment of heavy ions as drivers (HIF), and for fast ignition concepts with ion beams (FI). In the last three decades a variety of experiments [1-6] have been carried out to get a deeper insight into the physics of ion beam plasma interaction. Most of these experiments have investigated the so-called linear interaction regime, which corresponds to swift ions in an ideal plasma. This ideal non-coupled plasma is characterized by the coupling parameter

$$\Gamma = \frac{e^2}{k_B T_e} \left( \frac{4\pi}{3} n_e \right)^{1/3} \ll 0.1$$

In this regime, the stopping power can be well described by perturbative approaches like the standard stopping model (SSM) [7]. But as soon as the plasma becomes non-ideal, these
approaches are no longer valid and strong coupling effects have to be considered like multiple scattering, dynamic screening, bound states and continuum lowering [8]. Up to now only few experimental data exist for the interaction of heavy ions with non-ideal plasma due to the difficulty to create a dense and cold plasma confined for a sufficient time to be probed by an ion beam. One example to exploit this regime is shock-compression of a gas, achieving typical plasma parameters of $n_e \leq 10^{20} \text{cm}^{-3}$, $T_e = 1.8 \text{eV}$, $z = 0.3$, $\Gamma = 1$ [9].

In this paper we present an alternative approach which can create much higher electron densities up to $10^{22} \text{cm}^{-3}$ which are highly relevant for the HIF and FI regimes. A uniform moderately-coupled plasma ($0.1 < \Gamma < 1$) is generated from a solid foil by volumetrical heating with laser-driven hohlraum radiation. This plasma is probed by swift ions ($E = 3.6 \text{MeV/u}$) to measure the influence of non-ideality of the plasma in the stopping power. In an upcoming experiment, this plasma will be probed with slow ions ($E < 60 \text{keV/u}$) to explore the non-linear regime of beam-plasma interaction with a beam-plasma coupling constant $\gamma \geq 0.1$ [10].

2. The double hohlraum plasma target

An attractive way to create a uniform plasma state at high densities is using hohlraum cavities of a high-Z material which are heated by intense laser pulses up to radiation temperatures of tens or hundreds of electron volts. These X-rays can volumetrically heat a sample material inside the hohlraum to a hot and dense plasma state which is inertially and thermally confined for several nanoseconds. For the design of a hohlraum target allowing combined experiments with laser and ions beams, two aspects have to be considered. First, the laser light has to be efficiently converted into thermal radiation. Second, the entire interaction path of the ion beam has to be shielded against the inflow of wall material and debris coming from the exploding converter, at least during the measurement time of 4–6 ns. This is essential in order to guarantee an undisturbed energy loss measurement in the pure sample material plasma.

For that purpose, we developed a double hohlraum target consisting of a primary spherical hohlraum (converter hohlraum) in which the laser light is converted into X-rays and furthermore a secondary cylindrical hohlraum (target hohlraum) where the sample material is placed.

![Figure 1](image1.png)

**Figure 1.** a) Geometry of the double hohlraum plasma target. On the right a target b) with and c) without advanced shielding.

![Figure 2](image2.png)

**Figure 2.** 2D hydrodynamic simulations for a) an empty and b) a filled target hohlraum with electron density line out.
The target hohlraum is directly attached to the converter and is heated by the transmitted X-rays from the converter. The design and dimensioning of this sub-millimeter target is shown in Fig. 1. Both hohlraums are made of gold with a wall thickness of 15 µm. As sample material, two thin carbon foils with 100 µg/cm² areal density are attached at both openings of the cylinder. Extra shielding is added to shield the ion interaction path from debris of the fast expanding converter. The targets are manufactured in the Target Laboratory at Technische Universität Darmstadt. First positive blanks of either brass or steel are formed by micro-chipping and then electroplated with a gold layer. Then, the necessary holes are cut into the gold wall with a laser cutter and the blanks are etched out. The shieldings are directly cut out from 15 µm thick gold foils and the sample material from ≈ 500 nm carbon foils. Finally all parts are assembled using a microscope. All components can be fabricated and positioned with an accuracy of ±15 µm.

The converter is driven by a high energy laser beam generating an almost Planckian spectral distribution of X-rays. The hohlraum radiation of both cavities has been measured both time- and spectrally resolved [11] and is in good agreement with theory [13] and simulations [12]. The laser light heats the converter to a temperature of 100 eV and the target hohlraum to 30 eV. Moreover the radiation temperature in the target hohlraum remains above 20 eV for more than 6 ns. This guarantees a homogeneous and constant target heating during the full beam-plasma interaction time. The expansion of the gold into the beam path has been characterized by shadowgraphy measurements and ion probing through an empty hohlraum. As long as the ion bunches are not disturbed or delayed, one can assume that the electron density of the gold plasma on the interaction path is below 10^{16} cm^{-3}. The insets in Fig. 3 show two shadowgraphy measurements at 4 ns after laser impact without and with shielding where the expanding gold is successfully blocked. The graph in Fig. 3 shows the ion bunch delay with respect to vacuum. After the laser impact at t = 0 ns first perturbations occur after 6 ns.

The hydrodynamics of the converter as well as the empty and the filled target hohlraum have been studied extensively by simulations carried out with the RALEF2D code [14]. All simulations are in good agreement with the measurements. For the empty hohlraum they also predict a gold-free time window of about 5 ns, as shown in Fig. 2. Finally the parameters of the carbon plasma are extracted from the simulation of the filled hohlraum and are benchmarked by plasma interferometry measurements. A density plot and a line out of the electron density at t = 3 ns is given in Fig. 2. In summary, a weakly coupled carbon plasma is generated with 10^{21} < n_e \leq 0.8 \cdot 10^{22} \text{ cm}^{-3}, T_e = 25 \text{ eV} and z = 3.5 which corresponds to \Gamma = 0.2.

3. The experimental setup
The experimental setup at the UNILAC accelerator at GSI is shown in Fig. 4. The converter is heated by the high energy laser system PHELIX (150 J in 1.5 ns FWHM at 528 nm) and the generated plasma is probed by a Ca^{17+} ion beam at 3.6 MeV/u. After a time of flight distance (ToF) of 12 m the probe beam can either propagate directly onto a stop detector or be split up by a magnet into its charge states and analysed with a charge state spectrometer. The most critical part of the experiment is the precise alignment of the ion beam since it first has to pass a 500 µm aperture, then the hohlraum cylinder and finally it has to be focussed onto the detectors located 12 m behind the target. The reduction of the beam diameter is necessary to only probe the carbon plasma at the center of the target hohlraum. The radiation temperature in the hohlraum is measured by a streaked X-ray spectrometer through additional 150 µm diagnostic holes in the hohlraum wall [15]. The electron density of the outflowing plasma is measured time-resolved with a Nomarski multiframe interferometer which is also used for shadowgraphy to characterize the hydrodynamic expansion of the gold [15]. The heavy ion beam from the UNILAC accelerator has a bunch frequency of 108 MHz which leads to an ion bunch every 9 ns registered by the detector. Each of these ion bunches has a width of 2.5 ns at FWHM. This pulse length determines the minimum measurement time needed to probe the plasma state and
is the reason for the aforementioned time window of about 5 ns. Custom made CVD-diamond detectors [16] allow to record the ion-beam intensity with a fast oscilloscope over more than 50 µs. The temporal position of each ion bunch can be determined with an accuracy better than 0.1 ns by fitting these signals.

In a first campaign extensive measurements of the energy loss using only the stop detector were recorded. In 2014, a second campaign will be carried out in which the charge state distribution and the energy loss in each charge state channel will be measured. These results will be compared with existing stopping theories and Monte Carlo simulations of the charge state distribution [17].

**Figure 3.** ToF delay of the ion bunches probing an empty hohlraum target. The first disruption occurs after 5 ns. The inset shows two shadowgraphies of an unshielded a) and shielded b) target 4 ns after laser impact.

**Figure 4.** Schematics of the experimental setup: The plasma is generated by hohlraum radiation generated in the converter target and is then probed by a bunched ion beam and detected after a 12 m ToF distance.

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5. References
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