Project title: Time-resolved diffractive imaging of laser induced dynamics in materials

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Current state of the art

Driven by the ever growing number of laser based light sources, the characterization, manipulation, and machining of materials by light are meanwhile key technologies and of rapidly increasing importance. However, a complex interplay between various processes determines the outcome and an understanding of the mechanisms is crucial for the design of the respective laser treatment [1]. An in-depth characterization and analysis of the light induced processes are the basis of such an understanding. Since the material response varies with intensity across an irradiated spot and at the same time transport processes cause interactions between adjacent regions, spatially resolved methods for monitoring the light induced dynamics are necessary. Diffractive imaging and holographic approaches using ultrashort laser pulses have proven to combine a good spatial resolution with a femtosecond time resolution and a high flexibility due to the absence of sophisticated imaging optics [2]. Diffraction based imaging is currently intensively investigated for various applications and methods for image reconstruction have made dramatic progress [3].

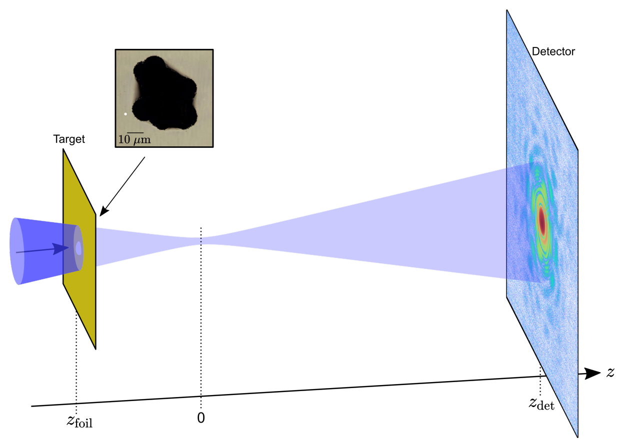

Figure 1: Experimental setup for measuring the diffraction image of a thin gold target.

Research goals and working program

In this project we will apply diffraction based imaging to study the formation and evolution of a plasma generated by the interaction of an intense femtosecond laser pulse with a thin metallic target foil. The research questions concern the collective response of the electrons to the driving laser field and their subsequent relaxation, the interaction between electrons and nuclei as well as the expansion dynamics of the plasma plume [4]. Experimentally, the plasma dynamics will be initiated by the fundamental of a femtosecond Ti:sapphire laser whilst the diffractive imaging will be performed, in a configuration similar to in-line holography, with the second and third harmonic. The experimental setting is depicted in Fig. 1 for the probe beam. By varying the time delay between initiating and imaging pulse the time depended plasma state will be encoded in the measured diffraction images. Afterwards, the time dependent and complex valued transmittance map of the target will be reconstructed from the diffraction images by a phase retrieval algorithm. To this end, an already established, close collaboration with the theoretical group Strong Field Nanophysics in Rostock and an intense exchange with the project Quantum coherent diffractive imaging of isolated nanostructures is exploited. Presently, the experimental setup for the probe beam is already implemented and first measurements, see Fig. 2 a), of a test object, see Fig. 2 b), were performed. With means of our recently developed phase retrieval algorithm we are able to reconstruct the shape of the test object, see Fig. 2 d), and the simulated diffraction pattern (Fig. 2 c) of the reconstructed object nicely matches the measured diffraction image. These proof of principle measurements demonstrate that the current approach is promising also for time resolved measurements.

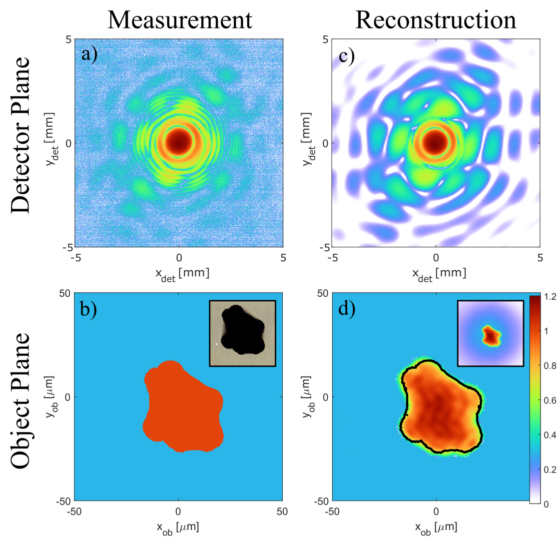

Figure 2: First diffraction images a) of a small structure in a gold foil b). The reconstruction of the shape d) and phase (not displayed) is possible by means of a phase retrieval algorithm resulting in a high quality with respect to the reconstructed shape (compare the initial shape of the object b) with the reconstructed shape in d)) and the simulated diffraction pattern (compare reconstructed diffraction image in c) with the measured diffraction pattern in a)).

Within the proposed project, we suggest the PhD candidate to implement in the setup the excitation beam path and delivery of the pump pulses and to perform time resolved diffraction imaging of the evolving plasma generated from a thin gold foil of 30 nm thickness. The subsequent reconstruction of the complex refractive index map will be performed in cooperation with the Strong Field Nanophysics group. In order to understand the complex dynamics in gold after excitation, we will develop a physical model taking the different time scales, electrons and ions as well as the excitation conditions into account. Followed by that, we will systematically examine the influence of the excitation power, pulse duration of the excitation pulse as well as photon energy on the plasma formation and evolution. Depending on the interest of the PhD candidate we can either look further in different materials, or adopt the setup for smaller structures using XUV pulses for probing such that nanostructures like (bio-)macro molecules can be imaged.

[1] L. Englert, M. Wollenhaupt, L. Haag, C. Sarpe-Tudoran, B. Rethfeld, and T. Baumert, Material processing of dielectrics with temporally asymmetric shaped femtosecond laser pulses on the nanometer scale, Appl. Phys. A - Mater. 92, 749 (2008).

[2] T. Gorkhover et al., Femtosecond X-ray Fourier holography imaging of free-flying nanoparticles, Nat. Photon. 12, 150 (2018).

[3] J. Miao, T. Ishikawa, I. K. Robinson, and M. M. Murnane, Beyond crystallography: Diffractive imaging using coherent x-ray light sources, Science 348, 530 (2015).

Y. Shechtman, Y. C. Eldar, O. Cohen, H. N. Chapman, J. Miao, and M. Segev, Phase Retrieval with Application to Optical Imaging, IEEE Signal Process. Mag. 32, 87 (2015).

[4] R. Ernstorfer, M. Harb, C. T. Hebeisen, G. Sciaini, T. Dartigalongue, and R. J. D. Miller, The Formation of Warm Dense Matter: Experimental Evidence for Electronic Bond Hardening in Gold, Science 323, 1033 (2009).