Intense THz radiation from gas targets

Generation of intense terahertz waves and creation of non-radiative dynamic current configurations in laser plasma

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In Short

- Optimization of the THz signal in intensity and pulse duration through studying its dependence on the laser and target parameters.
- Search of non-radiative configurations of plasma excited by laser radiation which ionizes a micron-size gas medium.
- Observation of non-radiative states in non-stationary microplasma would open a new way for control of secondary radiation emission from laser-created plasma sources.

Abstract. The project aims at the theoretical and numerical modeling of the interaction of moderately intense (with intensity around $10^{14}-10^{15}$W/cm^2 typical for nonlinear laser-atomic optics) laser fields with atomic gases under conditions favorable for the generation of strong terahertz waves from the plasma crated through the ionization process. Compact sources of THz radiation are of high interest both in fundamental physics where they can be used for creation of almost constant strong electric and magnetic fields useful in the excitation of spin waves and control of Rydberg atoms, and in applications including spectroscopy, distant diagnostics of materials and medical noninvasive diagnostics, see e.g. [1,2].

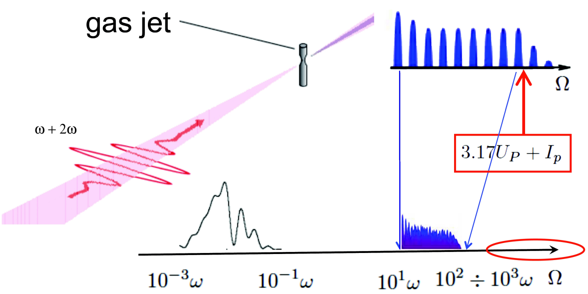

Figure 1: *Terahertz emission from gases driven by intense IR pulses. The second harmonic breaks the field symmetry* $\mathbf{E}(t+T/2) \neq -\mathbf{E}(t)$

Project Description. A broad variety of applications of THz waves including nonlinear atomic and molecular interactions with external fields, requires THz pulses of high intensity, short duration and high repetition rate. During the past decades, several methods for the generation of intense THz pulses have been advanced. One of the most promising approaches to the generation of broadband THz radiation with high peak intensity, controllable pulse duration (up to the single-cycle limit) and tunable carrier frequency is based on the ionization of gas media by strong bichromatic (two-color) optical or infrared (IR) laser fields, e.g. [3–7], consisted of a strong linearly or circularly polarized fundamental beam and its relatively weak second harmonic, Fig.1. Ionization of atoms in such bichromatic laser fields provides asymmetric momentum distributions of the photoelectrons leading to the excitation of a non-vanishing macroscopic electron current in the ionization-created plasma structure. Oscillations of this current at plasma frequencies falling for gas media of concentration $10^{16}-10^{19}$cm^{-3} into the far-IR and THz domain, lead to strong emission of THz waves which are well phase-matched due to the relatively small size of the plasma source.

Despite of a great number of results reported in the past decade on this topic, the problem of THz radiation control and, particularly, maximization of the THz wave strength, remains of high importance and attracts constant interest. The promising bichromatic scheme is being analyzed for different polarizations of laser radiation, laser wavelengths, intensities, gas concentration and plasma size, e.g. [6,8]. In this project, we will pursue a detailed analysis of the THz scheme outlined in [8,9] and based on the use of circularly polarized laser pulses. In order to increase the brightness of the plasma-based source and enhance the conversion efficiency from IR to THz waves we consider the bichromatic ionization of small gas targets with size 10-20 microns, comparable to the THz wavelength. Such a small source can be realized either by using tiny gas-filled fibers or ultra-thin gas jets or tightly focused laser pulses. Preliminary results reported in [8,9] show that plasma sources of 10-micron size driven by mid-IR radiation of (2-4)-micron wavelength appear up to one order in magnitude more efficient in conversion of IR laser energy into that in the THz domain, compared to more common extended sources and 800-nm laser drivers. Besides, our analysis has shown that the extremely efficient radiation of THz waves can lead, though the collective radiation reaction effect, to the formation of time-dependent non-radiative plasma current configurations.

Particle-in-Cell code – The essence of our work consists in the application of advanced computational methods realized in the 3D electromagnetic particle-in-cell (PIC) code UMKA. It employs state-of-the art, widely used numerical algorithms such as the Yee Cartesian lattice for electromagnetic fields, the Boris pusher to integrate the Lorentz force and the current reconstruction scheme to satisfy the continuity equation. Generally speaking, a PIC code implements a particle-grid numerical method, where a collisionless plasma is sampled by a large number of computational particles and electromagnetic fields are discretized on a grid. The computational particles move across the grid cells and are accelerated by the electromagnetic fields defined at grid points, which are computed by reconstructing the source current density from the particle positions and velocity. The present version of our code is suitable for multiple ion species simulations. The model of field ionization is based on the description of tunnel ionization of complex atoms in externally applied electric fields [10]. Our algorithms are local and allow for an efficient parallelization via domain decomposition. In the UMKA code, parallelization is implemented by a decomposition of the (y,z)-discretized coordinates, perpendicular to the x-propagation direction of the laser pulse. This choice provides an initially balanced partition of the particle numbers for problems where the particle density is initially uniform along the (y,z)-plane. As particles move across different domains, a dynamical load balancing techniques would be required to keep the data partition balanced.

Project tasks – Our research program consists of two main sub-projects:

1. Optimization of the THz signal in intensity and pulse duration through studying its dependence on the laser and target parameters with the scheme suggested in [8,9].
2. Search of non-radiative configurations of plasma excited by laser radiation which ionizes a micron-size gas medium. Non-radiative anapole states are well known in the physics of microstructures and meta-materials [11]. Observation of such states in non-stationary microplasma would open a new way for control of secondary radiation emission from laser-created plasma sources.

In order to conduct these studies, a 3D electrodynamics PIC modeling of the ionization process and the subsequent plasma oscillations and radiation will be performed. The interaction of intense coherent radiation with plasmas offers some of the most challenging problems for numerical physics. This is because the most important and interesting phenomena are multiscale and can not be described hydrodynamically. The first feature imposes the use of very large numerical grids since the spatial size and/or evolution time of the system is much larger than the smallest spatial and temporal scales to be resolved. This leads to an estimate that a "realistic" simulation would require a 3D spatial grid with thousands of gridpoints in each spatial direction, resulting in a total number of grid-points exceeding a billion. The second one implies that hydrodynamic description in real space must be abandoned and much more demanding kinetic equation in phase space have to be solved. While the PIC method allows a great saving of memory in allocating the momentum space with respect to an Eulerian approach, hundreds of particles per cell may be needed anyway to properly resolve high energy tails in the distribution as well as sharp density gradients which always occur for intense laser-plasma interactions. Thus, the progress in this area is directly related to the possibility to access larger resources.

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More Information

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Project Partners

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