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Strong terahertz fields: interaction with condensed matter and electron acceleration

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Recent years witness fast development of the sources of strong single-pulse terahertz radiation, with the record value for terahertz field being about 80 MV/cm [1]. There appeared quite a number of publications where the nonlinear interaction of such strong THz fields with matter was investigated and new effects in intense THz fields were sought for. In this presentation, we will discuss the specific nonlinear properties of graphene in strong electromagnetic fields and propose our approach of using short THz pulses for acceleration of electrons.

The first part of the presentation will be devoted to the discussion of the experimental and theoretical results on optical emission from graphene irradiated by a strong (up to 300 kV/cm) short terahertz pulse. The appearance of emission from graphene was observed in experiment in the 350–600 nm spectral range at high THz fields (Fig. 1). We detected the increase of the optical emission by nearly 3 orders of magnitude, while the THz field increased by a factor of 2 only. The spectrum of the optical emission corresponded to Planck's law for the spectral radiance of a black body. We attribute the optical emission to bias-induced spontaneous emission from energetic charge carriers in the graphene. On the basis of the theoretical analysis, we revealed the importance of the dynamic (ballistic) mechanism of electron-hole pair generation induced by an intense terahertz pulse with subsequent spontaneous radiative recombination.

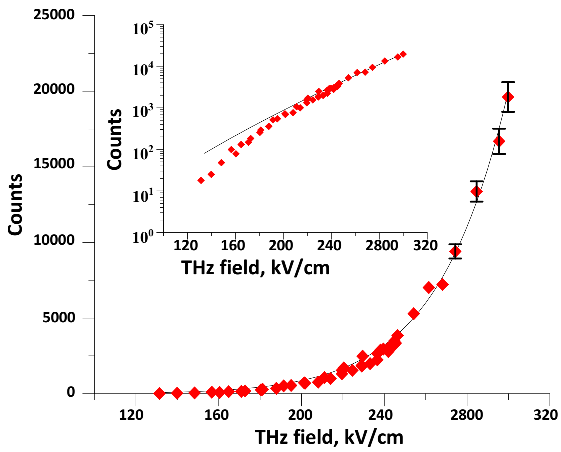

Fig.1. Optical emission from graphene vs THz field. Solid line – theoretical fit

In the second part of the presentation we will discuss our results on the generation of the second optical harmonic (SHG) of laser radiation from graphene in the presence of a high power terahertz pulse. We demonstrated essential amplification of SHG under the action of THz field. Polarization characteristics of SHG specific for graphene will be presented together with the dependence of SHG efficiency on optical and THz fields. Detailed theoretical analysis of von Neumann equation allowed us to propose a new mechanism for SHG in graphene under the combined action of optical and THz fields. This mechanism is caused by broadening of the interband resonance due to quasi-particle acceleration by an intense THz field in the process of interband transition. As a result of the "field" interband resonance broadening, the region of electron-hole generation in k-space becomes asymmetric, which leads to the appearance of necessary anisotropy allowing for SHG in the dipole approximation.

Intense single-cycle THz pulses produced by rectification of laser radiation are suitable for high gradient acceleration of electrons. Naturally, an accelerating structure fed by such pulses should be based on new principles, which would allow propagation of ultra-broadband radiation [2–4]. We propose an accelerating structure (Fig. 2) consisting of a set of waveguides with different adjusted lengths, in which the synchronism of accelerated particles with transversely propagating THz pulse is sustained [3]. A proper mirror shape allows the acceleration of both pre-accelerated particles and particles with zero velocity. The production technology implies a combination of a copper-aluminum "sandwich," electroplating of the reflecting cover mirror, and chemical removal of the aluminum.

For maximizing the acceleration gradient, it is natural to reduce the width of the structure. Unfortunately, this reduction is accompanied by strong diffraction losses due to pulse shape distortion in dispersive waveguides. That is why THz pulse focusing should be implemented in the new structure. The field strength in focus of a parabolic comprise periodic parabolic mirrors with constant focuses fed by a tilted THz pulse. The beam channel in this structure coincides with the focal line. Another problem is the transverse magnetic field of the THz pulse deflecting electrons. There are two solutions of the mentioned problem. First, a THz driven accelerator must have many sections with different directions of magnetic field, which, on the average, do not deflect electrons [3]. The second solution exploits magnetic field distortion (due to dispersion) inside the parabolic mirror. A proper choice of the parabolic mirror focal distance and aperture size allows satisfying the condition of accelerating field maximum and near to zero magnetic field at the same time moment when a bunch goes through the accelerating cell. Preliminary estimates show that for a THz pulse with 80 MV/cm in a 0.1×0.1 mm^2 spot in a structure consisting of 1-cm long parabolic sections, where each section is excited by its own single pulse, the accelerating gradient can be as high as 2.5 GV/m.

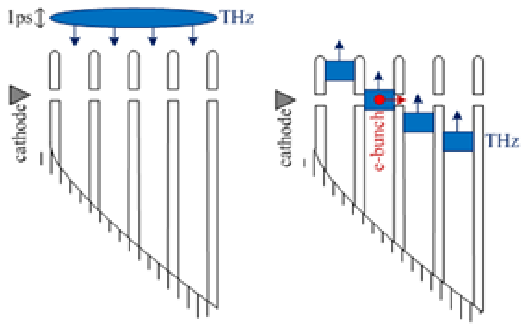

Fig. 2. Sketch of particle acceleration by picosecond THz pulse for two time moments

Another application for intense single-cycle THz pulses is high-brightness electron sources. It was recently proposed to use ~1 picosecond pulse to stimulate field emission in a high-gradient electron gun and simultaneously to provide preliminary acceleration of the electron bunch up to a relativistic energy [4]. A combined THz and RF field helps to overcome beam brightness reduction due to space-charge effects. To achieve high brightness, the beam generated at the cathode is accelerated to a higher energy before the space-charge effects lengthen the bunch. The calculations based on the Fawler-Nordheim equation show that in an accelerating gap fed by a focused mJ THz pulse a subpicosecond electron bunch of about 100 pC charge can be emitted and accelerated so fast that the brightness might be as high as $2\times\times10^{16}$ A/m^2.

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