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Wake effect in interactions of fast ions with supported two-dimensional electron gas

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ABSTRACT

We study the interactions of fast charged particles with a two-dimensional electron gas supported by an insulating substrate, describing its high-frequency plasmon excitations by a two-fluid hydrodynamic model with the parameters characteristic of graphene. The induced number density per unit area of electrons in the two-dimensional electron gas and the total electric potential in its plane are derived as functions of the projectile velocity and the particle position. We show that, when the speed of the particle moving parallel to the two-dimensional electron gas exceeds a threshold value for the collective excitations of σ and π electrons, the oscillatory wake effect develops both in the induced number density and in the total electric potential trailing the particle. When the particle speed matches the phase velocity of the quasiacoustic π plasmon, the induced number density shows usual wake oscillations, in contrast to the single-walled carbon nanotubes where oscillations precede the position of the particle.

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1. Introduction

The properties of two-dimensional (2D) electron systems have received renewed interest in the past few years, motivated by recent experimental discovery of graphene, a single sheet of carbon atoms forming hexagonal lattice [1]. One can consider various carbon nanostructures to be composed of interacting layers of 2D electron gas (2DEG) confined to a graphene sheet: highly oriented pyrolytic graphite (HOPG, a stack of graphene layers), carbon nanotubes (rolled-up cylinders of graphene) and fullerene molecules (consisting of wrapped graphene by the introduction of pentagons on the hexagonal lattice) [2,3].

Interactions of energetic heavy charged particles with layered materials have been studied extensively for some time, e.g., in investigations of the directional effects in ion and molecule implantation into HOPG [4,5], ion channelling through HOPG [6] and secondary electron emission from HOPG induced by fast ions [7] and clusters [8], as well as in ion channelling through carbon nanotubes [9–11].

The ability to screen an external electric field is an important property of any nanostructured material. Depending on the speed of the external charge, the screening mechanism changes its character dramatically, going from a Debye-like screening potential of a static charge to a dynamic regime characterized by an oscillatory potential contained in a cone trailing a fast-moving charge, which is commonly known as the wake effect [12]. While the wake effect in three-dimensional (3D) plasmas has been known for more than fifty years [13], its current significance encompasses diverse new areas, such as dust-crystal formation in complex plasmas [14], Coulomb explosion of large clusters, such as C_{60}, in thin solid foils [15], channelling of fast ions through nano-capillaries in solids [16], interactions of fast ions with carbon nanotubes [9,12] and interactions of charged particles with single 2D quantum electron gases (2DQEG) [17], parallel 2DQEG [18] and supported thin metal films [19].

The wake effect is characterized by the onset of collective oscillations in the polarization of the medium, which provide effective mechanisms of energy loss for a fast external charge. In that context, interactions of fast-moving charged particles with various carbon nanostructures have been studied by the electron energy loss spectroscopy (EELS). This technique has proven to be a powerful tool for investigating the dynamic response of carbon nanotubes [20] and graphene [21].

Our description of the dynamic response of a 2DEG is based on a 2D hydrodynamic model which proved itself to be a valuable theoretical tool for qualitative understanding of the high-frequency, collective excitations in carbon nanotubes [9,22]. This model allows many refinements including Thomas–Fermi and Dirac's corrections, as well as a generalization in a two-fluid version of the hydrodynamic model, making distinction between the contributions of carbon's σ and π electrons [9,10]. We have calculated, in our previous publication [23], the dynamic-polarization forces on both ions and molecules by solving the linearized two-fluid hydrodynamic model for a supported graphene.

In our previous publication [24], we used a simpler, one-fluid hydrodynamic model, which treats all four carbon's valence electrons as a single 2DEG, to present the oscillatory wake effect which

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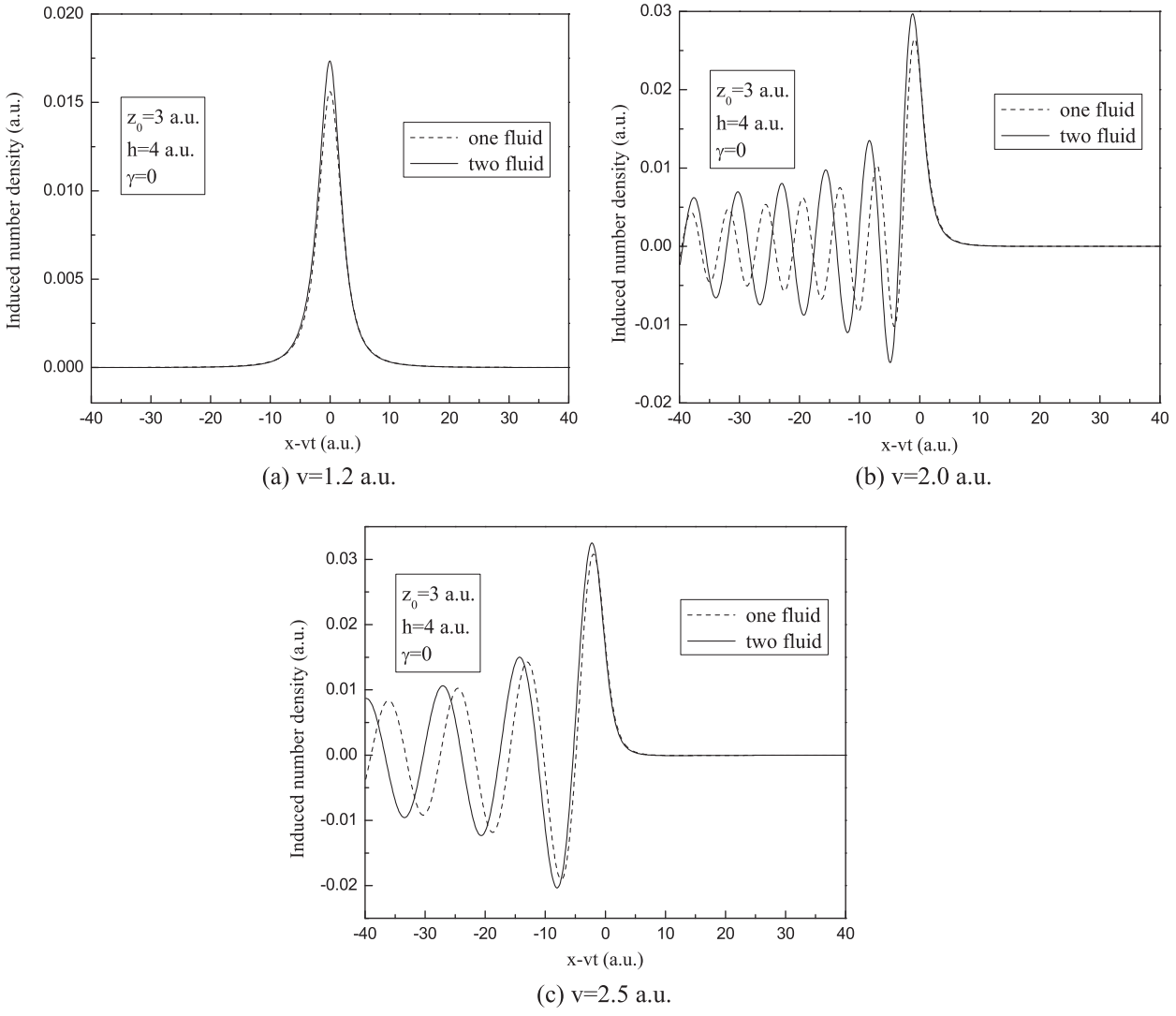

Fig. 1. The spatial distribution of the induced number density (in *a.u.*) along the projectile trail, for a proton moving along the x axis at distance $z_0 = 3$ *a.u.* above 2DEG with SiO_2 substrate (with $\varepsilon_s = 3.9$ and $h = 4$ *a.u.*) in the cases of the two-fluid model (solid lines) and the one-fluid model (dashed lines), with zero damping $\gamma = 0$, at three speeds.

develops in the induced number density when the particle speed exceeds a threshold value for the collective excitations in a 2DEG corresponding to the four valence electrons in graphene. We have found that the quantum diffraction (QD) effects, coming from the quantum pressure, in the case of a 2DEG with the parameters characteristic of graphene have a very little influence on the interaction process, which can be neglected.

In this paper, we use the linearized two-fluid hydrodynamic model to calculate the induced number density per unit area of electrons in the 2DEG and compare it with the induced number density in the one-fluid model. Besides, we present for the first time the calculations of the total electric potential in the 2DEG plane, induced by a fast point charge moving parallel to it. These results will demonstrate the oscillatory wake effect which develops in the induced number density when the particle speed matches the phase velocity of the quasiacoustic π plasmon. Moreover, these results will indicate a possibility of realizing the so-called wake riding effect [12,25]. It means that the presence of the potential, induced by a fast external charge, causes that the other charged particles may be captured, or their state manipulated.

We describe here the high-frequency plasmon excitations in a 2DEG corresponding to the four valence electrons in graphene. As regards graphene, it usually appears in experimental situations as supported by a substrate [26,27]. Surprisingly, all theoretical models of graphene's dynamic response assume a zero gap between the graphene and a substrate [28,29]. In our previous publications we have studied the interactions of slow ions, moving at the speeds below the plasmon excitation threshold for graphene's σ electrons, by means of a semiclassical Vlasov equation for graphene's π electrons [30] and by using the dielectric response formalism for graphene's π electron bands in the random phase approximation (RPA) [31], and pointed to a strong need to take into account the finite size of such a gap, which is on the order of the distance between graphene layers in graphite or even larger, as documented experimentally [27]. We have also found, in our previous publication [24], that the threshold for the wake effect moves to higher speeds and the oscillation periods of the induced number density decrease when the values of the 2DEG-substrate gap increase.

In contrast to the wake effect for a charged particle moving above free-standing single 2DQEG [17] and parallel 2DQEG [18], we study here the wake effect in interactions of fast ions moving parallel to the 2DEG, supported by an insulating substrate. While the configuration of graphene on metal [26] opens interesting possibility of exciting novel modes of collective electron excitations due to plasmon hybridization [10,32], we limit ourselves here to

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