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Criteria for the formation of an inverse electron distribution function and absolute negative plasma conductivity

A. Kudryavtsev, E. Bogdanov, J. Yao, C. Zhou, C. Yuan
Department of physics, Harbin Institute of Technology, Harbin, Cnina
e-mail (speaker): akud53@mail.ru; akud53@mail.hit.edu.cn

The search for non-equilibrium media with an inverse distribution of particles over energy states is of great interest for the further development of science and practice. Thus, the practical implementation of inversed populations of excited states of atoms and molecules made it possible to create a wide class of various lasers that have found their application in various fields of science and technology.

In turn, a plasma with an inverse distribution function of free electrons in gases with Ramsauer minimum of the elastic scattering cross section can have an absolute negative conductivity (ANC). In such an environment, electrons will transfer their energy to the electric field and thereby amplify electromagnetic waves in a wide range of frequencies [1].

And although the criteria for the conditions for negative electron conductivity in plasmas were formulated in the work of Bekefi *et al* [1] almost simultaneously with the creation of the first gas lasers, this practically important problem has not yet been solved.

Our works [2-4] has shown that the the main reason for the current uncertain situation with the search for inverse EDF and ANC is the fact that, as a rule, they are carried out on the basis of a significant simplification of the Boltzmann kinetic equation for electrons - a local approximation, when terms with spatial gradients and an ambipolar field are neglected [5]. In this case, the original EDF $f_0(r,v,t) = n_e(r,t)F_0(v,t)$ is factorized as the product of the electron density $n_e(r,t)$, which depends on coordinates and time, and the local EDF $F(v,t)$ depending on the speed (energy). Such a reduction of the kinetic equation reduces the original kinetic equation in partial derivatives to an equation that depends on only one variable of velocity (energy).

Since an inversion of EDF in the low-energy region, where the number of electrons is maximal, is necessary to create an ANC, the main efforts in the literature have been concentrated on the search for plasma-chemical processes that deplete the low-energy region of the EDF [5].

However, it is extremely difficult to obtain an inversion on the EDF under stationary conditions by a combination of plasma-chemical volumetric collisional processes, since a large cross section of the useful process of loss of slow electrons contributes to the momentum transfer cross section and leads to increasing the transport scattering frequency and suppression of energy diffusion [2].

Since real plasma objects are always localized in a limited volume, when searching for conditions for creating inverse EDFs, one should take into account the spatial inhomogeneity of the plasma parameters in the experimental devices under study [3,4]. In this case, to find the EDF, the complete kinetic equation must be solved, depending on both energy and spatial variables.

The analysis [3,4] showed that in an inhomogeneous plasma the EDF at zero kinetic energy must satisfy the boundary condition: $\left(\mathbf{E}\cdot\nabla f_0 - E^2\partial f_0/\partial w\right)\Big|_{w=0} = 0$ where $\mathbf{E} = -\nabla\varphi$ is the electric field. From this condition it follows that the EDF inversion at $w = 0$ ($\left(\partial f_0/\partial w\right)\Big|_{w=0} > 0$) should exist in those areas where

$$\left(\nabla\varphi\cdot\nabla f_0\right)\Big|_{w=0} < 0 \qquad (1)$$

Since the EDF value is maximum near zero energy $w = 0$, it is reasonable to assume that this part of the EEDF makes the main contribution to its integral characteristic – electron density $n_e(\mathbf{x})$. As a result, the inequality when the Boltzmann distribution for electrons from the plasma potential is violated

$$\nabla\varphi\cdot\nabla n_e < 0 \qquad (2)$$

will highlight areas in which the presence of EDF inversion is most likely.

The analysis showed that the conditions for EDF inversion (1,2) can be implemented in two-chamber discharges due to the specific formation of spatial distributions of electron density and energy fluxes there.

The theoretical conclusions are confirmed by modeling low-pressure two-chamber ICP discharges in the Comsol Multiphysics environment. As a result, regimes were found with violation of the Boltzmann distribution for the electron density (2), associated with the formation of a large electron temperature gradient in the active discharge chamber, where the input power is concentrated. As a result, it is possible to realize conditions in which inequality $\nabla\varphi\cdot\nabla n_e < 0$ is satisfied, signaling a possible inversion of the EDF.

We believe that the results obtained will stimulate both the design of experiments to search for inverse EDFs.

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