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Quantum relativistic theory of plasmas at high intensities and high plasma densities

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For high plasma densities, i.e. with a relativistic Fermi velocity, or very high field intensities, as approached in the next generation laser facilities, quantum relativistic effects comes into play. To study such regimes, the Dirac Heisenberg Wigner (DHW) formalism [1] is applied, which is a fully quantum relativistic kinetic theory, derived by making a gauge invariant Wigner transform of the Dirac equation. Importantly, in the DHW-formalism, particle and anti-particle states are not separated, and the evolution equations generally describe mixed electron-positron states. This approach allows several new phenomena to be studied. To perform such studies properly, however, the ultra-violet divergences associated with the finite vacuum contributions (the Dirac sea) must be accounted for, which leads to a charge renormalization [1,2]. As a result, the DHW-theory predicts a nonzero vacuum polarization. Interestingly, the vacuum polarization is associated with a Landau like damping even in the limit of infinite wavelength. It should be stressed, that a damping mechanism of this type only is possible if the pair-creation resonance exists, see Fig 1, implying ultra-high plasma densities, in which case the wave energy can be converted into electron positron pairs [2].

Furthermore, for an electric field strength approaching the Schwinger critical field E_{cr}, pair production due to the Schwinger mechanism comes into play. The dependence of this process on the plasma temperature, the plasma density, and on the electric field strength is studied. Similar dynamics has previously been analyzed starting from vacuum, in which case an electron-positron plasma is created self-consistently, see e.g. [3]. Using the DHW-formilism, previous results can be confirmed with good precision, see Fig. 2. With a plasma initially present, it is not necessary to start from an initially strong field (close to the Schwinger critical field), as the initial energy can be stored in a strong plasma current. Studying the pair production rate over time, it is found that generally there is a saturation after several plasma oscillation cycles, and for brief periods, the process may even be reversed, i.e. annihilation may take place. The saturation can be due to field depletion, in case the initial energy density is not very strong. However, for higher intensities, typically the saturation mechanism is due to Pauli blocking.

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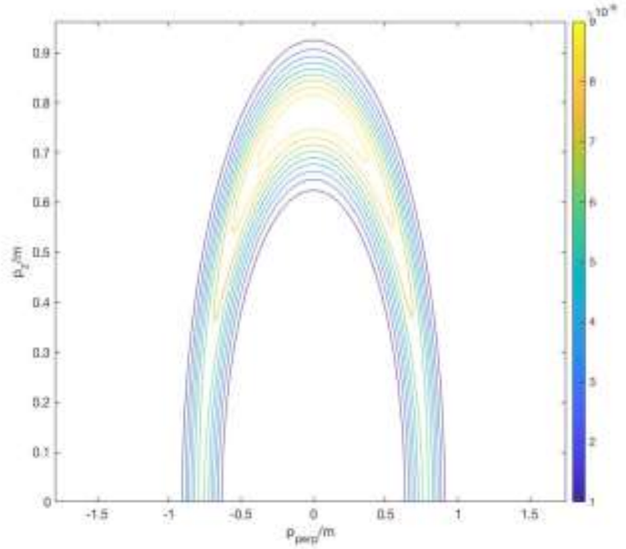

Figure 1. A contour plot of the produced pairs in momentum space. The produced pairs are created in a narrow region fulfilling the pair-creation resonance condition.

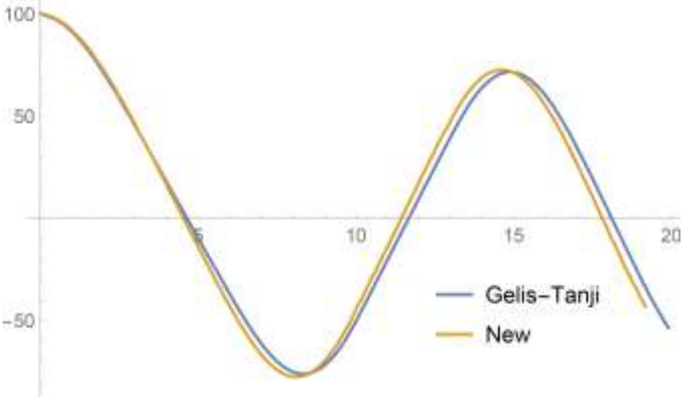

Figure 2. A comparison of the electric field evolution computed by Ref. [3] (Gelis-Tanji), with results based on the DHW-formalism (New). The pair-creation dynamics starts from an initial vacuum state, with an electric field $E = 100E_{cr}$.