Self-consistent Theory of High-Order Harmonic Generation by Relativistic Plasma Mirror

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The interaction between an ultra-intense laser pulse and an overdense plasma is a well-known source of copious coherent XUV emission. The latter follows either directly from the laser reflection off the oscillating plasma boundary (the so-called 'relativistic plasma mirror') [1], or, indirectly, from the energetic electron bunches injected into the target, via coherent wake emission [2] or optical transition radiation [3]. In the relativistic mirror regime, the laser pressure is strong enough to push the electron boundary inward, over a distance comparable to, or greater than the plasma skin depth. For specific laser and target parameters, the electron boundary can be made to oscillate at relativistic velocities. As a result, the reflected light is Doppler-shifted to high-order harmonics of the laser frequency and compressed into a train of ultra-intense, $10-100$ as pulses [4,5,6]. These pulses have great potential for time-resolved atomic spectroscopy, yet their efficient production implies finely controlled interaction conditions as well as a quantitative understanding of the underlying physics. In this respect, despite an abundant literature on the relativistic plasma mirror [7 and references therein], only recently have self-consistent models been worked out that describe in detail the electron dynamics and the resulting high-order harmonic generation (HOHG) [4,5,6], yet in restrictive interaction conditions.

We present the first semi-analytical model of the relativistic plasma mirror, based on the exact computation of the laser-driven surface oscillations within the cold-fluid approximation, that describes the high-order harmonic generation for a large set of plasma and laser parameters. It is found that efficient conversion of p-polarized laser pulses into high-order harmonics well above the plasma frequency requires either high laser intensities, low plasma densities, or incidence angles larger than a threshold value. This critical angle corresponds to a transition between a regime where the electron surface dynamics is mostly governed by the laser $J\times B$ force and a 'cyclotron Brunel' regime, where electrons perform many cyclotron gyrations when moving into vacuum. Under conditions relevant to current laser experiments, the latter regime gives rise to non-monotonic variations of the harmonic yield with the laser field. Our predictions are supported by particle-in-cell simulations [8].

[1] S. V. Bulanov, N. M. Naumova, and F. Pegoraro, *Phys. Plasmas* **1**, 745 (1994)
[2] F. Quéré, C. Thaury, P. Monot, S. Dobosz, P. Martin, J.-P. Geindre, and P. Audebert, *Phys. Rev. Lett.* **96**, 125004 (2006)
[3] J. J. Santos, F. Amiranoff, S. D. Baton, L. Gremillet, M. Koenig, E. Martinolli, M. Rabec Le Gloahec, C. Rousseaux, D. Batani, A. Bernardinello, et al., Phys. Rev. Lett. **89**, 025001 (2002)
[4] J. Sanz, A. Debayle, and K. Mima, *Phys. Rev. E* **85**, 046411 (2012)
[5] A. Debayle, J. Sanz, L. Gremillet, and K. Mima, *Phys. Plasmas* **20**, 053107 (2013)
[6] A. A. Gonoskov, A. V. Korzhimanov, A. V. Kim, M. Marklund, and A. M. Sergeev, *Phys. Rev. E* **84**, 046403 (2011)
[7] U. Teubner and P. Gibbon, *Rev. Mod. Phys.* **81**, 445 (2009).
[8] Y. Sentoku and A. J. Kemp, *J. Comput. Phys.* **227**, 6846 (2008)