Comment on "Packet Spreading, Stabilization, and Localization in Superstrong Fields"

In their recent Letter [1], Grobe and Fedorov examine the stabilization regime for an atom interacting with an intense laser field. Their work elucidates one of the physical mechanisms (packet spreading) underlying the suppression of ionization in superstrong fields. However, the very nature of their results points to a possible breakdown in the validity of the dipole approximation used in their model. By making the dipole approximation for the laser field, the drift of the electron parallel to the direction of laser propagation due to the ponderomotive ($\mathbf{v}\times\mathbf{B}$) forces has been neglected. Classically this is the well-known drifting "figure-eight" motion [2]. The drift takes the electron away from the atom and can prevent stabilization [3]. Here we show that this drift becomes important for very intense lasers and restricts the parameter window for which stabilization can occur.

Grobe and Fedorov show that stabilization is characterized by two stages in time. In the first few optical cycles of the laser pulse the electron is effectively decoupled from the atomic potential and oscillates like a classical free particle between its two turning points [1]. The atomic potential only becomes important later in time when the wave packet has spread to a width larger than the classical quiver amplitude. Finally, after the laser is turned off, they find a significant probability for the atom to be left in its ground state only when the electron is left near the atom with no drift at the end of the pulse.

In the early stage the classical drift velocity of an electron in a plane wave laser field is easily found from the two constants of the motion:

$$p_x - \frac{e}{c}A = -\frac{e}{c}A(0)\,, \tag{1}$$

$$p_z - \gamma mc = -mc\,, \tag{2}$$

where $\gamma=[1+(p_x/mc)^2+(p_z/mc)^2]^{1/2}$, $\mathbf{A}=x(E_0c/\omega)\times\sin(kz-\omega t)$ is the vector potential of the laser, $A(0)=(E_0c/\omega)\sin\phi$ is its value at the time the electron first responds classically to the field, and $k=\omega/c$. The first equation follows from the fact that canonical momentum is conserved in the x direction; the second follows by subtracting the z equation of motion ($dp_z/dt = -ev_xB_y$, $B_y=\partial_zA_x$) from the conservation of energy equation ($d\gamma mc^2/dt=-ev_xE_x$, $E_x=-\partial_tA_x/c$). Eliminating p_x between (1) and (2), substituting for $eA/mc^2\ll 1$, and averaging over a laser cycle gives the drift velocity [4] $v_z\approx(c/4)(V_{\text{osc}}/c)^2(1+2\sin^2\phi)$, where $V_{\text{osc}}=eE_0/m\omega$. The distance drifted after N laser cycles is then $\Delta z\ge N(\lambda/4)(V_{\text{osc}}/c)^2$.

To illustrate the effect of this drift motion, we consider the parameters of the example in Ref. [1]: $E_0=0.64$ a.u., $\omega=0.0628$ a.u. For this example, the motion remains basically classical for $N=16$ cycles [1], $V_{\text{osc}}/c=0.053$, $\lambda\approx 1.0$ μm, and assuming $\sin\phi=0$ (the electron starts at rest when $A=0$), we have $\Delta z\approx 110$ Å. Thus by the time packet spreading occurs the electron is already far from the nucleus and is for all practical purposes ionized.

More generally, we expect that the ponderomotive drift will prevent stabilization when the drift velocity v_z exceeds the packet spreading velocity v_s ($\approx\hbar/m\Delta z_0$, where Δz_0 is the initial packet width), or

$$(V_{\text{osc}}/c)^2 > \hbar/4mc\Delta z_0\,. \tag{3}$$

For the parameters of Ref. [1] this corresponds to $E_0>0.55$ a.u. In their Fig. 3, Grobe and Fedorov show an increase in the probability of unionized atoms for all laser fields greater than $E_0\approx 0.1$ a.u. With the inclusion of the ponderomotive drift, we expect that the unionized fraction may increase for $E_0\approx 0.1$ to 0.5 a.u. but decrease rapidly for $E_0\gtrsim 0.6$ a.u. for their parameters. Furthermore, even when the ponderomotive drift is less than the packet spreading velocity but large enough that Δz exceeds a few atomic units, one might expect the unionized fraction to be small.

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