Relativistic Plasma Mirrors

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Motivation

Attosecond pulses unlock access to electron dynamics and ultrafast phenomena across atomic, molecular, and plasma physics. A key challenge is generating them with sufficient intensity for applications.

Density spikes at the rear of a laser-driven plasma bubble act as relativistic mirrors [1, 2], transferring momentum to a counter-propagating pulse via the double Doppler effect, compressing and upshifting it to higher intensities.

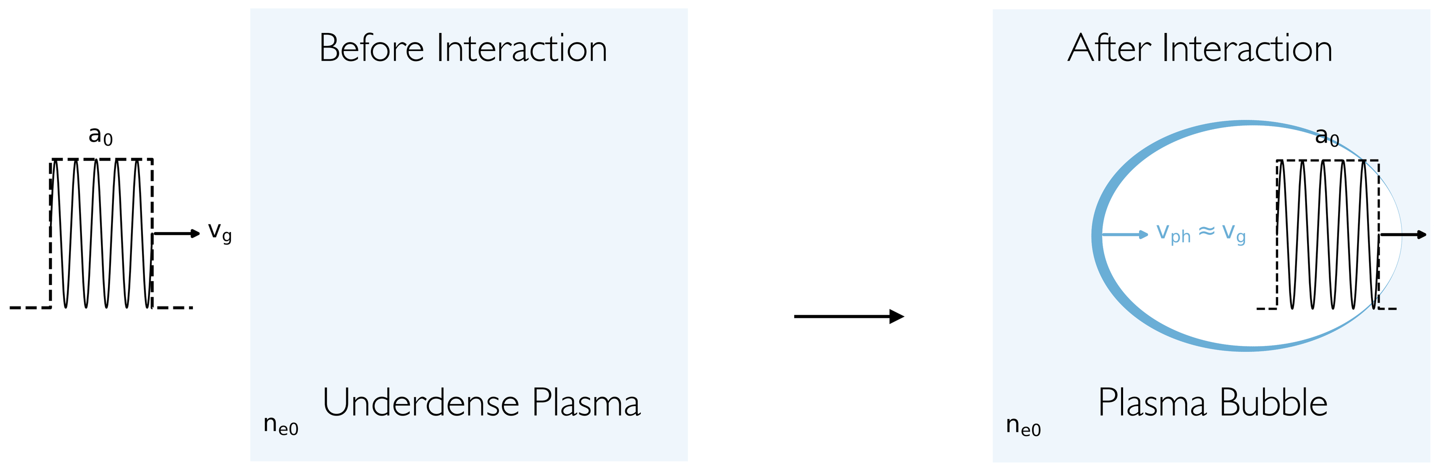

Figure 1: An intense laser driver propagates through an underdense plasma and forms a plasma bubble in its wake.

Density spike parameters at the rear of the plasma bubble

In the 1D quasi-static approximation for a cold, collisionless plasma:

$$n_e(\xi) = \frac{1}{2}\left[1 + \frac{1 + a^2(\xi)}{y^2(\xi)}\right]$$

$$\gamma_e(\xi) = \frac{1}{2}\left[y(\xi) + \frac{1 + a^2(\xi)}{y(\xi)}\right]$$

The maximum density, Lorentz factor, and thickness of the plasma mirror are [3]:

$$n_{\mathrm{e\,max}} = \tfrac{1}{2}\left(1 + \gamma_\perp^4\right) \qquad \gamma_{\max} = \frac{n_{\mathrm{e\,max}}}{\gamma_\perp^2}$$

$$l_{\mathrm{mirror}} = 4\gamma_\perp Im\left[E\left(\arcsin\,\gamma_\perp \middle| \frac{1}{\gamma_\perp^4}\right) - F\left(\arcsin\,\gamma_\perp \middle| \frac{1}{\gamma_\perp^4}\right)\right]$$

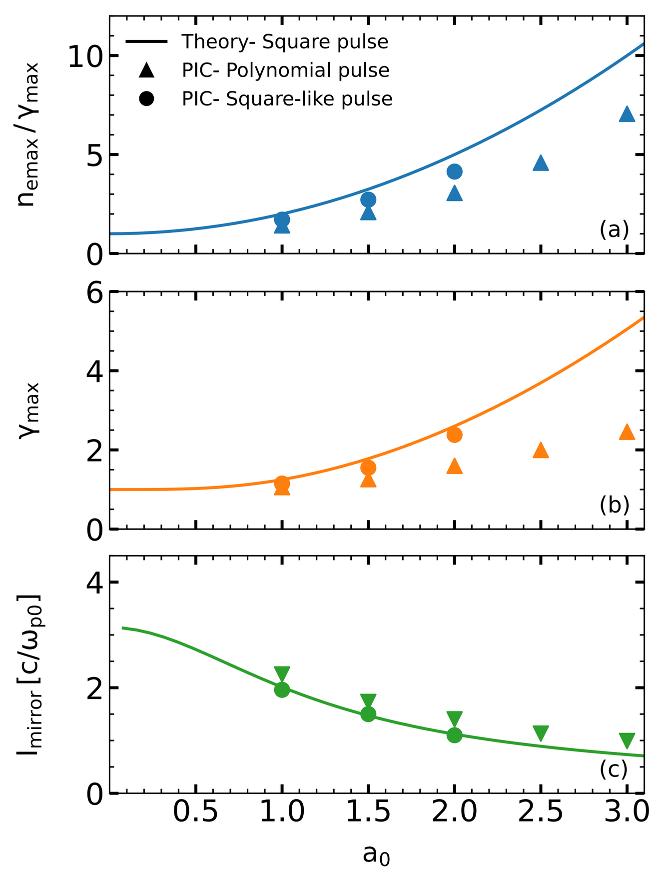

Figure 2: OSIRIS [4] results follow the analytical trends; simulation parameters are consistent with bubble regime theory [5] and modern laser facilities.

Density profile of the plasma mirror

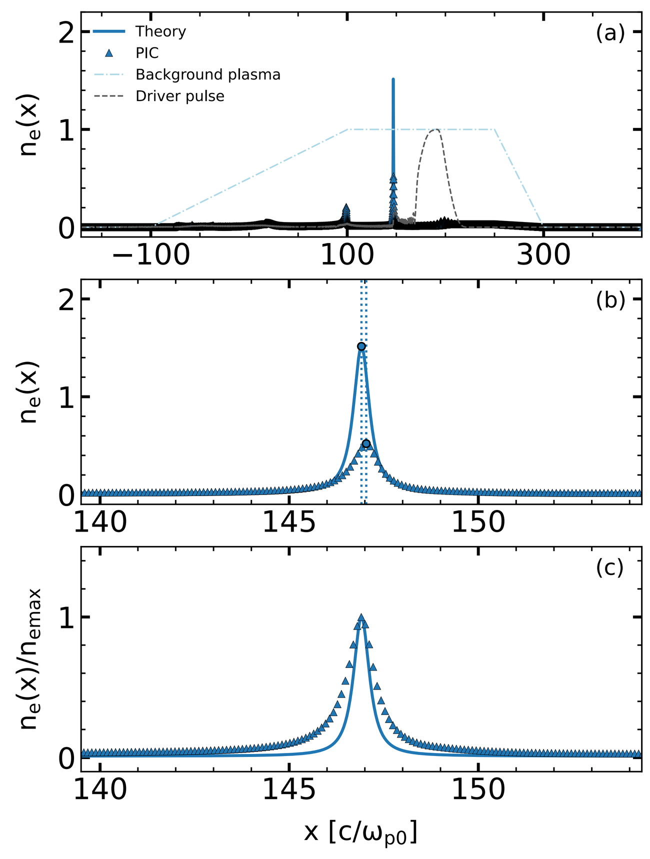

Figure 3: OSIRIS data validate the analytical density profile model.

Expanding the density spike about its maximum shows it is locally parabolic [3].

$$n_e(\xi) = [(1 + \gamma_\perp^4)/2] - [(\gamma_\perp^6(\gamma_\perp^4 - 1)/4)(\xi - \xi_{\mathrm{peak}})^2] + O\left[(\xi - \xi_{\mathrm{peak}})^4\right]$$

Reflection coefficient for flat-top, parabolic, and Dirac-limit plasma mirrors

Solving the Helmholtz equation in the mirror rest frame for three density profiles and transforming to the laboratory frame yields:

$$\left|R_{\mathrm{flat}}\right| = \Gamma^2\left|\frac{\omega^2_{\mathrm{cut\text{-}off}} - \frac{\omega_{p0}^2}{\Gamma^2}}{(2\omega_0^2 - \omega^2_{\mathrm{cut\text{-}off}} - \frac{\omega_{p0}^2}{\Gamma^2}) + 2i\chi\eta\sqrt{1 - \frac{\omega_{p0}^2}{\Gamma^2\omega_0^2}}\,\omega_0^2\cot\left(\chi\eta\gamma^2(1+\eta\beta)k_0 l_{\mathrm{mirror}}\right)}\right|$$

$$\left|R_{\mathrm{Dirac}}\right| = \Gamma^2\left|-\frac{1 - \frac{\omega_{p0}^2}{\omega_{\mathrm{p\,max}}^2}}{1 + \frac{\omega_{p0}^2}{\omega_{\mathrm{p\,max}}^2} - \frac{2i\sqrt{1 - \frac{\omega_{p0}^2}{\Gamma^2\omega_0^2}}(1+\eta\beta)\omega_0^2}{k_0 l\omega_{\mathrm{p\,max}}^2}}\right|$$

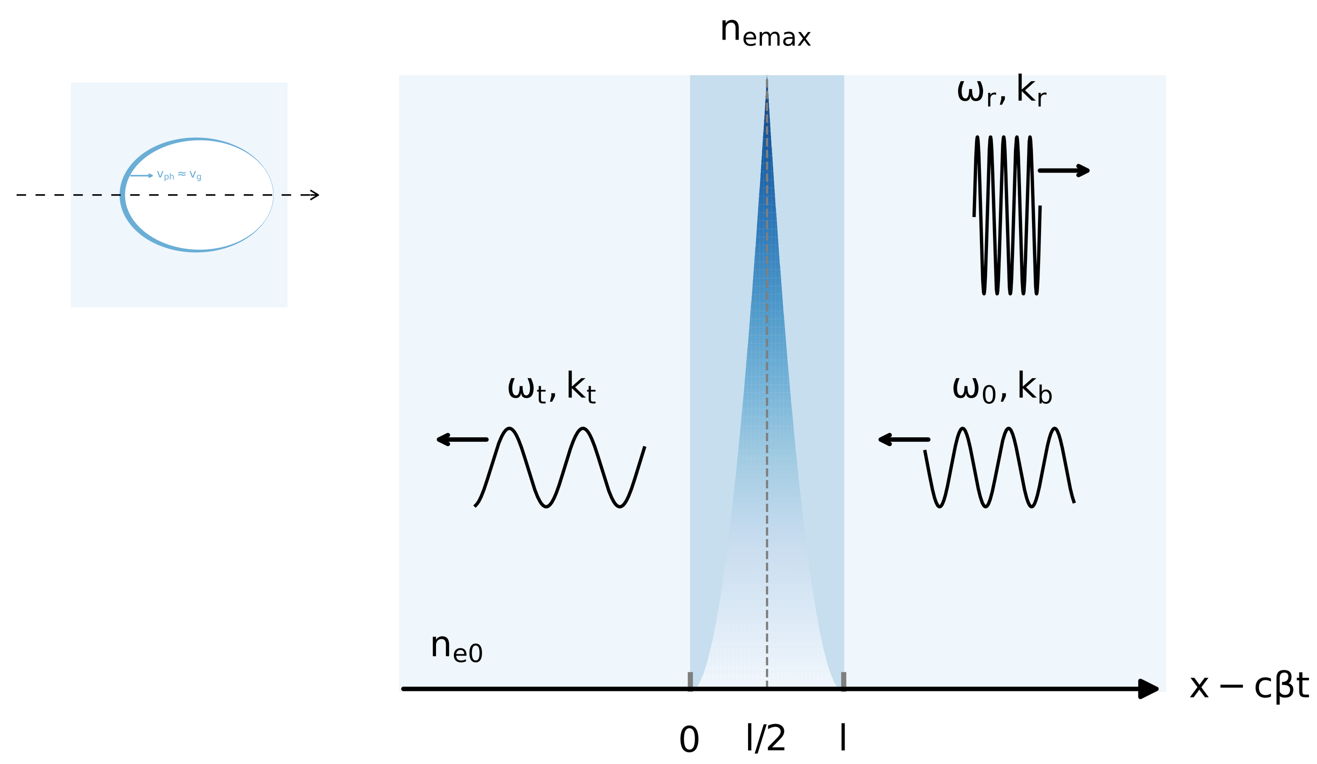

Figure 4: Laboratory-frame configuration of the moving mirror for flat-top, parabolic, and Dirac-limit density profiles.

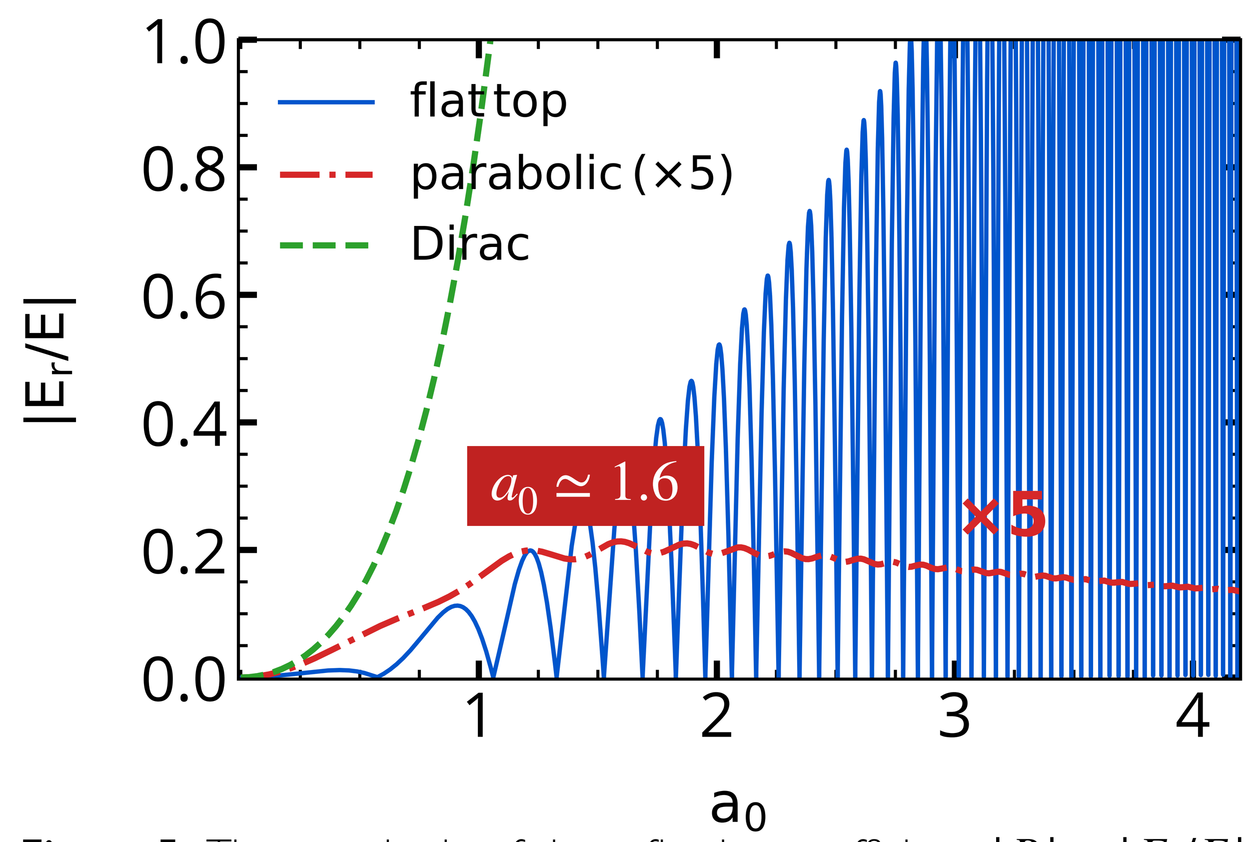

Figure 5: The magnitude of the reflection coefficient, $|R| = |E_r/E|$, versus a_0 for flat-top, parabolic, and Dirac-limit density profiles ($\omega_0 = 2\,\omega_{p0}$).

Conclusions

Real plasma mirrors have finite thickness and a non-ideal density profile.

Under the quasi-static approximation, $|R|$ can be expressed as a function of a_0 alone (for fixed ω_0/ω_{p0}).

2D OSIRIS simulations confirm the density spike is well described by a parabolic profile.

The parabolic mirror reflectivity peaks at an optimal a_0, set by the balance between electron compression, mirror thickness, and relativistic transparency.

References

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