PhD Open Days

Relativistic Plasma Mirrors

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Motivation

Ultrashort laser pulses provide access to ultrafast electron dynamics and, through laser–plasma interactions, enable laboratory studies of astrophysical phenomena on Earth.

Density spikes at the rear of a laser-driven plasma bubble act as relativistic mirrors [1, 2], compressing and frequency-upshifting a counter-propagating source pulse through the double Doppler effect.

We investigate how the mirror's finite thickness and density profile affect its reflection coefficient.

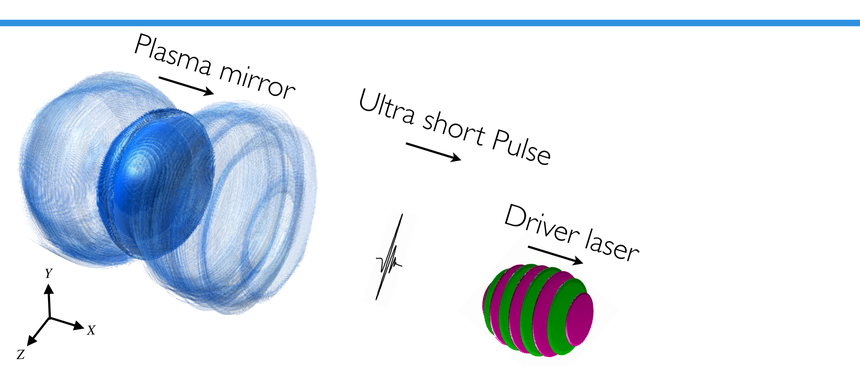


Figure 1: A laser-driven plasma mirror compresses and frequency-upshifts a counter-propagating pulse.

Density structure of laser-driven plasma mirrors

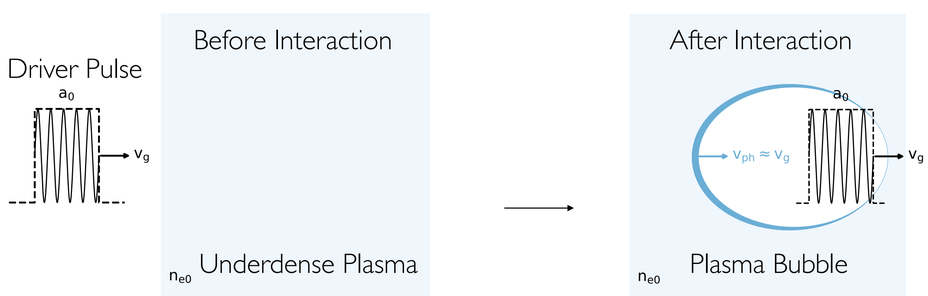


Figure 2: An intense laser driver propagates through underdense plasma, forming a bubble in its wake.

The 1D quasi-static model for a cold, collisionless plasma gives the following mirror parameters [3, 5]:

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

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

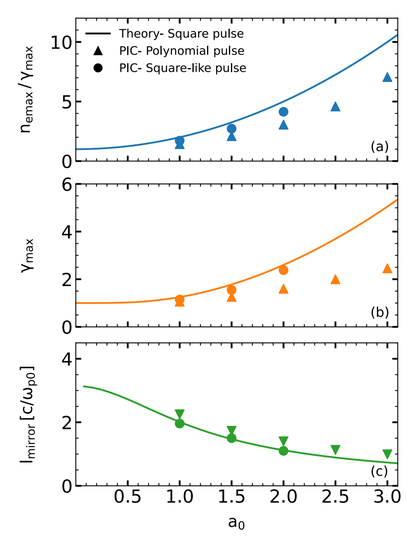


Figure 3: OSIRIS simulations [4] reproduce the trends predicted by quasi-static model [5].

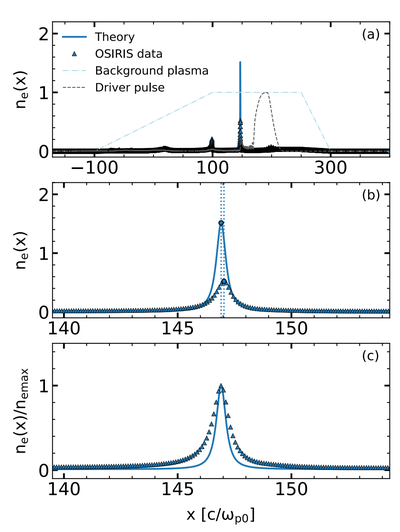


Figure 4: The analytical density profile agrees well with OSIRIS simulations [4, 5].

Reflection coefficient of non-ideal plasma mirrors

Solving the Helmholtz equation in mirror rest frame and transforming to the laboratory frame yields the reflection coefficients for flat-top and parabolic density profiles and in the Dirac-delta limit [5]:

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

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

$$\left|R_{\mathrm{parabolic}}\right| = \Gamma^2\left|1 - \frac{{}_1F_1\left(\frac{\mu_+}{4},\frac{1}{2},\nu_m\right)}{{}_1F_1\left(\frac{\mu_+}{4},\frac{1}{2},\nu_m\right) - i\frac{\gamma l}{2}\frac{\sqrt{(\Gamma\omega_0)^2-\omega_{p0}^2}}{c}{}_1F_1\left(\frac{\mu_++2}{4},\frac{3}{2},\nu_m\right)}\right.$$
$$+\frac{{}_1F_1\left(\frac{\mu_+}{4},\frac{1}{2},\nu_m\right) - \mu_{+1}F_1\left(\frac{\mu_+}{4}+1,\frac{3}{2},\nu_m\right)}{\mu_{+1}F_1\left(\frac{\mu_+}{4}+1,\frac{3}{2},\nu_m\right) - {}_1F_1\left(\frac{\mu_+}{4},\frac{1}{2},\nu_m\right)}\Bigg|$$
$$+i\left[\frac{\gamma l}{2}\frac{\sqrt{(\Gamma\omega_0)^2-\omega_{p0}^2}}{c}{}_1F_1\left(\frac{\mu_++2}{4},\frac{3}{2},\nu_m\right) + \frac{\Gamma\omega_0}{\Delta}\sqrt{1-\left(\frac{\omega_{p0}}{\Gamma\omega_0}\right)^2}\,{}_1F_1\left(\frac{\mu_++2}{4},\frac{1}{2},\nu_m\right)\right]$$

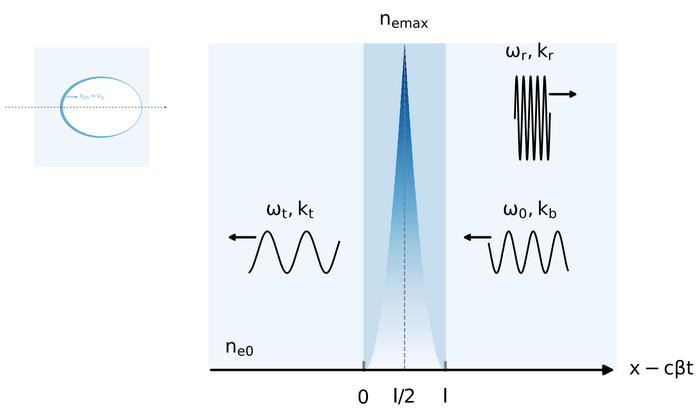


Figure 5: Laboratory-frame configuration of the relativistic plasma mirror with flat-top, parabolic, or Dirac-delta density profiles [5].

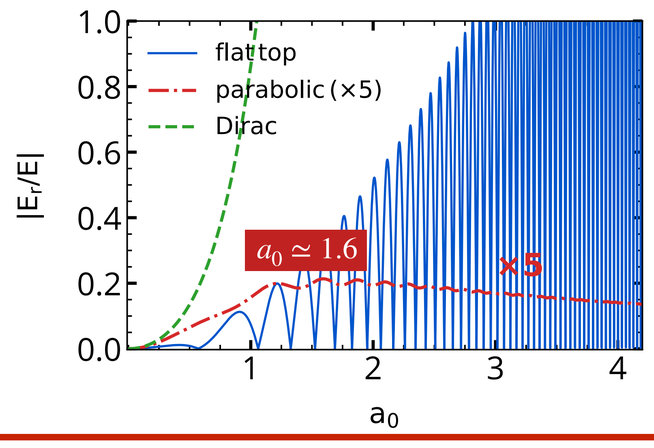


Figure 6: The magnitude of the reflection coefficient, $|R| = |E_r/E|$, versus driver pulse amplitude, a_0 for three density profiles. With $\omega_0 = 2\,\omega_{p0}$, the parabolic model peaks at $a_0 = 1.6$ [5].

Conclusions

Laser-driven relativistic plasma mirrors are non-ideal: their finite thickness and density profile strongly affect the reflection coefficient.

2D OSIRIS simulations confirm a parabolic profile provides a good approximation to the laser-driven density spike.

For a step-like driver in the quasi-static model, a parabolic mirror reflectivity peaks at an optimal a_0 for a fixed source frequency, set by the balance between electron compression, mirror thickness, and relativistic transparency.

References

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[4] R. A. Fonseca, et al., in P.M.A. Sloot et al., editors, ICCS (2002), LNCS 2331, 342-351 (2002).

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