Relativistic Mirrors as a Compact Source of Coherent Short-Wavelength Radiation

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ABSTRACT

Relativistic mirrors realized with strongly nonlinear Langmuir waves in laser plasmas offer a promising way for development of compact and tunable sources of coherent short-wavelength radiation. On reflection from the relativistic mirror, the incident light affects the mirror motion. The corresponding recoil effects are investigated analytically and using particle-in-cell simulations. It is found that if the fluence of the incident electromagnetic wave exceeds a certain threshold, the relativistic mirror undergoes a significant back reaction and splits into multiple electron layers. The reflection coefficient of the relativistic mirror and the factors of electric field amplification and frequency upshift of the electromagnetic wave are obtained.

RELATIVISTIC MIRRORS

the concept:

- theory of light reflection from relativistic mirror in vacuum formulated first by Einstein [1]
- frequency up-shift and electric field amplification of reflected wave caused by the double Doppler effect:

$$\frac{\omega}{\omega_0} = \frac{1+\beta_M}{1-\beta_M} \approx 4\gamma_M^2, \qquad \frac{E}{E_0} = \frac{\omega}{\omega_0}\sqrt{R}$$

relativistic mirrors in plasmas:

- thin dense electron or electron-ion shells traveling with velocities close to the speed of light [2]
- can be realized in various ways (e.g. double-sided mirror, relativistic oscillating mirror, nonlinear plasma waves, electron density singularities)
- feasibility proven in theoretical and experimental studies [3, 4]

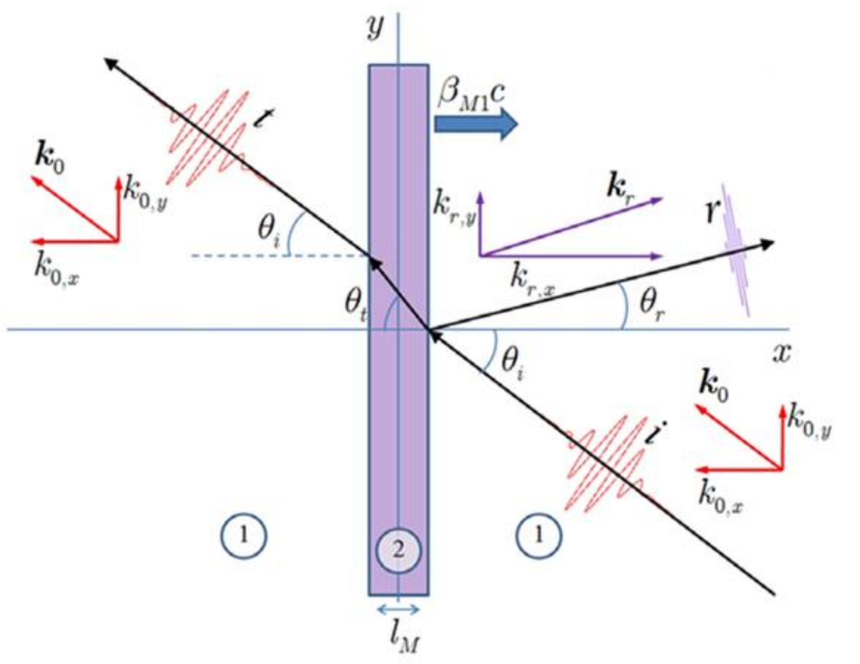


Figure 1: Reflection and refraction of the EM wave at a relativistic mirror moving along the *x*-axis in the laboratory frame of reference [5].

RECOIL EFFECTS ON REFLECTION

- conservation of momentum and energy:

$$\mathcal{N}_e p_{e0} - \mathcal{N}_\gamma p_{\gamma 0} = \mathcal{N}_e p_e + R\mathcal{N}_\gamma p_\gamma - (1-R)\mathcal{N}_\gamma p_{\gamma 0},$$
$$\mathcal{N}_e \mathcal{E}_{e0} + \mathcal{N}_\gamma \mathcal{E}_{\gamma 0} = \mathcal{N}_e \mathcal{E}_e + R\mathcal{N}_\gamma \mathcal{E}_\gamma + (1-R)\mathcal{N}_\gamma \mathcal{E}_{\gamma 0},$$

where

$$p_e = m_e c\sqrt{\gamma_e^2 - 1}, \quad p_\gamma = \hbar\omega/c,$$
$$\mathcal{E}_e = m_e c^2\gamma_e, \quad \mathcal{E}_\gamma = \hbar\omega,$$

- by combining above equations we get:

$$\frac{\omega}{\omega_0} \approx 4\gamma_{e0}^2 \frac{\frac{\mathcal{N}_e m_e c^2}{4\gamma_{e0}}}{\frac{\mathcal{N}_e m_e c^2}{4\gamma_{e0}} + R\mathcal{N}_\gamma\hbar\omega_0}$$

- resulting upshift factor determined by the relation between the terms in denominator:

$$\omega/\omega_0 \approx 4\gamma_{e0}^2 \quad \text{for} \quad R\mathcal{N}_\gamma\hbar\omega_0 \ll \frac{\mathcal{N}_e m_e c^2}{4\gamma_{e0}},$$
$$\omega/\omega_0 \approx \frac{\mathcal{N}_e m_e c^2 \gamma_{e0}}{R\mathcal{N}_\gamma\hbar\omega_0} \quad \text{for} \quad R\mathcal{N}_\gamma\hbar\omega_0 \gg \frac{\mathcal{N}_e m_e c^2}{4\gamma_{e0}}.$$

$$\boxed{R\mathcal{N}_\gamma\hbar\omega_0 = \varkappa\frac{\mathcal{N}_e m_e c^2}{4\gamma_{e0}}}$$

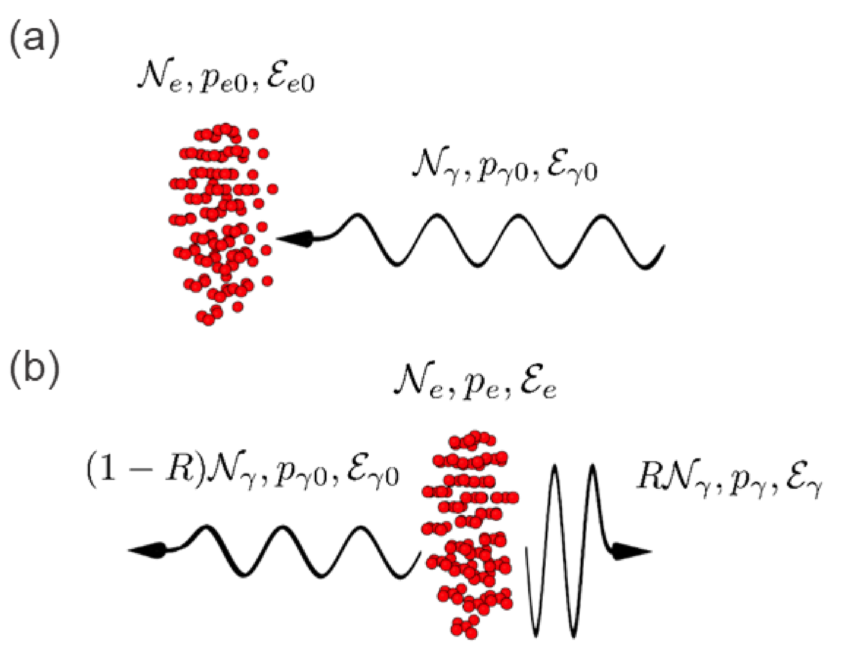


Figure 2: Schematic illustrating the analytical model, (a) before interaction, (b) after interaction.

LANGMUIR WAVE AS A RELATIVISTIC MIRROR

- number of electrons in Langmuir wave:

$$\mathcal{N}_e = \frac{n_e}{2}\lambda_w S$$

- number of photons in rectangular pulse:

$$\mathcal{N}_\gamma = \frac{I\tau S}{\hbar\omega_0}$$

- reflection coefficient of Langmuir wave [3]:

$$R \approx \frac{\Gamma^2(2/3)}{2^2\cdot 3^{4/3}}\left(\frac{\omega_{pe}}{\omega_0}\right)^{8/3}\frac{1}{\gamma_w^{4/3}}$$

- threshold for the fluence of rectangular laser pulse incident on Langmuir wave is:

$$I\tau = \varkappa\frac{3^{4/3}m_e c^2}{2\Gamma^2(2/3)}\left(\frac{\omega_0}{\omega_{pe}}\right)^{8/3}\gamma_w^{1/3} n_e\lambda_w$$

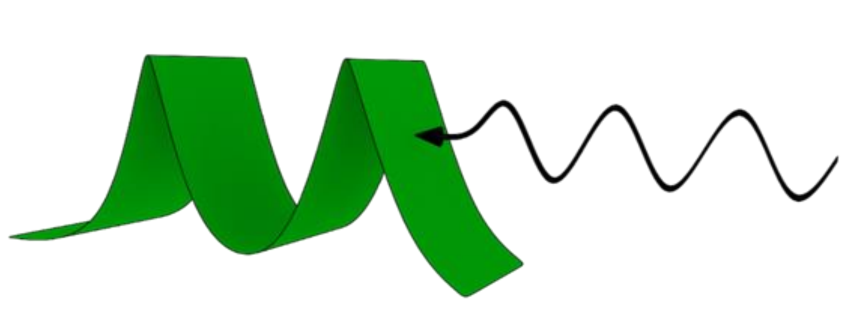


Figure 3: Schematic illustrating the interaction of incident EM radiation with Langmuir wave.

- condition for the minimum laser duration required for a recoil effect:

$$\boxed{\tau_{min} = \varkappa\frac{3^{4/3}m_e c^2}{2\Gamma^2(2/3)}\left(\frac{\omega_0}{\omega_{pe}}\right)^{8/3}\gamma_w^{1/3}\frac{n_e\lambda_w}{I}}$$

PARTICLE-IN-CELL SIMULATIONS

- EPOCH 1D [6], $\lambda_0^d = 1\,\mu m$, $a_0^d = 10$, $\tau_0^d = 10\,T_0^d$, $\lambda_0^s = 5\,\mu m$, $a_0^s = 10^{-4}$, τ_0^s semi-infinite, $n_e = 0.01\,n_c^d$, H_2:

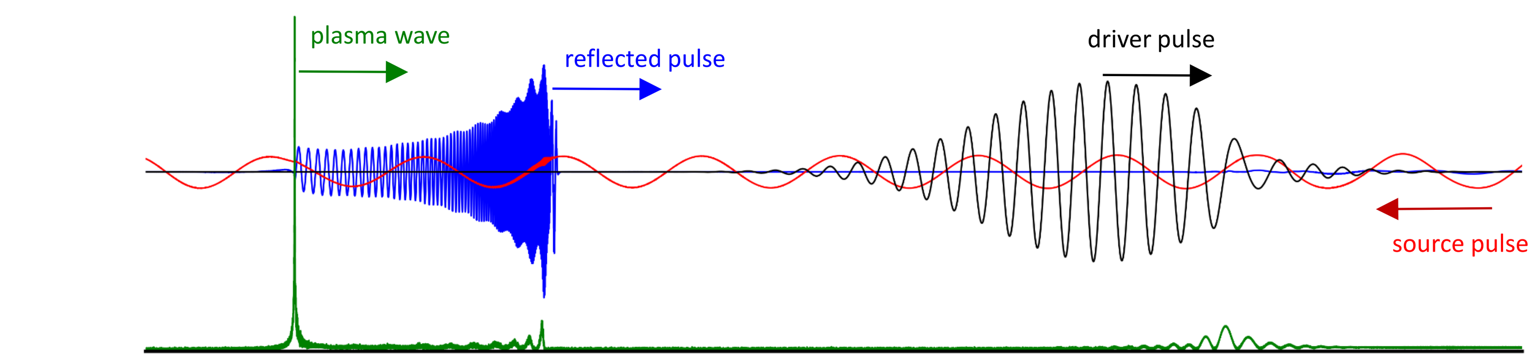
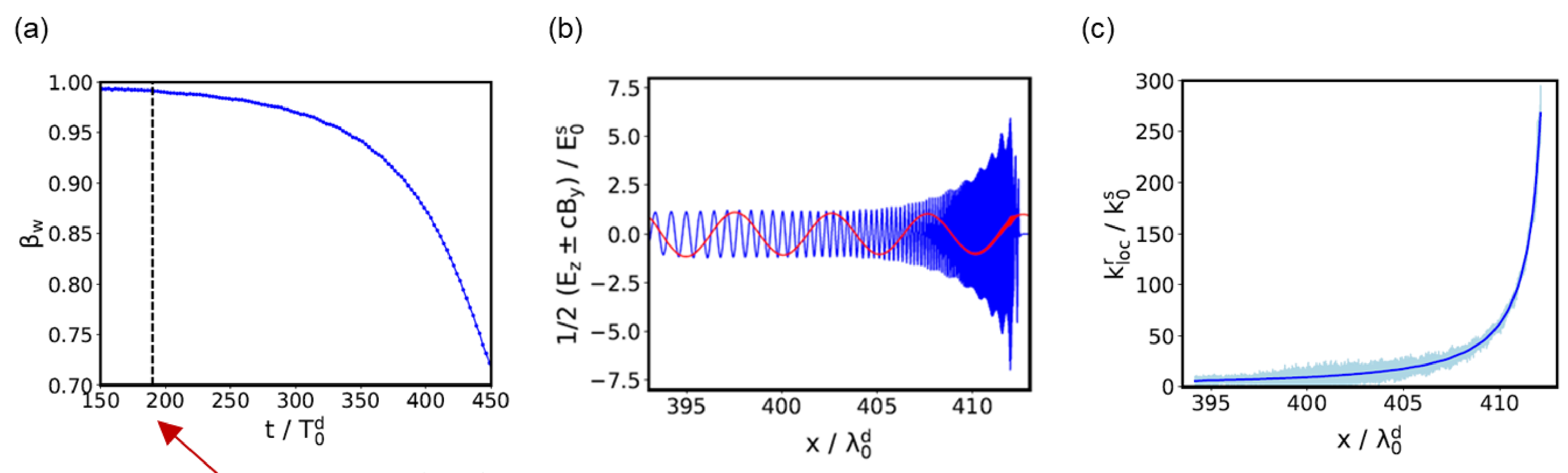


Figure 4: Schematic illustrating the setup of particle-in-cell simulations.



$$(1) \quad \frac{\max|E_x|e}{m_e\omega_{pe}c} > \sqrt{2(\gamma_w - 1)}$$

Figure 5: (a) The evolution of normalized phase velocity β_w of the density spike in time, (b) electromagnetic radiation incident at (red) and reflected from (blue) the density spike at $t = 450\,T_0^d$, (c) the evolution of the local carrier wavenumber of the reflected electromagnetic wave at $t = 450\,T_0^d$. In (a), the black dashed line marks the instant of time, when the Langmuir wave breaks (Eq. 1). In (c), the simulation data (light blue) are smoothed using the *Savitzky-Golay* filter [7] (blue).

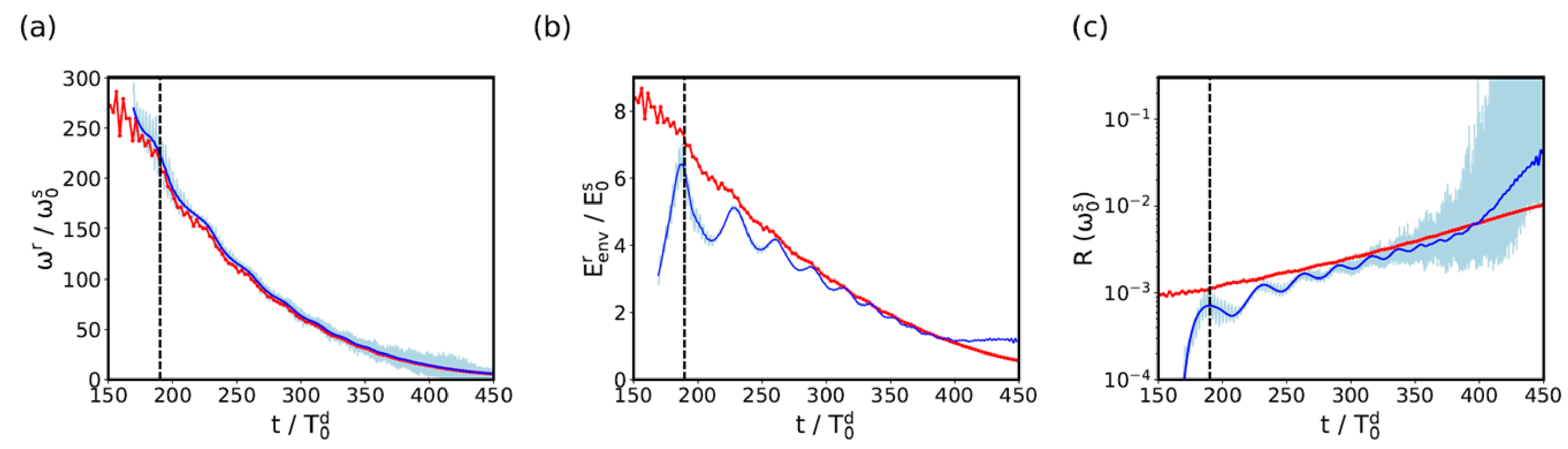
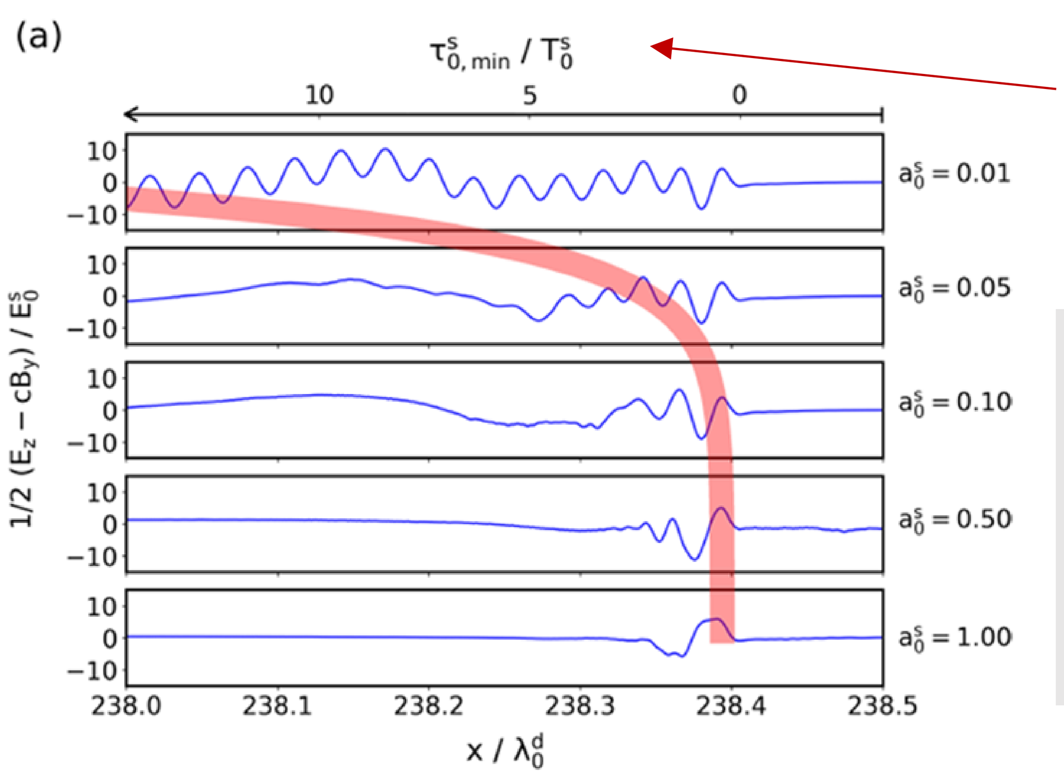


Figure 6: The properties of the reflection from the first electron density spike of the Langmuir wave behind the driver: (a) the instantaneous frequency upshift factor, (b) the instantaneous electric field amplification factor, (c) the instantaneous reflection coefficient in terms of photon number. The simulation data (light blue) are smoothed using the *Savitzky-Golay* filter (blue) and compared to analytical estimates (red). The black dashed line marks the instant of time, when the Langmuir wave breaks.



$$(2) \quad \tau_{0,min}^s = \frac{\varkappa}{4}\frac{n_e\lambda_w\lambda_0^s}{\gamma_w R\left(a_0^s\right)^2}$$

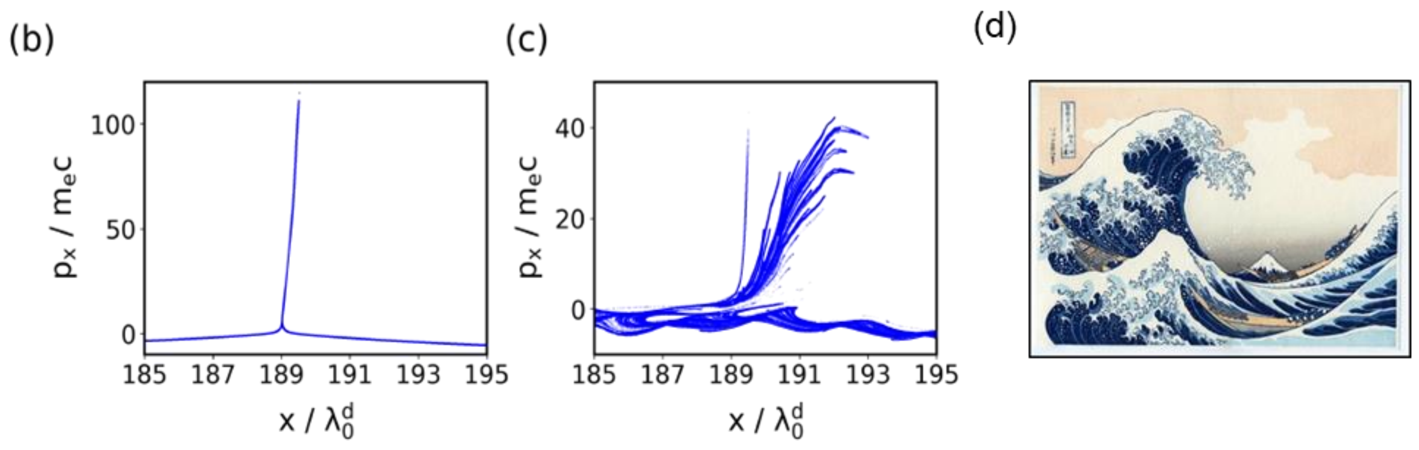


Figure 7: (a) Spatial profiles of the reflected wave for different source amplitudes. The thick red curve across the frames is the minimum source duration required for the recoil effect (Eq. 2) for $\varkappa = 1.5\times10^{-4}$. Phase space of electrons at $t = 230\,T_0^d$ for (b) $a_0^s = 0.01$ and (c) $a_0^s = 1.0$. (d) The Great Wave off Kanagawa by Hokusai.

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REFERENCES

[1] A. Einstein, Annalen der Physik 322, 891 (1905).
[2] S. V. Bulanov et al., Phys. Rev. Lett. 91, 085001 (2003).
[3] S. V. Bulanov et al., Phys.-Usp. 56, 429 (2013).
[4] M. Kando et al., Phys. Rev. Lett. 103, 235003 (2009).
[5] S. V. Bulanov et al., Plas. Sourc. Sci. Technol. 25, 053001 (2016).
[6] T. D. Arber et al., *Plasma Phys. Control. Fusion* 57, 11 (2015).
[7] A. Savitzky and M. J. Golay, Analytical Chemistry 36, 1627 (1964).

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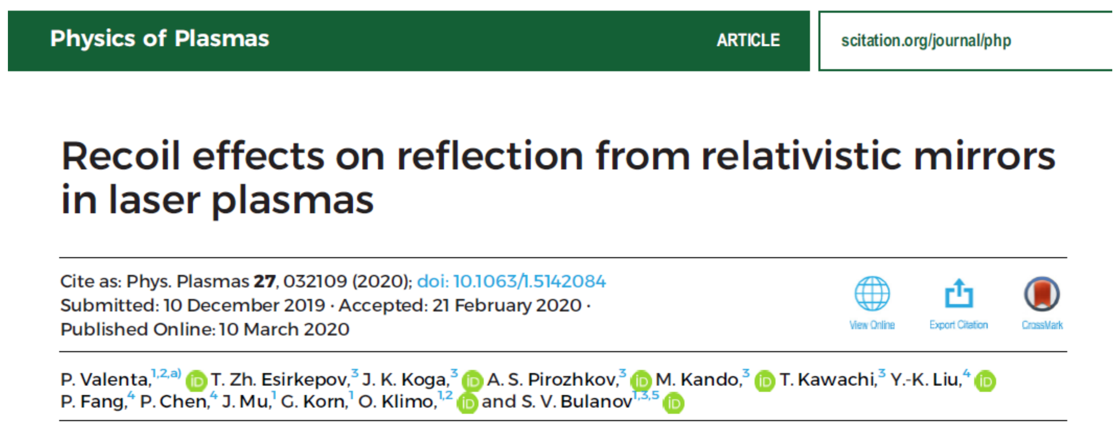
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