Proceedings of International Conference on "Recent Innovations in Engineering, Technology & Science for Sustainable Development (RIETSSD-2026)"
Career Point International Journal of Research (CPIJR)
©2022 CPIJR | Special Issue | ISSN : 2583-1895
Conference Paper | DOI: https://doi.org/10.5281/zenodo.20471040

Role of Plasma Mirror in Light Sail Regime

Arpit Dixit[1], Krishna Kumar Soni[2]

[1]Department of Physics, School of Basic and Applied Science, Career Point University, Kota (India)

[2]Assistant Professor, Department of Physics, School of Basic and Applied Science, Career Point University, Kota (India)

[1]arpitdixit500@gmail.com; [2] sonikrishna1490@gmail.com

Abstract*:*

The interaction of ultra-intense laser pulses with overdense plasmas has made it possible to open up new regimes of radiation pressure dominated acceleration, and especially lately the light sail (LS) regime. It is in this connection that plasma mirrors, i.e., self-generated, overdense, plasma layers generated at the surface of the target, play an important role in mediating a flow of momentum from the laser to the target. In this paper an integrated theoretical and phenomenological analysis of momentum transfer from high-power lasers to plasma mirrors is presented, which includes mechanisms of relativistic dynamics and non-linear interactions of lasers with plasma and scaling laws applicable to the experimental extremes. We discuss the formation and development of plasma mirrors, optimized laser parameters and plasma parameters giving maximum momentum coupling between plasma and electrons, and propose the application fields in ion acceleration, high harmonic generation, and ultrahigh field physics. Recent developments in high repetition rate mirrors and liquid targets are included in order to bridge the gap between theory and emerging technology.

Keywords: Plasma mirror, Light sail regime, Radiation pressure acceleration, Relativistic laser–plasma interaction, Momentum coupling.

I. INTRODUCTION

The introduction of new optomechanical technologies that developed very fast high-power and ultra-short laser systems, opened new prospects in the area of relativistic laser interactions with plasmas [1-5]. In the case that the laser intensity is above ~10^{18} W/cm^2, the radiation pressure of the laser becomes comparable to or even larger than thermal and electrostatic pressures in the plasma [1, 2]. Under such circumstances, radiation pressure acceleration (RPA) is an efficient mechanism for the transfer of laser momentum to plasma targets [1, 2, 6-9]. Among the different types of RPA regimes, the so-called LS regime which is analogous to photon-propulsion of a reflective sail has been much more studied because it has the potential for generating high-energy and quasi-monoenergetic ion beams [10].

A plasma mirror is created by ionizing and steepening the surface of a solid density target with an intense laser pulse to form an overdense plasma layer and reflect the incident electromagnetic wave [1]. In the LS regime, this plasma mirror actually behaves like an efficient relativistic reflecting surface effect allowing efficient momentum-transfer. Understanding the role of the plasma mirrors within this regime is therefore of great importance for the optimization of ion acceleration, for the improvement of the laser-to-plasma energy conversion, and for new applications that could be realized such as compact particle accelerators and laboratory astrophysics [11, 12]. The LS regime provides high energy and small energy spectrum of ion beams with bright prospects for medical therapies and mini accelerators [13-15]. Relativistic plasma mirrors are sources of high harmonics and attosecond pulses, facilitate the study of ultrafast spectroscopy and the strong field studies of quantum electrodynamics [2].

In this paper, we aim to focus on three main purposes: (i) Development of the theoretical modelling of momentum exchange processes from an ultra-intense laser and the plasma mirror, including relativistic and non-linear effects (e.g.,); (ii) Determination of the possible optimal laser pulse and plasma mirror parameters to maximize the momentum coupling coefficient; and (iii) Investigation of dynamics of the plasma mirror formation and evolution phenomena in the process of ultra-intense laser irradiation.

II. THEORETICAL FRAMEWORK

A. *Radiation Pressure and the LS Regime*

Radiation pressure on a perfectly reflecting surface is [2]

$$P_{rad} = \frac{2I}{c}, \qquad (1)$$

where I is the laser intensity and c is the speed of light. In the LS regime, ultrathin plasma targets behave as coherent reflectors when their areal density $\sigma = n_i \, m_i \, l$ satisfies

$$\sigma \leq \frac{I}{c^2},$$

(2)

ensuring that the entire plasma layer accelerates coherently under radiation pressure.

Scaling laws derived from RPA theory show that the maximum ion energy scales with laser intensity and target areal density [2]. Under ideal LS conditions with circular polarization and minimized electron heating, ion energies scale as

$$E_{ion} \sim \frac{2I\tau}{\sigma c},$$

(3)

where τ is the pulse duration. These scaling insights guide experimental design for high-energy ion beams.

B. *Plasma Mirrors in High Intensity Interaction*

A plasma mirror is used when the leading edge of a high-intensity laser pulse ionizes a solid or liquid target forming an over dense plasma, which is reflected by subsequent laser pulses. At relativistic intensities, the density surface of electrons is oscillating and deforming and can be considered a dynamic reflective layer. The plasma density must be greater than the relativistically corrected critical density $n_{cr}^{rel} = \gamma n_{cr}$, in which γ is the Lorentz factor. The generation of such a relativistic plasma mirror leads to an intense reflection of the incident wave and to the existence of various mechanisms (e.g. high harmonic generation, HHG, emission of attosecond pulses).

III. RELATIVISTIC MOMENTUM TRANSFER

A. *Lorentz-Boosted momentum Balance*

For a plasma mirror with velocity $v = \beta c$, the balance of momentum yields [16]

$$\frac{d}{dt}(\gamma M v) = \frac{2I}{c}\frac{1-\beta}{1+\beta},$$

(4)

where M is the areal mass density and $\gamma = (1-\beta^2)^{-1/2}$. The Doppler-shift factor $\frac{1-\beta}{1+\beta}$ accounts for the frequency change upon reflection from a relativistically moving surface.

The efficiency of energy transfer can be expressed as [2]

$$\eta = \frac{2\beta}{1+\beta}, \tag{5}$$

indicating that relativistic mirror motion is essential for high conversion efficiency.

B. *Nonlinear and Spatio-Temporal Effects*

Besides mere momentum balance, non-linear ponderomotive forces alter mirror dynamics. Significant surface deformation and broadening spectroscopy of reflected pulses resulting from allows surface deformation of the plasma mirror evolution in recent experimental studies. Such effects thereby affect the momentum coupling and give a spectral distribution of reflected radiation.

IV. PLASMA MIRROR FORMATION AND INSTABILITY

A. *Ionization and Ponderomotive Compression*

Plasma mirror formation starts with field ionization, which is very fast, and ponderolateral electron compression. This creates a large density gradient at the surface which is necessary for specular reflection. The steepness of this gradient is dependent on the laser contrast and pre-pulse suppression, issues important to the reflectivity.

Liquid Targets (e.g. Flat Jets) A continuous source of plasma mirrors at high repetition rate (i.e. repetition rate is the number or repetition rate is the rate in which a cycle is performed within a specified time frame) e.g. sustained experiments, advanced applications such as attosecond HHG.

B. *Transverse Instability and Target Expansion*

During the acceleration process, the plasma surface is prone to transverse instabilities like Rayleigh-Taylor type growth [17-20]. These instabilities lead to corrugation and thus can degrade momentum transfer. In ultrathin and mass limited targets also perpendicular expansion competes with coherent acceleration. Mitigation of such effects by shaping pulses, using target engineering and circular polarization plays a major role in stable LS RPA.

V. OPTIMIZATION OF MOMENTUM COUPLING

A. *Laser Parameters*

Optimal radiation pressure acceleration applies brightly contrasting, circularly-polarized pulses proportional to, and aimed at, the objective target areal density. Tailored chirp and pulse shaping are further used to optimize stability and energy transfer.

B. *Target and Plasma Properties*

Mass-limited targets with uniform are minimum expansion detrimental behavior and increases coupling efficiencyity. Ultrathin targets provide reduced energy spreading in accelerated ions, as well as narrow spectra.

VI. CONCLUSIONS

Plasma mirrors are a key part of achieving LS regime of RPA. By considering relativistic effects, nonlinear dynamic, and sophisticated optimization strategies, in this paper, a common theoretical and practical scheme of momentum transfer from high power lasers to overdense plasmas are presented. Future advances in high repetition rate plasma mirrors could promise to bring the theory to action in more concrete experimental models. This enlarged large framework places plasma mirrors at the crest of the tidal wave of high-power laser layout, superb acceleration ideas and the upcoming design of photon and particle sources.

ACKNOWLEDGEMENT

The authors of this paper are grateful to Career Point University, Kota, for providing a research-friendly environment and encouraging students to participate in research activities.

REFERENCES

1. Esirkepov, T., Borghesi, M., Bulanov, S. V., Mourou, G., & Tajima, T. (2004). Highly efficient relativistic-ion generation in the laser-piston regime. Physical Review Letters, 92(17), 175003.rown, L., & Green, K. (2022).
2. Bulanov, S. V., Esirkepov, T. Z., Kando, M., Pirozhkov, A. S., & Rosanov, N. N. (2013). Relativistic mirrors in plasmas. Novel results and perspectives. *Physics-Uspekhi*, 56(5), 429.
3. Miloshevsky, G. (2022). Ultrafast laser matter interactions: modeling approaches, challenges, and prospects. *Modelling and Simulation in Materials Science and Engineering*, 30(8), 083001.

4. Piccardo, M., Cernaianu, M. O., Palastro, J. P., Arefiev, A., Thaury, C., Vieira, J., Froula, D. H., & Malka, V. (2025). Trends in relativistic laser–matter interaction: the promises of structured light. *Optica*, 12(6), 732-752.
5. Badziak, J., & Domański, J. (2025). Acceleration of Heavy Ions by Ultrafast High-Peak-Power Lasers: Advances, Challenges, and Perspectives. *Photonics*, 12(3), 184.
6. Macchi, A., Veghini, S., Liseykina, T. V., & Pegoraro, F. (2010). Radiation pressure acceleration of ultrathin foils. *New Journal of Physics*, 12(4), 045013.
7. Macchi, A., Borghesi, M., & Passoni, M. (2013). Ion acceleration by superintense laser-plasma interaction. *Reviews of Modern Physics*, 85(2), 751-793.
8. Soni, K. K., & Maheshwari, K. P. (2016). Nonlinear interaction of ultraintense laser pulse with relativistic thin plasma foil in the radiation pressure-dominant regime. *Pramana*, 87(5), 76.
9. Svedung Wettervik, B., Marklund, M., & Gonoskov, A. (2019). Physics of the laser-plasma interface in the relativistic regime of interaction. *Physics of Plasmas*, 26(5).
10. Lv, C., Chai, J., Ban, X., & Sun, W. (2025). Study on the coupling and ion acceleration between ultraintense laser and multilayer solid targets. *The European Physical Journal D*, 79(1), 3.
11. Stockli, M. P., & Nakagawa, T. (2013). Ion injectors for high-intensity accelerators. *Reviews of Accelerator Science and Technology*, 6, 197-219.
12. Ledingham, K. W. D., & Galster, W. (2010). Laser-driven particle and photon beams and some applications. *New Journal of Physics*, 12(4), 045005.
13. Amaldi, U. (2024). Evolution of hadron therapy from 1935 to 2005: a personal view. *Health and Technology*, 14(5), 823-832.
14. Story, M. D., Davis, A. J., & Sishc, B. J. (2024). Current trends and future perspectives in hadron therapy: radiobiology. *Health and Technology*, 14(5), 867-872.
15. Rossi, S. (2022). Hadron therapy achievements and challenges: The CNAO experience. *Physics*, 4(1), 229-257.
16. Echkina, E. Y., Inovenkov, I. N., Esirkepov, T. Z., Pegoraro, F., Borghesi, M., & Bulanov, S. V. (2010). Dependence of the ion energy on the parameters of the laser pulse and target in the radiation-pressure-dominated regime of acceleration. Plasma physics reports, 36(1), 15-29.

17. Pegoraro, F., & Bulanov, S. V. (2007). Photon Bubbles and Ion Acceleration in a Plasma Dominated by the Radiation Pressure<? format?> of an Electromagnetic Pulse. Physical review letters, 99(6), 065002.
18. Pegoraro, F., Bulanov, S. V., Esirkepov, T. Z., Kando, M., Echkina, E. Y., Inovenkov, I. N., & Korn, G. (2011). Phase-locked ions and foil transparency in the radiation pressure acceleration regime. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 653(1), 153-155.
19. Sgattoni, A., Sinigardi, S., Fedeli, L., Pegoraro, F., & Macchi, A. (2015). Laser-driven Rayleigh-Taylor instability: Plasmonic effects and three-dimensional structures. Physical Review E, 91(1), 013106.
20. Guo, H. Y., Wang, L. F., Ye, W. H., Wu, J. F., Zhang, J., Ding, Y. K., Zhang, W. Y., & He, X. T. (2017). Nonlinear saturation of Rayleigh-Taylor instability in a finite-thickness fluid layer. Physics of Plasmas, 24(11).