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Laser Pulse Compression in Plasma

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Introduction

Since the invention of CPA [1], available peak power of laser pulses has increased rapidly up to the level of several petawatt from a single laser pulse. For experimental study of modern theoretical physics such as pair-production or radiation-reaction [2], the peak power of the pulse should be increased by several orders of magnitudes. One major obstacle on that path is in the technology of pulse compression; conventional solid-based gratings can stand just up to ~ J/cm^2 before break-down occurs by the strong electric field of the laser. To keep the pulse intensity below the threshold, diameter of gratings is already of order a meter. Simple extrapolation indicates that we need hundred-meter gratings to get exawatt or zettawatt pulses. That is just unrealistic, and completely different methods are required.

Plasma can be a good alternative medium for the pulse compression, as the plasma is already a broken-down state, hence no damage concern. Furthermore, fresh plasma structure can be readily re-generated, potentially making the system operation stable. Several different ideas have been investigated for the plasma-based pulse compression; Raman backscatter [3] and transient plasma gratings [4]. Those applications focus on generation of density alternation, which reproduces similar dispersion as in the solid-based gratings. However, we note that the electromagnetic wave is dispersive in plasmas even without density modulation. In this presentation, we introduce a novel idea of chirped-pulse compression using the intrinsic dispersive nature of plasmas. From one-dimensional particle-in-cell (PIC) simulations, we obtained up to 250-times amplification of a 2.5 ps-long pulse with initial peak intensity 2.7x10^{14} W/cm2. Assuming a cm-order pulse spot, the compressed pulse intensity can reach exawatt-class. Theoretical estimation shows that various negatively acting laser-plasma instabilities can be contained under acceptable level.

Novel Idea

When a negatively-chirped, stretched laser pulse is incident on a near-critical plasma with upward density gradient, higher frequency photons at the pulse front travel deep into the high density plasma before reflection, while lower frequency photons are reflected from shallow region of the plasma. The path difference can result in concentration of different frequency photons into a narrow region, leading to pulse compression. When the stretched laser pulse is linearly chirped, the most suitable plasma density profile is quadratic.

To demonstrate this idea, we conducted one-dimensional particle-in-cell (PIC) simulations. Figure 1 represents incident (red) and compressed (blue) pulses by reflection from quadratic density profile of the plasma (grey). The incident peak intensity is 2.7x10^{14} W/cm^2 and after compression, it reaches 6.7x10^{16} W/cm^2. Assuming several cm diameter of the pulse, it reaches several hundred petawatt or even exawatt power. Note that to get the similar power from conventional diffraction gratings, the beam diameter (and accordingly the grating diameter) should be hundreds of meters, which is impractical.

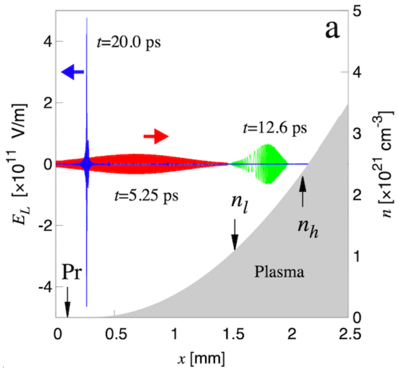

Figure 1. 1D PIC simulation of pulse compression.

We have theoretically estimated several laser-plasma instabilities (e.g. Raman scattering, two-plasmon decay, filamentation) and effects of density fluctuations. All those estimates indicate that the compression efficiency can be well controlled by order of hundred, and even considerably larger by optimizing chirp parameters.

Conclusion

In this presentation, we introduce a novel idea for high-power laser pulse compression in a plasma. The idea can potentially pave a way toward post-CPA concept to achieve exa- or zettawatt for experimental study of theoretical physics. As a proof-of-principle, from PIC simulations, we obtained 250 times amplification of initial intensity. From three-dimensional projection to a few cm diameters of the beam, exawatt-class peak power is expected. More optimization can lead to even stronger pulse.

References
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