Extreme focusing of high-power X-ray laser based on solid-density plasma

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Intense X-ray lasers have exceptional properties that are useful for broad applications. So far, many schemes have been proposed to achieve multi-TW of X-ray pulses on free-electron laser (FEL) facilities [1]. In addition, high-harmonic generation (HHG) from solid surface plasma can theoretically produce a single X-ray pulse of 8 as and 100 TW using currently available lasers [2]. However, these X-ray sources both have very large focal spot sizes, which reach tens of and even hundreds of micrometers. As a result, the power density of X-rays attained in existing regimes is still far below the relativistic threshold, which thus restricts the range of science that can be explored. For the X-rays propagating a transparent medium, the refractive index becomes less than and very close to unity, leading to that X-rays cannot be focused in the same way as visible or infrared light. Now the optical technology can focus hard X-rays to less than 10 nm (e.g. Ref. [3]), but the focal size is still about two orders of magnitude higher than the wavelength. To the best of our knowledge, there is still no efficient ways to focus high-power X-ray lasers.

In this presentation, we propose to use solid density plasma to focus high-power X-ray pulse at TW levels. It is shown that there is a certain range of wavelengths for X-ray laser that can be focused when the input power and plasma density are determined. However, for the X-ray pulses with micrometer-sized large spot, it is found that they suffer from disruptive multi-dimensional instabilities when propagating in plasmas [4], which involves a hybrid process of longitudinal modulation, transverse filamentation, and severe photon deceleration, as shown in Fig.1(a). This makes it difficult to focus high-power X-rays using solid density plasmas. In order to solve this critical issue, we further propose a novel approach using a well-designed concave plasma lens to generate an extremely intense X-ray laser [5]. Such a regime can effectively realize X-ray focusing at TW levels and meanwhile avoid the instabilities caused by laser-plasma interactions. Using three-dimensional particle-in-cell simulations, we further demonstrate that in the present regime TW-level X-ray pulses can be immensely focused while keeping well-defined spatiotemporal profiles, as shown in Fig.1(b). The resulting peak power density is enhanced hundreds of times and far exceeds the relativistic threshold. As far as we know, this is the first X-ray laser with relativistic intensity. Such intense laser provides unprecedented opportunities to elucidate unexplored phenomena in the X-ray region, which should advance the development of strong-field quantum electrodynamics, astronomical physics and high-energy density science.

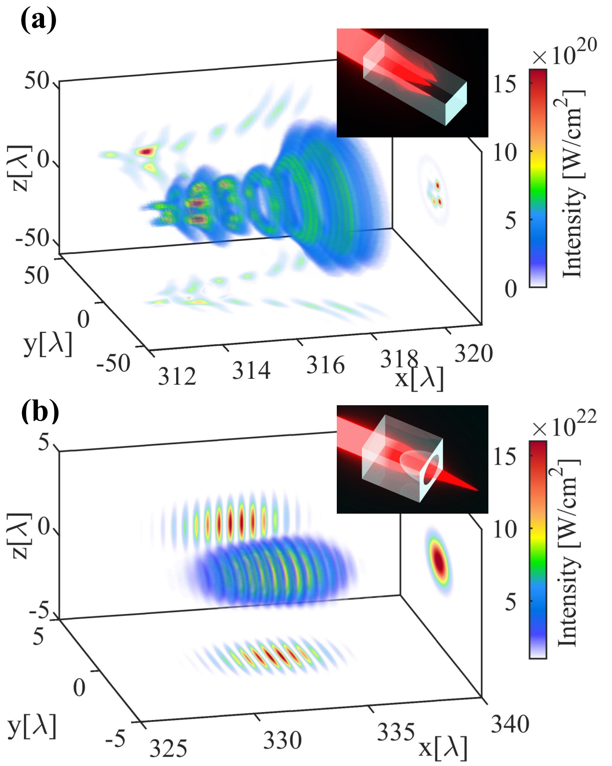

Figure 1. Spatial distribution of laser intensity just after the X-ray laser propagates through the plasma targets without (a) and with (b) a concave structure on the backside. The inset shows a schematic of the target-shaped structure, with the laser represented in red.

References

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