Self-compression of sub-TW laser pulses to a sub-10 fs duration through the propagation in a thin, dense gas target

D.-K Tran[1], M.-W Lin[1,2], Y.-L Liu[2], S.-W Chou[2], S.-H Chen[2]
[1] Institute of Nuclear Engineering and Science, National Tsing Hua University
[2] Department of Physics, National Central University
e-mail (speaker):s109013891@mx.nthu.edu.tw

Tackling the technological challenges for generating few-cycle, 10s-of-mJ laser pulses can substantially contribute to novel studies such as particle acceleration [1] and high harmonic generation of keV photons [2]. Once an energetic, multi-cycle pulse is obtained from a conventional fs laser system, broadening the spectrum of this pulse to a width capable of synthesizing a few-cycle duration can be realized by letting it pass through a nonlinear medium. When propagating in a plasma, this nonlinearity for inducing self-phase modulation (SPM) in a laser pulse is attributed to the temporal variation of the refractive index $\eta = [1 - \omega_p^2/\omega_0^2]^{1/2}$ according to the laser frequency ω_0 and the plasma frequency $\omega_p = (n_e q_e^2/m_e \varepsilon_0)^{1/2}$ determined by plasma electron density n_e, electron charge q_e, electron mass m_e, and vacuum permittivity ε_0. Therefore, compressing laser pulse in a plasma typically involves the ionization of gas atoms [3] and/or the excitation of a plasma wave [4] that can significantly change the refractive index η experienced by the laser pulse, such that the interplay of ionization, focusing, defocusing, and diffraction of laser field can finally lead to pulse compression.

3-D particle-in-cell simulations are conducted to investigate self-compression of sub-TW laser pulses within a dense gas target. Here, targets are defined to resemble properties of gas jets produced from a 100-µm nozzle [3, 4]; whereby neutral hydrogen or nitrogen atoms are distributed with an initial Gaussian profile having a length of 120 µm and a peak density that can provide $n_e > 10^{20}$ cm^{-3} when atoms are ionized by laser field. Figure 1 (a) illustrates the default 0.25-TW, 40-fs, 810-nm pulse for its early phase propagation in a hydrogen target. In the case that the hydrogen target exhibits a peak density $n_e = 1.2 \times 10^{20}$ cm^{-3}, the incident 0.25-TW pulse undergoes self-focusing and realizes a sufficiently high intensity to excite a plasma wave when moving across the region of density peak. This plasma wave in turn shapes the profile of co-propagating laser pulse and finally compresses it to a duration $\tau \sim 7$ fs as shown in Fig. 1(b) with a peak power reaching ~ 1.3 TW at output. As evident by the Wigner-Ville distribution in Fig. 1(b), the interaction between the laser pulse and the plasma wave causes the significant redshifting of field at pulse front side and the greatly blue-shifted field within pulse trailing edge, so that a bandwidth ~ 300 nm is achieved for the pulse from such a manifest SPM process. In contrast, using a nitrogen target of the same parameters tends to inhibit the spectral broadening as shown in Fig. 1(c), primarily because of the undesired defocusing of laser pulse that reduces the effectiveness of exciting a strong plasma wave and relevant SPM process. The spectral broadening also becomes less effective when using pulses of a lower peak power 0.125-TW as shown in Figs. 1(d) and 1(e), even an increased target density of $n_e = 1.8 \times 10^{20}$ cm^{-3} is applied to sustain the self-focusing of pulse therein. Our results guide the post compression technique for generating few-cycle, 10s-of-mJ laser pulse with the use of thin dense gas target.

References
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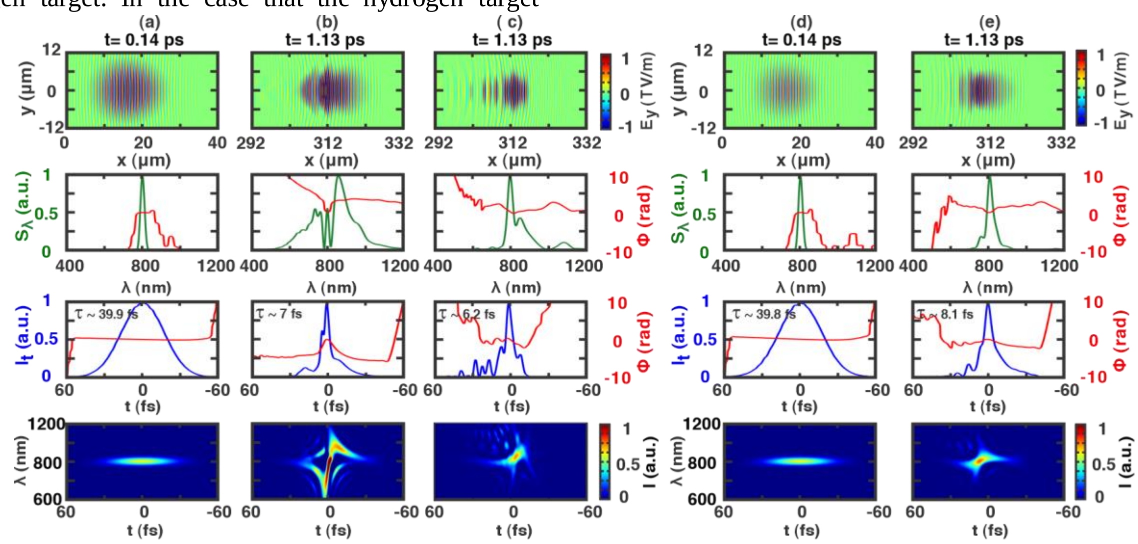

Figure 1. (a) Sampled E_y field, temporal and spectral intensities and phases, and Wigner-Ville distribution of the input 0.25-TW, 40-fs, 810-nm laser pulse. Output pulses after passing through (b) a hydrogen target and (c) a nitrogen target that both exhibit a peak plasma electron density $n_e = 1.2 \times 10^{20}$ cm^{-3}. Corresponding results for the (d) input 0.125-TW, 40-fs, 810-nm laser pulse and the associated (e) output pulse after passing through a hydrogen target with $n_e = 1.8 \times 10^{20}$ cm^{-3}.