Generation of ultra-high intensity few-cycle pulses using Raman backscattering in plasmas

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In this talk I review recent advances in laser pulse compression to sub-femtosecond duration using tenuous plasma as the nonlinear medium for parametric short pulse amplification. The standard approach to generating high-intensity ultra-short laser pulses is Chirped Pulse Amplification, in which a laser pulse is stretched, amplified, and re-compressed. CPA-based optical systems have been shown to generate sub-picosecond petawatt laser pulses with up to 500 J per pulse. The pulse energy is limited by the thermal damage to the compression gratings which become prohibitively large and expensive for kJ pulses.

A different approach to ultra-short pulse amplification by colliding it with a long counter-propagating pumping laser in the plasma has been suggested. What makes this process of superradiant amplification (SRA) of a short pulse promising from the standpoint of sub-femtosecond pulse generation is that the duration of the short pulse decreases in the course of amplification. Therefore, by selecting the appropriate plasma density, it should be feasible to compress 250nm pulses to sub-femtosecond duration.

The main advantage of using the plasma medium for amplification is that there is no thermal damage threshold – fresh plasma can be used for each shot. The counter-propagating geometry is chosen for two reasons. First, it enables the short pulse to sweep through the entire pump absorbing most of its energy and integrating over all the inhomogeneities and imperfections of the pumping signal. Second, the cold electron plasma exhibits remarkable properties as a parametric medium: its χ_3 coefficient has a very strong dependence on the wavenumber difference Δk between the two interacting laser pulses. In particular, for counter and co-propagating lasers ($\uparrow\downarrow$ and $\uparrow\uparrow$, respectively) the ratio of the χ_3 coefficients is $\chi_3(\uparrow\downarrow)/\chi_3(\uparrow\uparrow) \approx 4\omega_0^2/\omega_p^2$, where ω_0 and ω_1 are the frequencies of the amplified signal and the pump, ω_p is the plasma frequency. In a tenuous plasma this ratio can be several hundred, distinguishing plasma from gases, liquids, and fibers. Short pulse can be rapidly amplified by *backscattering* a counter-propagating pump in the plasma without suffering from forward-propagating instabilities (such as Raman forward scattering and filamentation).

Using semi-analytic model and particle-in-cell simulations, several features of the recent experiments at Max-Planck Institute for Quantum Optics are explained: (i) bandwidth expansion, and (ii) breakdown of the initially smooth amplified pulse into several spikes. Multiple pulse formation is shown to be due to the synchrotron motion of plasma electrons in the ponderomotive potential. Self-similar solutions consisting of multiple spikes are derived, and their nonlinear frequency shifts and bandwidth expansion are evaluated. The nonlinear focusing of the pulse by the pump is predicted and compared with experimental observations.