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Experimental Demonstration of Superradiant Amplification of Ultrashort Laser Pulses in a Plasma

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Nowadays, ultra-short powerful light pulses are generated using the chirped-pulse amplification CPA) scheme [1]. The bandwidth of the laser medium sets a lower limit on the duration of the pulses to be amplified. For titanium:sapphire, this is about 20 fs. Larger bandwidths can be obtained by optic parametric amplification of the stretched pulse [2, 3] in a non-linear crystal, but this technique has yet to prove its potential for high pulse powers and sub-10 fs pulses.

Direct amplification without stretching and recompression requires an amplification medium that can withstand the extreme field strengths of the laser pulse. Since they usually exceed the threshold for ionization, plasmas have to be considered. Two plasma processes have been identified allowing to amplify fs-laser pulses by the compression of a long counter-propagating pump pulse. The two processes are distinguished by the level of the involved pulse intensities. For low intensities, stimulated Raman backward scattering prevails (SRBS) [4]. It is a resonant three-wave process of a plasma wave and the two counter-propagating electromagnetic waves. For a rather modest pump pulse intensity of $(10^{12} - 10^{14}\ \mathrm{W/cm^2})$ and a relatively high plasma density, a pump depletion regime exists that allows the amplification of short laser pulses [5].

We report on an experiment carried out at high-intensities in the so-called superradiant amplification (SRA) regime [6]. The intensities of the pump and signal pulses are so high that their common ponderomotive force acting on the plasma electrons exceeds the electrostatic forces responsible for collective plasma oscillations. The electron dynamics reduces to the motion of an independent electrons in the ponderomotive potential of the laser pulses. Since the carrier frequencies of both pulses differ only slightly, the phase velocity of the potential is small and most electrons get trapped in its periodic structure. They start oscillating at the bouncing frequency $\omega_b^2 = 4a_{\mathrm{pump}}a_{\mathrm{sig}}\omega_{\mathrm{pump}}\omega_{\mathrm{sig}}$, where $a_{\mathrm{pump/sig}}$ are the normalized vector potentials of the pump and signal pulses, respectively. The initially homogeneously distributed electrons get bunched quickly in space to layers much thinner than the laser wavelength. The almost perfect bunching of the electrons in combination with the periodicity of the peaks of approximately half a laser wavelength leads to the coherent backscattering of the pump pulse into the signal pulse. The direction of the energy flow is determined by the slightly higher frequency of the pump pulse. The ongoing oscillation of the electrons distributes them again almost homogeneously in space. When the electrons get bunched a second time, they scatter the signal pulse back into the pump pulse. The rear part of the signal pulse is strongly attenuated and the signal duration is restricted to approximately one half of the bouncing period, π/ω_b. By this mechanism the pulse even shrinks, because ω_b increases when the signal is amplified. Simulations with a Particle-In-Cell (PIC) code show that the amplification continues until the amplitude of the signal pulse almost reaches relativistic intensities, where the signal pulse breaks up. For a pump wavelength of $\lambda = 0.8\,\mu$m, a maximally amplified signal pulse reaches an intensity of $\approx 10^{18}$ W/cm^2, a duration of < 7 fs, and a flux of 7 kJ/cm^2. For low initial laser intensities, the amplification can start in the SRBS regime and change to the SRA regime when the signal intensity becomes large enough for the threshold condition $\omega_b > \omega_p$ [6] to be satisfied.

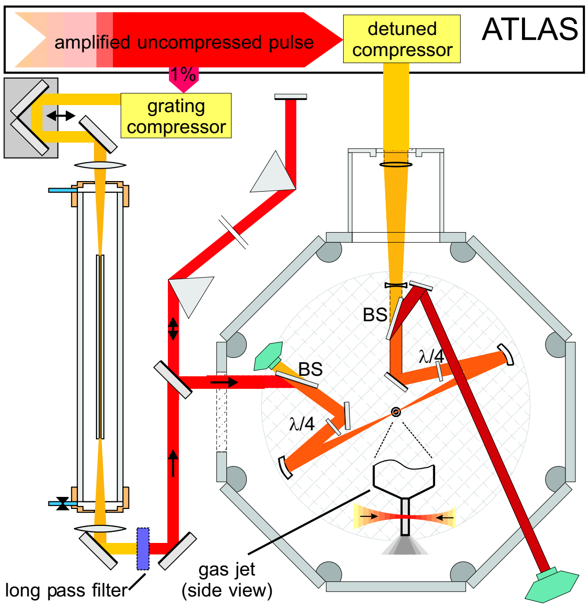

Figure 1: Experimental setup: BS - polarizing beam splitter; $\lambda/4$ - quarter wave plate.

We use the ATLAS (Advanced Ti:S Laser) facility at the MPQ, a CPA laser delivering 200 mJ-pulses in 120 fs at 790 nm and 10 Hz repetition rate. After the amplification, the pulse is not completely recompressed; with a duration of 1-7 ps it serves as the pump pulse in the SRA experiment. The seed pulse is generated from a small fraction split off from the main pulse before compression. It is compressed in a separate grating compressor to 120 fs, broadened by self-phase modulation in an Ar-filled fused silica capillary [7]. A dielectric filter blocks the wavelengths below 800 nm, thus shifting the central wavelength to 815 nm. After the final compression in a prism

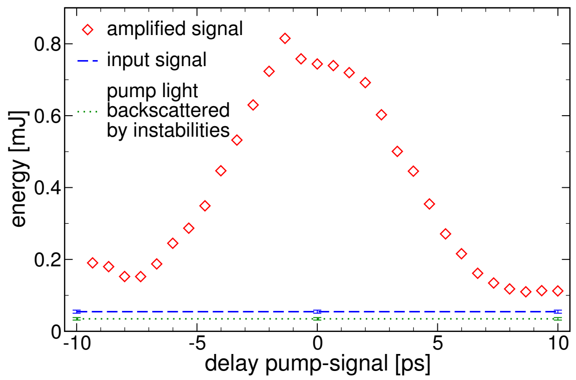

Figure 2: Energy of the amplified signal pulse (diamonds) versus the delay between the pump and signal pulses. The values are averaged over 20 shots.

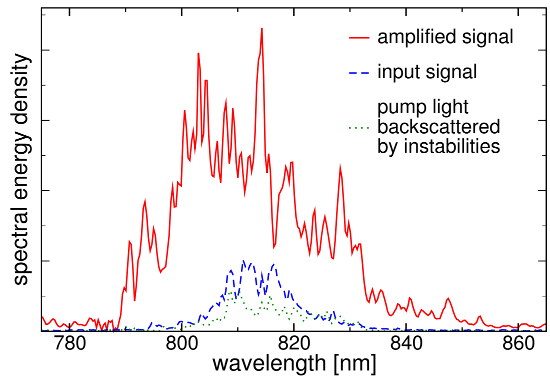

Figure 3: Spectra of the amplified (solid red line) and input pulses (dashed blue line); the delay between the pump and signal pulses is chosen as to maximize the energy gain.

compressor the input signal pulse has a duration of 80 fs and an energy of 90 μJ.

In the target chamber, the pump and signal pulses are focused into a hydrogen gas jet from opposite directions by two off-axis parabolas with a f/12 focusing. Their two foci overlap. They have diameters 25-30 μm and a Rayleigh length of $\approx$ 700 μm. The initial signal intensity reaches 2×10^{14} W/cm^2 and the pump intensity 2-5 $\times 10^{15}$ W/cm^2 depending on the pump pulse duration. The length of the gas jet is 1 mm. The gas nozzle is shaped like a chimney to guide the gas and create a more homogenous density profile. The Hydrogen gas is ionized by the leading edge of the pump pulse so that the interaction of the two pulses takes place in a channel of fully ionized plasma. A combination two polarizing beam splitters and two quarter wave plates are used to separate the pulses after the experiment (see Fig.2). On entering the target chamber the pulses are linearly polarized. The signal pulse is reflected on both beam splitters, while the pump pulse passes through them; the quarter wave plates change the linear to circular polarization of opposite helicity so that the pulses can interact.

Fig.2 shows the energy of the amplified signal varying with the delay between the signal and pump pulses, i.e., their arrival times in the plasma. The pump pulse duration is 4 ps and the electron density 3×10^{18} cm^{-3}. The output energy of the signal pulse is maximal when the pulses completely overlap in the plasma and within the Rayleigh length, where the intensities are highest and the amplification is strongest. The width of the curve depends on the Rayleigh length, the duration of the pump pulse and the length of the plasma column. The maximal energy gain is found to be 14. By increasing the electron density, it could be raised up to 20. Shot-to-shot fluctuations of the output energy are explained by fluctuations of the intensities of the input signal and pump pulses. The pump pulse can also be backscattered by instabilities, in particular thermal Raman instabilities. To obtain an upper limit for this contribution its energy level is measured with the signal pulse blocked. For the parameters given, the threshold condition for the SRA regime is not reached from the very beginning of the interaction, but only after pre-amplification in the SRBS regime. The way we presently generate the input signal pulse does not allow to make it sufficiently short and intense so that the SRBS regime could be overleapt.

The measurements of the spectra shown in Fig.3 confirm a transition from the Raman regime to the SRA regime. A broadening of the spectral width from 15 nm before amplification to 25 nm after amplification is found. The spectral broadening is a characteristic feature of the SRA regime, because signal shortening in time is predicted for growing signal amplitude which requires the spectrum to broaden in order to satisfy the minimum time-bandwidth product. The dominant narrow Stokes lines characteristic for SRBS is not observed.

In conclusion, the observed energy amplification of up to the mJ-level and the spectral broadening clearly evidence that the SRA regime has been reached. For further studies aiming at the realization of the full SRA potential, a shorter and stronger input signal pulse is needed that satisfies the threshold condition for SRA from the very beginning.

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