35th EPS Conference on Plasma Phys. Hersonissos, 9 - 13 June 2008 ECA Vol.**32D**, P-1.150 (2008)

Broad-band linear Raman chirped pulse amplification in plasma

X. Yang, A. Lyachev*, B. Ersfeld, G. Vieux, D.A. Jaroszynski

Dept of Physics, Strathclyde University, Glasgow, UK

The advent of laser systems based on the chirped pulse amplification (CPA) technique has allowed the production of femtosecond pulses with intensities up to $10^{21}\,\mathrm{W/cm^2}$. However reaching these intensities and beyond is proving very expensive and the development of future laser systems may need to use a different technology. Amplifiers based on stimulated Raman backscattering (RBS) in plasma could represent the next generation of amplifiers [1, 2]. Raman backscattering is a very promising means of transferring energy from a long pump pulse to a short probe pulse. Moreover, plasma can withstand extremely high power densities and therefore is a very robust gain medium.

Raman backscattering in plasma can be simply characterized as the resonant decay of an incident photon into a frequency downshifted scattered photon and an electron plasma wave (a Langmuir wave). The frequency and wave number matching conditions are given by:

$$\omega_0 = \omega_1 + \omega_p,\ k_0 = k_1 + k_p \tag{1}$$

where $\omega_{0,1,p}$ and $k_{0,1,p}$ are the frequencies and wave numbers of the incident wave, back scattered wave and the Langmuir wave, respectively [3].

Raman scattering is a parametric instability that can occur spontaneously or can be stimulated by a seed pulse at the Stokes frequency, which is amplified in this process. The latter case offers potential of amplifying laser pulses to powers exceeding the breakdown threshold of current state-of-the-art solid state amplifiers.

For simplicity, we describe the amplification process for two counter propagating monochromatic pulses. First, the interaction of the two beams generates a beatwave. The ponderomotive force associated with the beatwave excites a plasma wave leading to periodic density oscillations with a spatial frequency $\approx 2k_0$. The pump wave backscatters from the plasma density fluctuations into the probe beam. The growth of the probe beam reinforces the beatwave and therefore results in a feedback loop resulting in exponential amplification.

RBS amplification can be divided into the linear and nonlinear regimes respectively. In the linear regime pump depletion is negligible and the amplitude of the probe pulse increases exponentially in time as $a_1(t) = a_1(0)e^{\gamma_0 t}$ with the linear growth rate $\gamma_0 = |a_0|\sqrt{\omega_0\omega_p/4}$ (where

*Dr. Andrey Lyachev is now working at Rutherford Appleton Laboratory, STFC, Chilton, UK

$a_0 = eE_0/m\omega_0 c$ is the reduced vector potential of the pump, with E_0 the electric field amplitude). Although the gain can be high, the narrow frequency bandwidth $\sim \pi\gamma_0$ of the linear amplification process leads to lengthening of the probe pulse. The nonlinear regime is characterized by pump depletion and simultaneous temporal compression of the amplified pulse occurs.

We are investigating chirped pulse amplification through RBS in linear regime, experimentally aiming to develop an effective way to transfer energy from a long pump pulse to a counter-propagating short probe pulse. In order to maximize the energy transfer from the pump to the probe, we require the two beams to match the resonant condition (Eq.1). To achieve this, as shown on Fig. 1, the laser beam from the Strathclyde CPA laser chain is used. A large fraction of the beam energy is extracted before compression and used as a pump beam, while the probe beam consists of the remaining energy which is compressed and spectrally broadened in a controlled manner through self-phase modulation.

The two beams are then focused on each side of a 4 cm long preformed plasma channel, inside a 300 μm diameter sapphire capillary filled with hot H_2. The role of the plasma is two-fold: it acts as the gain medium and simultaneously a waveguide to obtain interaction with maximum intensity over many Rayleigh lengths [4].

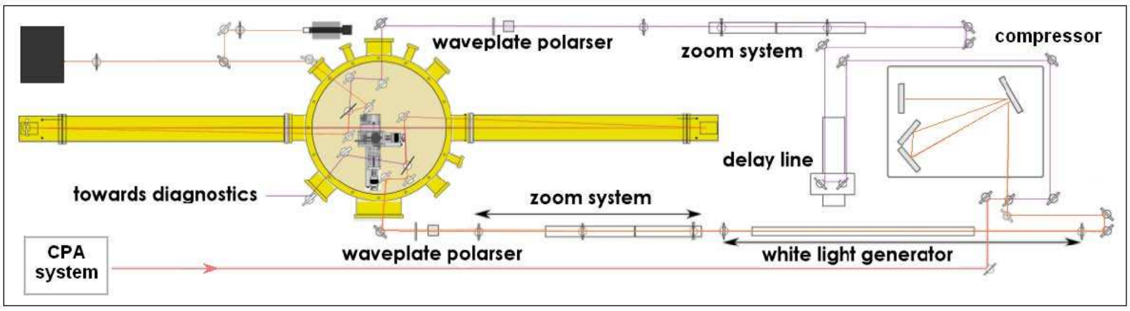
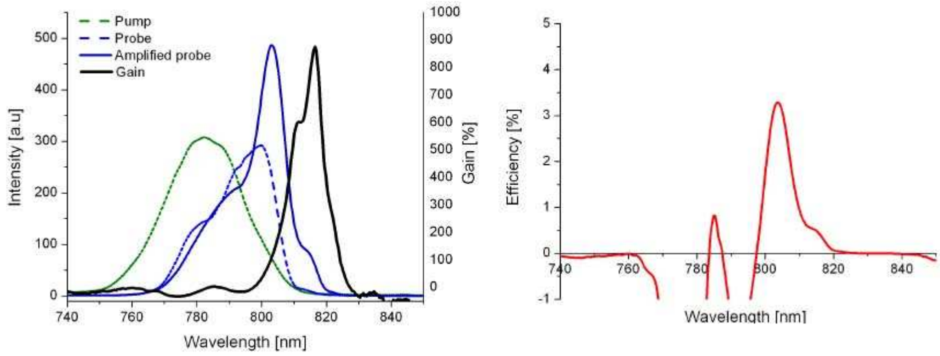


Figure 1: Schematic of the experimental setup

The main advantage of this set-up is that the full bandwidth of the probe beam is amplified by the broad bandwidth chirped pump pulse, and thus the resonant conditions for RBS are satisfied at different position in the plasma for the different frequencies. The gain of each spectral component is given by $G \cong e^{\gamma^2/2\alpha}$ (where α is the chirp rate of the pump beam and γ is the gain coefficient) [5]. The linear gain regime has a significant advantage of preventing pulse lengthening while providing a large enough amplification to reach the nonlinear regime, where pulse compression is expected.

The experimental layout shown in Fig. 1 is currently being set up, and therefore we present here the results of a previous experiment where optical cut-off filters are used to provide a

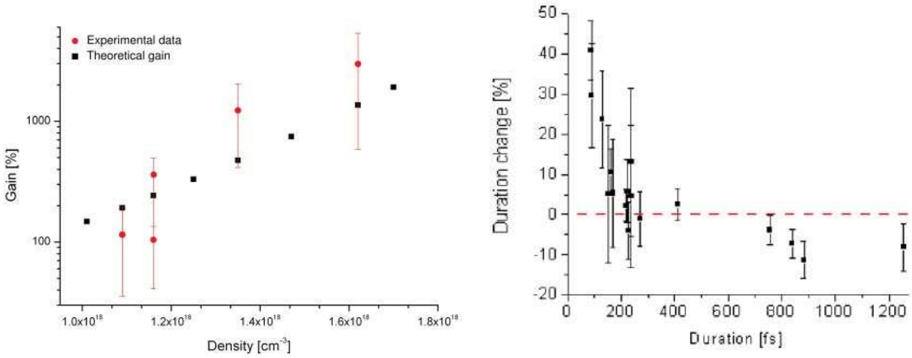


(a) Gain (b) Energy transfer efficiency

Figure 2

slightly detuned probe and pump beams. The pulse duration and energy of the probe and pump are 80 fs, 5 mJ and 137 ps, 220 mJ respectively, and the measured plasma density is $\sim 1.3\times10^{18}\,\mathrm{cm}^{-3}$. Under these conditions, the peak gain reaches 900% at $\lambda = 818\,\mathrm{nm}$, as shown in Fig. 2a. Moreover, as a promising sign, the total probe energy increases by 32%(calculated as the ratio between integrals of the probe spectra before and after interacting with the pump). The energy transfer efficiency has a peak of about 3.5% at a wavelength around 805 nm (Fig. 2b). As shown in Fig. 3a, the peak gain measured as a function of the plasma density follows the theoretical predictions. The large error bars are due to the exponential nature of the gain. The measured pulse duration of the probe versus the pump is presented in Fig. 3b. The partial pulse amplification induces pulse shortening, which however is not a signature of the nonlinear regime. Fig. 4 shows the amplification (gain and peak gain wavelength) measured as a function of the relative delay. The oscillations in the gain curve of Fig. 4a are caused by a slight mismatch in the coupling between laser and plasma channel. For these measurement the pulse durations and energies for the probe and pump are 600 fs, 5 mJ and 137 ps, 270 mJ respectively, and the plasma density is $\sim 1.2\times10^{18}\,\mathrm{cm}^{-3}$ [6].

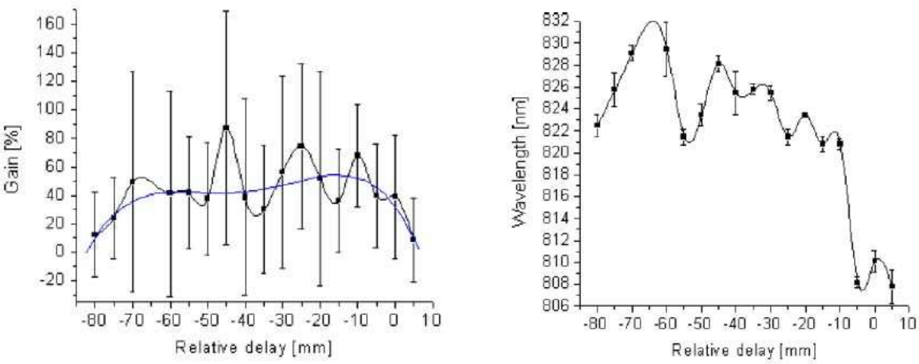
In conclution, we have carried out experiments on chirped pulse amplification based on Raman backscattering in plasma at the TOPS lab at the university of Strathclyde. We demonstrated a total energy increases of 32% for a frequency detuned short probe pulse with an energy transfer efficiency up to 3.5% from a chirped pump pulse. In the next stage of the experiment, we will optimize the resonant conditions for RBS by broadening the spectrum of the probe pulse using self phase modulation. With such further improvements, we expect to increase the energy transfer efficiency and reach the non-linear regime.



(a) Peak gain versus plasma density

(b) Pulse duration measured using a second order autocorrelator

Figure 3



(a) Gain versus delay

(b) Wavelength versus delay

Figure 4

References

[1] V.M. Malkin, G. Shvets and N.J. Fisch, *Phys. Plasmas*, 7(5):2232, 2000

[2] V.M. Malkin, G. Shvets and N.J. Fisch, *Phys. Rev. Lett.*, 82(22): 4448 - 4451, 1999

[3] W.L. Kruer, The Physics of Laser Plasma Interactions. Addison-Wesley, 1988

[4] S. M. Hooker. *American Institute of Physics*, 0-7354-0220-5/04, 2004

[5] B. Ersfeld, D.A. Jaroszynski, *Phys. Rev. Lett.*, 95:165002, 2005

[6] A. Lyachev, High gain ultra-short laser pulse Raman amplification in plasma, PhD thesis, 2007