Acta Polytechnica **53**(2):246–248, 2013

available online at http://ctn.cvut.cz/ap/

STIMULATED RAMAN BACKSCATTERING IN PLASMA — A PROMISING TOOL FOR THE GENERATION OF ULTRA-HIGH POWER LASER BEAMS

Hana Turčičová[a,*], Jaroslav Huynh[a,b]

[a] *Department of laser interactions, Institute of Physics of the Academy of Sciences of the Czech Republic, Prague, Czech Republic*

[b] *Department of physical electronics, Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Czech Republic*

[*] corresponding author: turcic@fzu.cz

Abstract. In the last fifteen years stimulated Raman backscattering (SRBS) in plasma has been intensively elaborated as a promising tool on the way towards high intense lasers. There are several advantages of this technique in comparison to the world-wide used the CPA-Chirped Pulse Amplification technique for a laser amplification. We present the principle of the SRBS technique, the best results so far obtained in theory and experiment, and a possible SRBS project at the PALS Research Centre in Prague.

Keywords: stimulated Raman scattering, laser plasma, high intensity lasers.

1. Introduction

Since the very beginning of the laser performing there has been a trend for the laser pulse shortening and power increasing. The first techniques manipulating the pulse duration were Q-switching and mode-locking. Nanosecond duration has been achieved and further optimization of laser devices has led to energy increase and output pulse intensity growing. In the middle of 80s, a revolutionary technique appeared [13], which profited from the results of [6] and that from a radar pulse coding and compression [3]. The technique is known as CPA – *Chirped Pulse Amplification* which enabled the amplification of ultra-short pulses up to a femtosecond range. However, a prerequisite for using this technique is a sufficient spectral broadness of the laser pulse being amplified. The pulse is first spectrally swept in space, and thus prolonged in time (in a tretcher). Its intensity is now much lower and in the forthcoming amplifying medium the pulse will be amplified without any danger of an optical damage of the medium. Having gained energy, in the following, the pulse has to be optically compressed to its original duration (in an optical compressor). Both stretcher and compressor contain diffraction gratings and if the pulse is intense and large-sized after the amplification, the diffraction gratings in the compressor have to be similarly large-sized as they can sustain only limited pulse intensity. In the 90s the CPA technique became a part of another revolutionary method in the ultra-short-pulse amplification, OPCPA – *Optical Parametric Chirped Pulse Amplification*. This technique brought many benefits, among others substantially improved pulse contrast, which is a very important parameter in laser–target interactions. At present both techniques are used in many prestigious laser facilities in the world. However, bulky compressors with demanding adjustment are an indispensable part of all of them.

In the last fifteen years again a new potentially revolutionary technique has emerged from theoretical studies of wave instabilities in laser plasma, which presents a possibility of the production of intense and ultrashort laser pulses even without the large compressors. Raman backscattering has been known as a bad acting parametric instability in the laser energy deposition into the hohlraum target during the *Inertial Confinement Fusion* process [2]. In underdense plasma, however, stimulated Raman backscattering, i.e the scattering seeded by a counterpropagating beam, revealed some features [12] that made it a new promising tool for the generation of intense ultrashort laser beams. It was found that a short (< 1 ps) and weak laser pulse can be amplified by a counterpropagating long pump and remain short or even get shortened [8]. Since that time the topic has attracted attention of many laser-plasma physicists and theoreticians. Here the laser plasma has ranked among the laser amplifying media, such as well-known solid-state materials (glass or crystals doped with Nd, sapphire doped with Ti, etc.) or gas mixtures (He−Ne mixtures, CO_2 or CO based mixtures, excited dimers etc.). Its eminent property is that it can withstand by several orders higher optical intensity than the latter laser media can. The simulations have reported even hundreds of petawatts of the output power [15], whereas the practical realization up to now has not surpass 100 GW.

In the paper we summarize the best results of simulations and experiments achieved in stimulated Raman backscattering (SRBS). In the following we propose a possible project on SRBS at the Research Center of PALS (*Prague Asterix Laser System*) in Prague, CZ.

2. SRBS in simulations and experiments

There is a long track of theoretical works on stimulated Raman scattering since 70s and 80s in the last century. Even in those works a plasma is shown as a suitable medium for the amplification and compression of laser pulses. In 90s demanding simulation works enabled better insight into this process and other generated instabilities, see e.g. [9]. It was found that a short weak laser pulse, a seed, can be efficiently amplified and compressed in a plasma prior to the harmful instabilities, such as forward Raman scattering, filamentation and others, will grow. The computational methods in that time were based either on the classical three-wave-interaction model with the assumption of slowly-varying wave envelopes, where one of the waves was not electromagnetic but a plasma one, or on the PIC simulations, mostly one-dimensional, under certain simplifying conditions. A new regime of a Raman amplification was identified [12], so called SRA – *superradiant amplification*, when the seed amplitude grows linearly with time and simultaneously the seed is contracted. Reaching this regime needs an initial seed pulse of sufficiently high intensity, the pump wave then can get strongly depleted. A characteristic feature of the superradiant amplification is that the participating electrons from the plasma wave backscatter the pump coherently. In [5] this regime was experimentally demonstrated and in 1D-PIC code numerically simulated. The plasma was produced in a H_2 gas jet by the leading edge of a picosecond pump wave from a Ti:sapphire laser. The initial signal was of 80 fs long and after the amplification in the plasma its energy increased from 70 µJ to ≥1 mJ and the duration was 56 fs. However, the output pulse was a train of several peaks. The experiment was explained as an initial SRBS process and when the seed intensity reached a certain value the process proceeded as the SRA amplification.

At present the highest seed output achieved experimentally in the SRBS amplification is given in [10]. The plasma channel of 2 mm long was generated in a C_2H_6 gas jet, the pump and seed pulses were derived from a Ti:sapphire laser. Double-pass geometry was used when the seed beam passed twice the interaction area. The energy transfer pump–seed was 6.4 % which led to the amplification of the seed by a factor of more than 20 000. The pulse compression was from 500 fs to about 50 fs. The seed intensity thus exceeded that of the pump by 2 orders. The output power of the seed was close to 100 GW level.

It is evident that the seed output power data provided by the simulations exceed those from the experiments by several orders. It was shown, see e.g. [17, 16], that mechanisms like detuning from the SRBS resonance conditions due to an unintentional pump chirp or plasma channel inhomogeneities, plasma wave breaking at higher plasma temperature, or an interplay between Brillouin and Raman scattering, effect negatively the SRBS efficiency. The achievement of the multipetawatt regime is presented in the simulations of [15]. They performed large-scale multi-dimensional PIC simulations and came to a conclusion that multi-PW peak powers are within reach, however, only in a narrow plasma parameter window. The plasma density should be kept in the range of $(4.5 \div 18) \times 10^{18}\,\mathrm{cm}^{-3}$. The limiting factor is the growth of deleterious plasma instabilities. The authors recommend Raman amplification in plasma channels of larger diameters so that the plasma density could be kept low enough. They report even 300 PW output if the plasma channel is of 1 cm (!) FWHM and pump beam ($\lambda = 1\,\mu\mathrm{m}$) of 1 PW in 25 ps. A too-many-orders difference thus persists between the seed output prognosis and the real up-to-now achieved value.

3. SRBS at PALS

A crucial factor in the SRBS process is the plasma channel. It should be thoroughly adjusted so as to keep its good wave guiding properties along the interaction region over many Rayleigh zones [4]. The radial profile of the refractive index should have its maximum on the axis which prevents diverging tendencies of both waves. If the laser beams are strong enough, such index profiling can be self-formed by relativistic or ponderomotive forces acting on the electrons. However, the beam peaking on the axis will push the charged particles away and their displacement might create new centers of diffraction. The pump and seed are usually focused into the plasma channel which imposes spherical form of their wavefronts. Therefore the fronts of the waves should move with a lower speed than peripheral parts. Balancing all the counteracting processes in the channel is a demanding task.

In any way, a high quality laser beam, smooth in time and space, will be beneficial for the production of a plasma channel with defined plasma density profile and wave guiding properties. The Research Center of PALS has a single beam photodissociation iodine laser [11] of such high qualities at a disposal. Its fundamental wavelength is 1315 nm and delivered energy ≤1 kJ@400 ps. Since 2000 the laser facility has been used by many international research groups namely due to the smooth top-hat beam profile in 1ω and also 3ω. A part of the beam could be used for the production of a gas-jet (e.g. C_3H_8) wave-guiding plasma channel. There is also experience with smoothing the laser plasma non-uniformities by additional gas jets [1]. The plasma channel can be produced in $\sim 0.25 \times 3\,\mathrm{mm}^2$ size with a plasma density of $n_\mathrm{e} \approx (1-2) \times 10^{19}\,\mathrm{cm}^{-3}$, corresponding to a plasma frequency of $\omega_\mathrm{pe} \approx 0.2 \times 10^{15}\,\mathrm{Hz}$. The pump and seed beams can be produced by a high-power Ti:sapphire laser system [7] which is also operated at the PALS Research Center, $\lambda = 810\,\mathrm{nm}$, ∼1 J@40 fs. The laser beam will be split and adjusted into the pump (∼1 J, pulse duration $\tau = 10\,\mathrm{ps}$) and the seed (0.2 mJ, $\tau = 500$ fs), both beams being focused into a 0.25 mm spot. Thus similar experimental conditions to those of [4] would be produced and get-in-touch SRBS experiments could be performed. The seed amplification of almost two orders of magnitude should be closely touched.

Another SRBS experiment on the PALS laser system can be proposed. It aims at an output power upgrade on the third harmonics of the iodine laser. At present 400 J in 250 ps is reached if the PALS beam is frequency tripled, i.e. 438 nm, corresponding wave frequency being 4.3×10^{15} Hz. The output power at the maximum is therefore ~ 1.6 TW. The third harmonics beam will be used as a source for both pump and seed waves, the remaining part of the fundamental beam after tripling will form a pre-pulse, i.e. generate the plasma channel, probably again in a gas jet with a low ionization potential. The channel should be of $1 \div 1.5$ mm diameter and 15 mm length. According to [14] the recommended ratio between the pump wave frequency $\omega_{\rm pu}$ and $\omega_{\rm pe}$ should be 20, giving the plasma frequency $\omega_{\rm pe} \sim 0.2 \times 10^{15}$ Hz and plasma density $n_{\rm e} \sim 1.5 \times 10^{19}$ cm^{-3}. The resonance condition provides the seed frequency, $\omega_{\rm s} = \omega_{\rm pu} - \omega_{\rm pe}$, which means 460 nm wavelength. As the pump beam duration is 250 ps, the seed beam one should be about 250 fs so as to keep up with the initial simulation parameters of [14]. Such a seed beam can be provided by the Ti:sapphire laser mentioned above, if doubling its beam. The doubling will be performed prior compression to the fs duration, i.e. at the full duration of 250 ps [7]. The beam with about 400 nm than has to be Raman shifted to 460 nm. This can be done in a gas Raman shifter with a relevant Stokes shift (e.g. D_2, CH_4). After the Raman shifting, the beam will be compressed to the desired 250 fs and will function as the seed beam. Following further the desired optimal plasma parameters given in [14], a pump intensity of about 6×10^{12} W cm^{-2} is required throughout the plasma channel. Performance parameters adjusted in this way would enable a conversion efficiency of about 40 % and in its consequence an output power of 30 TW. Using the Raman amplification in the plasma, more than one order increase in the third harmonic frequency can be expected.

4. Conclusion

The investigations of the stimulated Raman amplification in plasma performed in simulations are very optimistic regarding attainable output powers. The experimental results so far achieved, however, stay behind by several orders. In the experiment, it is very difficult to keep the optimal conditions for an efficient energy transfer from the pump to the seed along the whole interaction path in plasma. The channel should be long enough (≤ 10 mm) and all along with good wave guiding properties. Technically it is not easy to maintain a uniform plasma density along such a long channel. However, it can be believed a single high-quality intense beam, smooth in time and space, the same as the PALS laser system in Prague, would be a good candidate for the production of a suitable plasma channel for the SRBS studies.

References

[1] D. Batani, R. Benocci, R. Dezulian, et al. Smoothing of laser energy deposition by gas jets. *Eur Phys J Special Topics* **175**(1):65–70, 2009.

[2] R. L. Berger, C. H. Still, E. A. Williams, A. B. Langdon. On the dominant and subdominant behavior of stimulated Raman and Brillouin scattering driven by nonuniform laser beams. *Phys Plasmas* **5**(12):4337–4355, 1998.

[3] E. Brookner. Phased-array radars. *Scient American* **252**(2):94–103, 1985.

[4] W. Cheng. *Reaching the nonlinear regime of the Raman amplification of ultrashort laser pulses.* Princeton university, U.S.A., 2007. Ph.D. thesis.

[5] M. Dreher, E. Takahashi, J. Meyer-ter Vehn, K.-J. Witte. Observation of superradiant amplification of ultrashort laser pulses in a plasma. *Phys Rev Lett* **93**(9):095001, 2004.

[6] R. A. Fisher, W. K. Bischel. Pulse compression for more efficient operation of solid-state laser amplifier chains II. *Appl Phys Lett* **24**(10):468–470, 1974.

[7] J. Hrebicek, B. Rus, J. C. Lagron, et al. 25 TW Ti:sapphire laser chain at PALS. *SPIE* **8080**, 2011.

[8] V. M. Malkin, G. Shvets, N. J. Fisch. Fast compression of laser beams to highly overcritical powers. *Phys Rev Lett* **82**(22):4448–4451, 1999.

[9] V. M. Malkin, G. Shvets, N. J. Fisch. Ultra-powerful compact amplifiers for short laser pulses. *Phys Plasmas* **7**(5):2232–2240, 2000.

[10] J. Ren, S. Li, A. Morozov, et al. A compact double-pass Raman backscattering amplifier/compressor. *Phys Plasmas* **15**(5):056702, 2008.

[11] K. Rohlena, K. Jungwirth, B. Kralikova, et al. A survey of PALS activity and development, 2004.

[12] G. Shvets, N. J. Fisch. Superradiant amplification of an ultrashort pulse in a plasma by a counterpropagating pump. *Phys Rev Lett* **81**(22):4879–4882, 1998.

[13] D. Strickland, G. Mourou. Compression of amplified chirped optical pulses. *Optics Com* **56**(3):219–221, 1985.

[14] R. M. G. M. Trines, F. Fiuza, R. Bingham, et al. Production of picosecond, kilojoule, and petawatt laser pulses via Raman amplification on nanosecond pulses. *Phys Rev Lett* **107**(10):105002, 2011.

[15] R. M. G. M. Trines, F. Fiuza, R. Bingham, et al. Simulations of efficient Raman amplification into the multipetawatt regime. *Nature Physics* **7**(1):87–92, 2011.

[16] D. et al. Turnbull. Simulataneous stimulated Raman, Brillouin, and electron-acoustic scattering reveals a potential saturation mechanism in Raman plasma amplifiers. *Phys Plasmas* **19**(8):083109, 2012.

[17] N. A. Yampolsky, N. J. Fisch. Limiting effects on laser compression by resonant backward Raman scattering in modern experiments. *Phys Plasmas* **18**(5):056711, 2011.