Plasma-Based Methods for Amplification and Manipulation of High-Power Laser Pulses

G. Lehmann

published in

NIC Symposium 2018
K. Binder, M. Müller, A. Trautmann (Editors)

Forschungszentrum Jülich GmbH,
John von Neumann Institute for Computing (NIC),
Schriften des Forschungszentrums Jülich, NIC Series, Vol. 49,
ISBN 978-3-95806-285-6, pp. 433.
http://hdl.handle.net/2128/17544

Plasma-Based Methods for Amplification and Manipulation of High-Power Laser Pulses

Götz Lehmann

Institut für Theoretische Physik I, Heinrich-Heine Universität Düsseldorf, Germany
E-mail: goetz@tp1.uni-duesseldorf.de

Solid-state devices are limited by damage thresholds when it comes to the amplification and manipulation of very intense laser radiation. The current generation of high-power lasers operates very close to these thresholds. Plasma-based concepts may offer a route to the next generation of high-intensity lasers. We investigate the possibility of using plasma as amplification medium by making use of stimulated scattering processes and look into the potential of using spatially structured plasmas as photonic devices to manipulate high-power laser pulses.

1 Introduction

Since the invention of the laser in the 1960s, there has always been a drive to obtain higher and higher optical field intensities to be able to study ever new realms of laser-matter interaction. The range of topics goes from the fundamental aspects of optical ionisation processes of individual atoms to collective responses of laser-driven plasmas in e.g. inertial confinement fusion, plasma-based accelerators for relativistic particles, compact X- and gamma-ray sources or laboratory astrophysics[1]. The chirped-pulse amplification (CPA) technique became the basis that allowed for a steadily increase in the maximum achievable laser pulse intensity since the mid 1980s.

Todays high-power lasers can reach peak intensities of around 10^{22} W/cm^2. This is achieved by compressing laser pulses with a few Joules of energy down to only a few femtoseconds duration. The power of such laser-systems is around one petawatt. Long before the pulse maximum arrives at the target, ionisation takes place in the foot of the pulse and turns the target into a plasma. At intensities of 10^{18} W/cm^2, the interaction between laser pulse and plasma becomes relativistic. The electrons oscillate so rapidly in the laser field that they experience a relativistic mass increase. The already complex and nonlinear interaction between laser and plasma becomes even more complicated. However, the relativistic nonlinearity is at the heart of many acceleration mechanisms for electrons and ions, leading to plasma-based compact accelerators or to secondary radiation sources, in particular for X-rays. Outside of the currently achievable laser intensities is the realm of quantum electrodynamics (QED). In particular the prospect of experimentally testing nonlinear QED effects from photon-matter and photon-photon interaction such as pair-creation or vacuum birefringence drives the interest in achieving intensities of 10^{24} W/cm^2 and above[2]. These laser systems will require powers of some tens of petawatt to ultimately possibly even exawatt.

All current high-power laser systems rely on solid-state technology. The key elements in a CPA-based amplifier are the laser crystal and the stretcher/compressor gratings. Crystals and gratings are operated close to their damage threshold and the only way to achieve higher intensities is to up-scale these elements. This goes along with severe technological challenges and cost increases. As it becomes apparent that solid-state technology alone will possibly not be able to drive the next generation of high-intensity lasers, plasma-based concepts become discussed[3]. Plasma, as it is already ionised matter, has no inherent damage threshold. The underlying idea is to use processes in plasma that amplify and compress laser pulses at the same time.

Plasma can potentially not only be used as an amplification medium, but also to manipulate very intense laser pulses. A typical example for this is the self-focusing effect at relativistic laser intensities. Here, the refractive index of the plasma effectively becomes intensity dependent, leading to focusing effects and eventually to self-guiding of the laser pulse. In recent years a new direction in plasma-based optics emerged, where the possibility to use spatially structured plasmas as optical devices is studied[4,5]. A periodic spatial modulation of the plasma density translates into a modulation of the refractive index of the system, similar to solid-state photonic crystals. The plasma density modulation on the wavelength of the laser pulse can be imprinted by secondary laser pulses and lasts for a few picoseconds. The structured plasmas can then be used as polarisers or Bragg-type mirrors for ultra-short and ultra-intense laser pulses. The full potential of these structures has yet to be explored.

Our project on JURECA (and formerly JUROPA) started out to study various aspects of plasma-based laser-pulse amplification schemes and then lately shifted its focus on the use of structured plasmas as photonic devices for high-power lasers. Both topics are closely related and share common approaches in analytical and numerical treatment. The simulations carried out on the supercomputers are mostly particle-in-cell (PIC) simulations along with fluid-type three-wave coupling models.

This manuscript is organised as follows. Sec. 2 discusses pulse amplification and Sec. 3 gives an insight into results on using structured plasmas as photonic devices. Sec. 4 briefly describes how the resources on JURECA are used within the project. The manuscript concludes with a short summary and outlook.

2 Plasma-Based Laser-Pulse Amplification

The goal is to transfer as much energy as possible to a short seed laser pulse that propagates through plasma. The energy donor is a energetic counterpropagating pump pulse. The mediation of the energy from pump to seed is done via a plasma wave. The seed pulse has typically a duration of a few hundred down to some tens of femtoseconds and its intensity is around 10^{14} W/cm^2. The seed is assumed to be a very wide pulse, much wider than its wavelength. The pump pulse is of much longer duration than the seed pulse, usually at least some picoseconds, and more intense than the initial seed pulse. Both laser pulse have in general different frequencies, ω_{pump} and ω_{seed}, respectively. Once the pulses overlap, they will produce a beat at $\omega_p = \omega_{pump} - \omega_{seed}$. When the beat-frequency is equal to the frequency of a undamped plasma oscillation, resonant backscattering of the pump into the seed can occur, i.e. the seed pulse will be amplified at the cost of the pump. Once this process has been initiated the energy transfer will be upheld even as the seed intensity surpasses the pump intensity. The plasma mode can either be a high-frequency electron Langmuir wave (stimulated Raman scattering, SRS) or a low-frequency ion wave (stimulated Brillouin scattering, SBS)[6,7]. A seed amplification from 10^{14} W/cm^2 to 10^{16} W/cm^2 would be sufficient, as the wide pulse is only focused in a later stage and only then reaches the ultra-high intensities.

In order to generate a resonant beat-signal, the two laser pulses will have to be wavelength detuned from each other. The amount of detuning required differs for both proposed amplification processes. For Raman amplification, the two pulses have to be detuned by the electron plasma frequency $\omega_{pe} = (4\pi ne^2/m_e)^{1/2}$. Typical plasma densities n are on the order of 10^{-3} to $10^{-2}n_c$, where $n_c = \omega_0^2 m_e/4\pi e^2$ is the critical plasma density. For a 800 nm pump pulse, the seed pulse wavelength will thus have to be detuned by up to 100 nm. Efficiently shifting the central wavelength by this amount is experimentally challenging. On the other hand, Raman-type amplifiers can potentially deliver amplified pulses as short as ten femtoseconds. The reason for this is that only the electrons, and not the much heavier ions, participate in the wave motion. The electrons react almost instantly to the beat of the overlapping laser pulses and thus drive the wave, of which the backscattering takes place, to sufficient amplitude within a few femtoseconds.

Using ion waves, known as Brillouin modes, for short pulse amplification has been initially discarded. The heavy ions react much slower than the electrons to the beat of pump and seed pulse. The growth rate γ_{IAW} of the classic ion acoustic wave is much smaller than its frequency $\omega_{IAW} = c_s k$, where $c_s = \sqrt{T_e/m_i}$ is the ion sound speed. For typical temperatures and densities it takes several picoseconds for the ion wave to be driven to substantial amplitudes. However, for sufficiently large pump amplitudes (around 10^{14} W/cm^2 for plasma densities on the order of $0.01n_c$), we enter the regime of strongly coupled (sc) Brillouin scattering. In this regime, the ion mode becomes a pump-driven quasi-mode and is no longer a plasma eigenmode. The frequency ω_{sc} is much larger than ω_{IAW} and the growth rate γ_{sc} is approximately ω_{sc}. Now it takes only around 50 fs to establish the ion wave and this is sufficiently short for amplification purposes[7]. Even though the shortest duration for an amplified laser pulse is now limited to only approx. 50 fs, the Brillouin process has the experimental advantage of not necessarily requiring a wavelength offset between pump and seed pulse. The natural bandwidth of a short seed pulse already covers the frequency required to drive the strongly coupled ion wave.

All the above is motivated from monochromatic wave theory for the linear regime, where the seed pulse intensity is assumed to be smaller than the pump pulse intensity. Once the seed has grown to the same amplitude as the pump we enter the nonlinear regime. It turns out that the flow of energy from pump to seed is maintained in the nonlinear regime and the seed can become completely depleted by the pump[6,7]. The seed pulse will undergo a self-similar evolution in this phase. While the maximum amplitude is growing, the pulse also compresses in longitudinal direction. Fig. 1 shows simulation results that illustrate this evolution for the case of sc-Brillouin amplification.

The possible issues with Raman- or Brillouin-type amplification schemes are plenty. Foremost, spontaneous Raman backscatter of the pump pulse of random density fluctuations has to be avoided. In Raman type schemes breaking of the plasma wave has to be avoided in order to keep up the energy transfer. But even before wave breaking, particle trapping will set in and a cause degradation of the efficiency. In particular Brillouin amplification is likely to be operated at higher plasma densities, where, in combination with large seed amplitudes, filamentation of the pulses can occur.

Spontaneous backscatter, wave-breaking and filamentation are only three examples for processes that restrict the parameter regime in which amplification can be realised. Experimental factors impose further restrictions. The goal of the simulations we carried out was

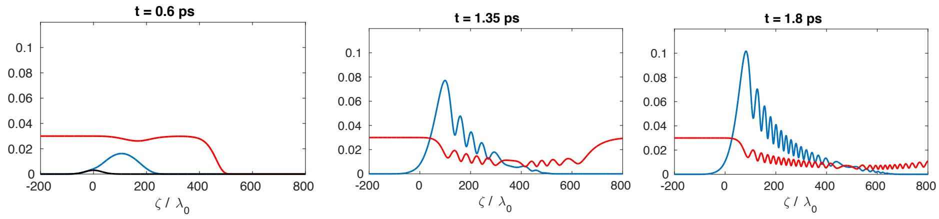

Figure 1. Strongly coupled Brillouin amplification of a 250 fs seed pulse (blue) with initial intensity 10^{13} W/cm^2 (seed at $t = 0$ shown in black) by a counterpropagating pump pulse (red) with intensity 10^{15} W/cm^2 in a plasma of density $n_0 = 0.1n_c$. Calculations were performed in a reference frame co-moving with the seed pulse. Shown are the envelopes of the electric fields of the pulses in normalised units. The final seed maximum intensity is approx. 2×10^{16} W/cm^2.

to study on the one hand the fundamental dynamics of the amplification process in different scenarios and on the other hand to provide assistance to experiments performed at HHU Düsseldorf and HHI/FSU Jena on Brillouin and Raman amplification, respectively.

The particle-in-cell simulations are by their nature far from noise-free and might introduce artificial scattering off noise. Additionally, they give little analytical insight in the basic process. An alternative approach is the derivation of reduced analytical models. Starting from two-fluid descriptions of plasma, envelope models can be derived. These models consist out of three coupled wave equations that describe the spatio-temporal evolution of the (complex) amplitudes E_p of the pump, E_s of the seed and N of the plasma wave. The details of the model differ between Raman and Brillouin amplification, but the implementation into a parallel code is almost the same. In our project we developed an envelope code that allows to study the different amplification processes up to full three-dimensional geometry.

With the help of PIC- and three-wave simulations performed on JURECA, we have been working on a wide variety of aspects concerned with Raman and Brillouin amplification, respectively. We studied the principal dynamics of the linear and nonlinear stages for both amplification processes[8,9], the influence that a chirp of the pump-frequency has on regular[10] and on strongly-coupled Brillouin amplification[11], the interplay between amplification and filamentation in Raman amplification[9], and the influence of the plasma temperature on strongly-coupled Brillouin amplification[12]. Additionally, we have studied the dynamic transition between weak and strong coupling in Brillouin amplification[13], and performed post-experiment simulations to help the interpretation of experimental results on Raman amplification[14].

3 Transient Plasma Photonic Crystals for High-Power Lasers

Photonic crystals (PCs) are structures in which the dielectric function ϵ of the material is periodically modulated, causing the structure to have interesting optical properties. The main feature of PCs are optical band-gaps, i.e. frequency ranges for which the structure appears opaque. PCs are a very active field in solid-state physics as they can be used to precisely guide light, operate as optical filters and may, via nonlinear effects, offer the possibility to realise fully optical switches, where light controls light[15].

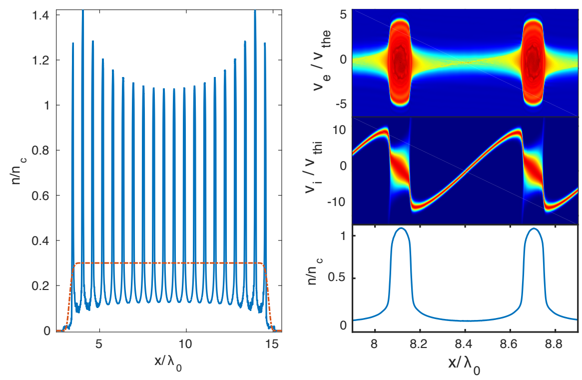

Figure 2. Left: Initial (red line) and final (blue line) plasma density profile of a plasma that has been irradiated by two counterpropagating laser pulses with $\lambda_0 = 800$ nm and $I = 10^{15}$ W/cm^2 for 300 fs. The final plasma density is periodic with a period of around $\lambda_0/2$. Right: Final electron and ion phasespace, showing that the electrons become trapped in the density peaks.

The most simple PCs consist of alternating layers of two different dielectric materials, effectively giving a one-dimensional PC as the dielectric function ϵ depends on only one spatial coordinate. In plasmas, the dielectric function is a function of the electron density $\epsilon = \sqrt{1 - \omega_{pe}^2/\omega^2}$. To manipulate electromagnetic waves in a PC, the spatial period of ϵ has to be of the order of the wavelength λ_0. For microwaves this is on the order of a few mm to cm and can be achieved by using a micro-array of individual plasmas. This is not anymore possible in the optical regime, where λ_0 is only a few hundred nm. However, it is possible to use the ponderomotive force that results from the overlap of two counterpropagating laser pulses to drive an initially homogeneous plasma into a grating structure with substantial density modulation. Fig. 2 shows a simulation example of a density grating that has been produced in this way. The dynamic creation of the density gratings can be divided into four phases. In the first phase, the standing electromagnetic wave that results from the overlap of two laser pulses pushes the light electrons into the nodes of the wave. This sets up a space-charge field, as the ions initially remain in place due to their large mass. The density modulation of the electrons in this stage is only a few percent of the background density. In phase two, the ions slowly start to move towards the piled up electrons due to the electrostatic field that has been set up. Once the ions have gathered sufficient momentum, the two lasers can be switched off. The third phase now consists of ballistic motion of the ions towards the former nodes of the standing wave. There is no force stopping their motion. The electrons bounce between the inward moving ions and become more and more trapped at their position in the centre. This is the stage in which the large density spikes in the grating are assembled. The timescale for this is determined by the ballistic velocity of the ions. In the fourth phase, taking place after the situation shown in Fig. 2, the ions overshoot the density peaks and pull the electrons out of the peaks. This initiates the degradation of the structure. Depending on the precise parameters (plasma density and temperature, ion mass, and laser intensity) the structure lasts between one and up to several tens of picoseconds.

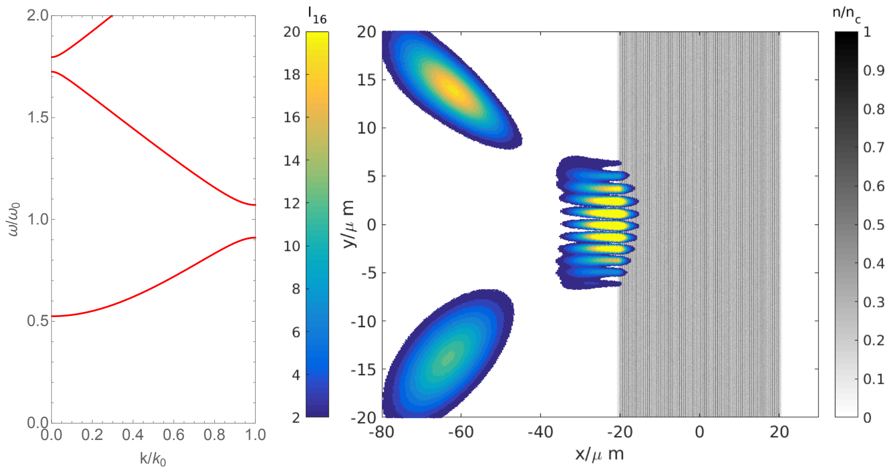

Figure 3. (a) Dispersion relation for light-waves in the structure shown in Fig. 2. Around $\omega = \omega_0$ a wide bandgap is established, where ω_0 is the frequency of the lasers that created the plasma grating. (b) As a result of the bandgap, laser pulses with central frequency $\omega = \omega_0$ can not penetrate the plasma grating. Shown is the reflection of a 30 fs laser pulse with with intensity of the order 10^{17} W/cm^2. The pulse is shown at three different times.

The dispersion relation for light in plasma gratings is obtained similar to that in regular photonic crystals. Starting from Maxwell's equations, first the wave equations of the electric field and the magnetic field in plasma are formulated. Then, we look for Bloch-wave type solutions for the fields. As the dielectric function is periodic, it is assumed that the solutions for the fields also have the same periodicity. This eventually gives the dispersion relation $\omega(k)$ for the light-wave. Fig. 3 (a) shows the dispersion relation for light-waves in the structure shown in Fig. 2. The axes are normalised by the frequency ω_0 and the wavenumber k_0 of the lasers that created the grating. For frequencies around ω_0 we find a bandgap, i.e. light-waves with frequencies in the gap can not propagate inside the grating. As a consequence, light with frequency ω_0 that is incident on the structure from the outside is not able to penetrate and becomes reflected. Fig. 3 (b) demonstrates this behaviour for a 30 fs laser pulse with maximum intensity above 10^{17} W/cm^2. The pulse is shown at three different times and the pulse enters the simulation box at the bottom left. In total about 90% of the pulse energy is reflected. Note that the pulse intensity is many orders of magnitude larger than what solid-state optical devices can sustain. This Bragg-type mirror demonstrates the potential that structured plasmas have as optical devices for high-intensity laser pulses[16,17]. In the same context it has been shown that plasma gratings can also act as polarisers or wave-plate[5].

4 The Use of JURECA in this Project

The main part of the granted computing time for our project is dedicated to PIC simulations. We make use of the EPOCH PIC code[18], which is a open-source code developed by T. Arber *et al.*.

Most commonly we run 1D and 2D simulations. All our simulations usually have to cover timespans of multiple picoseconds and large spatial extend at the same time. The combination of high spatial resolution, large simulation volume and a long simulation time is what could not be done efficiently without the use of a supercomputer.

A typical 2D simulation for the plasma grating project for example has a simulation box covering 300 μm $\times$ 50 μm with about 50 nodes per μm, i.e. a grid of about 15000 $\times$ 5000 nodes. Per cell we use around 10 to 25 particles per species, i.e. in total around 4×10^9 particles. The strong scaling performance depends slightly on the precise target geometry and laser pulses, but in general, the scaling is close to perfect up to 1536 or 3072 cores. On 3072 cores a regular run takes around one to two hours. Data analysis is performed both on the visualisation partition of JURECA and offside.

5 Summary and Outlook

Our project investigates the use of plasma as a damageless amplification medium and explores the possibility to use structured plasmas as optical components for high-power laser pulses. While laser pulse amplification in plasma remains to be experimentally challenging, we were able to uncover many principal features of the amplification dynamics[8–10,12,11,13] and to contribute to the data analysis of a recent experiment[14].

Our investigations on structured plasmas as photonic devices show that they have a clear potential as optical elements for high-power lasers[16,17]. Even though the plasma gratings are only transient and exist only for several picoseconds, it is sufficiently long to interact with femtosecond laser pulses. At the same time the gratings prove to be very robust and can sustain intensities far beyond what any solid-state material can. It remains to be seen which solid-state photonic structures can really be implemented experimentally at reasonable effort, but at the same time the flexibility of plasma compared to solid-state material might allow completely new concepts.

Acknowledgements

The simulations were performed with computer resources on JUROPA and JURECA granted by the John von Neumann Institute (NIC) at Forschungszentrum Jülich under project HDD10. This work was in part funded by the UK EPSRC grants EP/G054950/1, EP/G056803/1, EP/G055165/1 and EP/ M022463/1.

References

1. P. Gibbon, *Short pulse laser interactions with matter, 2nd edition*, Imperial College Press, London, 2013.
2. A. Di Piazza, C. Müller, K.Z. Hatsagortsyan, and C. H. Keitel, *Extremely high-intensity laser interactions with fundamental quantum systems*, Rev. Mod. Phys. **84**, 1177, 2012.
3. G. A. Mourou, N. J. Fisch, V. M. Malkin, Z. Toroker, E. A. Khazanov, A. M. Sergeev, T. Tajima, and B. Le Garrec, *Exawatt-Zettawatt pulse generation and applications*, Optics Comm. **285**, 720, 2012.

4. S. Suntsov, D. Abdollahpour, D. G. Papazoglou, and S. Tzortzakis, *Femtosecond laser induced plasma diffraction gratings in air as photonic devices for high intensity laser applications*, Appl. Phys. Lett. **94**, 251104, 2009.
5. P. Michel, L. Divol, D. Turnbull, and J. D. Moody, *Dynamic Control of the Polarization of Intense Laser Beams via Optical Wave Mixing in Plasmas*, Phys. Rev. Lett. **113**, 205001, 2014.
6. V. M. Malkin, G. Shvets, and N. J. Fisch, *Fast Compression of Laser Beams to Highly Overcritical Powers*, Phys. Rev. Lett. **82**, 4448, 1999.
7. A. A. Andreev, C. Riconda, V. T. Tikhonchuk, and S. Weber, *Short light pulse amplification and compression by stimulated Brillouin scattering in plasmas in the strong coupling regime*, Phys. Plasmas **13**, 053110, 2006.
8. G. Lehmann and K. H. Spatschek, *Nonlinear Brillouin amplification of finite-duration seeds in the strong coupling regime*, Phys. Plasmas **20**, 073112, 2013.
9. G. Lehmann and K. H. Spatschek, *Non-filamented ultra-intense and ultra-short pulse fronts in three-dimensional Raman seed amplificaiton*, Phys. Plasmas **21**, 053101, 2014.
10. G. Lehmann and K. H. Spatschek, *Control of Brillouin short-pulse seed amplification by chirping the pump pulse*, Phys. Plasmas **22**, 043105, 2015.
11. F. Schluck, G. Lehmann, and K. H. Spatschek, *Amplification of a seed pumped by a chirped laser in the sc-Brillouin regime*, Phys. Plasmas **22**, 093104, 2015.
12. G. Lehmann and K. H. Spatschek, *Temperature dependence of seed pulse amplitude and density grating in Brillouin amplification*, Phys. Plasmas **23**, 023107, 2015.
13. F. Schluck, G. Lehmann, C. Müller, and K. H. Spatschek, *Dynamical transition from weakly to strongly coupled Brillouin backscattering during laser seed pulse amplification*, Phys. Plasmas **23**, 083015, 2017.
14. B. Landgraf, B. Aurand, G. Lehmann, T. Gangolf, M. Schnell, T. Kuehl, and C. Spielmann, *Broadband Stimulated Raman Backscattering*, New J. Phys. **18**, 073048, 2016.
15. Editorial, *Early lights: 25 years of photonic crystals*, Nat. Mater. **11**, 995, 2012.
16. G. Lehmann and K. H. Spatschek, *Transient plasma photonic crystals for high-power lasers* , Phys. Rev. Lett. **116**, 225002, 2016.
17. G. Lehmann and K. H. Spatschek, *Laser-driven plasma photonic crystals for high-power lasers*, Phys. Plasmas **24**, 056701, 2017.
18. T. D. Arber, K. Bennett, C. S. Brady, A. Lawrence-Douglas, M. G. Ramsay, N. J. Sircombe, P. Gillies, R. G. Evans, H. Schmitz, A. R. Bell, and C. P. Ridgers, *Contemporary particle-in-cell approach to laser-plasma modelling*, Plasma Phys. Controlled Fusion **57**, 1, 2015.