RELATIVISTICALLY INDUCED TRANSPARENCY AND COMPRESSED FUSION TARGETS

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We study impact of QED effects on relativistically induced transparency in plasma. The relativictic induced transparency is the key phenomenon in the fast igntion schemes for Inertial Confinement Fusion. We have simulated propagation of 100 kJ, 15 fs in a compressed ICF target. The γ quanta generation appears to be the main mechanism of laser energy absorption while the positrons carry less than a percent of the laser energy. The laser pulse propagates 50 μm distance in the dense plasma and an empty channel has been created.

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The laser technology has experienced a tremendous development over the last decades. The ever higher laser peak powers and focused intensities have been achieved that revolutionized science. The revolution begann in 1985 with the invention of CPA (Chirped Pulse Amplification) Today, it is the workhorse of most laser amplification systems. Later, the OPCPA (Optical Parametric Chirped Pulse Amplification) has been introduced. Being based on CPA, it employs nonlinear crystals to transfer energy from a long pump pulse to the seed. It is now used for broadband, few cycles pulse amplification. Finally, about 15 years ago, a new compression technique based on Backwards Raman Scattering (BRA) and Backwards Compton Scattering Amplification (BCSA) were proposed. These two do not require expensive gratings, and thus eliminate the major hurdle in ultrahigh high peak power pulse amplification. The laser pulse can be amplified in plasma – a medium that can survive extremely high intensities. Extremely high energy fluencies can be achieved, many orders of magnitude above the limitation set up by solid density gratings. This opens the path beyond the exawatt, towards the zettawatt in the laser power.

The C^3 (Cascaded Conversion Compression) concept has been recently put forward within the European iZEST project (International Center for Zettawatt-Exawatt Science and Technology) that targets possible efficient compression of 10 kJ to MJ, ns pulses delivered by NIF or LMJ-like laser, into fs pulses of the highest quality. This technique employs CPA to produce a first-stage compression, followed by BRA for a second-stage compression, together with OPCPA to produce a strong seed pulse. The combination of the three is optimized over the joint compression technologies of both compression stages.

If successfull, the C^3 technology will result in ultimate laser power and intensity. Assuming, we succeed compressing 100 kJ energy in a focal spot of $\sigma = 10\ \mu$m and pulse duration of $\tau = 10$ fs, the peak intensity would be as high as $I_0 = 3\cdot 10^{24}$ W/cm^2. If the laser pulse has the wavelength of $\lambda = 1\mu$m, the normalized laser amplitude $a_0 = eE/mc\omega_0$ would be $a_0 > 1000$. Because of the huge amplitude, any solid state material would become transparent to these ultra-intense laser pulses.

Plasmas with densities above the critical one

$$n_c = \frac{m\omega_0^2}{4\pi e^2} \tag{1}$$

are opaque for linear elecromagnetic waves with the frequency ω_0. However, when the plasma particles become relativistic and acquire large relativistic γ-factor, the critical density must be renormalized:

$$n_c^{rel} = \frac{\gamma m\omega_0^2}{4\pi e^2}. \tag{2}$$

Due to the relativistic mass correction of the electrons, the ultra-intense laser pulse can propagate much deeper into the dense material.

According to the similarity theory [7], the relativistic laser-plasma interaction is governed by the main similarity parameter

$$S = \frac{n}{a_0 n_c}. \tag{3}$$

The S – number can be roughly interpreted as a relativistically corrected critical density ratio. Yet, it does not mean that media with $S > 1$ are always opaque and media with $S < 1$ are always transparent. The particular interaction depends also on other details like the laser polarization, focal spot radius, density gradient, etc. However, the similarity theory claims that if a plasma with the density n_0 is transparent for a laser with $a_0 > 1$, then a plasma with the density n_1 will be transparent for a laser pulse with the amplitude $a_1 = a_0 n_1/n_0$. In this sense, the $S \approx 1$ indeed marks the boundary of relativistic transparency.

One of the potential applications for the relativistically induced transparency mught be the fast igntion in ICF (Inertial Confinement Fusion). The original fast ignition scheme [8] suggests two laser pulses. The first laser pulse should drill a channel through overdense plasma corona and was intended to be some 100 ps long. The second shorter and intenser pulse, the igniting one, would propagate through the preform channel and deliver enough energy to the compressed target core for the ignition. However, it is unclear whether the channel boring can be completed by a low intensity long laser pulse as the plasma surrounding the channel is heated continously by the same laser pulse and at some point the kinetic plasma pressure may overcome the light pressure of the drilling laser. This would stop the channel boring.

If one succeeds compressing an ICF laser into 10 fs and focus it down to the amplitude $a_0 > 1000$, the compressed ICF target may become relativistically transparent very close to the core. Such a laser pulse would propagate through the corona shoveling the plasma aside and open an empty channel, in which a lower intensity ignition laser pulse can freely propagate. In this work, we try to simulate this scenario using the full three dimensional code VLPL (Virtual Laser Plasma Laboratory) [9].

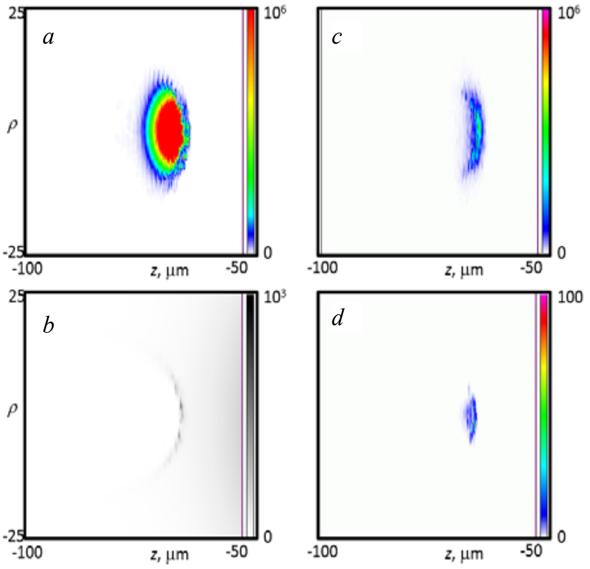

Fig. 1. Laser pulse at 70 μm before the center of the compressed target. (a) Normalized laser intensity $I = (eE/mc\omega_0)^2 + (eB/mc\omega_0)^2$*; (b) plasma density in critical densities* n/n_c*; (c) normalized energy density of γ-quanta* $n_\gamma = W/n_c mc^2$*; (d) normalized density of positrons* n_p/n_c

At the laser intensities $I = 10^{24}$ W/cm^2 and above, QED (quantum electrodynamics) effects must be taken into account. The emission of γ-quanta and the correspoding momentum recoil must be incorporated into the electron equation of motion. Also, the electromagnetic fields are so huge that the γ-quanta start producing abundand electron-positron pairs. All these effects were introduced into the VLPL code. In our simulations, we took a compressed ICF target consisting of pure deuterium with the density profile $n(r) = n_0 \exp\left(-r^2/\sigma^2\right)$ with $n_0 = 10^{25}\,\mathrm{cm}^{-3}$ and $\sigma = 30$ μm. The laser pulse was a circularly polarized Gaussian one with the envelope $a(r,t) = a_0 \exp\left(-\rho^2/\sigma_\rho^2\right)\exp\left(-t^2/\tau^2\right)$ with the peak amplitude $a_0 = 2000$, the focal spot radius $\sigma_\rho = 5$ μm and the pulse duration $\tau = 14$ fs. The laser was focused to converge exactly at the center of the target. The first laser pulse harmonic at the wavelength of $\lambda = 1$ μm was assumed. In this configuration, the similarity parameter at the target center is $S = 5$.

Fig. 1 shows the simulation results when the laser pulse is about 70 μm away from the target center. We see a shock wave formed at the sharp laser-plasma interface. Abundand production of γ-photons and positrons begins at this point. The energy density of the γ-quanta becomes comparable with the laser energy density and the peak positron density is higher than 10^{23} cm^{-3} here that is above the solid density.

Finally, the laser pulse stops some 50 μm before the geometrical center of the compressed core as is shown in Fig. 2. The background plasma density here was about $n \approx 6 \cdot 10^{23}\mathrm{cm}^{-3}$. About 40% of the laser energy has been converted into energetic particles at this point.

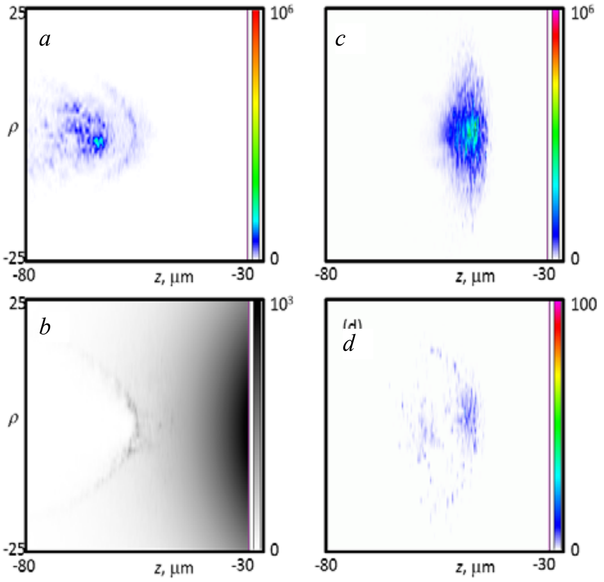

Fig. 2. Laser pulse is completely absorbed at about 50 μm before the geometrical center of the compressed target. (a) Normalized laser intensity $I = (eE/mc\omega_0)^2 + (eB/mc\omega_0)^2$*; (b) plasma density in critical densities* n/n_c*; (c) normalized energy density of γ-quanta* $n_\gamma = W/n_c mc^2$*; (d) normalized density of positrons* n_p/n_c

Fig. 3 shows the energy spectra. Apparently, the deuterons acquire the highest energies per particle via the relativistic shock wave acceleration [10]. The laser energy has been deposited into different particles as shown in Fig. 4. Surprizingly, most of the laser energy has been spent to generate radiation. About 60% has been converted into γ-quanta. Some 35% percent remain in deuterons, and only 5% carry the electrons. Less than 1% of the laser energy is converted into positrons. It is the radiation damping that prevented electrons from acquiring too much energy. As soon as the electrons became energetic enough, they radiated their energy away. Thus, plasma at these extreme intensities is an efficient convertor of laser energy into hard electromagnetic radiation.

In conclusion, we have simulated relativistic transparency of a compressed ICF target irradiated by a 100 kJ, 15 fs laser pulse of amplitude $a_0 = 2000$. We have shown that laser-plasma interaction at these intensities is dominated by QED effects. Our PIC simulations have included generation of γ-quanta and electron-positron pairs in the strong laser fields. The γ-quanta generation appears to be the main mechanism of laser energy absorption. We also observe dense bunches of positrons. Yet, the positrons carry less than a percent of the laser energy.

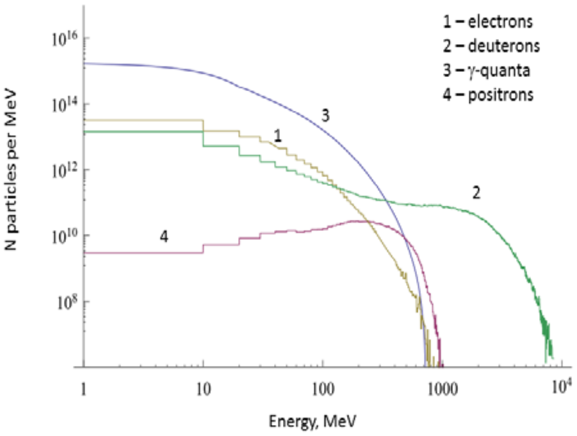

Fig. 3. Energy spectra of particles

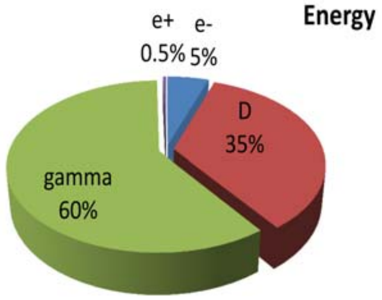

Fig. 4. Percentage of energy deposited into particles of different species

The laser was able to propagate up to 50 μm distance from the target geometric center. An empty channel has been created up to the plasma density of about $6{\cdot}10^{23}$cm^{-3}. This channel can be used to send an igniting beam of lower intensity to the compressed core.

ACKNOWLEDGEMENTS

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REFERENCES

1. D. Strickland and G. Mourou. Compression of amplified chirped optical pulses // *Optics Communications*. 1985, v. 56(3), p. 219-221.
2. I.N. Ross et al. The prospects for ultrashort pulse duration and ultrahigh intensity using optical parametric chirped pulse amplifiers // *Opt. Commun.* 1997, v. 144, p. 125.
3. V.M. Malkin, G. Shvets, and N.J. Fisch. Fast Compression of Laser Beams to Highly Overcritical Powers // *Physical Review Letters*. 1999, v. 82, p. 4448-4451.
4. G. Shvets, N.J. Fisch, A. Pukhov, J. Meyer-ter-Vehn. Superradiant amplification of an ultrashort laser pulse in a plasma by a counterpropagating pump // *Physical Review Letters*. 1998, v. 81 (22), p. 4879-4882.
5. G.A. Mourou et al. Exawatt-Zettawatt pulse generation and applications // *Optics Communications* 285, iss. 5, 1 March 2012, p. 720-724.
6. http://www.izest.polytechnique.edu/
7. S. Gordienko, A. Pukhov. Scalings for ultrarelativistic laser plasmas and quasimonoenergetic electrons // *Physics of Plasmas*. 2005, v. 12, p. 043109.
8. M. Tabak et al. Ignition and high gain with ultrapowerful lasers // *Phys. Plasmas*. 1994, v. 1, p. 1626.
9. A. Pukhov. Three-dimensional electromagnetic relativistic particle-in-cell code VLPL (Virtual Laser Plasma Lab) // *Journal of Plasma Physics*. 1999, v. 61(3), p. 425-433.
10. L. Ji, A. Pukhov, B. Shen. Ion acceleration in dragging field of a light-pressure-driven piston // arXiv:1302.4611v1 (2013).

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РЕЛЯТИВИСТСКАЯ ИНДУЦИРОВАННАЯ ПРОЗРАЧНОСТЬ И ОБЖАТИЕ ЛАЗЕРНОЙ МИШЕНИ ДЛЯ ИТС

А.М. Пухов, И.Ю. Костюков

Исследовано влияние КЭД-эффектов на релятивистскую индуцированную прозрачность в плазме. Релятивистская индуцированная прозрачность – ключевое явление в различных схемах «быстрого поджига» для реализации инерциального термоядерного синтеза. Проведено численное моделирование распространения лазерного импульса с энергией 100 кДж и длительностью 15 фс в скомпрессированной лазерной мишени. Из результатов моделирования следует, что генерация гамма-квантов является, по-видимому, основным механизмом поглощения лазерной энергии. Показано, что лазерный импульс распространяется 50 мкм в плотной плазме, образуя плазменный канал.

РЕЛЯТИВІСТСЬКА ІНДУКОВАНА ПРОЗОРІСТЬ ТА СТИСКАННЯ ЛАЗЕРНОЇ МІШЕНІ ДЛЯ ІТС

А.М. Пухов , І.Ю. Костюков

Досліджено вплив КЕД-ефектів на релятивістську індуковану прозорість у плазмі. Релятивістська індукована прозорість – ключове явище у різних схемах «швидкого підпалу» для реалізації інерціального термоядерного синтезу. Проведено числове моделювання поширення лазерного імпульсу з енергією 100 кДж та тривалістю 15 фс у скомпресованій лазерній мішені. З результатів моделювання виходить, що генерація гама-квантів є напевно основним механізмом поглинання лазерної енергії. Показано, що лазерний імпульс поширюється 50 мкм у щільній плазмі, створюючи плазмовий канал.