Raman backscattering in plasma as method for the phase correction of intense ultrashort laser pulses

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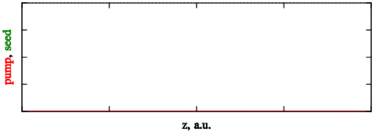
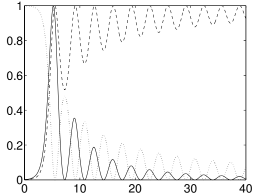
Raman scattering in plasma

Backward Raman scattering equations:
(resonance condition $\omega_a = \omega_b + \omega_p$)

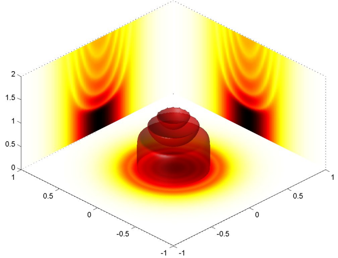
$$\partial_t a + \partial_z a = bf$$
$$\partial_t b - \partial_z b = -af^*$$
$$\partial_t f = -ab^*$$



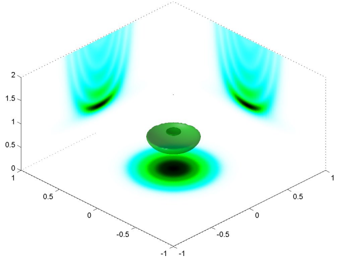
π-pulse
solution



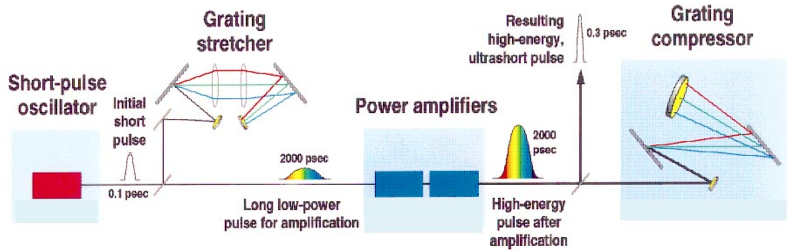
Pump pulse



Seed pulse



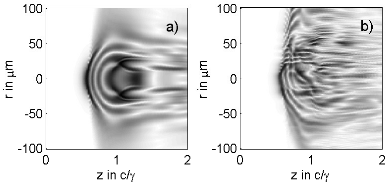
Why Raman backscattering in plasma?



The threshold of thermal destruction of the compressor gratings determines the maximal value of the energy flux $\sim 0.1 - 0.3$ J/cm^2.

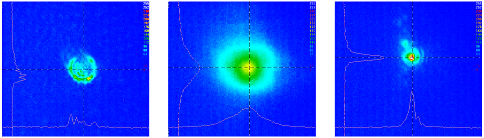
This result in using of large-scale gratings (about 10^3 cm^2 for petawatt laser pulses) or using of *plasma*.

Raman compression (experiment)

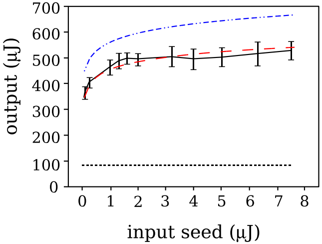


Ionization disturb pulse profile in the presence of any inhomogeneities in density or pulse profiles.

Exactly this can be seen in experiment

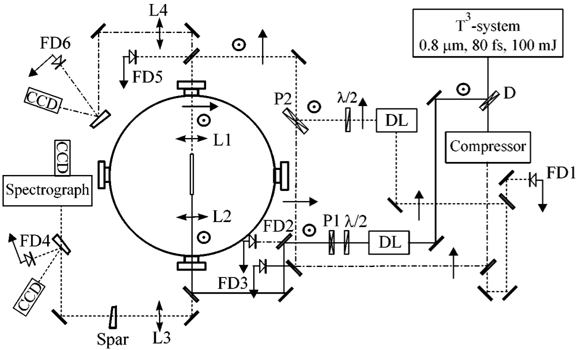


PRE **72**, 036401 (2005).



Ionization is the only mechanism which stop amplification so sharply. Secondary ionization threshold exceeds ones for nonlinear regime. So, we reach nonlinear stage of Raman amplification in plasma!

Raman amplification in capillary plasma



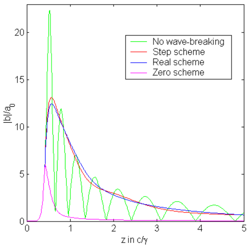
JETP Lett. **80**, 12 (2004).

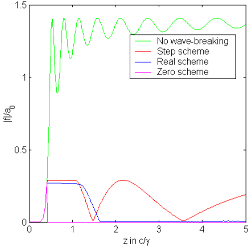
Features

- Capillary as wave-guide
- Homogeneous plasma
- Ultra-short pulse $\tau\omega_p \leq 1$
- Same laser for both pulses

Plasma wave-breaking (experiment)

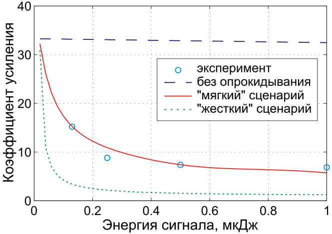
Plasma wave-breaking take place when $f_{wb} = \frac{mc}{2e}\left(\frac{\omega_p}{\omega}\right)^{\frac{3}{2}}$. There are several ways to take it into account using hydrodynamic approach.





Experiment confirm “real” scenario – wave-breaking just prevent plasma wave growth, but don’t disturb existed one.

JETP Lett. **80**, 12 (2004).



Peculiarities of 3-wave equations

Equations for Raman compression have the important property – if phases of EM waves φ_a, φ_b are constant or linear increase along the pulse then equations become equations for absolute values $(a = Ae^{i\varphi_a}, b = Be^{i\varphi_b}, f = Fe^{i(\varphi_a - \varphi_b)})$

$$\partial_t A + \partial_z A = BF$$
$$\partial_t B - \partial_z B = -AF$$
$$\partial_t F = -AB.$$

By other words, all phase perturbations of pumping pulse become "absorbed" by plasma wave.

Such phase profiles are typical for pulses after Raman compression due to media stationarity on the time scale of seed pulse.

Peculiarities of 3-wave equations

In general case of non-constant phases φ_a, φ_b, one can derive equation for seed pulse

$$\partial_{tt} b - \partial_{tz} b = (|a|^2 - |f|^2) b - f^* \partial_z a$$

So, phase of output seed can be modulated only by inhomogeneous chirp of input pulse.

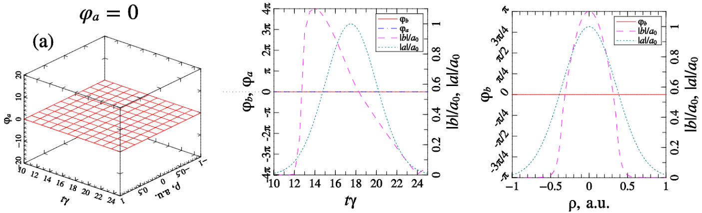
This give us estimation for phase variation of ouput pulse $\Delta\varphi_b$

$$\boxed{\Delta\varphi_b = -i \int (a^* \partial_z a - c.c.) dz / |a| \approx 2|a| \cdot \Delta\varphi_a \ll \Delta\varphi_a}$$

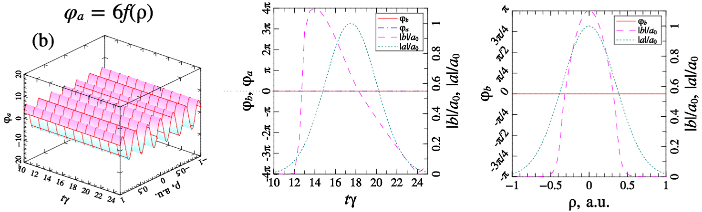
So, any transverse perturbation of input phase $\Delta\varphi_a$ become much smaller in output pulse.

Example of phase cleaning

Nothing interesting for homogeneous φ_a

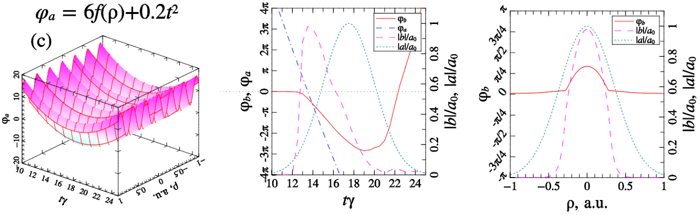


Inhomogeneous but constant φ_a also don't change the ouput pulse

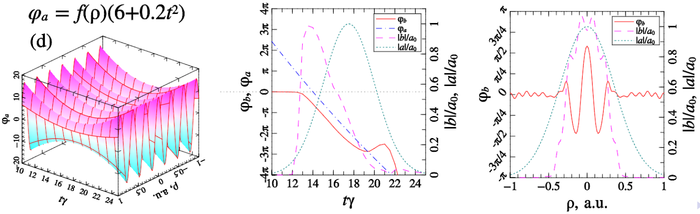


Example of phase cleaning

Homogeneous chirp plus inhomogeneous phase just slightly decrease the output amplitude.



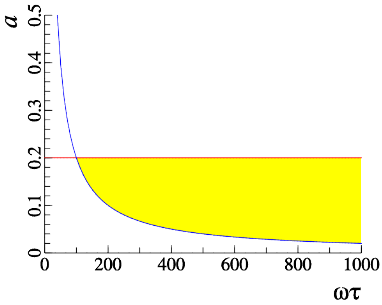
At this, inhomogeneity of chirp can not only modulate the phase of output beam, but also modulate its amplitude profile



Phase cleaner

Pulse duration should be large enough to make possible Raman amplification

$\gamma\tau \equiv \tau a\sqrt{\omega_p\omega/2} \gg 1$



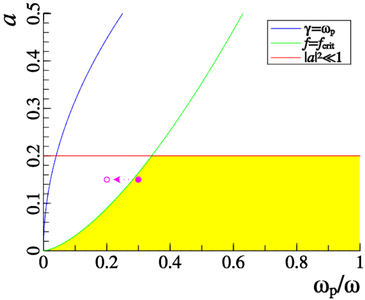
For realistic plasma densities this give $\tau \geq 100$ fs for 1 μm.

Amplitude should be small to provide quasi-adiabatic regime

$\gamma \ll \omega_p$ or $a \ll \sqrt{\omega_p/\omega}$

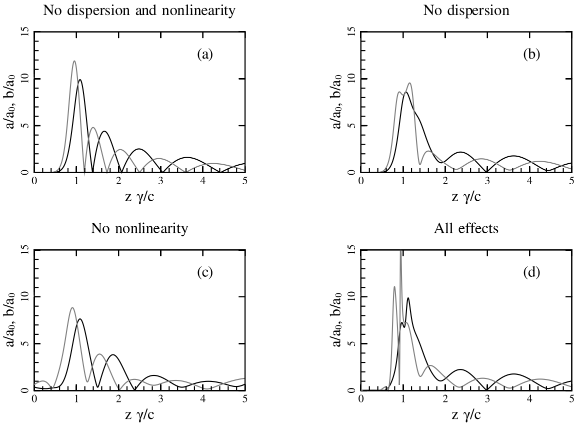
Plasma density should be high to avoid plasma wave-breaking

$a \leq (\omega_p/\omega)^{3/2}$



Limitation for high amplitude

Dense plasma have to be used for quasi-transient regime. But most of parasitic effects become stronger in dense plasma.



Phys. Plasmas **18**, 102311 (2011).

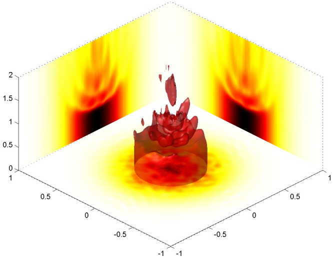
Raman compression in inhomogeneous plasma

Equations for Raman compression are (resonance condition $\omega_a = \omega_b + \omega_p$)

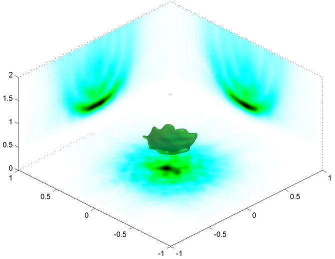
$$\partial_t a + \partial_z a = bf + i\Delta_\perp a - i\varkappa\delta n a$$
$$\partial_t b - \partial_z b = -af^* + i\Delta_\perp b - i\varkappa\delta n b$$
$$\partial_t f = -ab^* - i\kappa\delta n f$$

Even small density inhomogeneity (1%) lead to noticeable perturbation of the pulse phase front and reduce overall efficiency.

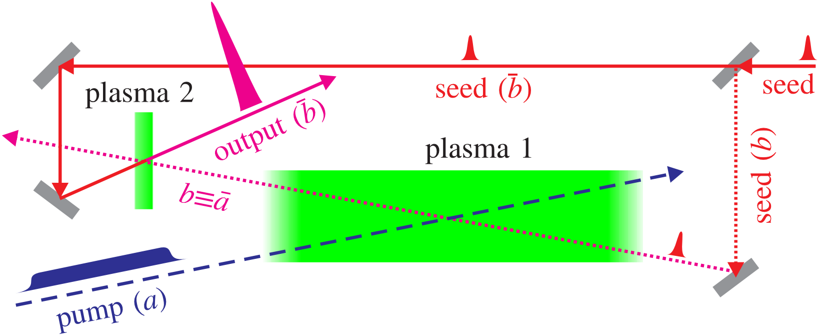
Pump pulse



Seed pulse



Double layers for Raman scattering

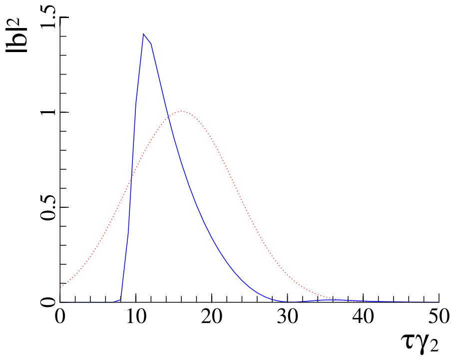


The idea is using amplified seed pulse as pump for second stage of compression.

For simplification of an experiment, one can use the same seed for first and for second stage of compression.
But this require extremely short pulse $\tau\omega_p \leq 1$.

Second stage of compression

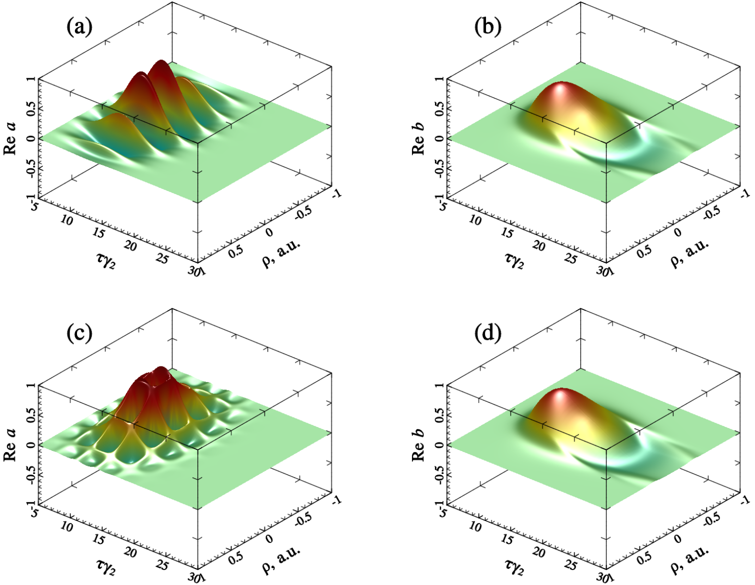
The problem of energy transfer between amplified and initial (non-amplified) seed pulses need poor compression at first stage.



Raman compression require $1 \ll \gamma_2\tau_2 \ll \omega_p\tau_2$, but we want $\omega_p\tau_{ini} \leq 1$ for satisfying resonance condition without frequency shift. This result $\tau_2 \ggg \tau_{ini}$.

Also, one need much dense plasma for second layer to provide better amplification.

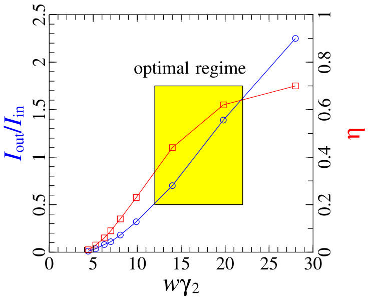
Example of bad phase cleaning



Efficiency of compression

Let use typical Raman parameters:

- $\omega_p/\omega = 0.01$ or 10^{17} cm^3 for $\lambda = 1\mu$m;
- 20 fs seed pulse;
- $\tau_{pump}/\tau_2 = 100$ or compress 10 ps pump pulse to 100 fs pulse at first stage.



As output, we obtain well focusable seed of 70 fs with 50% of pump energy with plasma length for second stage of order of 30 μm (or 1/600 of 2 cm plasma for first stage).

Conclusion

- The phase cleaning method for pulses with durations about 100 fs or longer is suggested. The efficiency is of order of 70%.
- The method of producing well focusable SRBS-amplified ultrashort ultraintense electromagnetic pulses by performing the Raman scattering in two stages is proposed.