Compression of High Power Laser Pulses in Plasma

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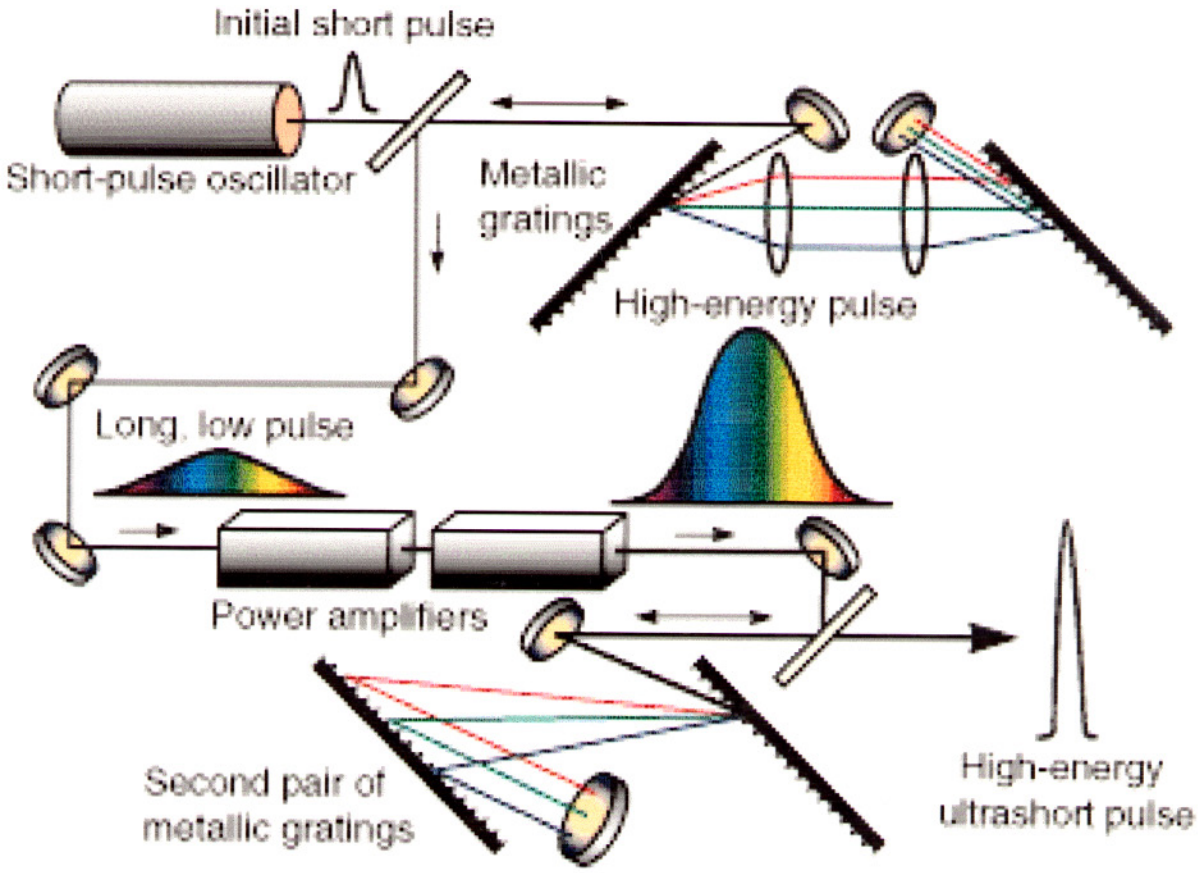
Key Papers:

G. Shvets et al., *Superradiant Amplification of a Ultrashort Laser Pulse in a Plasma by a Counterpropagating Pump*, PRL 81, 4879 (November 1998).

V. Malkin et al., *Fast Compression of Laser Beams to Highly Overcritical Powers*, PRL 82, 4448 (May 1999).

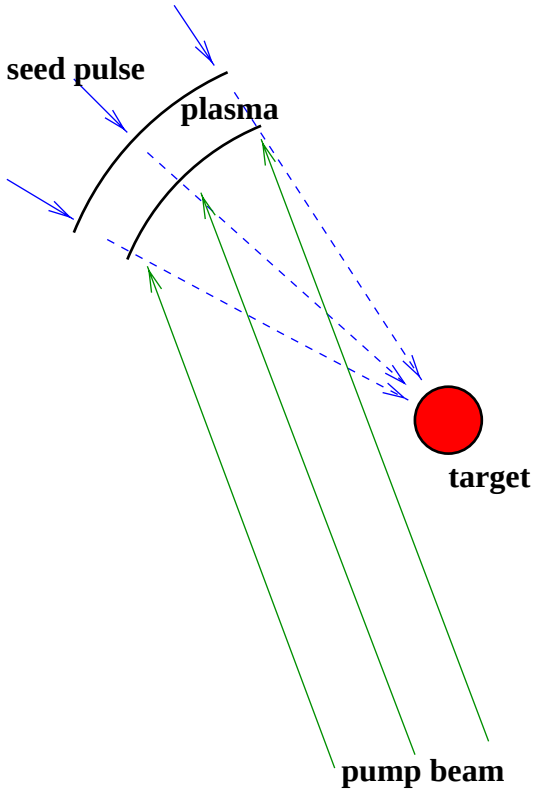
V. Malkin et al., *Detuned Raman Amplification of Short Laser Pulses in Plasma*, PRL 84, 108 (February 2000).

Chirped Pulse Amplification (CPA)

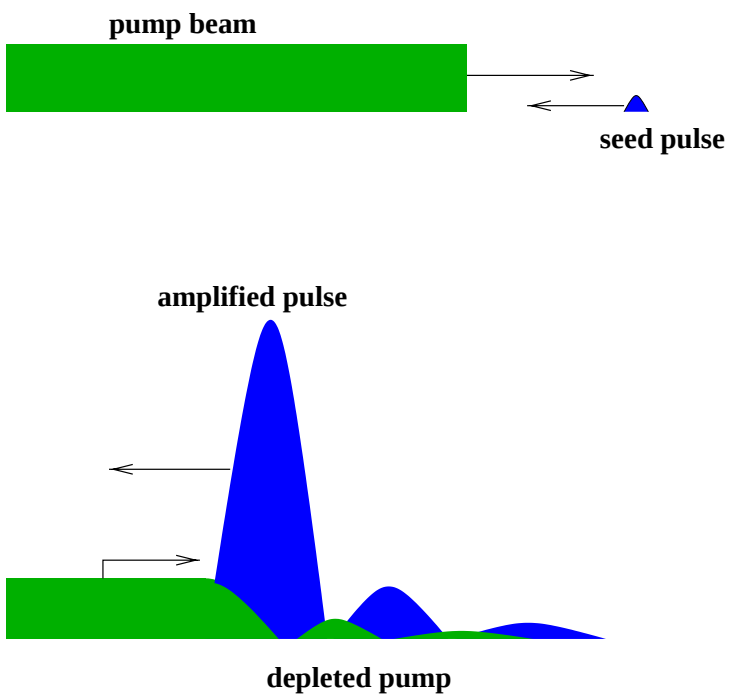


Limitations of CPA

- Thermal damage to (expensive) gratings
- Requires broad-bandwidth high-fluence amplifiers
- GW/cm^2 in amplifier $\Rightarrow$ $\overbrace{\Rightarrow}^{10^3 \text{ compression}}$ TW/cm^2 $\Rightarrow$ $\overbrace{\Rightarrow}^{\text{for PW}}$ 10^3 cm^2 gratings

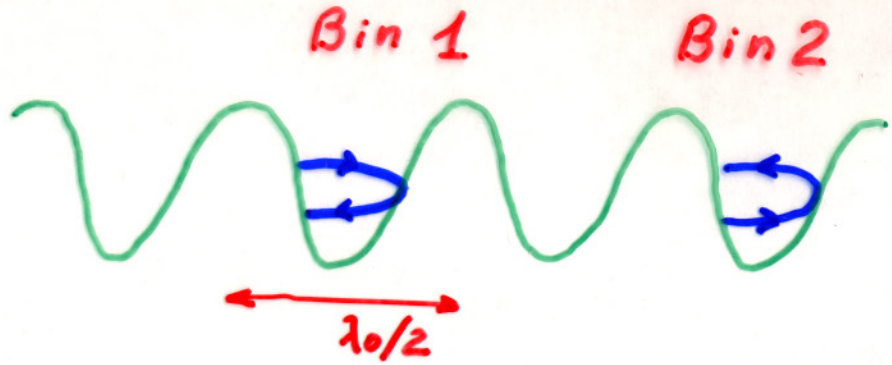


Conceptual scheme for obtaining ultrahigh energy laser pulses by means of stimulated backscattering in a plasma.



Time-Averaged Equations of Motion

Plasma electron oscillates inside "optical lattice":



Ponderomotive phase in the "lattice": $\theta_j = 2k_0 z_j - \Delta\omega t_j$

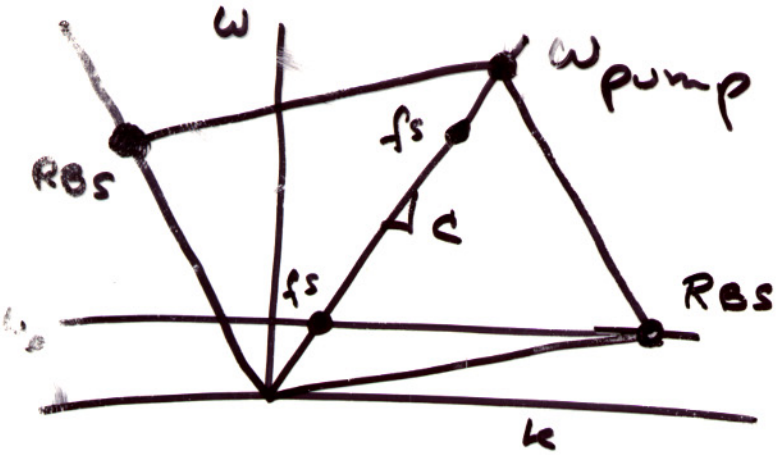
$$\ddot{\theta}_j + \omega_B^2 \sin\theta_j = -\omega_p^2 \sum_{l=1}^{\infty} \frac{1}{l} \left[e^{il\theta_j} \left\langle e^{-il\theta_j} \right\rangle + e^{-il\theta_j} \left\langle e^{il\theta_j} \right\rangle \right] - \frac{2\omega_0 e E_z}{mc^2}$$

$\vec{v} \times \vec{B}$ — space-charge — global E-field

Strongly nonlinear regime: $\boxed{\omega_B^2 = 4\omega_0^2 a_0 a_1 > \omega_p^2}$

G. Shvets et al (1998)

Raman Backscattering in Plasma



$$\omega_p = \omega_{pump} - \omega$$

$$k_p = k_{pump} - k$$

$$= k_{pump} - \omega/c$$

$$\frac{k_{BS}}{k_{fs}} = 2\,\frac{\omega}{\omega_p} \gg 1$$

$$\left(\frac{\partial^2}{\partial t^2} - c^2\nabla^2 + \omega_{pe}^2\right)\vec{A}_{BS} = -\omega_p^2\,\frac{\tilde{n}}{n_0}\,\vec{A}_{pump}$$

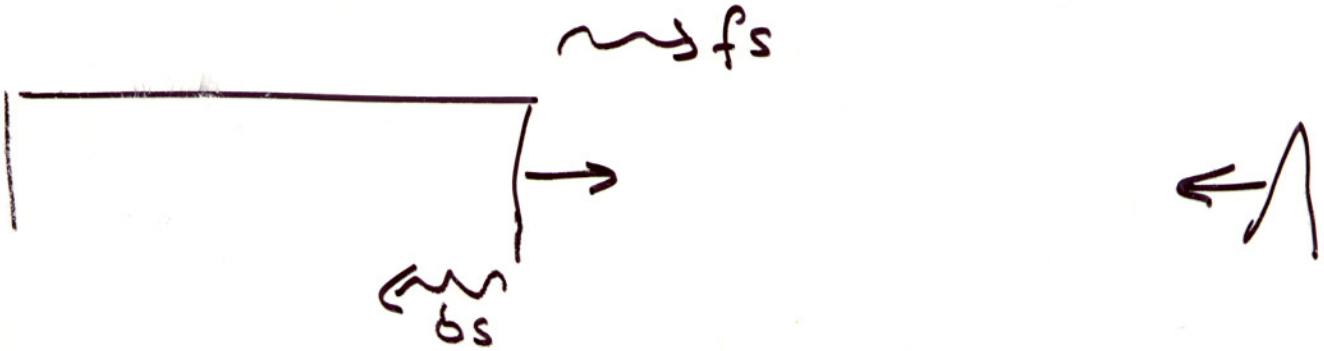
$$\left(\frac{\partial^2}{\partial t^2} + \omega_{pe}^2\right)\frac{\tilde{n}}{n_0} = \left(\frac{e}{mc}\right)^2 \nabla^2\left(\vec{A}_{BS}\cdot\vec{A}_{pump}\right)$$

$$\Rightarrow \quad \gamma_{BS} = \frac{k_p V_{osc}}{4}\left(\frac{\omega_p}{\omega}\right)^{1/2} \propto k_p$$

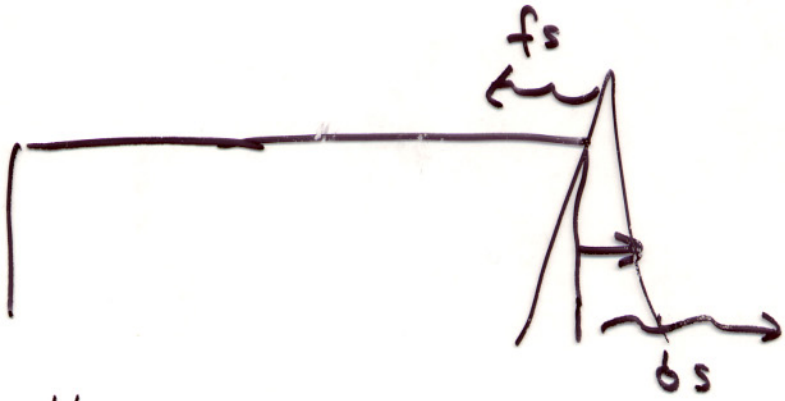
$$\gamma_{fs} = \left(\frac{\omega_p}{\omega}\right)^2 \gamma_{BS}$$

Issues for gases

Raman forward scattering ≡ RBS

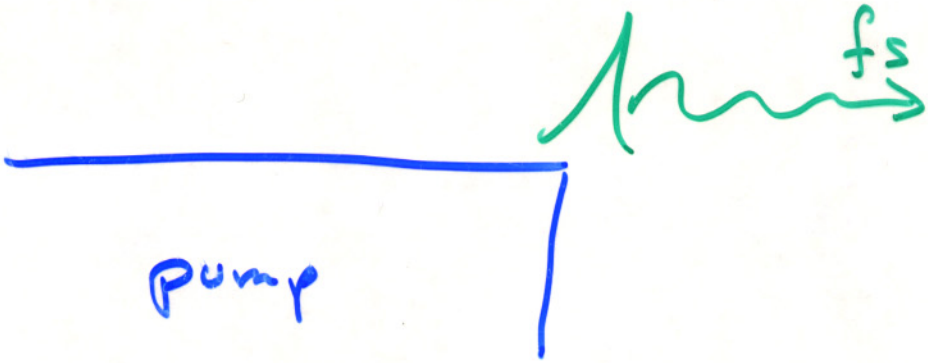


forward scattering of pump
copropagates w/pump full plasma length

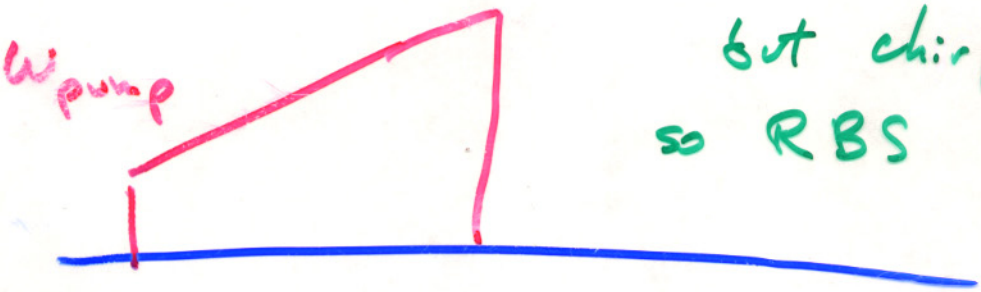


forward scattering of pulse
copropagates with pulse

Suppression of Raman FS in gases



use detuning
to suppress fs

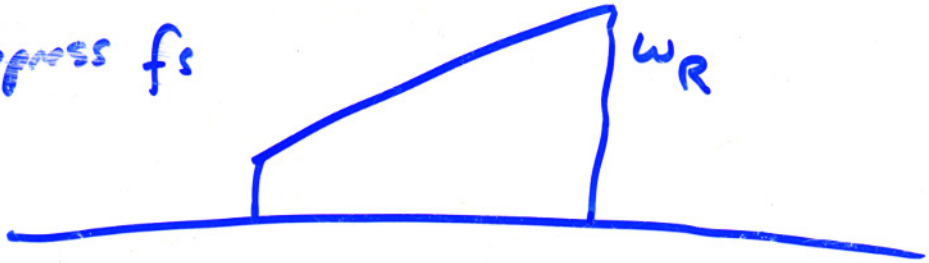


but chirp pulse
so RBS remains resonant

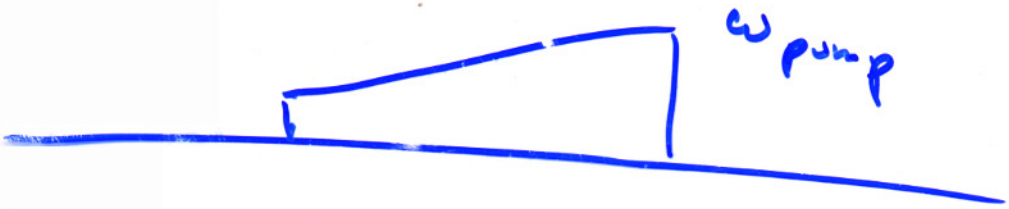
(Caird, 1980)

Suppression of Raman FS in Plasma

to suppress fs



but note large $\Delta\omega_{pulse}$



use chirped pulse

but use nonlinear effects in RBS to overcome detuning (attractor solutions)

BASIC EQUATIONS

$$a_t + ca_z = \omega_p f b,$$

$$b_t - cb_z = -\omega_p f^* a,$$

$$f_t + i\delta\omega f = -\omega a b^*/2;$$

$$\delta\omega = \omega_p + \omega_b - \omega_a \ - \ \text{detuning};$$

$$\omega_b \approx \omega_a \approx \omega \gg \omega_p \ - \ \text{well undercritical plasma};$$

$$a = \frac{eA_{\text{pump}}}{m_e c^2}, \quad b = \frac{eA_{\text{pumped}}}{m_e c^2} \ -$$

laser vector potentials in units of $m_e c^2/e \approx 0.5$ MV;

$$f = \frac{eE_{\text{Langmuir}}}{m_e c \omega_p} \ -$$

Langmuir wave electrostatic field in units of

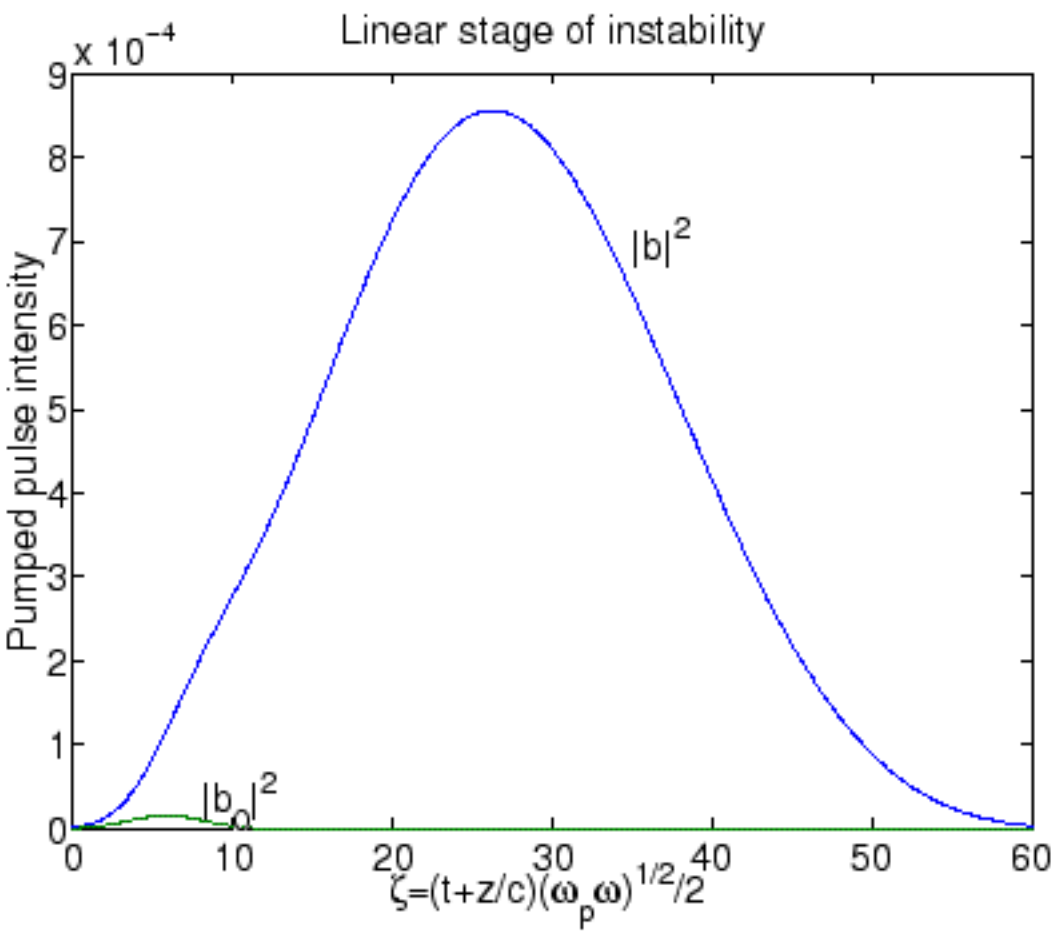
$$m_e c\omega_p/e = c\sqrt{4\pi m_e n_e} \approx \sqrt{n_e[\text{cm}^{-3}]} \ \text{V/cm}.$$

EXACTLY RESONANCE CASE, $\delta\omega = 0$

Malkin V. M., Shvets G. and Fisch N. J.,
Phys. Rev. Lett., **82**, 4448 (1999).

Linear stage of the pump backscattering instability

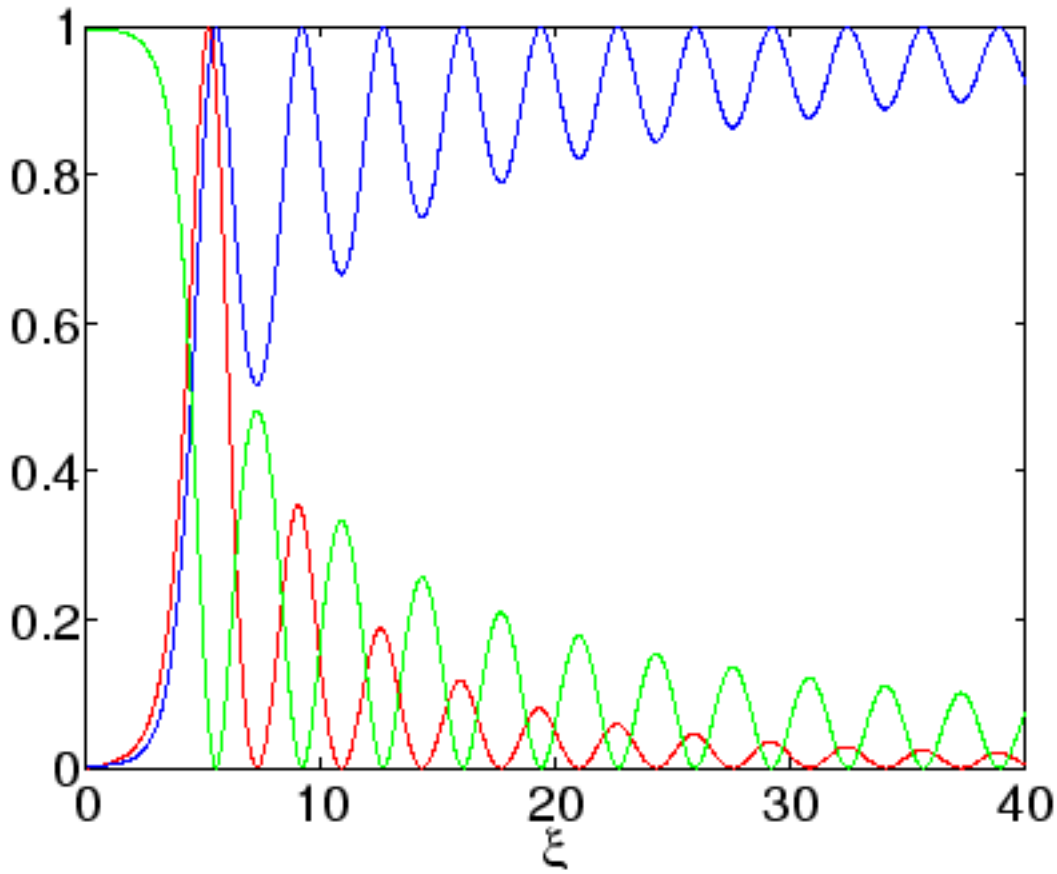
Bobroff D. L., Haus H. A., J. Appl. Phys., **38**, 390 (1967).



$$b \propto \exp(a_0\sqrt{2\omega\omega_p(t+z/c)|z|/c}),$$
$$\max_z |b| \propto \exp(ta_0\sqrt{\omega\omega_p/2}) -$$

pulse broadens and its maximum at $z = -ct/2$ increases with the top growth rate for the monochromatic wave instability.

Self-similar solution for $\epsilon = 0.1$:



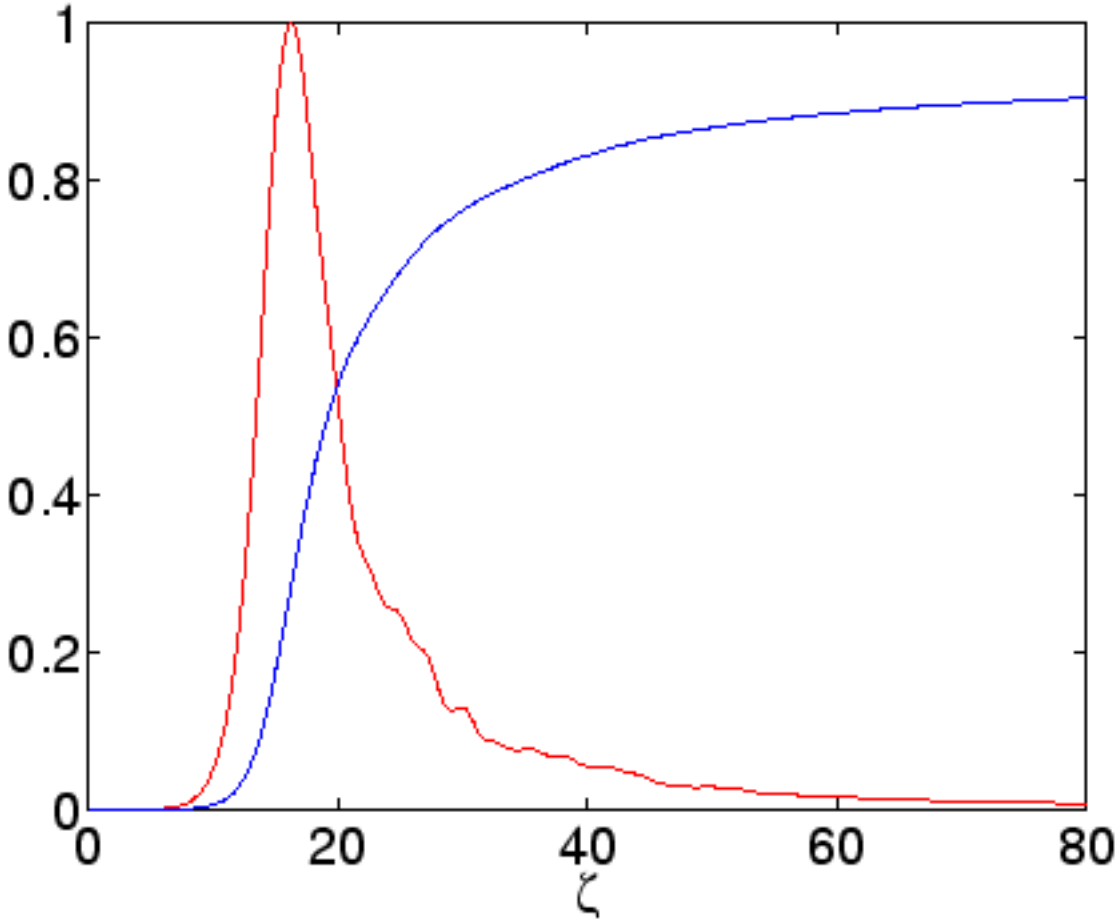
pulse: $(u_\xi/\max(u_\xi))^2 = \xi b^2/\max(\xi b^2)$ – red line,

pump: $(\cos(u/2))^2 = a^2/a_0^2$ – green line,

Langmuir: $(\sin(u/2))^2 = \frac{f^2\omega_p}{a_0^2\omega}$ – blue line.

The leading spike of the π-pulse wavetrain (where red and blue lines are close) is close to the 2π-pulse, $\tilde{u} \approx 4\,\mathrm{arctg}\left(\epsilon e^{\xi}/4\sqrt{2\pi\xi}\right)$, which maximum is located at $\xi_M \approx \ln(4\sqrt{2\pi\xi_M}/\epsilon)$. The portion of the total π-pulse energy contained in the leading spike is $I_1 \approx \dfrac{4}{\xi_M + 2}$; for $\epsilon = 0.1$, $I_1 \approx 0.53$

Extra benefit of near-breaking regime, $\omega_p \approx \omega_p^{br}$: the breaking suppresses secondary spikes

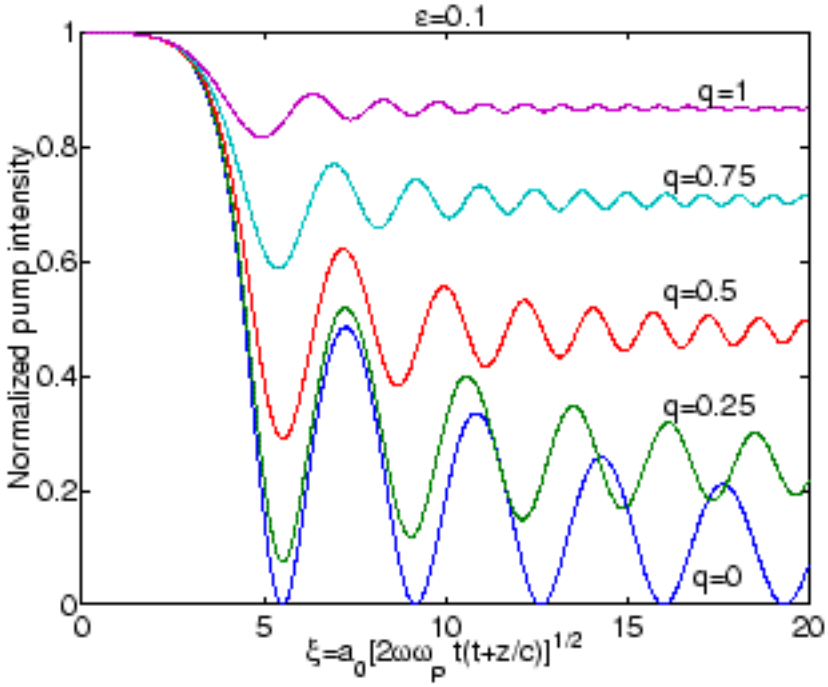


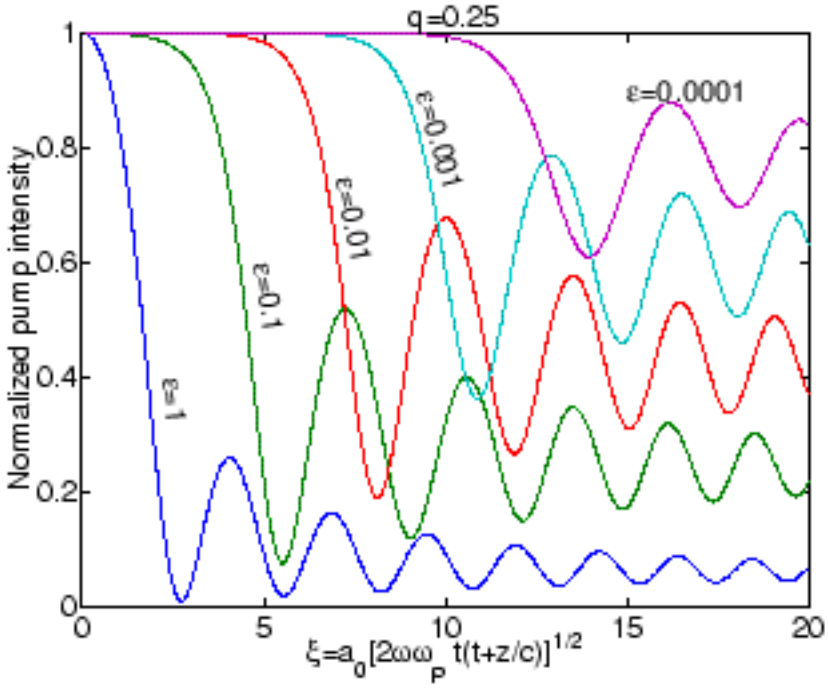
1D PIC simulation: almost 80% of the pump energy is in the single spike.

The pumped pulse normalized energy density – red line,

The pump depletion – blue line.

Detuned self-similar solutions





Small seeds do not deplete the pump => stability to noise.
For moderate seeds – high pumping efficiency.

EXAMPLES:

Wavelength of laser μm	1/40	1/4	1	10
Duration of pump ps	1.25	12.5	50	500
Intensity of pump W/cm^2	1.6×10^{17}	1.6×10^{15}	10^{14}	10^{12}
Pump vector-potential a_0	0.006	0.006	0.006	0.006
Laser-to-plasma frequency ratio	12	12	12	12
Concentration of plasma cm^{-3}	1.1×10^{22}	1.1×10^{20}	7×10^{18}	7×10^{16}
Linear e-times growth length cm	.00043	.0043	.013	.13
Total length of amplification cm	.018	.18	.7	7
Output pulse duration fs	1	10	40	400
Output pulse fluence kJ/cm^2	160	16	4	0.4
Output pulse intensity W/cm^2	1.6×10^{20}	1.6×10^{18}	10^{17}	10^{15}

Summary

- Raman compression in plasma for ultrahigh power
- Requires nonlinear effect
- Compton regime: wave breaking; pulse length shorter than plasma period
- Depletion regime: pulse length longer than plasma period; coherent interaction.
- Optimum regime: lower density to wave breaking limit
- Detuning enhancement: intensity selective noise filtering

Indicated Directions

- Focusing of high fluence laser output
  - No detuning
  - Detuning
  - Dispersion management
  - Ultrashort pulses

- Fast Igniter Physics
  - Relativistic propagation into “overdense plasma”
  - Damping, heat deposition, xray, energetic electrons
  - Note (Denavit) surprise: ion heating in intense laser on solid

- Effects of High Compression
  - $> 10^{21}$ W/cm^2 (γ=16) propagation and damping
  - $> 10^{23}$ W/cm^2 enhanced beta decay
  - $> 10^{25}$ W/cm^2 pair creation in dense plasma
    high compression of material
  - Magnetic field generation
  - Other uses for very short bursts (p-B^{11}?)

- Relativistic limit of compressor regimes?