# Backward Raman Amplification and Compression in Plasma

*Or, how exactly do we build exawatt-zetawatt laser?*

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IZEST: International Zettawatt-Exawatt Science and Technology Workshop
Ecole Polytechnique, Amphitheater Becquerel
Palaiseau, France
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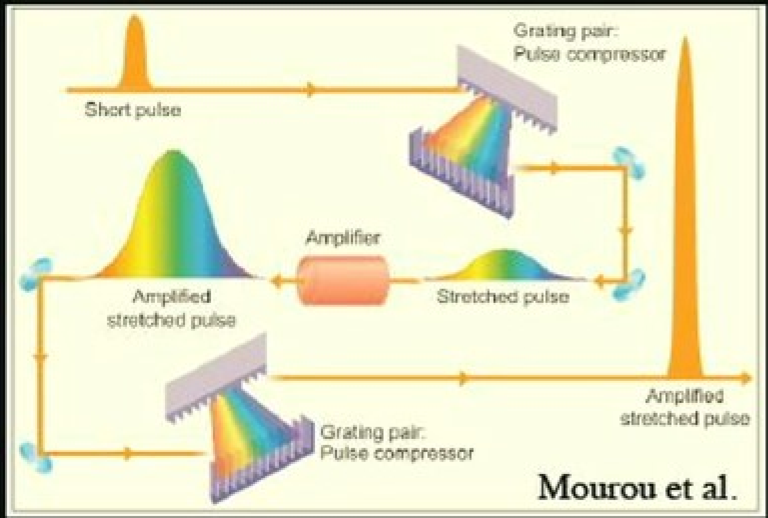
*Pulses of laser light can be compressed in time through resonant Raman backscattering in plasma.*

## Outline: Backward Raman Amplification and Compression in Plasma

1. Raman Compression of Lasers in Transient Regime
2. Opportunities in compressing micron light, experimental results
3. Next steps
4. Compression of x-rays, short wavelength optical
    a. Quasi-transient regime
    b. Moderately under-critical regime

Goal: Achieve next generation of light intensities

# Chirped Pulse Amplification: stretch, amplify, then recompress




Gratings for Petawatt ($10^{15}$ W) Laser

Limitations of CPA

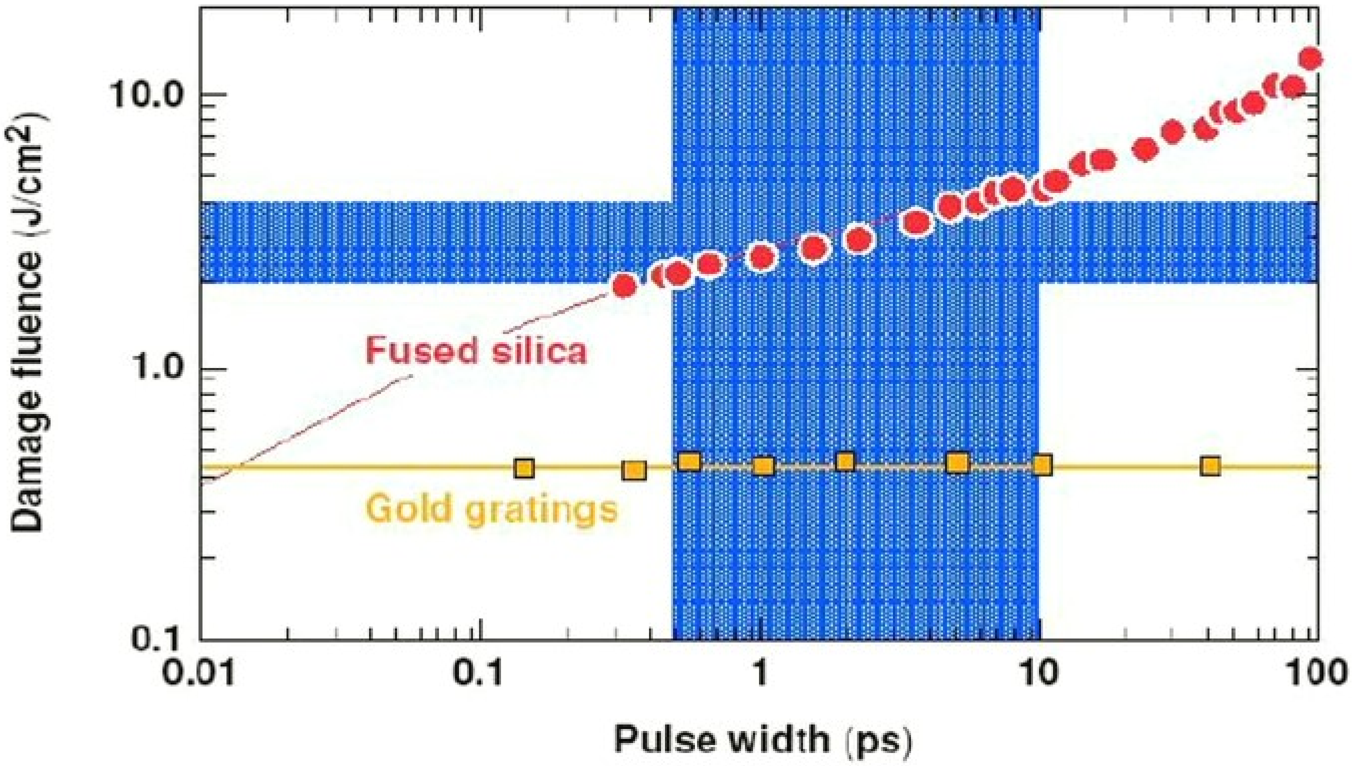
- Thermal damage to expensive gratings
- Requires broad-bandwidth high-fluence amplifiers

For PW

GW/cm$^2$ in amplifier → $10^3$ compression → TW/cm$^2$ < 10 ps → $10^3$ cm$^2$ gratings

Damage Thresholds

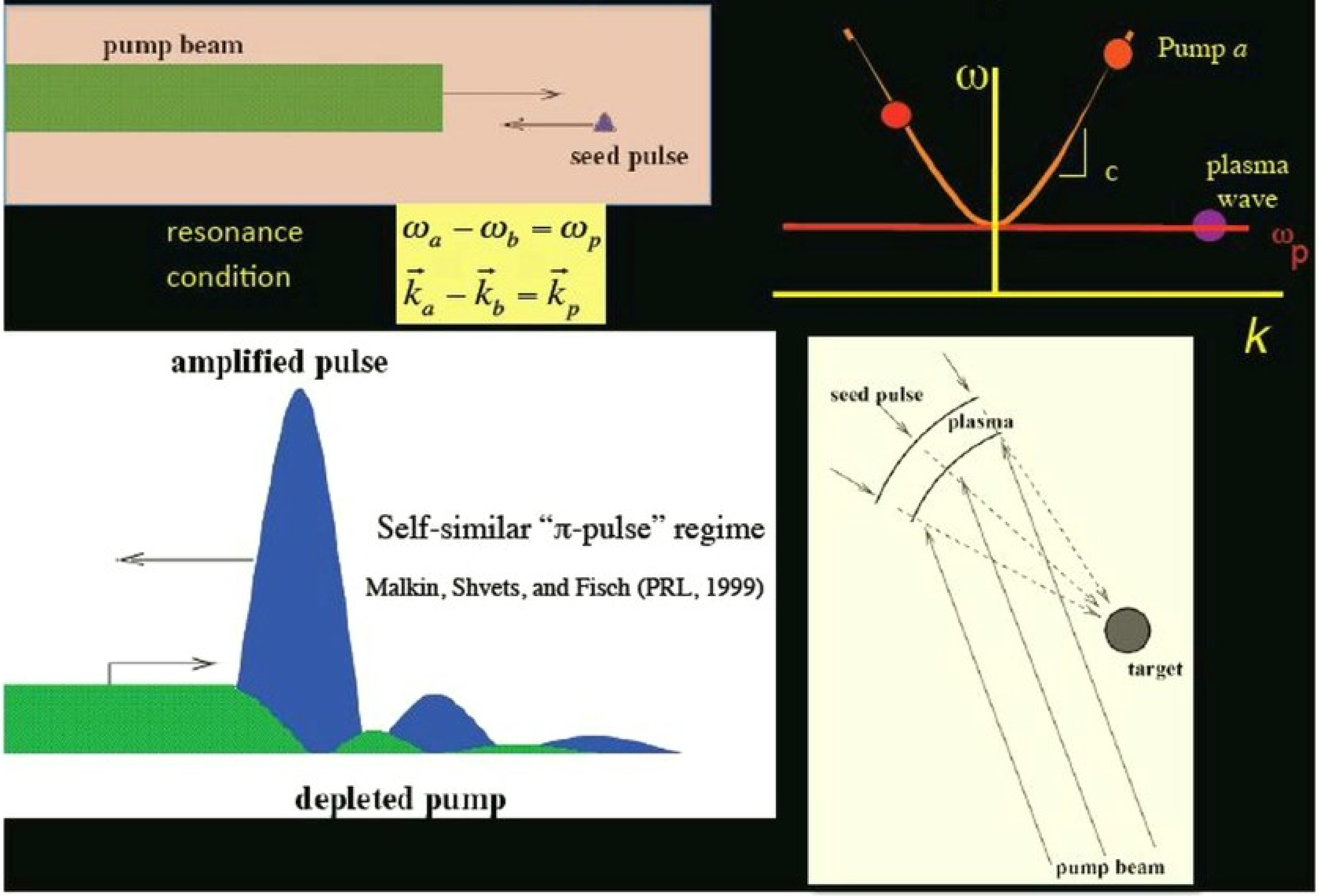
# Fused-silica damage threshold is between 2-4 J/$cm^2$ over the pulse widths of interest




G5607

B. C. Stuart *et al.*, J. Opt. Soc. Am. B 13, 459 (1996).

# Resonant Raman Amplification and Compression



# Fast Compression By RBS

$$a_t + c a_z = -V f b\ ,$$

$$f_t = V a b^*$$

$$b_t - c b_z = V a f^*$$

$$V = \sqrt{\omega_p \omega}\ /2$$

Malkin, Shvets, and Fisch, (PRL, 1999)

$$a \equiv \frac{eA_{\text{pump}}}{m_e c^2}, \quad b \equiv \frac{eA_{\text{pulse}}}{m_e c^2},$$

$f$ is normalized plasma wave amplitude

$$\omega >> \omega_p$$

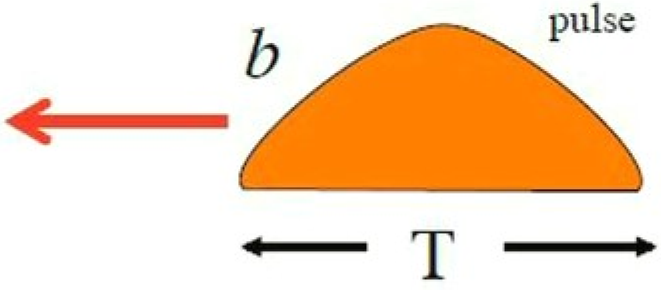
Self-similar solutions:

$b \sim t$

$T \sim 1/t$

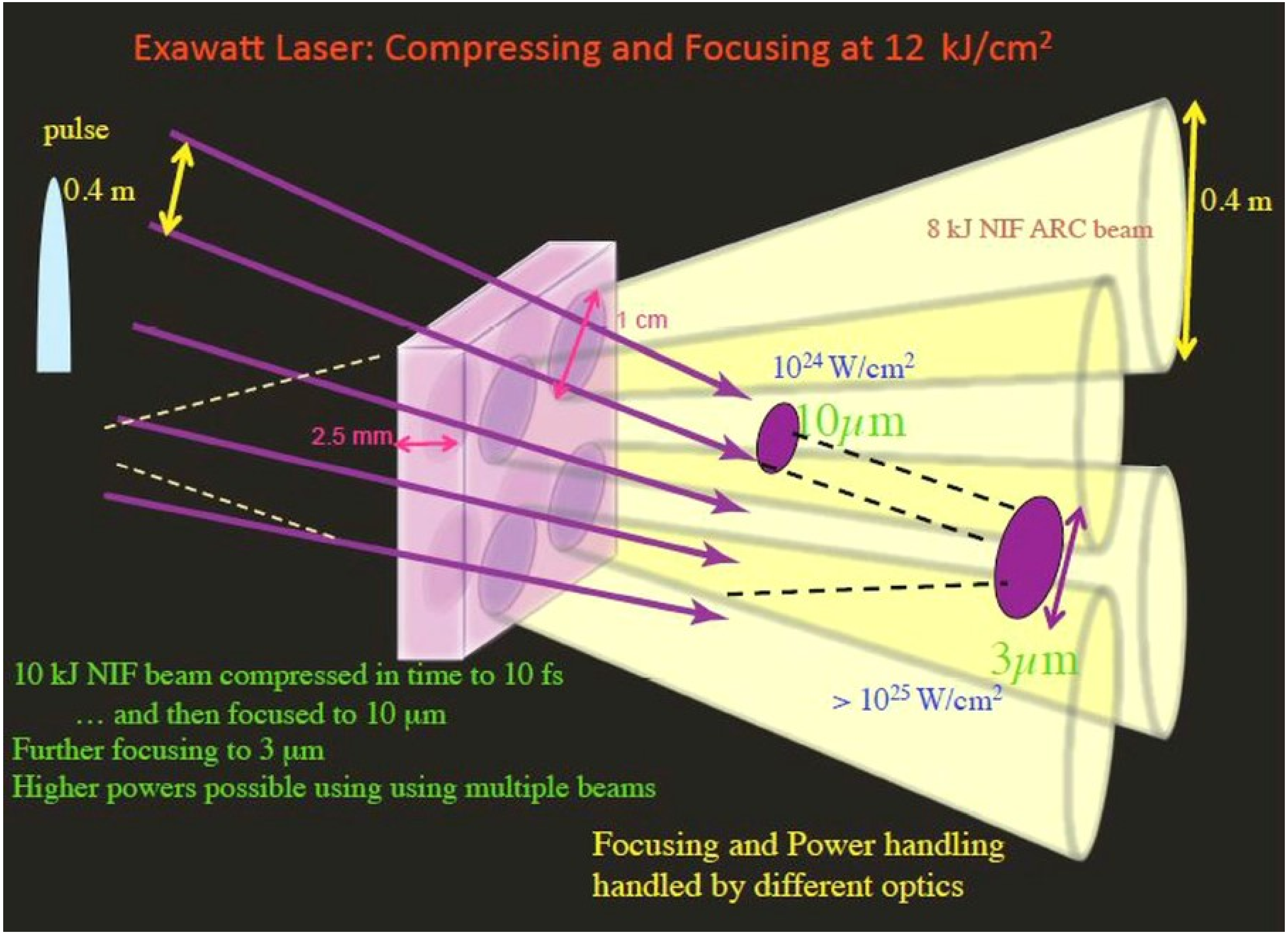
$E = b^2 T \sim t$

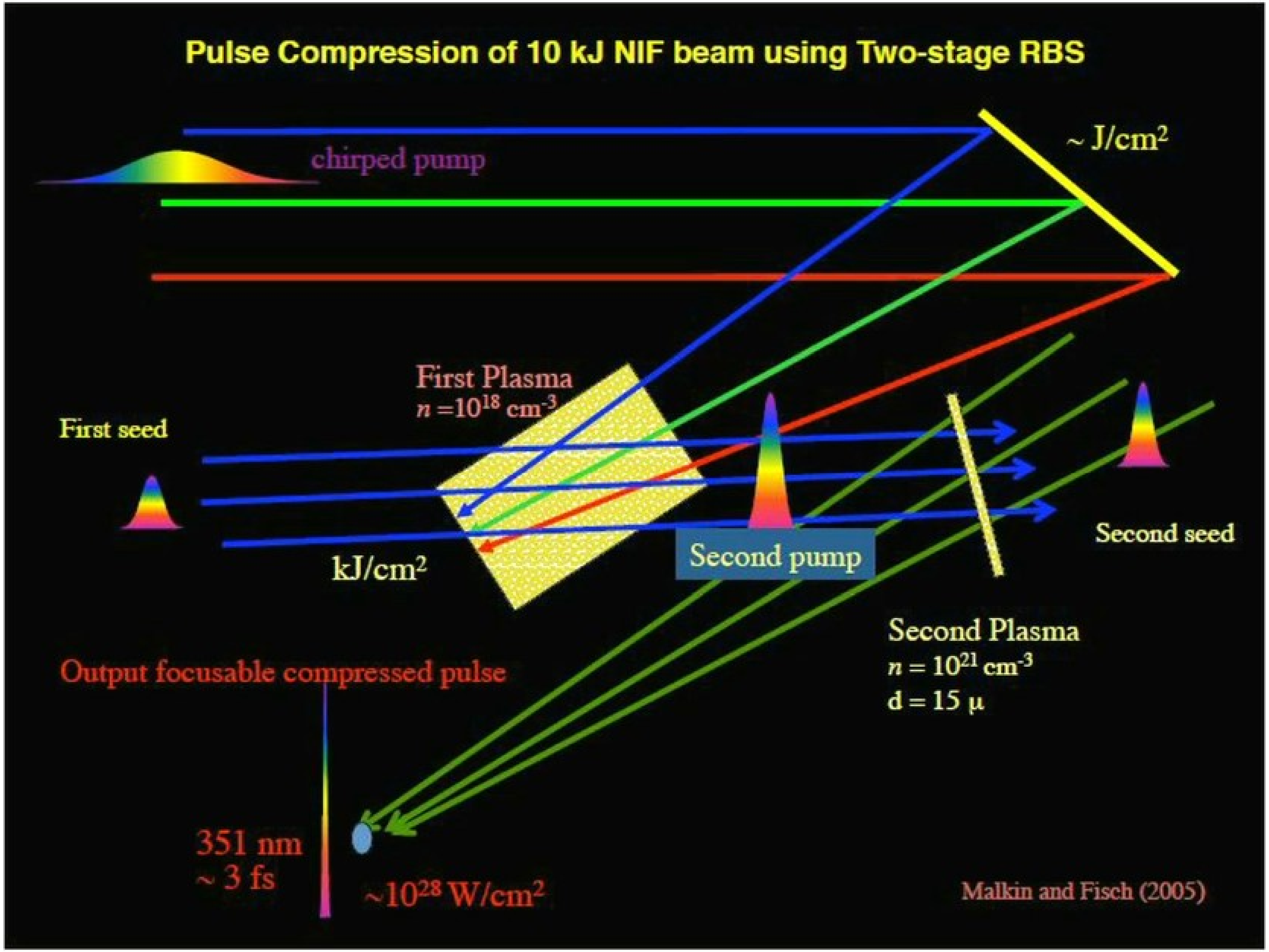
$z \sim t$



# Examples

| | | | | |
|---|---|---|---|---|
| Wavelength of laser $\mu$m | 1/40 | 1/4 | 1 | 10 |
| Duration of pump ps | 1.25 | 12.5 | 50 | 500 |
| Intensity of pump W/cm$^2$ | $1.6 \times 10^{17}$ | $1.6 \times 10^{15}$ | $10^{14}$ | $10^{12}$ |
| 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$^{-3}$ | $1.1 \times 10^{22}$ | $1.1 \times 10^{20}$ | $7 \times 10^{18}$ | $7 \times 10^{16}$ |
| 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$^2$ | $1.6 \times 10^{20}$ | $1.6 \times 10^{18}$ | $10^{17}$ | $10^{15}$ |


Exawatt Laser: Compressing and Focusing at 12 kJ/cm²
pulse
0.4 m
0.4 m
8 kJ NIF ARC beam
1 cm
2.5 mm
10²⁴ W/cm²
10μm
3μm
> 10²⁵ W/cm²
10 kJ NIF beam compressed in time to 10 fs
… and then focused to 10 μm
Further focusing to 3 μm
Higher powers possible using using multiple beams
Focusing and Power handling
handled by different optics

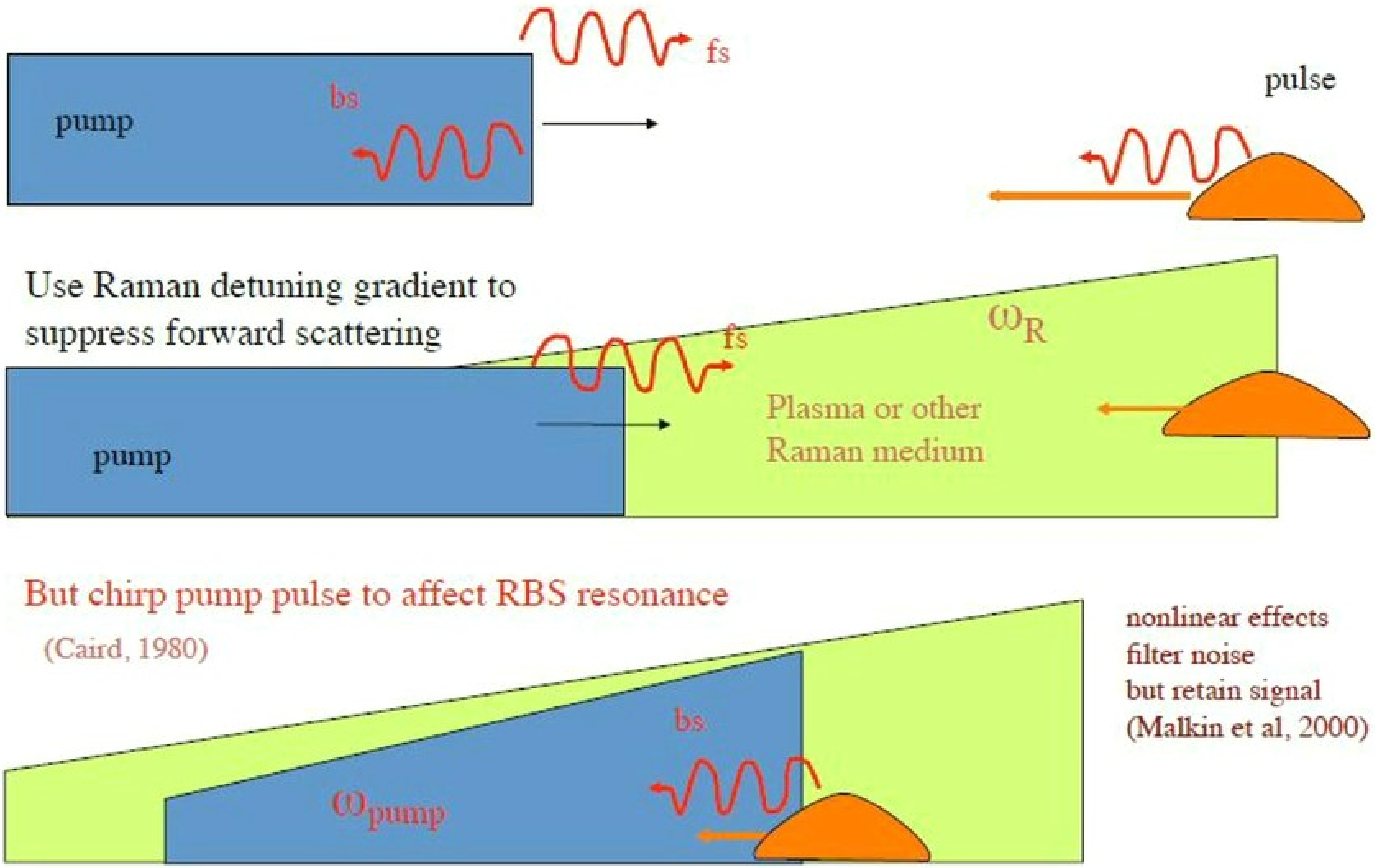

Pulse Compression of 10 kJ NIF beam using Two-stage RBS
~ J/cm2
chirped pump
First Plasma
n =1018 cm-3
First seed
Second seed
Second pump
kJ/cm2
Second Plasma
n = 1021 cm-3
d = 15 μ
Output focusable compressed pulse
351 nm
~ 3 fs
~1028 W/cm2
Malkin and Fisch (2005)

# Issues in Robust Compression

- Timing and coincidence of pulses
- Stability of pump and pulse to instabilities
- Quality of pump, seed pulse
- Variability of plasma density
- Retention of focusing upon entering and leaving plasma

Exploit: Resonance, Detuning, and Averaging
Employ: Density Gradient and Chirping

# Suppression of *unwanted* Raman Scattering

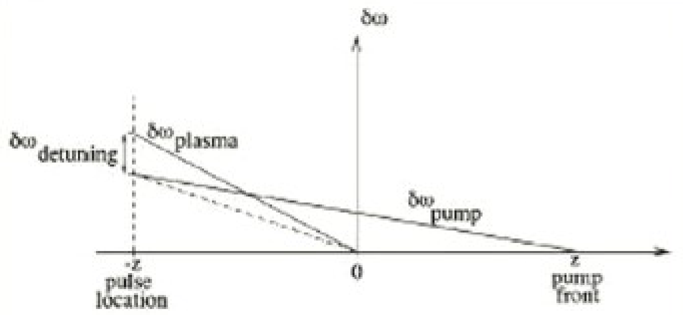


# Pulse Compression Detuning Solutions

$$a_\varsigma = -bf$$
$$b_\tau = af^*$$
$$f_\varsigma + ia_0^2 q\tau\, f = ab^*$$

$$\boxed{q = \frac{2\left(\omega_p' - 2\omega'\right)c}{a_0^2 \omega \omega_p}}$$

detuning factor



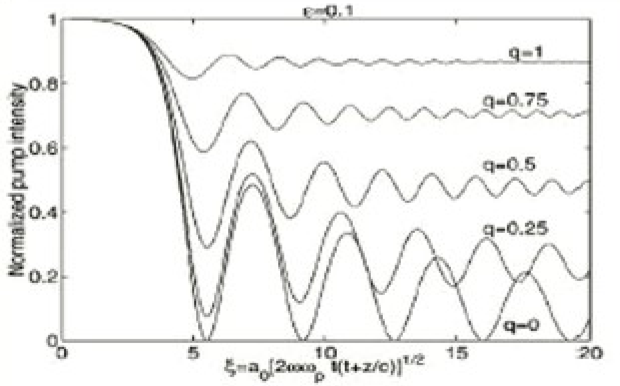

Partial compensation of the detunings caused by the pump chirp and the plasma density gradient.

Self-similar solution has the same form if both detuning and pump depletion are taken into account. Pulse compression is possible due to:

1. Nonlinearity, pump depletion.
2. Inhomogeneity, detuning.

$$b = a_0^2 \tau B\left(a_0^2 \varsigma \tau\right)$$
$$a = a_0 A\left(a_0^2 \varsigma \tau\right)$$
$$f = a_0 F\left(a_0^2 \varsigma \tau\right)$$

$$b_{\max} \sim \tau$$
$$\Delta\varsigma \sim 1/\tau$$

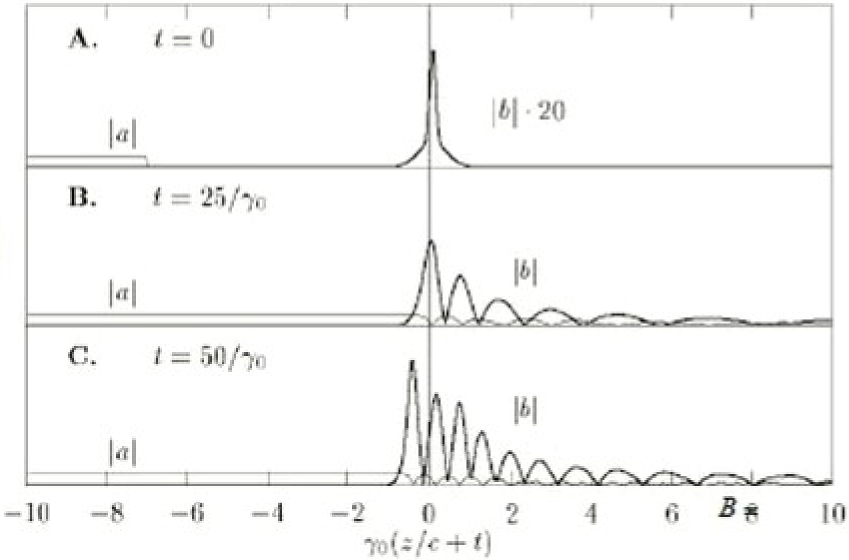



Reduced efficiency at high detuning factor

V. M. Malkin, G. Shvets, and N. J. Fisch, "*Detuned Raman Amplification of short laser pulses in plasma*", PRL 84, 1208 (2000).

## Detuning also may suppress superluminous precursors

a



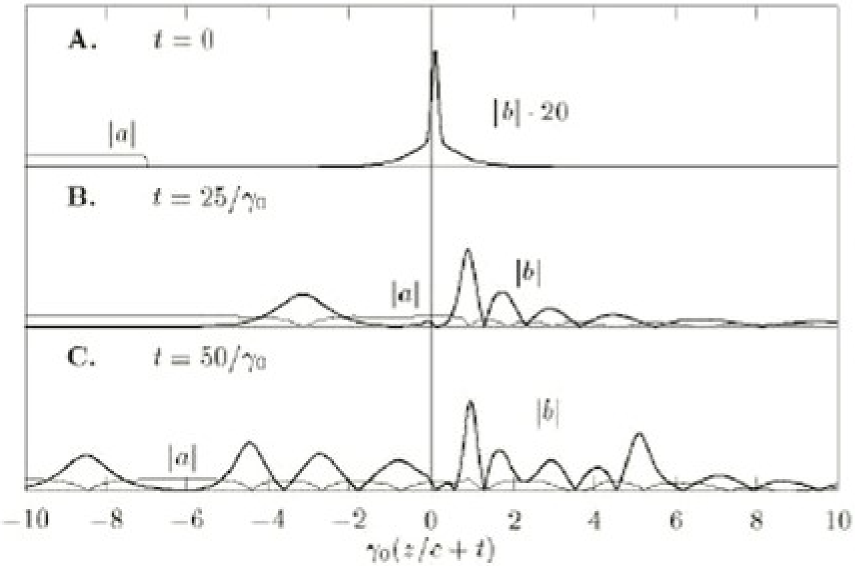

**Well-prepared seed pulse:**

$$B=\frac{a_0}{\sqrt{\pi}}e^{-100(z\gamma_0/c-0.1)^2}$$

Gaussian prepulse

$$\tilde{b}=\frac{0.2a_0}{\sqrt{\pi}}e^{-4(z\gamma_0/c-0.1)^2}$$

b




Not well-prepared seed pulse

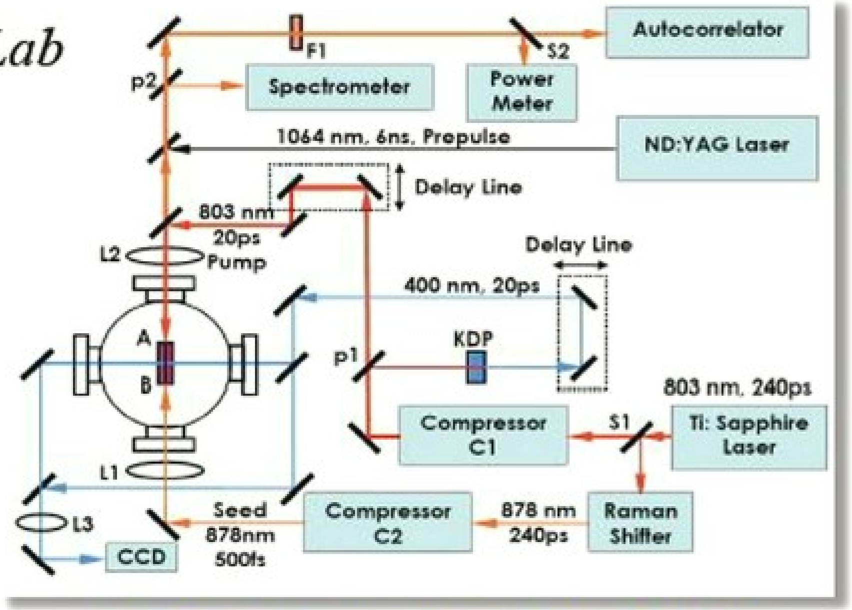
Exponential decay prepulse

$$\tilde{b}=\frac{0.2a_0}{\sqrt{\pi}}\cosh\left[2(z\gamma_0/c-0.1)\right]$$

Tsidulko, Malkin and Fisch (2001)

*Experimental setup in Suckewer Lab*

Pump Seed

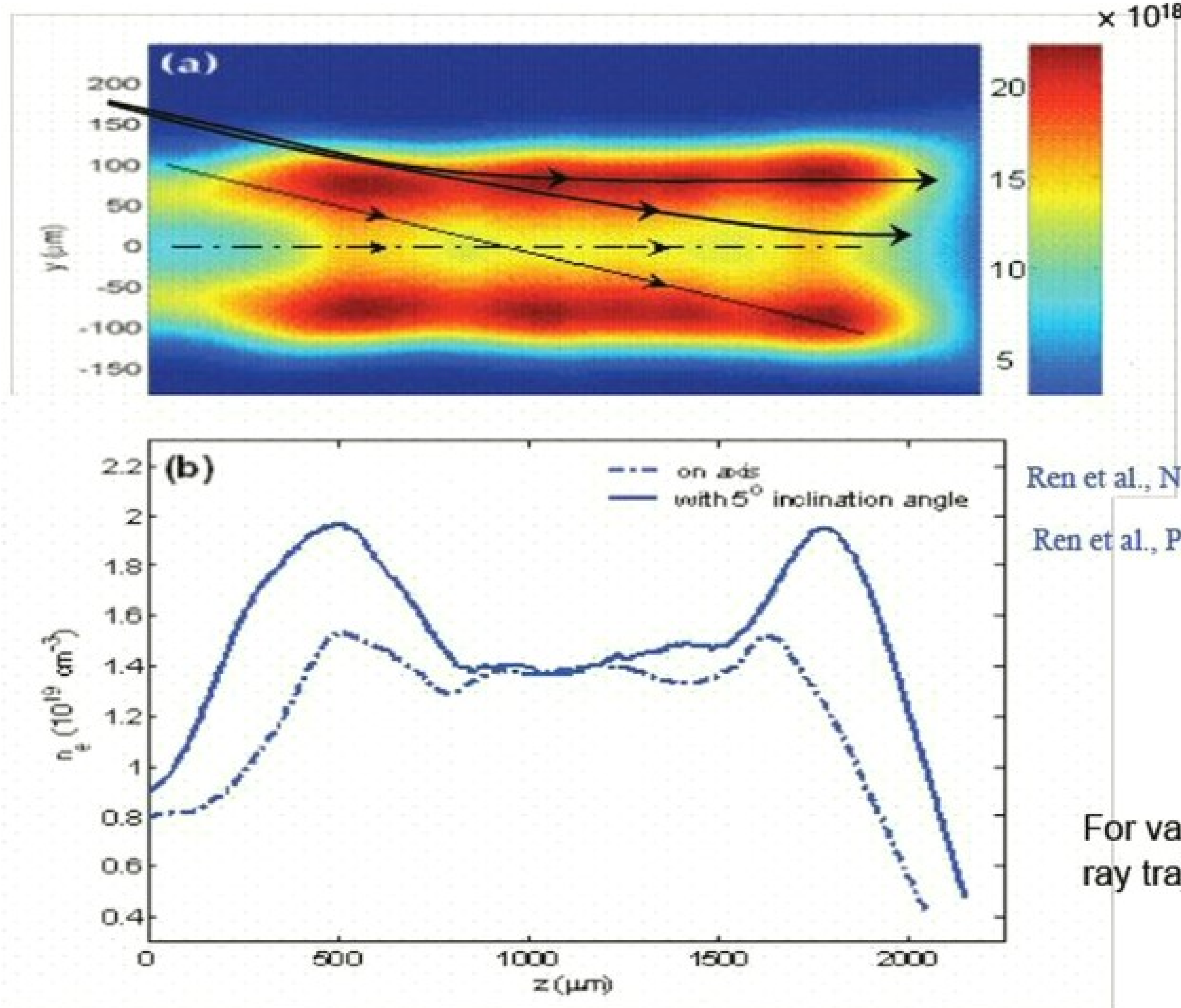



J. Ren, et al. Nature Phys. (2007); POP (2008).

*Typical parameters:*

| | | | | | |
|---|---|---|---|---|---|
| Plasma | $n \sim 1.5 \cdot 10^{19}$ cm$^{-3}$, | $\omega/\omega_p \sim 10$, | $L \sim 2$mm, | $T_e \sim 50$ eV | |
| Pump | $\lambda = 0.8$ μm,<br>$I \sim 2 \cdot 10^{14}$ W/cm$^2$, | $c/\gamma \sim 80$ μm,<br>$\Delta t \sim 20$ ps, | | W<150 mJ, | $d_\perp \sim 20$-55 μm |
| Input seed | $I \sim 10^{12}$ W/cm$^2$, | $\Delta t \sim 500$ fs, | $c\Delta t \sim 150$ μm | $W \sim 15$ μJ, | $d_\perp \sim 55$ μm |
| Output seed | $I \sim 10^{16}$ W/cm$^2$ | $\Delta t \sim 90$ fs, | $c\Delta t \sim 25$ μm, | $W \sim 1$-6 mJ, | $d_\perp \sim 15$ μm |

# Tilted Laser Experiments in Suckewer Laboratory




Ren et al., Nature Physics (2007)

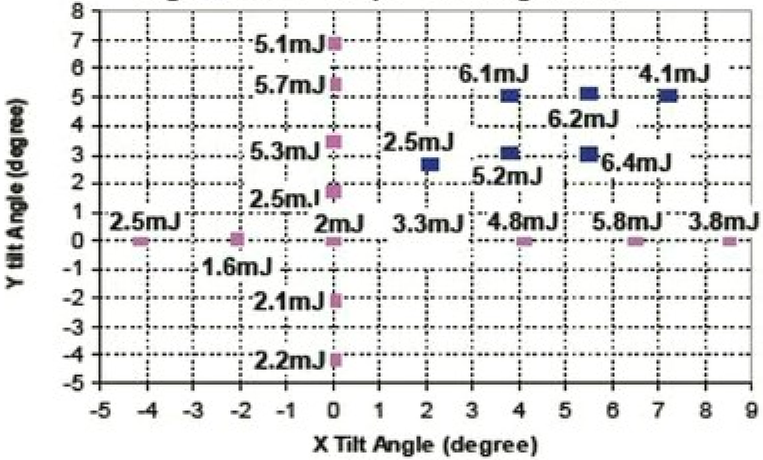
Ren et al., POP (2008)

For vacuum
ray trajectory

# Experiments with reversed chirp in Suckewer Lab

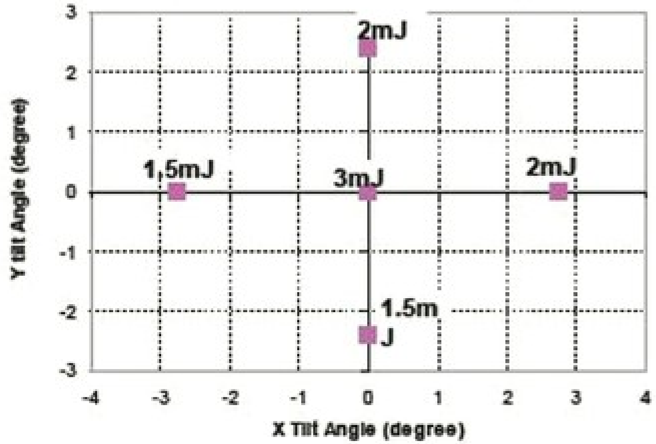
Ren et al., POP (2008)

Pump Energy ~100 mJ, 19ps
Input Seed ~ 16μJ 2mm plasma




Experiments with "regular" pump chirp

Pump Energy ~100 mJ, 19ps
Input Seed ~ 18μJ 2mm plasma

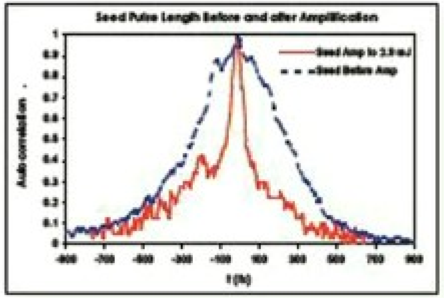


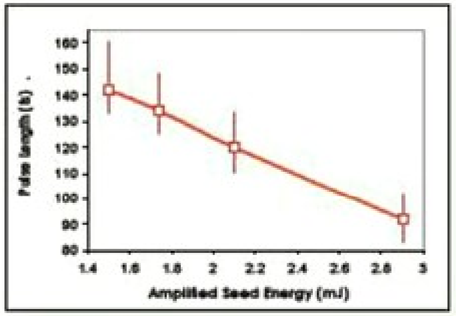

Experiments with "reversed" pump chirp

Flipping the sign of the pump chirp (red harmonic first instead of blue harmonics first) results in reduced efficiency of the amplification in the tilted experiments.

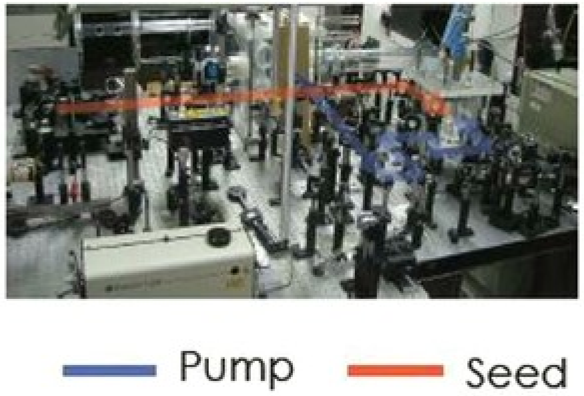
Demonstrates importance of detuning compensation in the experiment since now detunings add instead of compensating each other. Yampolsky et al., POP (2009)

# Reaching nonlinear self-similar regime (Suckewer)




Suckewer Lab




Factors of 100 in seed intensity over pump intensity

Decreased duration of the amplified pulse (50-90 fs)

Pedestal in the autocorrelation function evidences either precursors or secondary spikes

Duration of the amplified pulse decreases inversely with the pulse energy, as in nonlinear $\pi$-pulse solution regime

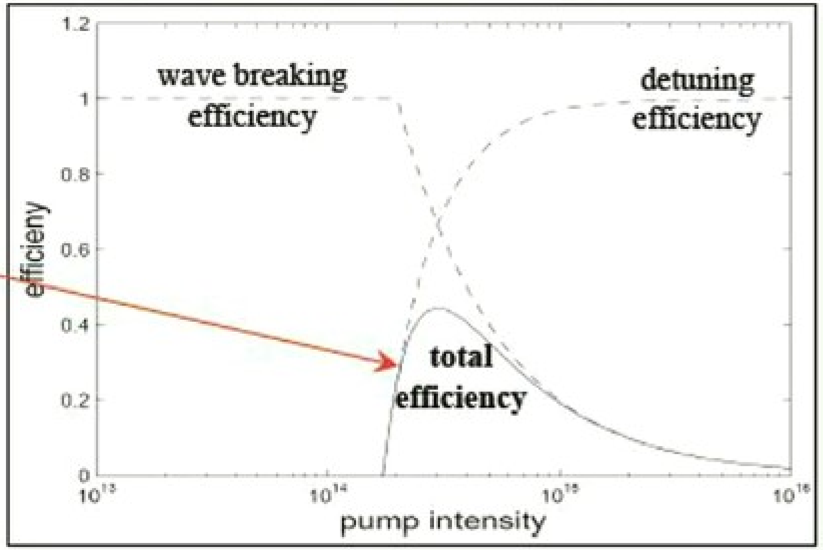
Large-- but still lower than theoretical maximum efficiency (up to 6.5%, but more adjusting for temporal and spatial overlap)

Amplification tends to saturate at high pump intensity.

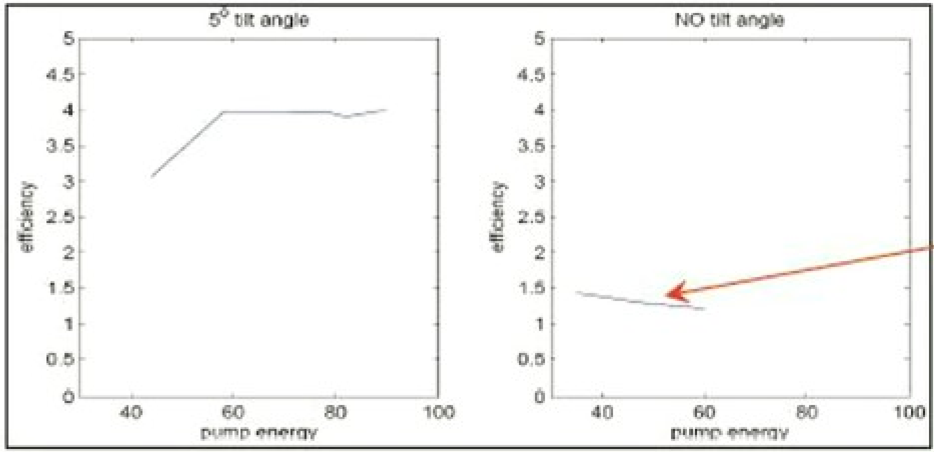
# Competition between detuning and wave breaking

Detuning reduces efficiency at small pump intensity since $q \sim 1/I_{pump}$

Plasma wave breaking limits efficiency at high pump intensity since scattering of only some pump energy ($I \sim 2 \cdot 10^{14}$ W/cm$^2$) can be supported by the plasma wave.




Yampolsky et al., 2008




Ren et al., POP (2008)

The apparent wave breaking regime at smaller pump energies in no tilt experiments might be caused by better focusability of the axial pump.

# Conclusions

1. Experiments now show seed intensities far exceeding pump intensities!
2. The average pump depletion rate in the interaction region is ~25% (overlap in cross section and channel length) *in axial case*. More in *tilted case.*
3. Limiting mechanisms could be *detuning* and *wave breaking*.
4. Detuning compensation is demonstrated experimentally in the reversed chirp experiments.
5. An intensity window is identified wherein wave breaking is limiting at high pump power and detuning at low pump power. Such a window is found experimentally.
6. The enhanced efficiency in tilted experiments is due to detuning compensation in the entrance-side (low pump intensity) region. In the exit-side region, either detuning is reduced due larger pump intensity (pump intensity window) or pump is refracted away from density gradient.

# *Compressing from nanoseconds to femtoseconds*

*Two step: compress using CPA to picoseconds and then using BRA to compress to femtoseconds.*

*C3 method: optimize first stage at about 20 picoseconds Mourou et al. (2011).*

*Step 1: Compress from 5 ns to 20 ps.*

*Use CPA*

*Note dielectric gratings withstand 5 $J/cm^2$*

*Step 2: Compress from 20 ps to 35 fs.*

$n = 2 \times 10^{19}$

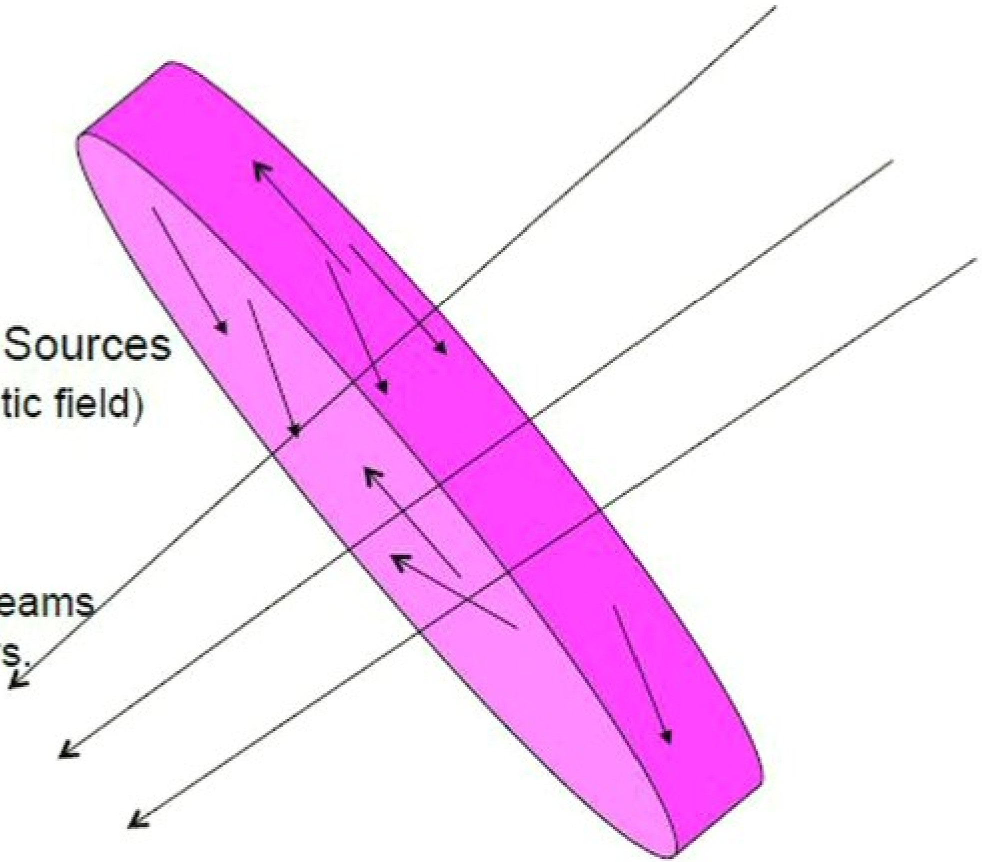
$L = 3$ mm

$E = 46\%$

*Issues in going from Joules to kilo-Joules*

# Some Issues in large Plasma Coupler

1. Sidescatter
2. Backscatter
3. Focusability



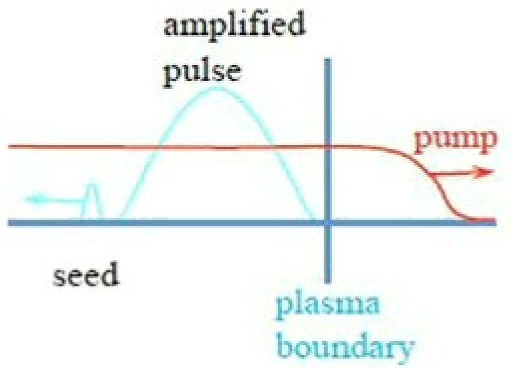
Possible (uniform) Plasma Sources

1. Ionize droplets (in magnetic field)
2. Ionize foam
3. Gas bag

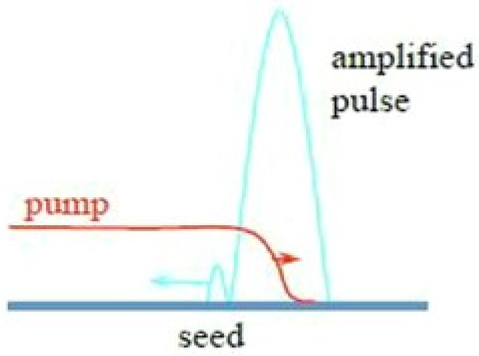
Alternative is to focus many beams from high aspect-ratio couplers.

# Group Velocity Dispersion

*Linear and nonlinear stages*

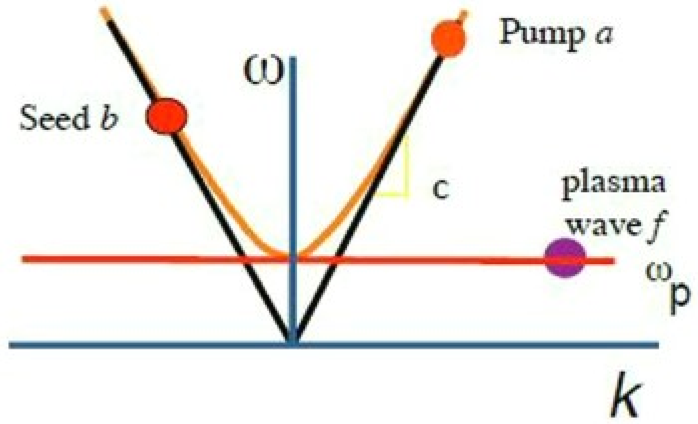



Amplified pulse stretches out due to limited bandwidth of the instability




Amplified pulse compresses due to spectrum broadening caused by nonlinear harmonic coupling

# Moderately under-critical plasma

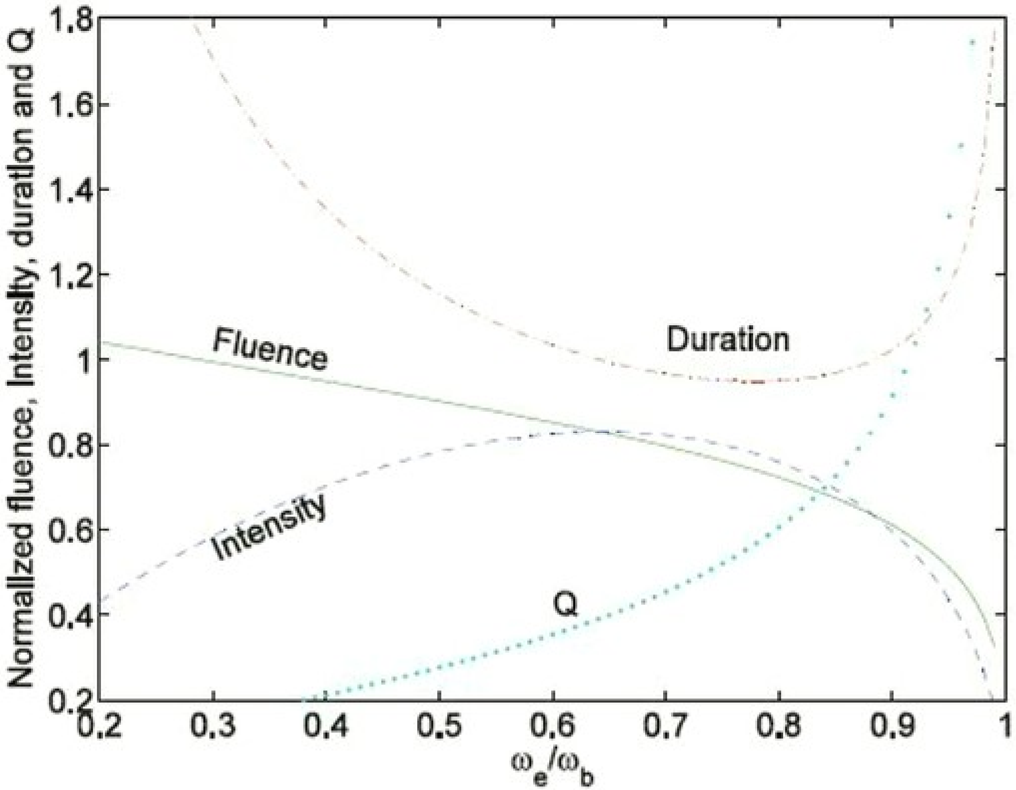



$$a_t + c_a a_z = V_3 f b$$

$$b_t - c_b b_z = -V_3 a f^* - i\kappa b_{tt} + iR\,|b|^2\, b$$

$$f_t = -V_3 a b^*$$

# Output intensity and fluence

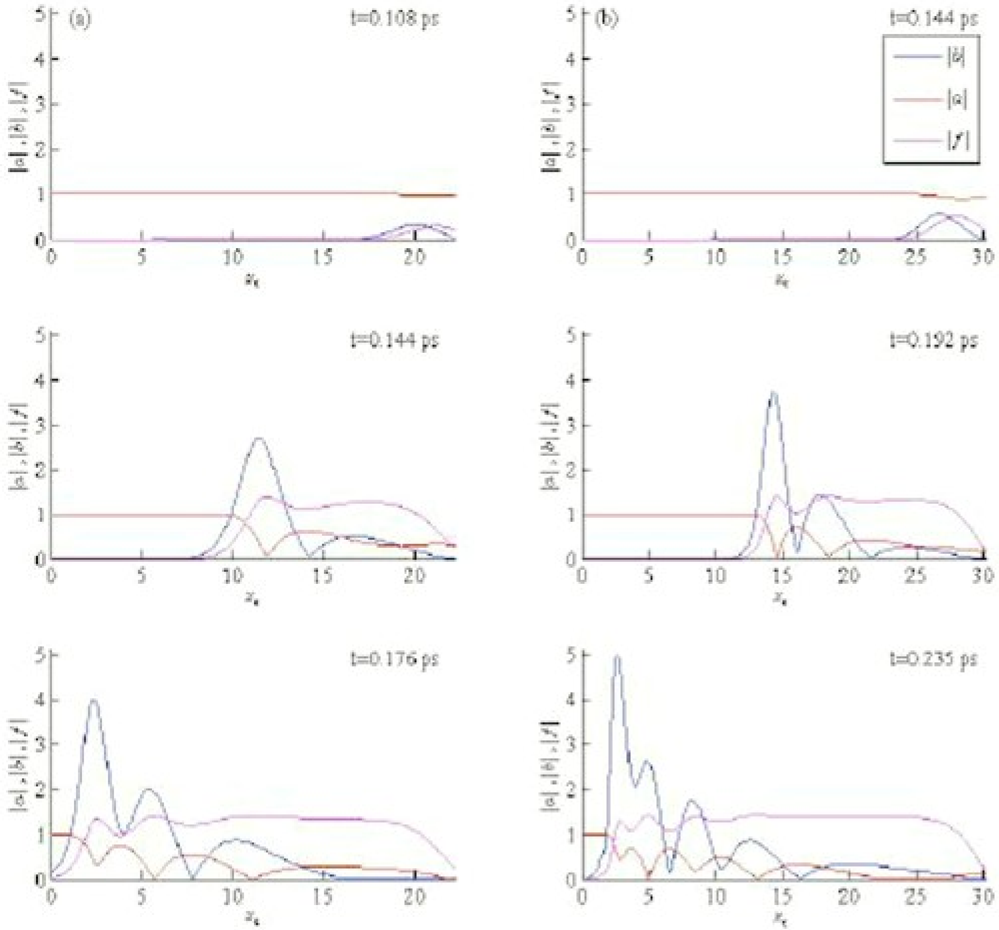



initial zero seed duration

$$Q = \frac{\delta_{dsp}}{\delta_{nl}}$$

Malkin, Toroker and Fisch (2011)

# *Group Velocity Dispersion with Seed Pulse Chirping*




No chirp

chirp

Chirping pulse increases intensity by 66%.

Toroker, Malkin and Fisch (2011)

# X-Ray Compression: *Quasitransient Regime*

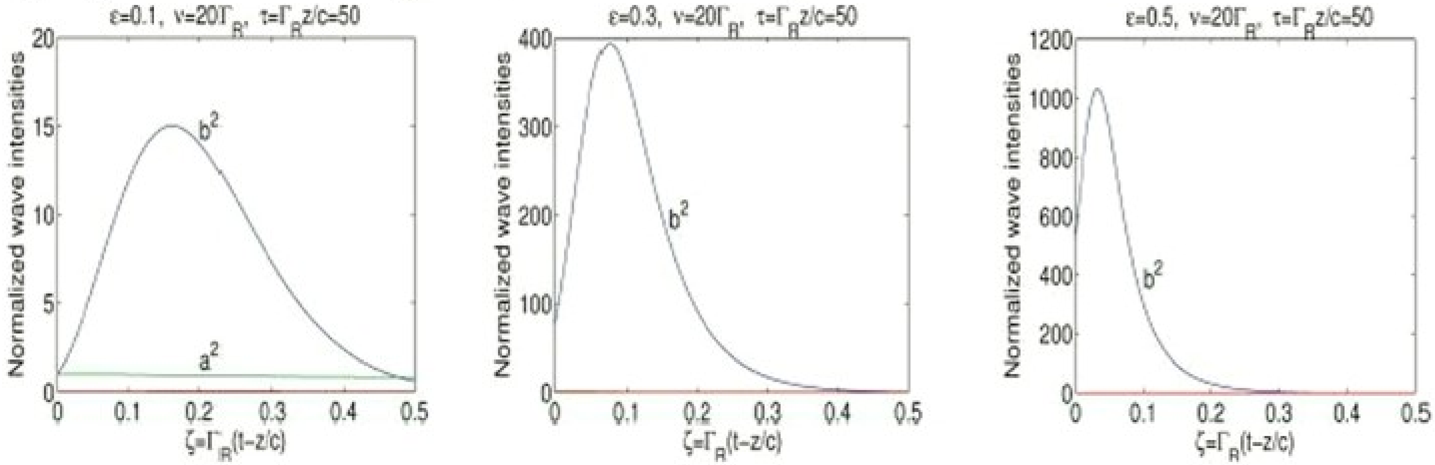
Malkin & Fisch, 2009

Amplified pulse $\sim e^{S(\mathbf{x},t)}$ , $S(z,t) \approx 2\Gamma_R \sqrt{\left(t - \frac{z}{c}\right)\frac{z}{c}} - \nu\left(t - \frac{z}{c}\right)$

*Quasitransient* regime: $\nu/\Gamma_R >> 1$
but leading edge is amplified where $\frac{\tilde{\nu}^2}{1+\tilde{\nu}^2} < \frac{z}{ct} < 1, \qquad \tilde{\nu} \equiv \frac{\nu}{2\Gamma_R}$

Pulse maximum now occurs closer to leading edge $\quad z = \frac{ct}{2}\left(1 + \frac{\tilde{\nu}}{\sqrt{1+\tilde{\nu}^2}}\right) \equiv z_M(t)$

Pump depleted even at $\nu/\Gamma_R = 20$, for intense enough seeds



# Laser energy vacuum breakdown

Suppose critical electric field $E_c$ =1.3 × 10$^{16}$ V/cm$^2$

Suppose laser compression and focusing to laser wavelength $\lambda$

then the energy located within the volume $\lambda^3$ would be

$$W_c \sim \lambda^3 E_c^{\,2}/8\pi \sim \lambda^3\ 8 \times 10^{18}\ \text{J/cm}^3$$

| | | | | | |
|---|---|---|---|---|---|
| $\lambda$ | 1 µm | 100 nm | 10 nm | 1nm | 1 Å |
| $W_c$ | 8 MJ | 8 kJ | 8 J | 8 mJ | 8 µJ |

Use MJ optical or mJ x-ray lasers?

Malkin, Fisch and Wurtele (PRE, 2007)

## Laser energy $W$ vs. $W_c$

| Device | NIF or LMJ | LCLS |
|---|---|---|
| $\lambda$ | 0.35 μm | 0.15 nm |
| $W$ | 2 MJ | 2 mJ |
| $W_c$ | 1/3 MJ | 1/40 mJ |
| $W/W_c$ | 6 | 80 |

However, current ideas of compressing soft x-rays utilize RBS in the "quasi-transient regime".

# Conclusions

1. Next generation increase in laser intensities will likely involve plasma step.
2. Experiments now show seed intensities far exceeding pump intensities!
3. Chirping pump, seed and plasma all have advantages. (Detuning compensation has been demonstrated experimentally).
4. Important next steps in backward Raman compression will involve larger lasers (cf. Jarozinski, 2012), and will encounter new issues.
5. Many uncertainties to retire in developing Exawatt-Zetawatt lasers, but so far no showstoppers are apparent.