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Numerical studies of nonlinear Raman amplification of laser pulses in Plasma

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Background

Why pulse amplification in plasma?

- Solid crystal: max. intensity 10^{12} W/cm^2
- Plasma: max. intensity 10^{17} W/cm^2

Main schemes

- Superradiant amplification: scattering off individual electrons [1]
- Raman amplification: scattering off a Langmuir wave [2]

[1] G. Shvets *et al.,* Phys. Rev. Lett. **81**, 4879 (1998).
[2] V.M. Malkin *et al.,* Phys. Rev. Lett. **82**, 4448 (1999).

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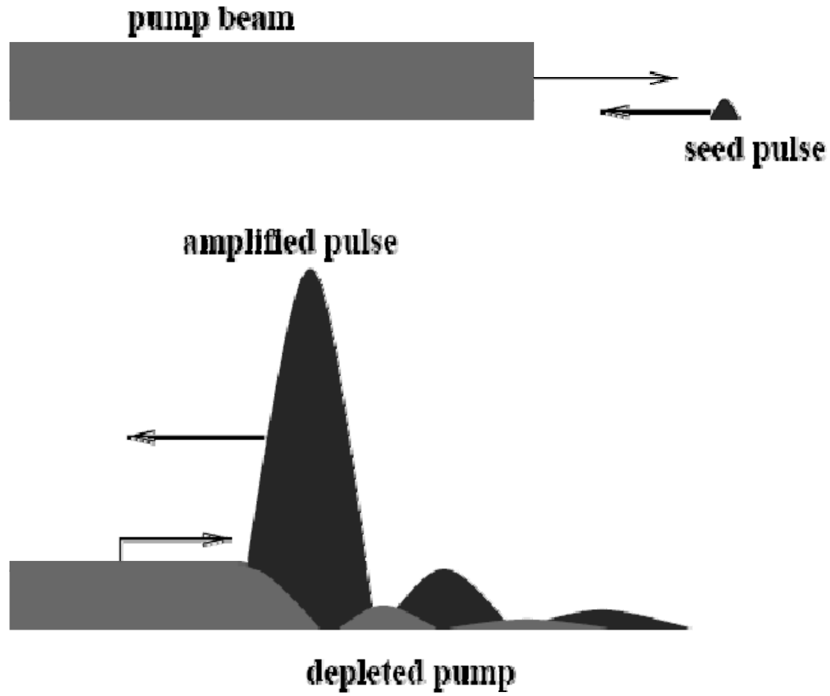
How it works

- A long laser pulse (pump) in plasma will spontaneously scatter off Langmuir waves (Raman scattering) or individual electrons (Compton scattering)
- Stimulate this scattering by sending in a short, counter propagating pulse at the frequency of the scattered light (seed)
- Because scattering happens mainly at the location of the seed, most of the energy of the long pump will go into the short seed: efficient pulse compression



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Best results to date

- 1-D simulations: up to ~$2 \cdot 10^{17}$ W/cm^2 [1], in agreement with early analytical predictions [3];
- 2-D simulations: up to $5 \cdot 10^{15}$ W/cm^2 in a homogeneous plasma on a ~10 μm spot, or $5 \cdot 10^{17}$ W/cm^2 in a ~6 μm guiding plasma channel [4];
- Experiments: ~$2.5 \cdot 10^{16}$ W/cm^2 on a 15 μm spot, in a ~40 μm guiding channel [5].

[3] V.M. Malkin *et al.,* Phys. Plasmas **7**, 2232 (2000).
[4] P. Mardahl *et al.,* Phys. Lett. A **296**, 109 (2002).
[5] J. Ren *et al.,* Nature Physics **3**, 732 (2007).

Promises

The following promises for the future have been made:

- From 10^{14} W/cm^2 in 50 ps to 10^{17} W/cm^2 in 40 fs on a 10x10 cm^2 spot, then focus down to 10^{25} W/cm^2 on a 10 μm spot [6]
- From 2×10^{12} W/cm^2 in 5 ns via 10^{17} W/cm^2 in 100 fs to 3×10^{18} W/cm^2 in 3 fs on a 0.6 cm^2 spot, then focus down to 2×10^{27} W/cm^2 on a 0.35 μm spot (or combine all 196 NIF beams to reach 4×10^{29} W/cm^2) [7]

Under the following assumptions:

- Existing weakly nonlinear theory can be scaled this far
- Conversion efficiency close to 100%
- Transverse effects on cm-size spots do not affect the process significantly (but this has never been investigated)

[6] N.J. Fisch and V.M. Malkin, Phys. Plasmas **10**, 2056 (2003).

[7] V.M. Malkin and N.J. Fisch, Phys. Plasmas **12**, 044507 (2005).

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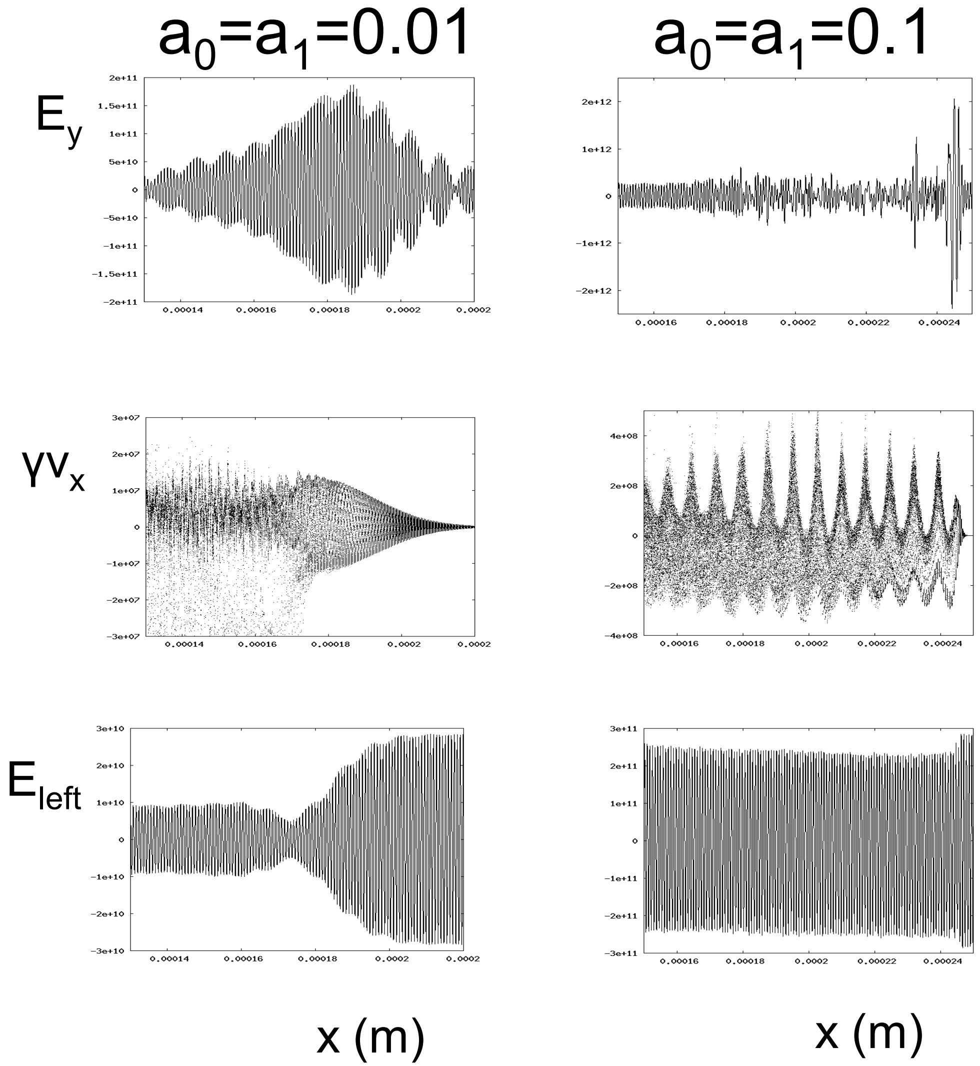
Nonlinear effects

The following will be discussed:

- Breaking of the RBS Langmuir wave
- RFS / modulational instability
- Gain narrowing
- Self-focusing and filamentation

The first two may limit the seed intensity, while the last two may limit the seed width

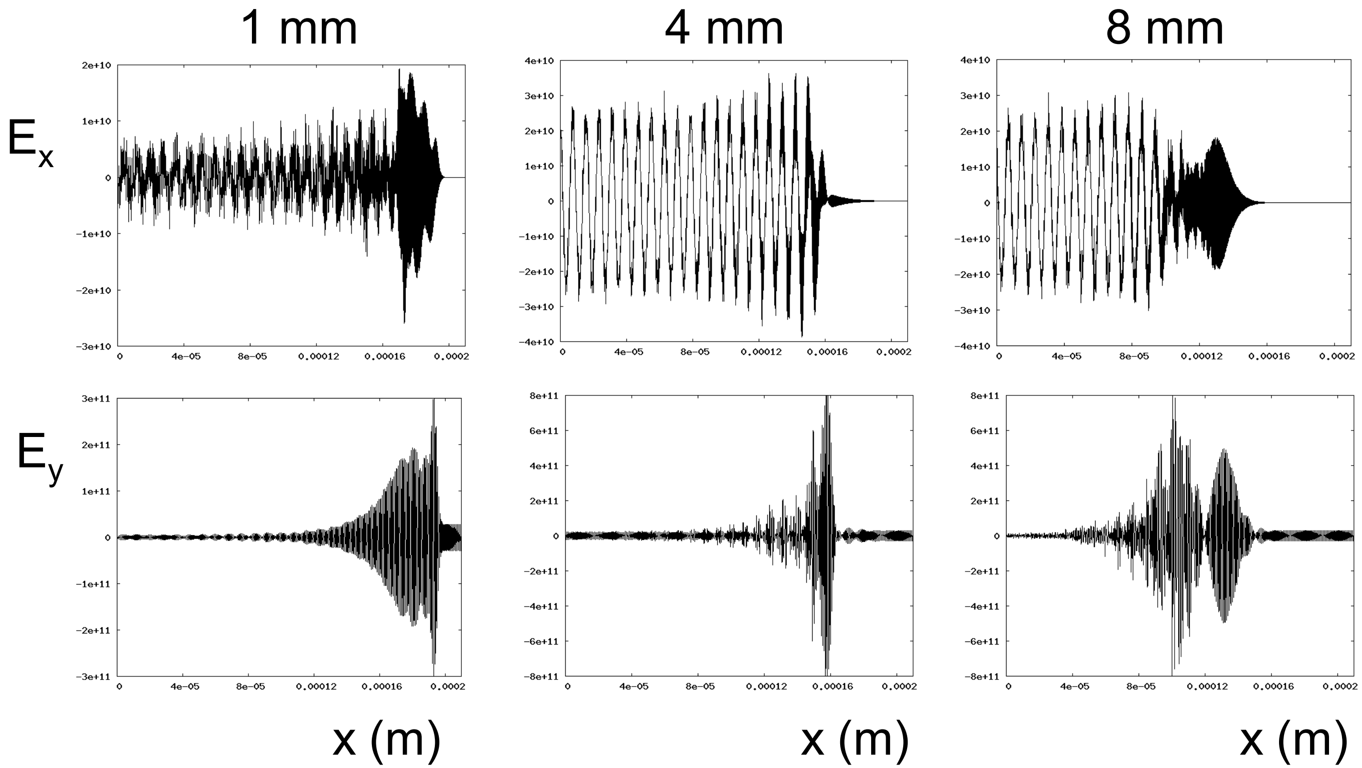
Langmuir wave breaking



RBS Langmuir wave couples pump and seed, but grows as seed grows and breaks eventually, so coupling vanishes

Shown is the interaction of 500 fs seed pulses with long pumps in a $1.75 \cdot 10^{19}$ cm^{-3} plasma after 1 mm.

RFS / modulational instability



Modulational instability seeds RFS. RFS scatters energy out of the seed, thus spoiling the amplification process. RFS moves with seed: you cannot escape!

seed: 50 fs, a_1 = 0.1;
pump a_0=0.01;
$n_0 = 1.75 \cdot 10^{19}$ cm^{-3}

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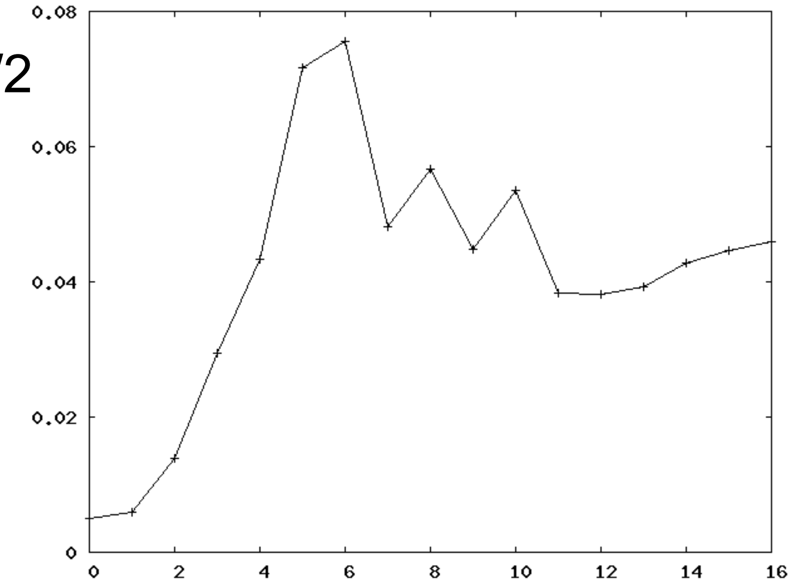
Saturation

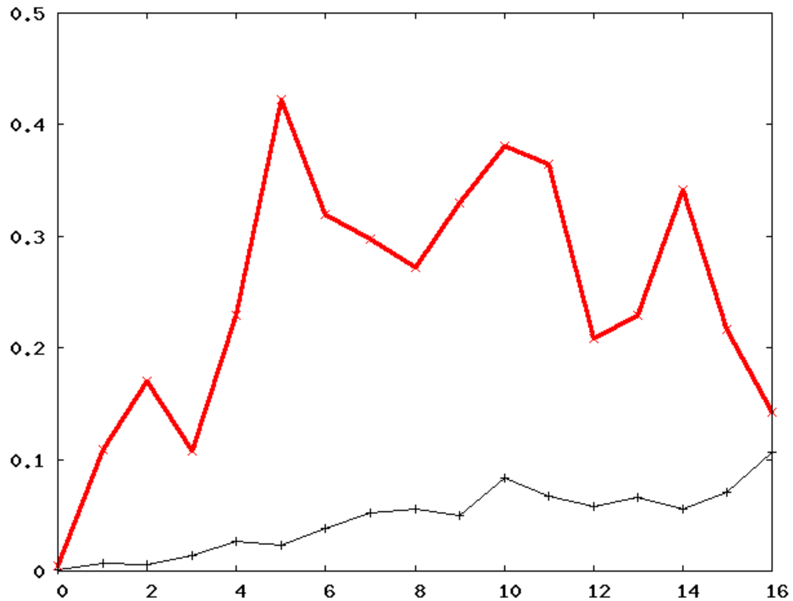
Raman amplification

$a_1^2/2$



seed: 50 fs, a_1 = 0.1;
pump a_0=0.1;
$n_0 = 1.75 \cdot 10^{19}$ cm^{-3}

Superradiant amplification [1]



red: high density ($1.0 \cdot 10^{19}$ cm^{-3})
→ saturation
black: low density ($2.5 \cdot 10^{18}$ cm^{-3})
→ poor energy transfer

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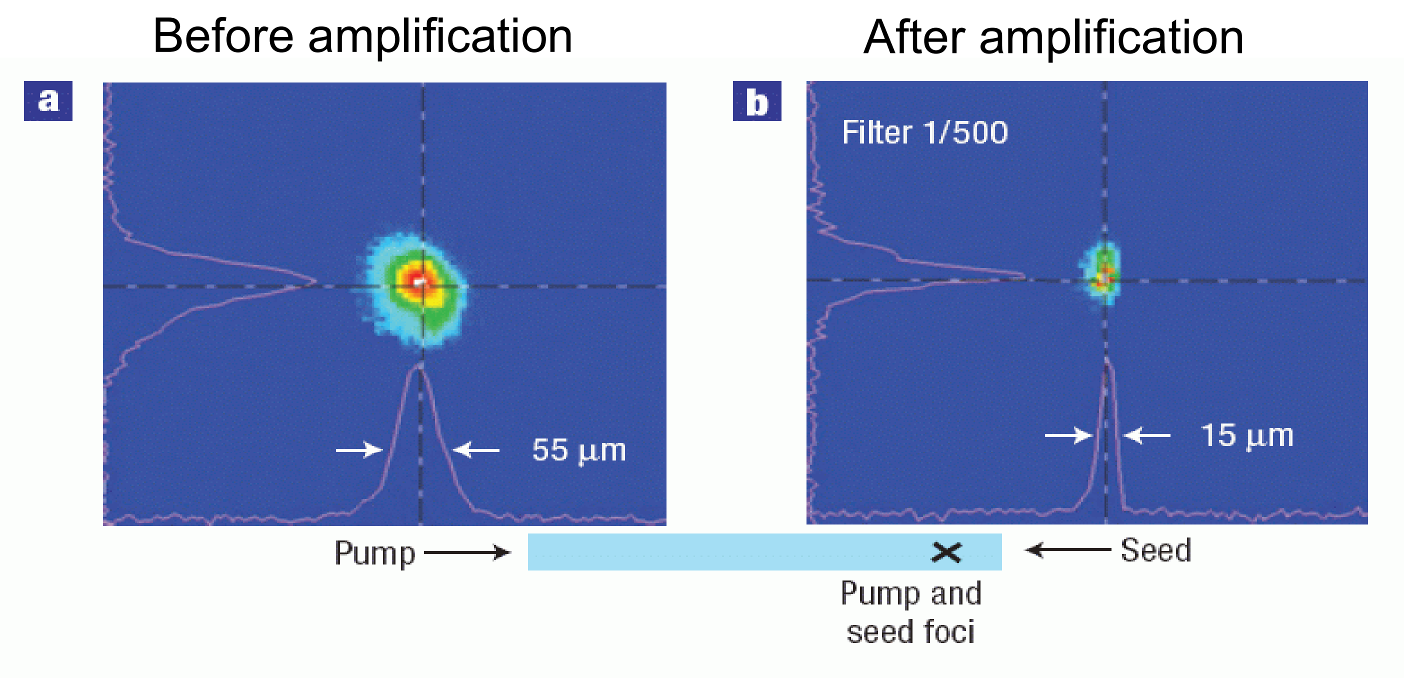
Gain narrowing

Seed centre has highest intensity and is amplified more strongly than the “wings”. This leads to an effective narrowing of the seed



Source: J. Ren *et al.,* Nature Physics **3**, 732 (2007).

Other effects

Self-focusing and filamentation

→Occurs above $17(\omega_0/\omega_p)^2$ GW, i.e. 1.7 TW for $\omega_0/\omega_p=10$, or 10^{17} W/cm^2 on a 50 micron spot

→Destroys the seed, so must be avoided at all cost

Premature RBS of pump

→May cause pump to deplete even before it meets the seed

→Might be reduced by chirping the pump

Non-solutions

RBS grows faster than RFS, filamentation, etc.

→ RFS and filamentation move with the seed, so have all the time in the world

→ Amplification of 50 ps to 5 ns pulses proposed, so enough time for instabilities to grow

Use lower plasma density, or density gradient, to suppress instabilities

→ Energy transfer efficiency goes down

Use chirped pump to suppress premature RBS

→ Need a short pulse to produce a long chirped pump, which can then be recompressed to a short pulse… this is leading nowhere

Solutions

Langmuir wave breaking

→ Amplify in superradiant regime (no Langmuir wave)

RFS and self-modulation

→ Limit seed power to ~10^{17} W/cm^2 ; use limited interaction length

Gain narrowing

→ Use “top hat” pulses (both pump and seed)

Self-focusing and filamentation

→ Seed power below self-focusing threshold; use “top hat” pulses

Pump depletion to premature RBS

→ Use low-intensity pump of moderate length

Everything points to use of wide pulses of limited length and duration. However, effects of using centimetre-wide pulses are hardly investigated at all, so still a lot of work to do here

Conclusions

–Works well for moderate intensities and pulse widths, but…

–Will only become competitive for much higher intensities/widths

–This regime is dominated by various nonlinear effects that have hardly been investigated at all

–Simple extrapolation not possible…

–So we need to do a lot more work to make this happen