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Intense laser pulses for inertial fusion and high-energy density physic

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Intense laser pulses for inertial fusion and high-energy density physics

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R. Trines, F. Fiúza *et al.*, Nature Physics **7**, 87 (2011)
R. Trines, F. Fiúza *et al.,* Phys. Rev. Lett. **107**, 105002 (2011)

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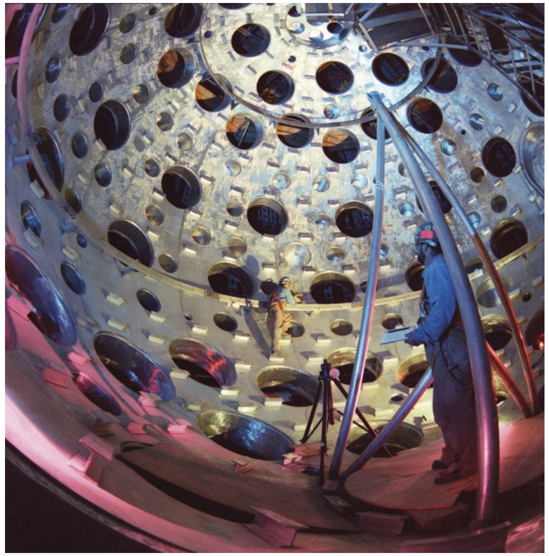
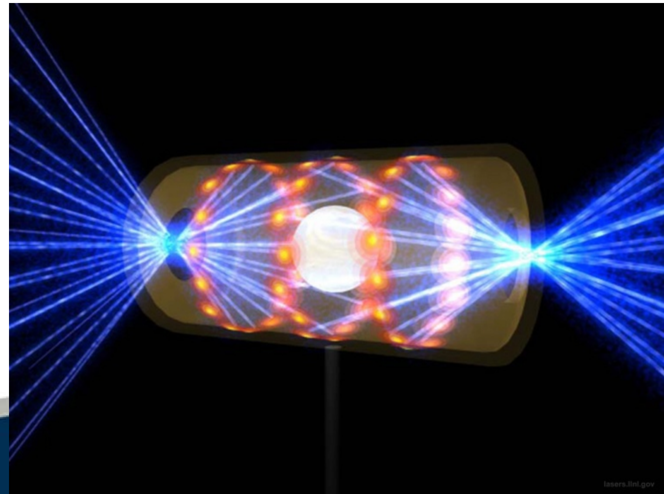




If it could only be more compact...

Background

Pulse compression in plasma, or: making an instability work for you

Why pulse compression in plasma?

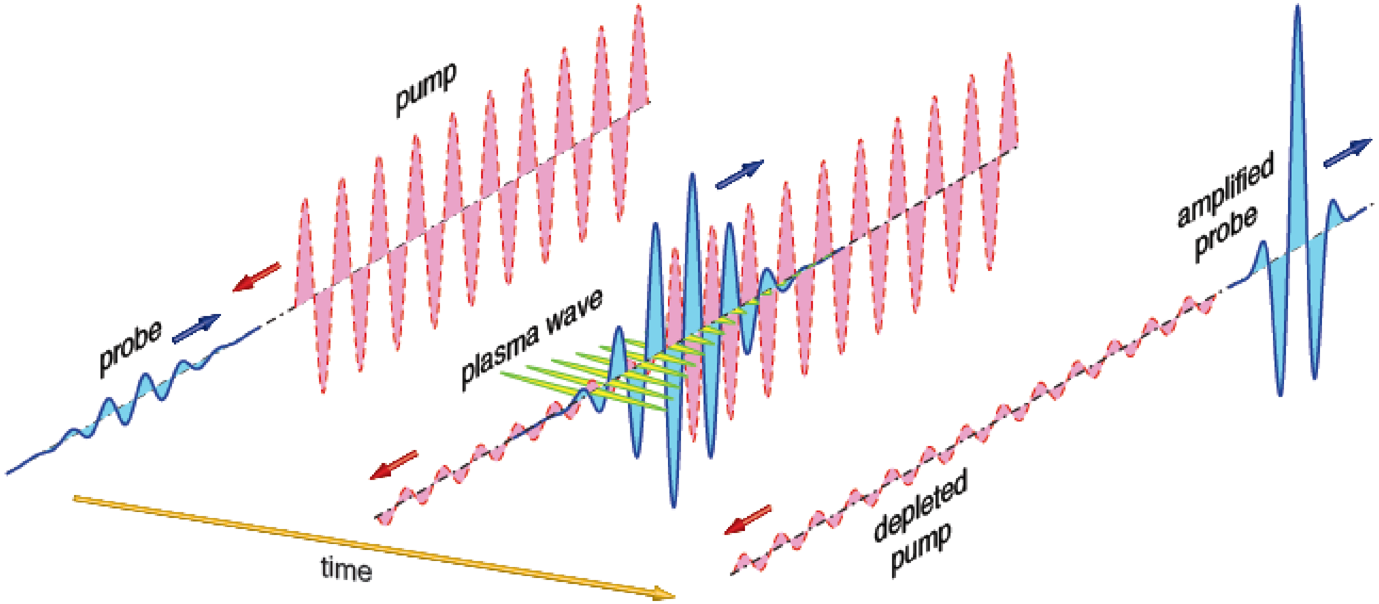
- Solid optics: max. intensity 10^{12} W/cm^2
- Plasma: max. intensity 10^{17} W/cm^2 [1,2]

Promises:

- Visible light: $10^{25} – 10^{27}$ W/cm^2 [3,4]
- X-rays: 10^{29} W/cm^2 [5]

[1] G. Shvets *et al.,* Phys. Rev. Lett. **81**, 4879 (1998).
[2] V.M. Malkin *et al.,* Phys. Rev. Lett. **82**, 4448 (1999).
[3] Fisch & Malkin, PoP **10**, 2056 (2003).
[4] Malkin & Fisch, PoP **12**, 044507 (2005).
[5] Malkin, Fisch & Wurtele, PRE **75**, 026404 (2007).

How it works



A long laser pulse (pump) in plasma will spontaneously scatter off Langmuir waves: Raman scattering

Stimulate this scattering by sending in a short, counter propagating pulse at the frequency of the scattered light (probe pulse)

Because scattering happens mainly at the location of the probe, most of the energy of the long pump will go into the short probe: efficient pulse compression

Miniature pulse compressor

Solid state compressor (Vulcan)

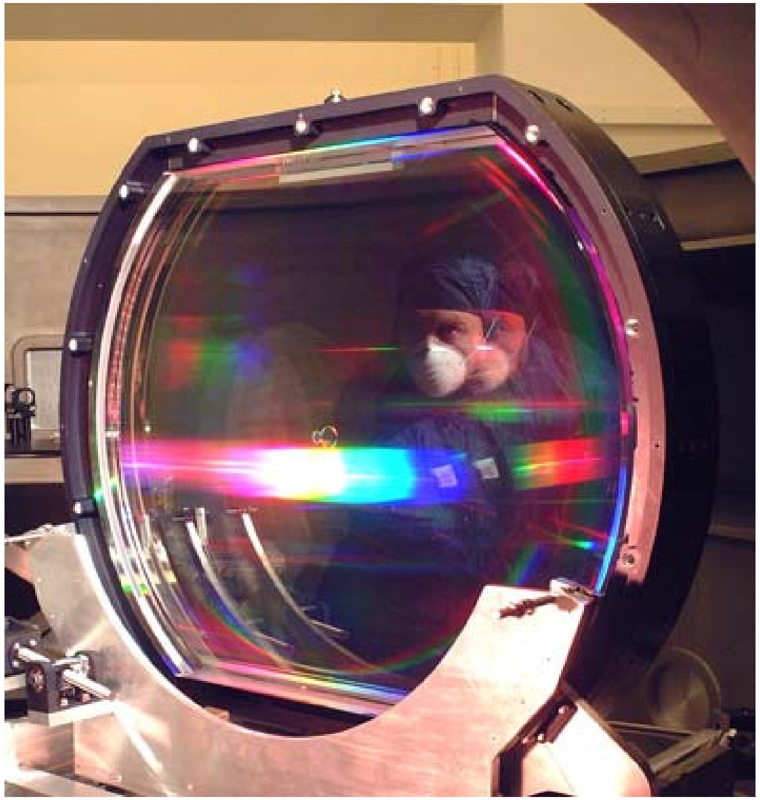
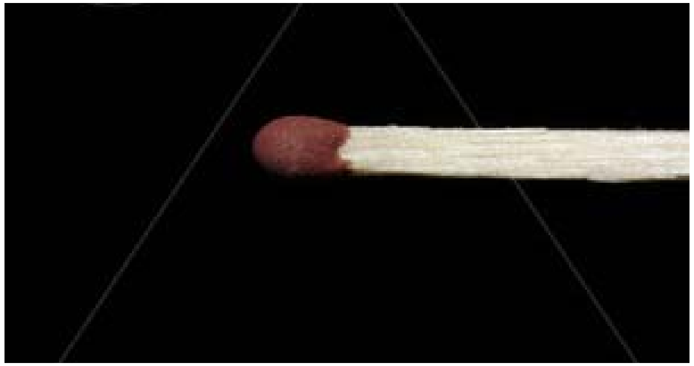


Image: STFC Media Services

Volume of a plasma-based compressor



A brief history

- 1998-99: First papers by Shvets, Fisch, Pukhov, Malkin (Princeton)
- 2001-02: First dedicated PIC development and simulations (XOOPIC at UC Berkeley)
- 2003-10: 2-D full-PIC abandoned in favour of 1-D PIC with averaged fields, or 1-D fluid simulations
- 2008-now: PIC codes pressed back into service
- 2004-now: Experimental campaign at Princeton
- 2007-now: Experimental campaign at Livermore

Actively being studied by many groups: Princeton, LLNL, UCB, U. Strathclyde, LULI/U. Bordeaux, South Korea, LANL, Taiwan...

Boosting the pulse energy

- High power = (high intensity)*(large spot)
- High energy = (high power)*(long duration)

- High intensity: studied by “almost everyone” (theory, simulations, experiments)
- Large spot: few results (theory mostly1-D; some quasi-2D fluid simulations; LLNL experiments); see [6] for details
- Long duration: only Clark & Fisch, and not even for the probe pulse [7]

[6] R. Trines, F. Fiúza *et al.*, Nature Physics **7**, 87 (2011).
[7] D. Clark and N. Fisch, Phys. Plasmas **9**, 2772 (2002); *ibid*. **10**, 4837 (2003)

High intensity

Analytic theory: many 1-D models, limited 2-D/3-D effects, mostly Princeton (Malkin, Fisch et al.). Predict 10^{17} Wcm^{-2} and beyond

Simulations:

1-D fluid (MBRS at Princeton, F3D at Princeton/Livermore)

1-D PIC (XOOPIC at UC Berkeley, aPIC at UCB and South Korea, Zohar at Princeton/Livermore).

All predict 10^{17} – 10^{18} Wcm^{-2}

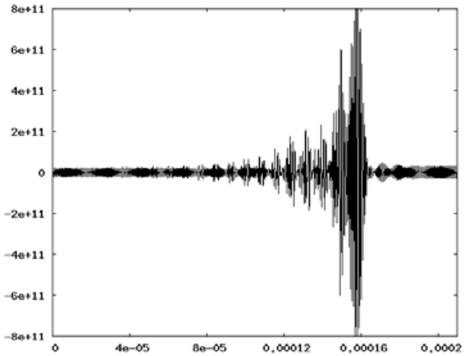
Experiments:

Various groups (Princeton, LLNL, LANL, LULI/Bordeaux, Taiwan, U. Strathclyde, ...).

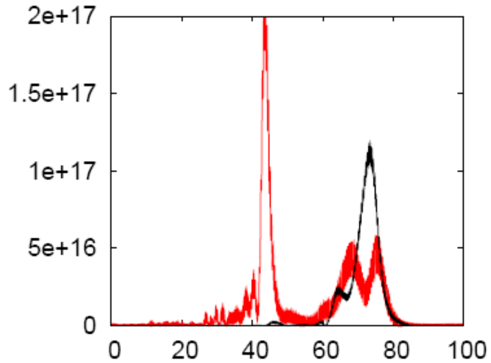
Found 10^{16} – 10^{17} Wcm^{-2}

Limits to high intensity

Modulational instability, RFS



For high density (ω_0/ω_p = 10)

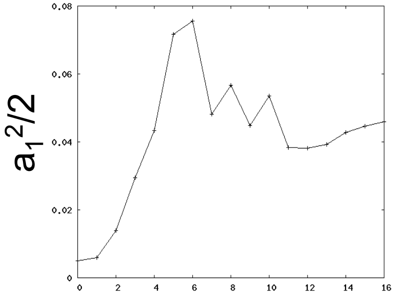


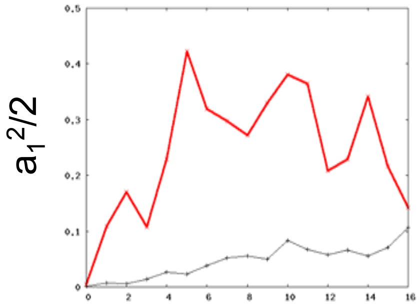
Ditto, for intense pump

Pump: I=2*10^{15} W/cm^2 or

I=2*10^{16} W/cm^2 (ω_0/ω_p = 20)

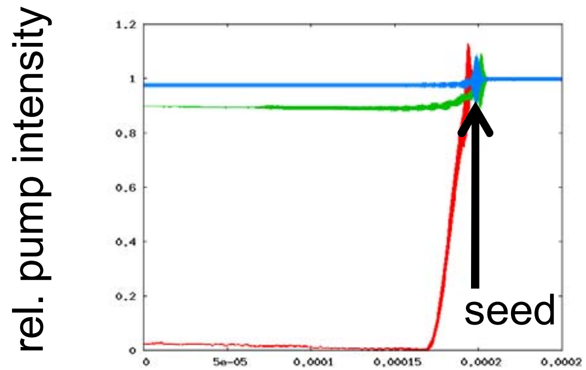
Saturation (wakefields)





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

Langmuir wave breaking



Pump intensity before and after seed; ω_0/ω_p = **10**, **20**, **40**
Low plasma density triggers wave breaking, which halts amplification and reduces efficiency

Thermal effects

- Landau damping of Langmuir wave
  - Feared to be a major problem (Clark & Fisch, PoP 2003; Malkin & Fisch, PRE 2009)
  - Later shown to saturate (Vu et al, PRL 2001, PoP 2002; Hur et al., PoP 2004)
- Langmuir frequency detuning
  - Via the Bohm-Gross dispersion relation
  - Via trapped electrons (Vu et al.; Hur et al.)
- Collisions and collisional heating (Princeton/LLNL)
  - Pump absorption before it meets the probe
  - Damping of Raman scattering
  - Plasma heating by probe: energy losses, thermally driven instabilities, ...

A lot of work still needs to be done here

Landau damping as current drive

Langmuir wave accelerates background electrons:

–Wave loses energy, electrons gain

–Plateau in velocity distribution function

–Landau damping saturates

Saturation is called "kinetic inflation" by laser physicists, but same principle as current drive!

See Karttunen, Salomaa, Pättikangas and Sipilä, Nuclear Fusion (1991), Fisch and Karney, Phys. Fluids (1981)

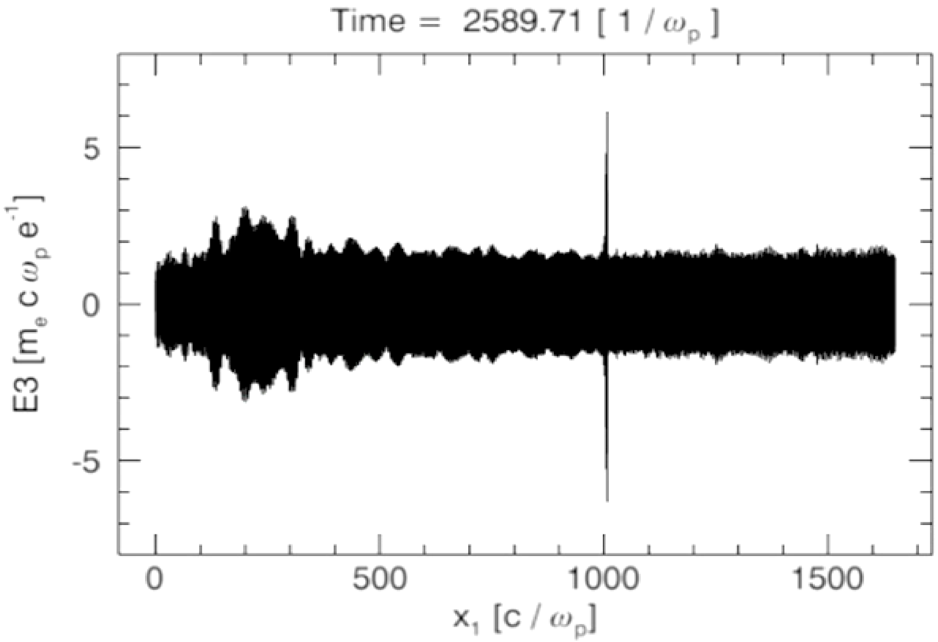
It pays to look "across the fence" at what the other side is doing!

Pump (in)stability

- Pump beam must travel through plasma column before it meets the probe, and may go unstable: RBS, RFS, modulation, filamentation...
- Two movies by F. Fiúza to illustrate premature pump RBS (Malkin, Shvets and Fisch, PRL 2000)
- Pump with $I = 10^{15}$ or 10^{16} Wcm^{-2} will propagate though 4 mm plasma with $\omega/\omega_p = 20$
- At the higher intensity, the pump is so unstable that the probe does not even amplify properly

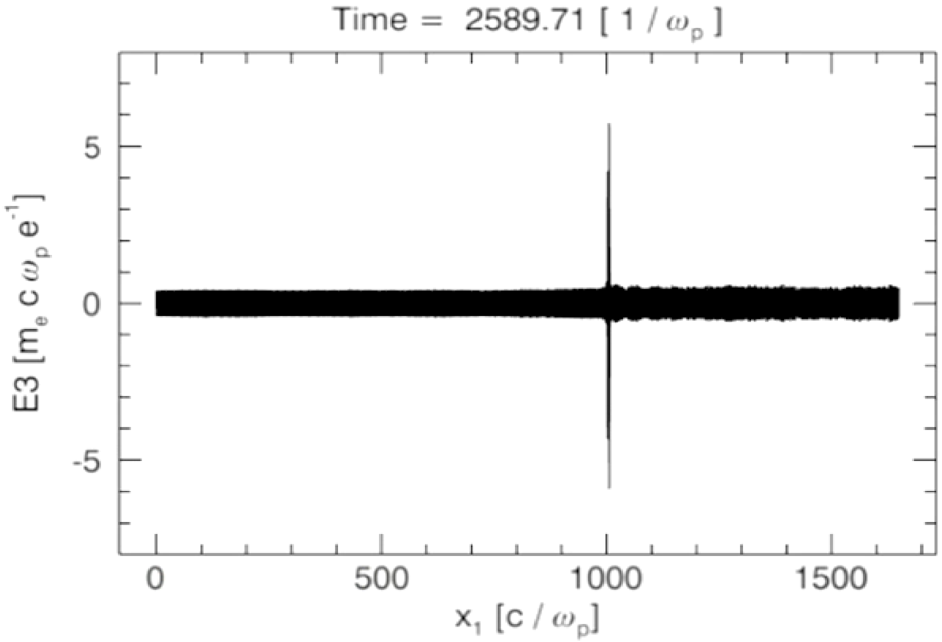
A clear limit on either pump intensity or interaction length!

10^{16} Wcm^{-2} pump



Pump is unstable, probe does not grow

10^{15} Wcm^{-2} pump



Pump is stable, probe grows nicely

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High intensity – round-up

- Raman amplification can be used to amplify 1 μm laser light to $\geq 10^{17}$ Wcm^{-2}
- Pump and probe instabilities, saturation and Langmuir wave breaking limit the maximum intensity
- Thermal effects (detuning, Landau damping, collisions) may be important: more research needed here

Any questions so far?

Large spot size

Extra dimensions, extra problems

Analytic theory:

- Some work on Raman side scatter (Solodov, Malkin, Fisch, PRE 2004)
- No effort to include analytic models of self-focusing or filamentation

Fluid simulations:

- F3D is capable, but only used in 1-D (Clark and Fisch, PoP 2003; Berger et al., PoP 2004)
- MBRS does not model transverse effects or dispersion properly (Balakin, Fraiman et al., PoP 2002, PoP 2003, PRE 2005)

Large spot: experiments

Livermore experiments: large spot (200 μm) but low intensity: 10^{13} – 10^{14} Wcm^{-2} probe output (Kirkwood et al., PoP 2007; Ping et al., PoP 2009)

Princeton experiments: high intensity (10^{16} – 10^{17} Wcm^{-2}) but small spot: 15 μm (Ping et al., PRL 2004; Cheng et al., PRL 2005; Ren et al., Nature Physics 2007)

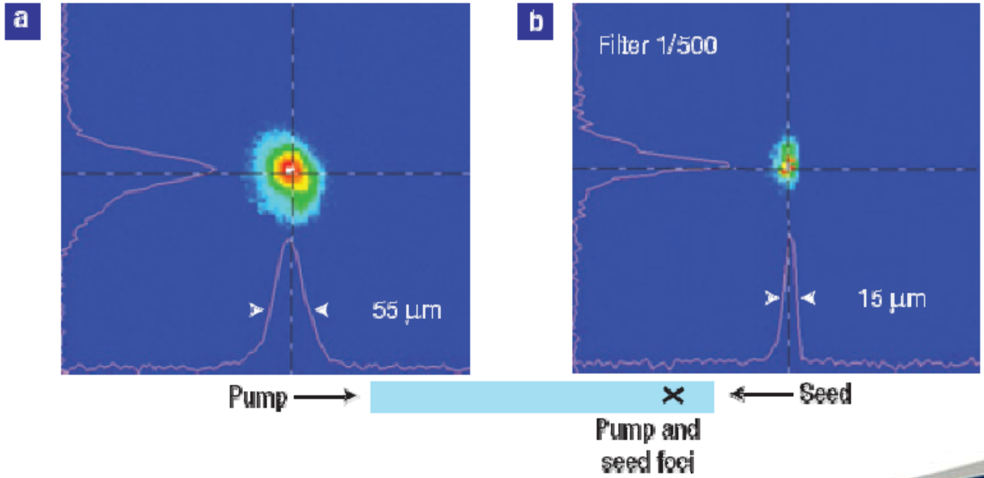

Figure taken from Ren et al., Nature Physics (2007)

2D/3D PIC simulations

- A brute-force method, but it does the job
- First Raman-ready 2-D PIC code: XOOPIC at UC Berkeley (Mardahl et al., PLA 2002)
  Later efforts include Zohar (LLNL) and Osiris (UCLA/IST Lisbon)
- Incredibly, first 2-D PIC simulations with mm-wide laser spots only in 2008! (Trines, Fiúza et al., Nature Physics 2011).
- Proper treatment of self-focusing and filamentation almost by default
- Collisions, ionisation, kinetic thermal effects etc. can be added

These help us figure out what is going on!

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PIC simulations II

We need large-scale 2-D/3-D PIC simulations to find out what is going on

- We have performed 1-D, 2-D and 3-D PIC simulations using the codes XOOPIC (UC Berkeley, [8]) and OSIRIS (UCLA and IST Lisbon, [9])
- Results in similar situations were used to mutually verify the codes
- We used a wide moving window in 2-D XOOPIC and a narrow static window in 2-D OSIRIS, so the simulations complement each other.
- We gratefully acknowledge UC Berkeley and the Osiris Consortium for the use of their codes
- We are grateful to RAL Didcot, IST Lisbon, UCLA and FZ Juelich for the use of their computing facilities

[8] J.P. Verboncoeur *et al.,* Comp. Phys. Comm. **87**, 199 (1995).
[9] R. Fonseca *et al.,* Lect. Notes Comput. Sci. **2331**, 342 (2002).

PIC simulation setup

Physical Parameters

Pump

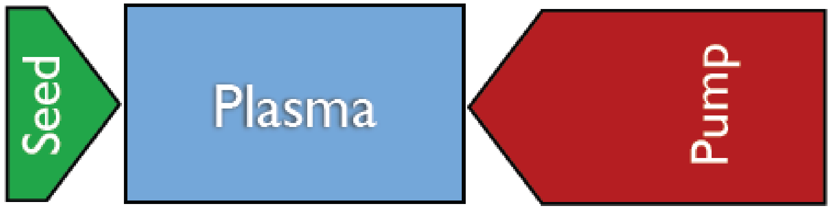
- $\lambda_0 = 0.8\ \mu m$
- $W_0 = \infty$
- $I_0 = 10^{14} - 10^{16}\ Wcm^{-2}$
- circular polarization

Seed

- $\omega_1 = \omega_0 - \omega_p$
- $W_1 = 600\ \mu m$
- $I_1 = 10^{16}\ Wcm^{-2}$
- circular polarization

Plasma

- $L = 4\ mm$
- $\omega_0/\omega_p = 10 - 40$
- $m_i/m_e = 1836$



Numerical Parameters

- $\Delta x_\perp k_p = 0.3$
- $\Delta z\ k_0 = 0.2$
- Particles per cell = 16 (2D); 1 (3D)
- # particles = 10^9 (2D); 3×10^9 (3D)
- # time steps = 2×10^5

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Overview of results

ω_0/ω_p

Intensity (W/cm^2)

	10	14	20	40
$2x10^{14}$	RFS, (fil?)	$\sim 10^{17}$	$2x10^{17}$	ineff.
$2x10^{15}$	RFS, fil.	$8x10^{17}$	$8x10^{17}$	ineff.
$2x10^{16}$	RFS	RFS	RFS, fil.	RFS, ineff.

For each combination of pump intensity and ω_0/ω_p, either the maximum reached probe intensity is listed in W/cm^2, or the reason for failure (probe Raman forward scatter, probe filamentation, inefficient energy transfer from pump to probe)

It is simply very hard to get it right!

Issues

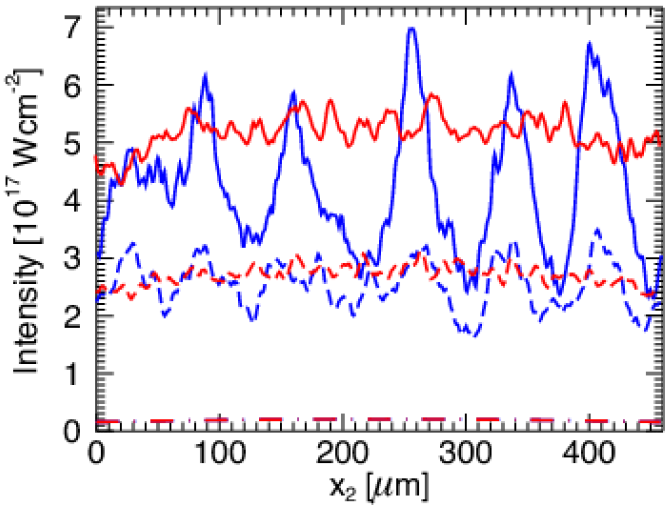
A parametric instability as foundation for pulse compression... Doesn't that become unstable?

- Probe filamentation and self-focusing (new!)
- Probe RFS/modulation
- Pump instabilities
- Saturation
- Langmuir wave breaking

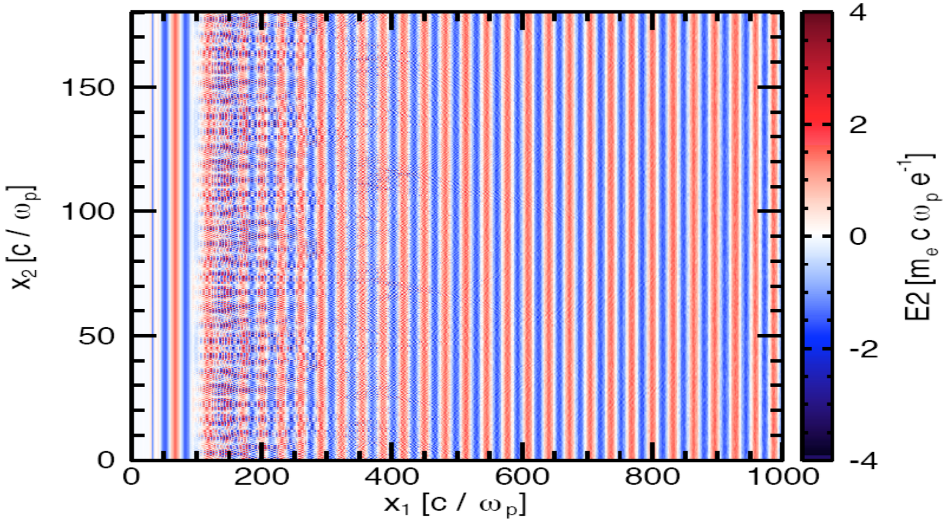
Rule of thumb: any instability that undergoes more than 10 e-foldings will be a problem

Filamentation and self-focusing

Probe filamentation in 2-D,
a_{pump} = 0.03 (red) or 0.1 (blue)

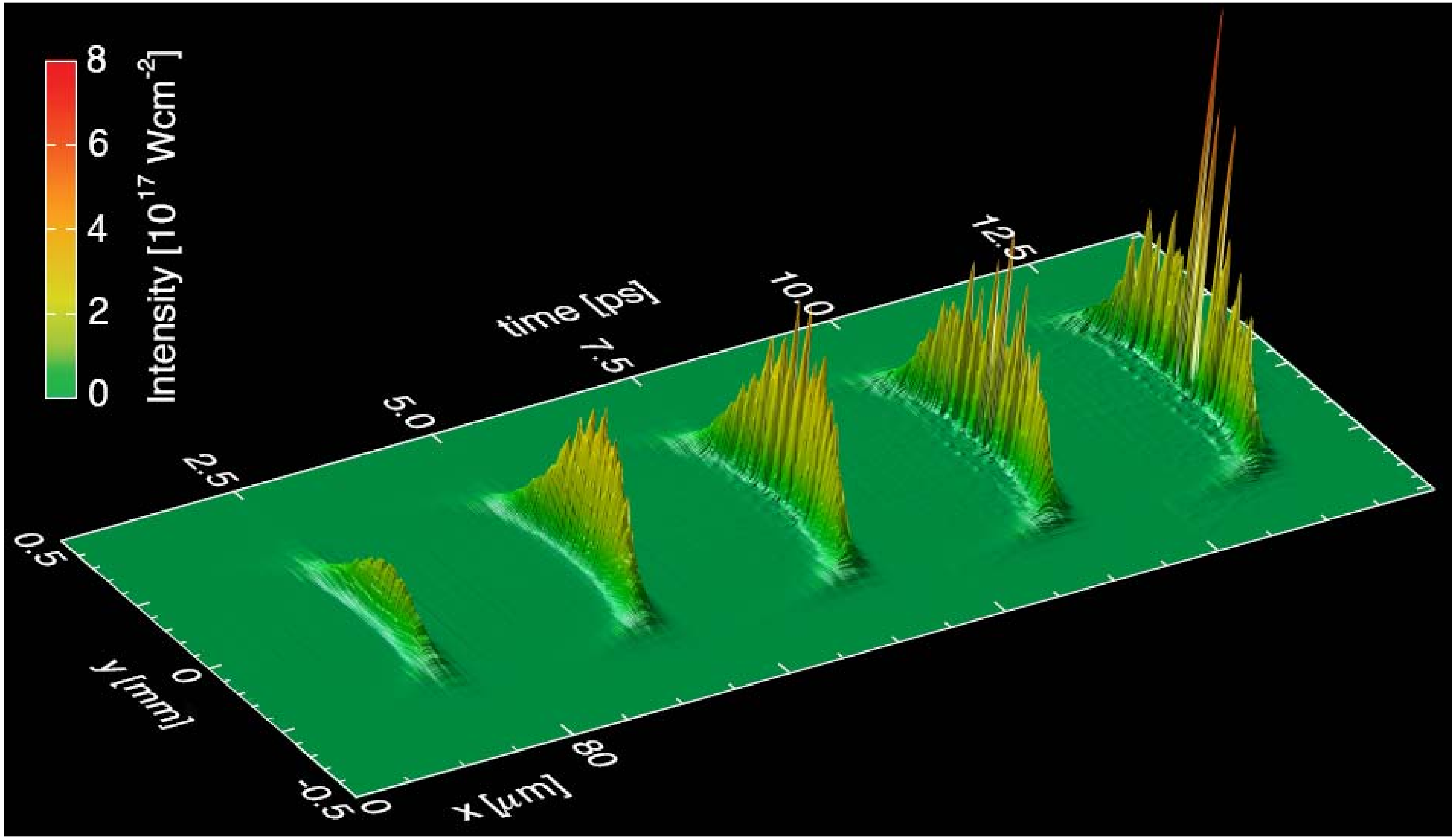


Pump filamentation, a_{pump} = 0.1;
ω_0/ω_p = 20; after 2.5 mm



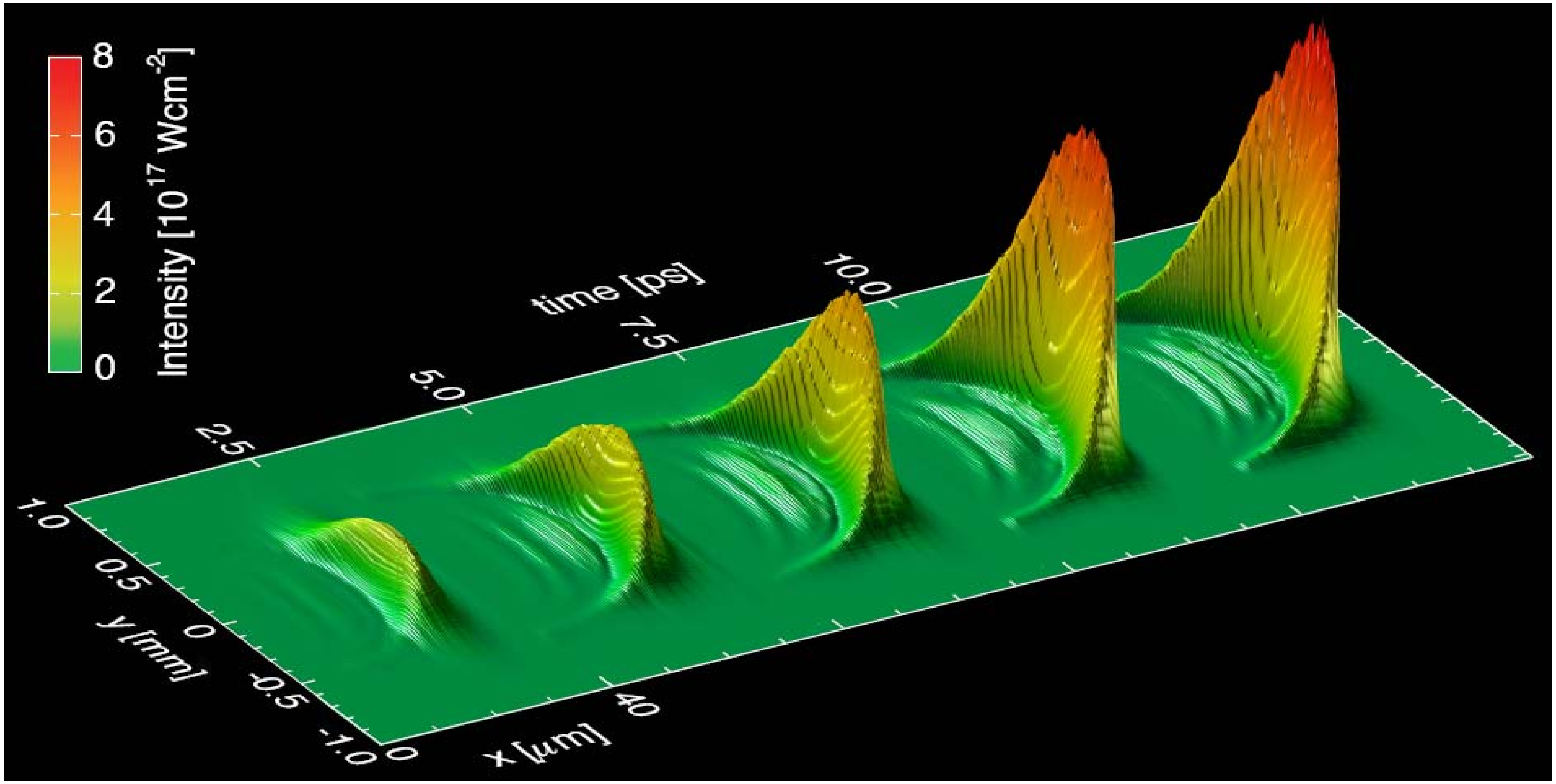
Probe self-focusing not a problem, surprisingly: characteristic length for self-focusing always much larger than interaction length!

A bad result



For a $2*10^{15}$ W/cm^2 pump and ω_0/ω_p = 10, the probe is strongly amplified, but also destroyed by filamentation

A good result



For a $2*10^{15}$ W/cm^2 pump and ω_0/ω_p = 20, the probe is amplified to $8*10^{17}$ W/cm^2 after 4 mm of propagation, with limited filamentation

10 TW → 2 PW and transversely extensible!

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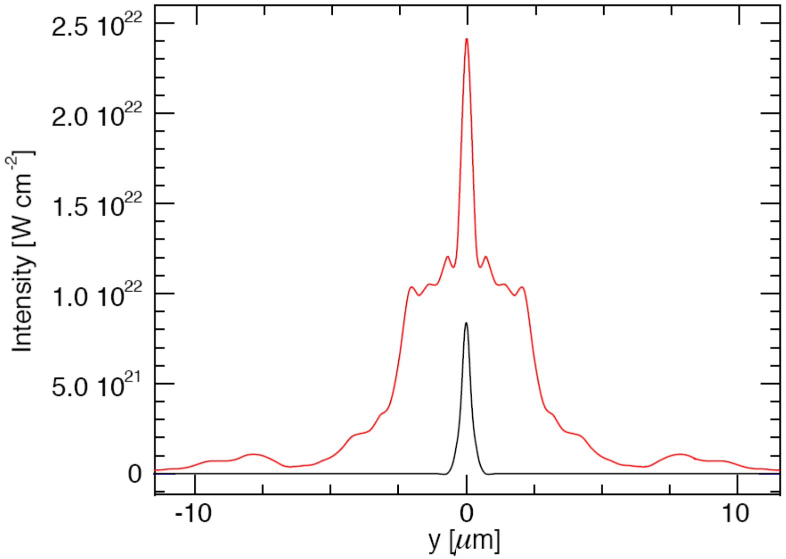
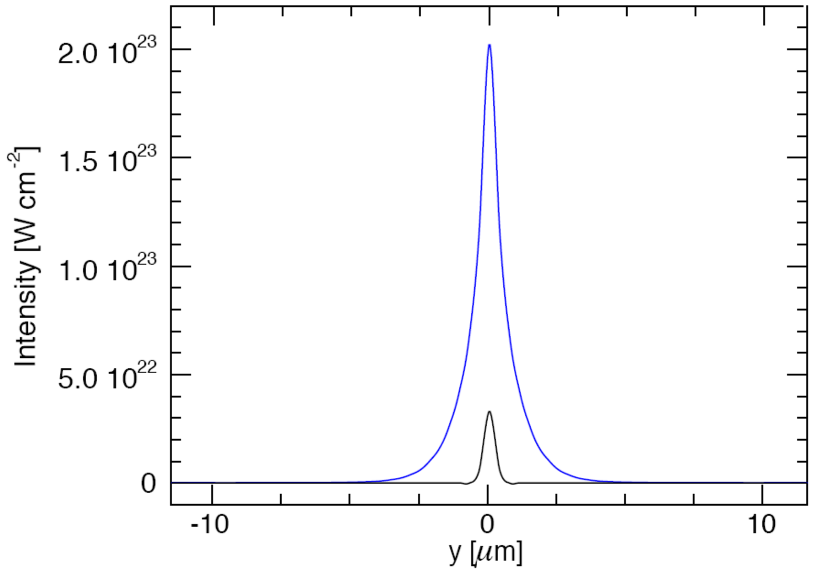
Focusability

focused envelope
for 'spiky' pulse



focused envelope
for smooth pulse



Smooth pulse can be focused to 2.3 times the bandwidth limit. A 200 PW pulse with 1 cm diameter could be focused to 10^{25} Wcm^{-2}.

R. Trines, F. Fiúza et al., Nature Physics **7**, 87 (2011)

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Large spot size – round-up

- Large spot size needed for high power:
  - Not well studied in early theory/simulations
  - Not yet demonstrated in experiments
- Stable amplification of mm-wide probes to multi-PW powers found in PIC simulations
- Probe filamentation is the biggest enemy: a spiky probe cannot be focused
- Reduce plasma density to prevent filamentation. Langmuir wave breaking is not so bad...

Any questions so far?

Long pulse duration

Raman amplification with a long pump and a short probe studied by D. Clark and N. Fisch (Clark & Fisch, PoP 2002, PoP 2003)

Nobody ever attempted to keep the probe long

So there's still some work to do!

Raman with long pulses?

- Raman amplification has been studied for the compression of ps pulses to fs duration [10]
- ICF requires kJ energies in ps pulses, not fs
- Most powerful laser systems are Nd:glass, producing narrowband ns pulses, in particular at 351 nm
- Raman with ns pumps suffers from:
  - pump instabilities
  - probe saturation
  - probe shortening
- What to do, what to do?

[10] R. Trines, F. Fiúza et al., Nature Physics **7**, 87 (2011)

Self-similar theory revisited

Use self-similar theory by Malkin, Shvets and Fisch [2] to obtain:

$$\omega_0 \omega_p a_0^2 t_{pu} t_{pr} = \xi_M^2 \sim 25-50$$

Use t_{pu} = 1000*t_{pr} and ω_0/ω_p = 20 to obtain:

$$I_{pu} = 4\times10^{-13} \big/ t_{pr}^2 \; [\mathrm{W\ cm^{-2}}]$$

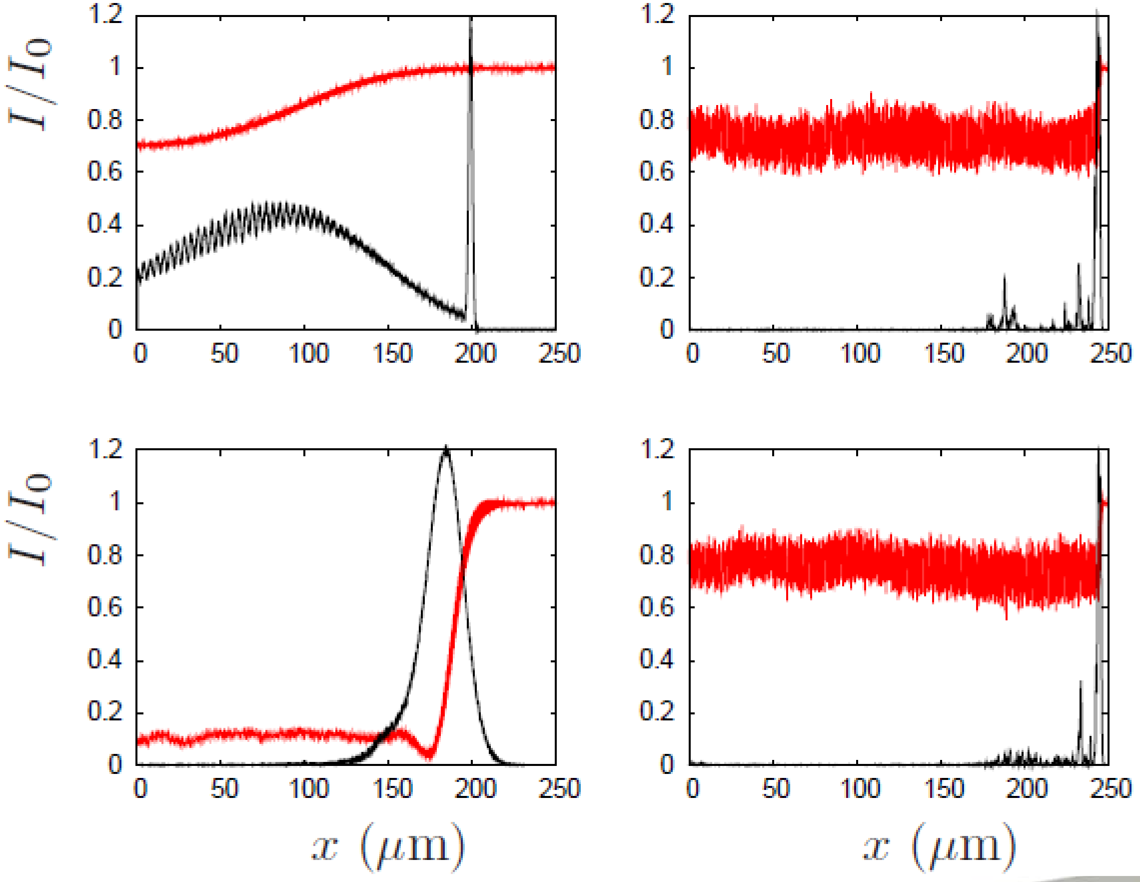
[2] V.M. Malkin *et al.,* Phys. Rev. Lett. **82**, 4448 (1999).

Probe length control

a_0=0.01 a_0=0.1

50 fs probe

500 fs probe



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Simulation results

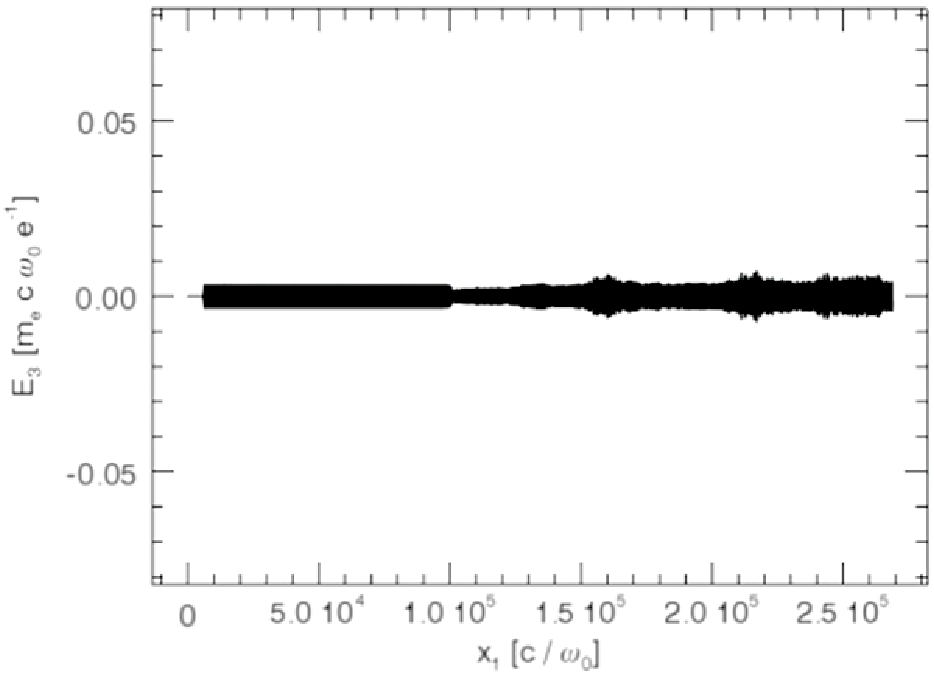
Parameters: Cold plasma, 351 nm wave length, $\omega_0/\omega_p = 20$, compression ratio ~1000

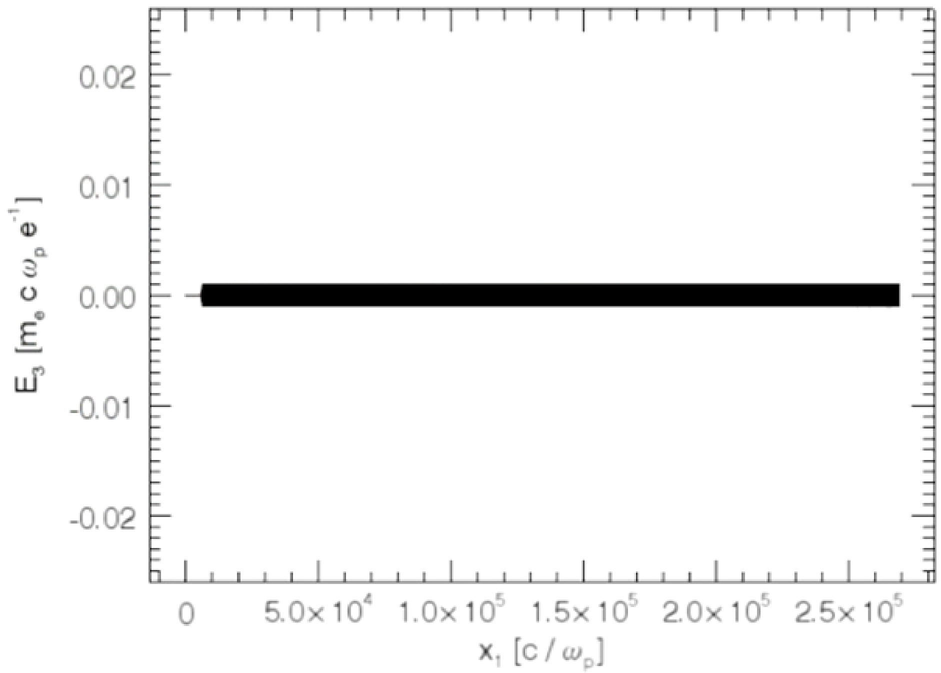
	I	II	III	III'	IV	V	VI
a_0	0.0044	0.003	0.0016	0.0016	0.001	0.001	0.00056
a_1	0.0044	0.003	0.0044	0.0044	0.003	0.001	0.00056
t_{pu} (ps)	100	133	100	100	67	133	133
t_{pr} (fs)	65	28	230	330	400	283	2180
Eff.(%)	20	39	50	40	60	44	7
ξ_M	14.2	7.0	8.9	10.6	6.2	7.3	11.5

$$\xi_M^2 \equiv \omega_0 \omega_p a_0^2 t_{pu} t_{pr}$$

(II)-(V) show good results, (III') is (III) with moving ions, (I) continued too long, (VI) had a long start-up period because of low intensities (linear vs. non-linear regime)

10^{14} Wcm^{-2} pump (I) 10^{13} Wcm^{-2} pump (III)





Pump is unstable, probe does not grow well

Pump is stable, probe grows nicely

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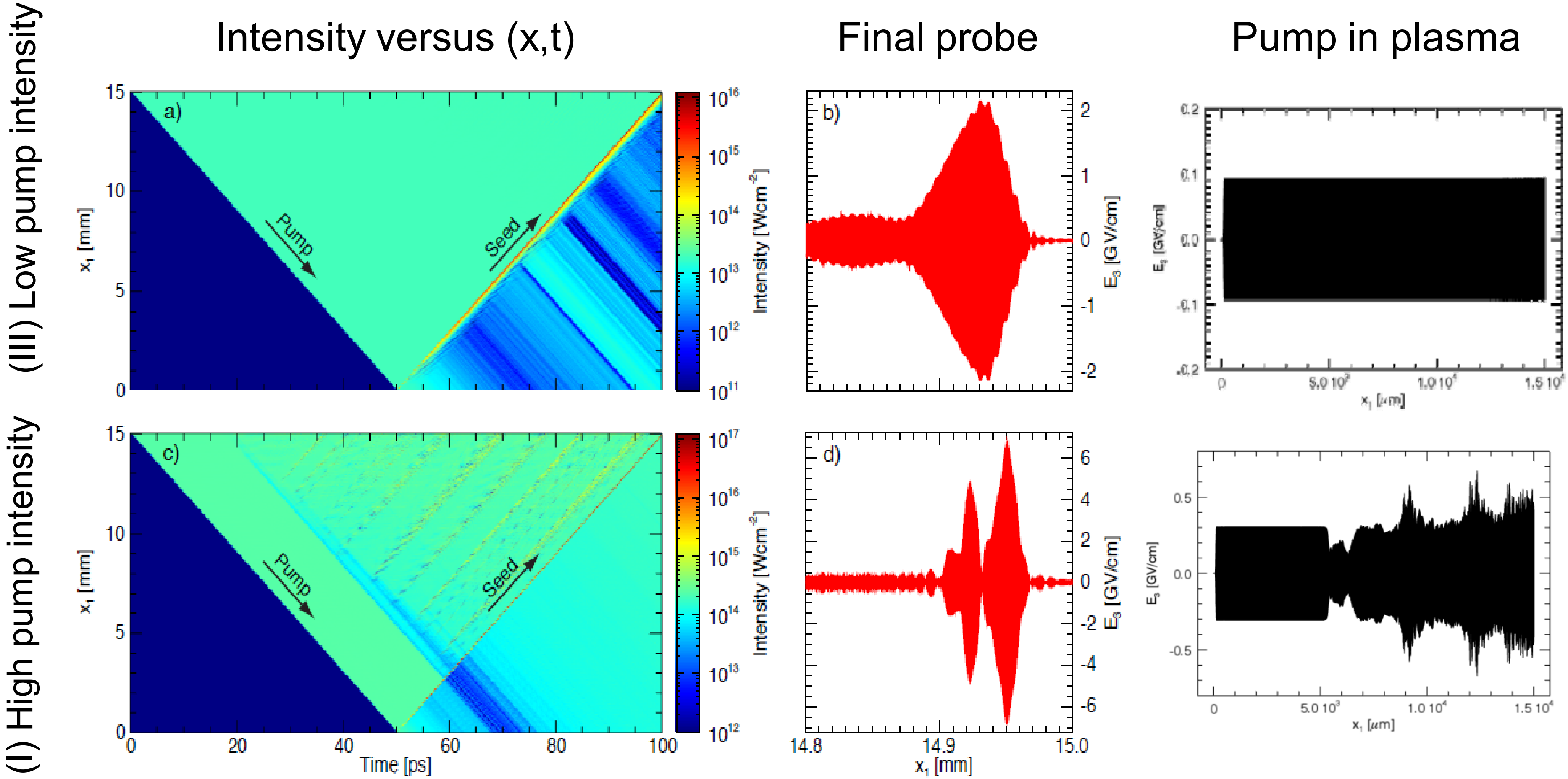
Detailed comparison of (I) and (III)



Instability control

Fix compression ratio:

- Parasitic SRS:

$$t_{pu} \propto 1/a_0$$

- Filamentation:

$$t_{pu}/t_{SRS} \propto 1$$

- Modulational:

$$t_{pu}/t_{fil} \propto a_0$$

$$t_{pu}/t_{mod} \propto a_0^{1/3}$$

Filamentation:

- Spot radius:

$$R = R_0\sqrt{1 - z^2/z_0^2}$$

$$z_0 = z_R/\sqrt{P/P_c - 1}$$

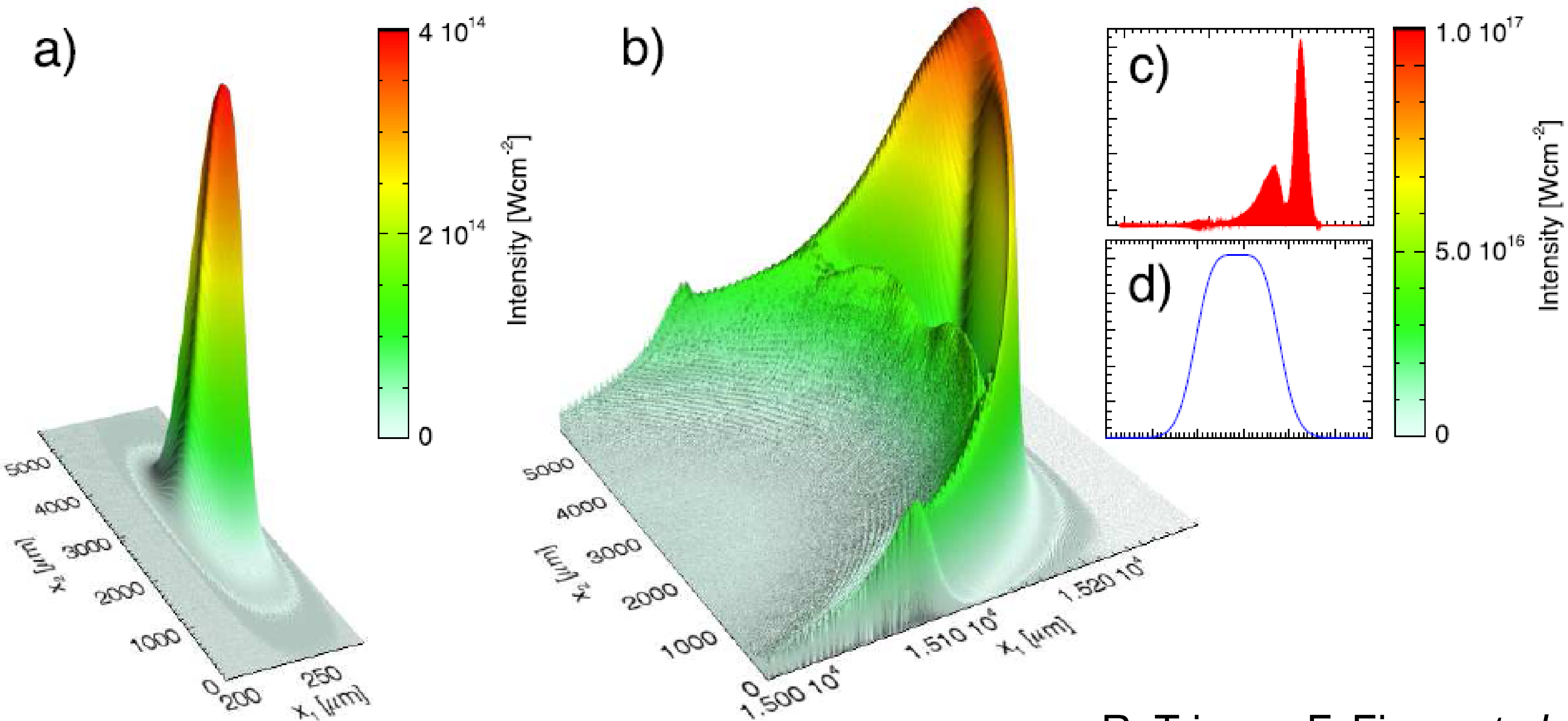
- Higher powers:

$$z_R \propto P/I \propto Pt_{\mathrm{pu}}^2$$

$$z_0/(ct_{\mathrm{pu}}) \propto t_{\mathrm{pu}}\sqrt{P}$$

Higher P is better

2-D simulations



R. Trines , F. Fiuza *et al.*,
PRL **107**, 105002 (2011)

Simulation (III) was repeated in 2 dimensions with 1.2 mm trans. FWHM and moving window

Result: efficient amplification, no probe instabilities or self-focusing visible

(Ack: N. Loureiro)

Long probe – round-up

- Raman-amplified probe self-shortens but can be kept long for low pump intensities
- Instabilities less important for lower pump intensities
- Self-focusing less important for higher powers!
- Thermal effects may be more important for longer interaction lengths

What next?

- Limit pump length: compression ratio 1:1000
- Limit plasma density: $\omega/\omega_p \sim 14\text{-}20$, may be higher for lower pump intensities
- Pump intensity: 10^{14} -10^{15} W/cm^2 , lower for long probes:

  –acceptable (25-30%) or high (50%) efficiency

  –no RFS or filamentation yet
- Wide pulses, mm-cm or more
- Investigate the various roles of thermal effects on Raman amplification

Conclusions

- Simulations show Raman amplification to truly high output intensities, petawatt powers and kilojoule energies
- Choose the right parameters to avoid instabilities
- Final probe duration controlled via pump intensity
- Nano- to picosecond compression possible, useful for fast-ignition ICF and HED physics
- Everything scales with pump wave length, so may also work for X-rays: attosecond X-ray pulses

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Thank you for attending!

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