Efficient Raman amplification into the petawatt regime

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R. Trines, F. Fiúza et al., Nature Physics,
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CLF central laser facility

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Background

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

Why pulse compression in plasma?

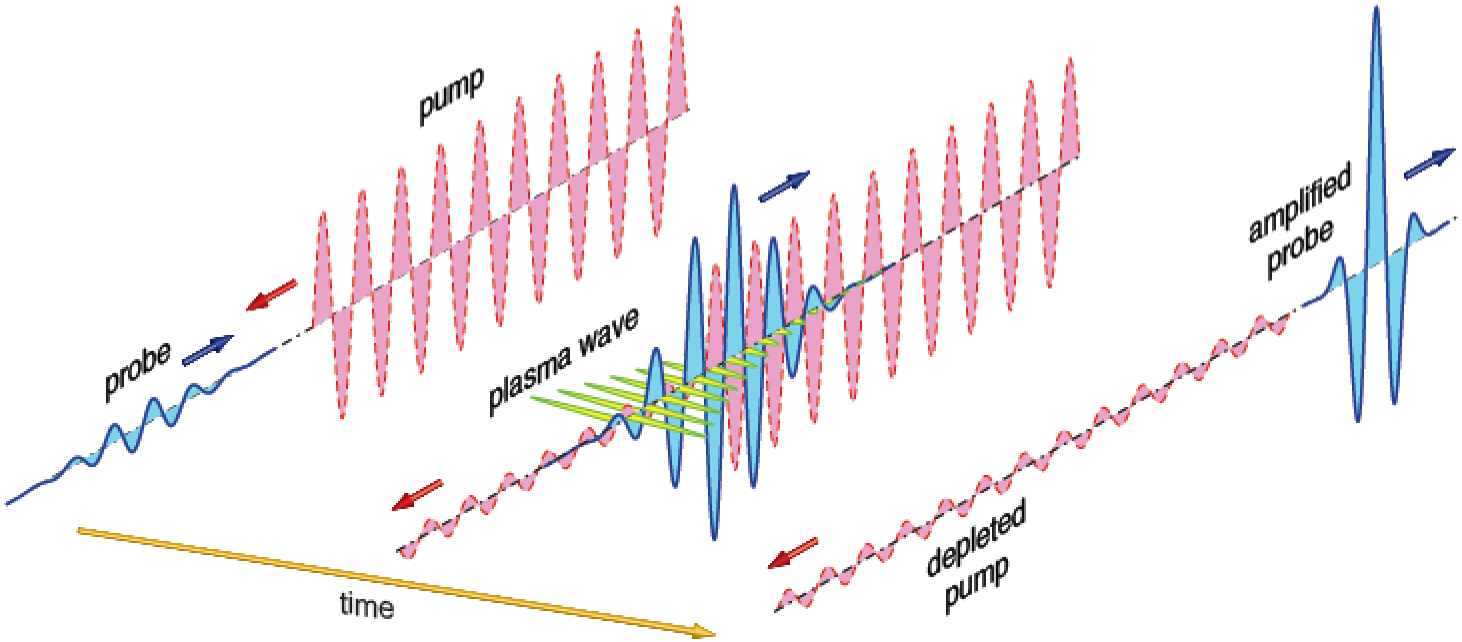
- Solid optics: max. intensity 10^{12} W/cm^2
- Plasma: max. intensity 10^{17} W/cm^2 [1,2]

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)

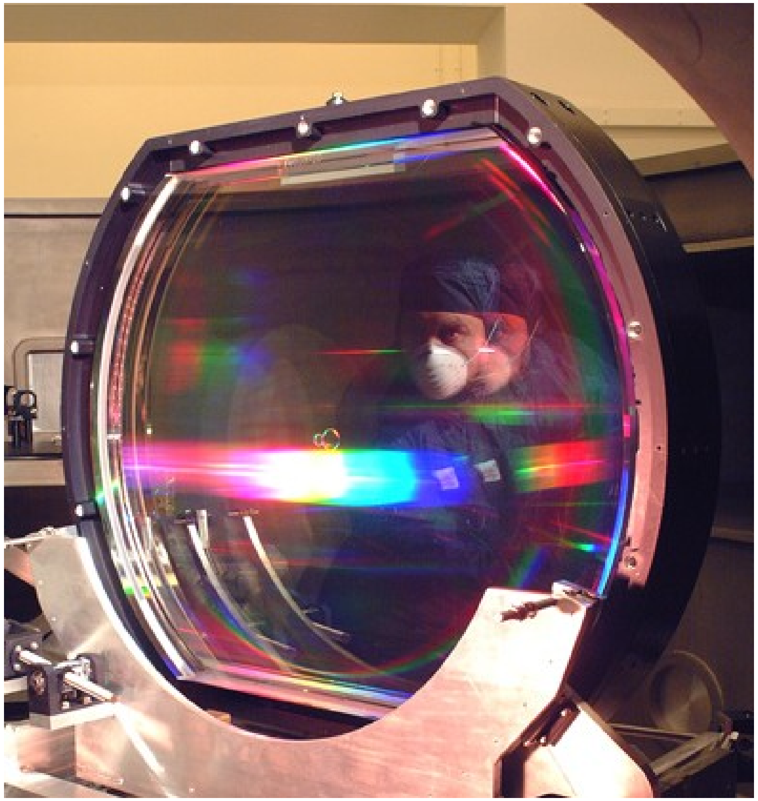
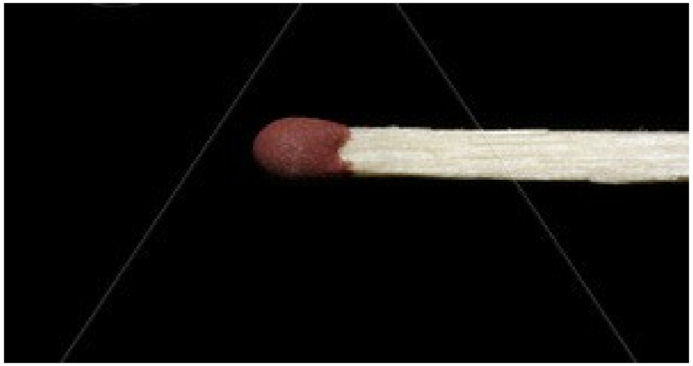


Image: STFC Media Services

Volume of a plasma-based compressor



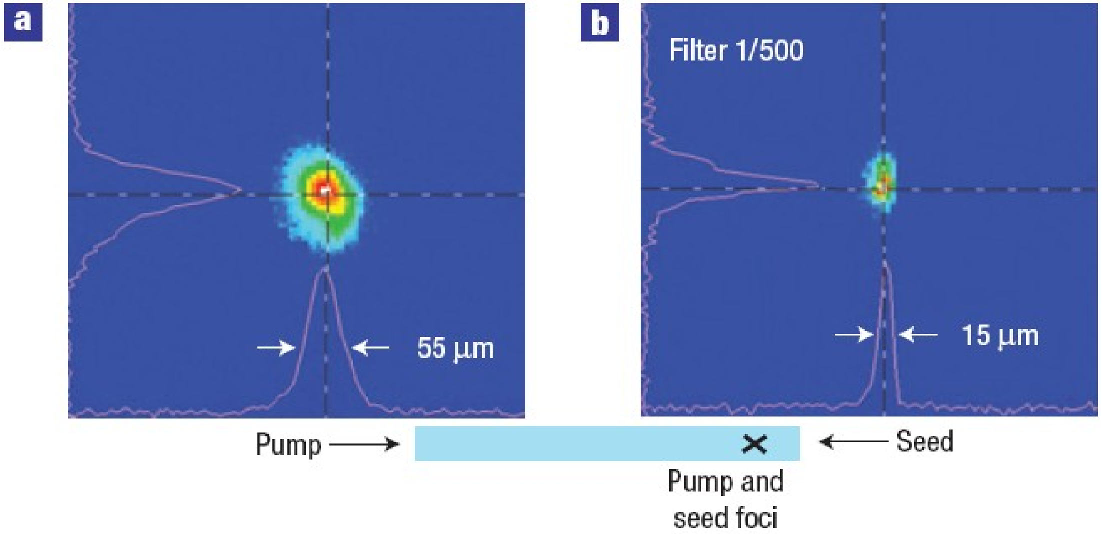
A brief history

- 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 codes
- 2004-10: Experimental campaign at Princeton
- 2007-10: Experimental campaign at Livermore

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

Current status

- Theory: mostly linear, for low intensities, 1-D, no regard for instabilities like RFS and filamentation
- Numerics: envelope models, 1-D fluid/particles
- Best experiment: $2.3*10^{14}$ W/cm^2 pump → $2.5*10^{16}$ W/cm^2, 15 μm wide probe: 60 GW [6]



Why the difference between promises and results?

[6] J. Ren *et al.*, Nature Physics **3**, 732 (2007).

Simulations

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

- We have performed 1-D and 2-D PIC simulations using the codes XOOPIC (UC Berkeley, [7]) and OSIRIS (UCLA and IST Lisbon, [8])
- 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 and UCLA for the use of their parallel computing facilities

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

Simulation setup

Physical Parameters

Pump

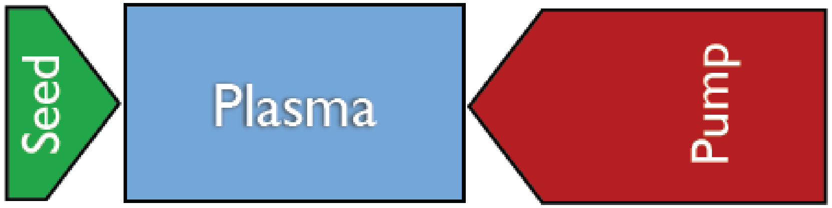
- $\lambda_0 = 0.8\ \mu m$
- $W_0 = \infty$
- $I_0 = 10^{14} - 10^{16}\ Wcm^{-2}$
- circular polarization

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

Overview of results

ω_0/ω_p

Intensity (W/cm^2)

	10	14	20	40
$2x10^{14}$	RFS, (fil?)	~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

Instability as foundation for pulse compression... Doesn’t that become unstable?

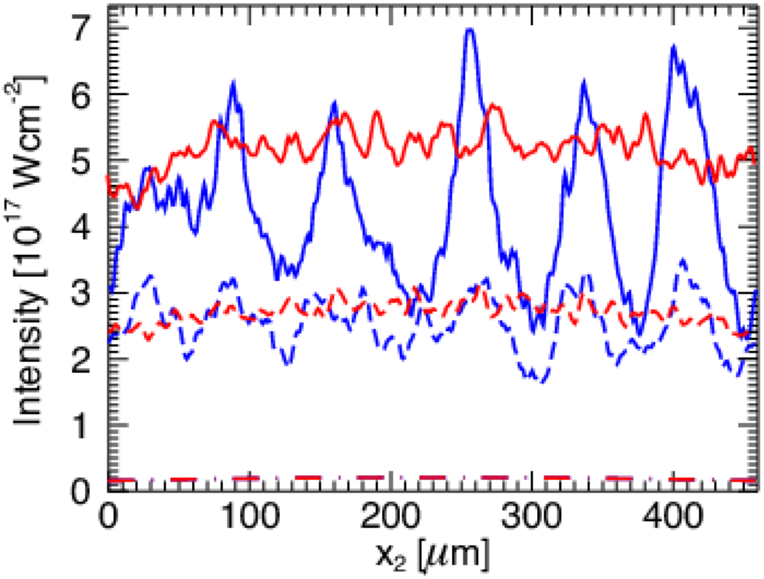
The four horsemen of the Apocalypse:

- Probe filamentation
- Probe Raman forward scattering
- Inefficient energy transfer
- Saturation

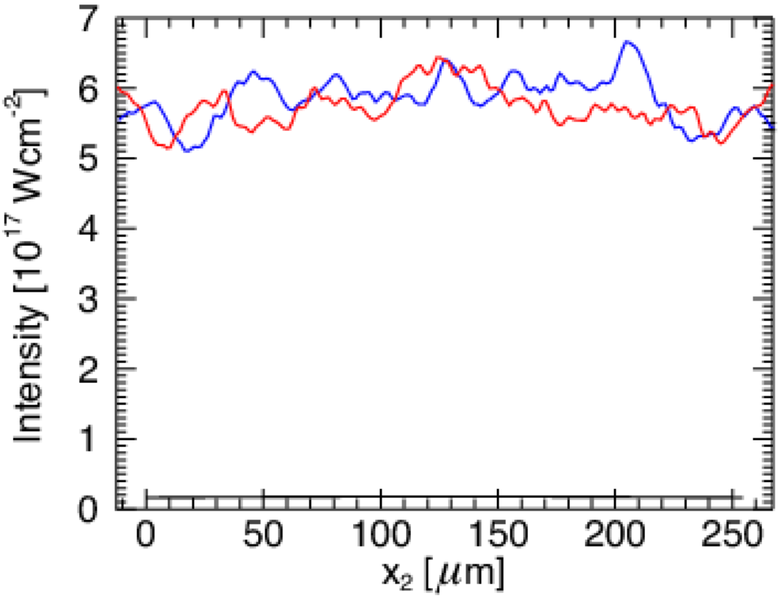
Filamentation

2-D and 3-D Osiris simulations of the central part of the probe, by F. Fiuza

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



Transverse filamentation in 3-D, a_{pump} = 0.03, both directions

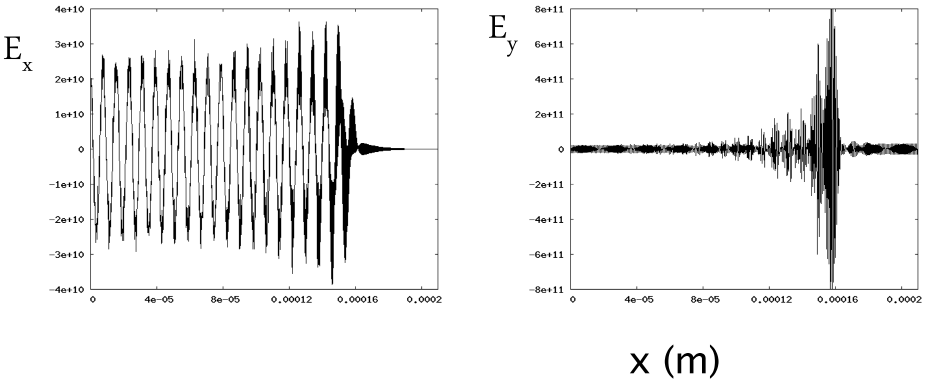


Filamentation can be kept in check if both the pump intensity and plasma density are not too high

Probe RFS

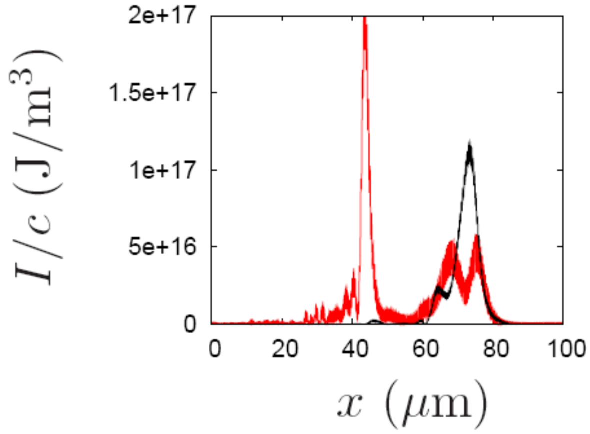
Probe Raman forward scatter occurs when either the plasma density or the pump intensity is too high and will give the probe a poor longitudinal envelope

probe RFS for high density



Pump: I=2*10^{14} W/cm^2
n_0 = 1.75*10^{19} cm^{-3}
(ω_0/ω_p = 10)

probe RFS for intense pump



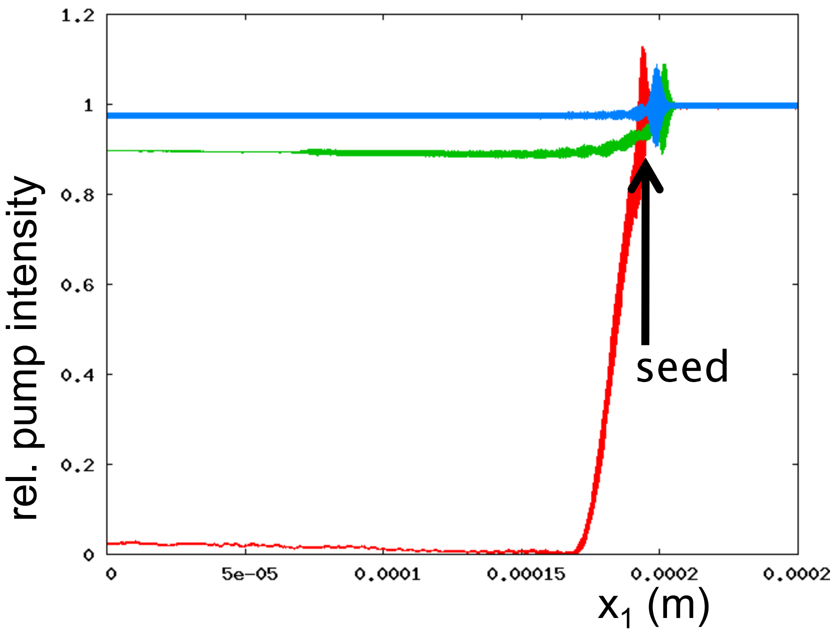
Pump: I=2*10^{15} W/cm^2 or
I=2*10^{16} W/cm^2
ω_0/ω_p = 20

Efficiency versus density

Low plasma density: energy transfer is inefficient

High plasma density: instabilities destroy probe

Stick to middle ground: ω_0/ω_p = 14-20

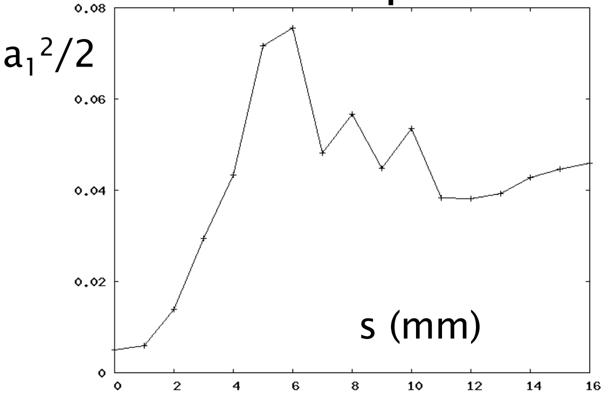


Pump intensity before and after seed; a_0=0.01; a_1=0.1; ω_0/ω_p = **10**, **20**, **40**; after 1 mm

Saturation

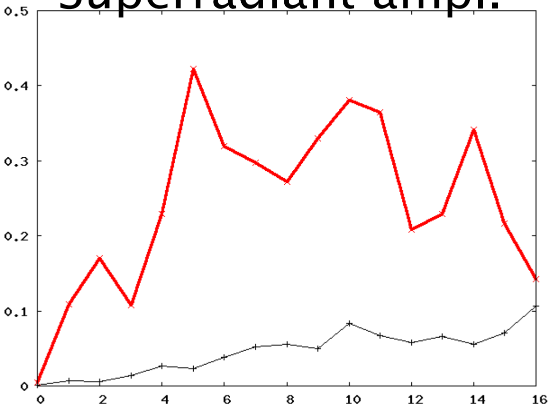
Probe growth *will* saturate:

- Probe RFS; probe also generates a wakefield
- Probe limited to 300-1000 times pump
- Higher pump intensity yields higher absolute growth but lower relative growth



Raman amplification

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



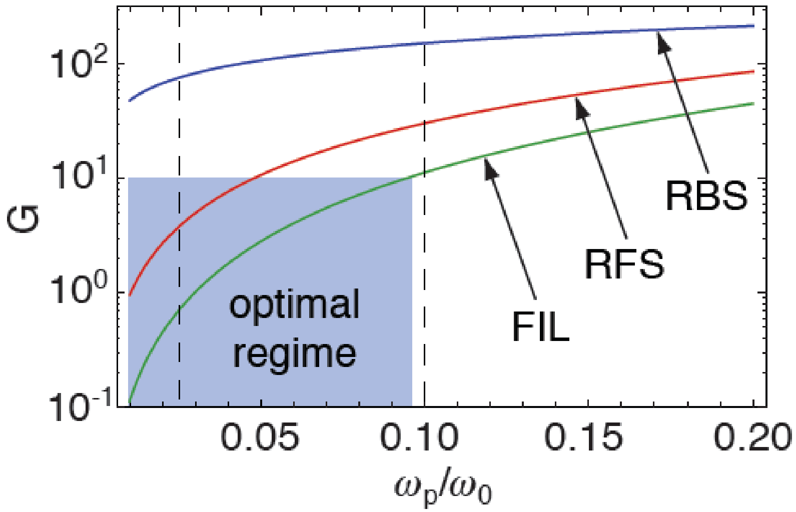
Superradiant ampl.

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

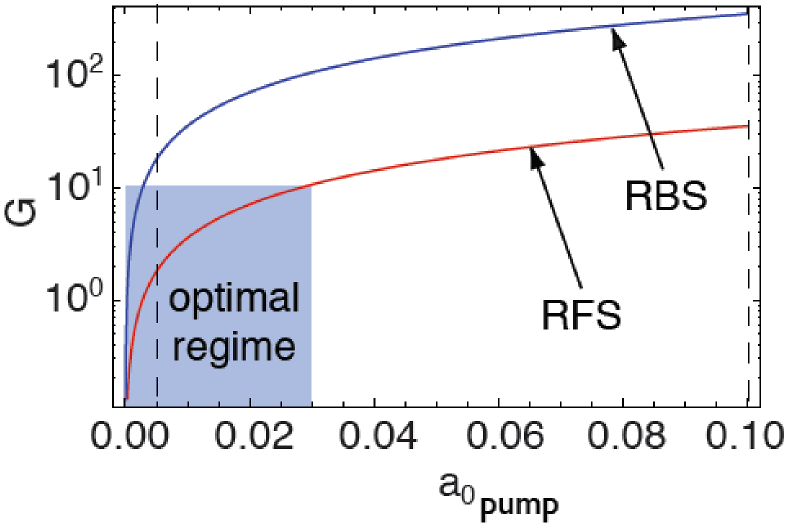
Simulations versus theory

- RBS growth increases with pump amplitude and plasma density, but so do pump RFS and probe filamentation
- Optimal simulation regime corresponds to at most 10 e-foldings for pump RFS and probe filamentation

Growth versus plasma density

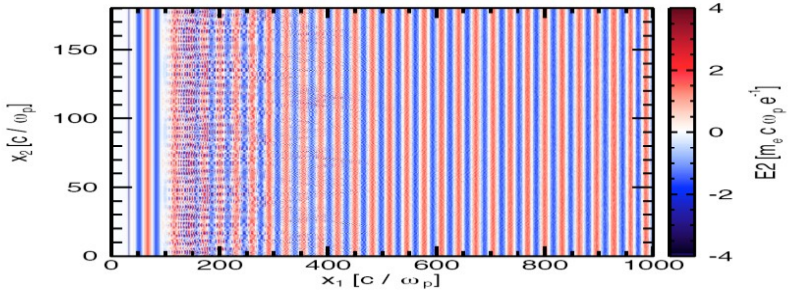


Growth versus pump amplitude



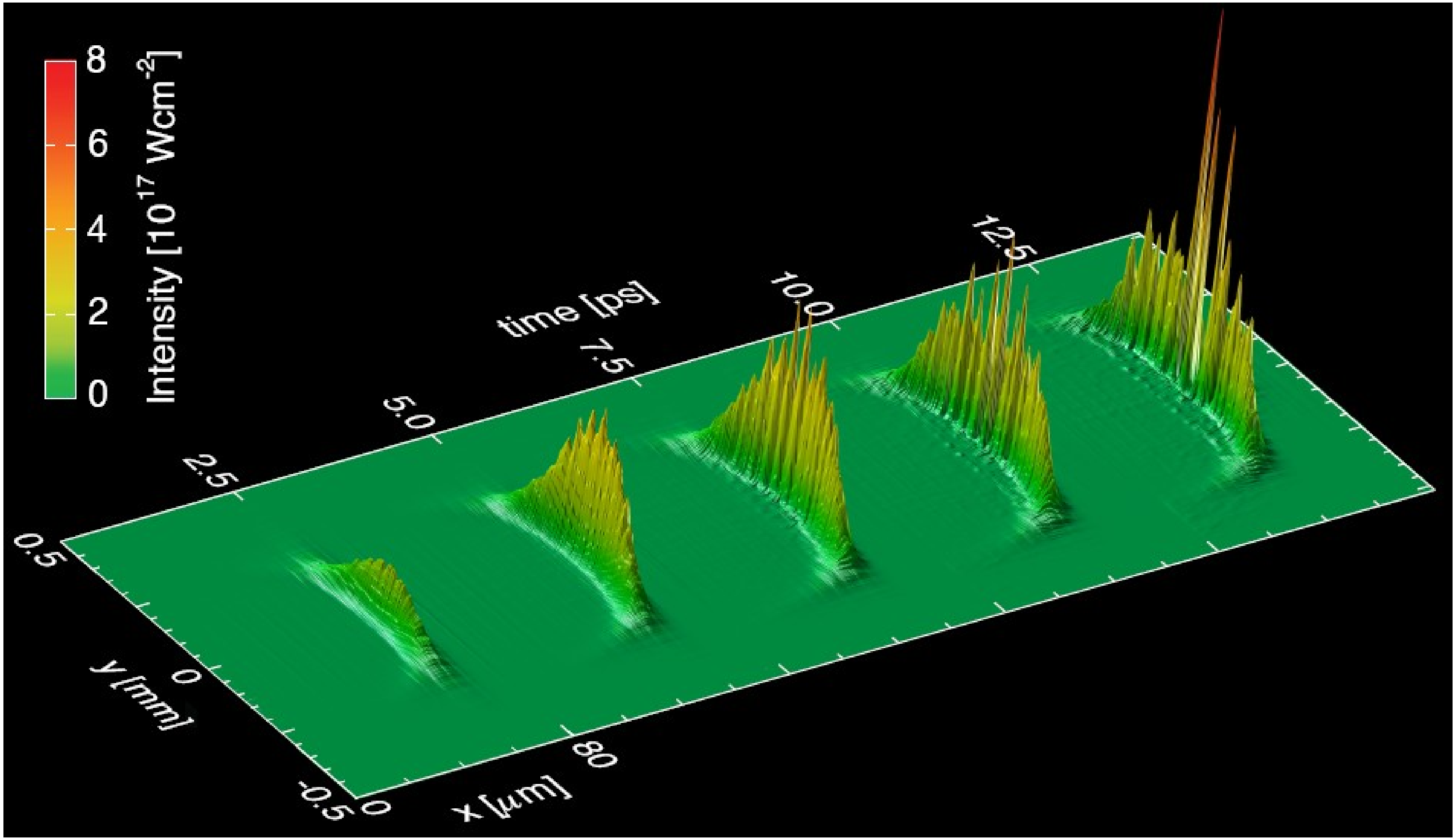
Bonus issue: pump stability

- 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 will illustrate this
- 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



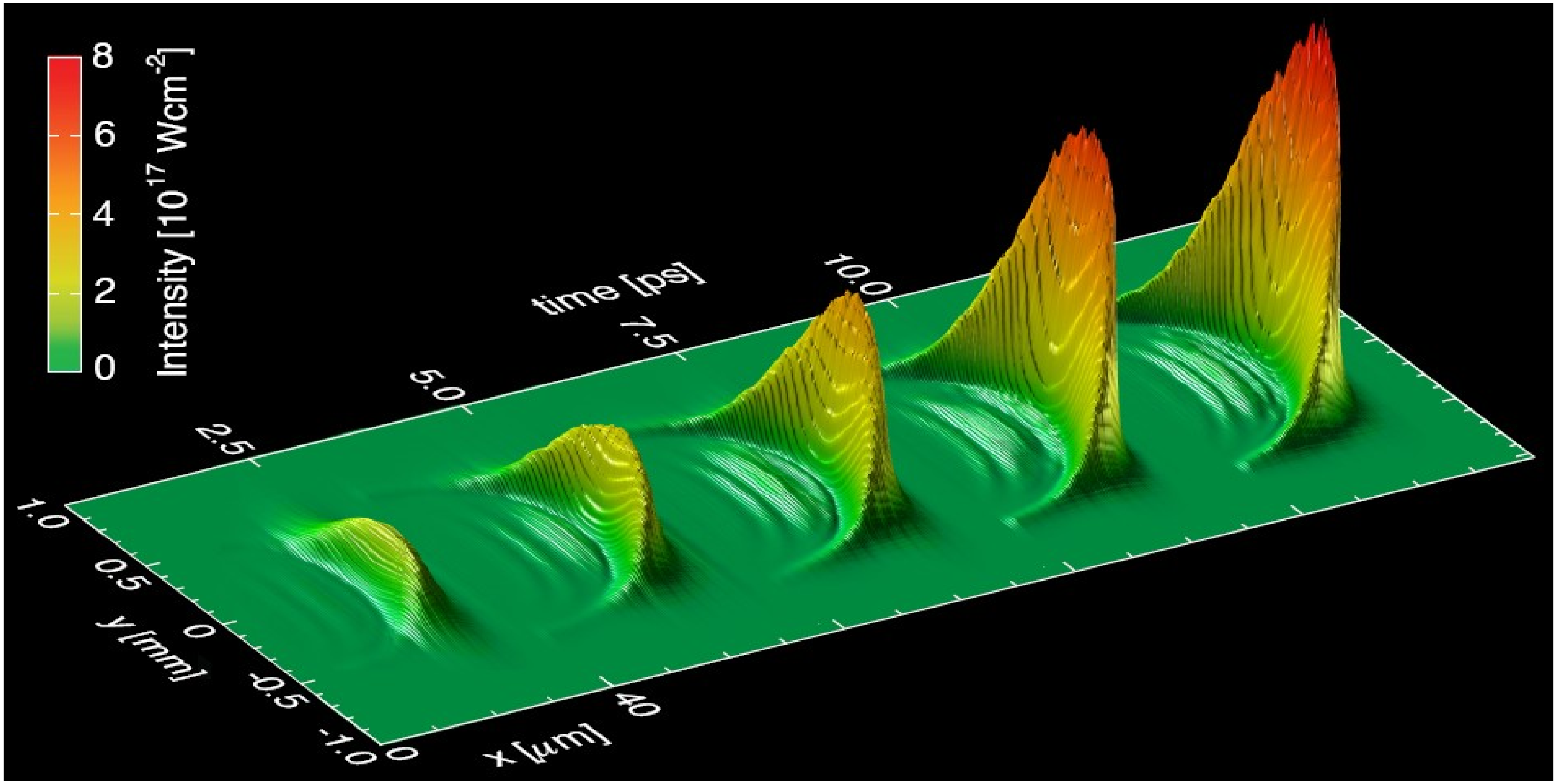
Pump filamentation, $a_0 = 0.1$; $\omega_0/\omega_p = 20$; after 2.5 mm

A bad result



For a $2*10^{15}$ W/cm^2 pump and $\omega_0/\omega_p = 10$, the probe is still amplified, but also destroyed by filamentation

A good result

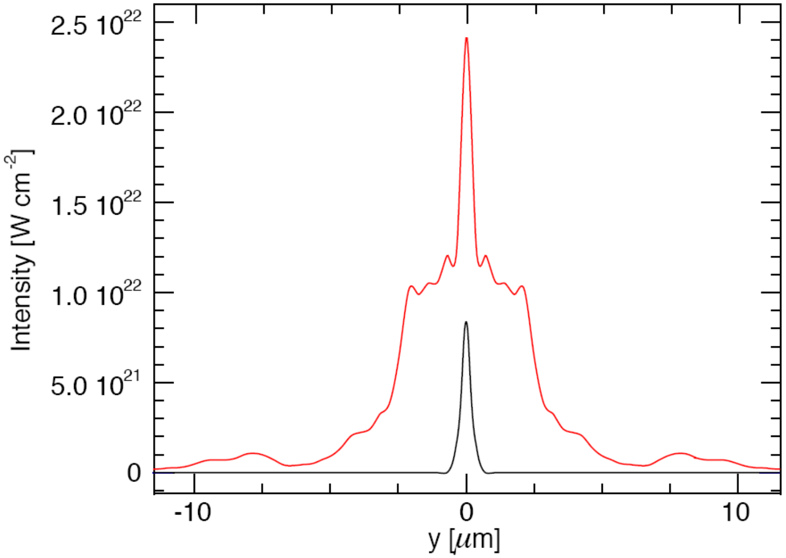


For a $2*10^{15}$ W/cm^2 pump and $\omega_0/\omega_p = 20$, the probe is amplified to $8*10^{17}$ W/cm^2 after 4 mm of propagation, with limited filamentation

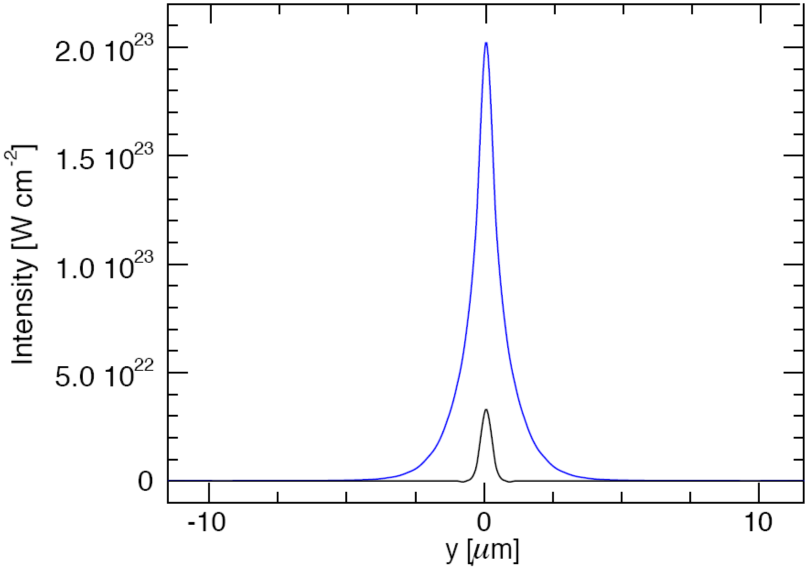
10 TW → 2 PW and transversely extensible!

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}.

What next?

- Limit pump length to ~25 ps (compression ration 1:1000), to avoid saturation and instabilities
- Fairly low density, $\omega/\omega_p \sim 14\text{-}20$
- Not too intense pump: 10^{14} -10^{15} W/cm^2
  - acceptable efficiency (25-30%)
  - no RFS or filamentation yet
- Wide pulses, 1 mm or more

Need to move away from “classical” parameter regime

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Scalability

	Not	But
Pump duration	t	ct/λ_0
Interaction length	L	L/λ_0
Spot diameter	d	d/λ_0
Pump intensity	I	$I\lambda_0^2$
Pump power	10 TW	10 TW
Pump energy	E	E/λ_0
Plasma density	ω_p^2	$\omega_p^2\lambda_0^2$
Probe intensity	I	$I\lambda_0^2$
Probe duration	t	ct/λ_0

Everything scales with pump wave length λ_0!

Raman at different wave lengths

Microwave experiments

EISCAT radar beam experiments

X-ray amplification (see also talk by B. Bingham)

EISCAT Raman amplification

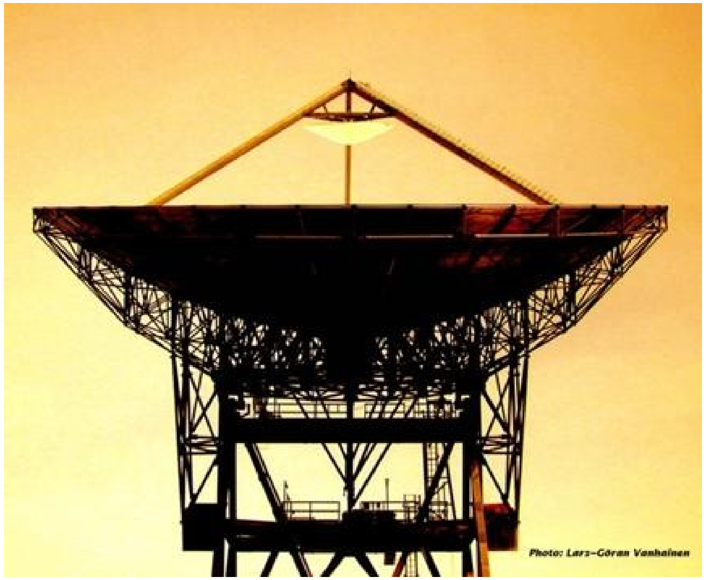

Photo: Lars-Göran Vanhainen

Scale everything up to use cm or metre wave lengths – space is big enough

Space plasma is the “best” plasma: large plasma parameter, no collisions

Proposal submitted to EISCAT and granted time on the facilities, spring 2011

EISCAT Raman amplification

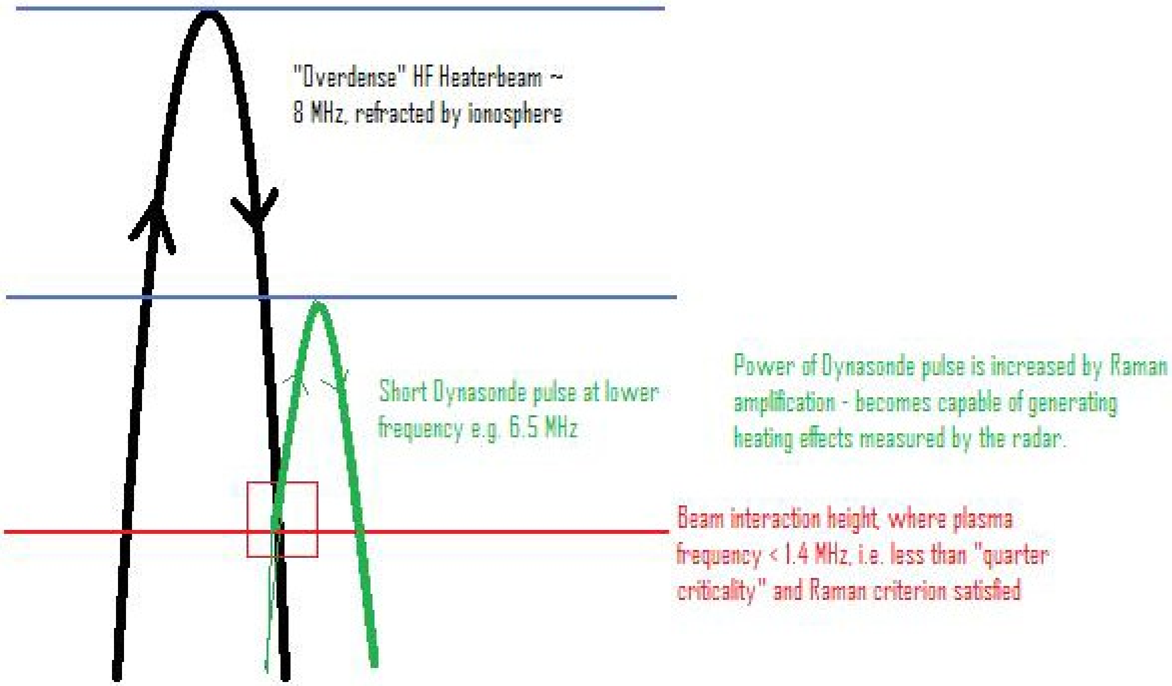

Figure 1: Counter-propagating HF Heater and Dynasonde pulses exchange energy by Raman amplification, producing a short, powerful Heater pulse at the Dynasonde frequency.

EISCAT Raman amplification

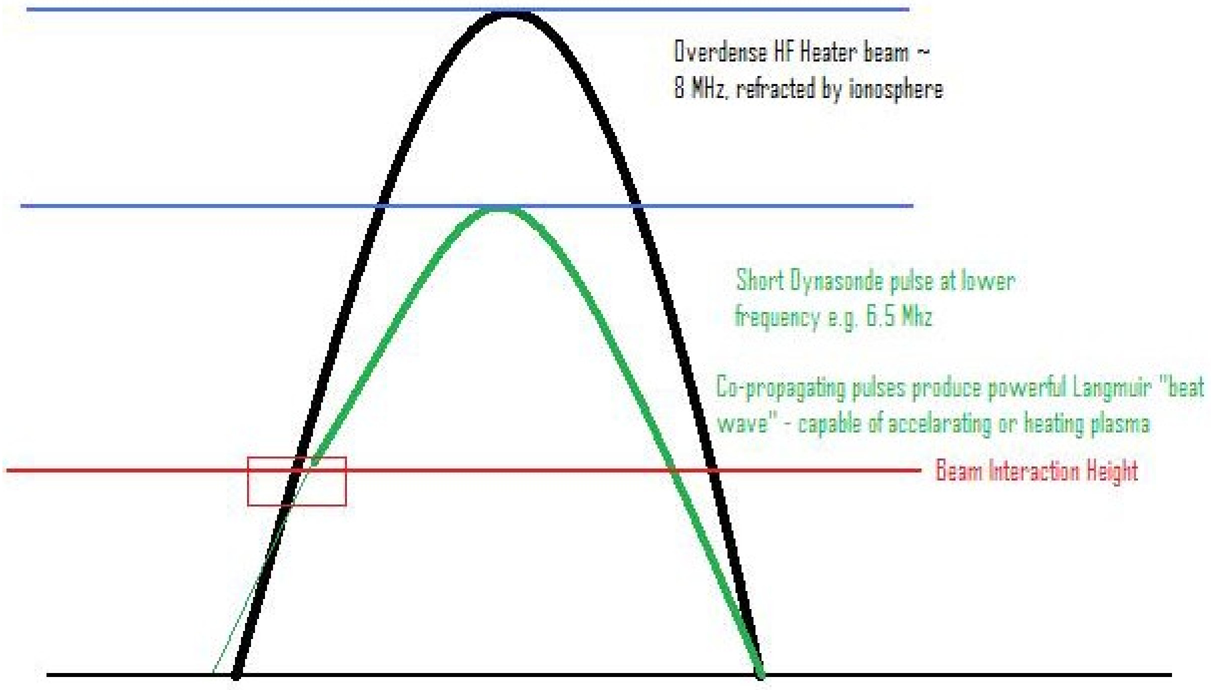

Figure 2: Co-propagating Heater and Dynasonde pulses produce a Langmuir “beat wave”, capable of heating or accelerating the plasma.

Raman for X-rays

	Visible	X-ray
Wave length	800 nm	10 nm
Pump duration	25 ps	300 fs
Interaction length	4 mm	50 μm
Spot diameter	600 μm	7.5 μm (0.1 μm?)
Pump intensity	10^{15} W/cm^2	10^{19} W/cm^2
Pump power	10 TW	10 TW
Pump energy	250 J	3 J (3 mJ?)
Plasma density	$5\text{x}10^{18}$ cm^{-3}	$3\text{x}10^{22}$ cm^{-3}
Probe intensity	10^{18} W/cm^2	10^{21} W/cm^2
Probe duration	25 fs	300 as
Facility	Vulcan at CLF	FLASH/LCLS

Conclusions

- Extending Raman amplification to reach truly high output intensities is possible for the right parameters
- Beware of the four horsemen: filamentation, RFS, inefficiency, saturation
- Amplification of wide probes to petawatt level is within reach
- Everything scales with pump wave length, so also works for X-rays: attosecond X-ray pulses possible