Tunable Plasma-Wave Laser Amplifier

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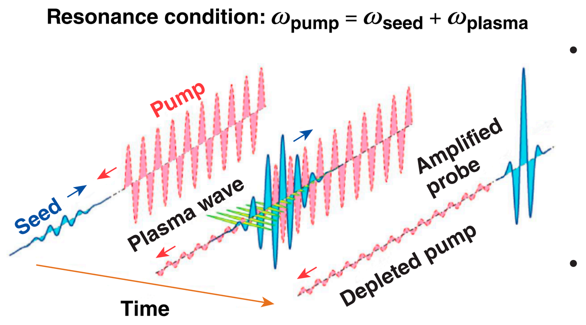
Plans for a tunable Raman amplifier at the Laboratory for Laser Energetics

Resonance condition: $\omega_{pump} = \omega_{seed} + \omega_{plasma}$



Technological novelty

- Energetic lasers: picoseconds
  - narrowband gratings
  - multilayer dielectric coated
  - ~2.5-J/cm² damage threshold
- Powerful lasers: femtoseconds
  - broadband gratings
  - gold gratings
  - ~0.15-J/cm² damage threshold

G11058

The best experiments to date have only reached energy-transfer efficiencies of <10%

Year	Author	Facility	Pump laser	E_{pump} (mJ)	Δt_{pump} (ps)	I_{pump} (10^{14} W/cm²)	E_{seed} (μJ)	ΔT_{seed} (fs)	n_e (10^{18} cm^{-3})	$\omega_{pump}/\omega_{pe}$	Efficiency (overlap) (%)
2004	M. Dreher	Max Plank	Ti:Sa	140	3.5	57	60	80	3	24	0.67
2005	W. Cheng	Princeton	Ti:Sa	40	10	2	7.5	550	11	13	1.1
2007	J. Ren	Princeton	Ti:Sa	82	20	2	16	500	13	12	3.9 (7.8)
2007	J. Ren	Princeton	Ti:Sa	56	20	1.4	3300	90	13	12	4.1 (5.9)
2012	D. Turnbull	Princeton	Ti:Sa	300	25	1.5	100	200	15	11	4.0
2015	X. Yang	University of Strathclyde	Ti:Sa	880	250	1.2	560	270	1	42	0.4

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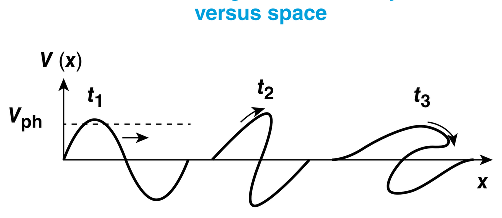
EPW Limitation

At high amplitudes, the EPW can break if the particle velocity carrying the wave approaches the wave's phase velocity

Particle longitudinal velocity versus space



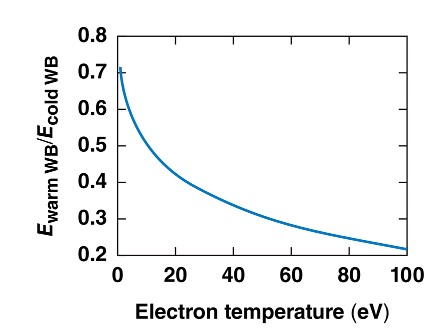
Prevention

$v_{osc} < v_{ph}$

$\frac{n_e}{n_c} > 2.5(a_{pump})^{4/3}$

Finite temperature affect on wave breaking

$$\frac{E_{warm}}{E_{cold}} = \left(1 - \frac{1}{3}B - \frac{8}{3}B^{1/4} + 2B^{1/2}\right)^{1/2}$$



D. S. Clark and N. J. Fisch, Phys. Plasmas 10, 3363 (2003);
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E25524a

There are three parameter regimes of interest where potentially new experimental progress can be achieved in the field of Raman amplification

Seed power

Regime	Thermal SRS	Filamentation	Landau damping (LD)	Resonance detuning	Wave breaking
High energy	×	×	×	—	×
Seed ionization	o	o	×	—	×
Pump depletion	o	o	o	—	×

Seed ionization
1. Avoids pump limitations
2. Produces a very cold plasma (<10 eV)

The seed-ionization and pump-depletion regimes will be realized at LLE for the first time because of our high-power seed pulses.

E25525a

Summary

The capabilities afforded by the lasers and diagnostics at LLE will allow for multiple areas of new exploration into the field of Raman amplification

- The promise of Raman amplification to amplify and compress short pulses to high peak powers in a plasma has largely been contained within theory and simulations
- Experiments are hindered by many plasma-physics phenomena that are difficult to predict and therefore require careful measurement
- The characteristics of the pump and seed lasers at LLE make it possible to access regimes that were not possible in past experiments, where much of the limitations of Raman amplification are avoided

E25519a

Pump Limitation

Stimulated Raman backscatter from thermal noise can deplete the pump energy before reaching the seed pulse

General SRS

$$\gamma_{SRS} = a_{pump}(\omega_{pump}\,\omega_{pe})^{1/2}$$

$$a_0 = \left(\frac{I \times \lambda^2_{\mu m}}{1.3 \times 10^{18}}\right)^{1/2}$$

$$\omega_{pe} = \left(\frac{e^2 n_e}{m_e \epsilon_0}\right)^{1/2}$$

Effect of chirp

$$\Delta v_{SRS} = \gamma_{SRS}/2\pi$$

$$G = \exp(\Delta v_{SRS}\, t_{lim})$$

$$t_{lim} = \Delta t_{pump}\frac{\Delta v_{SRS}}{\Delta v_{pump}}$$

	$\Delta\lambda_{SRS}$ (nm)	$\Delta\lambda_{pump}$ (nm)	G
M. Dreher	4.5	8	41
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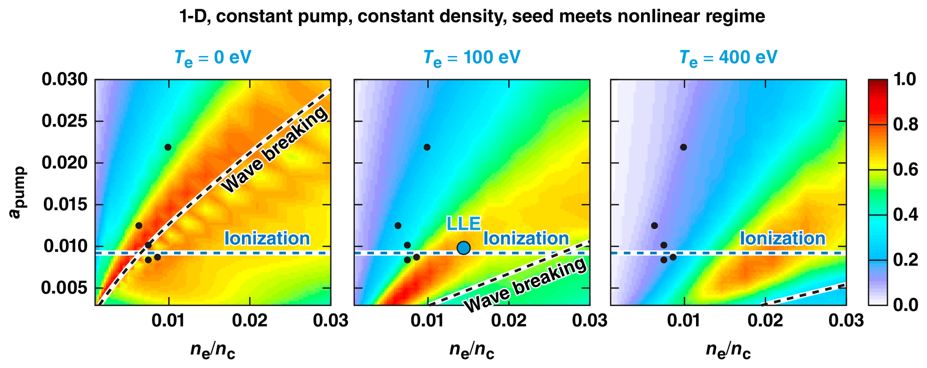
A large parameter scan over pump intensities and densities has been run in particle-in-cell (PIC) to study the effect of wave breaking

1-D, constant pump, constant density, seed meets nonlinear regime



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The high-energy regime aims to produce the highest energy amplifier using the maximum energy of the pump: 50 J

Regime	E_{pump} (mJ)	Diameter (μm)	Δt_{pump} (ps)	I_{pump} (10^{14} W/cm²)	E_{seed} (mJ)	Δt_{seed} (fs)	I_{seed} (10^{14} W/cm²)	n_e (10^{18} cm^{-3})
High energy	50000	800	25	4	75	75	3	15

Advantages
- Most-energetic amplifier
- Possibility of producing a medium-range Raman amplifier (first)

Disadvantages
- Fighting all previously mentioned limitations

SRS

$\Delta\lambda_{SRS}$ (nm)	$\Delta\lambda_{pump}$ (nm)	G
4.4	8	1620

Detune

q
0.03

Landau

$k\lambda_{De}$ (50 eV)	$k\lambda_{De}$ (150 eV)
0.16	0.28

E25531a

The primary application of Raman amplification is to produce PW-scale laser pulses not limited by the damage thresholds of grating compressors

Physics milestones

Amplification of seed
- Strong coupling between pump and seed mediated by an electron plasma wave (EPW)

Reach pump depletion
- Demonstrate that the slice efficiency of a Raman amplifier can be high (>30%)

Efficient amplifier
- Demonstrate pump depletion across the entire amplifier such that the overall efficiency is high (>30%)

High-fidelity seed
- Demonstrate that the amplified seed has good wavefront and temporal characteristics required for experiments (focusability, contrast, etc…)

LLE objectives

- Develop advanced diagnostics to identify limiting phenomena
- Develop mitigation strategies
- Identify an empirical optimal parameter regime for efficient Raman amplification
- Elucidate the road map to scaling to large laser systems based on these results

E25520a

EPW Limitation

The pump chirp detunes the resonant interaction, which can reduce the efficiency of energy transfer in the pump-depletion regime

Pump chirp

$$q \approx \frac{613}{\Delta t\,(\text{ps})}\frac{\Delta\lambda}{\lambda}\left(\frac{10^{19}\ \text{cm}^{-3}}{n_e}\right)^{1/2}\frac{10^{14}\ \text{W/cm}^2}{I\lambda^2(\mu m)}$$

$$Eff_{max} < 1 - q$$

	q
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N. Yampolsky and N. Fisch, Phys. Plasmas 18, 256711 (2011).

E25523a

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  - strongly reduces the threshold for thermal and ponderomotive filamentation
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- Changing temperature as the pump heats the plasma can detune a resonance in the linear regime
- In literature
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  - analytic estimate based on inverse bremsstrahlung heating (many different models)
- At LLE we plan to build a time resolved Thompson scattering diagnostic (~2 ps resolution)*

Absolute temperature measurements versus time are extremely important for the interpretation of results.

*A. Davies *et al.*, UO6.00003, this conference.

E25526a

The seed-ionization regime takes advantage of our intense seed to produce the plasma, thereby avoiding the pump limitations

Regime	I_{seed} (10^{14} W/cm²)	E_{pump} (mJ)	Diameter (μm)	I_{pump} (10^{14} W/cm²)	Δt_{pump} (ps)	E_{pump} (mJ)	n_e (10^{18} cm^{-3})
Seed ionization	2.6	75	700	0.8	50	16000	10

Advantages
- Avoid pump limitations
- Test of seed ionization (first)
- Possibility of producing a medium range-raman amplifier (first)

Disadvantages
- Fighting all previously mentioned limitations

E25532a

There are many phenomena that can interrupt the Raman amplification process

Pump: Amplification

Thermal stimulated Raman scattering (SRS)
- SRS growing from thermal noise can deplete the pump and degrade amplified seed contrast

Filamentation
- Thermal or ponderomotive filamentation degrades the pump pulse wavefront

EPW: Pump depletion

Wavebreaking
- Nonlinear effect where electrons dephase from the EPW, destroying the coherence of the structure

Resonance detuning
- Resonance condition not satisfied over the whole interaction (pump chirp, density gradients, temperature gradients…)

Landau damping
- Collisionless damping of the EPW

Seed: Amplification limits

Thermal forward raman scattering
- Intense seed can decay into a forward-propagating photon and backward-propagating EPW

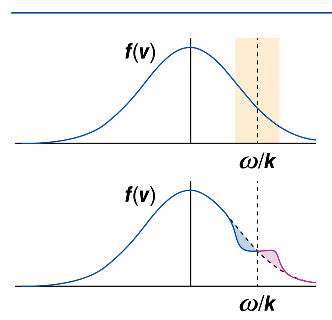
Relativistic filamentation/focusing
- Wavefront degradation caused by filamentation driven by a relativistic mass increase of electron

Wakefield generation
- An intense seed expels electrons, changes density, destroys resonance, and loses energy

E25521a

EPW Limitation

Landau damping (LD) is a wave–particle interaction that transfers energy from a plasma wave to particles that are traveling near the phase velocity of the wave



$$k_{EPW}\lambda_{De} \le 0.29$$

$$\lambda_{De} \propto \sqrt{T_e/n_e}$$

	$k\lambda_{De}$ (50 eV)	$k\lambda_{De}$ (150 eV)
M. Dreher	0.48	0.83
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- Weak seed (noise): LD damps the wave amplitude to zero
- Strong seed: LD reduces growth rate, increasing the time in the linear regime
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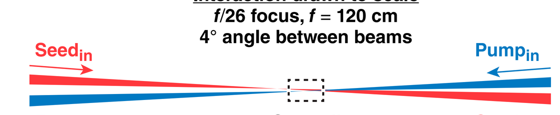
J. L. Kline *et al.*, Phys. Plasmas 13, 055906 (2006).

E25530a

The LLE experimental setup is designed to be flexible to allow changing of parameters to follow feedback from experimental results

Interaction drawn to scale
f/26 focus, f = 120 cm
4° angle between beams



Target/geometry
- Gas cell
  - long homogeneous plasma density
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  - $\omega_{pump}/\omega_{pe}$ = 8 to 13
- Noncolinear interaction
  - isolate scattering sources

	λ_{cen}	$\Delta\lambda$	E_{max}	Δt
Pump	1053 nm	8 nm	50 J	1 to 100 ps
Seed	1140 to 1200 nm	60 to 120 nm	75 mJ	75 to 100's fs

S. Bucht *et al.*, GP10.00050, this conference.

E23504d

The pump-depletion (PD) regime aims to produce the highest-efficiency amplifier possible by depleting the pump from the beginning

Regime	Δt_{seed} (fs)	E_{seed} (mJ)	Diameter (μm)	I_{seed} (10^{14} W/cm²)	n_e (10^{18} cm^{-3})	I_{pump} (10^{14} W/cm²)	Δt_{pump} (ps)	E_{pump} (mJ)
Pump Depletion	200	75	150	21	10	0.9	50	800

$$a_{seed}\Delta t_{seed}\sqrt{\omega_{seed}\omega_{pe}} \sim 5$$

	PD
M. Dreher	0.31
W. Cheng	0.28
J. Ren	0.32
J. Ren	2.0
D. Turnbull	0.27
X. Yang	0.60
LLE-PD	5.07

Advantages
- Highest possible efficiency, no linear gain (first)
- Test of pump-depletion theory (first)

Disadvantages
- Requires a small spot size, therefore little energy in the pump

E25533a

UNIVERSITY of ROCHESTER

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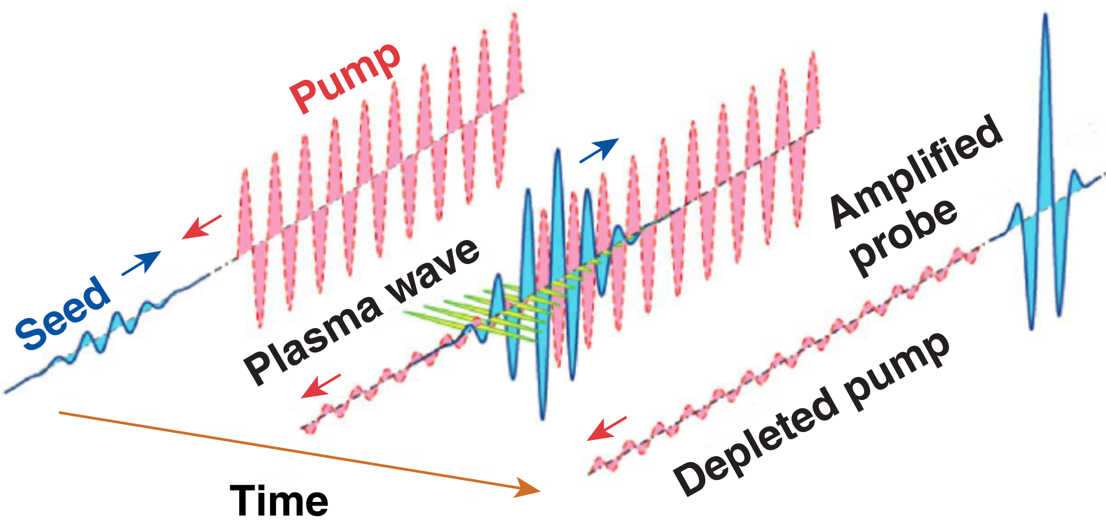

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UR LLE

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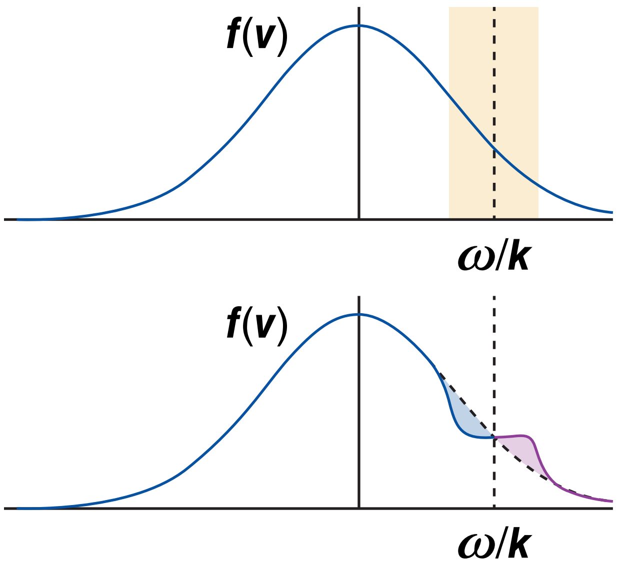

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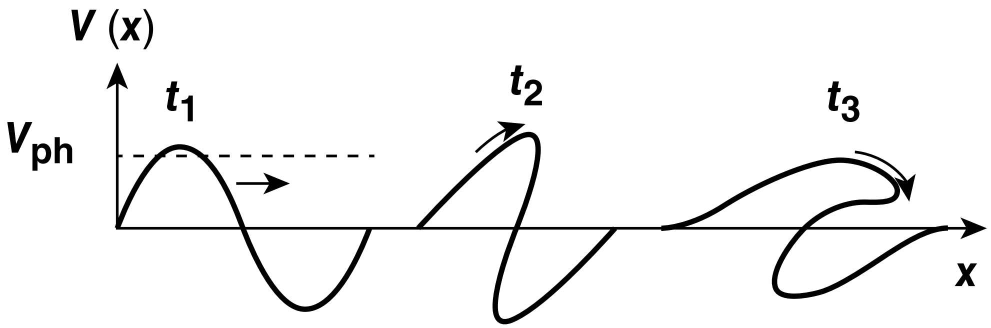

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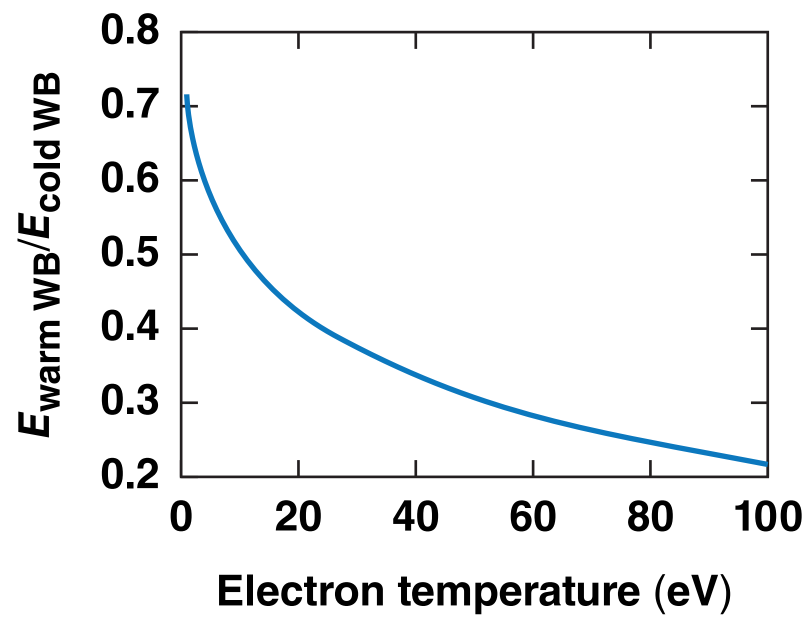

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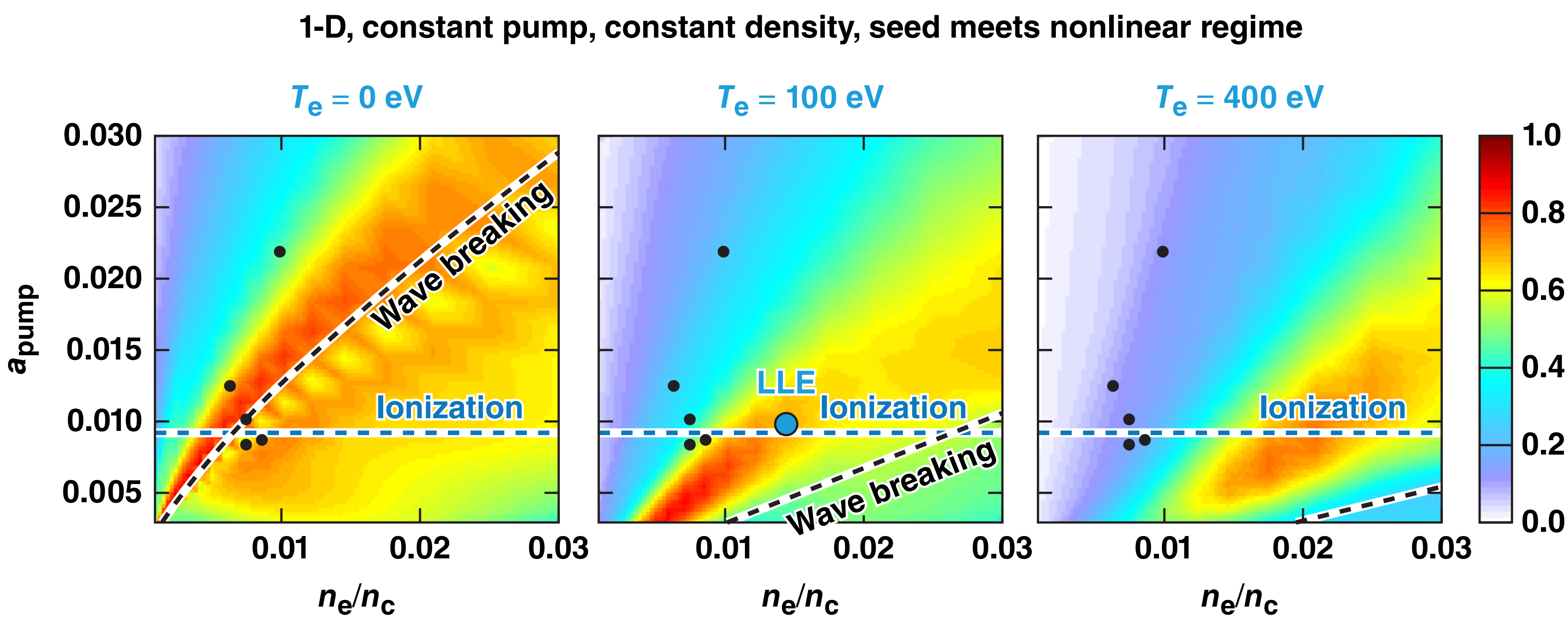

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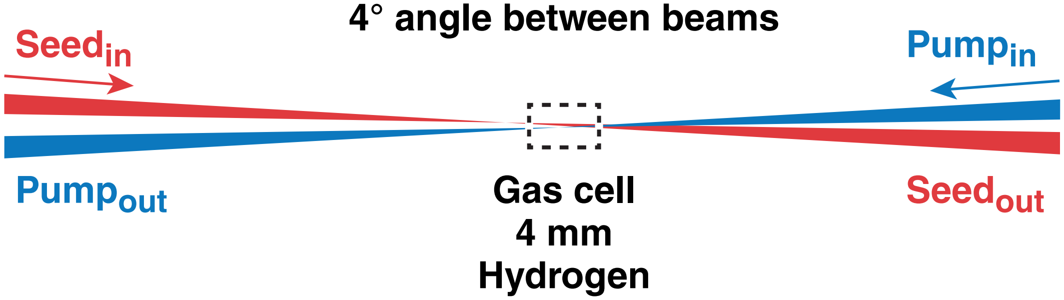

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E25532a

The pump-depletion (PD) regime aims to produce the highest-efficiency amplifier possible by depleting the pump from the beginning

Regime	Δt_{seed} (fs)	E_{seed} (mJ)	Diameter (μm)	I_{seed} (10^{14} W/cm^2)	n_e (10^{18} cm^{-3})	I_{pump} (10^{14} W/cm^2)	Δt_{pump} (ps)	E_{pump} (mJ)
Pump Depletion	200	75	150	21	10	0.9	50	800

$$a_{seed}\Delta t_{seed}\sqrt{\omega_{seed}\omega_{pe}} \sim 5$$

	PD
M. Dreher	0.31
W. Cheng	0.28
J. Ren	0.32
J. Ren	2.0
D. Turnbull	0.27
X. Yang	0.60
LLE-PD	5.07

Advantages

- Highest possible efficiency, no linear gain (first)
- Test of pump-depletion theory (first)

Disadvantages

- Requires a small spot size, therefore little energy in the pump