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Kinetic simulations of intense light pulses generated by Brillouin backscattering in laser-plasma interaction

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PLAS@PAR
Plasmas à Paris

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Collaborations

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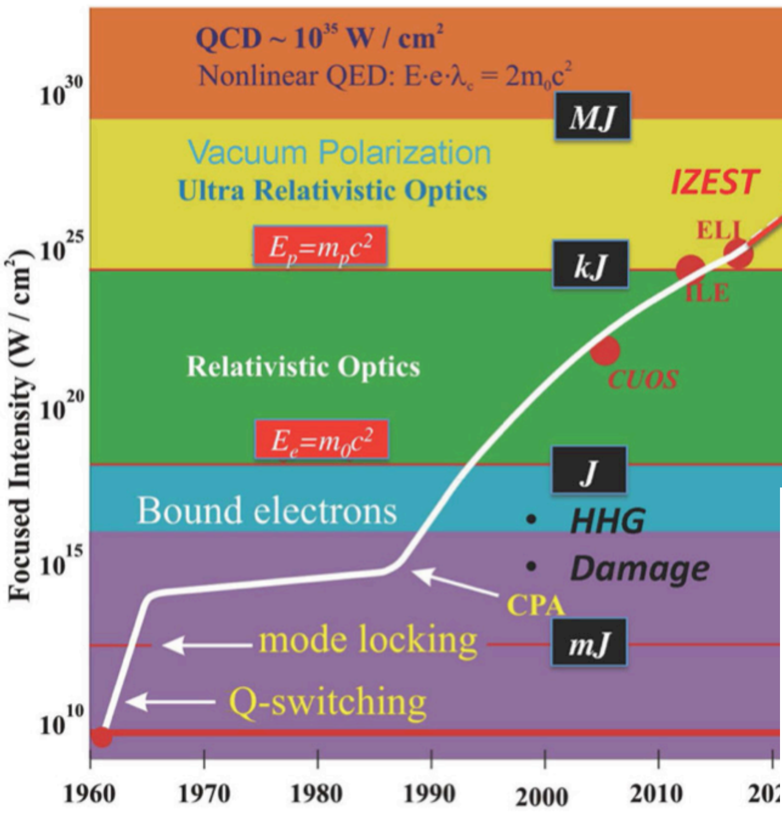
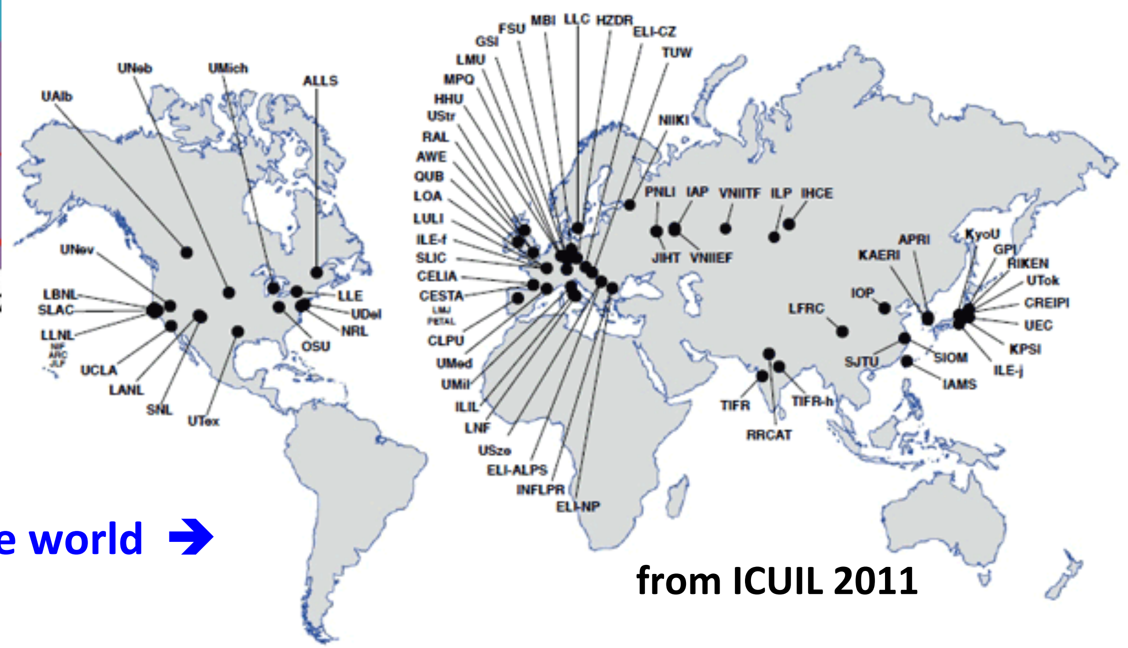
SAPIENZA UNIVERSITÀ DI ROMA	L. Lancia, A. Giribono, L. Vassura
IZEST International Zeta-Exawatt Science Technology	M. Quinn, G. Mourou
GSI	A. Frank
eli beamlines	S. Weber

High-intensity laser in time and space



← since invention of laser: constant push towards increasing focused intensity of the light pulses

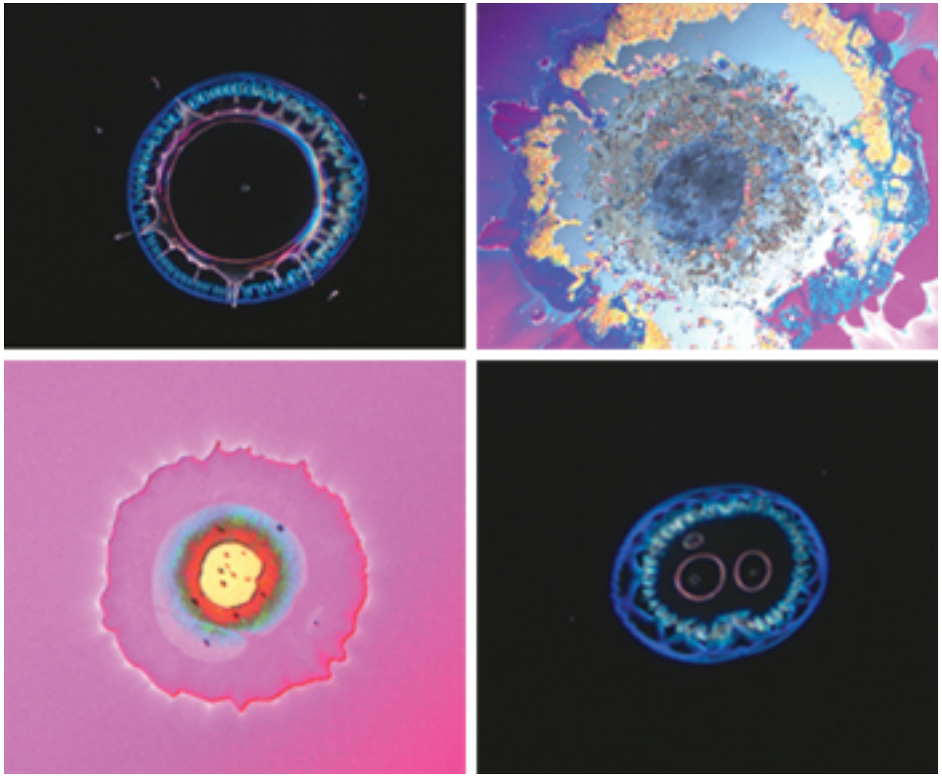


from ICUIL 2011

UHI light infrastructures in the world →

The problem of damage threshold for optical materials

Laser-induced damage of optical coatings



Chirped pulse amplification

D. Strickland, G. Mourou, Optics Comm. 55, 219 (1985)
G.A. Mourou et al., Phys. Today 51, 22 (1998)

⇒ ionisation intensity-limit: $I \leq 10^{12}$ W/cm^2

⇒ damage threshold of gratings: ≤ 1 J/cm^2

⇒ 1 EW & 10 fs → 10 kJ

→surface areas of order 10^4 cm^2 = 1m x 1m

⇒ difficult to produce and very expensive

↓

PLASMA OPTICS

BUT : Laser Propagation in a Plasma?

Natural modes in a non-magnetized plasma

Electromagnetic wave (EMW)

$\omega^2 = \omega_p^2 + k^2 c^2$ → limiting frequency $\omega = \omega_p$

plasma behaves as 'transparent' dielectric

Electron plasma wave (Langmuir wave, EPW)

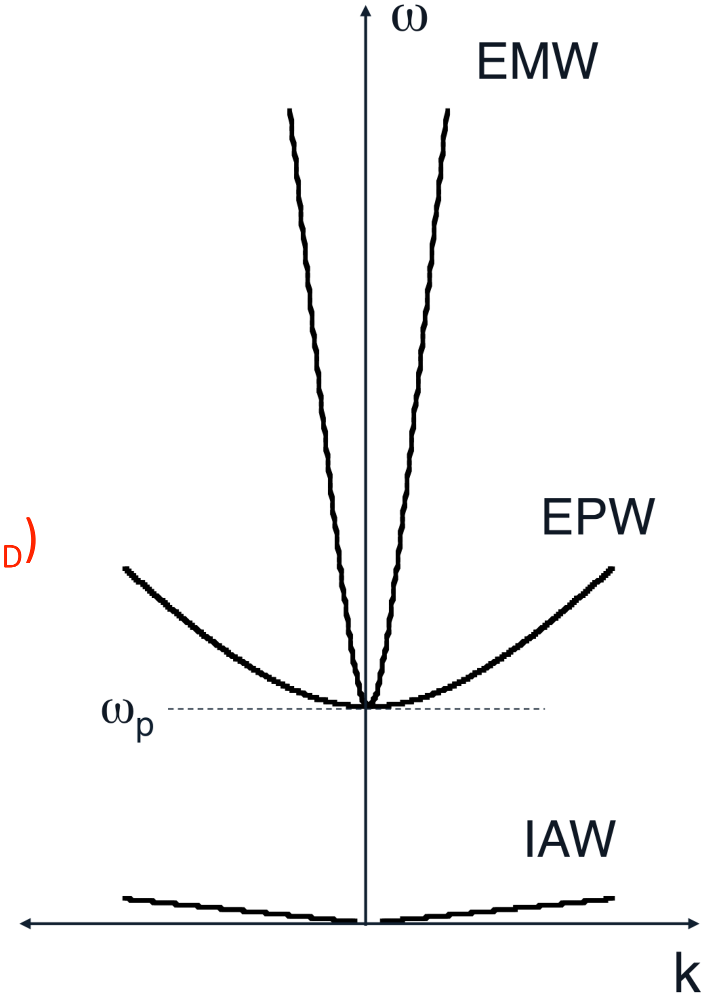
$\omega^2_{epw} \approx \omega^2_p + 3\,k^2_{epw}\,v^2_{Te} \approx \omega^2_p\,(1 + 3\,k^2_{epw}\,\lambda^2_D)$

Ion-acoustic wave (IAW)

$\omega_{iaw} \approx c_s\,k_{iaw}$ $c_s \ll v_{Te}$

$\omega_p = (4\pi n_e e^2/m_e)^{1/2}$; $ve = (k_B T_e/m_e)^{1/2}$;

$\lambda_D = v_e/\omega_p$; $c_s = (k_B T_e/m_i)^{1/2}$

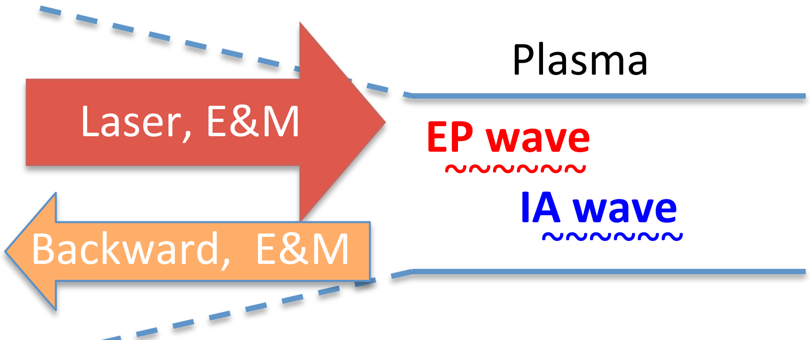


➔ „Un"-natural modes are of great interest (see later) !

Wave coupling in a plasma

➔ Waves in a plasma can couple:

intensity of one or two waves can grow in an uncontrolled way at the expense of the intensity of another wave if a resonance condition is fulfilled:

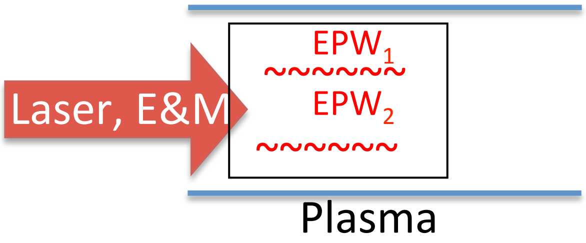


Backscattering

$\omega_0 = \omega_1 + \omega_2$ (energy)

$\mathbf{k_0} = \mathbf{k_1} + \mathbf{k_2}$ (momentum)

➔ 3-wave coupling due to conservation of energy and momentum

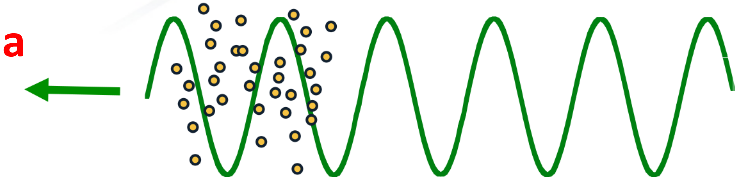


Two plasmon decay

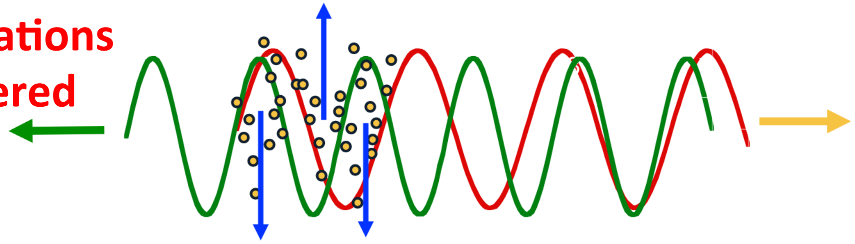
A classic exemple of Laser-Plasma Interaction (LPI):
Parametric Instabilities (PI) , energy transfer among waves

Parametric Instability growth: from noise to coherent motion

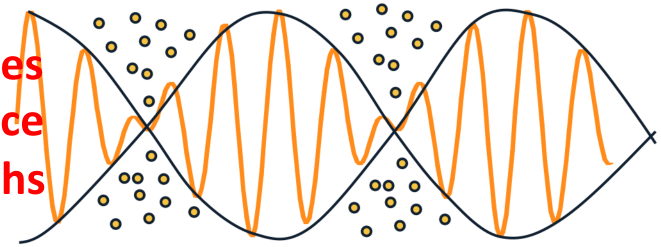
Laser into plasma



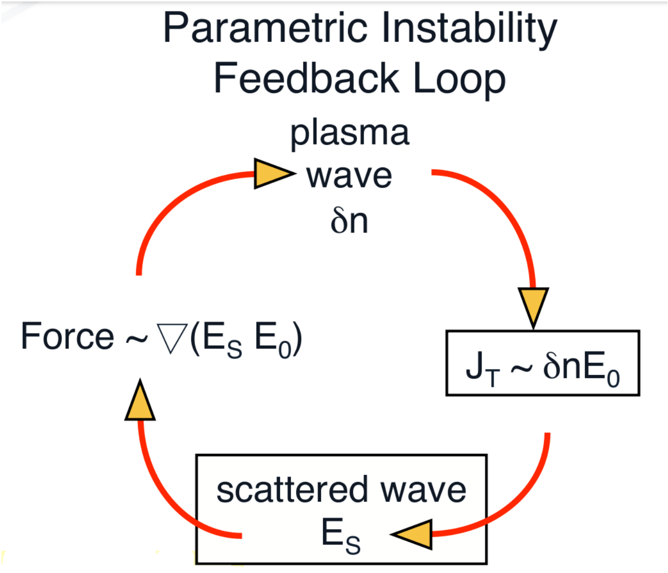
Plasma oscillations radiate scattered light



Beating of 2 em. Waves
→ponderomotive force
→particles into troughs



Bunching matches electrostatic mode
→ 3 waves resonant
→ growth of instability



Parametric Instability Feedback Loop

plasma wave δn

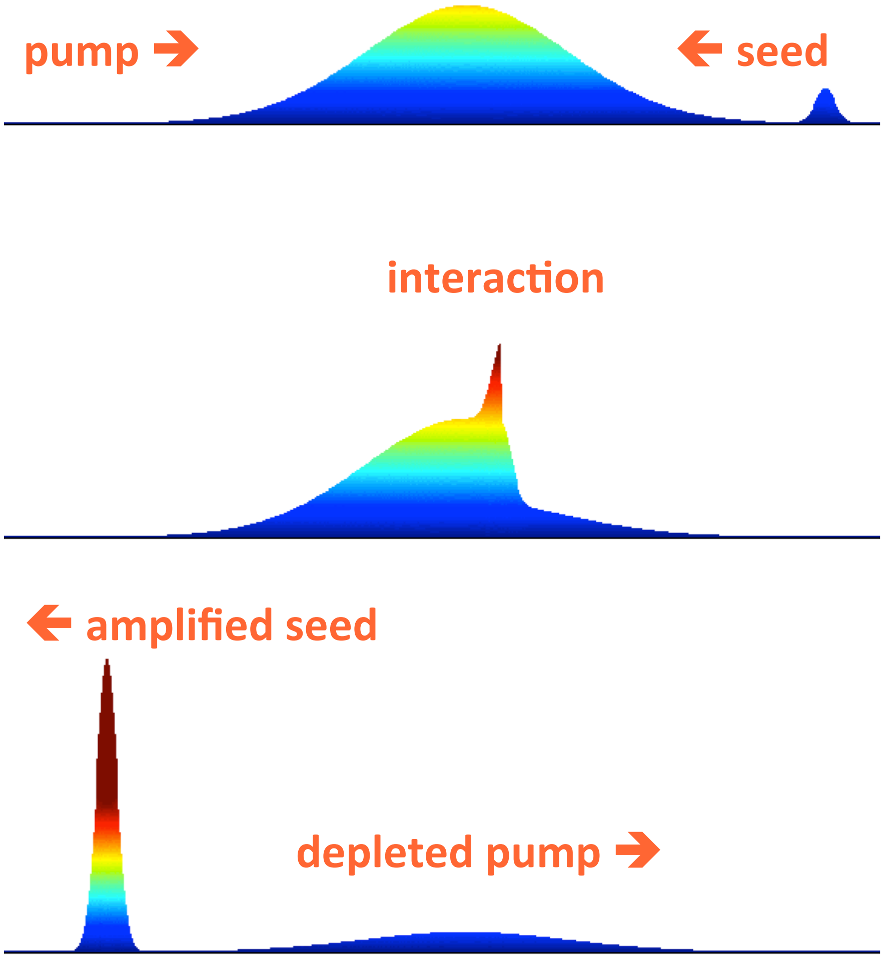
$J_T \sim \delta n E_0$

scattered wave E_S

Force ~ $\nabla(E_S E_0)$

from noise to coherent motion
How to control it?

The basic principle of plasma amplification



pump →

← seed

interaction

← amplified seed

depleted pump →

”NO” damage threshold in plasmas

high-energy long pump

↑↓

low-intensity short seed

Standard parametric instabilities :
3 wave coupling where the
plasma response is taken up by

- electron plasma wave –→ Raman
- ion-acoustic wave –→ Brillouin

conservation equations

- $\omega_{pump} = \omega_{seed} + \omega_{plasma}$
- $k_{pump} = k_{seed} + k_{plasma}$

time scales

- Brillouin $\tau_s \geq \omega_{cs}^{-1} \sim 1 - 10$ ps
- Raman $\tau_s \geq \omega_{pe}^{-1} \sim 5 - 10$ fs

Raman allows higher intensity since contraction to shorter scales

Brillouin in the strong-coupling regime (sc-SBS)

➔ in contrast to before: sc-SBS is a non-resonant mode (not an **eigen-mode**)

When the laser intensity is above a treshold that depends on the plasma temperature, transition from eigen-mode regime → quasi-mode regime characterized by:

$$\omega_{sc} = (1 + i\sqrt{3})\, 3.6 \times 10^{-2} (I_{14} \lambda^2_o)^{1/3} (Zm_e/m_i)^{1/3} (n_e/n_c)^{1/3}$$

i.e. pump wave (laser) determines the properties of the electrostatic wave !

➔ instability growth rate: $\gamma_{sc} = \mathrm{Im}(\omega_{sc})$

➔ New characteristic time scale for IAW: $\sim 1/\gamma_{sc}$ → can be a few 10s of fs !!

➔ More compression = higher intensity, and some advantages with respect to Raman

Particle-in-cell approach

➔ Idea: initial condition is a large number of particles with a given temperature distribution - they then evolve according to the following equations (Maxwell + Newton)

Electromagnetic field

$\nabla \times \mathbf{E} + \partial \mathbf{B}/\partial t = 0$

$\nabla \times \mathbf{B} - (1/c^2)\, \partial \mathbf{E}/\partial t = \mu_0\, \mathbf{J}$

$\nabla \bullet \mathbf{E} = \rho/\varepsilon_0$

$\nabla \bullet \mathbf{B} = 0$

Constituent relations for each cell

$\rho = \Sigma\, q_p$

$\mathbf{J} = \Sigma\, q_p\, \mathbf{u}_p/\gamma_p$

Characteristics of Vlasov-eqn.

$d\mathbf{x}_p/dt = \mathbf{u}_p/\gamma_p$

$d\mathbf{u}_p/dt = q_p\, (\mathbf{E}_p + \mathbf{u}_p \times \mathbf{B}_p/\gamma_p)$

$\gamma_p = (1 + p^2/(mc)^2)^{1/2}$

Reality versus simulation

$L \gg \lambda_{D,}$ $N_D = O(10^2 \ldots 10^6)$

➔ millions of billions of particle impossible !

BUT: simulation same for 10 and 10.000 since collective motion, particles ‘enslaved‘

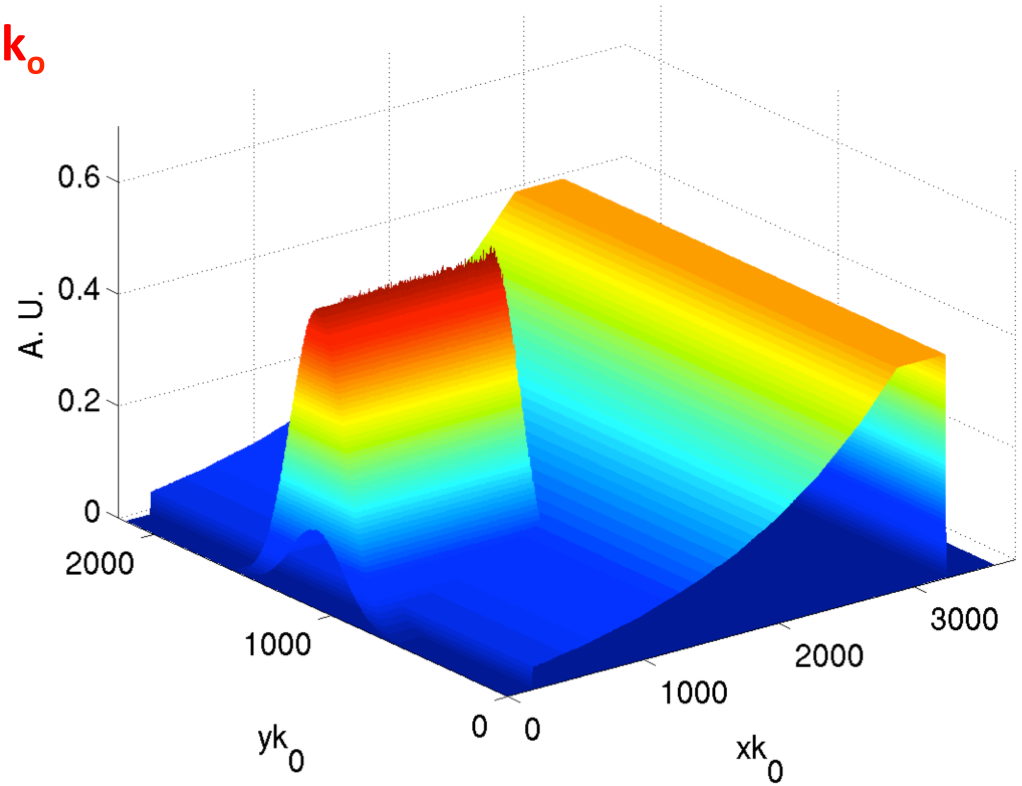
Computational aspects: laser propagation in a density ramp

- ➔ Need to resolve: **$1/\omega_{pe}$, $1/\omega_o$ & $1/k_o$**
- ➔ Particular case: $\Delta x = \Delta y = 0.18\ k_o^{-1}$

and $\Delta t = 0.18\ \omega_o^{-1}$; CFL: $c\ \Delta x \leq \Delta t$

- ➔ 2.4×10^8 computational cells
- ➔ 1.4×10^5 time steps
- ➔ $10^{8\ldots9}$ macro-particles

(a small fraction of real number!)



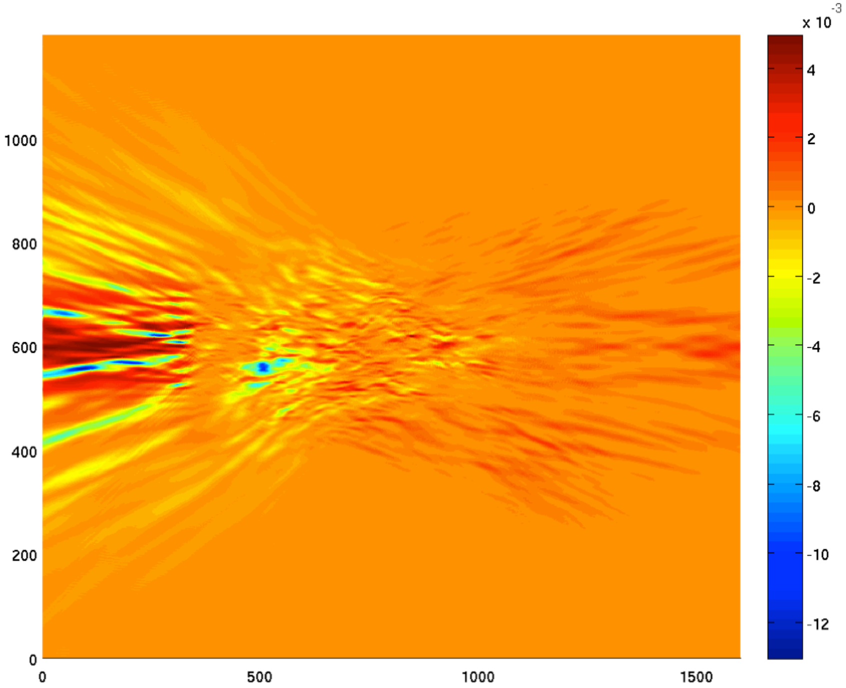
- ➔ **Order of 500‘000 CPU-hours !!** (~1 month running on 600 cores-57 yrs on 1 core)
- ➔ Producing hundreds of GB data
- ➔ **Multidimensional kinetic equations require VERY BIG computers !!!**

Competing instabilities

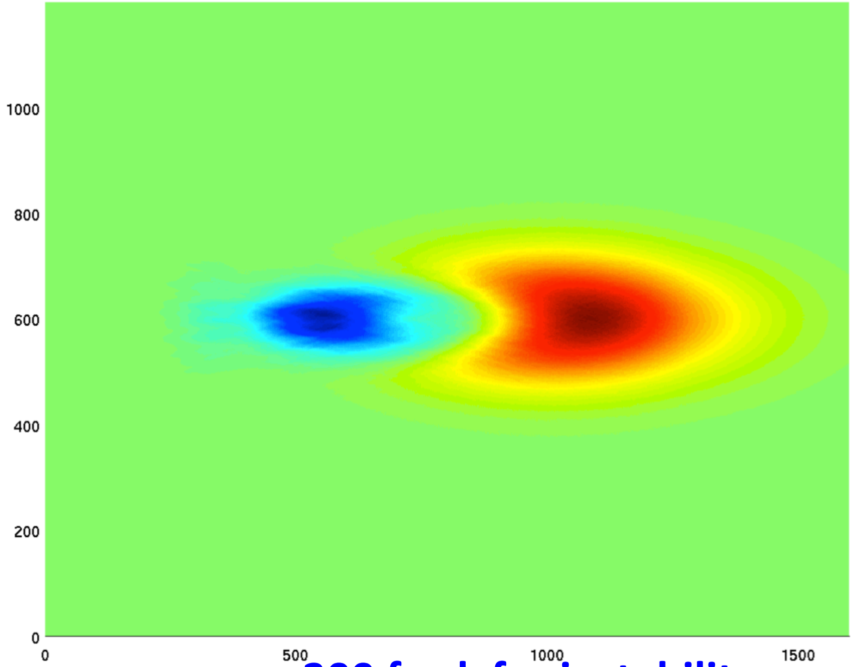
➔ amplification process has to be optimised in concurrence with other plasma instabilities !

1) avoid filamentation for pump and seed: $\tau_{p,s}/(1/\gamma_{fil}) < 1$ with $\gamma_{fil}/\omega_o \approx 10^{-5} I_{14} \lambda^2[\mu m](n_e/n_c)$

→ upper limit for τ_p & plasma amplifier length;



τ_{pump} = O(10ps) too long for the given density



τ_{pump} = 300 fs ok for instability
But not much energy transfert

Competing instabilities cont'd

2) avoid SRS if possible: $\tau_p/(1/\gamma_{srs}) < 1$ with $\gamma_{srs}/\omega_o \approx 4.3 \times 10^{-3} \sqrt{(I_{14}\,\lambda^2[\mu m])}\,(ne/nc)^{1/4}$

→ $1/\gamma_{srs} \approx 25$ fs !!

BUT can be controlled by plasma profile and temperature, associated energy losses small

➔ **Other limit related to efficency of energy transfer: $(1/\gamma_{sc}) \sim \tau_{wb}$** → $a_{max} = v_{osc}/c \approx \sqrt{(m_i/Zm_e)}\,(n_e/n_c)$

→ for $n_e = 0.05\, n_c$ get **$I_{max} \approx 10^{18} W/cm^2$**

high density → filamentation

low density → weak coupling

short pulse → low efficiency

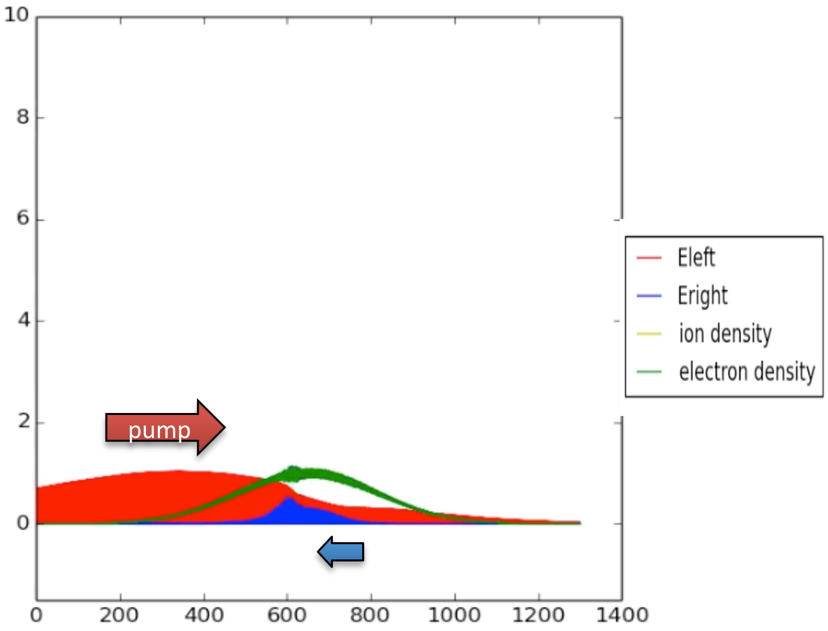
long pulse → wavebreaking

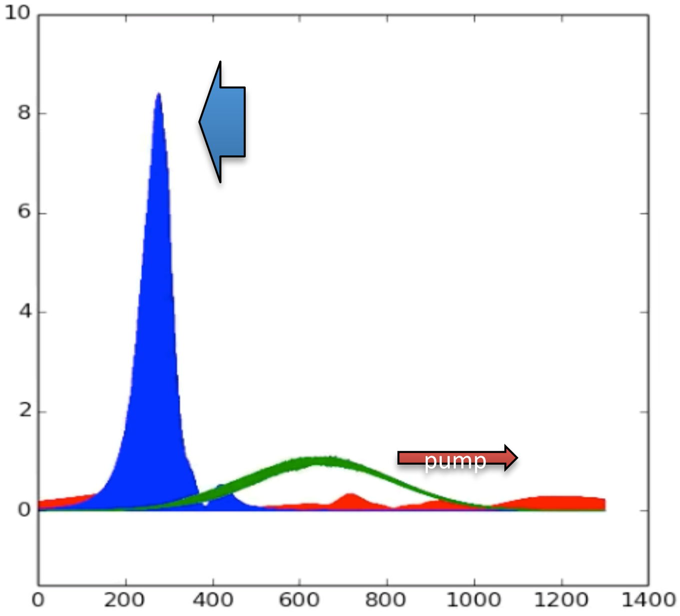
➔ From these consideration one obtains a parameter space of operation

➔ Optimization is required wrt

➔ to plasma profile, seed duration, pump intensities

1D sc-SBS plasma amplification simulations

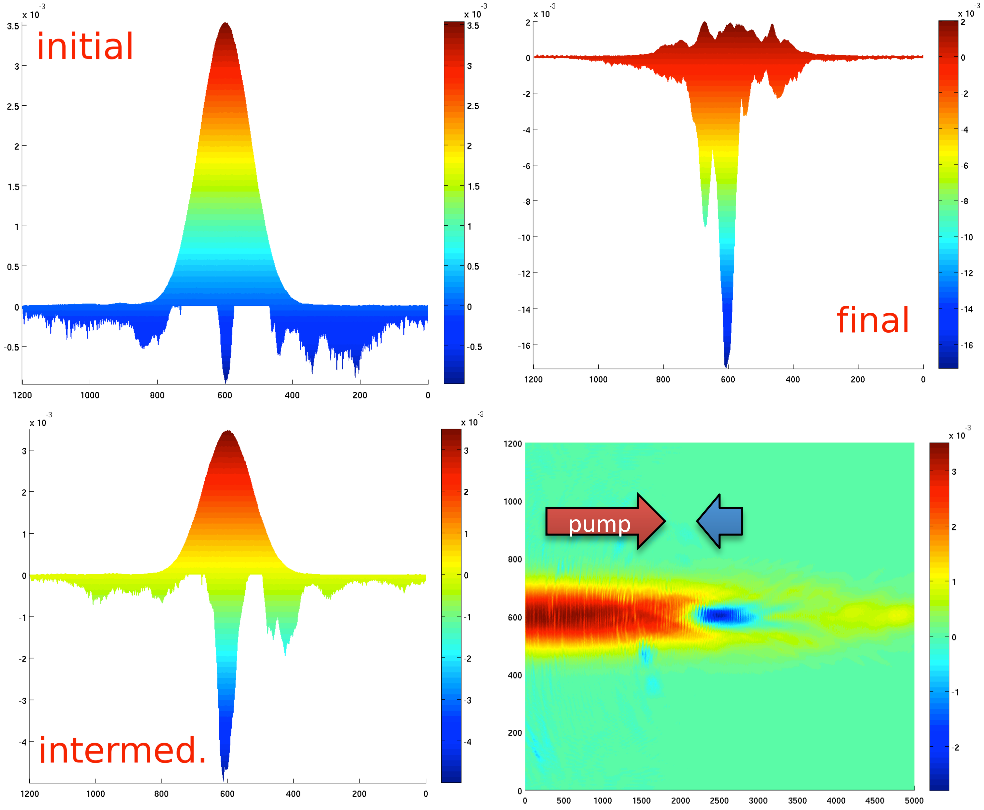




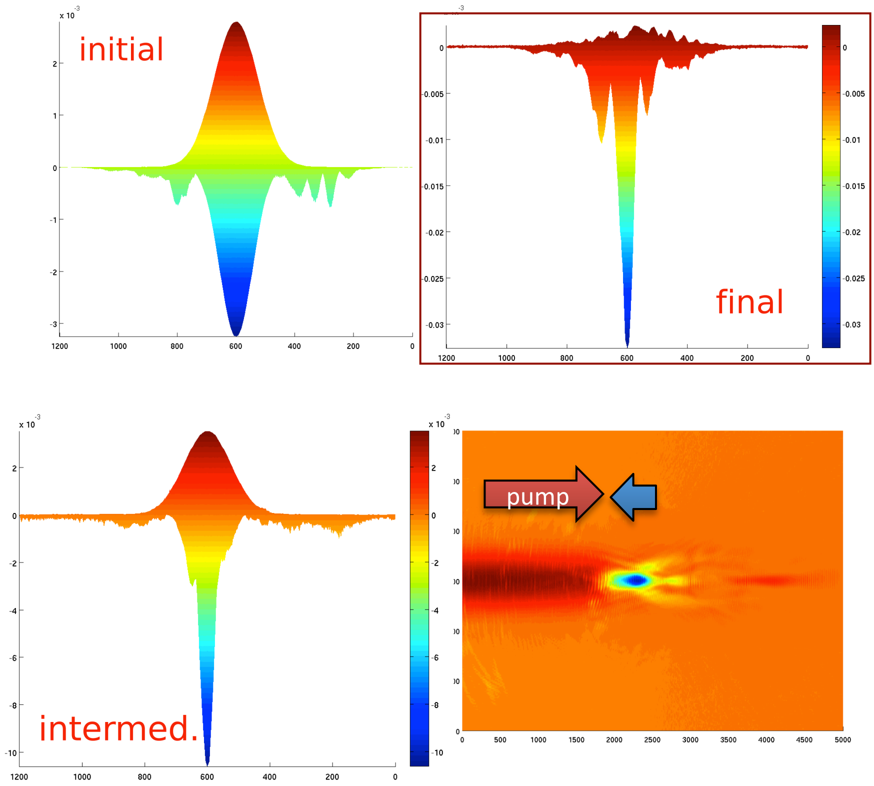
Density profile motivated
by gas-jet experiments

2D sc-SBS plasma amplification results

$I_s = 3 \times 10^{14} \rightarrow 5 \times 10^{16}$

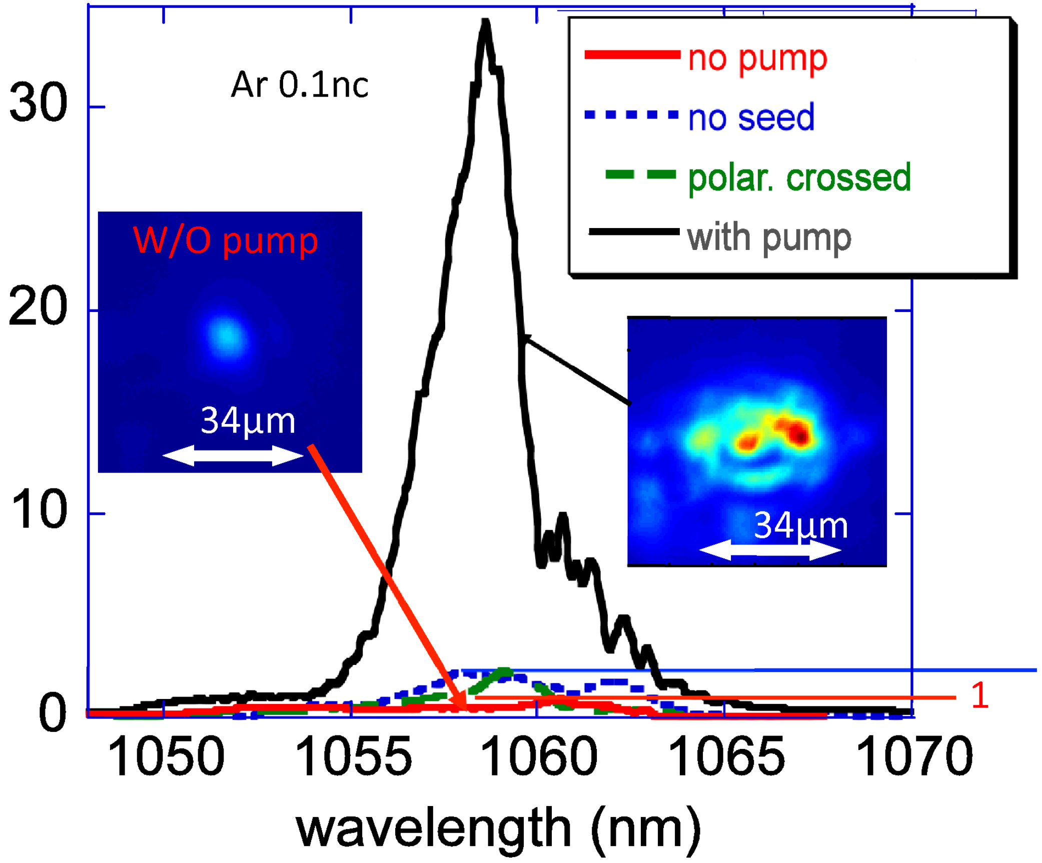


$I_s = 1 \times 10^{16} \rightarrow 1 \times 10^{17}$



- pump depletion obtained w/o problem (210 fs seed)
- close to actual experimental regime

A first proof-of-principle experiment @ LULI 100 TW



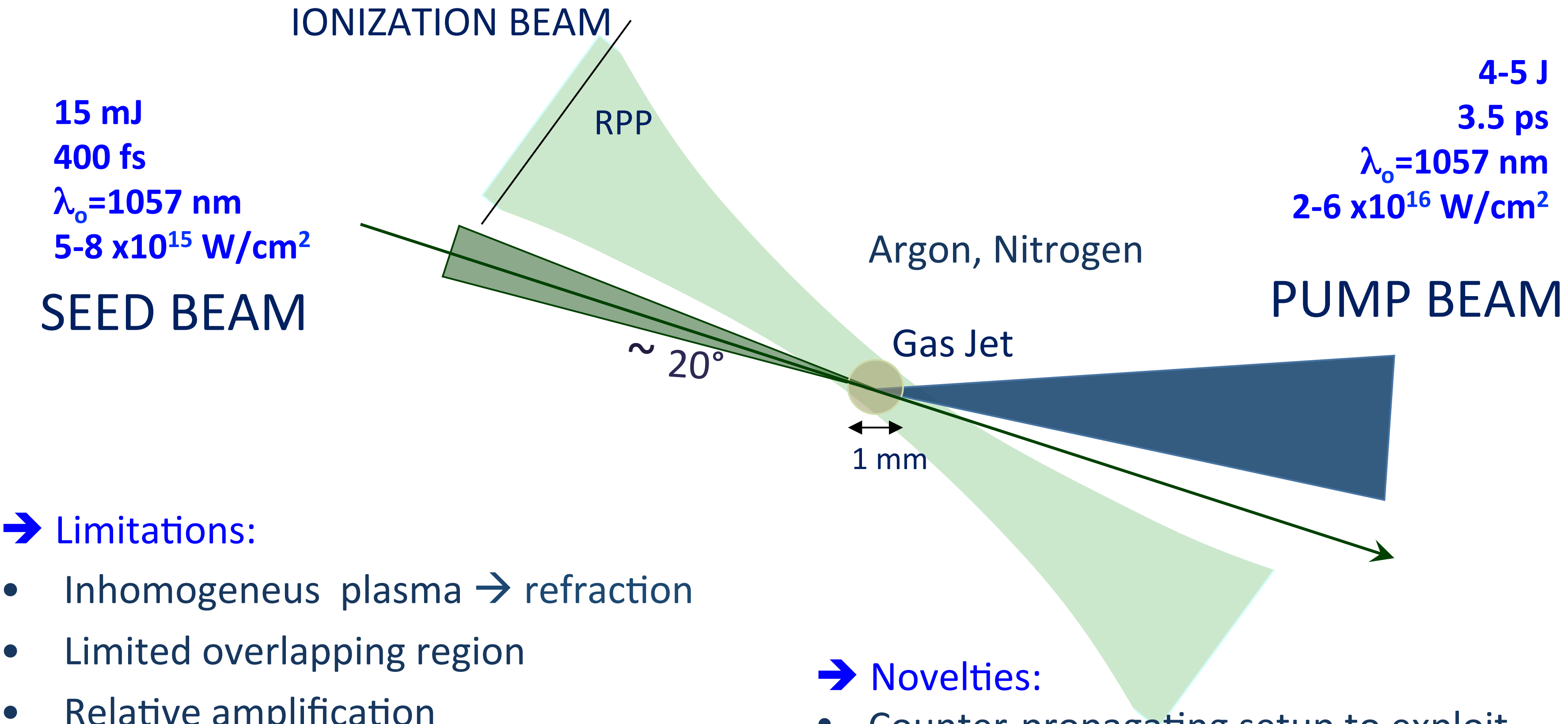
E_p = 2 J, $I_p = 6.5 \times 10^{16}$ W/cm^2
τ_p = 3.5 ps

E_s = 15 mJ, $I_s = 5 \times 10^{15}$ W/cm^2
τ_s = 400 fs

- pump & seed cross under angle interaction length: ≈ 100 µm
- energy uptake of seed 45 mJ
- Relative amplification factor of 35 (Is/Is0) achieved
- pump depletion achieved ! (100% on trajectory)
- crossed polarization ⇒ NO amplification

➔ **L. Lancia et al. PRL (2010)**

Experimental set-up



➔ Limitations:

- Inhomogeneus plasma → refraction
- Limited overlapping region
- Relative amplification

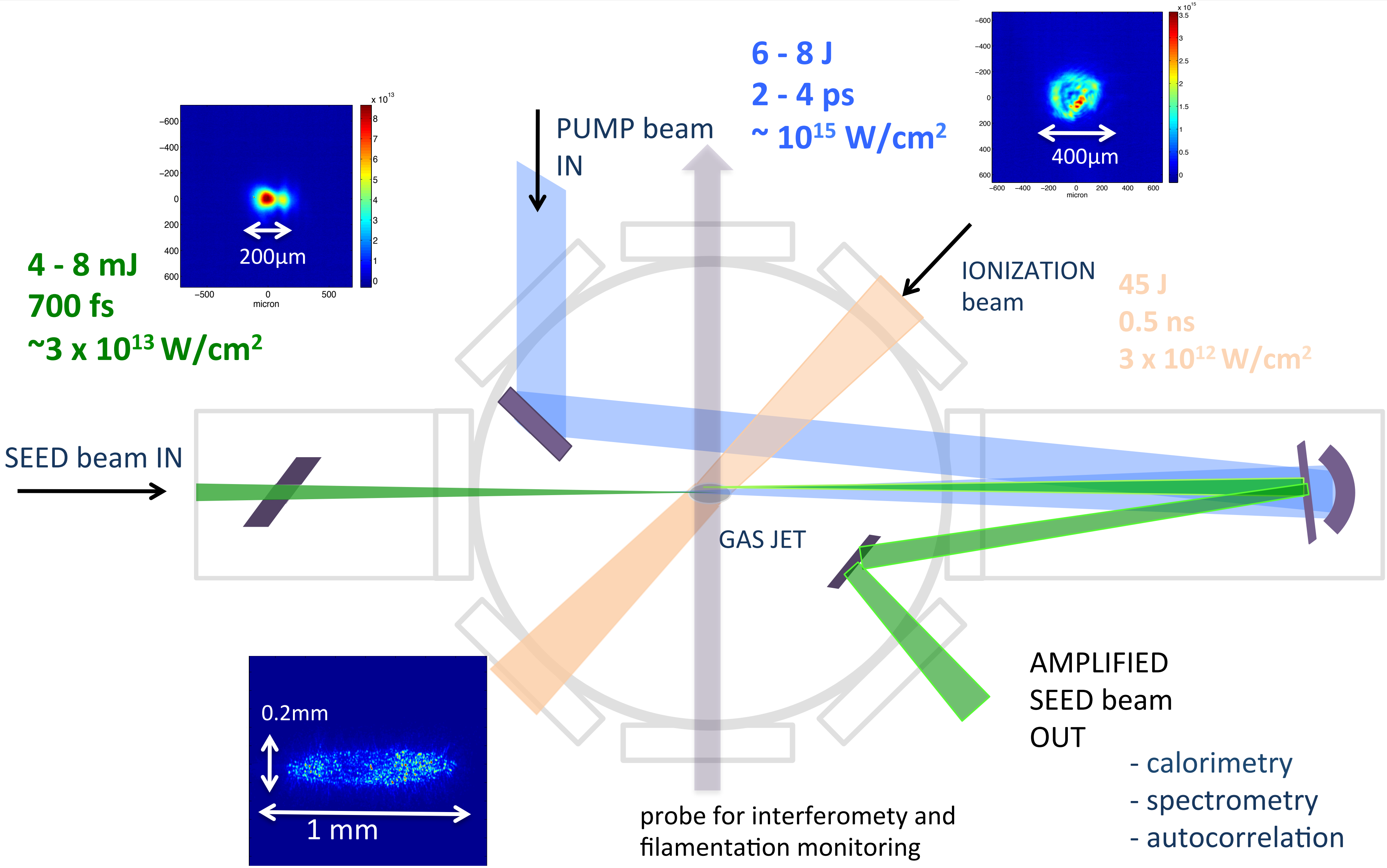
➔ Path for improvements:

- Plasma quality and characteristics
- More energy available for transfer

➔ Novelties:

- Counter-propagating setup to exploit whole plasma length
- More homogeneous plasma ionization
- Very low seed intensity !

Recent experiment @ LULI 100 TW



4 - 8 mJ

700 fs

~3 x 10^{13} W/cm^2

PUMP beam IN

6 - 8 J

2 - 4 ps

~ 10^{15} W/cm^2

IONIZATION beam

45 J

0.5 ns

3 x 10^{12} W/cm^2

SEED beam IN

GAS JET

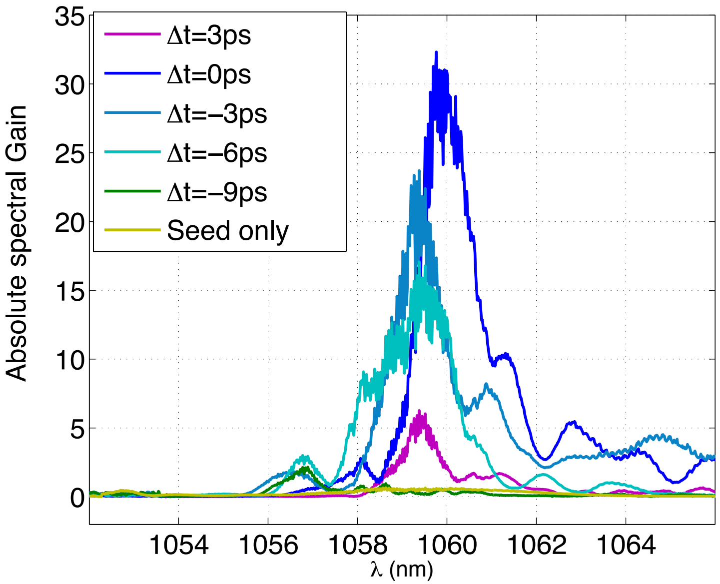
AMPLIFIED SEED beam OUT

- calorimetry
- spectrometry
- autocorrelation

probe for interferomety and filamentation monitoring

Absolute amplification obtained

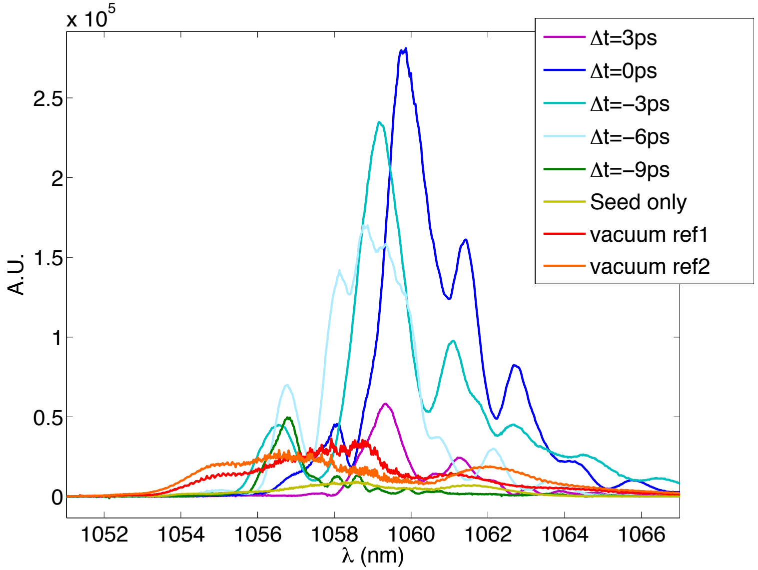
Spectral amplification for different delays



➔ A narrow range of frequencies favoured,

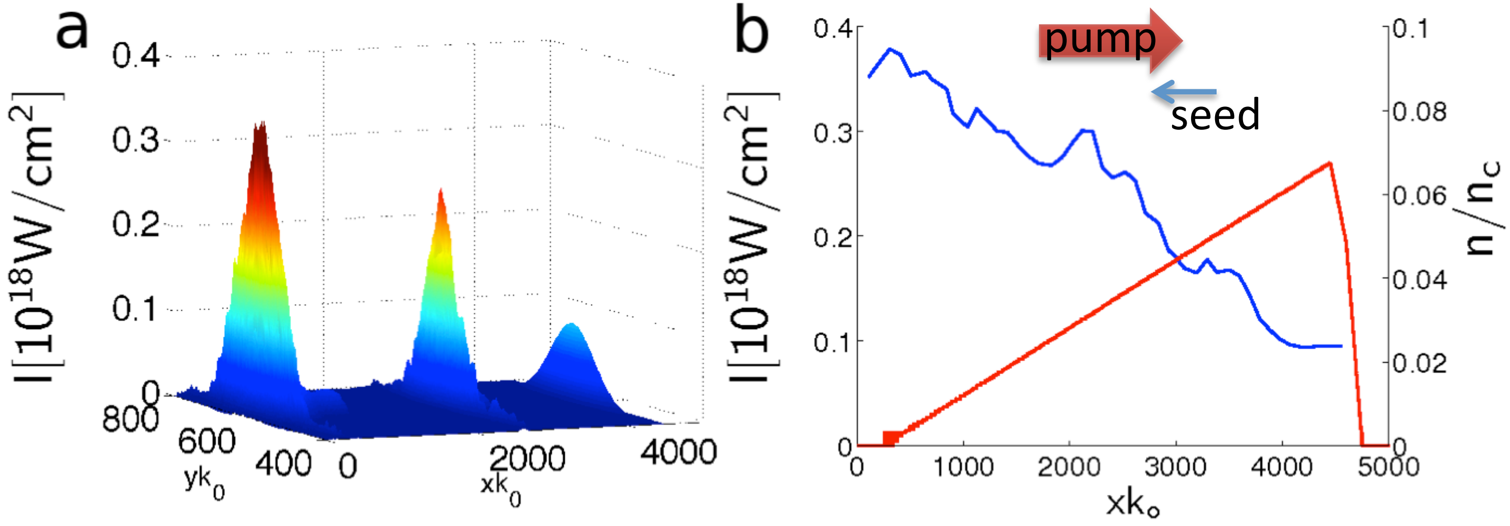
➔ More efficient amplification corresponds to a wider range

Spectrally resolved signal of the amplified seed for different delays



➔ The more efficient amplification is the more spectrum is shifted to lower frequencies

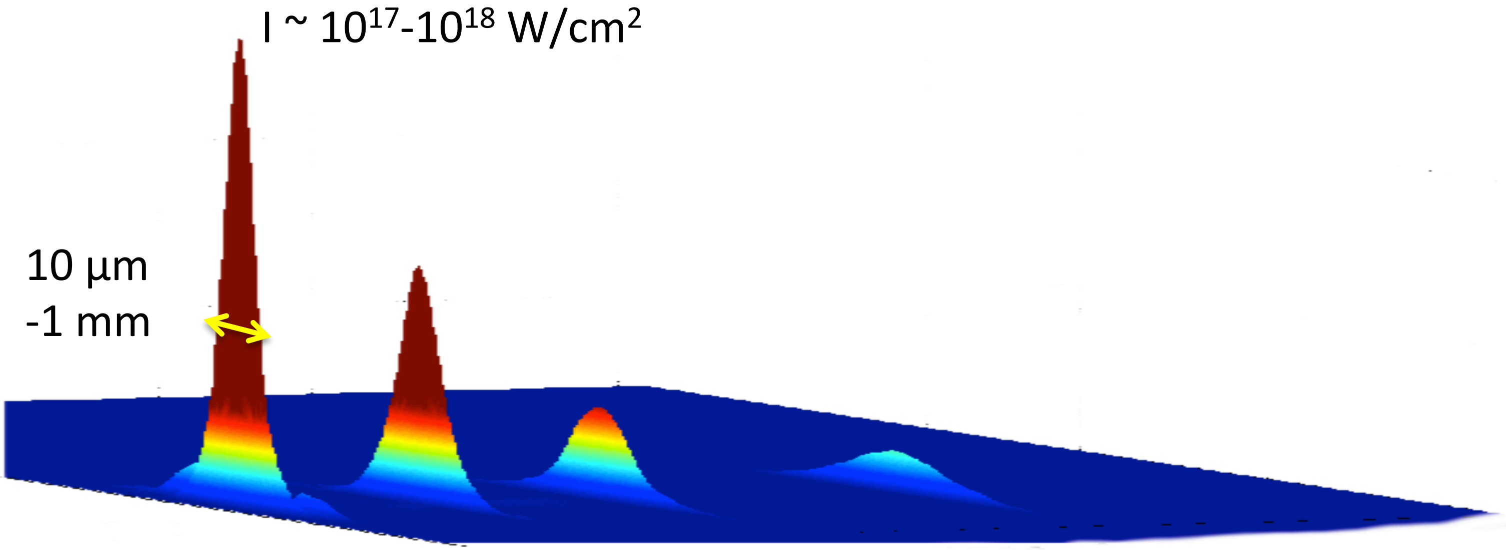
Going further, high-energy-transfer-efficiency



- **80 fs** seed pulse at 10^{17} W/cm^2 is amplified down a plasma ramp
- high energy extraction efficiency of 53%, final intensity ~ 4 x 10^{17}W/cm^2
- ramp profile: reduces thermal SRS on pump, but SBS coupling robust
- pump & seed meet at high-density edge of ramp where coupling is strong from beginning
- such profiles can be easily generated from gas jets
- increase final intensity by optimizing plasma profile

S. Weber, C. Riconda et al. PRL ***111****, 055004 (2013)*

2D plasma based amplification : 'large' transverse spot

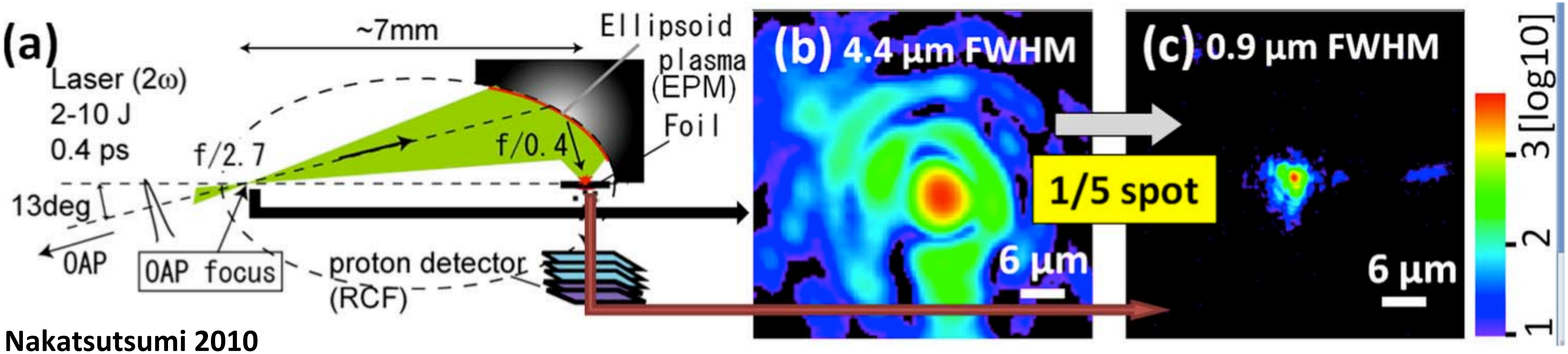


Simulations of Raman and strong coupling Brillouin have shown the possibility of amplifying wide spots to relativistic intensities.

*R. M. G. M. Trines et al. PRL **107**, 105002 (2011)*
*S. Weber, C. Riconda et al. PRL **111**, 055004 (2013)*

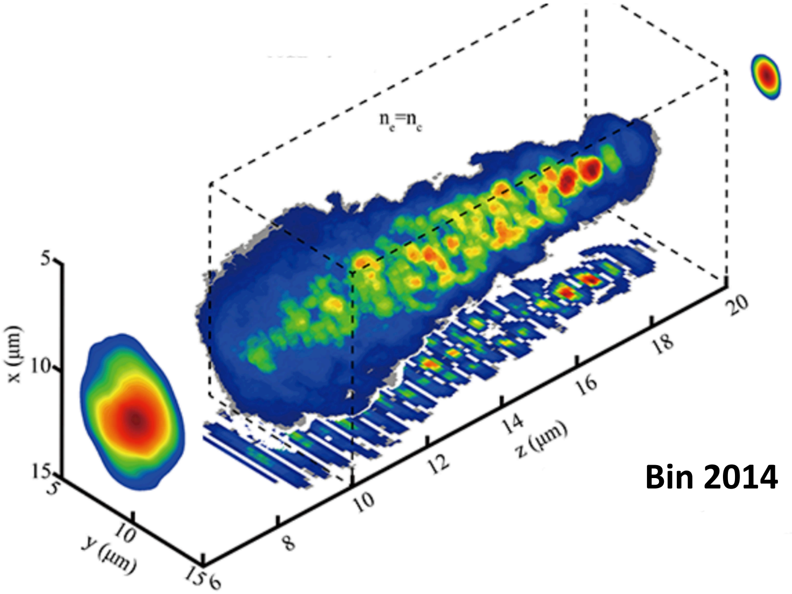
Plasma focusing mirror – plasma lens

➔ The amplified pulse needs to be focused somehow



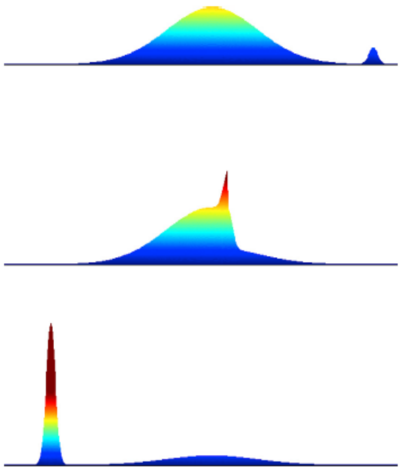
Nakatsutsumi 2010

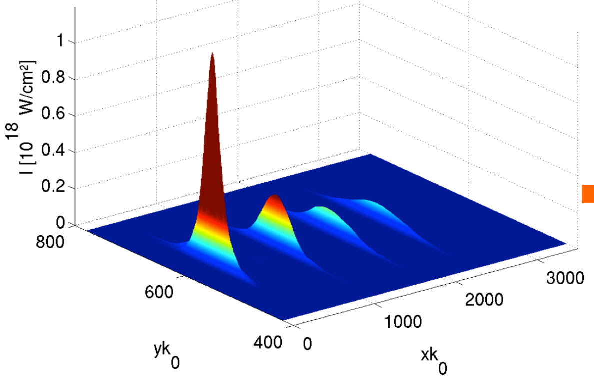
➔ plasma lens based on relativistic self-focusing: another controlled instability usage

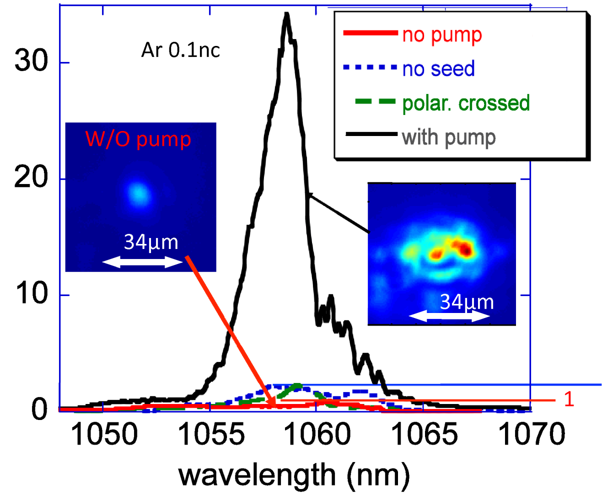


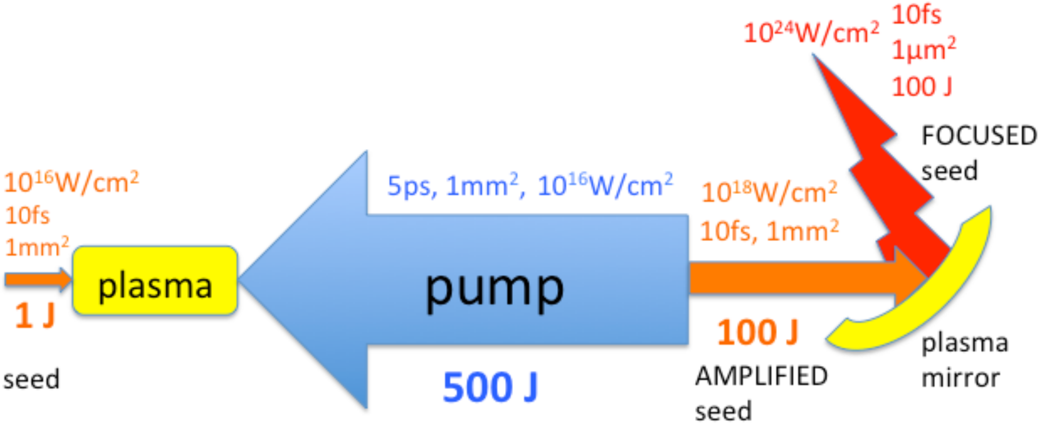
Bin 2014

Plasma amplification: a longterm perspective









10^{16}W/cm²
10fs
1mm²

1 J

seed

plasma

5ps, 1mm², 10^{16}W/cm²

pump

500 J

10^{18}W/cm²
10fs, 1mm²

100 J

AMPLIFIED
seed

10^{24}W/cm²

10fs
1µm²
100 J

FOCUSED
seed

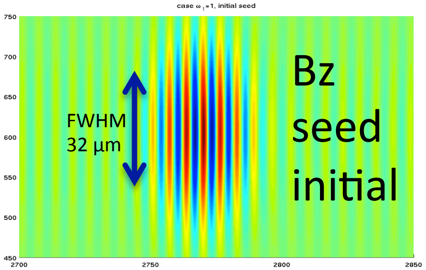
plasma
mirror

➔ **The future of UHI light pulse generation ?!**

Conclusions and work in progress

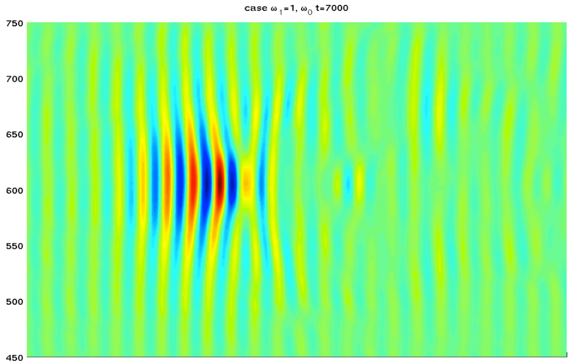
- sc-SBS (regime of today experiments) very robust
- As seed pulse shortens, and intensity grows, transition to mixed SBS/SRS regime → needs further study
- Possibility of amplifying large spots
- What is the best strategy to focus the amplified seed?

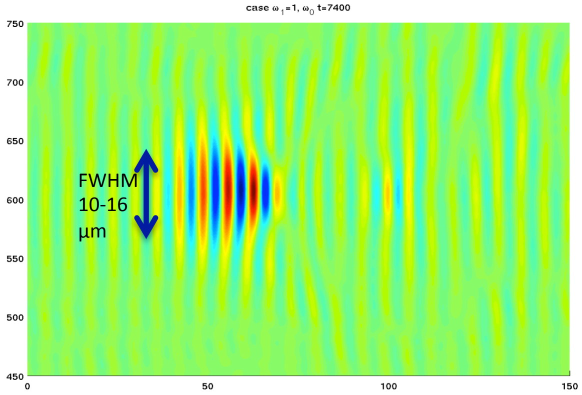
Comparison SBS-mixed mode/SRS : wavefront



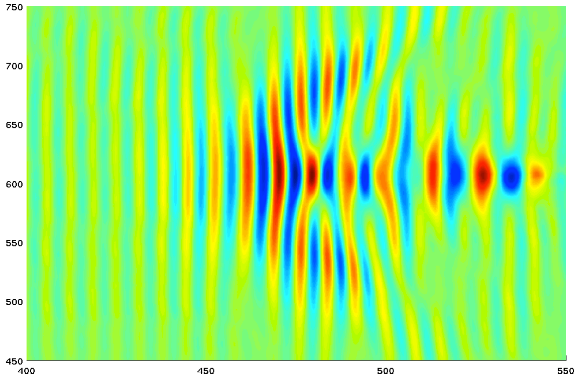
Bz
seed
initial

$\omega_1 = \omega_0$

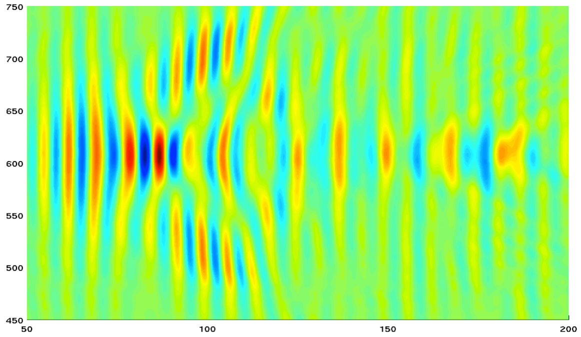




$\omega_1 = 0.8\ \omega_0$



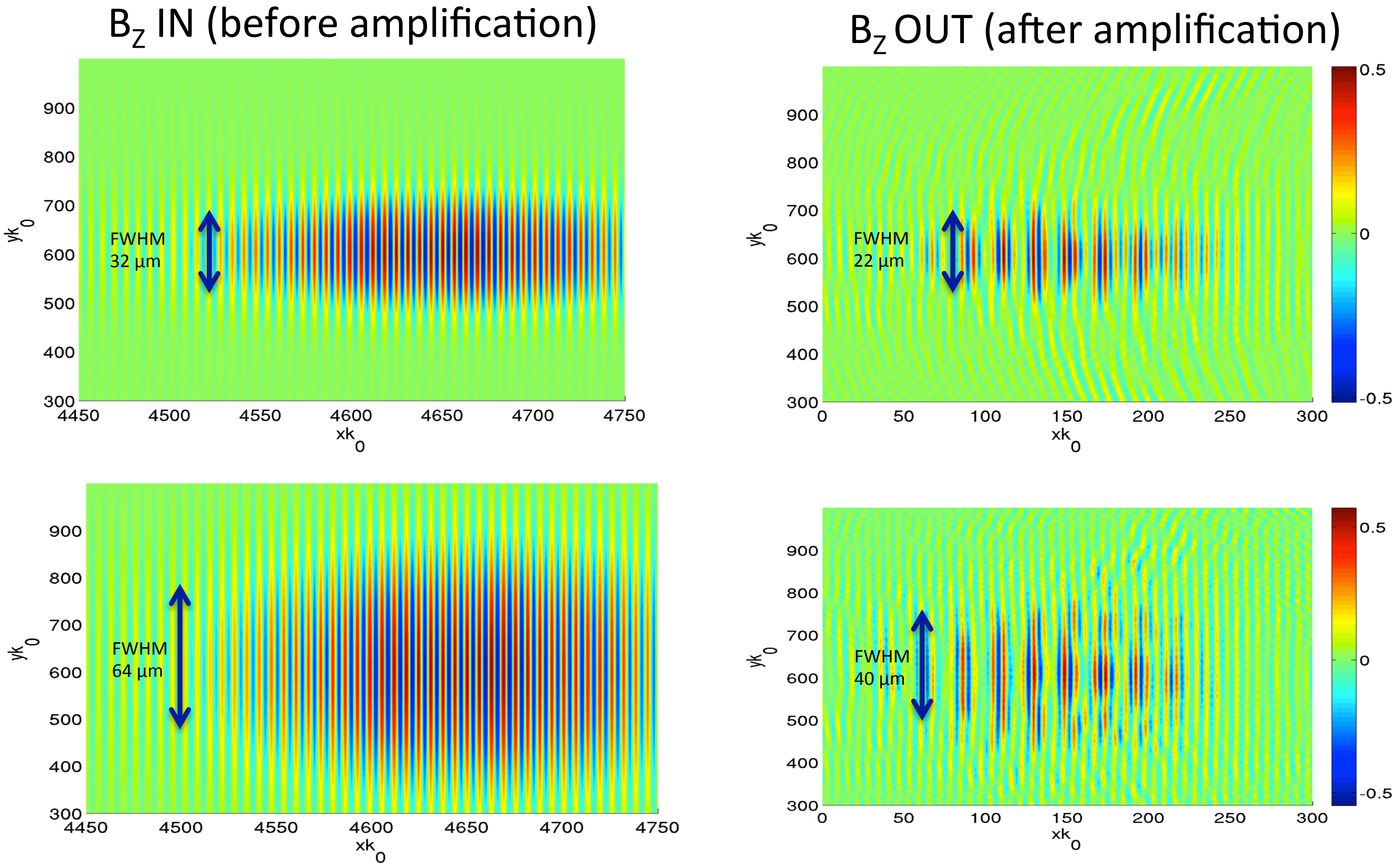
B_z towards end of amplification



B_z out of the plasma

Deformation of the wavefront for SRS-amplification

Transverse size and wavefront (seed 80 fs)

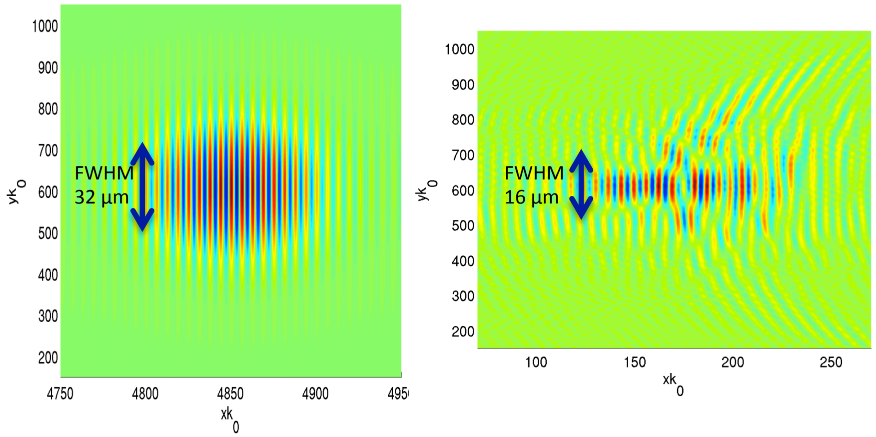


B_Z IN (before amplification)

B_Z OUT (after amplification)

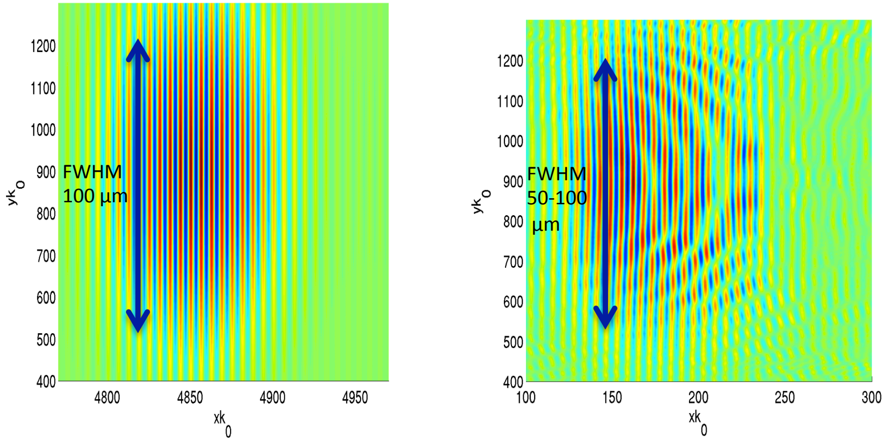
TRANSVERSE SIZE SLIGHTLY REDUCED (2/3), PHASE FRONT PRESERVED
COUPLING WITH PLASMA MIRROR WOULD ALLOW FOCUSING AND
FURTHER INTENSITY ENHANCEMENT

Transverse size and wavefront (seed 30 fs)



I_p=10^{16}

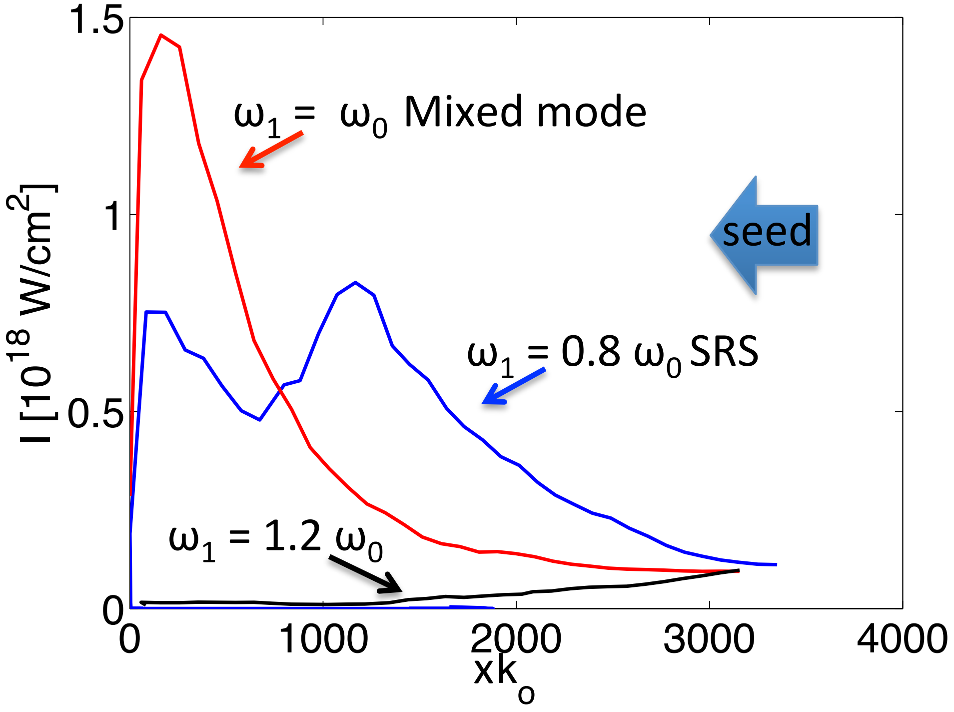
Short seed :
the center tends
to be amplified.



I_p= 5 x 10^{15}

↓ pump strenght to preserve size and wavefront, but ↓ amplification

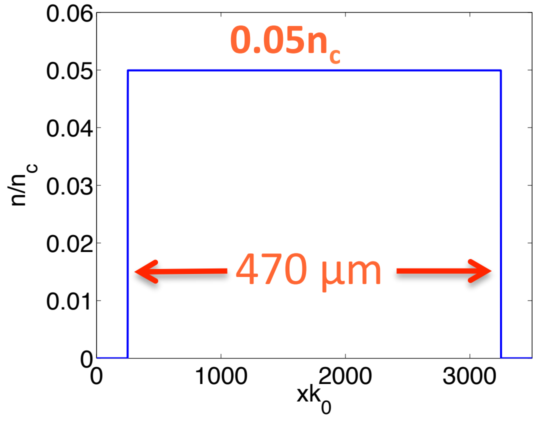
Comparison of mixed mode/ SRS amplification (downshifted seed)



For all cases

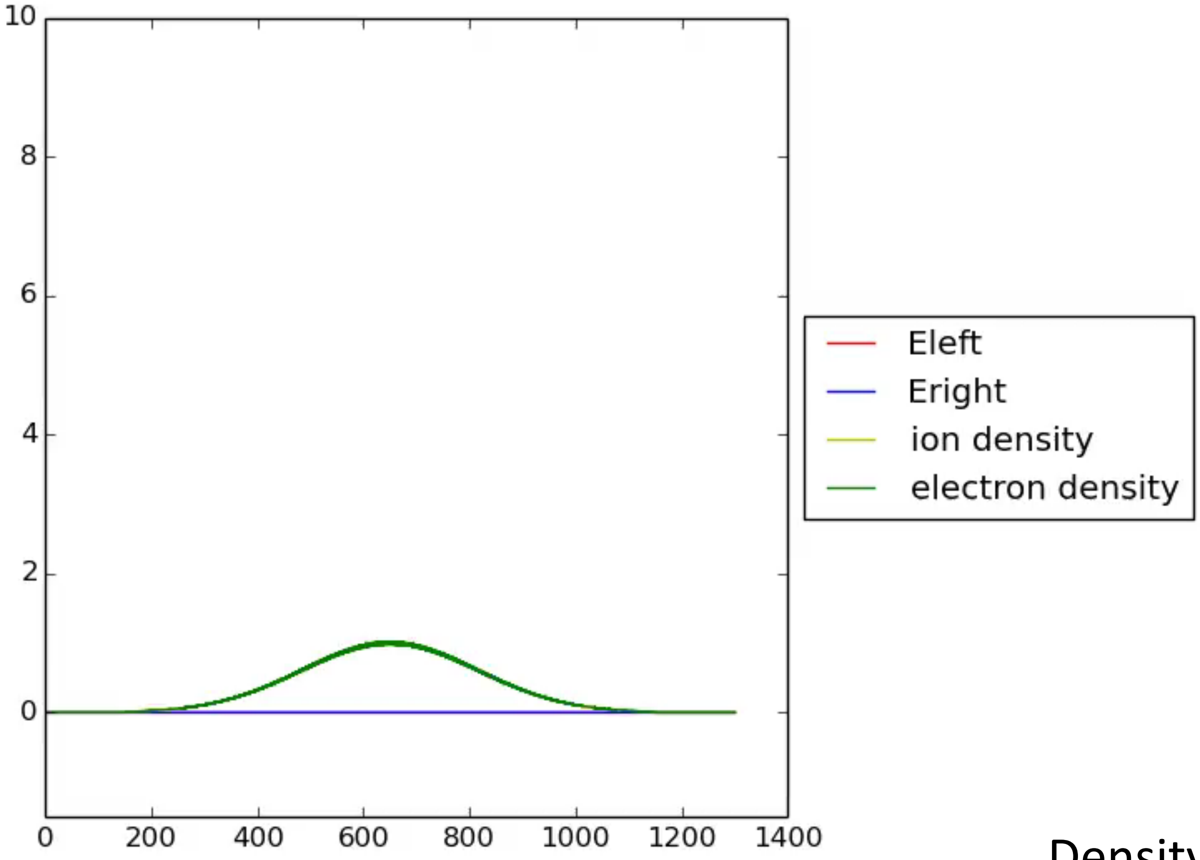
τ_s =13 fs

Plateau, no ramps



- SRS amplification starts earlier, but saturates earlier as well!
- Mixed mode starts more slowly but then grows to much larger amplitude
- Upshifted signal does not grow.

1D sc-SBS plasma amplification simulations



Density profile motivated
by gas-jet experiments