Investigation on parametric instabilities in laser-plasma interaction regime relevant to the generation of very strong shock waves.

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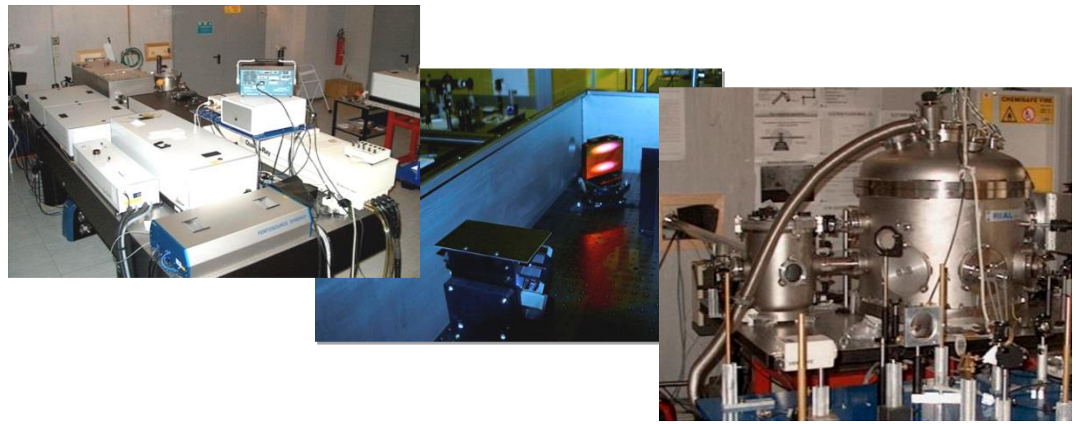

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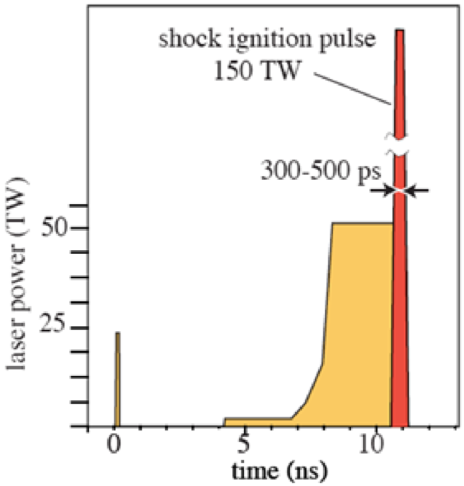
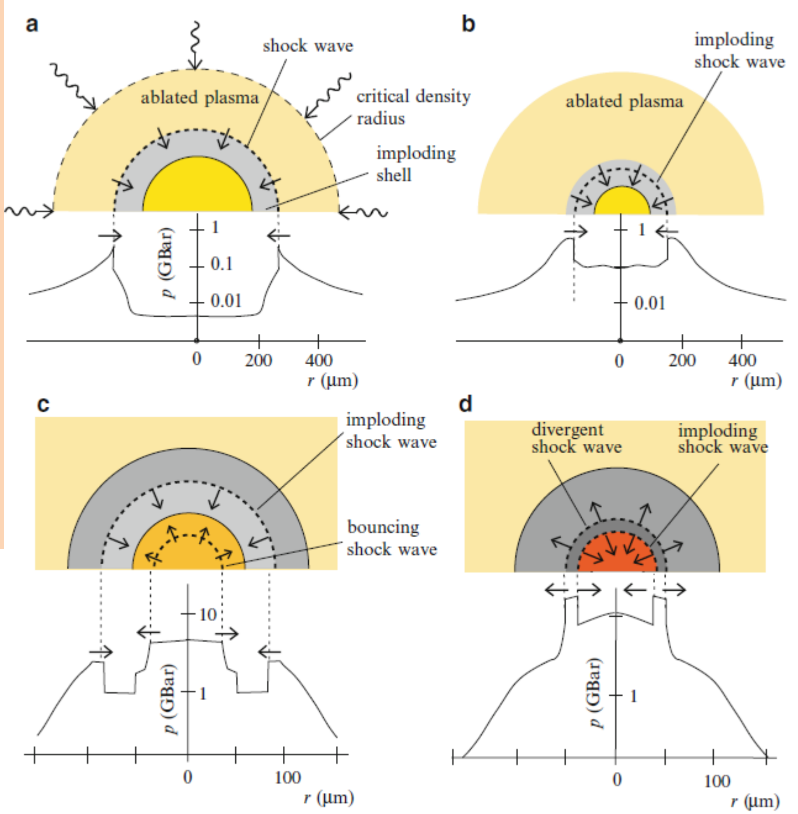
The Shock Ignition approach to ICF

- Separation of compression and ignition phase ⇨ lower implosion velocity
- Strong shock at end of compression phase to generate hot spot (intensity: 10^{15}-10^{16} W/cm^2)
- Geometrical amplification of spherically converging shock (ablation pressure 200-300 Mbar)



Advantages vs. standard ICF and fast ignition

- Lower implosion velocity (250 km/s vs. 350-400 km/s) ⇨ lower Rayleigh Taylor Instability, higher energy gain (50-100)
- Scheme robust: target displacement up to 15 μm, tolerance to nonuniform spike irradiation , non critical syncronization of the ignition pulse (150-250 ps)
- A single laser can be used for compression and ignition
- Lasers needed for shock ignition are already available (LMJ, NIF)



X. Ribeyre et al., PPCF 51, 015013 (2009)
R. Betti et al., PRL 98, 155001 (2007)
S. Atzeni, PPCF 51, 124029 (2009)

Shock Ignition – Open Issues

Laser-Plasma Interaction regime of ignition pulse (10^{15}-10^{16} W/cm^2) is dominated by parametric instabilities - Stimulated Brillouin Scattering (SBS), Stimulated Raman Scattering (SRS) and Two Plasmon Decay (TPD) – and filamentation

→ a significant **backscattered energy** can increase laser energy requirements.

→ generation of **fast electrons** (SRS, TPD)

Expected energy < 100 keV → stopped in the high-ρR shell (>> 17 g/cm^2) of the pre-compressed capsule at end of compression.

Simulations including fast electrons show no gain degradation and larger time window.

L.J. Perkins et al., PRL 103, 045004 (2009)., R. Betti et al., J.Phys.:Conf.Ser. 112, 022024 (2008)

↓

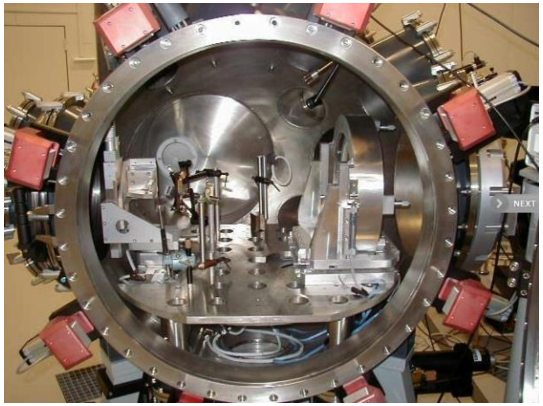
They can have a beneficial effect on pressure

Nora et al. Phys. Rev. Lett. 114, 045001 (2015)

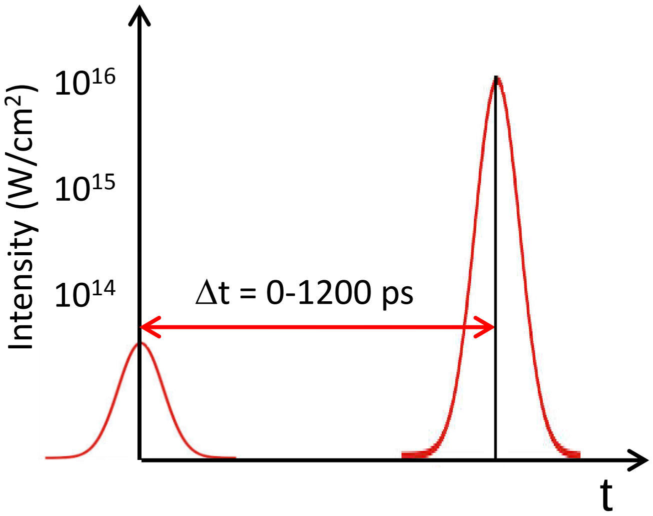
(Effects of non-local heat transport must be investigated but it might also be beneficial,

A.R. Bell and M. Tzoufras, PPCF **53**, 045010 (2011))

Laser-plasma interaction studies at Prague Asterix Laser System



1ω	λ=1.315 μm, t ≈ 250 ps E = 1000 J
3ω	λ=438 μm, t ≈ 250 ps, E_{max} = 300 J
	f/2 focussing lens



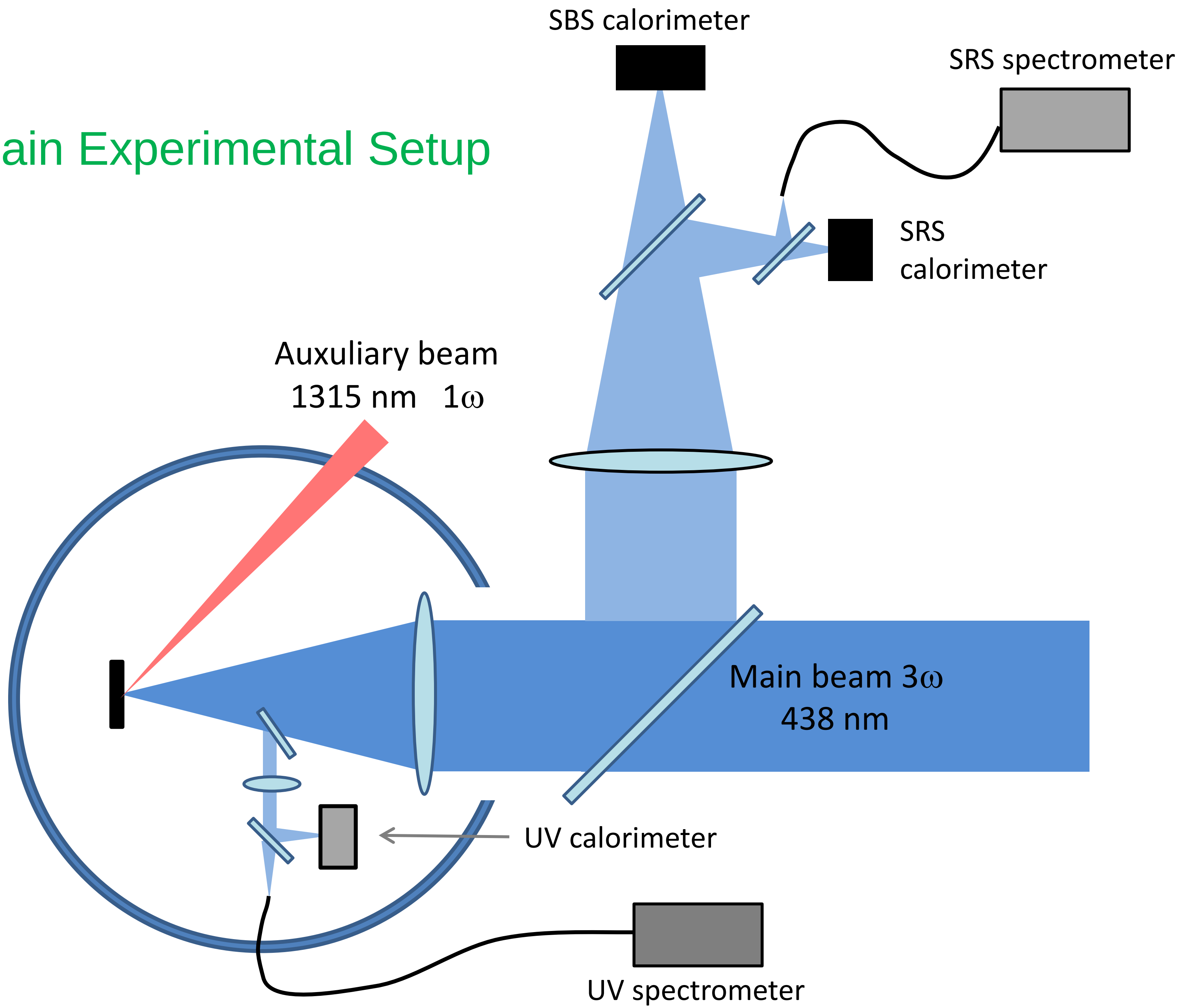
Pre pulse 1ω
$7 \cdot 10^{13}$ W/cm²
Produces a preplasma

Ignitor pulse 1ω o 3ω
$10^{15} - 10^{16}$ W/cm²
Launches the shock

Objectives

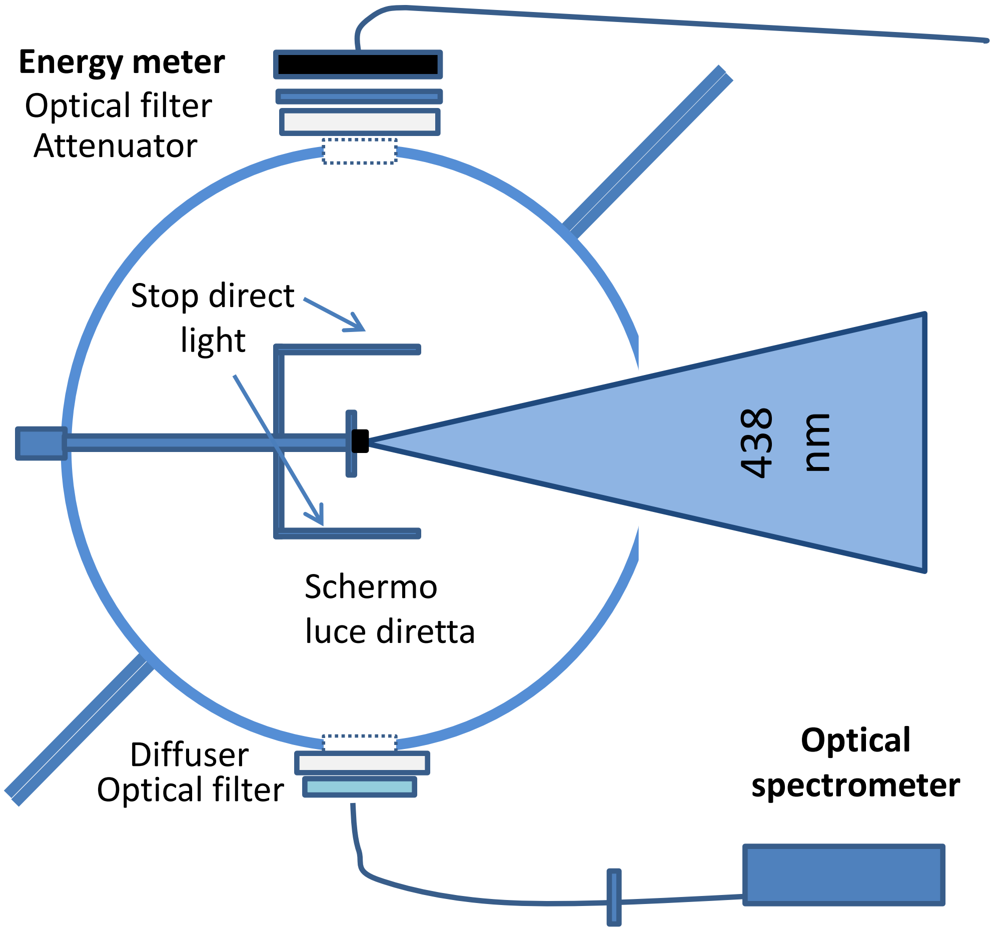
- Assessing the importance of parametric instabilities
- Characterization of fast electrons
- Determination of shock pressure
- Assessing the dependence on preplasma scalelength

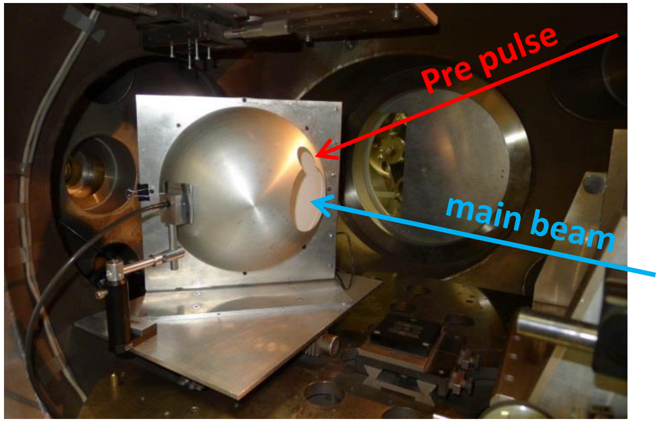
Main Experimental Setup

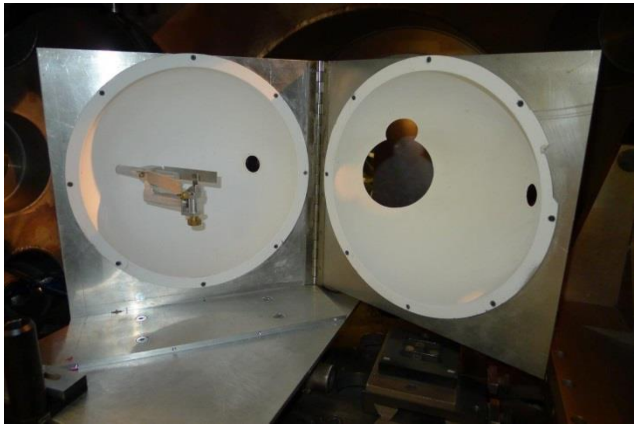


Experimental setup 2

Aim: quantifying the visible radiation reflected outside the lens cone (SBS, SRS, TPD, laser)





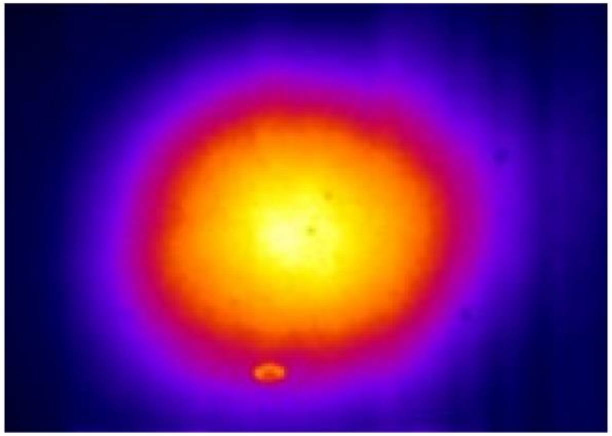


The role of filamentation

Pre pulse spot = 900 μm
(1D plasma)

Random Phase Plate (RPP)

Gaussian FWHM =100 μm



no evident hot spots

Spatial coherence

the random pattern of phase shifters along the laser path results in the reduction of spatial coherence length

$\lambda_\perp \approx 2F\lambda_0$ $\lambda_\parallel \approx 8F^2\lambda_0$

Speckles ≈ 1.6 μm x 1.6 μm x 14 μm

Intensity distribution in speckles

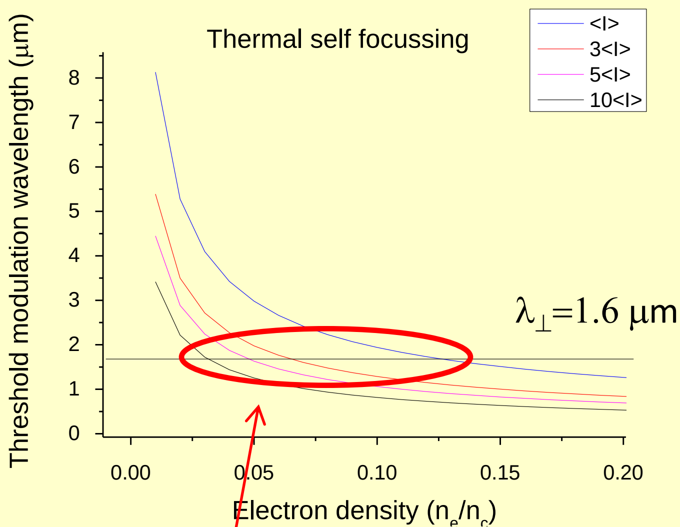
$u = I_{sp}/\langle I \rangle$ $f(u) \propto ue^{-u}$

$\langle I \rangle = (3-9)\cdot 10^{15}$ W cm^{-2}

High-energy tail up to 5-10 $\langle I \rangle$

$5\langle I \rangle = (4.5)\cdot 10^{16}$ W cm^{-2} $10\langle I \rangle = 9\cdot 10^{16}$ W cm^{-2}

Smallest perturbation length $\lambda_\perp$ able to drive thermal filamentation



Thermal spatial growth rate

$$k_\perp = 2\pi / \lambda_\perp$$

$$k_g = \frac{\omega_0}{2c\sqrt{\varepsilon}}\left\{2\frac{n_e}{n_c}\gamma_T\left[1+\left(30k_\perp\lambda_e\right)^{4/3}\right]-\frac{k_\perp^4}{k_0^{\,4}}\right\}^{1/2}$$

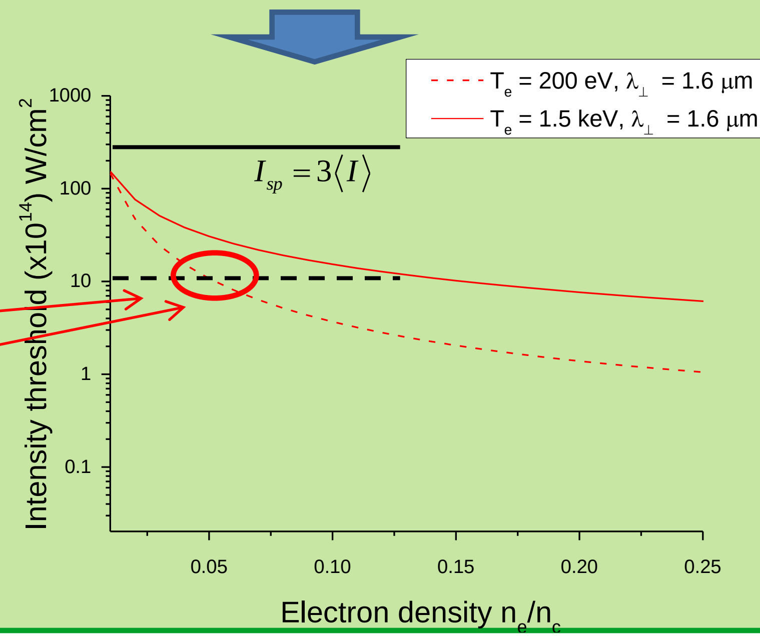
non local electron heat transport effects

$k_\perp\lambda_e > 0.1$

γ_T is the ratio between inverse bremsstrahlung and thermal conduction rates given by Spitzer-Harm conductivity

$$k_g L_{SP} = 1$$

$$L_{SP} = 14\,\mu m$$

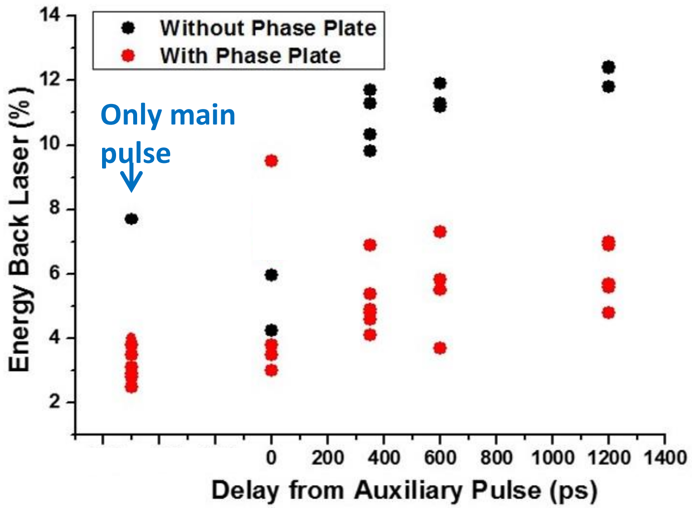


- thermal filamentation prevails at early times while ponderomotive filamentation is dominant near the peak of the laser pulse
- filamentation is expected to occur at densities larger than $n_e \sim 0.05\, n_c$
- Filamentation is expected to occur at early times

Stimulated Brillouin Scattering and backreflected laser

Backscattered energy into the lens cone vs. delay

$\omega_S \approx \omega_0$

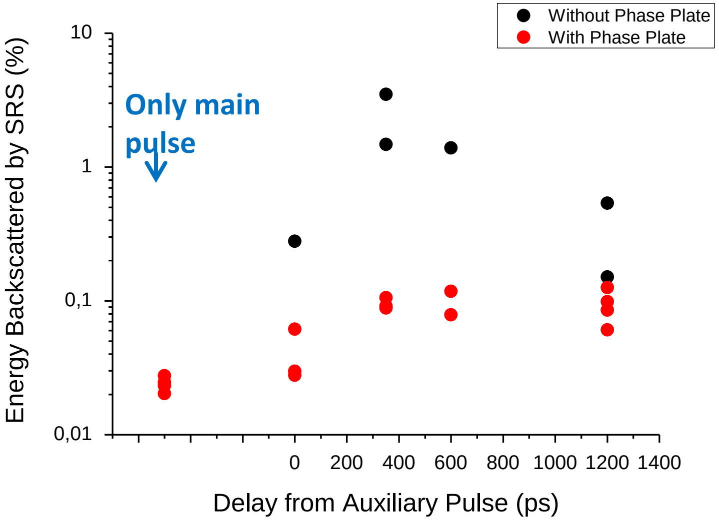


- Backscattered energy in the lens cone is 2-7% of laser energy.
- Scattered energy in all the solid angle (integrating sphere) is > 17-23%.
- Dominant contribution from backreflected laser and SBS, in agreement with similar experiments*.
- Signal increases with increasing preplasma extension.

* C. Goyon et al., Phys. Rev. Lett. 111, 235006 (2013).
S. Depierreux, Phys. Plasmas **19**, 012705 (2012).

Stimulated Raman Scattering $(n_e < n_c/4)$

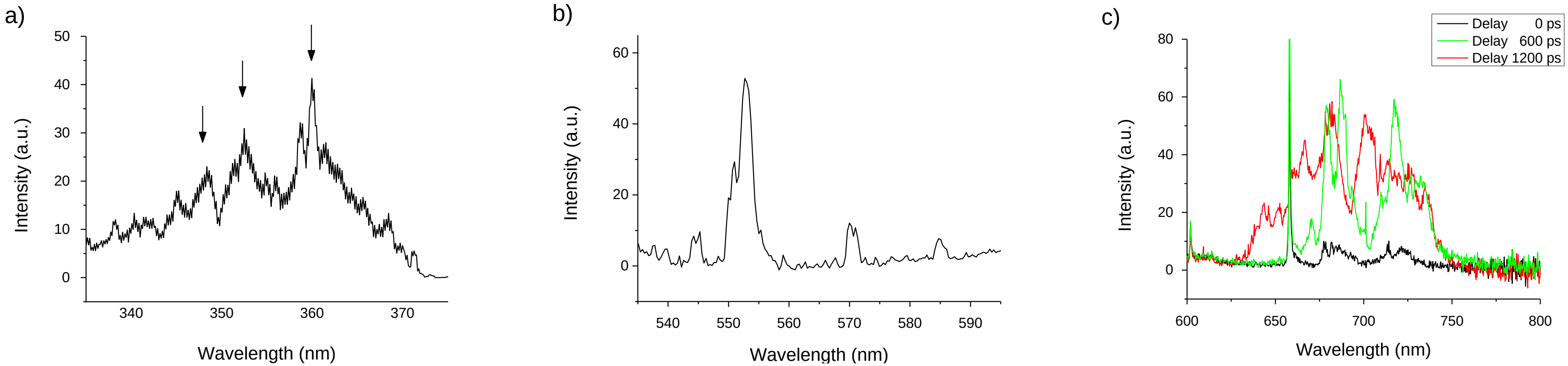
$\omega_0 < \omega_S < 2\omega_0$



- Energy backscattered by SRS is < 0.12% of laser energy (not relevant for energy dissipation).

- Signal increases with increasing preplasma extension.

Stimulated Raman Scattering



SRS threhsold due to inhomogeneity mismatch and Landau damping

Inhomogeneity $\kappa = k_0 - k_s - k_e$ $\int_o^l \kappa dx \approx 1/2$

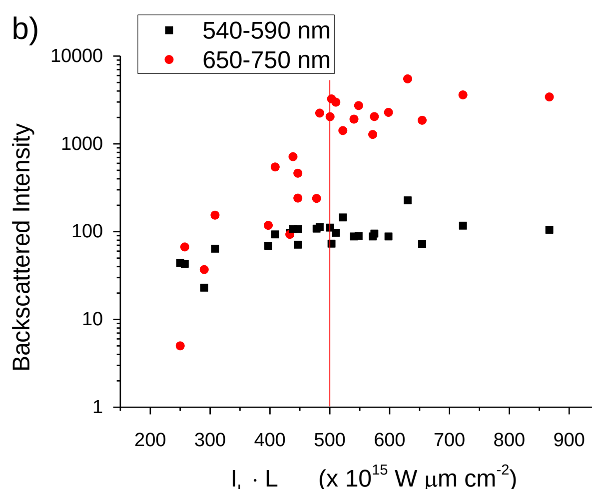
Exponential profile exp (-z/L) can be considered linear since *l* ≈ 2 μm and *l* << *L*

For linear mismacth $\kappa(x) = \kappa' x$

Standard convective theory

$$I_{SRS} = \exp(\pi\lambda)$$

$$\lambda = \gamma_0^2 / \kappa' |v_e v_s| \propto I \cdot L$$



laser energy

0.12 %

~10^{-3}-10^{-2} %

Backward SRS

$0.1 < n_e/n_c < 0.16$

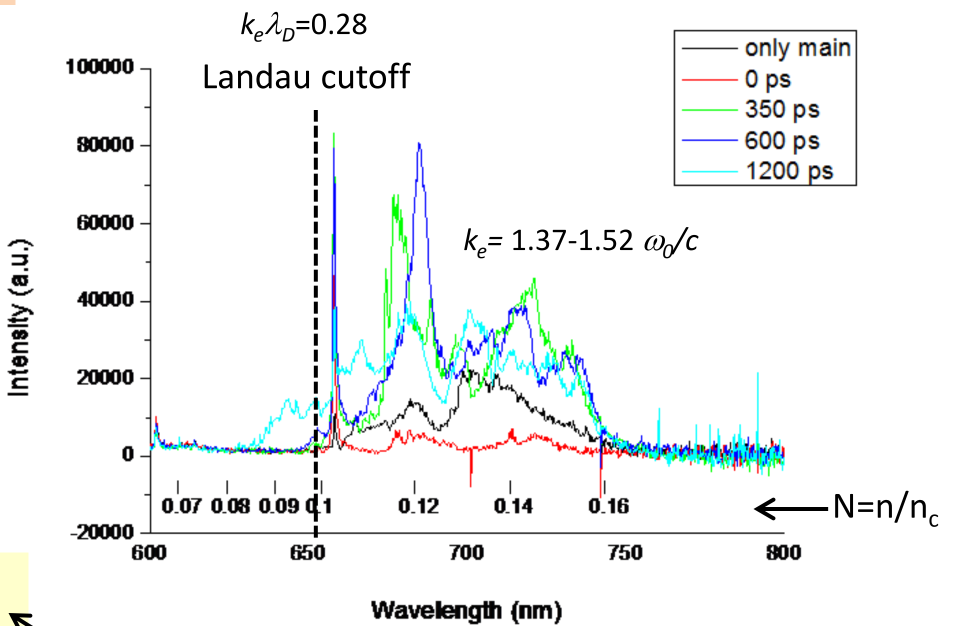
Absolute vs. Convective SRS discussion

$\lambda >> 1$ ⟹ Absolute SRS can occur

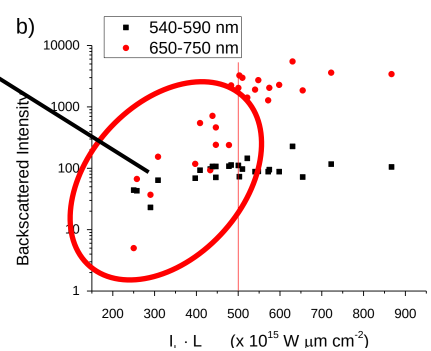
$$\frac{v_0^2}{c^2} > 4\left|k_e - k_0\right| / k_e^2 L$$

BRS threshold

$I^{BRS} = (4\text{-}8)\cdot 10^{15}$ $\qquad I_L\cdot L = 500$



1 - SRS growth at $\langle I\rangle < I^{BRS}$ can be due to the overcome of the threshold in speckles

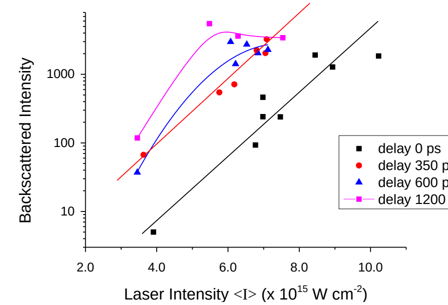


2 - We observe a rapid growth 1-2 orders of magnitude in a factor 2 laser intensity and then a rapid saturation.

In agreement with simulations accounting for kinetic effects ($k_e\lambda_D$>0.15) and with experiments at Trident laser facility aimed at investigating SRS occurring in single hot spots.

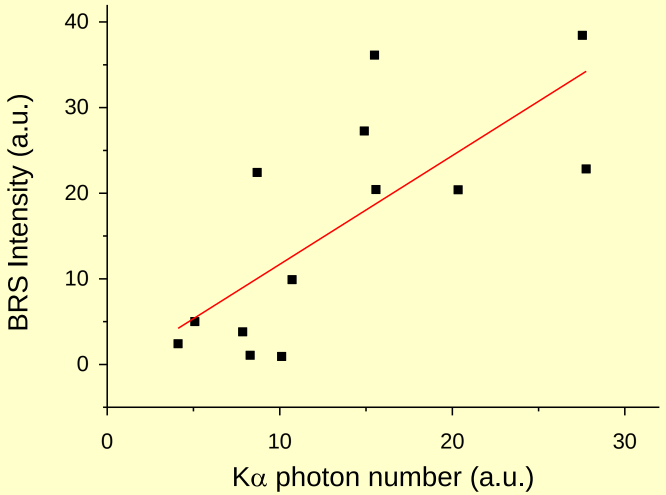
3 -Saturation can be due to nonlinear frequency detuning produced by bowing and filamentation of plasma waves in speckles; LDI, electron trapping in nonlinear

4 - Intensity dependent spectral broadening is attributed to nonlinear saturation of BRS with large bursts and quasi-periodic pulsations in intensity (not necessarily different densities)



Backward SRS and hot electrons

1 – Correlation between Raman signal and Kα photon number



Hot electron temperature calculated from stopping power and Ti/Cu layers

T_{hot} = 28 keV ± 4 keV

$$v_{hot} = v_{ph}^{EPW}$$

Hot electron energy expected from BRS at 0.1-0.15 n_c

T_{hot} = 20 keV ± 3 keV

Hot electron energy expected from TPD

$k_e=3k_0$

T_{hot} = 10 keV

$k_e=k_0$

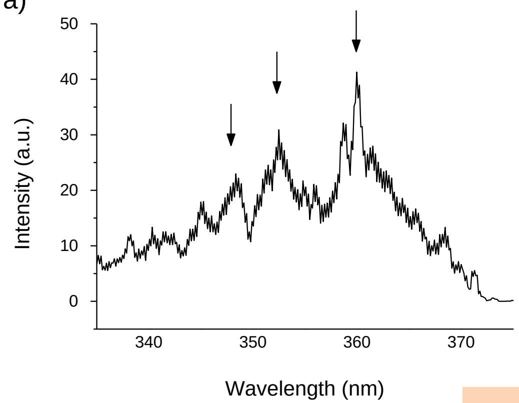
T_{hot} = 114 keV

2 – Experimental hot electron temperature agrees with energy expected from SRS EPW breaking.

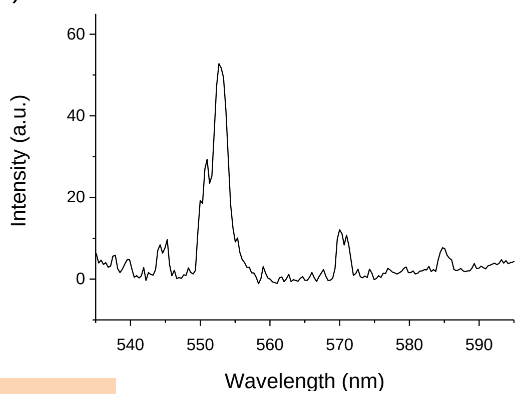
fast electron generation is mainly due to SRS

Forward SRS

a) Anti - Stokes emission



b) Stokes emission



$n_e/n_c \approx 0.04$

- It is difficult to associate these peaks to BRS $k_e\lambda_D = 1$, unless it occurs in inflationary regime
- We observe AntiStokes peaks at intensities comparable to Stokes peaks

threshold $$(v_{osc}/c)^2 > \frac{4}{k_0 L}\left(\frac{\omega_0}{\omega_p}\right)^3$$

$I^{FRS} = (3\text{-}6)\cdot 10^{17}$ $\quad I_L \cdot L = 30000$

Forward Raman Scattering

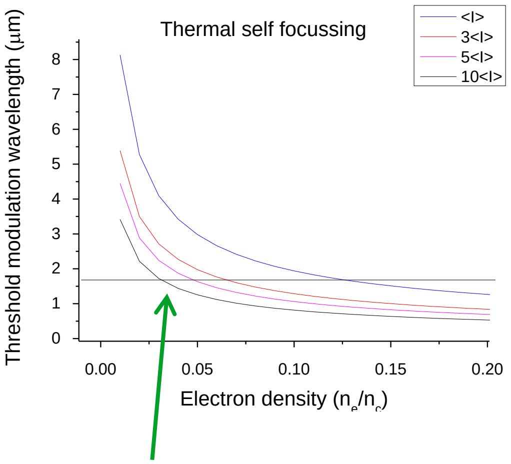
But how we can we see it ?

- Reflection at n_c ?
- SBS of FRS bursts*

SBS threshold in the range 10^{14}-10^{15} W cm^{-2}

*A.B. Langdon, D.E. Hinkel, Phys. Rev. Lett. 89, 015003 (2002)

Forward SRS and filamentation



We expect filamentation at n_e = 0.05-0.07 n_c

Filamentation into speckles

-> modify density profile, saddles, local maximums, ecc.

-> Local increase of laser intensity

In steady state filaments

$$n_0 = N_0 e^{-v_0^2/4v_e^2} \qquad \frac{v_0}{v_e} \cong \sqrt{2}/2$$

$$\varepsilon = \frac{N - n_0}{N} \approx 0.12$$

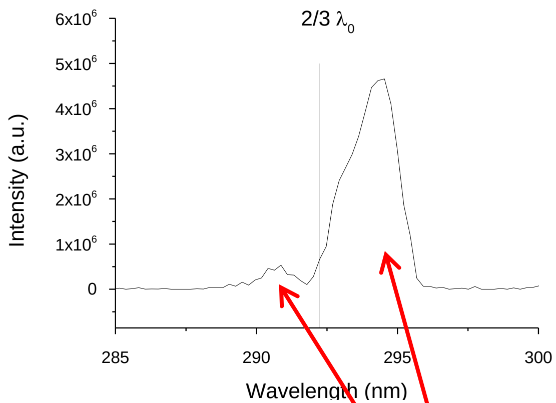
Depletion at the bottom of the filament

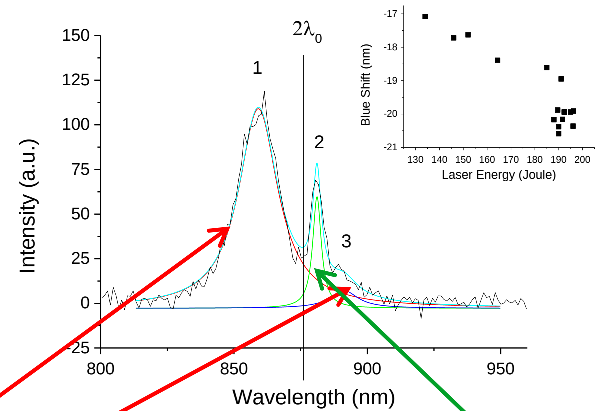
Real expected ε = 0.1-0.2

Therefore, intense speckles $I_{sp} > 5\langle I \rangle = 5 \cdot 10^{16}$ W cm^{-2} undergo filamentation at n_e = 0.05-0.07 n_c , FRS occurs at the bottom of filaments where $n \approx 0.04\ n_{cr}$

Half-harmonics: $3/2\omega_0$ and $\omega_0/2$

$n_e/n_c \approx 0.25$





$\omega_0 + \omega_P$

TPD

$\omega_0 - \omega_P$ or $\omega_P \rightarrow \omega_s$

Hybrid TPD/SRS

TPD: a laser photon decays into 2 EPWs

Energy gap between plasma waves

$$\Delta\omega/\omega_0 = \frac{9}{4}\left(v_e^2/c^2\right)\kappa$$

$$\kappa = \mathbf{k_B} \cdot \mathbf{k_0} / k_0^2 - 1/2$$

$\kappa \approx 2 \rightarrow k_e \approx 3k_0$

$k_e\lambda_D \approx 0.3$

near the Landau cutoff

$\kappa = ½ \rightarrow k_e \approx k_o$

$$\Delta\lambda_{therm} = \frac{9}{2}\frac{T(keV)}{511}\lambda_L$$

$T_e \approx 1.5$ keV

Considerations on energy dissipated at $n_c/4$

- Laser photons reach $n_c/4$ surface but half-harmonics generation efficiency is very low ($\eta_{1/2} \approx 10^{-3}$ %, $\eta_{3/2} \approx 10^{-1}$ %)

- Non relevant degradation of laser-plasma coupling; it is however plausible, that such efficiency could be much higher at early times, when TPD is expected to prevail on other instabilities.

- Absolute SRS occurring at $n_c/4$ is here replaced by a hybrid TPD/SRS instability giving rise to a blue plasmon with $k \approx k_0$, which is contrast with large-scale kinetic simulation of laser-plasma interaction in SI conditions+. Some simulations, however, refer to plasma temperatures of 5 keV, which result in a strong Landau damping of SRS at $n_e < n_c/4$. These simulations are either 1D simulations, overestimating SRS extent, or they are 2D simulations but limited to a few picoseconds time. TPD seems to prevail according to Weber et al.*

+ O. Klimo, V.T Tikhonchuk, Plasma Phys. Control. Fusion 55 (2013) 095002; O. Klimo, J. Psikal, V. T. Tikhonchuk, S. Weber, Plasma Phys. Control. Fusion **56** (2014) 055010.

* S. Weber, C. Riconda, High Power Laser Science and Engineering, 3, e6 doi:10.1017/hpl.2014.50, (2015).

Conclusions

• The energy backscattered in the lens cone is 2-7% and dominated by laser/Stimulated Brillouin Scattering, slightly increasing with plasma scalelength. Overall scattered light is >20%.

• Energy backscattered by SRS is limited to 0.03-0.12%, dominated by BRS occurring in the density region 0.10-0.15 n_c, near the Landau cutoff.

• Two Plasmon Decay instability prevails on absolute SRS at $n_c/4$ density. The odd-harmonics generation efficiency - $\eta_{1/2}$~10^{-3} %, $\eta_{3/2}\approx10^{-1}$ % - gives rise to an irrelevant loss of laser energy. There is a striking difference with numerical simulations in SI conditions, all resulting in a relevant fraction of energy scattered by the absolute SRS in this density region.

• RPP results in a strong suppression of FRS and in a weak reduction of BRS (~a factor 2). This effect is produced by the large fraction of laser energy in high-intensity hot spots in shots w/o RPP, which is much higher than the fraction of energy included in high-intensity speckles when RPP is used.

• The impact of small-scale filamentation is a determining factor in laser-corona interaction. The occurrence of filamentation is suggested by 1) the overcome of FRS threshold, 2) the strong increase of FRS in shots without RPP, 3) the density regions where filaments are expected to form, 4) the modulation of FRS light spectra, which are compatible with eigenfunctions of EPW energy into the filaments.

• Experimental results suggest that hot electrons are generated by the breaking of BRS plasma waves.

• RPP shots with higher energy and longer delay show evident signs of BRS saturation. This agrees with the complex profile of BRS light spectra, explained by frequency detuning in strong EPW, due to ponderomotive or electron trapping as for example in bowing and filamentation of plasma waves. Saturation could limit BRS extent at longer density scalelength, which becomes essential in real SI conditions, but the effect of temperature could be very important (to be investigated).

THANK YOU FOR YOUR ATTENTION !

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- J. Badziak et al., Laser and Particle Beams 33, 161, 2015
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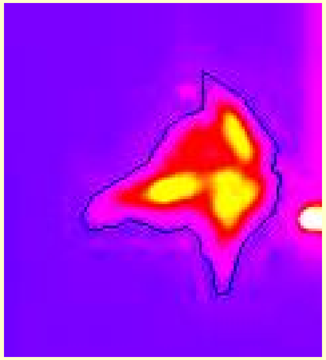
Pre pulse spot = 900 μm
(1D plasma)

The role of filamentation: focal spot

Original beam

Diameter 60 μm



2-3 hot spots

$\lambda_{\perp}$=15-20 μm

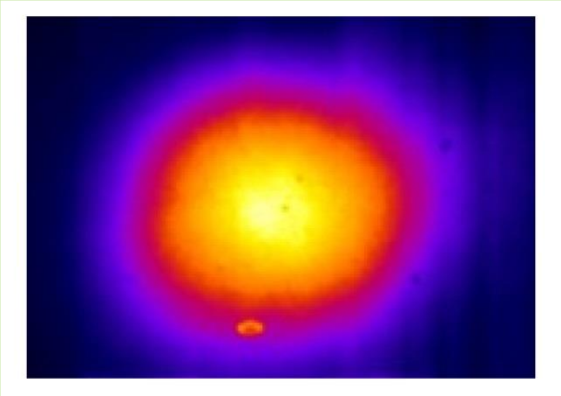
$\langle I \rangle = (1-2)\cdot 10^{16}$ W cm^{-2}

More than 50% energy enclosed in hot spots

$\langle I \rangle = (3-4)\cdot 10^{16}$ W cm^{-2}

Random Phase Plate (RPP)

Gaussian FWHM =100 μm



no evident hot spots

$\lambda_{\perp} \approx 2F\lambda_0$ $\lambda_{\parallel} \approx 8F^2\lambda_0$

Speckles ≈ 1.6 μm x 1.6 μm x 14 μm

$u = I_{sp} / \langle I \rangle$ $f(u) \propto ue^{-u}$

$\langle I \rangle = (3-9)\cdot 10^{15}$ W cm^{-2}

High-energy tail up to 5-10 $\langle I \rangle$

$5\langle I \rangle = (4.5)\cdot 10^{16}$ W cm^{-2} $10\langle I \rangle = 9\cdot 10^{16}$ W cm^{-2}

Original beam

Thermal growth rate

$$k_g = \frac{\omega_0}{2c\sqrt{\varepsilon}}\left\{2\frac{n_e}{n_c}\gamma_T\left[1+\left(30k_\perp\lambda_e\right)^{4/3}\right]-\frac{k_\perp^4}{k_0^4}\right\}^{1/2}$$

$$k_\perp = 2\pi/\lambda_\perp$$

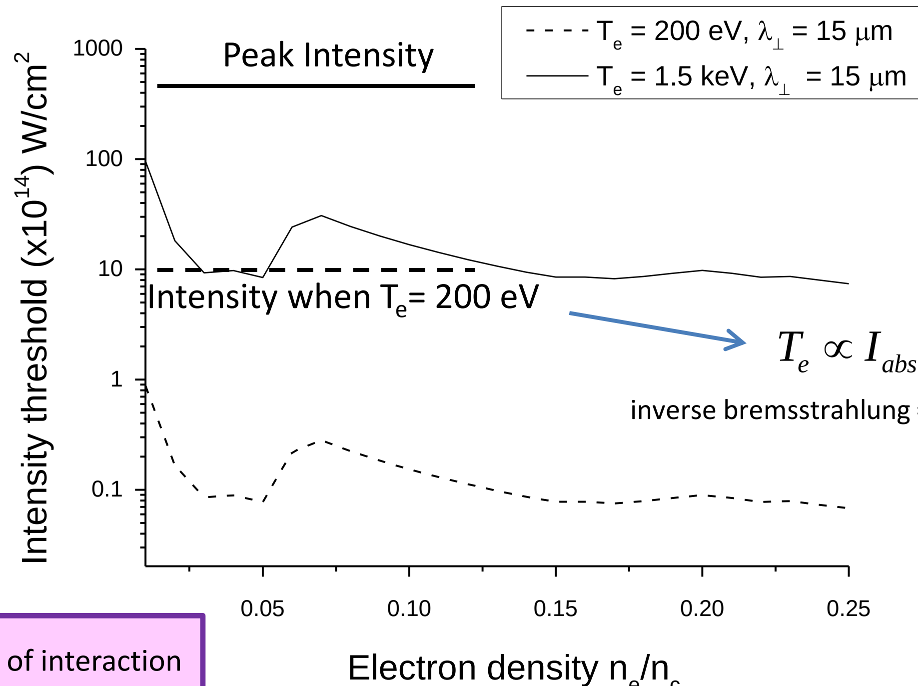
γ_T is the ratio between inverse bremsstrahlung rate and thermal conduction rate given by Spitzer-Harm conductivity

non local electron heat transport effects $k_\perp\lambda_e > 0.1$

$$k_g L = 1$$

$L = n/(dn/dx)$ from hydrodynamic simulations

L = 35-70 μm preplasma L = 50-100 μm main pulse



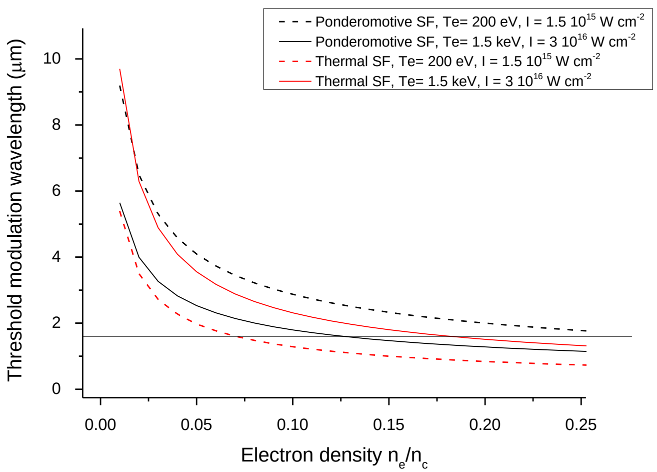
$T_e \propto I_{abs}^{2/3}$

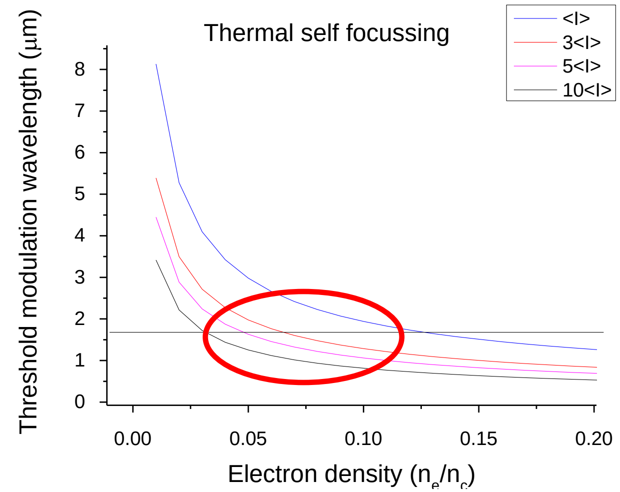
inverse bremsstrahlung = heat flux

- Self-focusing of hot spots occurs at early times of interaction and at low densities, modifying the following propagation of the laser beam.
- Filaments successively could break in smaller radius filaments, of the order of 3-6 μm, (optimal modulation wavelengths)

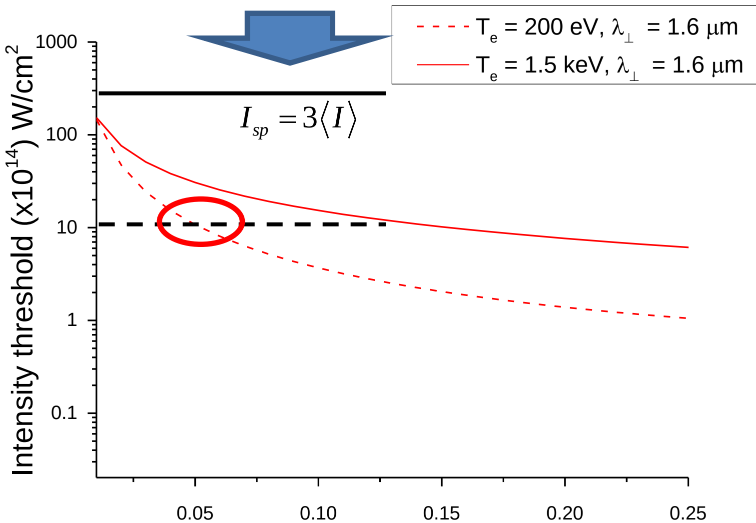
Random Phase Plate

$$I_{sp} = 3\langle I \rangle = 3 \cdot 10^{16} \quad \text{W cm}^{-2}$$





$$k_g L = 1$$



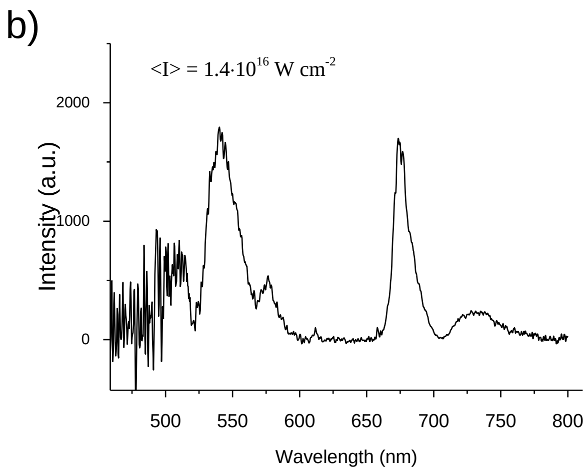
- thermal filamentation prevails at early times (dashed lines) while ponderomotive filamentation is dominant near the peak of the laser pulse (solid lines)
- filamentation does not occur for densities lower than $n_e \sim 0.07\, n_c$
- Filamentaion is expected to occur at early times

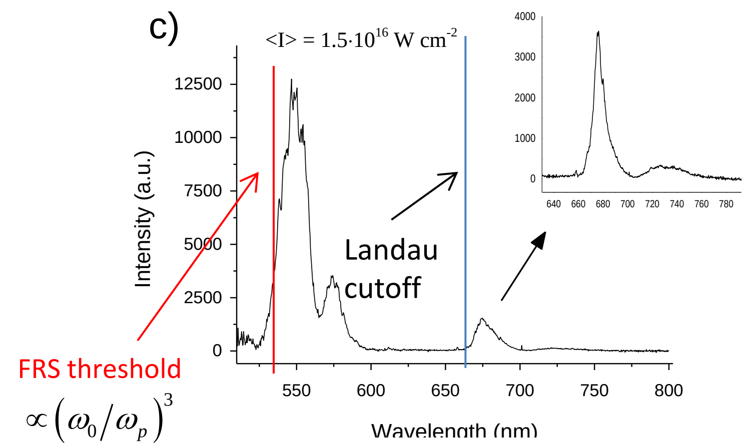
Shots w/o RPP

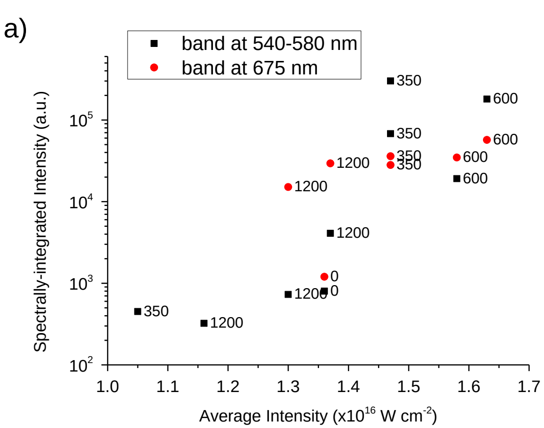
$\langle I \rangle \approx (1\text{-}2)\cdot 10^{16}$ W cm^{-2}

More than 50% energy at $I_{hot\ spots} \approx (3\text{-}4)\cdot 10^{16}$ W cm^{-2}

- Laser/SBS backscatter = 6-12% of the laser energy
- Energy backreflected by SRS =0.3-3% of the laser energy, most of which (~90%) from $n_e \approx 0.04\text{-}0.06\ n_c$







FRS grows very rapidly

BRS saturates

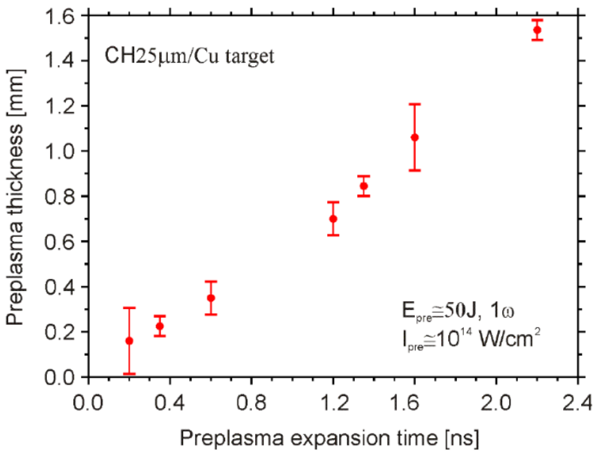
(According to theory)

Frequency modulation could be due to self focussing of the 2-3 large hot spots in the beam

Preplasma characterization

- **Preplasma density through optical 3-frame interferometry**

Preplasma size at density 10^{19} cm^{-3}



• Plasma expands linearly in time

• At largest experimental delay (1200ps) plasma dimension (at 10^{19} cm^{-3}) is 0.7mm.

- **From hydrodynamic simulations, the preplasma scalelength at density $0.05<n_c<0.2$, typical of SRS instability the density scalelength is in the range 30-70 μm**

- **Preplasma temperature through high resolution X-ray spectroscopy**

Preplasma temperature ~175 eV (time-integrated)

$3/2\omega_0$ emission

Considering maximum growth rate of TPD and plasmon propagation required for the coupling

$$k_y = 3\omega_0 \sin\theta / 2c \quad \Rightarrow \quad T_e = 1.7\text{-}3.3 \text{ keV}$$

depending on laser intensity

In agreement with hydrodynamic simulations but other diagnostics lead to temperature of 1.5-2 keV

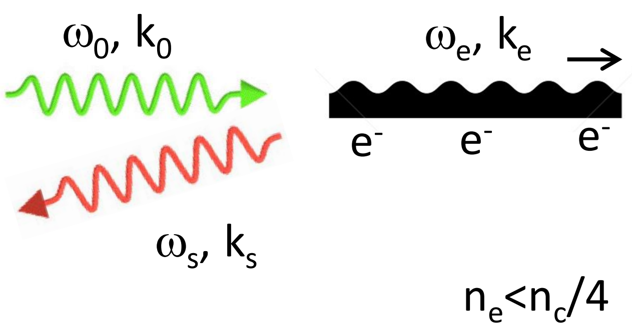
It is known that $3/2\omega_0$ emission is not suitable for temperature diagnostics because it is affected by geometry of interaction and 2D effects (filamentation, turbulence, cavitation). Usually it overestimates the temperature

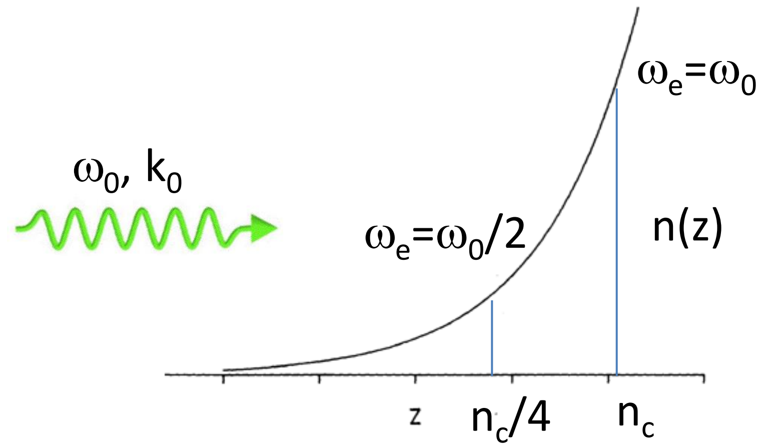
For example, by using the approach of Short et al.* of $3/2\omega_0$ formation in filaments we estimate a lower plasma temperature of ~ 1.1-1.5 keV

* R.W. Short, W. Seka, K. Tanaka, E.A. Williams, Phys. Rev. Lett. 52, 1496, 1984.

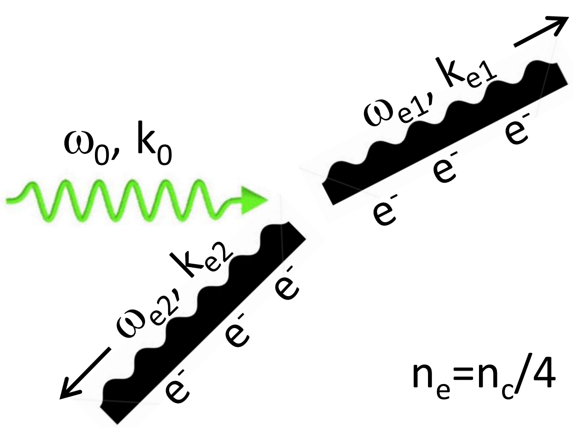
1 -Introduction

Stimulated Raman Scattering

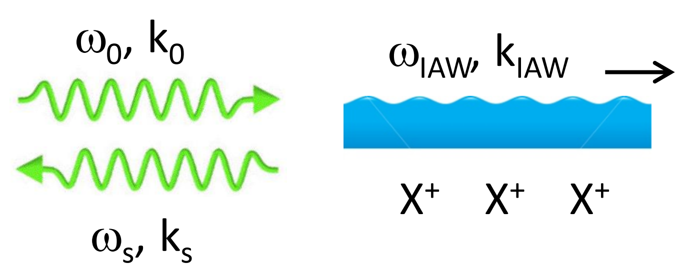




Two Plasmon Decay

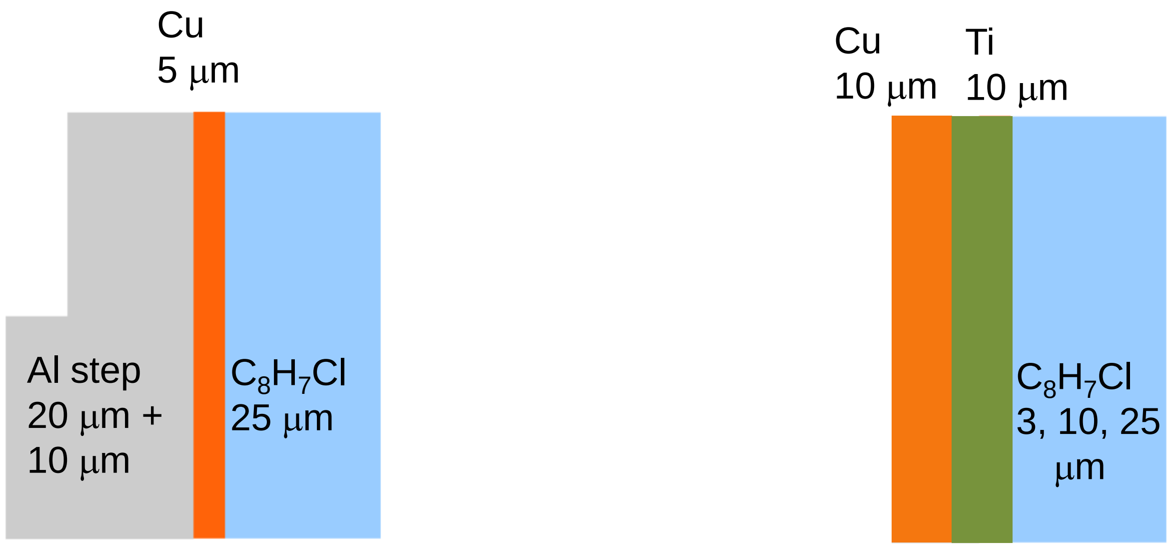


Stimulated Brillouin Scattering

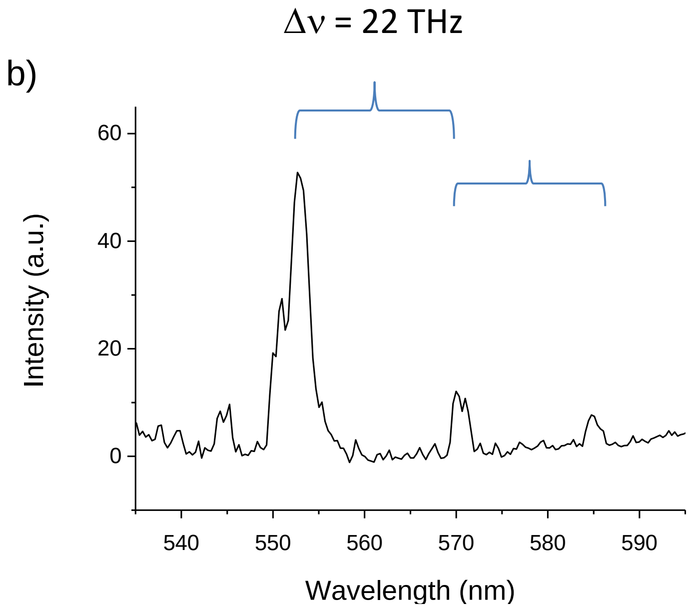


Targets

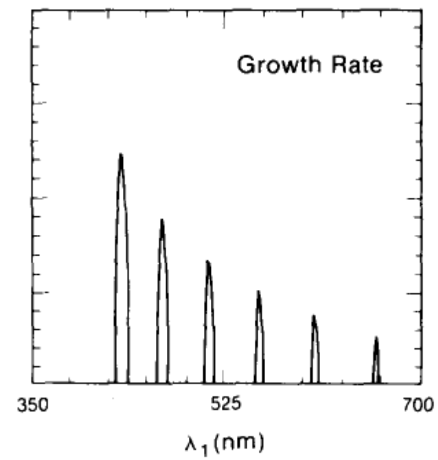
- **Plastic layer to simulate capsule ablator material**
- **Cl in plastic to perform temperature measurements (X-ray spectroscopy)**
- **Cu and Ti layers for fast electron detection (Kα measurements)**
- **Al layer for shock chronometry (EOS of Al is well known)**



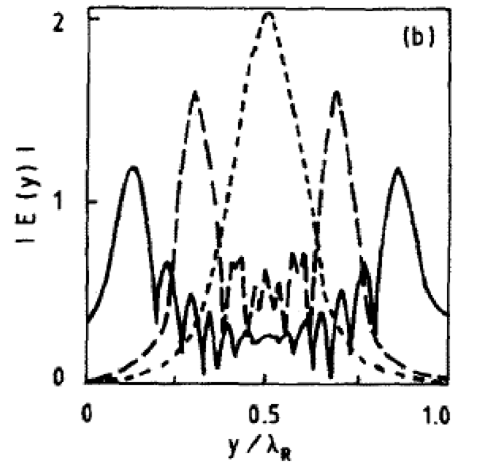
Modulation of Forward SRS



R.W. Short et al., Phys. Fluids 30, 3245, 1987



H.C. Barr et al., Phys. Fluids 31, 641, 1988.



Plasma waves propagate in a filament as in a waveguide in discrete bound modes, corresponding to the eigenfunctions of the Schroedinger equation describing radial distribution in the potential well

$$\Delta\omega_{mod} = (6\varepsilon)^{1/2} \frac{\pi}{2a} v_e$$

a is the filament radius

$\varepsilon = 0.15$

$a \approx c/\omega_p$ skin depth

$\Delta\lambda_{exp} = 22$ nm

It supports our hypothesis !