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# Stimulated Raman Scattering and Two-Plasmon-Decay instabilities in laser-plasma interaction regime relevant to shock ignition.

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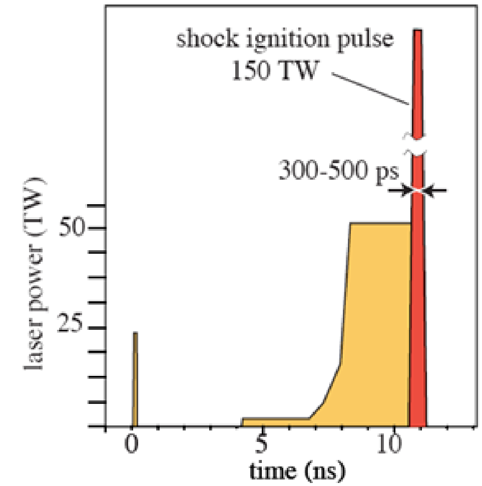
# Outline

- 1 - A brief introduction: The Shock Ignition scheme for ICF
- 2 - Experimental setup at PALS
- 3 - The role of filamentation
- 4 – TPD/SRS at $n_c/4$
- 5 - Shots with Random Phase Plate:
    - Backward Stimulated Raman Scattering
    - Hot electrons
    - Forward Stimulated Raman Scattering
- 6 -Shots w/o Random Phase Plate
- Conclusions

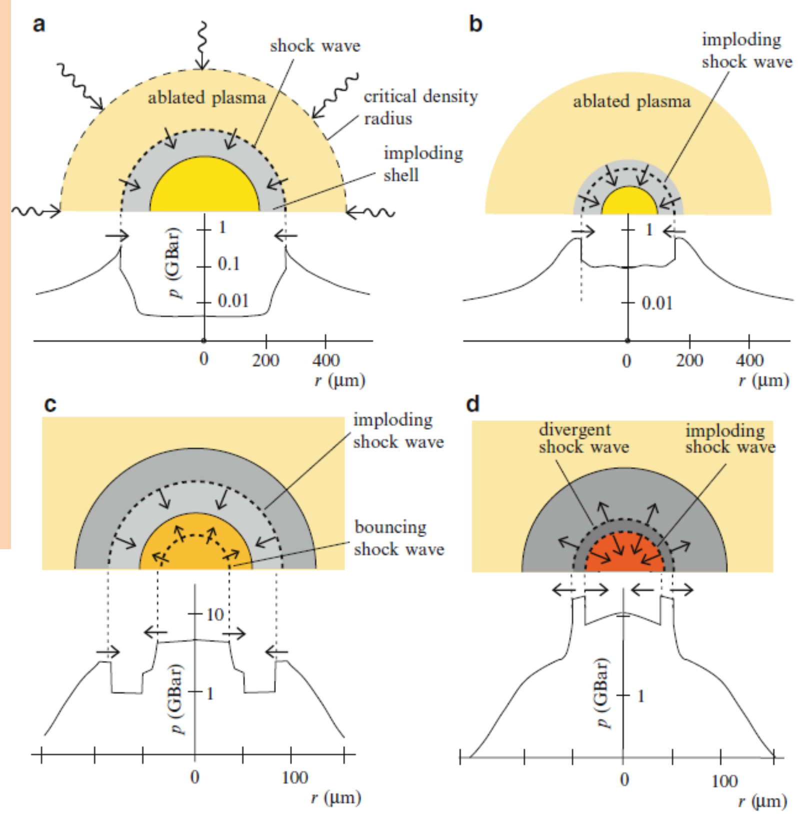
# The Shock Ignition approach to ICF

- 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-$\rho$R 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.

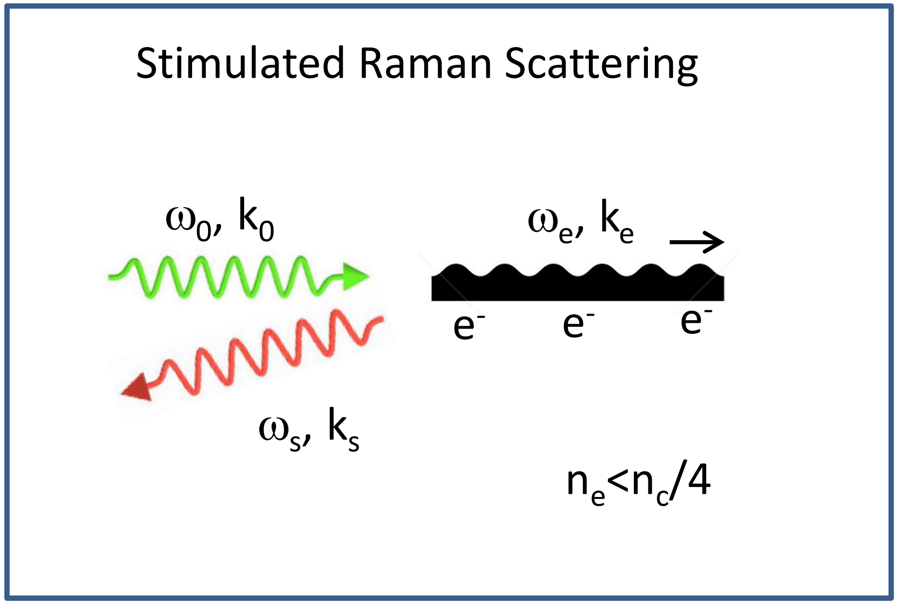
L.J. Perkins et al., PRL 103, 045004 (2009)., R. Betti et al., J.Phys.:Conf.Ser. 112, 022024 (2008)

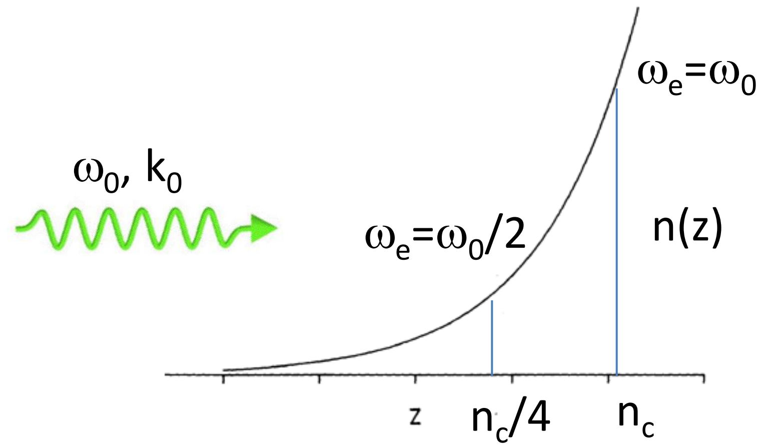
↓

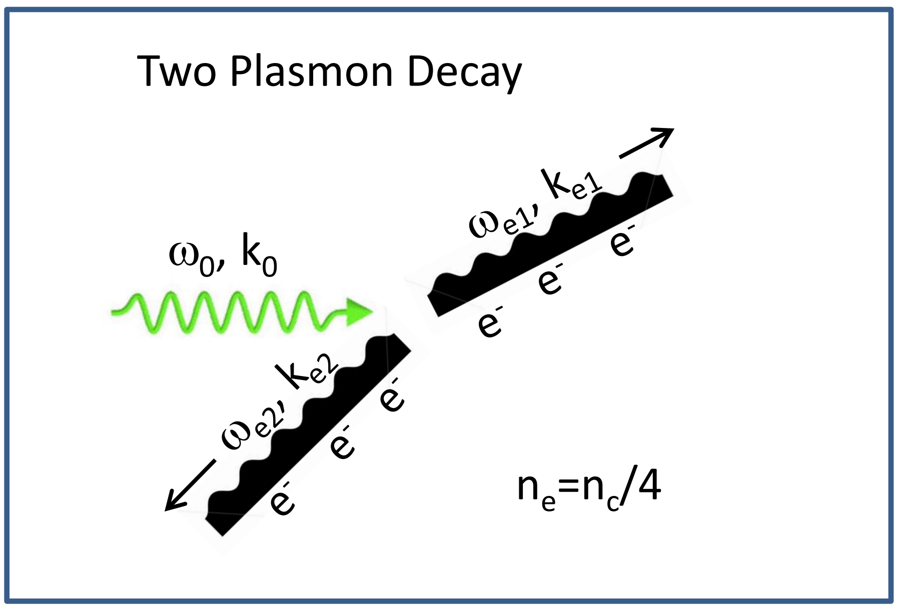
They can have a beneficial effect on pressure

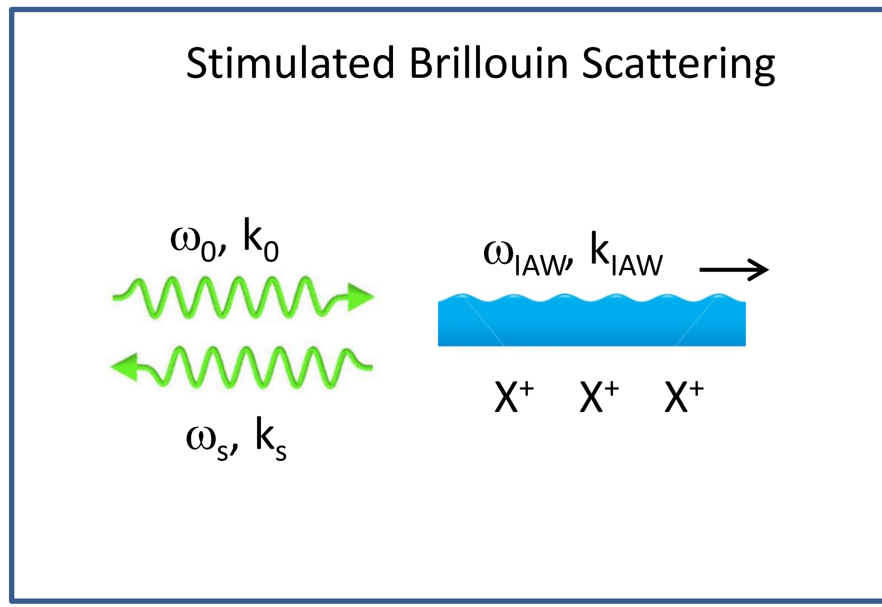
(Effects of non-local heat transport must be investigated but it might also be beneficial,
A.R. Bell and M. Tzoufras, PPCF **53**, 045010 (2011))

## 1 -Introduction



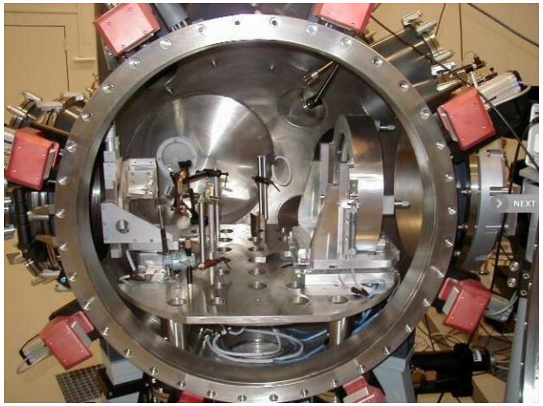



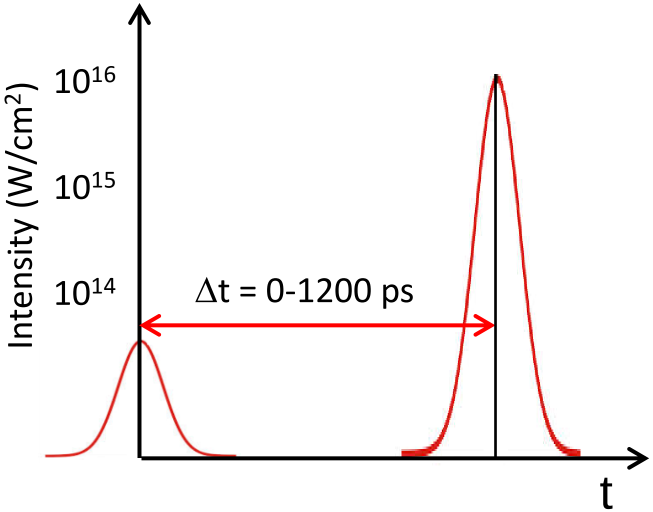



# Laser-plasma interaction studies at Prague Asterix Laser System

Aim: Investigation of the role of parametric instabilities in shock ignition relevant intensity regime and the effect of fast electrons on the shock pressure in a planar geometry.



| | |
|---|---|
| 1ω | λ=1.315 μm, t ≈ 300 ps E = 1000 J |
| 3ω | λ=438 μm, t ≈ 300 ps, $E_{max}$ = 500 J |
| | f/2 focussing lens |



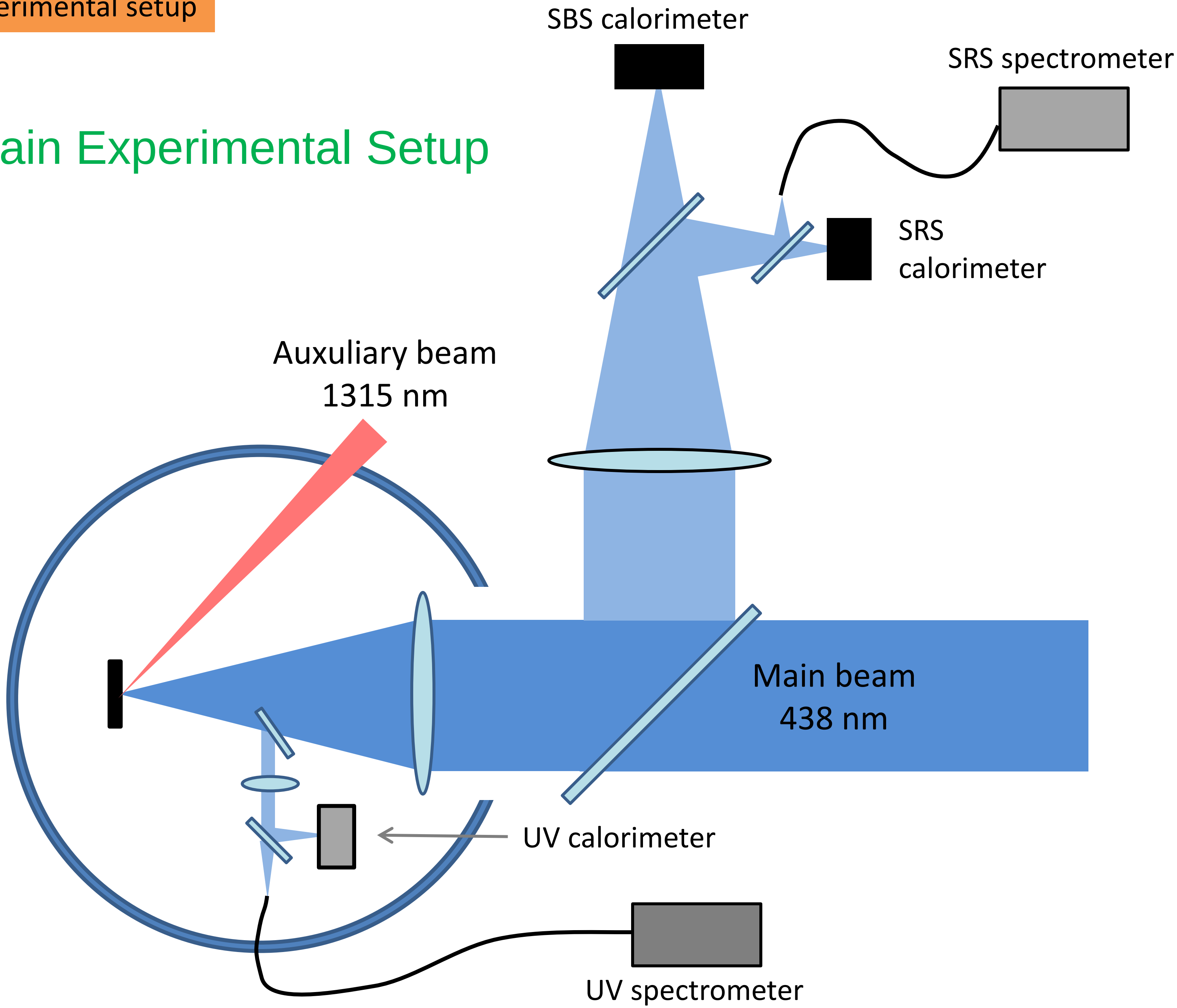

Pre pulse 1ω
$7 \cdot 10^{13}$ W/cm²
Produces a preplasma

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

## Objectives

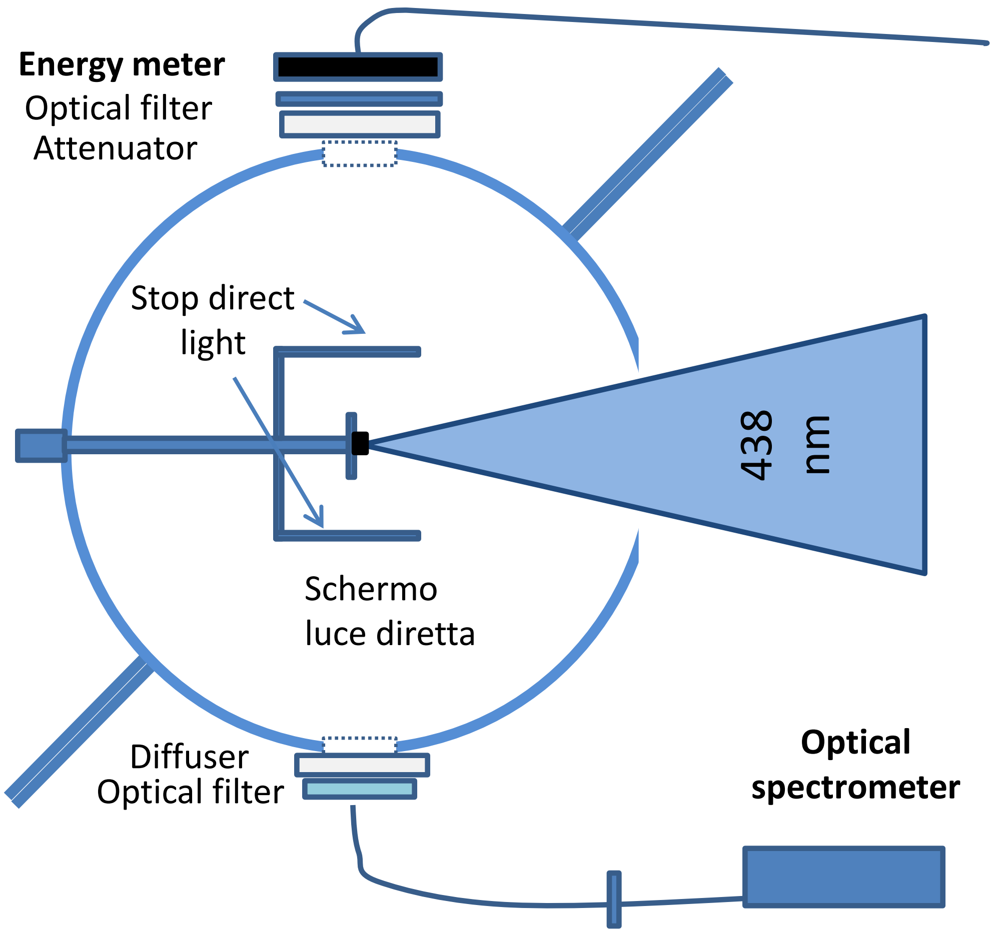
- Assessing the importance of parametric instabilities
- Characterization of fast electrons
- Determination of shock pressure
- Assessing the dependence on preplasma scalelength

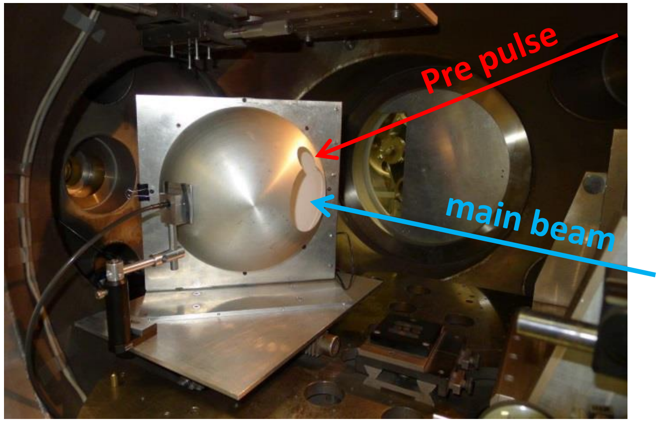
# Main Experimental Setup

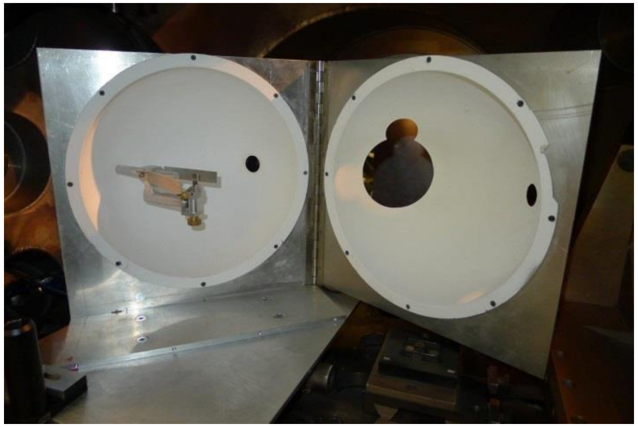


# Experimental setup 2

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

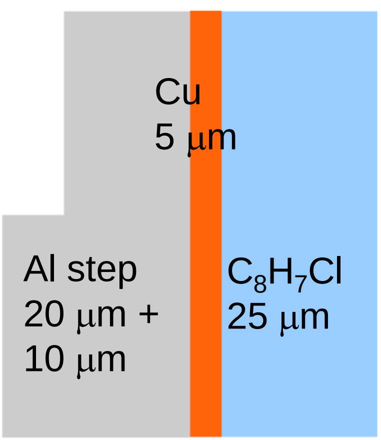


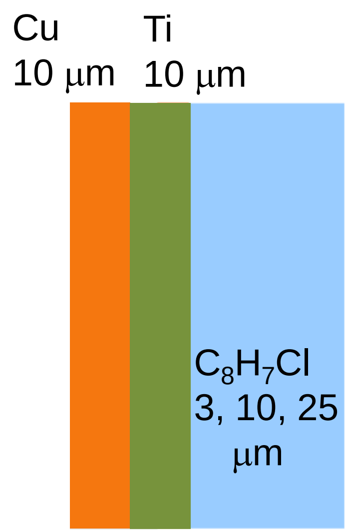



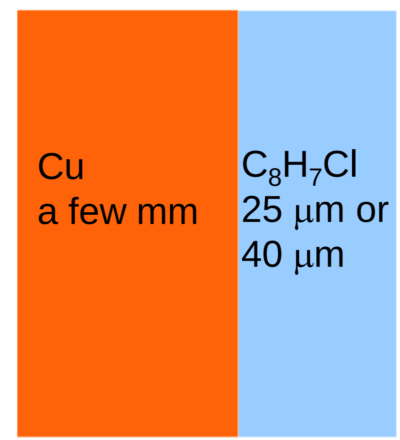



# Targets

- **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)**
- **Thick Cu for crater measurements**
- **Al layer for shock chronometry (EOS of Al is well known)**



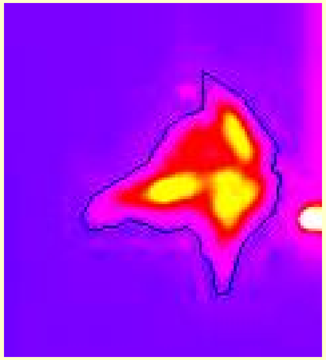



Pre pulse spot = 900 μm
(1D plasma)

# The role of filamentation: focal spot

## Original beam

Diameter 60 μm



2-3 hot spots

$\lambda_\perp$=15-20 μm

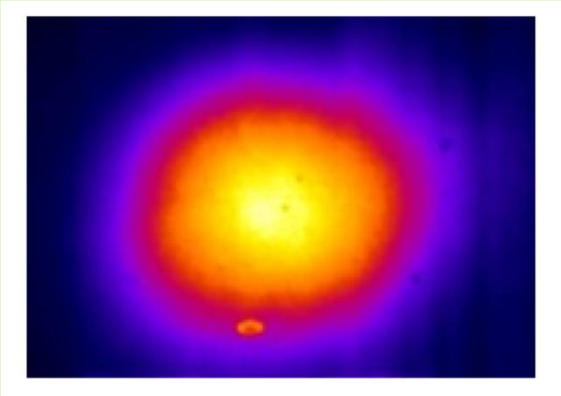
$$\langle I \rangle = (1-2)\cdot 10^{16} \quad \text{W cm}^{-2}$$

More than 50% energy enclosed in hot spots

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

## 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

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

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

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$^{-2}$

3 –Filamentation

# Original beam

Thermal growth rate

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

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

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

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

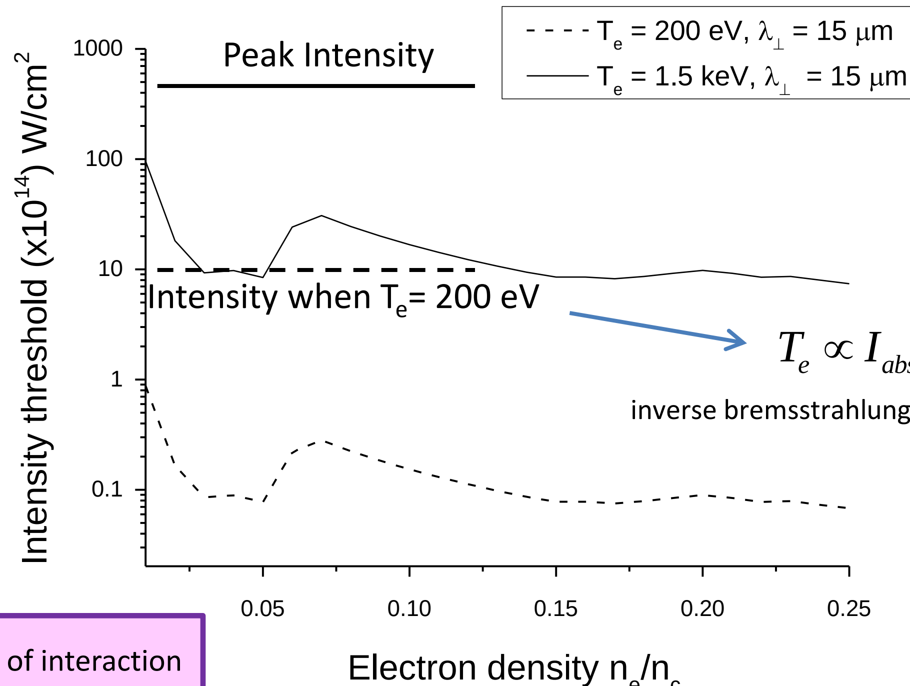
$$k_g L = 1$$

$$L = n/(dn/dx)$$

from hydrodynamic simulations

L = 35-70 μm preplasma

L = 50-100 μm main pulse



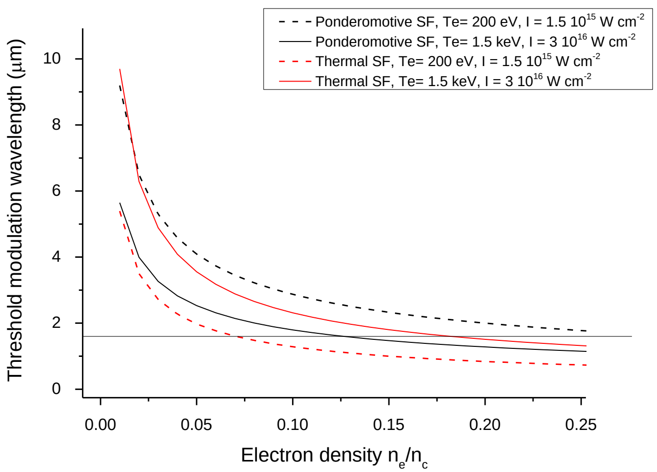

$$T_e \propto I_{abs}^{2/3}$$

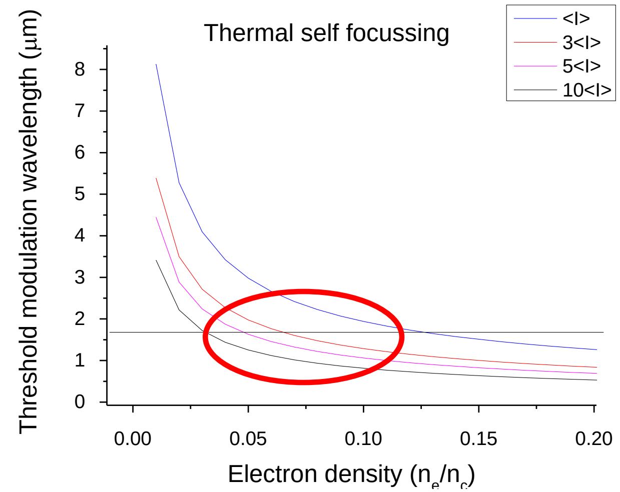
inverse bremsstrahlung = heat flux

- 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)

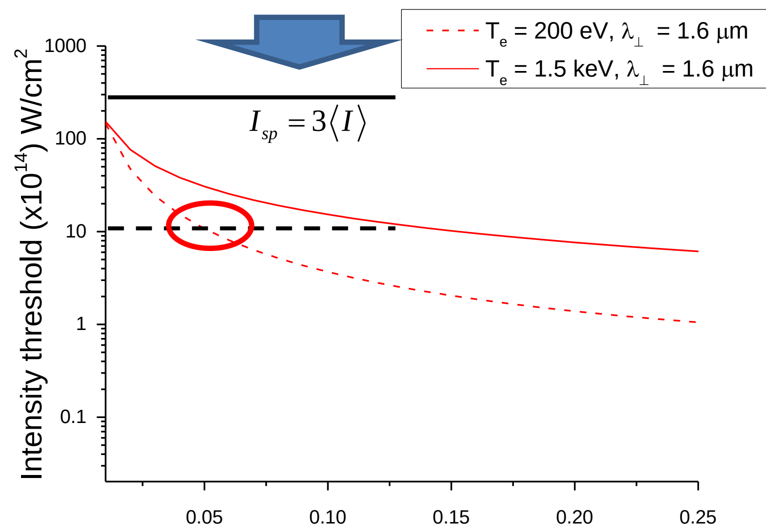
# Random Phase Plate

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



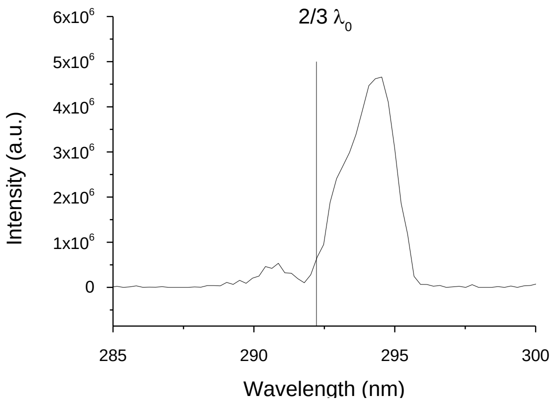

$$k_g L = 1$$

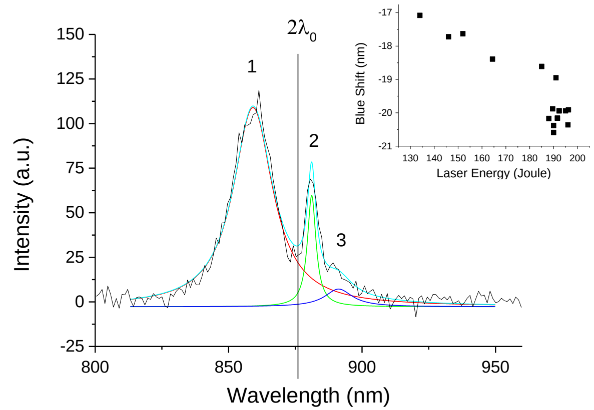



- thermal filamentation prevails at early times (dashed lines) while ponderomotive filamentation is dominant near the peak of the laser pulse (solid lines)
- filamentation does not occur for densities lower than $n_e \sim 0.07\ n_c$
- Filamentaion is expected to occur at early times

# $3/2\omega_0$ and $\omega_0/2$

Interaction at $n_c/4$



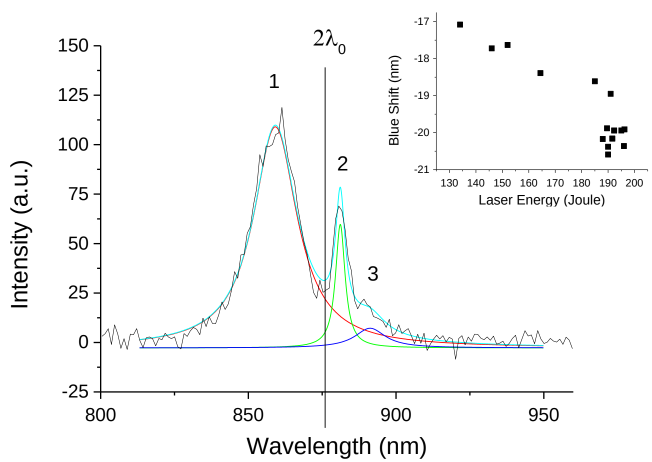

Energy gap between TPD plasma wave

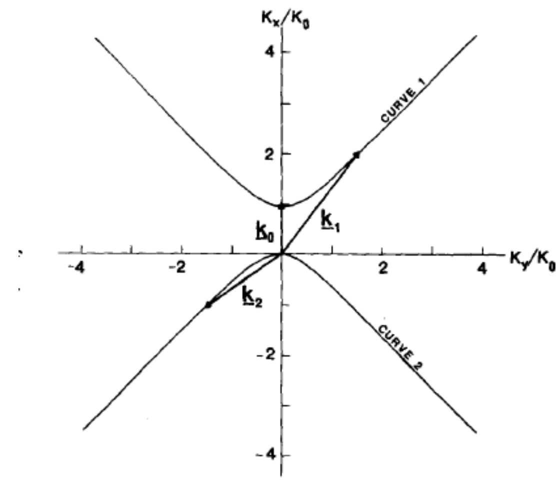
$$\Delta\omega/\omega_0 = \frac{9}{4}\left(v_e^2/c^2\right)\kappa$$

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

In principle we can use $\Delta\omega$ for temperature diagnostics if k is known

# $\omega_0/2$ emission and temperature




Peaks 1-3 generated by Inverse Resonance Absorption (IRA) or by Raman Downscattering (RD)*
We are no able to discriminate (also in literature long discussion !)
$\Delta\lambda_B \approx 20$ nm → $k \approx 2$, $k_e \approx 3k_0$; near the Landau cutoff $k_e\lambda_D \approx 0.3$

Peak 2: It could be absolute SRS but in literature appears at $I < I_{thres}^{SRS}$
→ hybrid TPD/SRS instability: the e.m. wave decays in a forward electrostatic wave (as TPD and SRS) and in a backward partly electrostatic and partly e.m. wave.
Hybrid TPD/SRS instability can be considered as the limit of TPD when the red plasmon wavevector vanishes $k_e \approx k_0$

$k = ½$

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

Te= 1.37 keV a 1.68 keV

According to literature, the use of this peak very reliable

* R.L. Berger, L.V. Powers, Phys. Fluids, 28, 2895, 1985.

# Considerations on energy

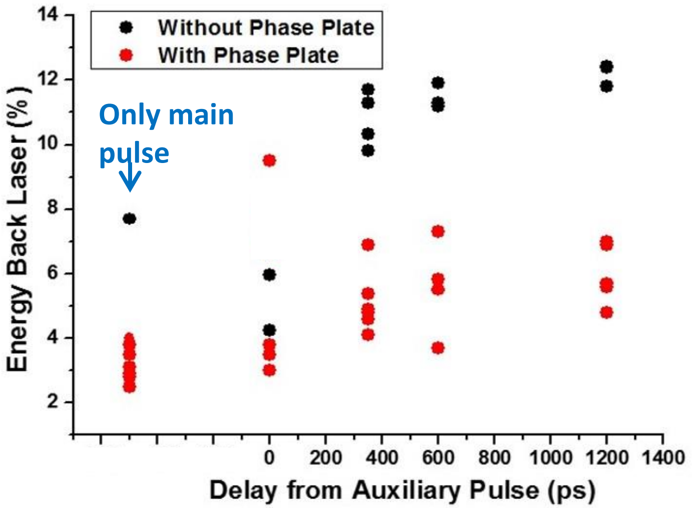
- Laser photons reach $n_c/4$ surface but odd-harmonics generation efficiency is very low ( $h_{1/2}$~$10^{-3}$ %, $h_{3/2} \approx 10^{-1}$ % )
- Non relevant degradation of laser-plasma coupling; it is however plausible, that such efficiency could be much higher at early times, when TPD is expected to prevail on other instabilities.
- No evidence of SRS occurring at $n_c/4$ exists (or it is very low), 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.*

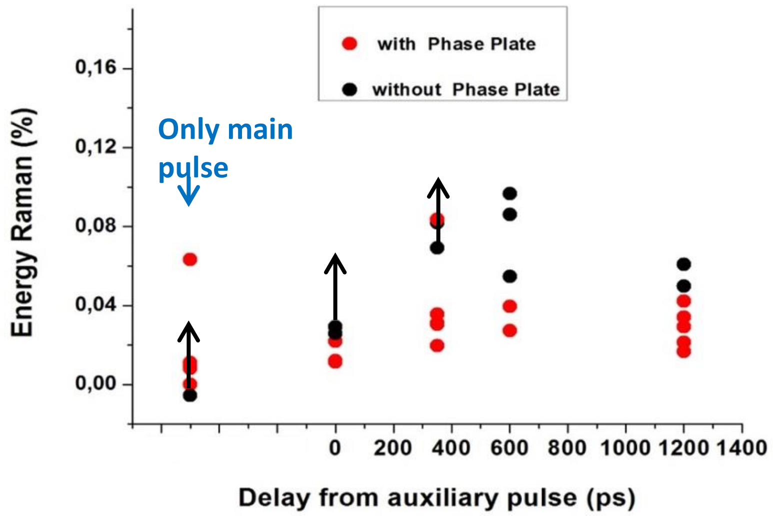
+ O. Klimo, V.T Tikhonchuk, Plasma Phys. Control. Fusion 55 (2013) 095002; O. Klimo, J. Psikal, V. T. Tikhonchuk, S. Weber, Plasma Phys. Control. Fusion **56** (2014) 055010.

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

# Parametric Instabilities - SRS/SBS

Backscattered energy vs. delay



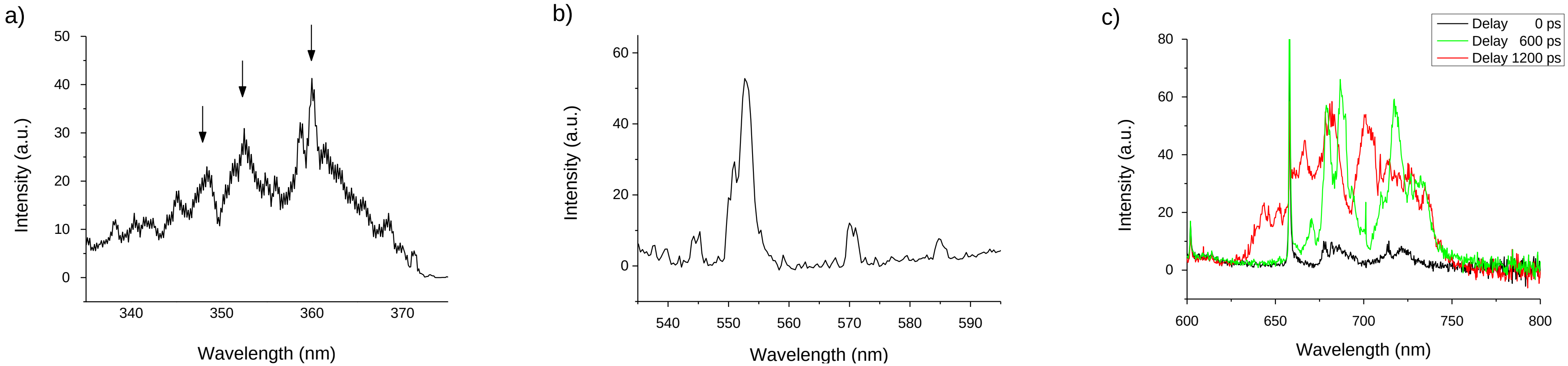




- Backscattered energy in the lens cone of the order of 6% or less of laser energy.
- All the backscattered energy 20-30% (not definitive)
- Dominant contribution from backreflected laser and SBS, agreement with similar experiments*.
- SRS less than 0.1% of laser energy.
- Signal increases with increasing preplasma extension.

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

5 – RPP shots

# Stimulated Raman Scattering




SRS threhsold due to inhomogeneity mismatch and Landau damping

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

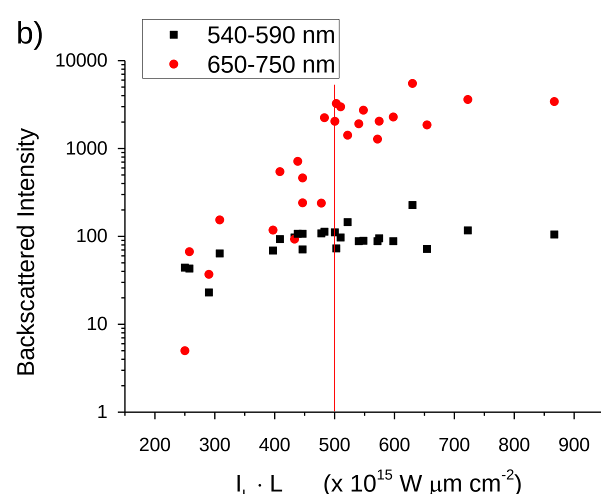
Exponential profile exp (-z/L) can be considered linear since $l \approx$ 1-2 μm and $l << L$

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

$4 \cdot 10^{-2}$ %

$\sim 10^{-3}$-$10^{-2}$ %

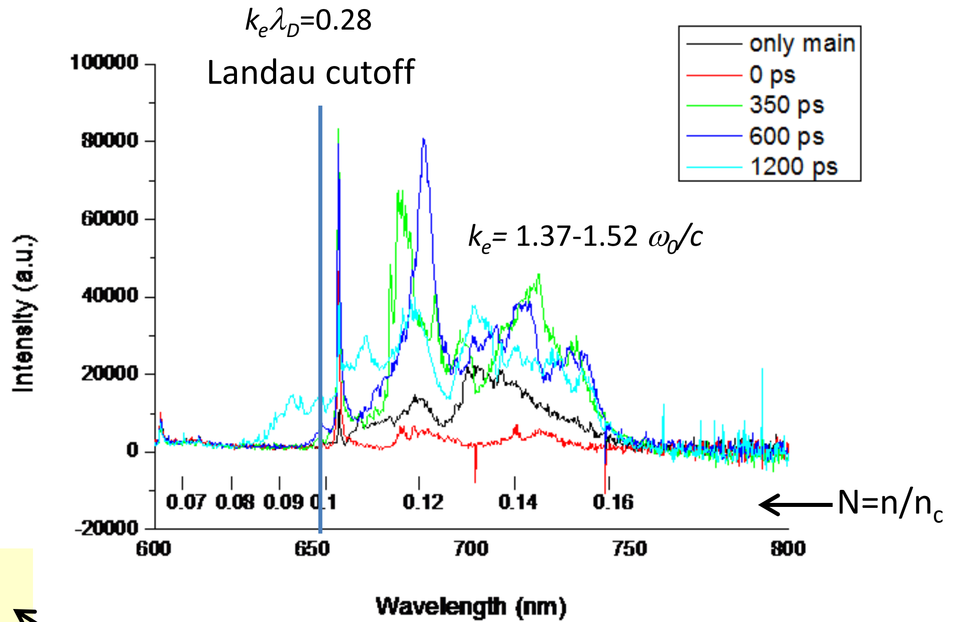
# Backward SRS

Absolute vs. Convective SRS discussion

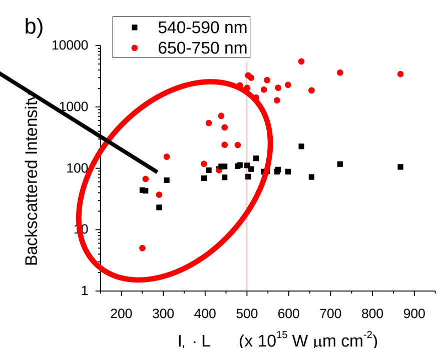
$\lambda >> 1$ ⟹ Absolute SRS can occur

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

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




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

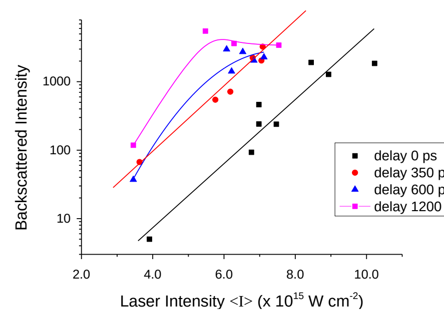



2 - We observe a rapid growth 1-2 orders of magnitude in a factor 2 laser intensity and then a rapid saturation

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.

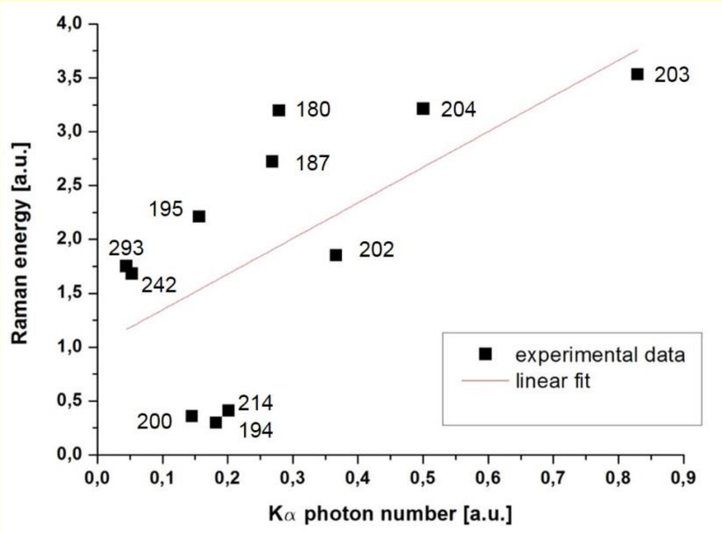
3 -Saturation can be due to nonlinear frequency detuning produced by bowing and filamentation of plasma waves in speckles; LDI, electron trapping in nonlinear

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

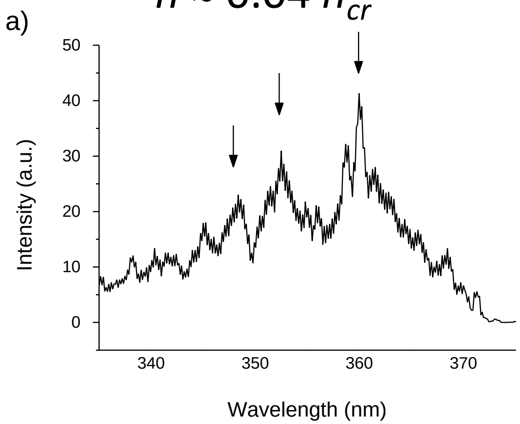
**2 – Experimental hot electron temperature agrees with energy expected from SRS EPW breaking.**

**fast electron generation is mainly due to SRS**

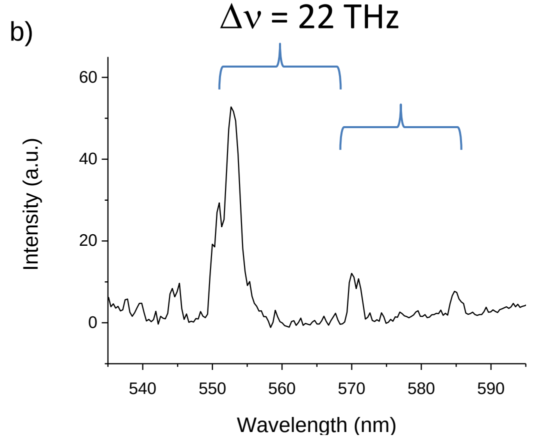
(However there is still a problem of energy matching to fit)

# Forward SRS

$n \approx 0.04\, n_{cr}$




$\Delta\nu$ = 22 THz




- It is difficult to associate these peaks to BRS $k_e\lambda_D = 1$
- AntiStoke peaks

Forward Raman Scattering

threshold

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

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

But how we can we see it ?

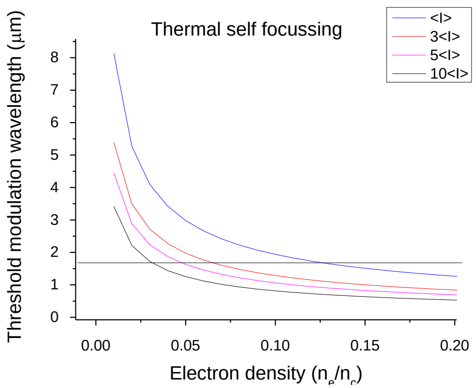
- Reflection at $n_c$ ?
- SBS of FRS bursts*

Threshold in the range $10^{14}$-$10^{15}$ W cm$^{-2}$

Filamentation of speckles -> modify density profile, saddles, local maximums, ecc.
-> Local increase of laser intensity
-> restricted region of EPW propagation

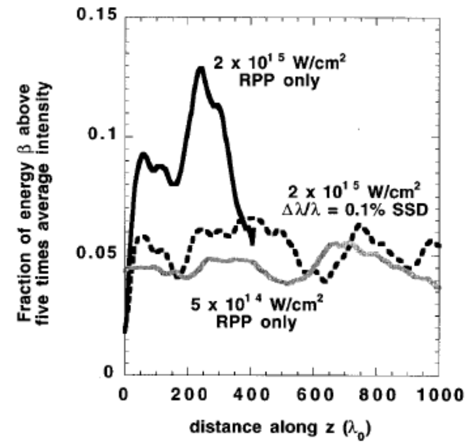
*A.B. Langdon, D.E. Hinkel, Phys. Rev. Lett. 89, 015003 (2002)

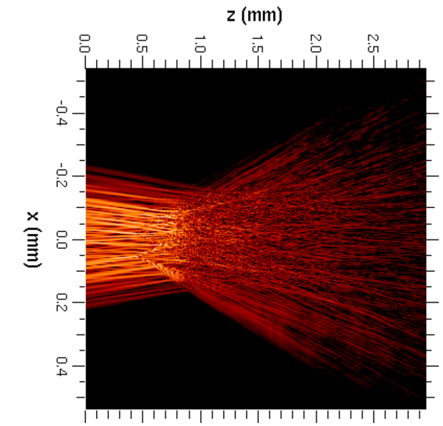
# Forward SRS and filamentation




We expect filamentation at $n_e = 0.05\text{-}0.07\ n_c$

* D. S. Montgomery, Phys. Plasmas 3, 1728 (1996).




In steady state filaments

$$n_0 = N_0 e^{-v_0^2/4v_e^2}$$

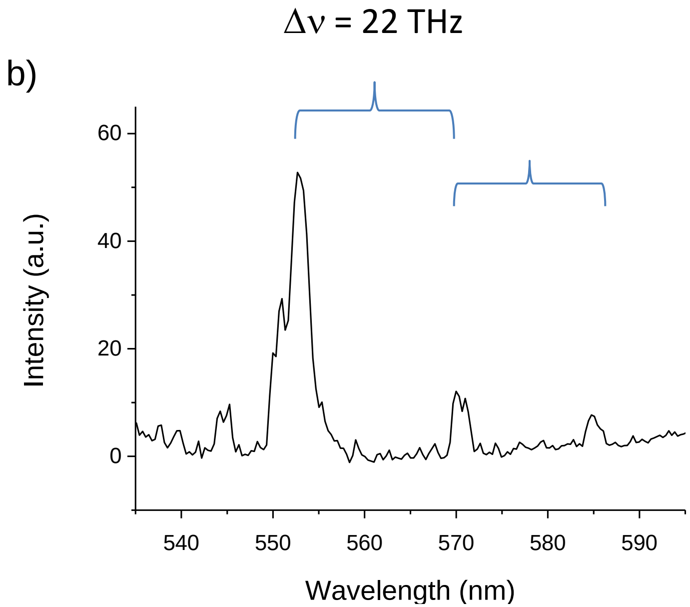
$$\frac{v_0}{v_e} \cong \sqrt{2}/2$$

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

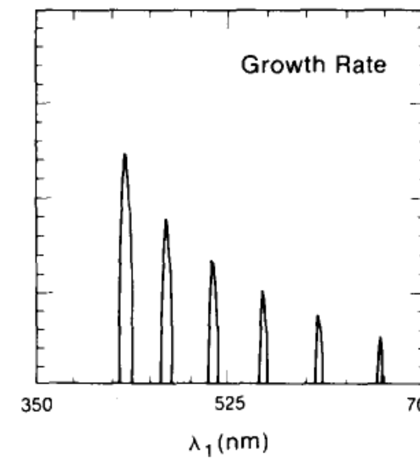
Real expected $\varepsilon$ = 0.1-0.2

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

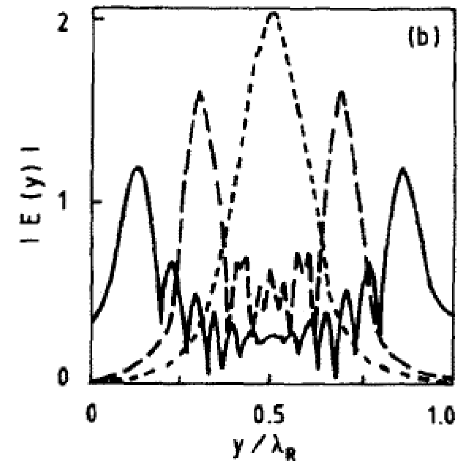
# Modulation of Forward SRS




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

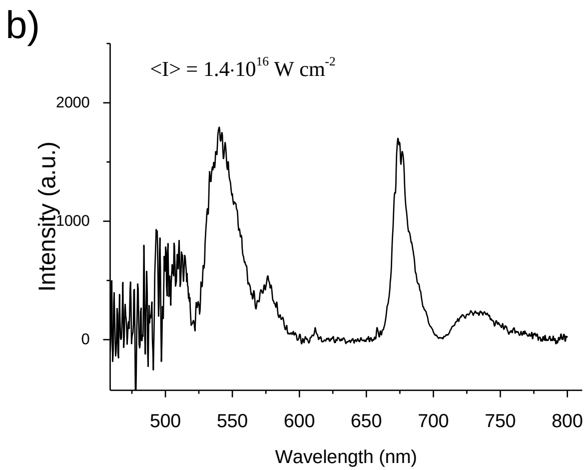
It supports our hypothesis !

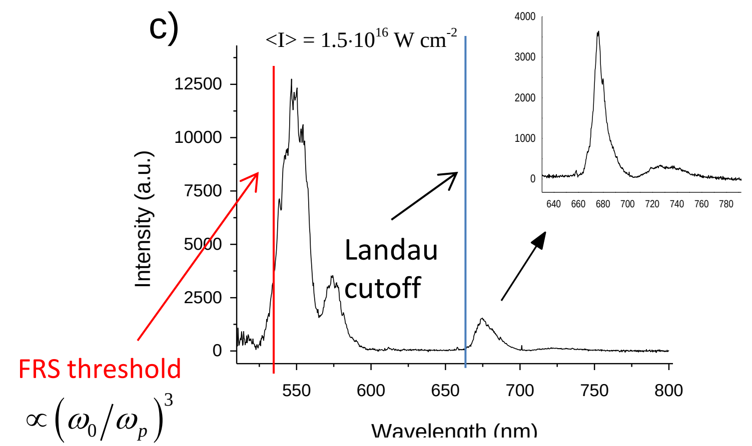
# Shots w/o RPP

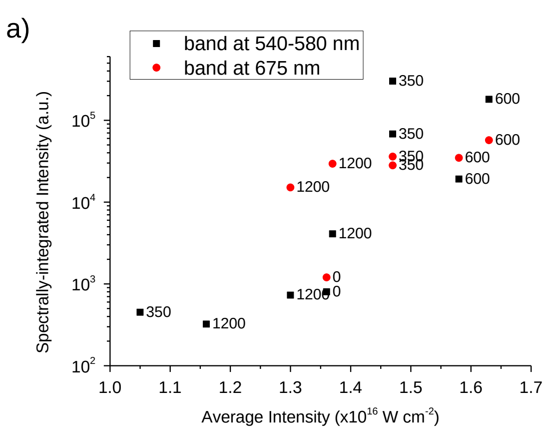
$\langle I \rangle \approx (1\text{-}2)\cdot 10^{16}$ W cm$^{-2}$

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 =0.1-1% 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

# Conclusions

• In all shots the energy backscattered is dominated by laser/Stimulated Brillouin Scattering with a loss 2-8% (RPP) and of 6-12 % (no RPP) of laser energy, slightly increasing with plasma scalelength. Measurements with the integrating sphere in laser shots with RPP, show that the overall scattered light is of the order of 20-30%. Results agree with previous experimental works in hot - long scalelength inhomogeneous plasmas at SI relevant intensities.

• Energy backscattered by SRS is limited to 0.01-0.04% in case of RPP, dominated by BRS occurring in the density region 0.10-0.15 $n_c$, near the Landau cutoff. In shots w/o RPP the energy backscattered is an order of magnitude higher, dominated by FRS occurring in low density region 0.04-0.06 $n_c$. Such values are much lower than those measured by Goyon et al. and those derived with 2D numerical simulations by Klimo et al., but with a hotter plasma ($T_e$= 5 keV).

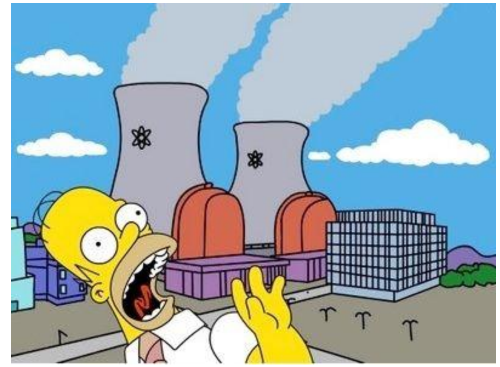
• Two Plasmon Decay instability prevails on absolute SRS at $n_c/4$ density. The odd-harmonics generation efficiency - $\eta_{1/2}$~$10^{-3}$ %, $\eta_{3/2}\approx10^{-1}$ % - gives rise to an irrelevant loss of laser energy. There is a striking difference with numerical simulations in SI conditions, 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 and the hot spot self-focussing is a determining factor in laser-corona interaction. The occurrence of filamentation is suggested by 1) the overcome of FRS threshold, needing a laser intensity at least a factor 10 higher than that available in hot spots/speckles; 2) the strong increase of FRS in shots without RPP, where large hot spots favor self focusing in the beam; 3) the density regions where filaments are expected to form, corresponding to the regions where FRS occurs; 4) the modulation of FRS light spectra, which are compatible with eigenfunctions of EPW energy into the filaments.

• In shots with RPP, a strong correlation is found between the BRS backscattered energy and the $K\alpha$ photon number. Moreover, the energy of suprathermal electrons $E_{hot}$=28 keV agrees with the energy calculated from the phase velocity of plasma waves induced in the density region 0.10-0.15 $n_c$, $E_{hot} \approx 20$ keV. These findings are an indication that suprathermal 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.



# THANK YOU FOR YOUR ATTENTION !

References: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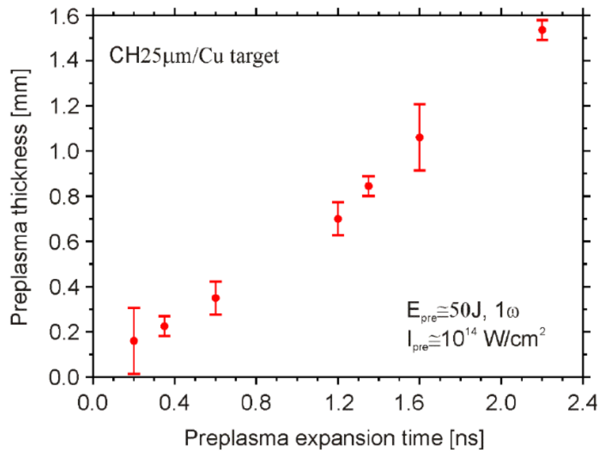
# Preplasma characterization

- **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

$$k_y = 3\omega_0 \sin\theta / 2c$$ ⇒ $T_e$ = 1.7-3.3 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.