Laser interaction with a coronal plasma in the conditions relevant to shock ignition

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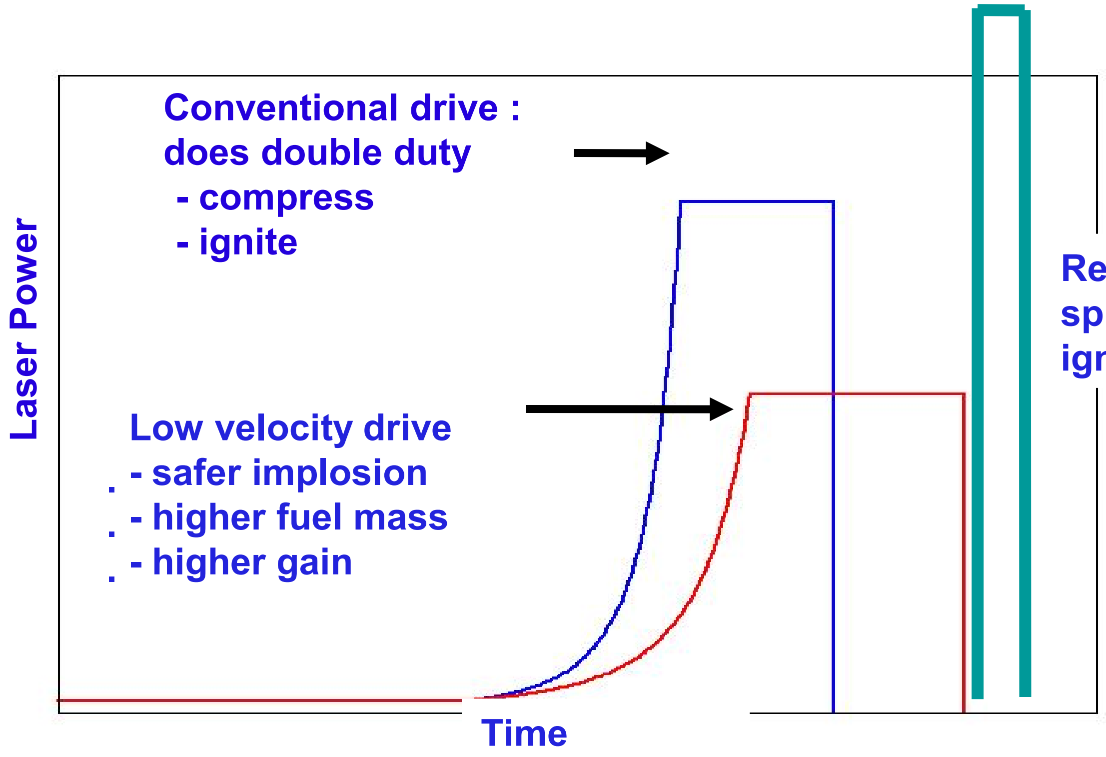
Shock ignition in a nutshell

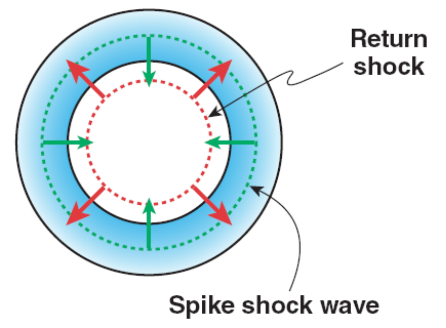
Ignition of the fuel from a converging shock launched from a short intense laser pulse



Conventional drive : does double duty
- **compress**
- **ignite**

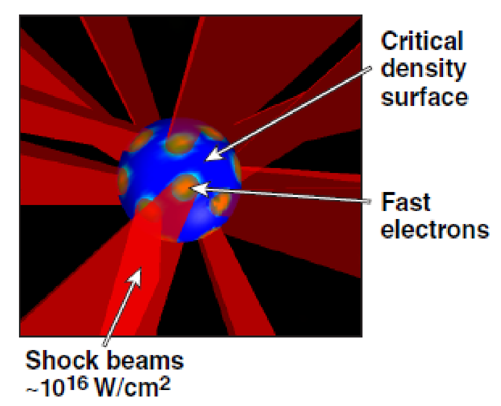
Low velocity drive
- **safer implosion**
- **higher fuel mass**
- **higher gain**

Requires ~200 TW spike to launch the ignitor shock

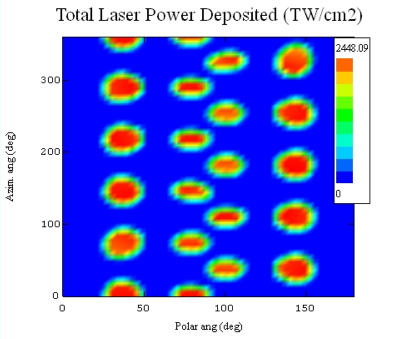


The physics of laser plasma interaction is not understood and controlled

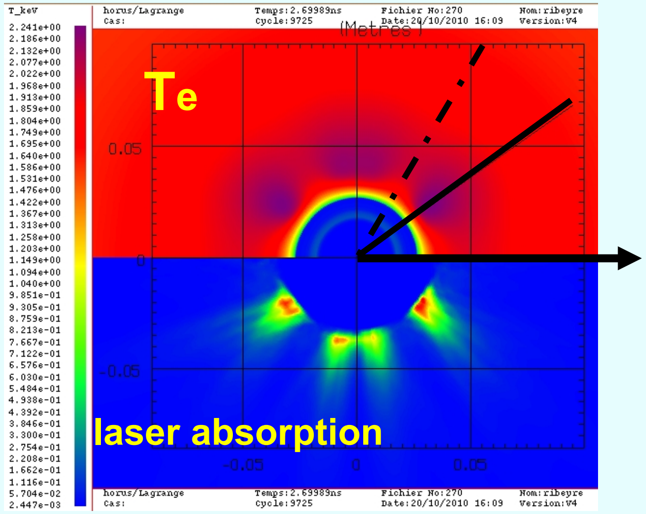
Laser plasma interaction physics in Omega experiments

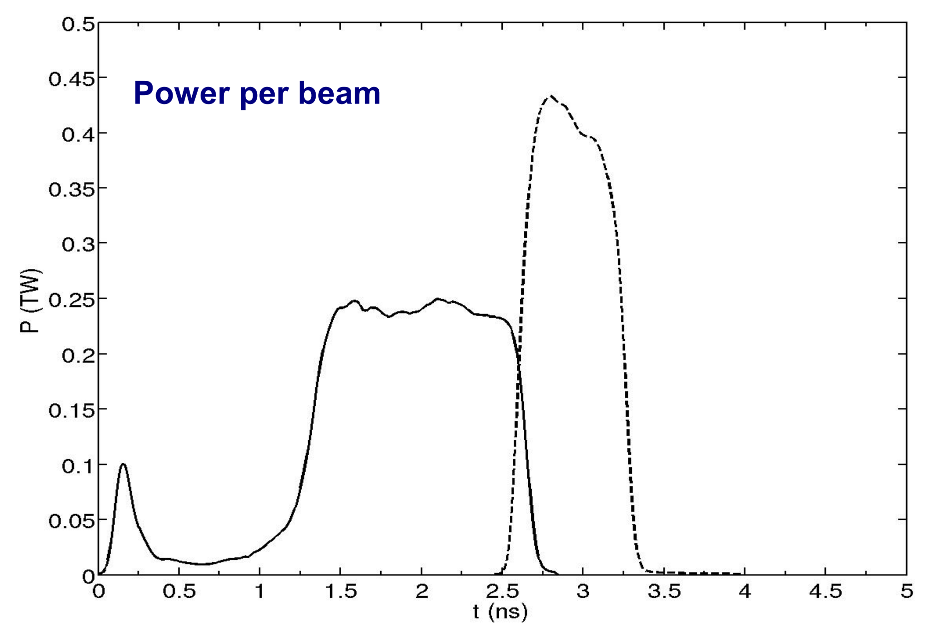


Spike irradiation



Omega experiments under the conditions relevant to shock ignition

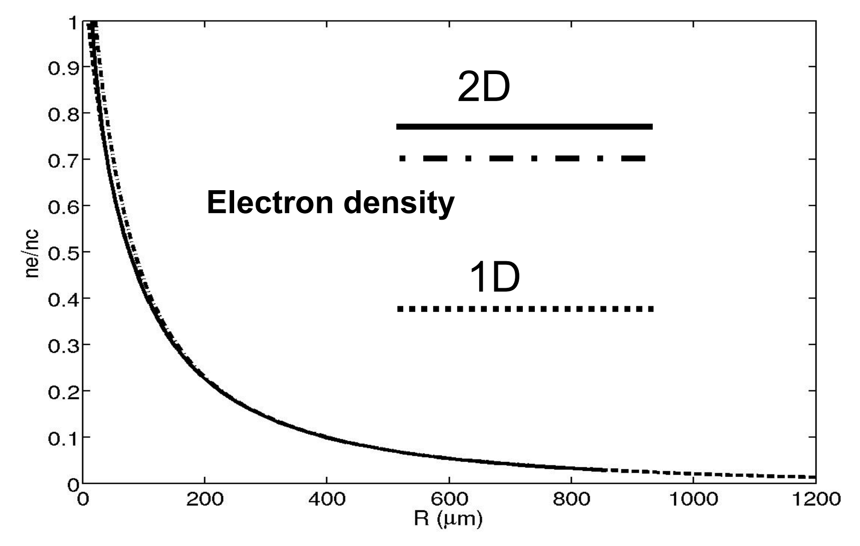


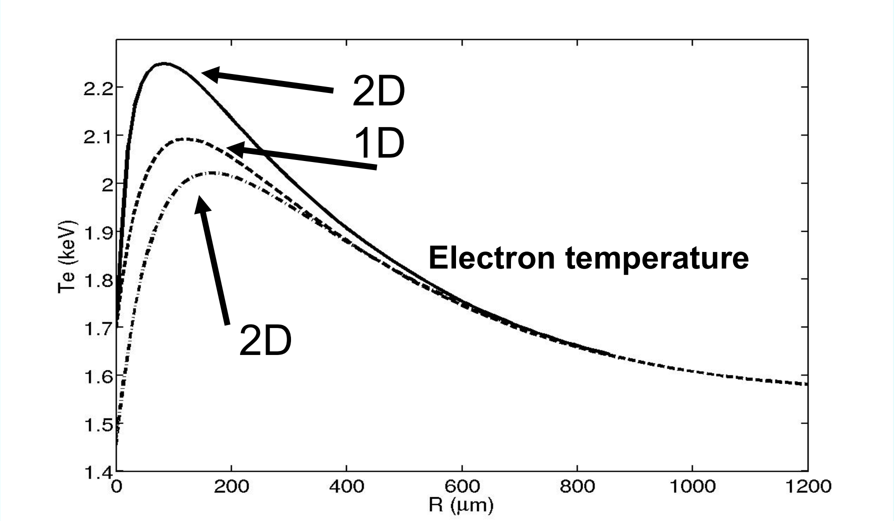


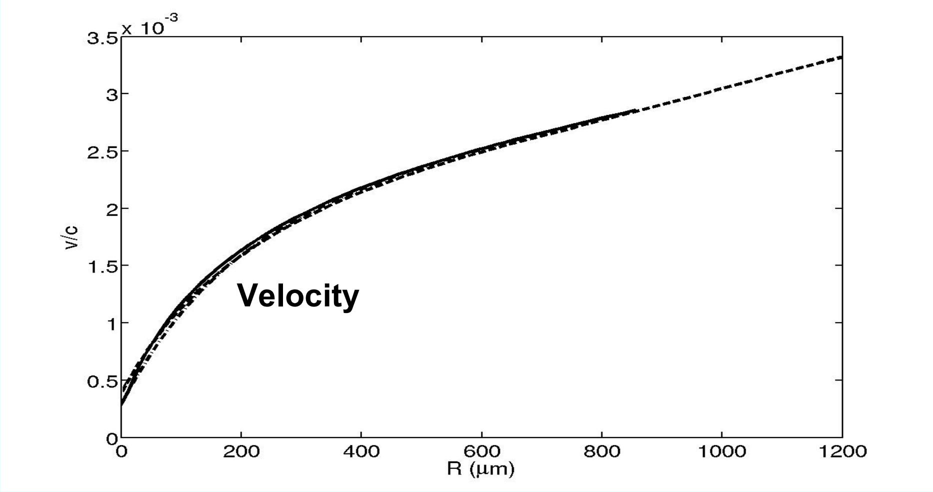
W.Theobald 2009
X.Ribeyre 2011

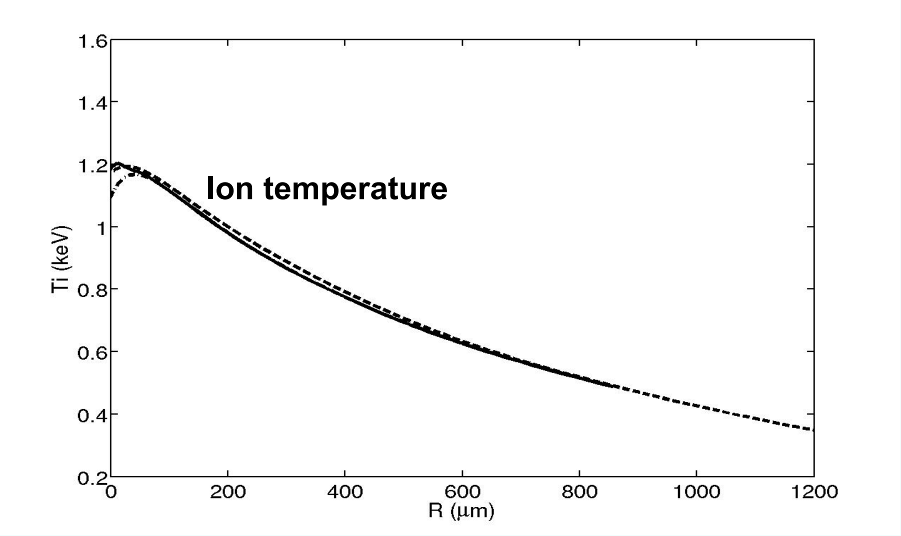
Interaction conditions are defined by hydro simulations

The plasma corona is hot and it extends over a mm scale

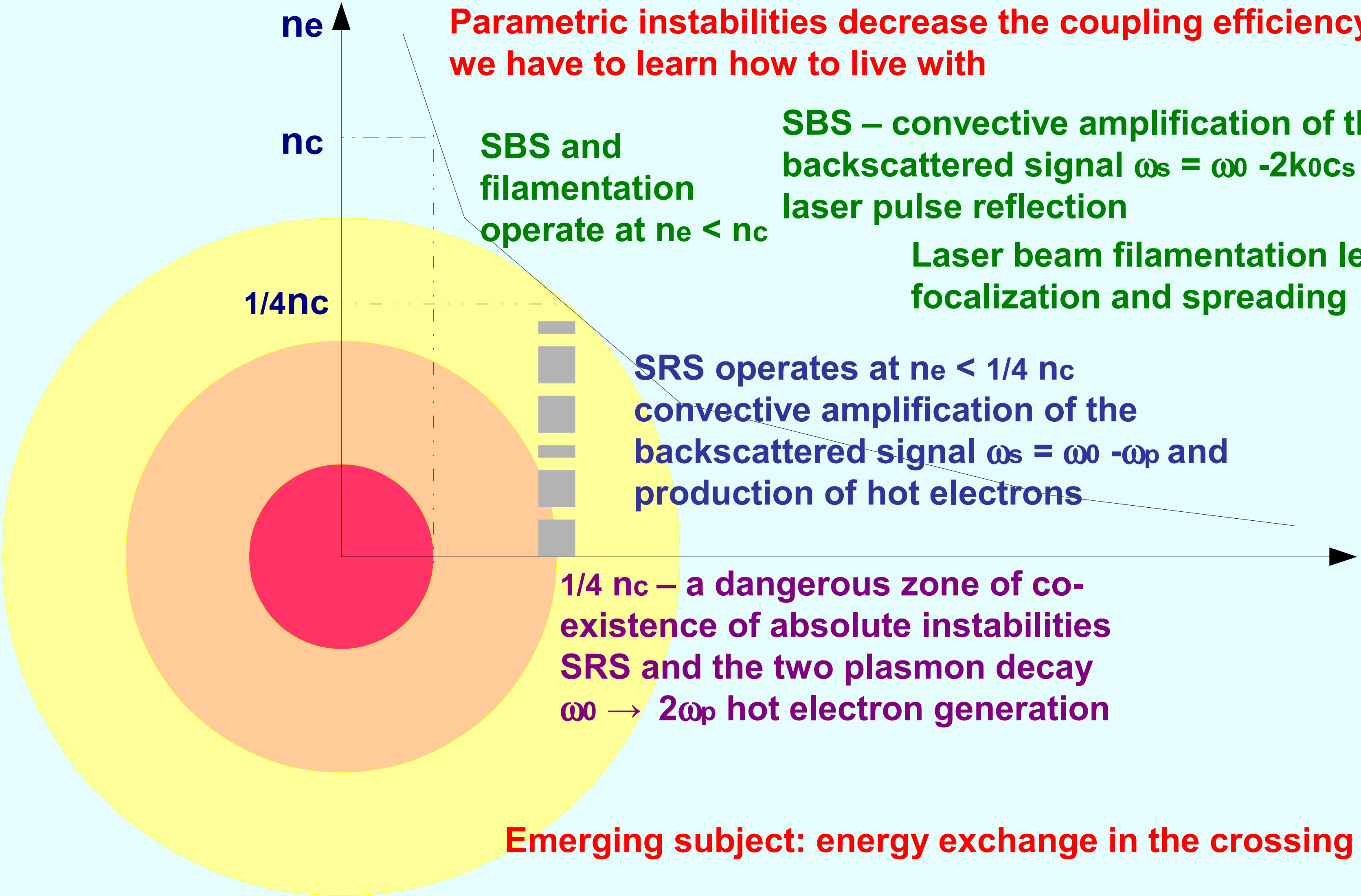








Parametric instabilities in the corona: SBS, FI, SRS, TPD



Parametric instabilities decrease the coupling efficiency but we have to learn how to live with

SBS and filamentation operate at $n_e < n_c$

SBS – convective amplification of the backscattered signal $\omega_s = \omega_0 - 2k_0c_s$ laser pulse reflection

Laser beam filamentation leads to focalization and spreading

SRS operates at $n_e < 1/4\ n_c$ convective amplification of the backscattered signal $\omega_s = \omega_0 - \omega_p$ and production of hot electrons

$1/4\ n_c$ – a dangerous zone of co-existence of absolute instabilities SRS and the two plasmon decay $\omega_0 \rightarrow 2\omega_p$ hot electron generation

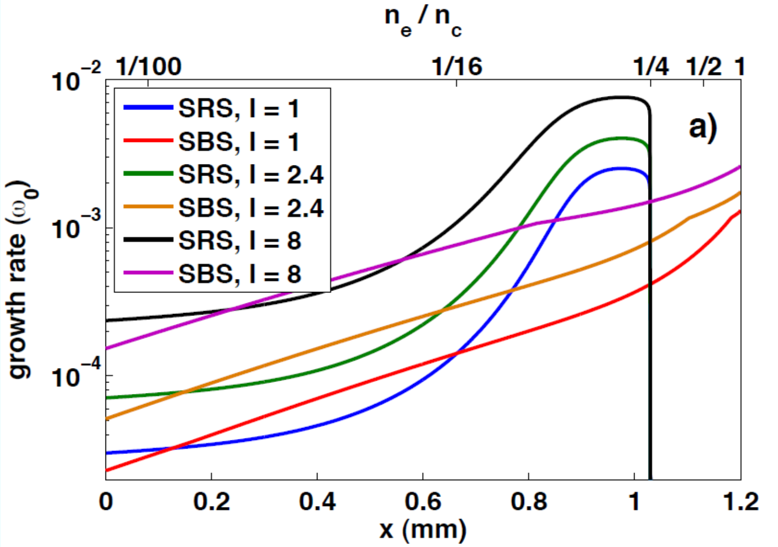
Emerging subject: energy exchange in the crossing beams

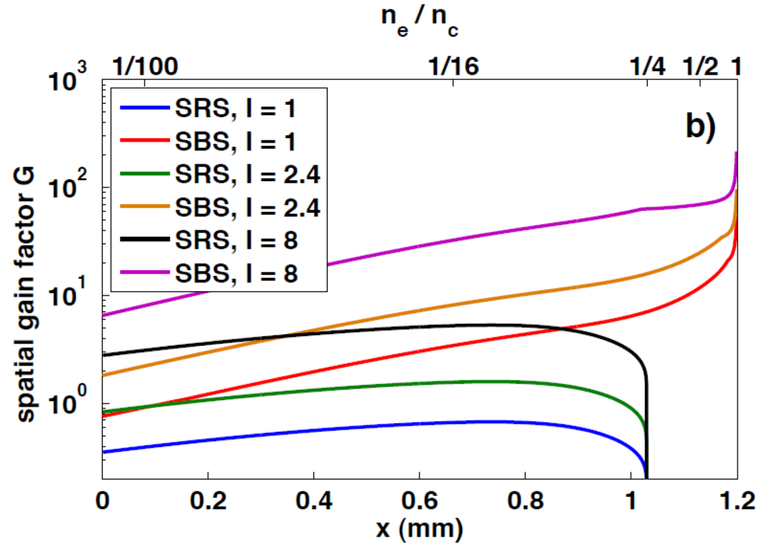
SBS and SRS gains for intensities × 10^{15} W/cm^2 for 3ω

Convective instabilities: stationary spatial gain R = R_{th} exp (1-R)G

$$G = \frac{\pi \gamma_0^2}{|\kappa' v_{g1} v_{g2}|}$$

Although the gains are relatively low, the instability may be excited either in hot spots (speckles) or due to the kinetic effects (particle trapping)

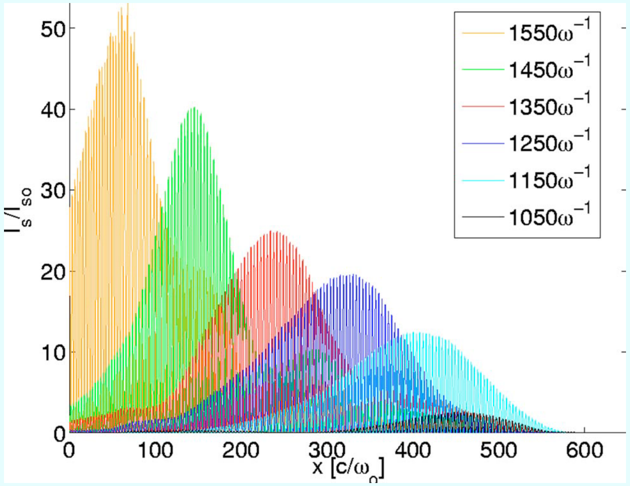


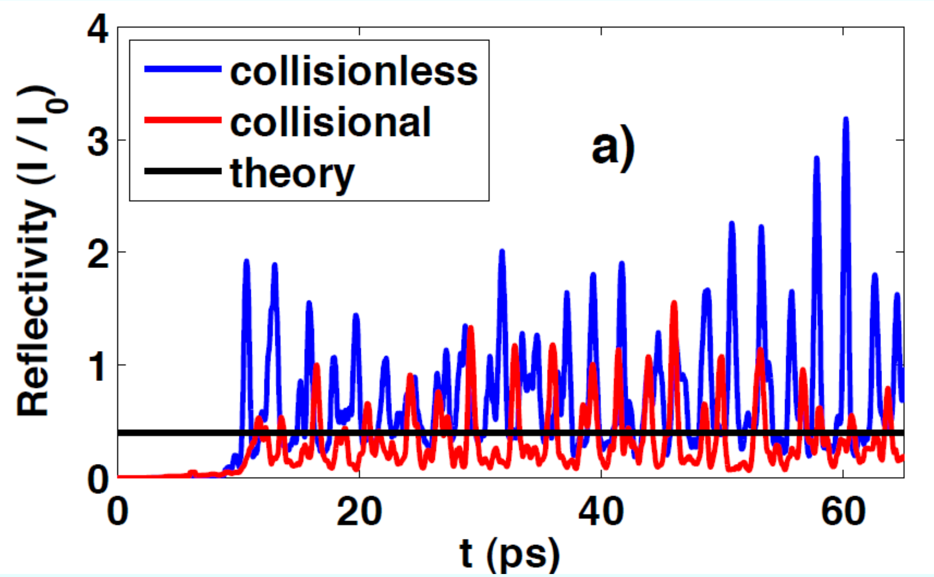


Pulse amplification goes well above the stationary level

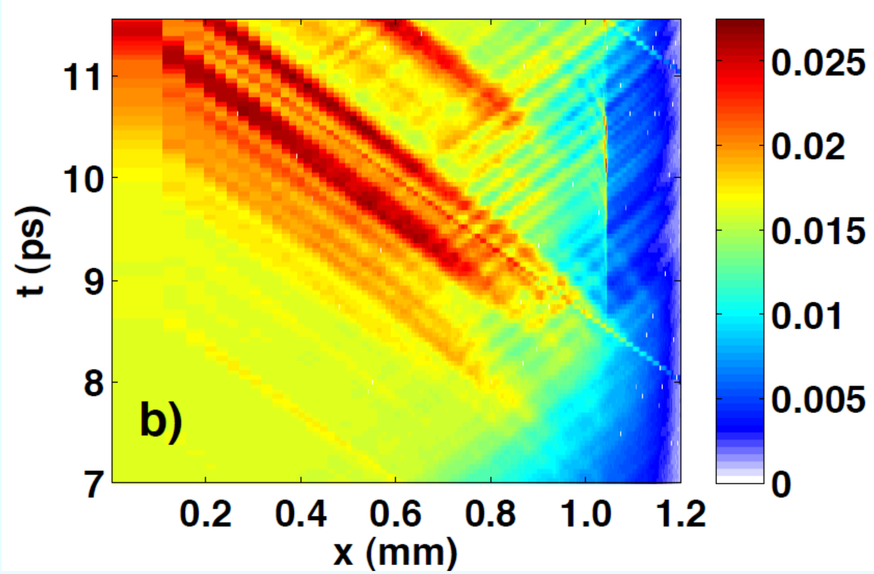
SBS: generation of giant reflected pulses

Danger of SBS in periodic generation of intense pulses that are amplified on their way down the density profile





1D×3V simulation: 10^{15} W/cm^2

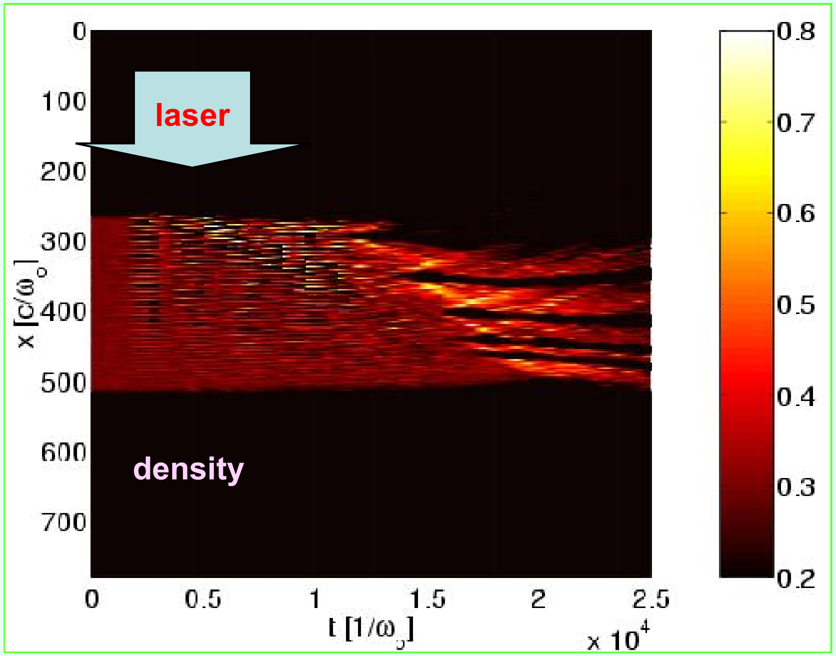


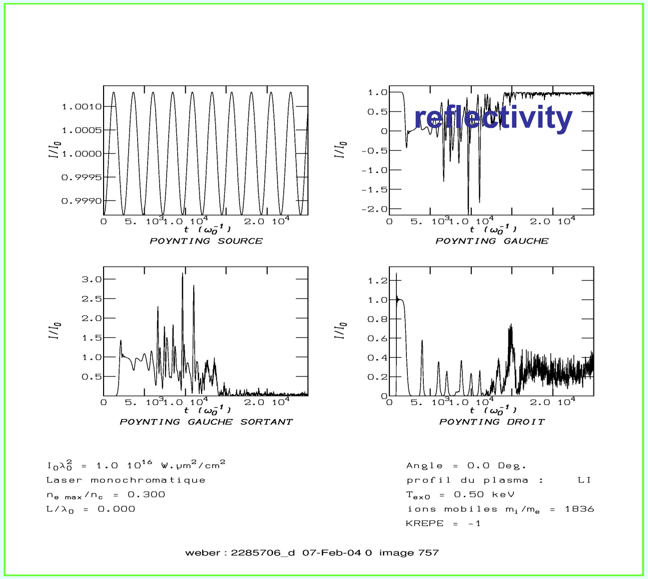
A.Andreev et al PoP 2006
O.Klimo et al PPCF 2011

SBS: laser energy absorption in density cavities

Energy absorption starts in the cavities created by the backscattered pulse at higher laser intensities Iλ^2 = 10^{16} W/cm^2

1D×3V simulation: cavity assisted laser absorption



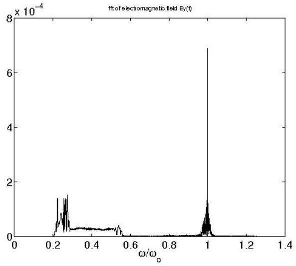


$I_0\lambda_0^2$ = 1.0 10^{16} W.μm^2/cm^2
Laser monochromatique
$n_{e\ max}/n_c$ = 0.300
L/λ_0 = 0.000

Angle = 0.0 Deg.
profil du plasma : LI
T_{ex0} = 0.50 keV
ions mobiles m_i/m_e = 1836
KREPE = -1

weber : 2285706_d 07-Feb-04 0 image 757

spectrum of reflected wave

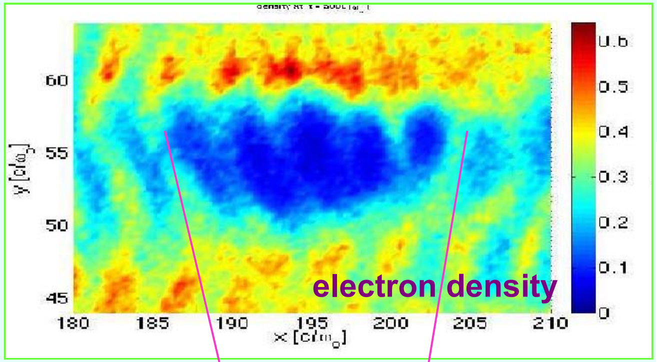


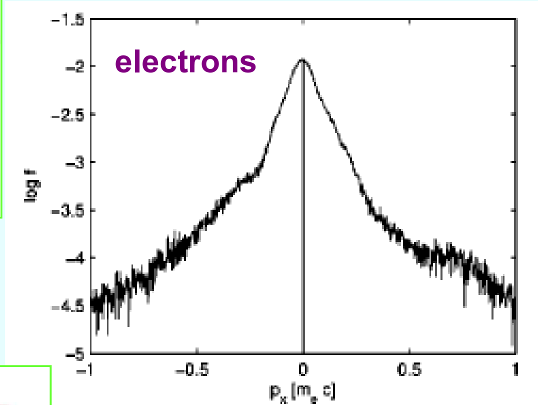
S.Weber et al PRL & PoP 2005

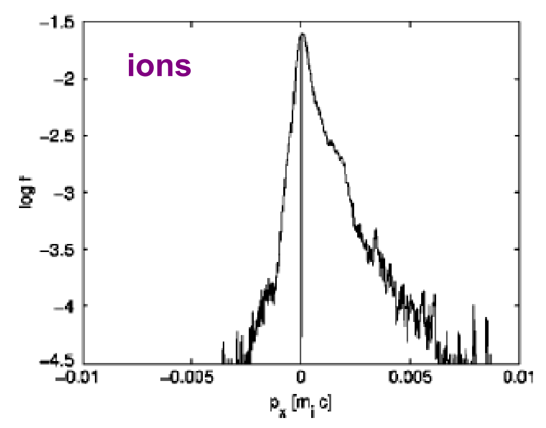
SBS: density cavities & electron acceleration

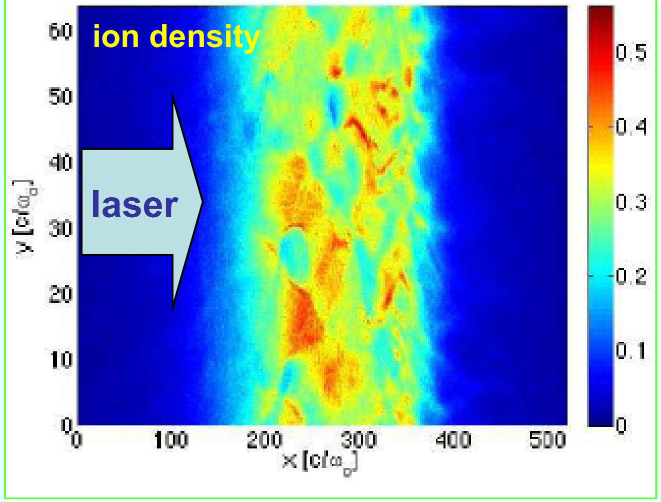
Laser energy absorption in the cavities results in electron and ion heating and acceleration to 100 keV

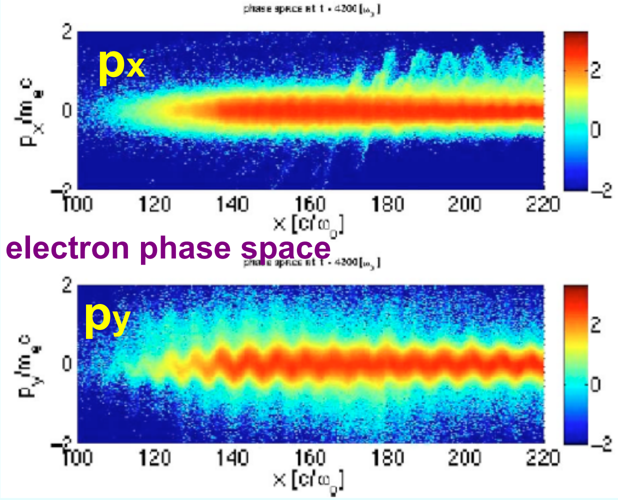
2Dx3V simulations in a homogeneous plasma layer







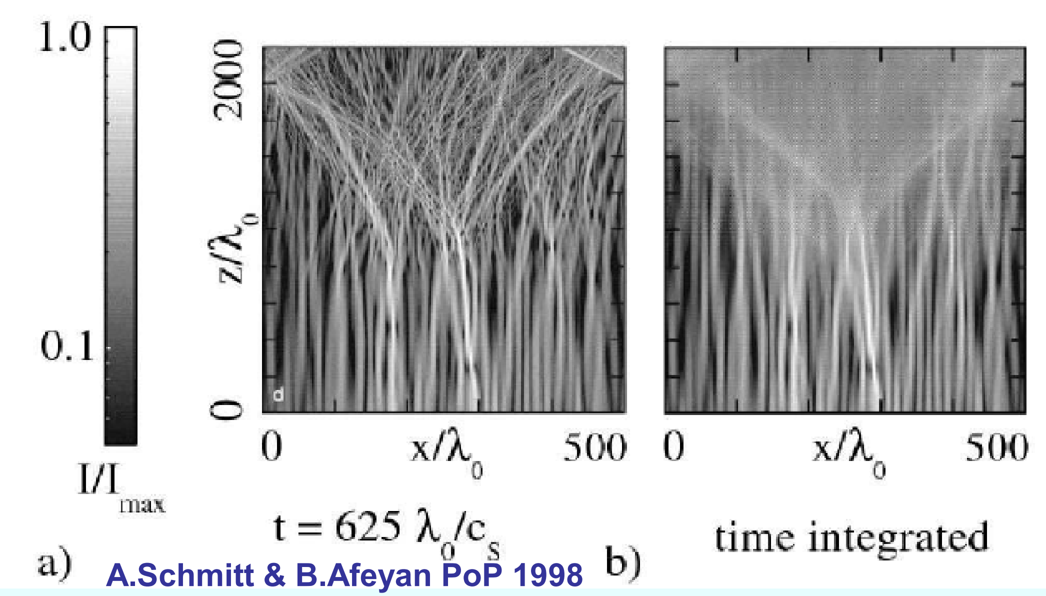




S.Weber et al PRL & PoP 2005

Forward SBS and plasma smoothing effect

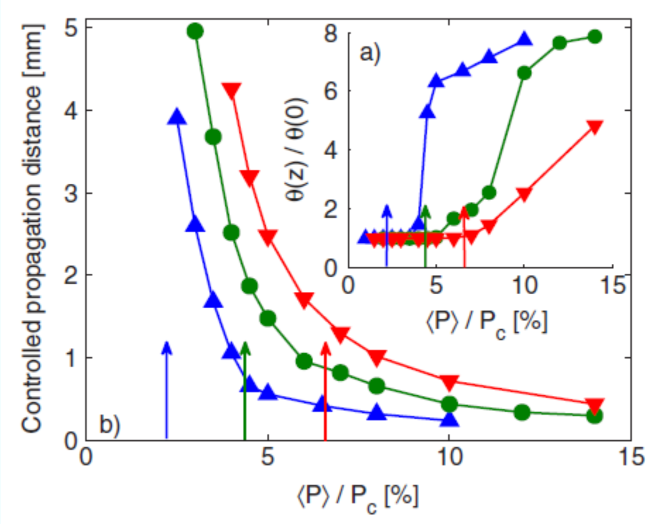
Multispeckle laser beam experiences angular and frequency spreading in plasma. This effect is due to the speckle instability and the forward SBS



A.Schmitt & B.Afeyan PoP 1998

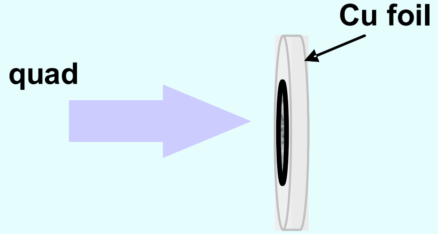
Criterion for the laser beam smoothing is defined by the average speckle power

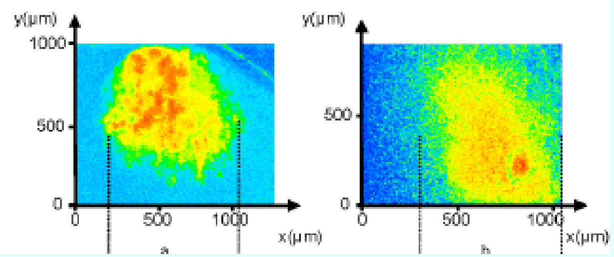
$$C = \sqrt{\frac{\pi}{2}}\gamma_T \frac{\langle P\rangle/P_c}{\nu_{\mathrm{IAW}}/\omega^{(\mathrm{IAW})}}$$



M.Grech et al PRL 2009

This effect is observed in a foam produced plasma



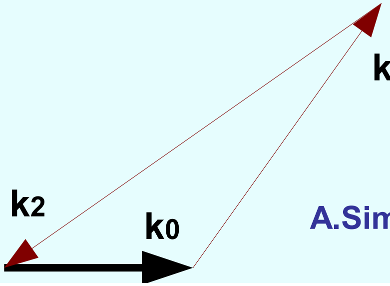


S.Depieurreux et al PRL 2009

TPD & SRS instabilities near the quarter critical density

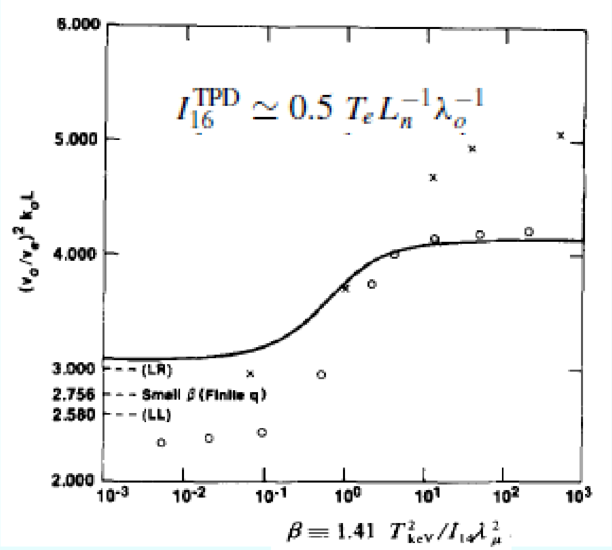
Two plasmon decay instability is excited near 1/4 nc, it develops as an absolute instability as slow plasma waves do not escape the resonance

$$k_{1y} = -k_{2y} = k_y,\ k_{1,2x} = \tfrac{1}{2}k_o \pm \Delta k,\ \text{and}\ \ \Delta k^2 = \tfrac{1}{4}k_o^2 + k_y^2.$$

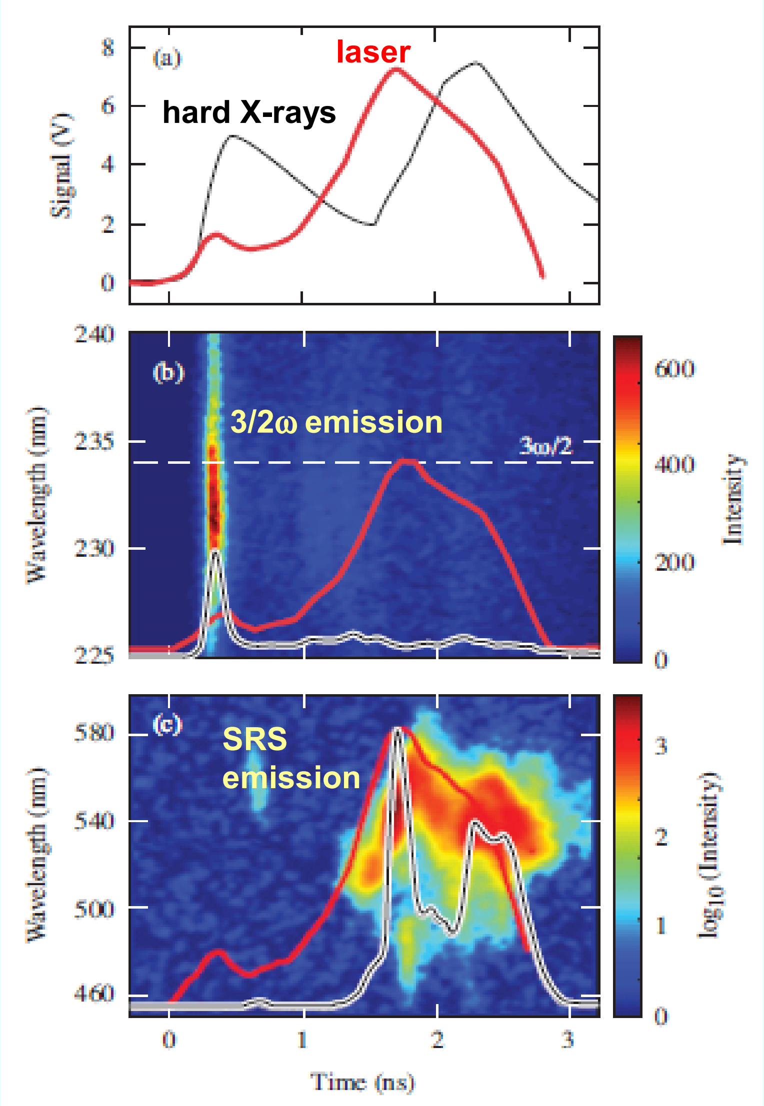


TPD be easily excited above 3-5×10^{14} W/cm^2

A.Simon et al PF 1983



Omega experiments are confirming the TPD excitation threshold, but they also show a competition with SRS



S.P.Regan et al PoP 2010

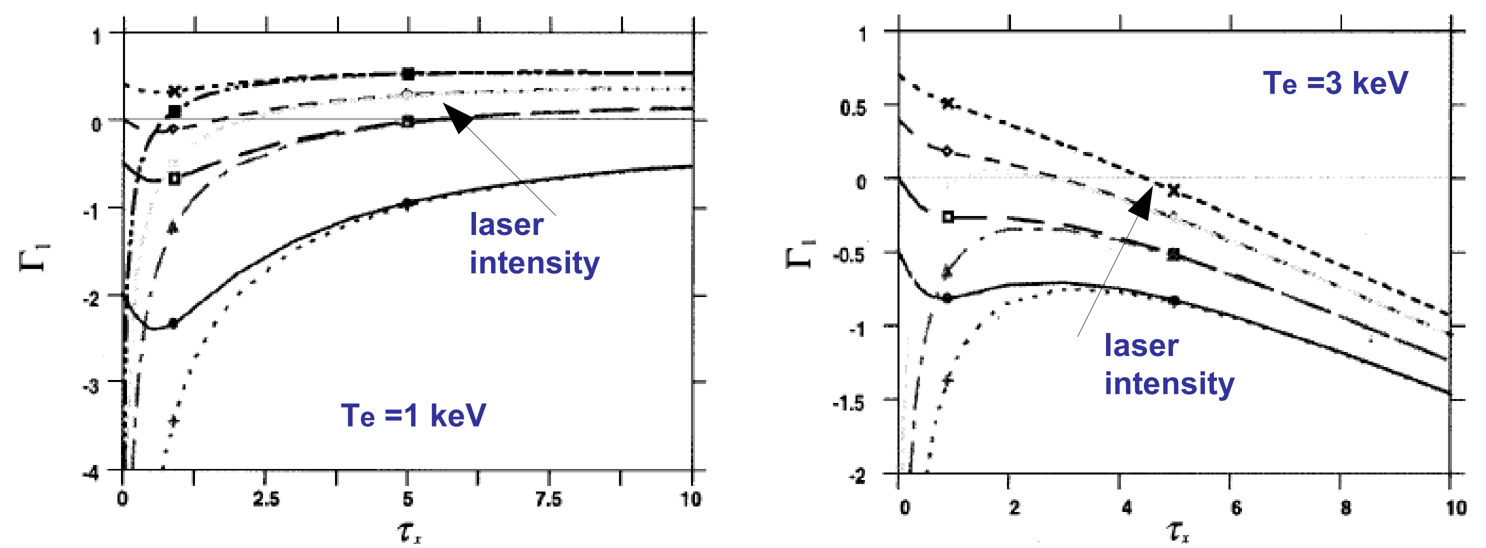
SRS – TPD competition → hybrid instability HFHI

SRS and TPD are in competition as their thresholds are comparable

B.Afeyan & E.Williams
PRL 1995 & PoP 1997

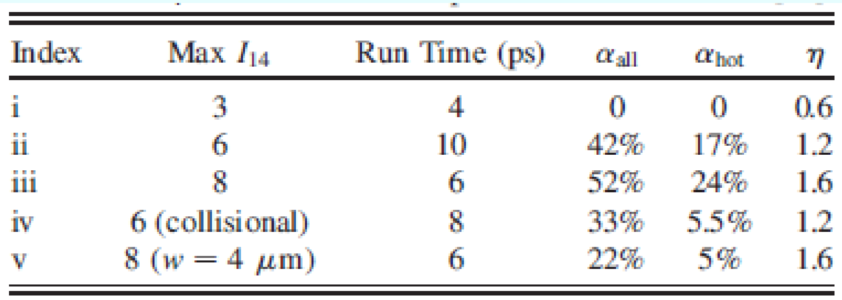
$I_{16}^{\mathrm{TPD}} \simeq 0.5\, T_e L_n^{-1} \lambda_o^{-1}$

$I_{16}^{\mathrm{SRS}} \simeq 12\, L_n^{-4/3} \lambda_o^{-2/3}$



Angular dependence of the high field hybrid instability (HFHI) growth rate

Recent 2D simulations in the zone near 1/4 nc show rather fast excitation of the SRS and TPD instabilities associated with the hot electron generation

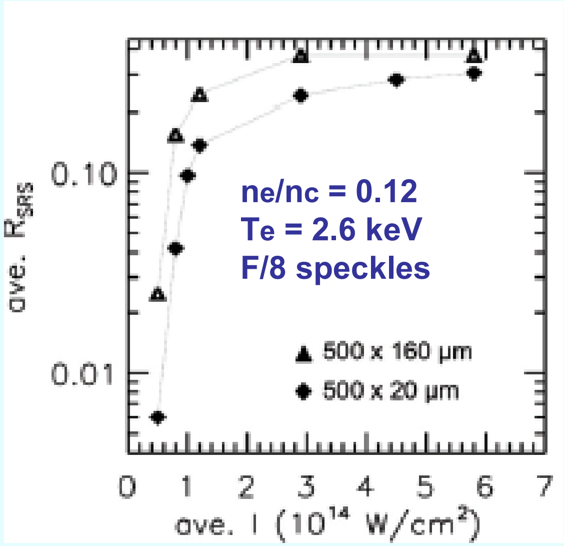


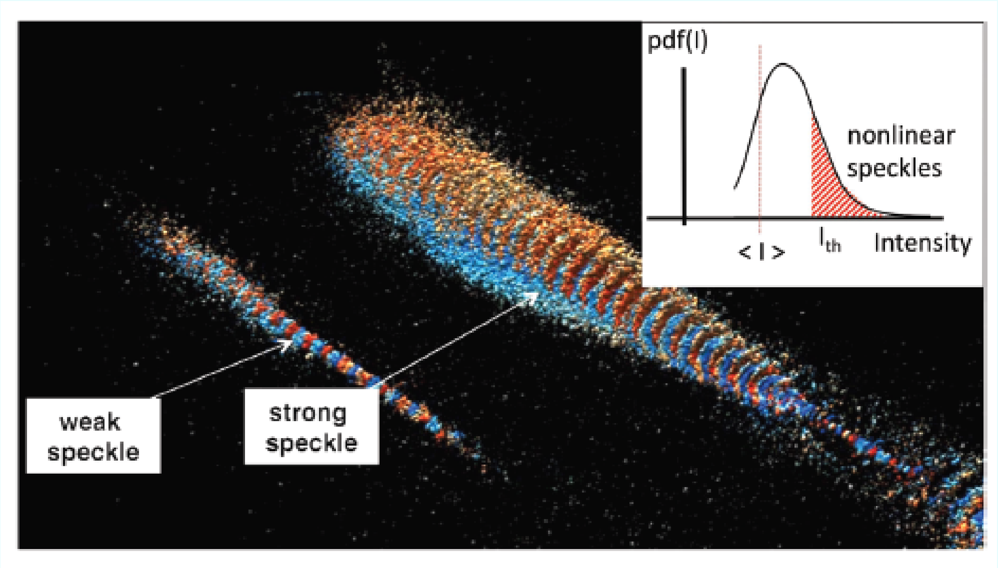
Index	Max I_{14}	Run Time (ps)	α_{all}	α_{hot}	η
i	3	4	0	0	0.6
ii	6	10	42%	17%	1.2
iii	8	6	52%	24%	1.6
iv	6 (collisional)	8	33%	5.5%	1.2
v	8 ($w = 4\ \mu$m)	6	22%	5%	1.6

R.Yan et al PRL 2012

Destabilization of the SRS in the hot spots

SRS in a low density plasma can be destabilized due to presence of the laser speckles and the electron trapping – inflationary regime



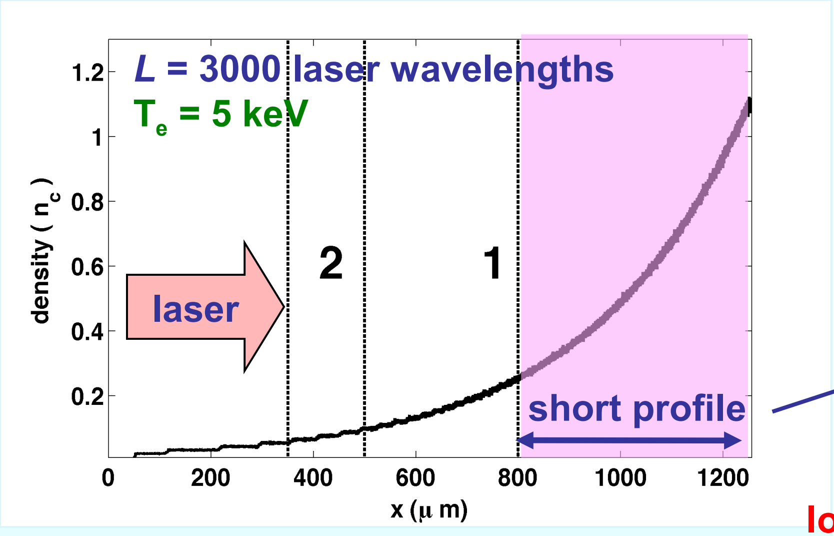


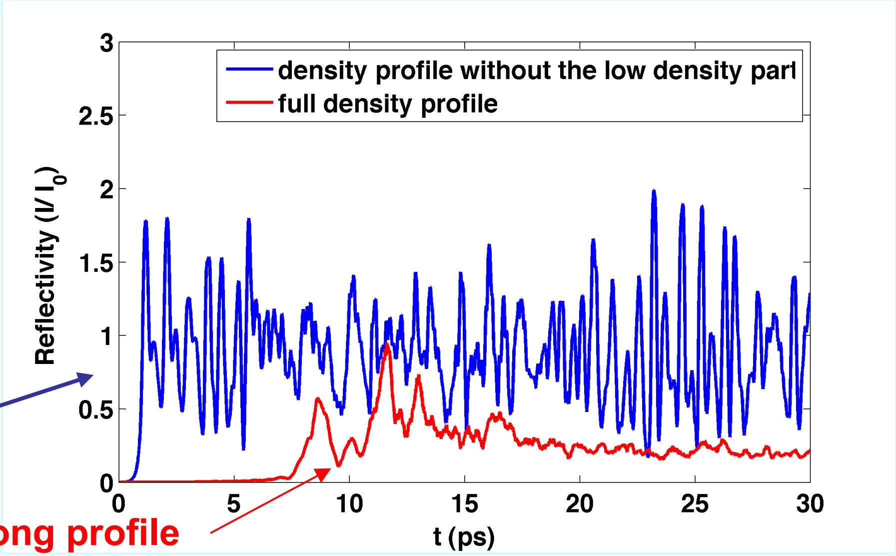
Linear theory predicts higher onset intensity than the multi-speckle simulations and experiments – strong speckles destabilize the weaker ones

L.Yin et al PoP 2009 & 2012

SBS – SRS interaction in inhomogeneous plasma

Numerical simulations in an inhomogeneous plasma at at 10^{16} W/cm^2: SBS is suppressed by SRS

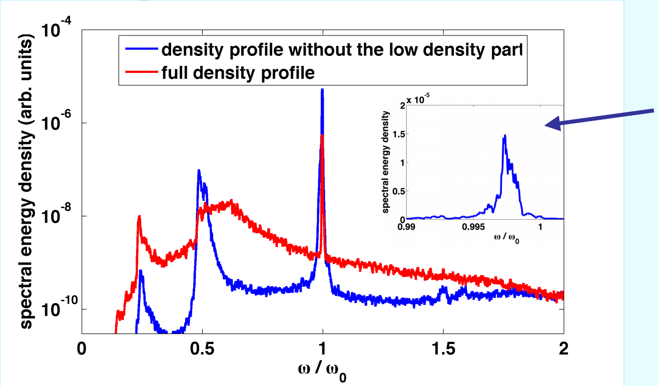




long profile

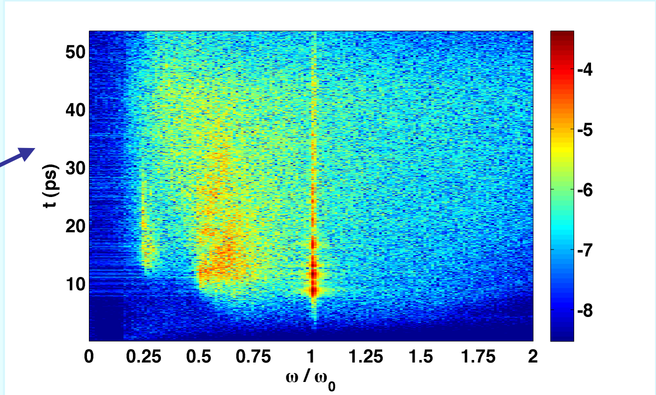
short profile: SBS dominated

long profile: SRS dominated → better absorption



Time integrated spectrum for the short and long density profiles

Time-resolved spectrum of reflected light – long profile²



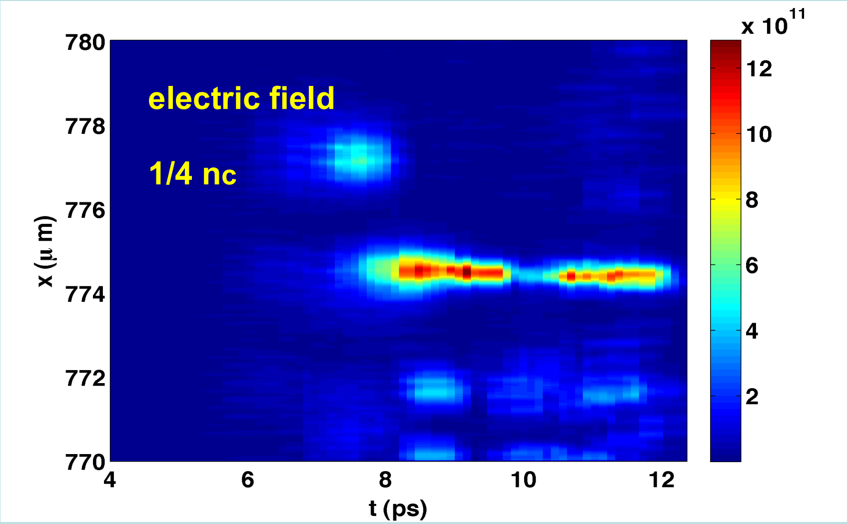
O.Klimo et al PPCF2010

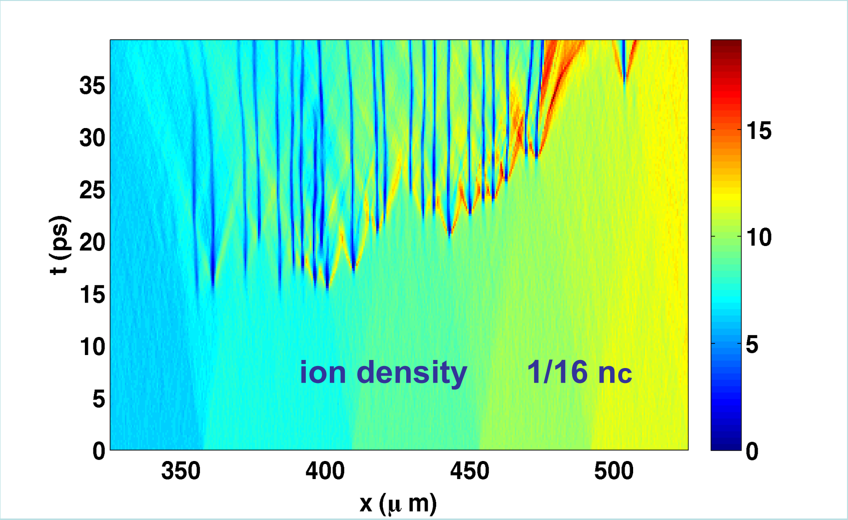
Laser energy absorption in density cavities

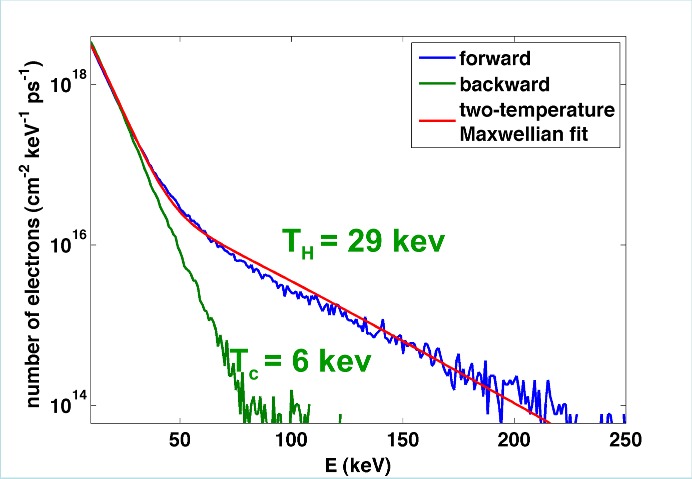
Energy absorption starts in the quarter critical density where SRS develops as an absolute parametric instability. Nonlinear saturation is accompanied by cavity development

Backscattered electromagnetic wave produces secondary absolute SRS in the 1/16 of the critical density where multiple cavities are produced

Major absorption takes place between 1/4 and 1/16 of n_c and produces hot electrons



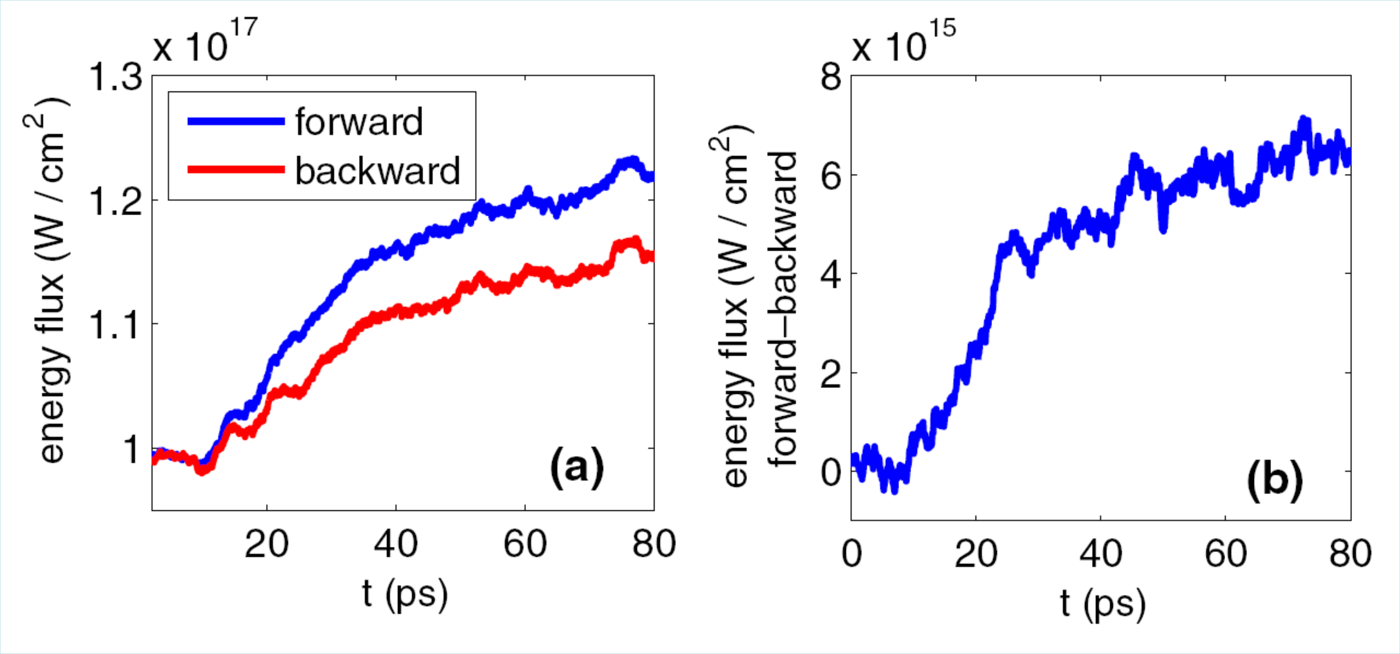




O.Klimo et al PPCF2010

Energy flux transported by fast electrons

Energy balance between the forward and backward fluxes agrees with the absorbed energy: $n_{hot} \approx 0.022\ n_c$

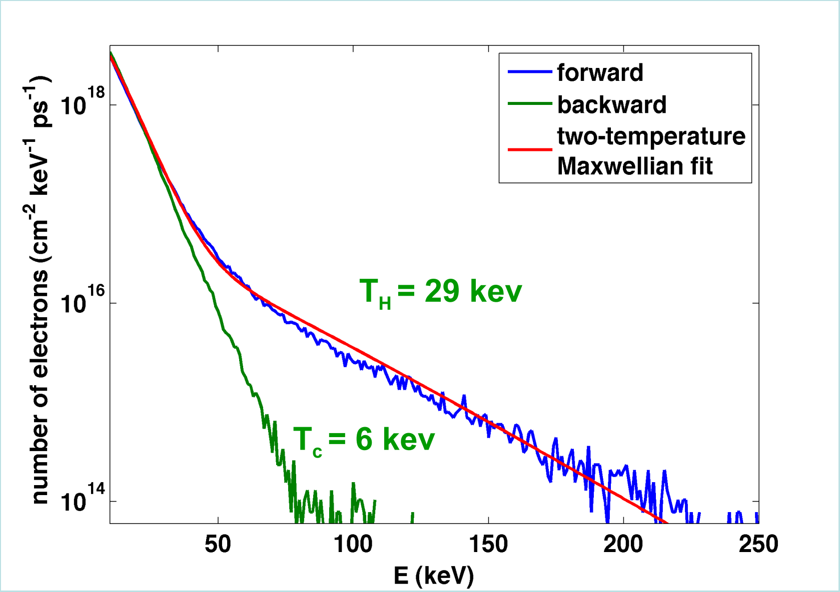


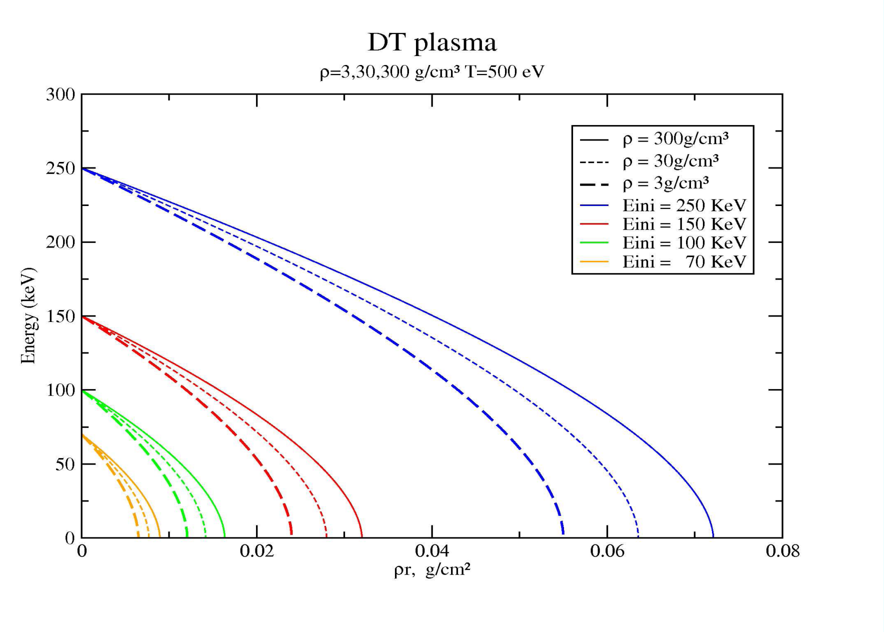
Kinetic simulations demonstrate feasibility of the shock ignition scenario

Nonlinear effects dominate the absorption and the hot electrons are supposed to transport energy to the ablation zone

Fast electron stopping length

The stopping length of 30 keV electrons is smaller than the shell thickness at the time when the shock is launched

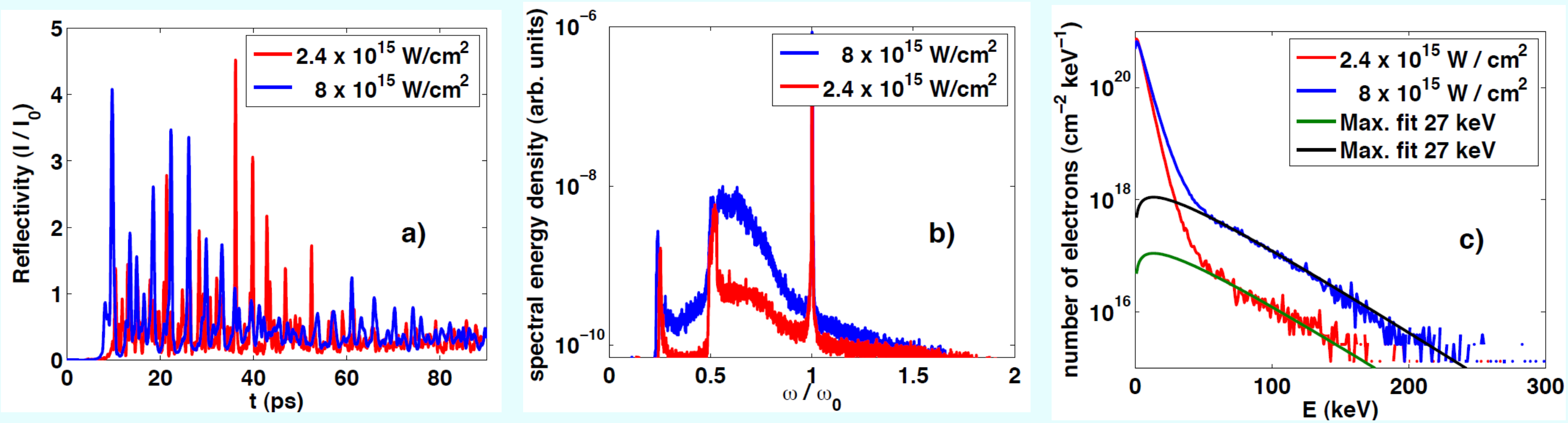




Fast electrons may provide a better hydrodynamic efficiency for the shock

Transition from collisional to collisionless absorption

The quality of absorption shanges in the intensity range 10^{15} – 10^{16} W/cm^2

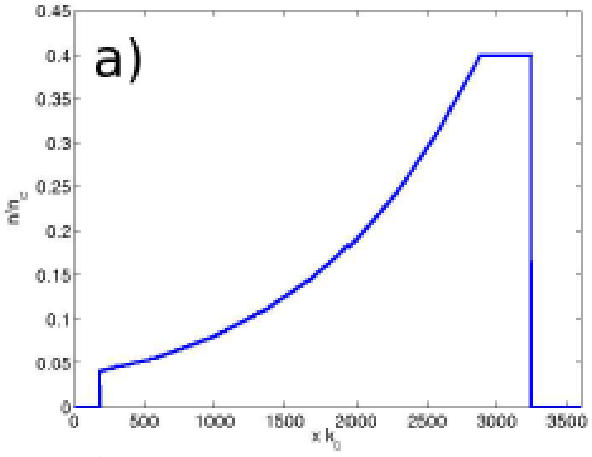


- Reflectivity saturates at the level 36 – 38% independently on the laser intensity
- The number of energetic electron increases while their temperature remains at the same level of 30 keV
- Hot electrons transport up to 90% of the absorbed energy
- The spectral lines in the backscattered light at 1/2 ω_0 and 1/4ω_0 indicate the increasing role of the cavitation process

O.Klimo et al PoP2011

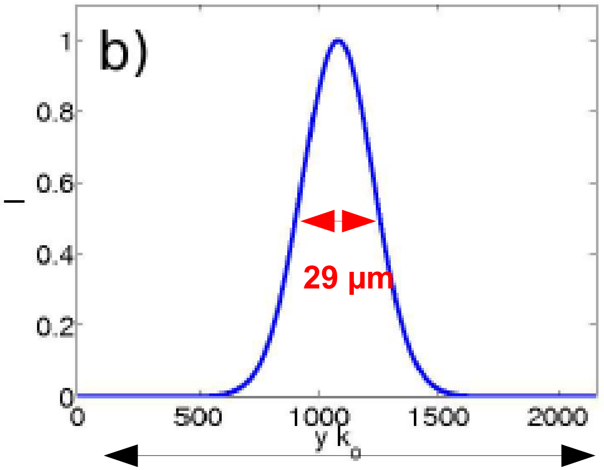
2D simulations of LPI in inhomogeneous plasmas

Density profile



160 µm

Intensity profile



100 µm

Issues for 2D:
1. is absorption affected ?
2. how does electron DF change ?
3. role of 2D-effects: filamentation, self-focusing & 2PD
4. inflationary SRS ?

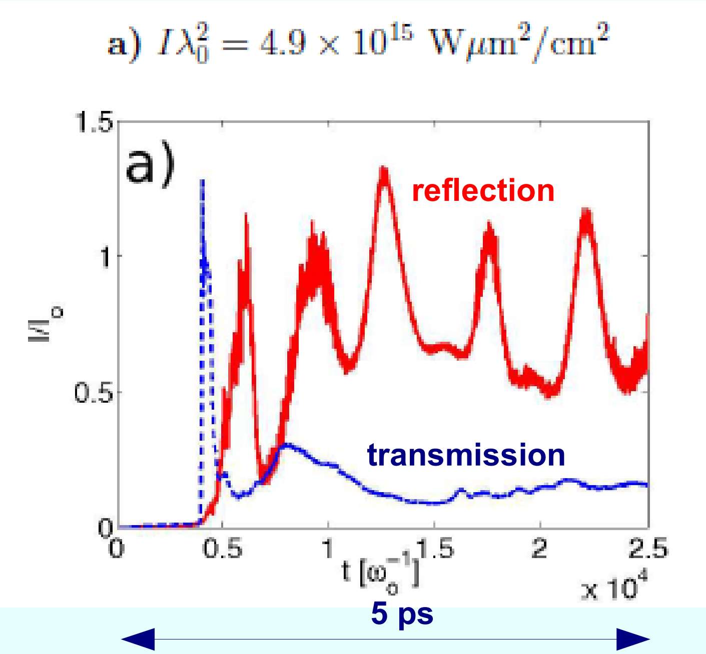
2D simulation set-up

- plasma: 160 $\mu m \times 103 \mu m$; $T_e = 5\,\mathrm{keV}$, $T_i = 1\,\mathrm{keV}$ exp. profile scale length $L_n = 186\,\lambda_o \approx 60\,\mu m$
- laser: $I_o\lambda_o^2 = 1.2 - 4.9 \times 10^{15}\,\mathrm{W}\mu\mathrm{m}^2/\mathrm{cm}^2$ @ 3ω
- simulation time: $\approx 2.5 \times 10^4 \omega_o^{-1} \Rightarrow \approx 5\,\mathrm{ps}$
- full-speckle (FWHM $\approx 29\,\mu m$)

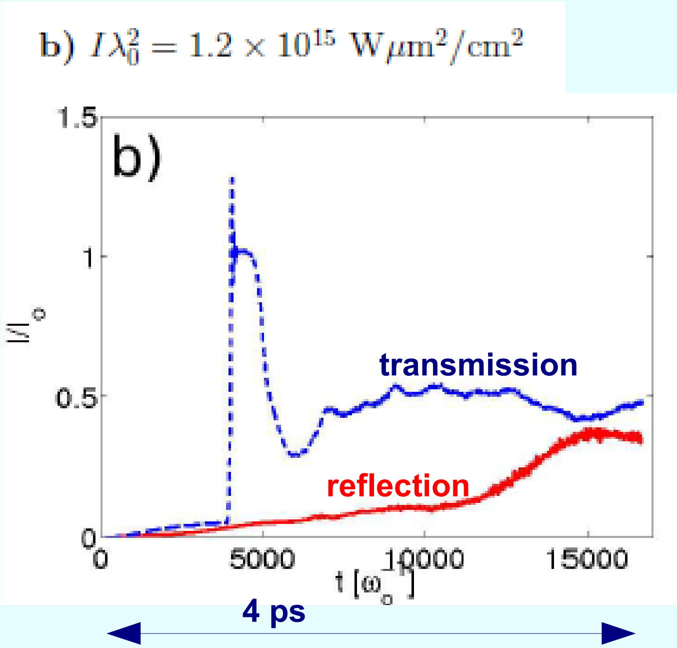
2D full scale one speckle collisionless simulation requires 320.000 h CPU time on 600 proc.

C.Riconda et al PoP2011

Total reflectivity in 2D simulations



a) $I\lambda_0^2 = 4.9 \times 10^{15}$ Wμm^2/cm^2



b) $I\lambda_0^2 = 1.2 \times 10^{15}$ Wμm^2/cm^2

Instability develops in the time scale of 0.2 – 0.3 ps

Reflection increases strongly with the laser intensity

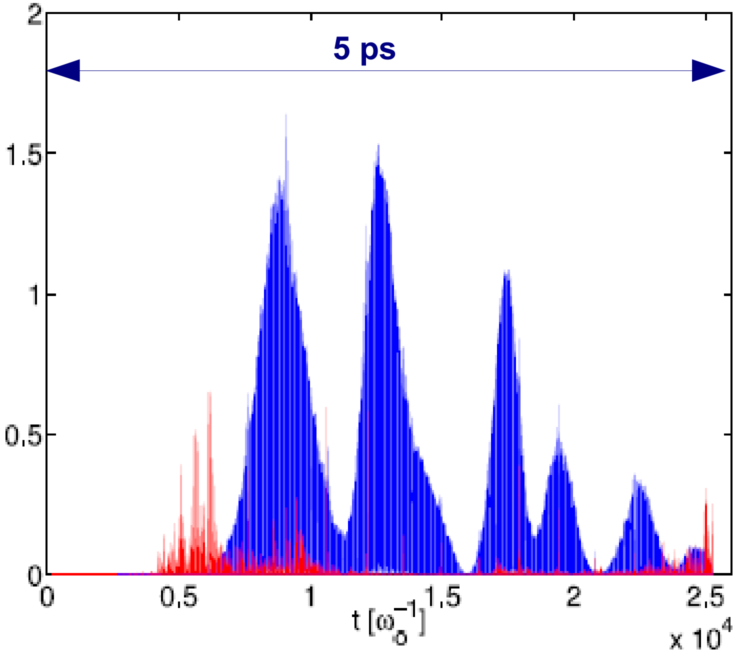
Large reflectivity bursts – filamentation

Very low transmission

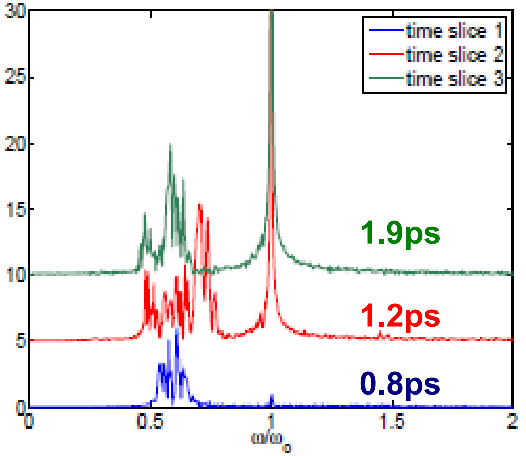
C.Riconda et al PoP2011

SBS – SRS competition in 2D simulations

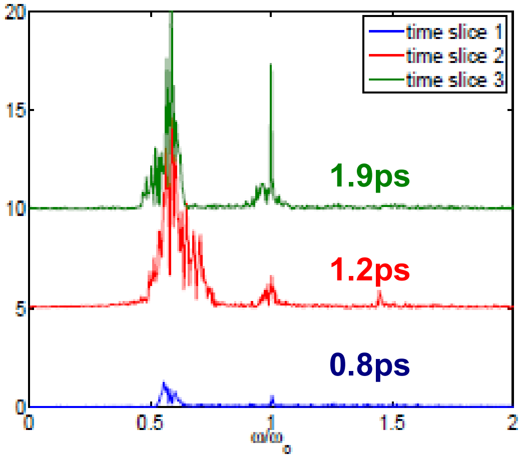
central point of speckle, $I\lambda_0^2 = 4.9 \times 10^{15}$ Wμm^2/cm^2



center of speckle

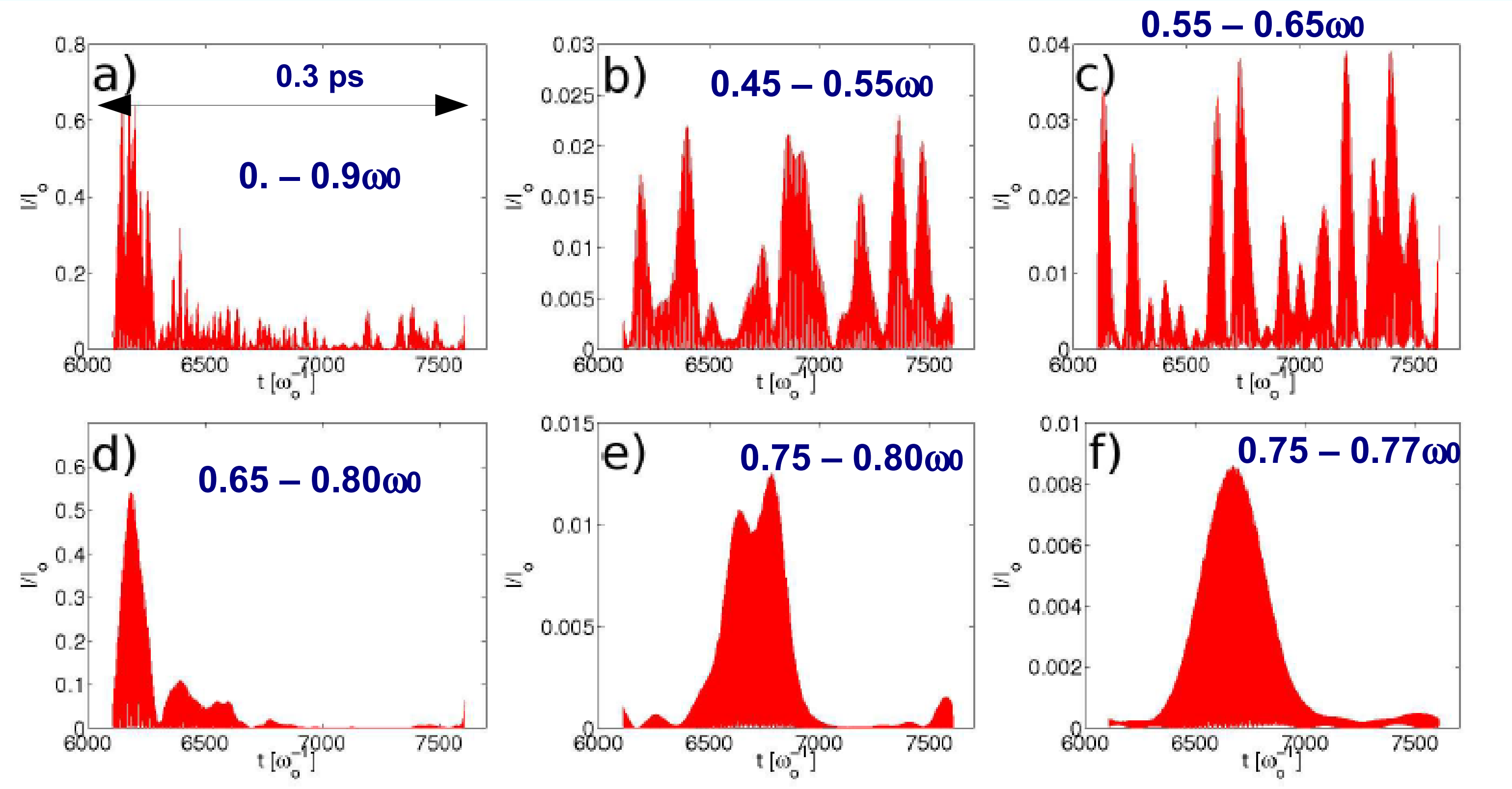


wings of speckle



- contribution to reflectivity from SBS $(0.9 - 1.1\,\omega_o^{-1})$ and SRS $(0.0 - 0.9\,\omega_o^{-1})$
- SRS activity strong initially and reappears later on in a different location (more later)
- compared to 1D spectrum much broader (2PD ?!)
- spectra of center and wings differ considerably

Inflationary SRS development: single event



Each SRS pulse contains a broad frequency spectrum

Larger the scattered frequency – broader the pulse (coupling to strongly damped modes)

Low density plasma dominates the response

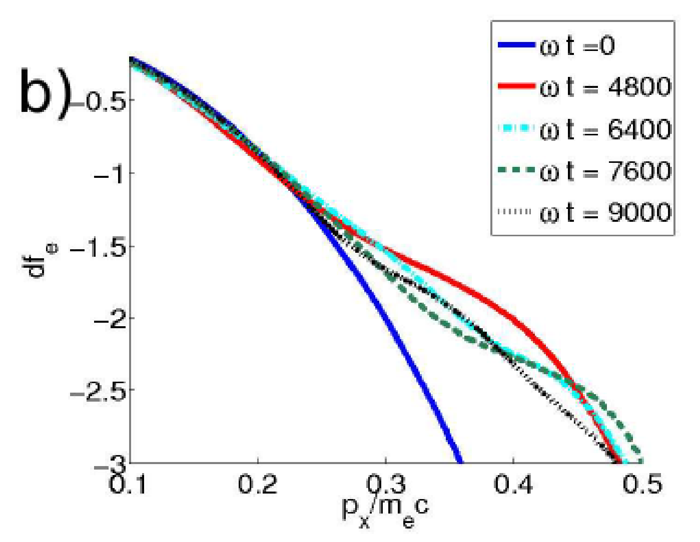
C.Riconda et al PoP2011

Electron distribution function induced by the SRS

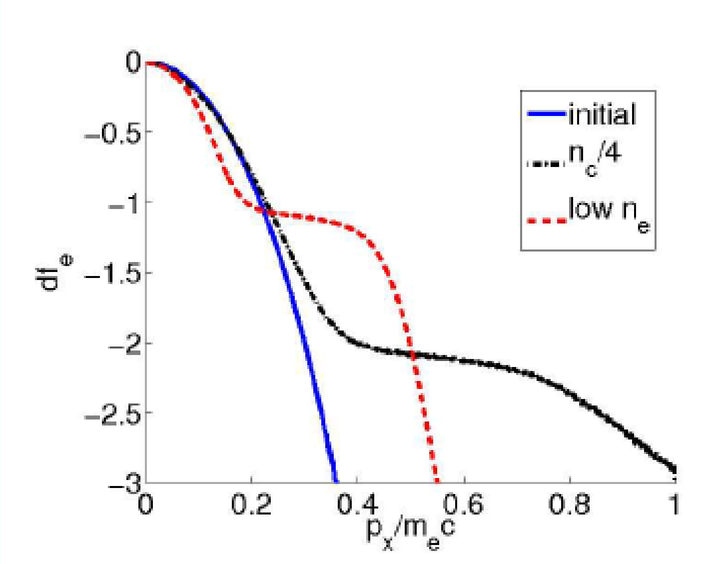
SRS reflectivity is associated with the hot electron generation

Electrons generated from the zone 1/4nc are more energetic

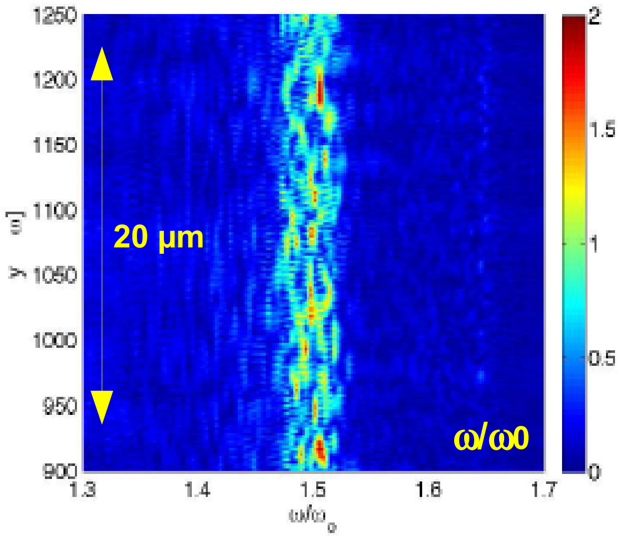
Electron distribution function averaged over the speckle cross section time interval from 0 to 2 ps



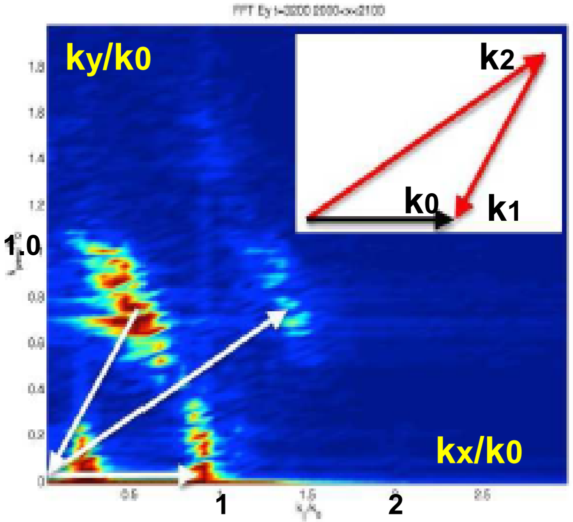
Electron distribution function at t = 0 and at the time instant of 0.9 ps



Two-plasmon decay instability excitation

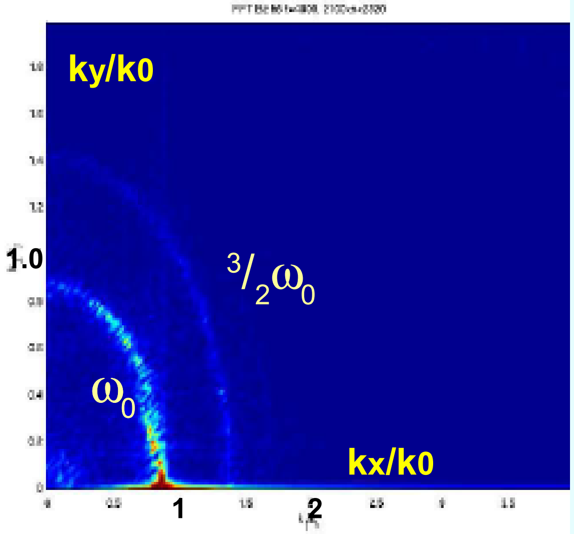


transmitted light



electrostatic waves

momentum matching for the TPD

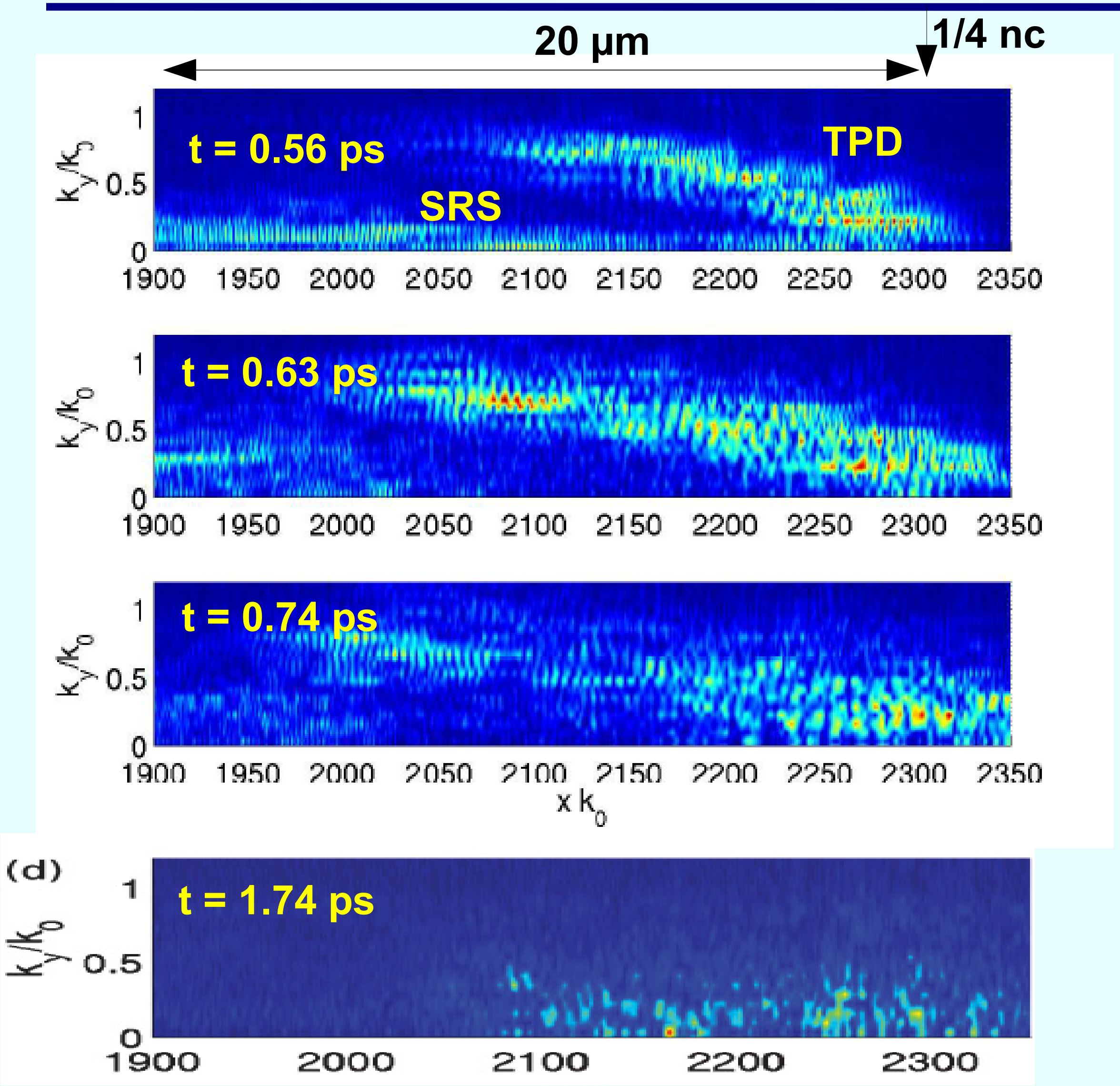


k-vectors of B_z

harmonic 3/2 generation due to the TPD

- 2PD driven far above absolute threshold, $I_{14}\lambda_o^2 > 51\frac{Te[keV]}{(L/\lambda_o)}$,
  $\Rightarrow$ rapid nonlinear saturation as shown for $3/2\omega_o$-signature in transmitted light (turbulent structure, cascading ?)
- no hot electrons and limited in time
- negligible energy contribution

TPD and SRS competition



Spectra of electric fields provide information about the TPD – SRS competition

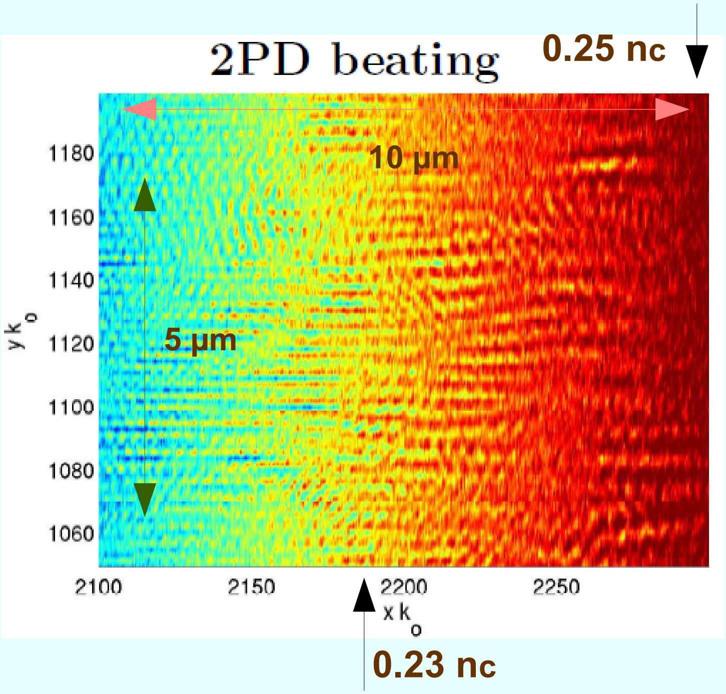
TPD and SRS are excited almost at the same time

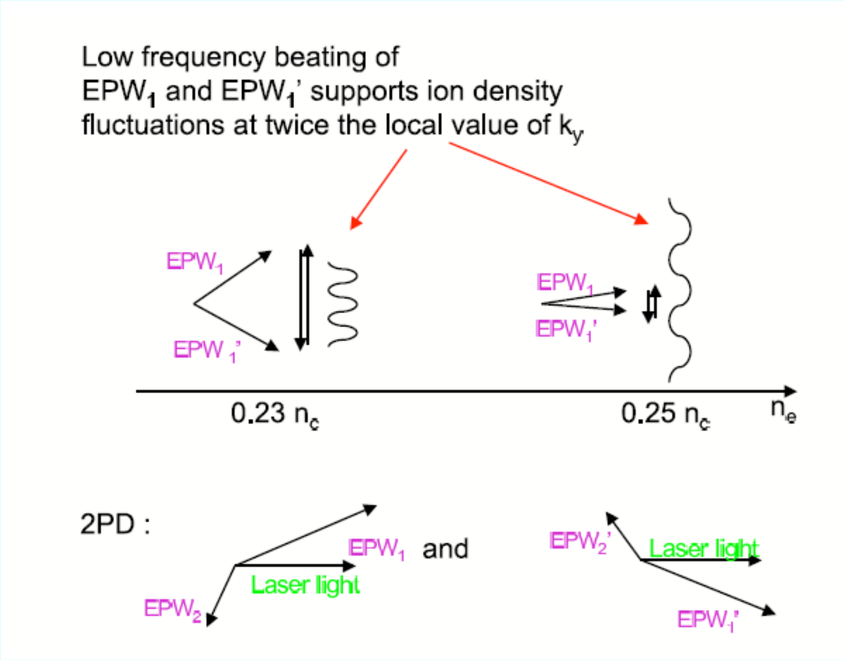
The instability zone is shrunk and the wave activity is reduced due to the cavity formation

No signatures of TPD after 1.5 ps

Cavitation scenario in 2D simulations

The plasma cavitation in the quarter critical density is enhanced due to TPD activity

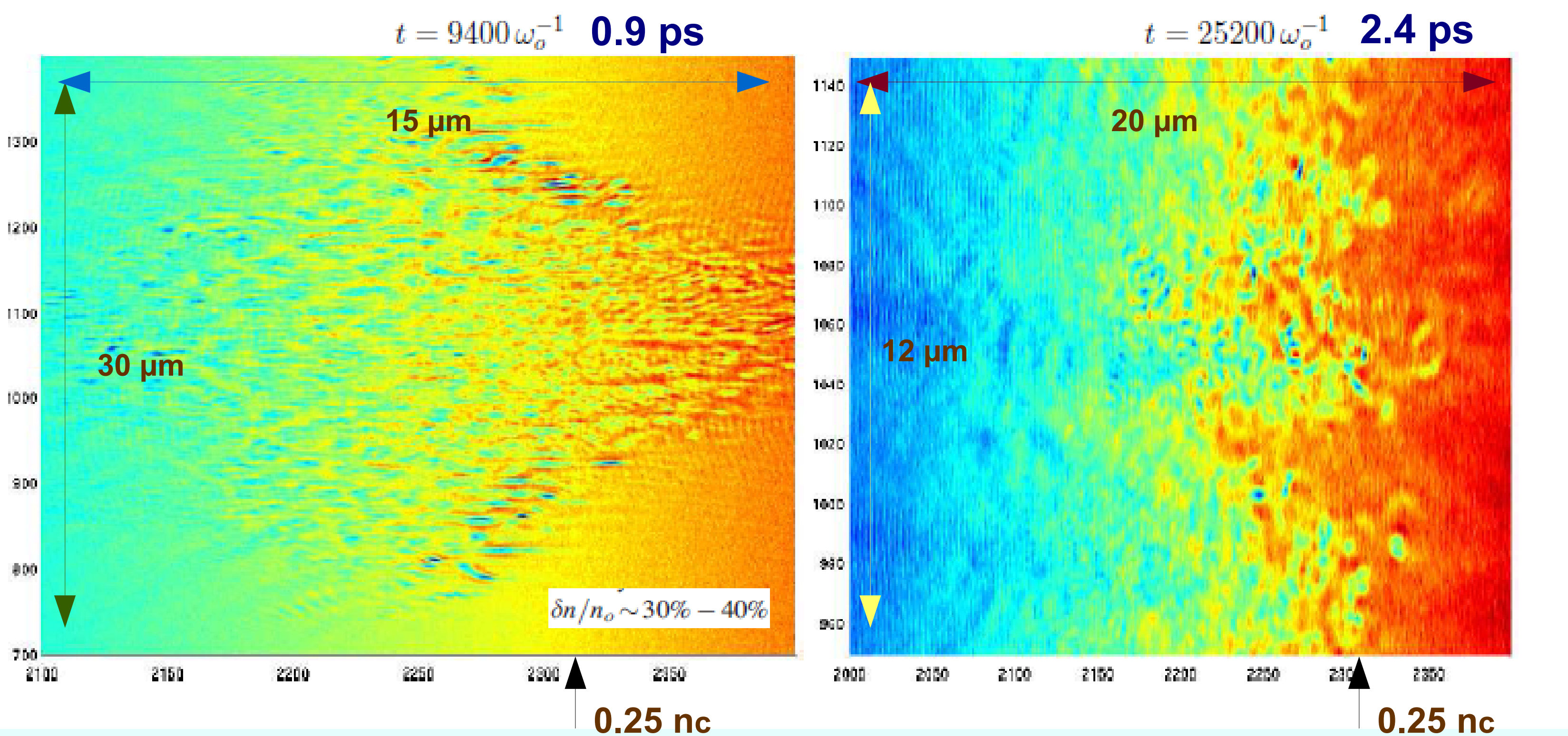



Low frequency beating of EPW_1 and EPW_1' supports ion density fluctuations at twice the local value of k_y

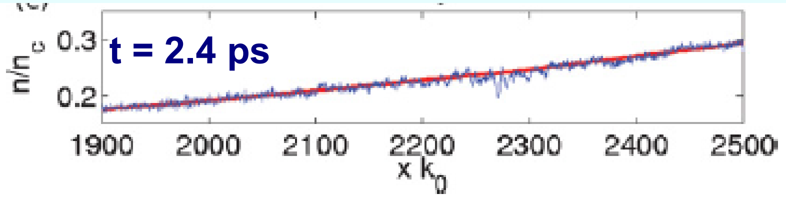
Beating of plasma waves excited by TPD creates quasistationary density modulations that are transforming later in cavities

Cavitation scenario in 2D simulations

The plasma cavities have much smaller size than the laser speckle
They are quenching the SRS and TPD in the region near 1/4 nc

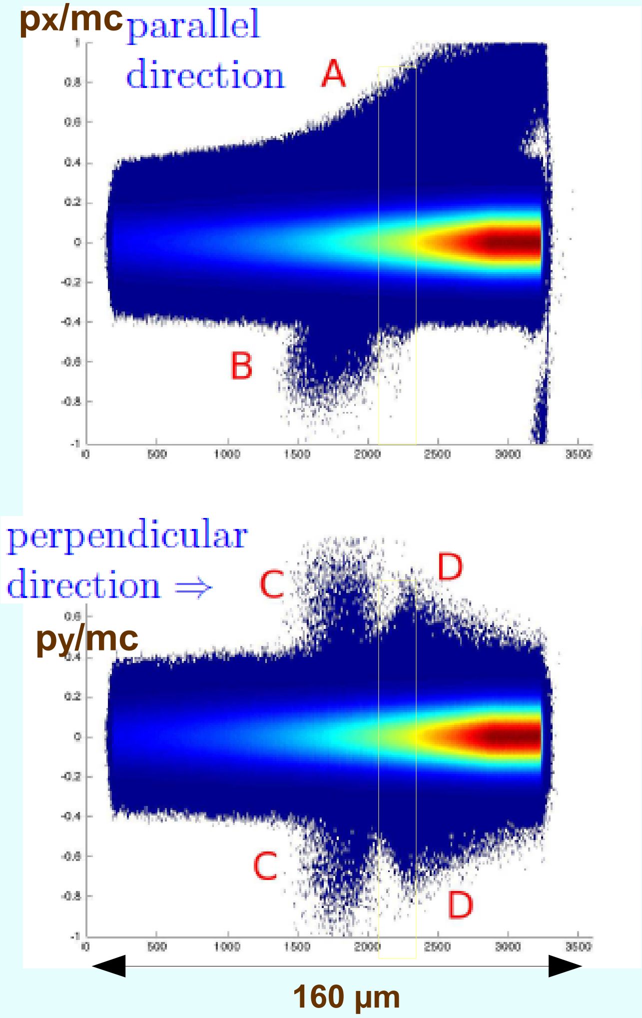


There is no profile steepening as it was supposed in smaller size simulations



Electron heating due to the SRS and TPD

The SRS and TPD create the electrons with different energy distributions



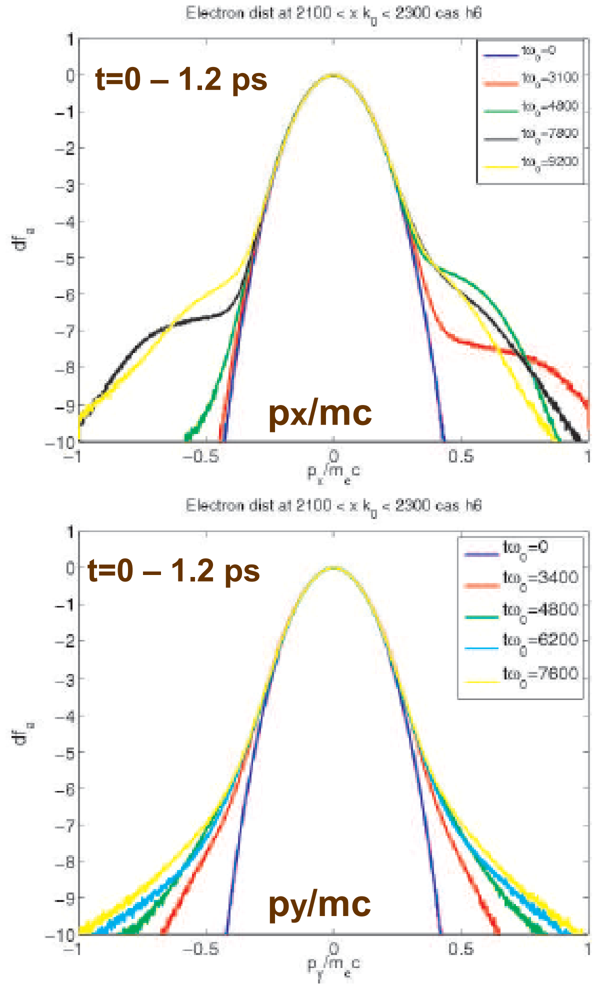
Asymmetric evolution of the electron distribution function

A : SRS and 2PD

B : 2PD

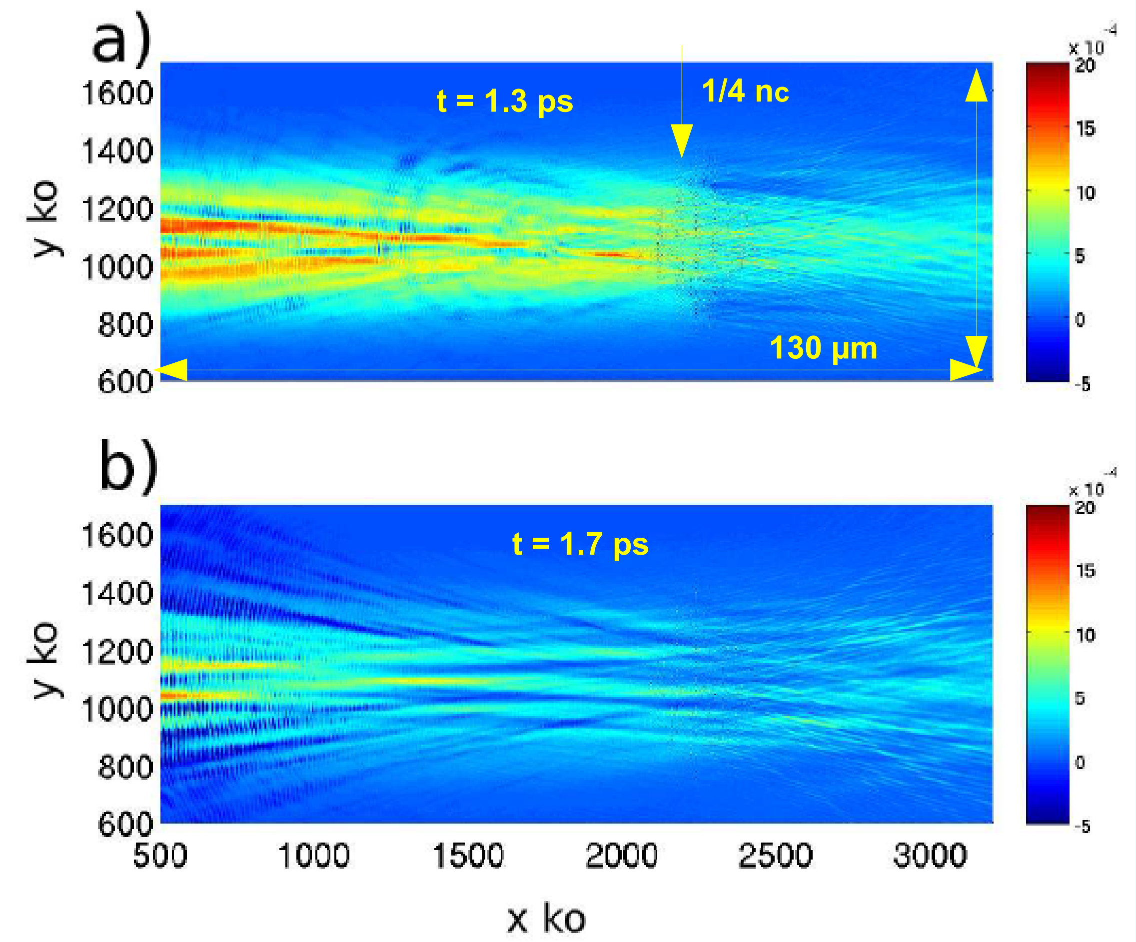
C : 2PD

D : 2PD & cavitation



Large scale filamentation of the laser beam

Poynting vector shows three distinct zones



Low density zone ne < 1/4 nc – large scale filamentation

Near quarter critical zone – cavitaiton

High density zone ne > 1/4 nc – small scale filamentation and beam spreading

Later time the SBS activity moves down over the density profile

Conclusions

Laser plasma interaction studies predict 70% absorption of the spike:

- **high intensities/high temperatures: suppression of the SBS by a strong SRS, cavitation absorption, hot electrons at 30 keV**
- **low intensities collisional suppression of the SBS, efficient electron heating**
- **2D simulations show early saturation of the two plasmon decay, SBS-SRS competition**