Modeling laser plasma interaction in shock ignition

Competition and coexistence of different processes

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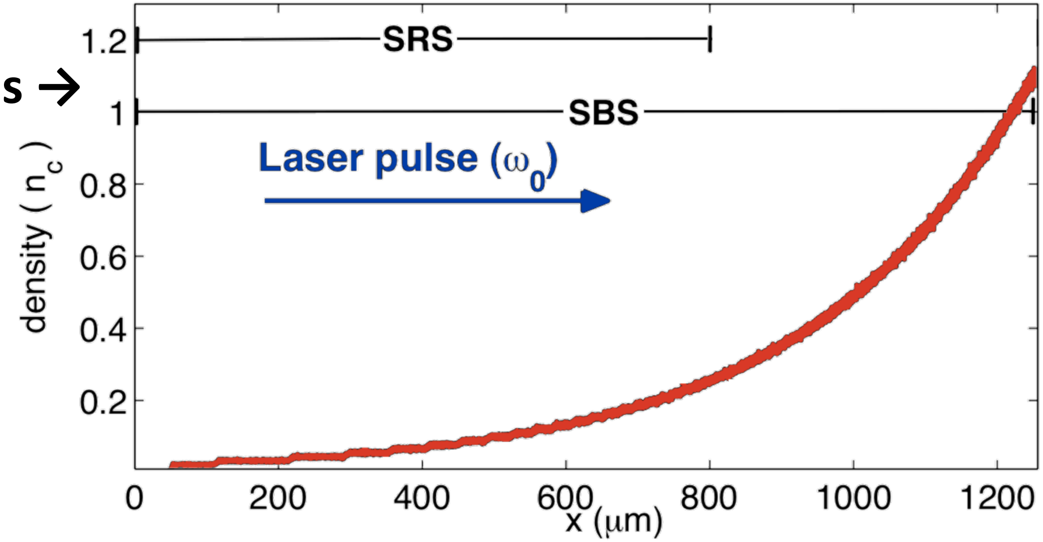
Absorption of ignition pulse – important questions

- The aim of our work is to answer several questions concerned with absorption of the ignition laser pulse energy and its transport into the target. These questions are:
  - What is the overall absorption efficiency?
  - Where does the absorption take place?
  - Which processes contribute to absorption?
  - Which processes are the most detrimental?
  - What is the energy (angular) distribution of particles?
  - How is the energy transported deeper into the target?
- There is a wide range of different processes in the laser plasma interaction and their competition and coexistence is hardly understandable from theory. Among the most important are:
  - IB (Inverse Bremsstrahlung)
  - SRS (Stimulated Raman Scattering), SBS (Stimulated Brillouin Scattering)
  - TPD (two plasmon decay), filamentation, SF (self-focusing)
  - Cavitation etc.
- To study these processes, we use fully kinetic PIC simulations.

Shock-ignition in full scale ICF – parameters

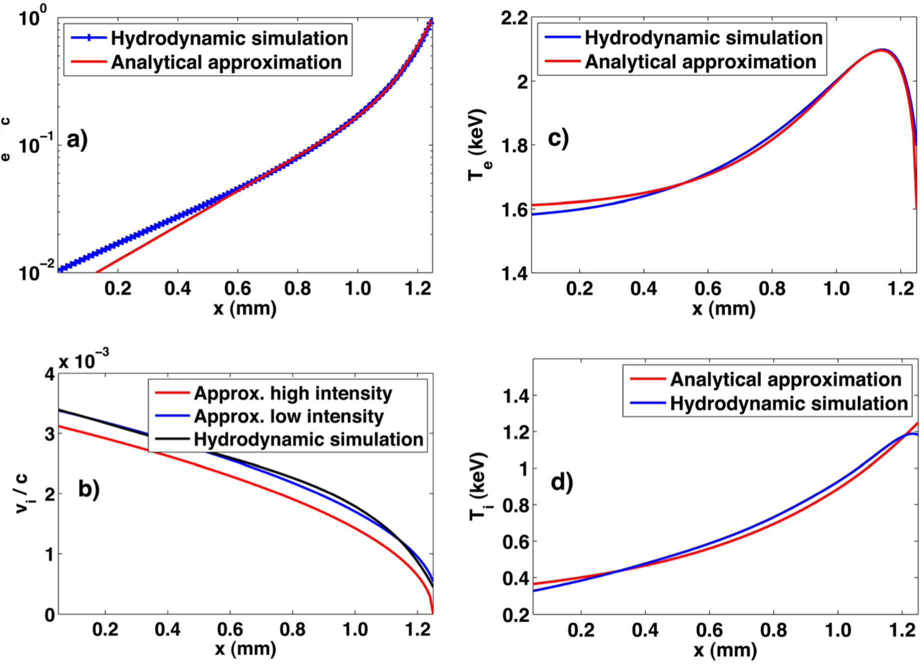
- **High intensity $I_0 \lambda^2 = 10^{14} - 10^{15}$ W/cm² × μm² →** ranging from collisional dominated to strongly nonlinear regime
- **High plasma temperatures 2 – 5 keV →** Coulomb collisions are not efficient in low density plasma, while Landau damping of electron plasma waves is very strong → suppression of SRS
- **Long plasma density profile L > 300 μm →** high gain of SBS expected, but also strong absolute SRS (and possibly TPD) near the ¼ critical density → necessary to study all processes at once to understand their competition
- **Time scale studied - tens of ps →** not significant hydrodynamic motion, but enough long to overcome the initial phase of turbulent interaction and establish quasi-stationary regime of laser absorption.



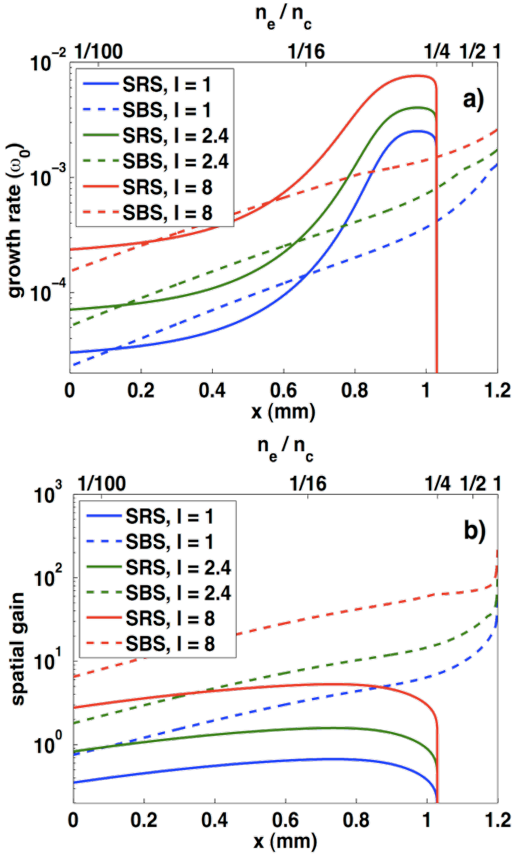
Initial conditions - profiles

- Initial plasma conditions are taken from hydrodynamic simulations of spherical SI experiment at Omega

Dens., temp. and vel. profiles



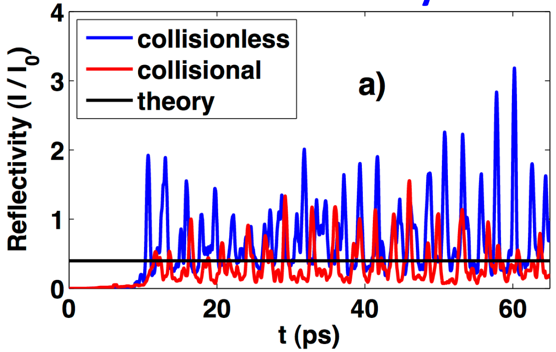
Growth rate & linear gain



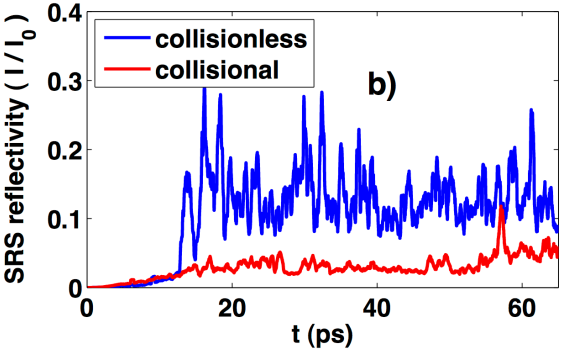
- **Laser parameters are:**
  I_0 = 1, 2.4, 8, 24 × 10^{15} W/cm^2 , λ = 0.35 µm, with and w/o Coulomb collision
  – SRS gain is low but growth rate below ¼ n_c is high - **absolute instability**
  – **SBS may dominate** unless limited by e.g. cavities or pump depletion

Lower laser intensity $I_0 = 10^{15}$ W/cm^2 – collisional regime

Total reflectivity



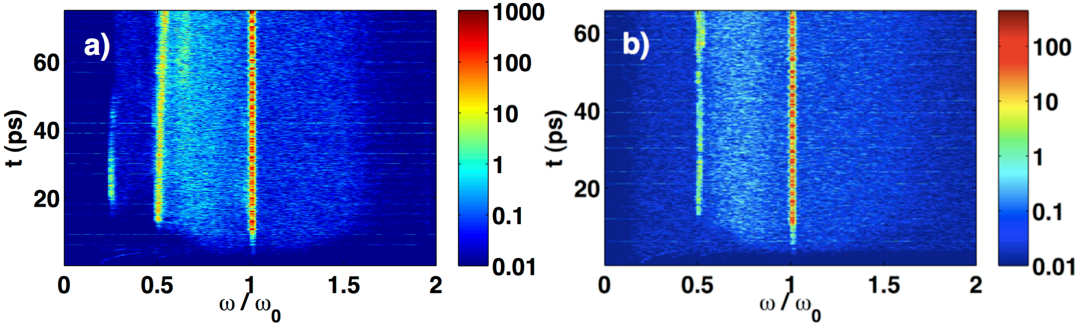
SRS reflectivity



Spectra of reflected light vs. time

collisionless

collisional



- **Collisional absorption important** - strong reduction of the reflectivity from 70% to about 30% when collisions are switched off.

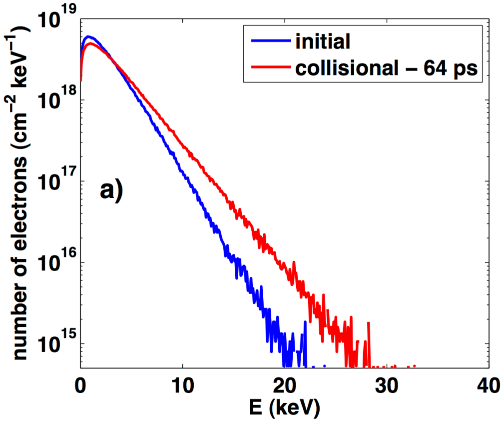
- Absorption corresponding to the theoretical one

$$\alpha_{abs} = 1 - \exp\left(-\int \frac{\nu_{ei}(n_c)}{c}\left(\frac{n_e}{n_c}\right)^2\left(1-\frac{n_e}{n_c}\right)^{-1/2} dx\right)$$

- **SBS dominates**, SRS plays secondary role (< 5% in the collisional case).
- **SRS** strongest at ¼ n_c corresponding to **absolute instability** - responsible for **partial absorption**

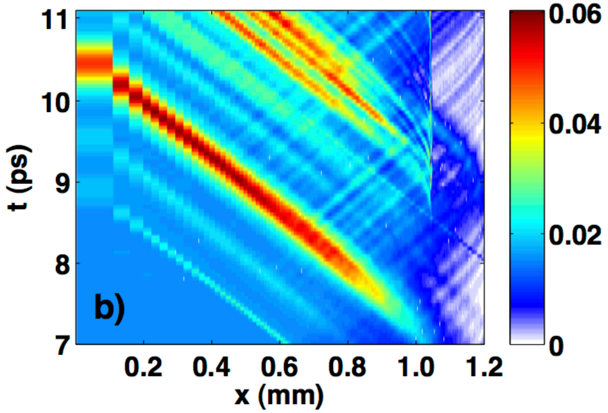
Energy absorption and SBS amplification

Electron energy distribution

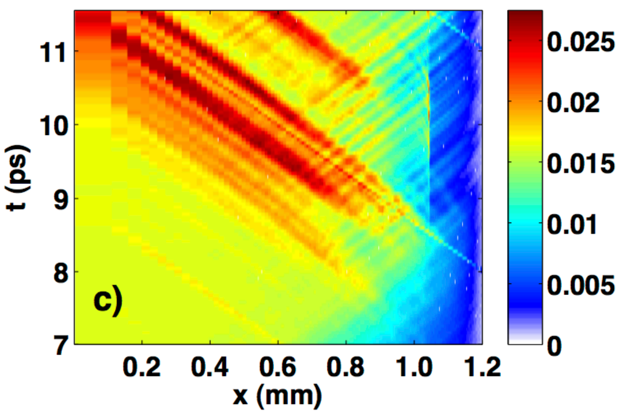


EM field energy density

Collisionless – SBS flashes



Collisional – SBS flashes

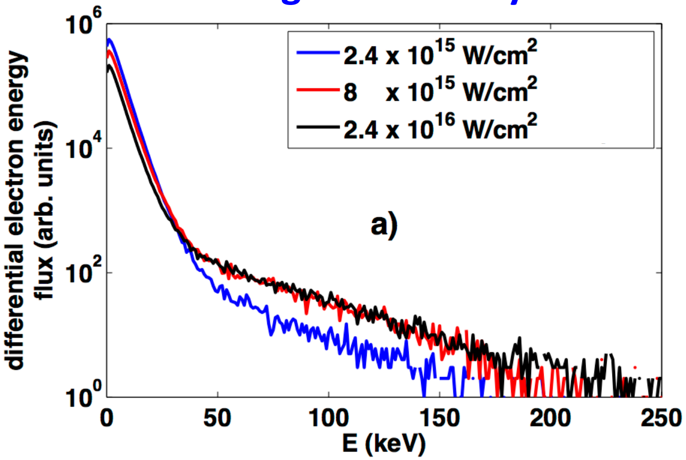


- **Absorption in the collisional case is 66%** (28% in the collisionless case).
- The energy distribution of bulk electrons shows temperature increase from 2 to 2.5 keV.
- **SBS is seeded in denser plasma ($n > ¼ n_c$)** deeper in the target (1.1 mm).
- Collisionless case - SBS takes all the pump energy - depletion & pulsation.
- Collisional case - **SBS weaker due to collisional damping**.
- **At laser intensity 10^{15} W/cm^2, the interaction is dominated by collisions and parametric instabilities play only secondary role.**

Higher laser intensity – collective effects

- The situation is very different at higher intensities.
- There is a strong hot electron component, while the bulk electron temperature does not change.
- This indicates transition to the regime dominated by collective effects.

Electron energy distributions, higher intensity

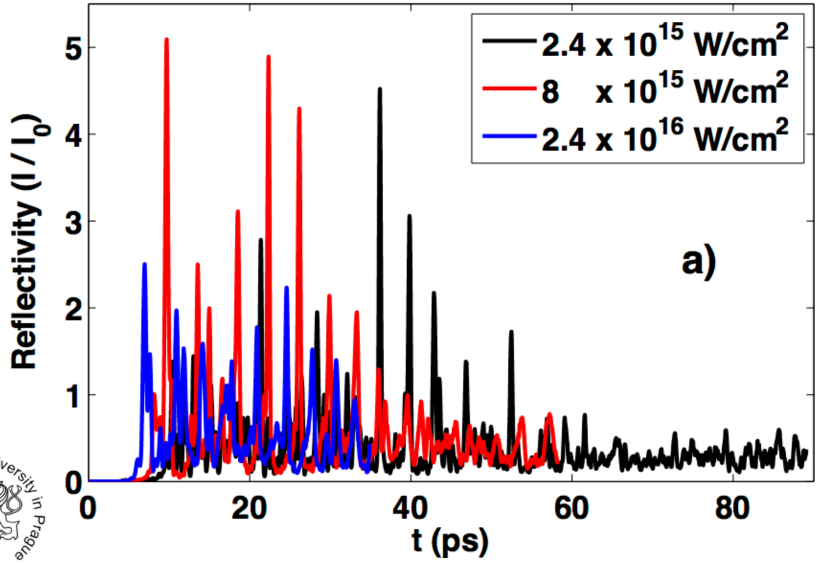


- **Increasing laser intensity to several times 10^{15} W/cm^2, most of laser pulse energy is absorbed by hot electrons** (73% at 2.4×10^{15} W/cm^2 and more than 90% for higher intensities).
- The temperature of hot electrons does not significantly depend on laser intensity and it is in the **20-40 keV** domain in the high energy tail.

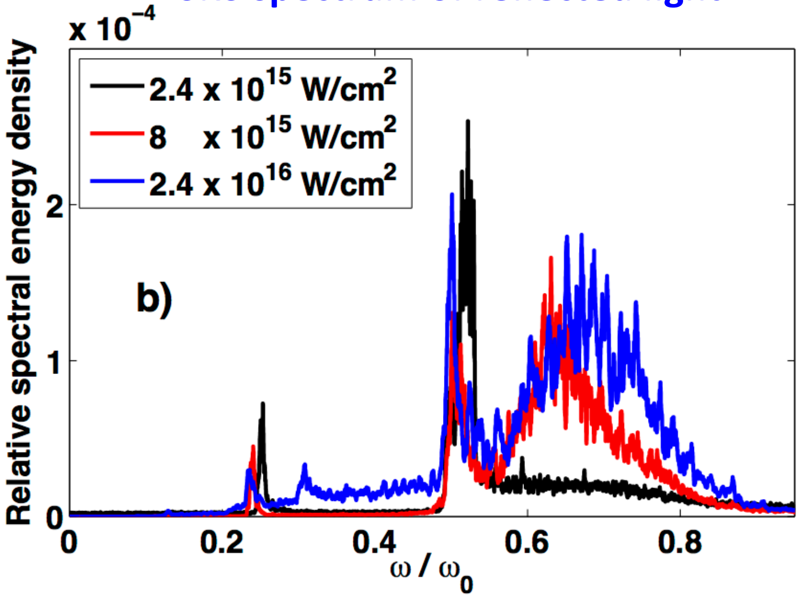
Reflectivity and spectrum of reflected light

- After transient stage, **reflectivity saturates 35-40%** - almost independent of laser intensity → **absorption coefficient similar like in collisional case → SBS must be suppressed by some collisionless mechanism.**
- Spectra of reflected light show **absolute SRS** at ¼ n_c (the signal at ½ ω_0).
- At higher intensity, even **convective SRS** below ¼ n_c becomes strong and its spectra shift towards higher ω (i.e. scattering is induced in lower density plasma and suppressed at higher density due to pump depletion).

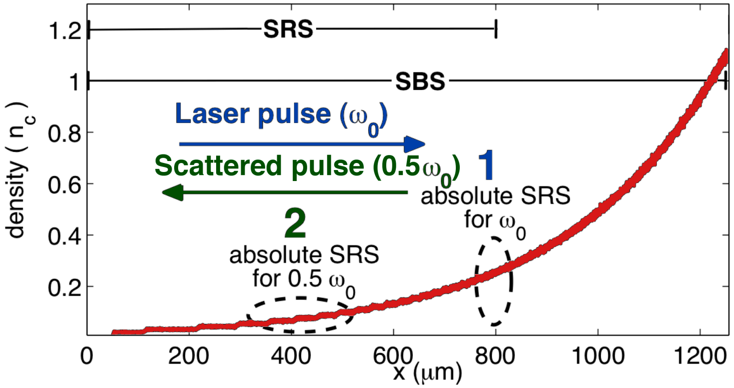
Reflectivity



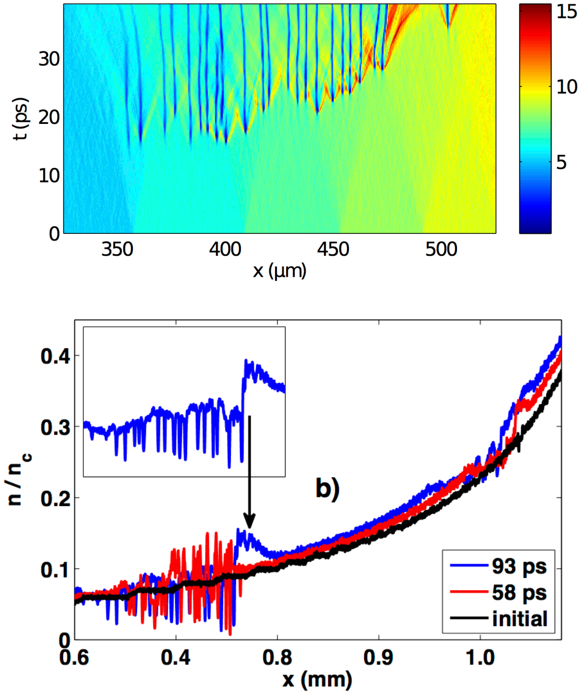
SRS spectrum of reflected light



Raman cascade and cavitation



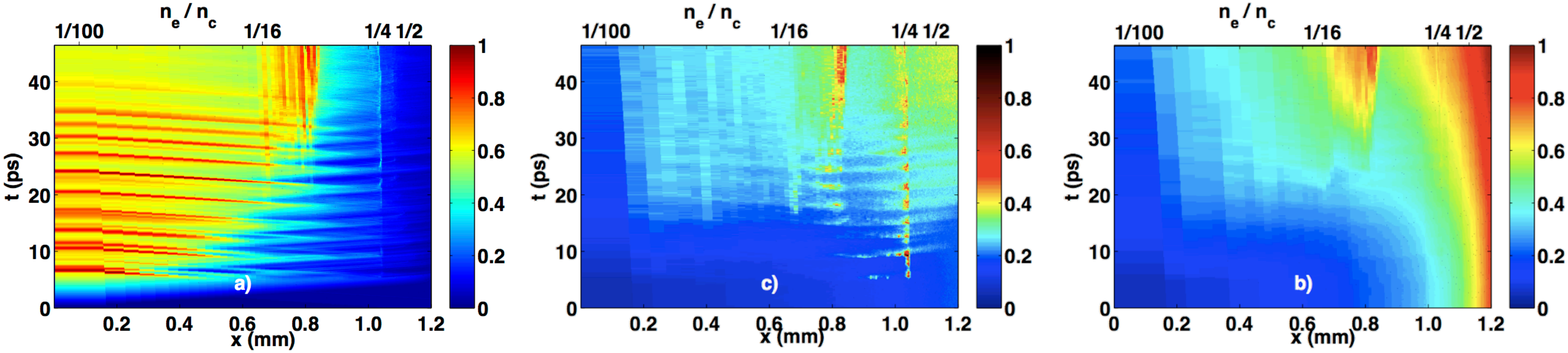
- SRS excited at resonance point ¼ n_c (as absolute instability) and producing ½ ω_0 backscattered light.
- This backscattered light excites absolute SRS at its own resonance point 1/16th n_c producing ¼ ω_0 forward-scattered light (down the density gradient).
- This **SRS cascade** may continue if scattered light overcomes threshold $(k_0L_n)^{4/3} (v_{osc}/c)^2 > 1$.
- Absolute instability grows locally in time → pond. force expels electrons → ions undergo Coulomb explosion → **cavitation** → trapping of EM. field in cavity.
- Cavitation observed at ¼ n_c and 1/16th n_c **converts EM. field energy into kinetic energy of hot electrons**.



Cavities and density profile modification

SBS amplification and energy absorption

- SBS is strong during the transient stage (several tens ps) resulting in intense spikes and high overall reflectivity.
- Strong SBS disappears after the development of cavities at 1/16th n_c, **cavities prevent efficient SBS amplification**.
- In the quasi-stationary phase of interaction, the electromagnetic energy is concentrated in the resonance regions around ¼ and 1/16th n_c, where the conversion into electrostatic and kinetic energy takes place.
- **Most of the interaction takes place in less dense plasma in front of ¼ n_c.**



EM field

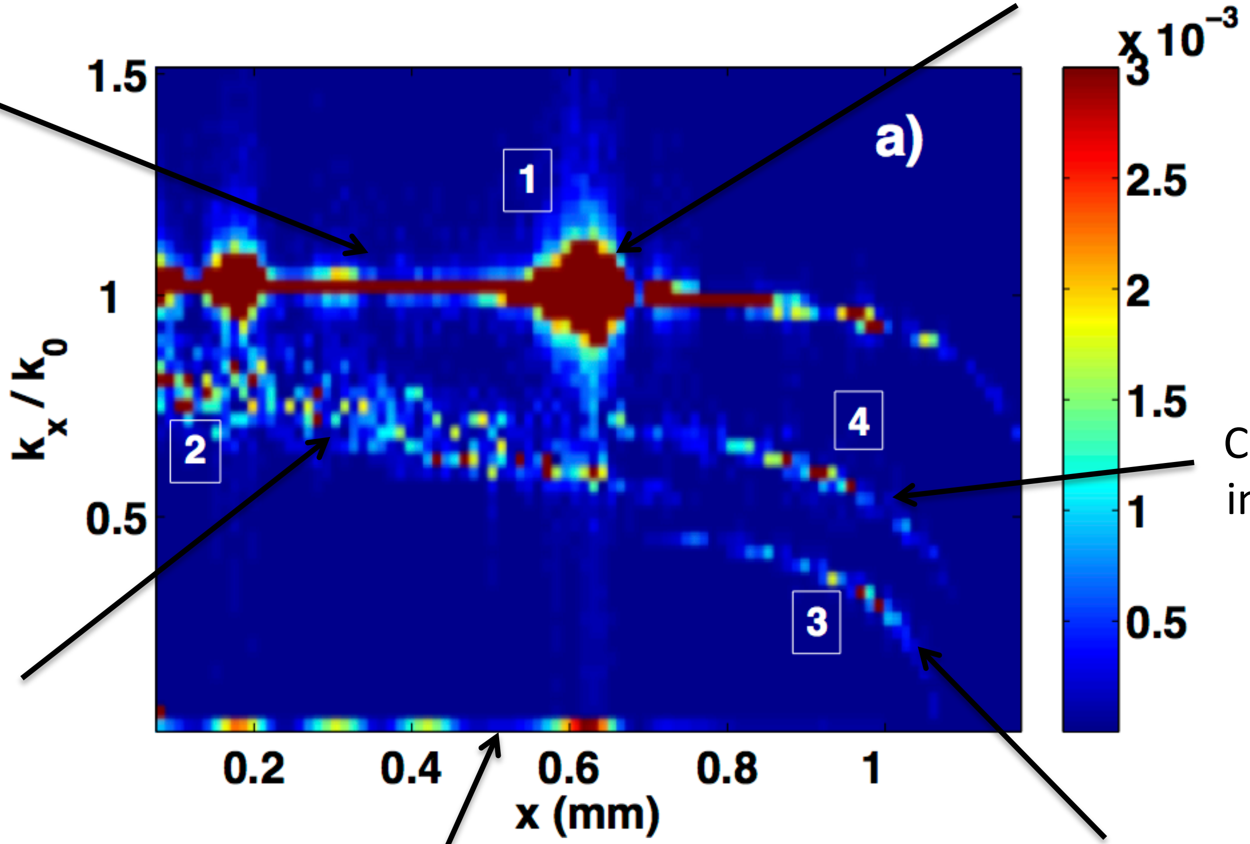
ES field

Kinetic energy

Energy density $I_0 = 8 \times 10^{15}$ W/cm²

EM field inside the target & SBS induced SRS

k-spectrum of EM field $I_0 = 8 \times 10^{15}$ W/cm^2



Flash of SBS

Incident wave

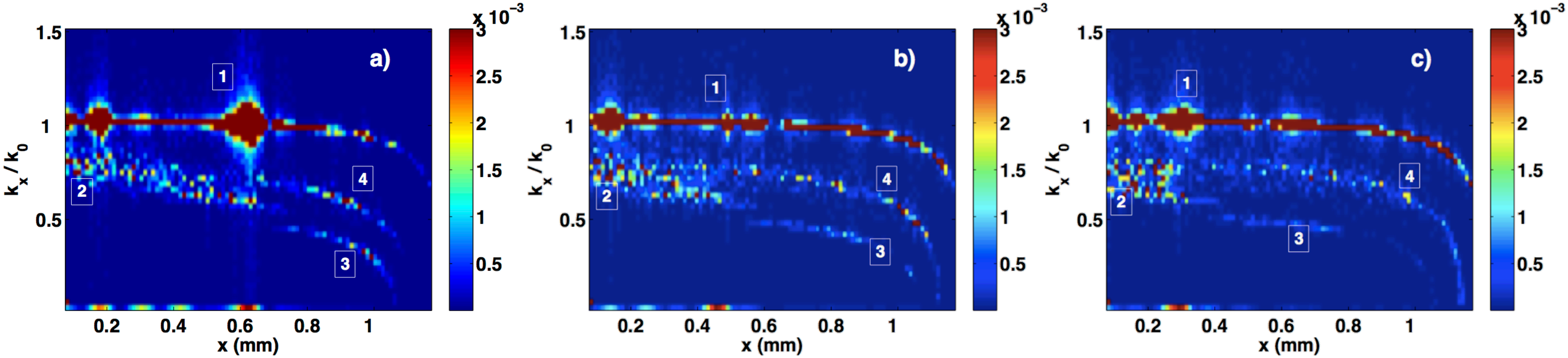
Convective SRS induced by the SBS flash

Convective SRS induced by the incident wave

Absolute SRS coming from ¼ n_c

Bottom line – field strength integrated in the vertical direction

EM field inside the target & SBS induced SRS



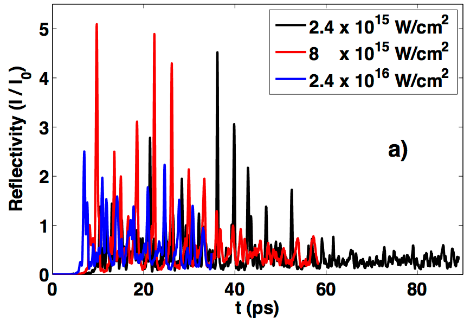
t = 7.6 ps

t = 8.2 ps

t = 8.8 ps

k-spectrum of EM field $I_0 = 8 \times 10^{15}$ W/cm^2

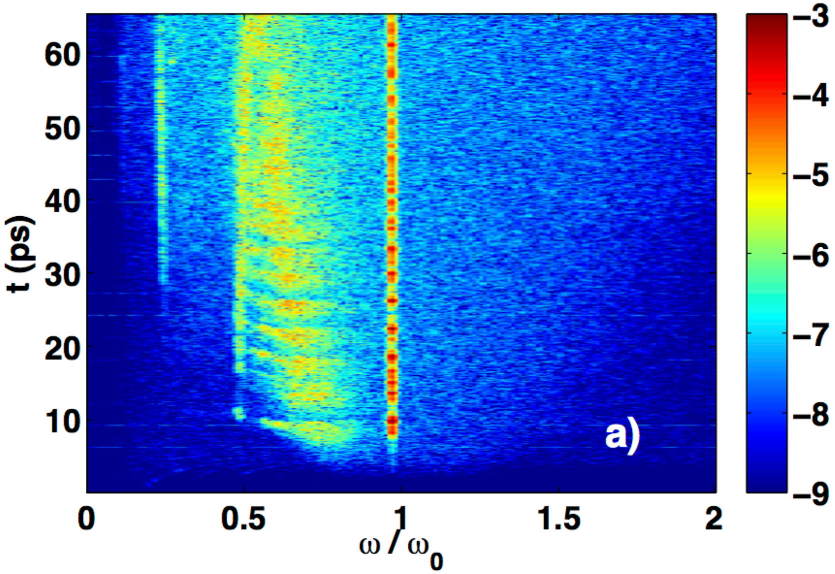
- The white numbers point to:
  1. Flash of SBS (short pulse - broad frequency spectrum)
  2. Broad spectrum of convective backward SRS
  3. Absolute SRS coming from ¼ n_c
  4. Convective backward SRS induced by SBS.
     This radiation propagates into the target and can be confused with forward SRS.



- This rescattering mechanism imposes constraint on the amplitude of SBS flashes. Also note that the forward propagating SRS will induce less parametric instabilities because of its broader spectrum.

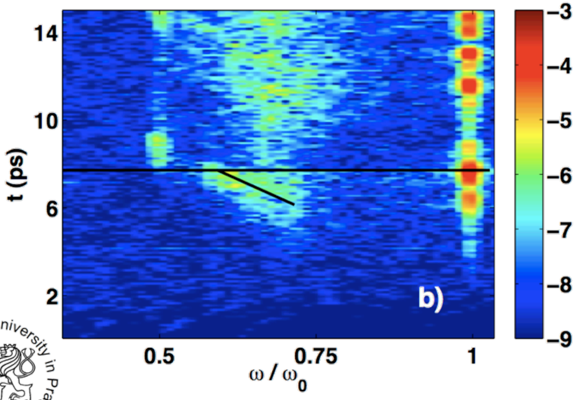
Temporal evolution of the reflected light spectrum

Backward in front of the target

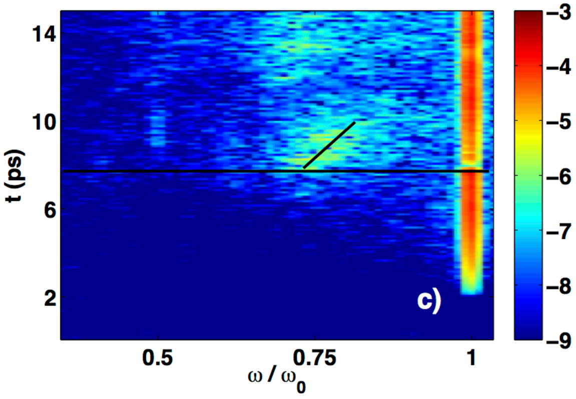


- Spectrum of the reflected light recorded inside the target at position 0.93 - local density 0.2 n_c.
- Frequency of scattered light depends on time because it depends on the scattering position, which gives different propagation distance.
- **BSRS** – higher ω induced earlier and shorter propagation **dω/dt<0**

Backward inside target



Forward inside target

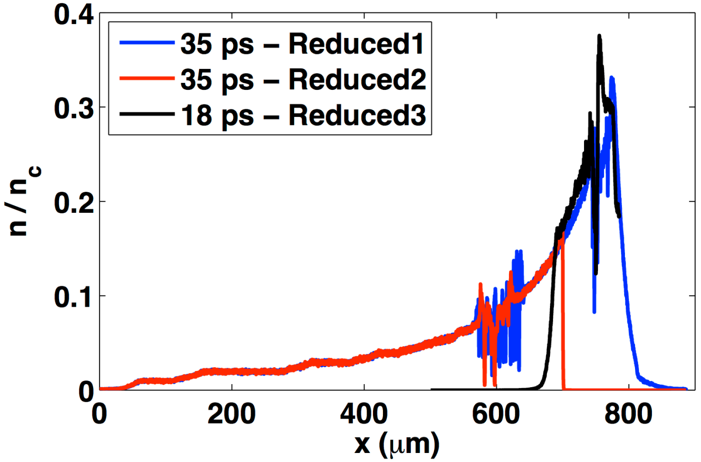


- **BSRS by SBS** – higher ω induced later and longer propagation **dω/dt>0**

Reduced simulations – absorption and cavitation

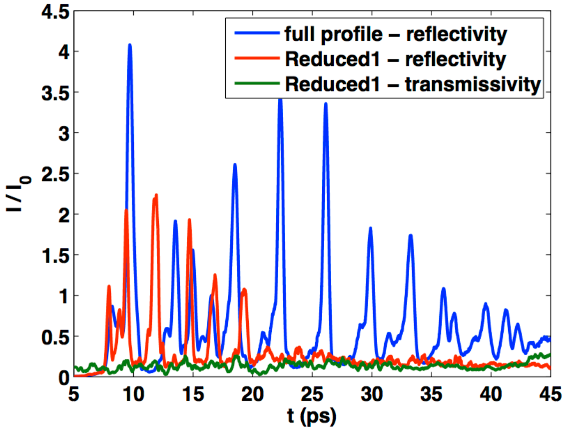
- Reduced simulations with shorter scale length for 8 × 10^{15} W/cm^2:
  - **Reduced1** 0-0.3 n_c (contains ¼ and 1/16th n_c)
  - **Reduced2** 0-0.16 n_c (contains only 1/16th n_c) realized from Reduced1 by removing dense part of the profile after the cavities develop
  - **Reduced3** 0.16-0.3 n_c (contains only ¼ n_c)

Reduced density profiles

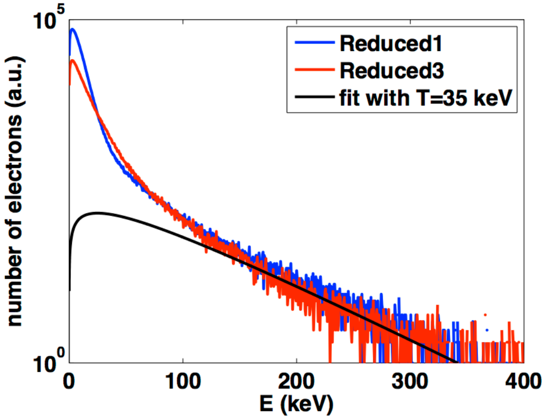


- Transmissivity of Reduced1 profile 15%.
- Reflectivity of Reduced1 profile saturates at about 15 %.
- SBS spikes are less intense and more often → seeded in less dense plasma.
- **Energy spectrum of hot electrons does not change when the profile is reduced just to the region containing ¼ n_c.**

Reflectivity



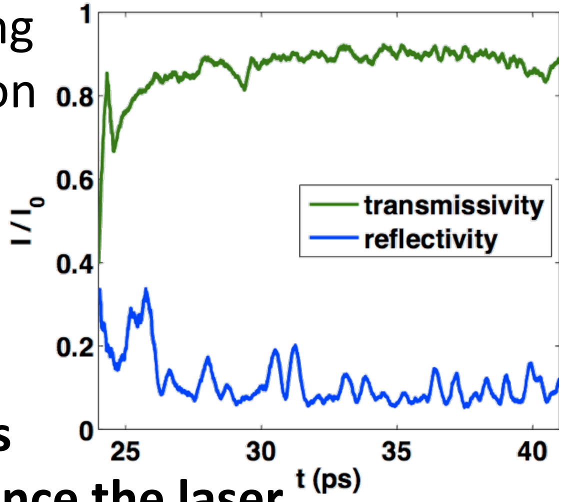
Electron energy spectrum

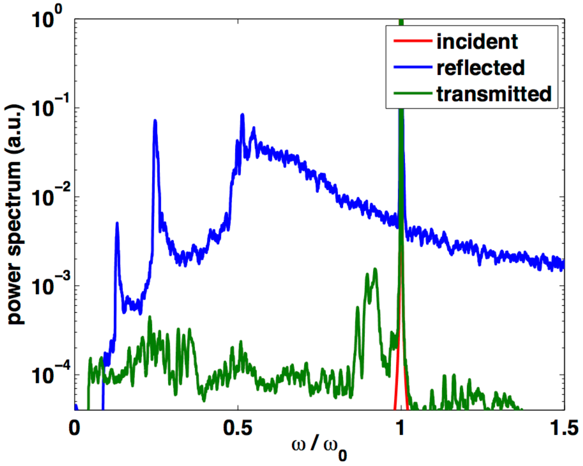


Reduced simulations – absorption and spectrum

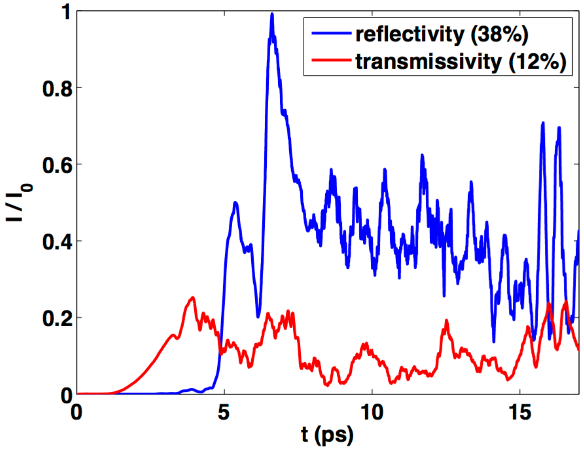
- **90%** of light is **transmitted**, **10% reflected** and nothing absorbed in the simulation **Reduced2**
- The spectrum of the transmitted light is not altered significantly.
- It results that **the cavities at 1/16th n_c do not influence the laser light propagating into the target.**
- Reduced3 – absorption 50%, transmissivity 12%, reflectivity 38%
- Reflectivity due to absolute SRS – i.e. **38% abs. due to absolute SRS and 12% due to trapping of light in cavities**. Including 50% absorption of 38% at 1/16th n_c gives overall absorption 69%.

Reflectivity/transmissivity and light spectrum in Reduced2





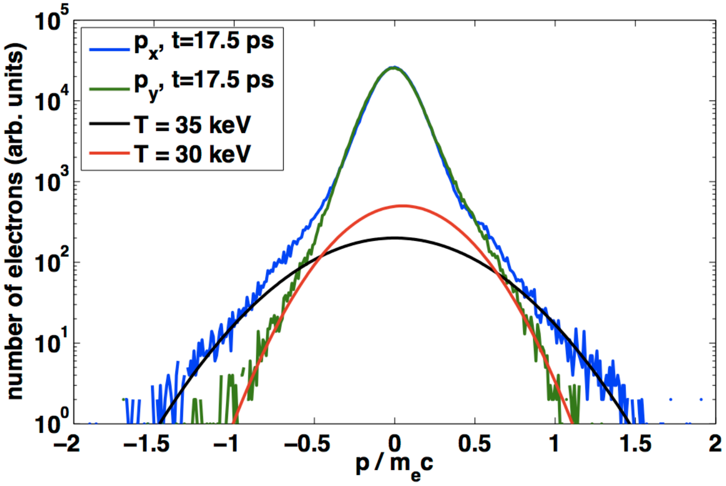
Refl./transmis. Reduced3



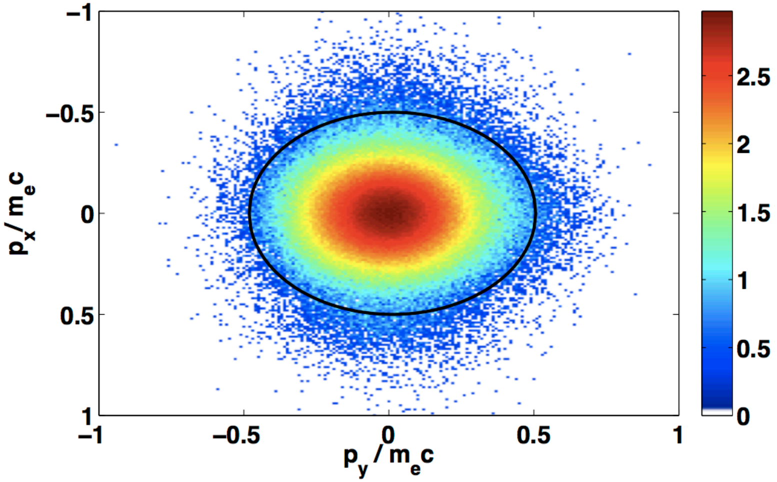
Momentum distribution – SRS and cavities

- The electrons accelerated in electron plasma waves induced by SRS propagate in the x direction.
- Acceleration of electron in cavities produces almost symmetric momentum distribution – i.e. it is responsible for hot electrons in the y direction.
- We can use this asymmetry to find the temperature of electrons accelerated by SRS and by cavities
  - cavities – about 30 keV assuming symmetry
  - SRS – about 35 keV assuming monodirectional

Electron momentum distribution



Momentum distribution px vs. py



Summary and conclusions

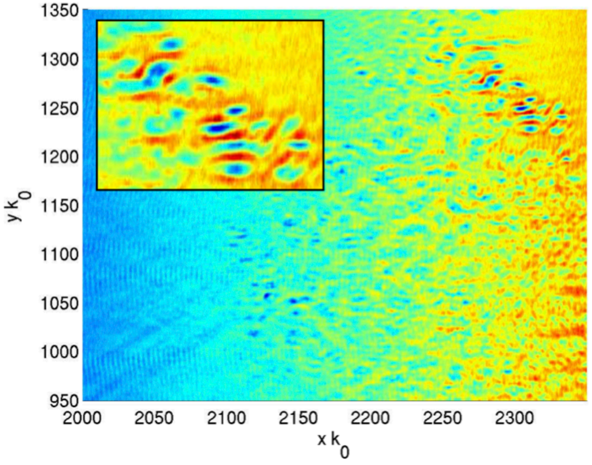
- **1D kinetic laser plasma interaction studies predict up to 70% absorption of the spike almost independent of intensity.**
- **The temperature of hot electrons seems to be acceptable for SI.**
- **Low intensities**
  - Suppression of the SBS by collisions.
  - Efficient collisional heating of electrons.
- **High intensities**
  - Suppression of the SBS by strong SRS accompanied by cavitation.
  - Rescattering of strong SBS flashes contributes to SBS saturation.
  - Absorption goes into hot electrons with temperature of about 20-40 keV.
  - Reduced simulations – 50% absorption at ¼ n_c (38% SRS, 12% cavitation).
  - Cavitation produces isotropic distribution of hot electrons with T about 30 keV, SRS directional distribution with T about 35 keV
  - Competition among SRS, TPD and cavitation in the region around ¼ n_c will be studied next in 2D simulations.

Thank you for attention

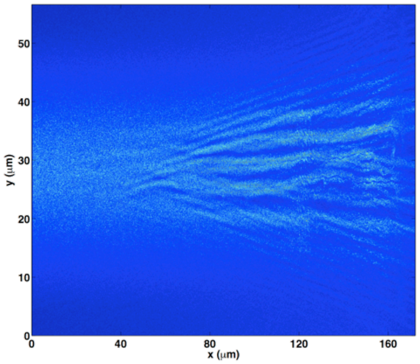
2D simulations

- As a result of reduced 1D simulations, we can study most of the absorption process (cavitation, SRS and TPD) taking into account only plasma around ¼ n_c – great advantage.
- Cavitation and SRS and TPD around ¼ n_c already studied in PRE **85**, 016403 (2011).
- Other preliminary simulation with intensity 4×10^{16} W/cm^2, density scale length 180 µm and spot size 15 µm shows strong filamentation.
- The temperature of hot electrons in 2D is similar like in 1D, but the absorption is much lower because the simulations do not reach quasi-steady state.

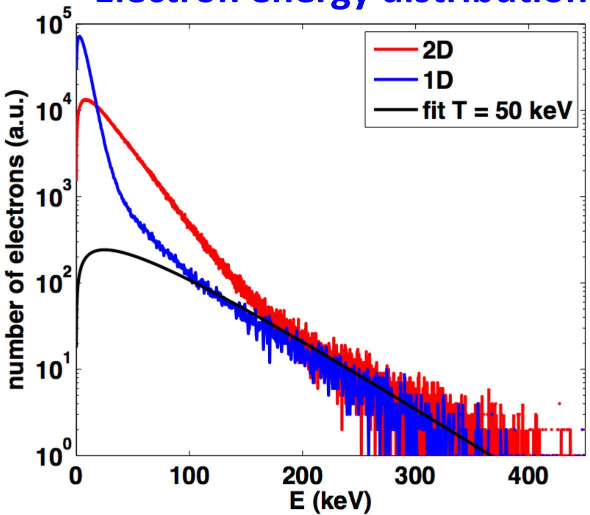
Ion density around ¼ n_c



Poynting vector



Electron energy distribution



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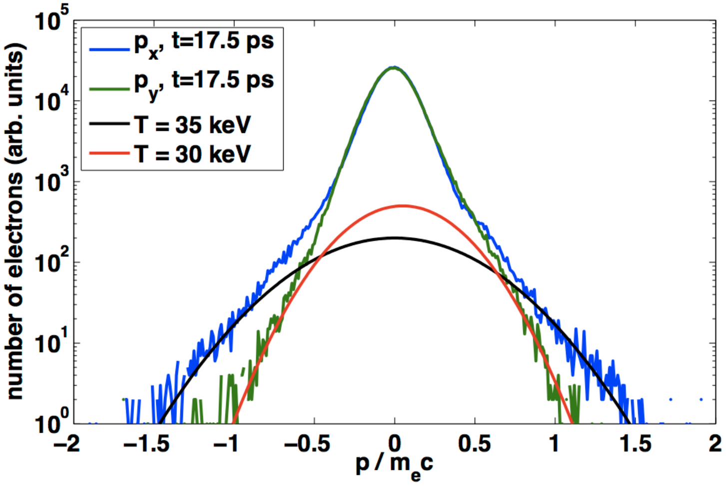
  - Suppression of the SBS by strong SRS accompanied by cavitation.
  - Rescattering of strong SBS flashes contributes to SBS saturation.
  - Absorption goes into hot electrons with temperature of about 20-40 keV.
  - Reduced simulations – 50% absorption at ¼ n_c (38% SRS, 12% cavitation).
  - Possible to limit 2D simulations to region around ¼ n_c.
- **Low intensities**
  - Suppression of the SBS by collisions.
  - Efficient collisional heating of electrons.
- **2D simulations**
  - Confirm cavitation around ¼ n_c.
  - Collisionless absorption - similar electron temperature like in 1D.
  - Strong filamentation of the laser beam
  - Short simulation time - the asymptotic regime not attained.

Momentum distribution – SRS and cavities

- The electrons accelerated in electron plasma waves induced by SRS propagate in the x direction.
- Acceleration of electron in cavities produces almost symmetric momentum distribution – i.e. it is responsible for hot electrons in the y direction.
- We can use this asymmetry to find the temperature of electrons accelerated by SRS and by cavities
  - cavities – about 30 keV assuming symmetry
  - SRS – about 35 keV assuming monodirectional
- SRS accelerated electron – characteristic velocity = phase velocity = $\omega/k < \frac{1}{2}\,\omega_0/k_0$ i.e. $v_x < \frac{1}{2}c$ corresponding to $T < 41$ keV

Electron momentum distribution



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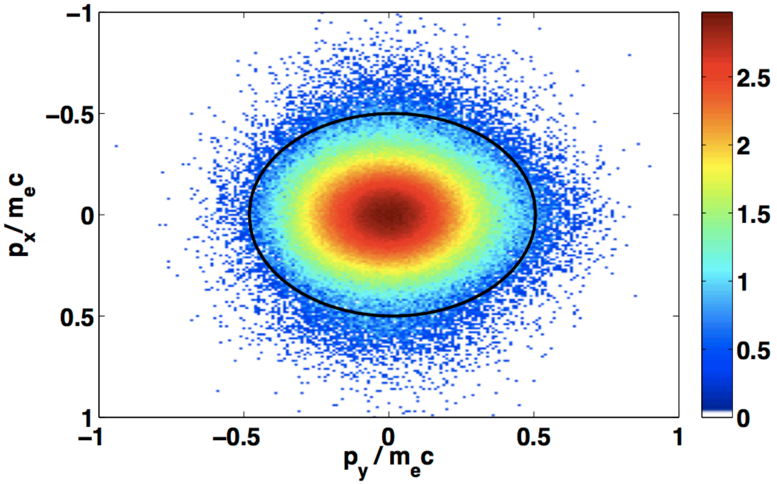

Kinetic modeling using PIC method

- Fully kinetic PIC simulations with relativistic electromagnetic code in 1D3V and 2D3V geometry (massively parallel with dynamic load balancing, up to 2^{10} cores).

- **Plasma length & simulation time in 1D – 1.2 mm and up to 100 ps** (4×10^5 cells, 2×10^7particles, 10^7 time steps, 6×10^4 CPU hours)

- **Plasma size & simulation time in 2D – 170 µm × 60 µm and up to 5 ps** – density profile must be reduced and intensity increased to accelerate the growth of parametric processes (5×10^7 cells, 2×10^8 particles, 10^5 time steps, 10^5 CPU hours)

- Important issues solved:
  - Including relativistic Coulomb collisions
  - Numerical noise (cubic spline particle shape to reduce the number of particles per cell and maintain numerical noise on reasonable level)
  - Boundary conditions (absorb the flux of energy and maintain the temperature of return current)