Kinetic modelling of laser absorption in foams

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Outline

1. Characterize the laser absorption process at high intensities when the state of material changes during the irradiation (ablation-expansion);

2. Characterization of the ablation and expansion competition: homogenization time;

3. Characterization of ablated plasma: average energies of electrons and ions, polarization dependence;

more about experiments with porous targets: J. Limpouch (O4 S2)

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Theoretical model: solid cylinder in an empty pore

We consider two different cases:

1 homogeneous cylinder

$$\epsilon = 1 - \left(\frac{\omega_{pe}}{\omega}\right)^2 \frac{1}{1 + i\,\nu_e/\omega}$$

$$N = const$$

S P

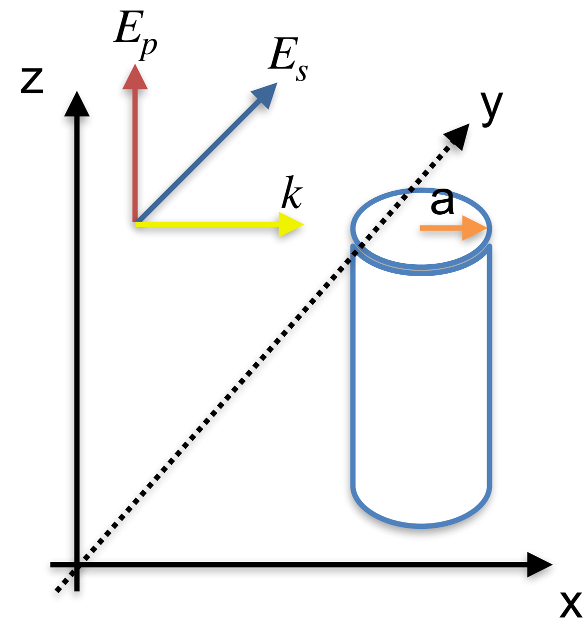
2 inhomogeneous cylinder

$$\epsilon(r) = 1 - \left(\frac{\omega_{pe}}{\omega}\right)^2 \frac{N(r)}{1 + iN(r)\,\nu_e/\omega}$$

$$N(r) = \exp[-(r/a)^2 \ln 2]$$

S P

We compare const density profile with the Gaussian profile on a cylinder of radius $k \cdot a$



Ep: p-polarisation

Es: s-polarisation

significant difference: resonance absorption

Theoretical model: main equations

We build the absorption model based on the Mie theory of scattering on small objects. The difference from standard Mie model is in radial dependence of epsilon.

P $$E_z \to E_0 \sum_n e^{in\theta} u_n(\rho)$$

S $$B_z \to B_0 \sum_n e^{in\theta} v_n(\rho)$$

$$\rho = k \cdot r$$

$$u_n'' + \frac{1}{\rho} u_n' + \left(\epsilon - \frac{n^2}{\rho^2}\right) u_n = 0$$

$$v_n'' + \left(\frac{1}{\rho} - \frac{\epsilon'}{\epsilon}\right) v_n' + \left(\epsilon - \frac{n^2}{\rho^2}\right) v_n = 0$$

$$\epsilon = \epsilon(r)$$

Where:

$$u_n(\rho) = \sqrt{\epsilon}\, a_n J_n(\sqrt{\epsilon}\rho)$$

$$v_n(\rho) = \sqrt{\epsilon}\, b_n J_n(\sqrt{\epsilon}\rho)$$

for laser wave incident normally on homogeneous cylinder these are just Bessel functions of first kind

cross-section of the process:

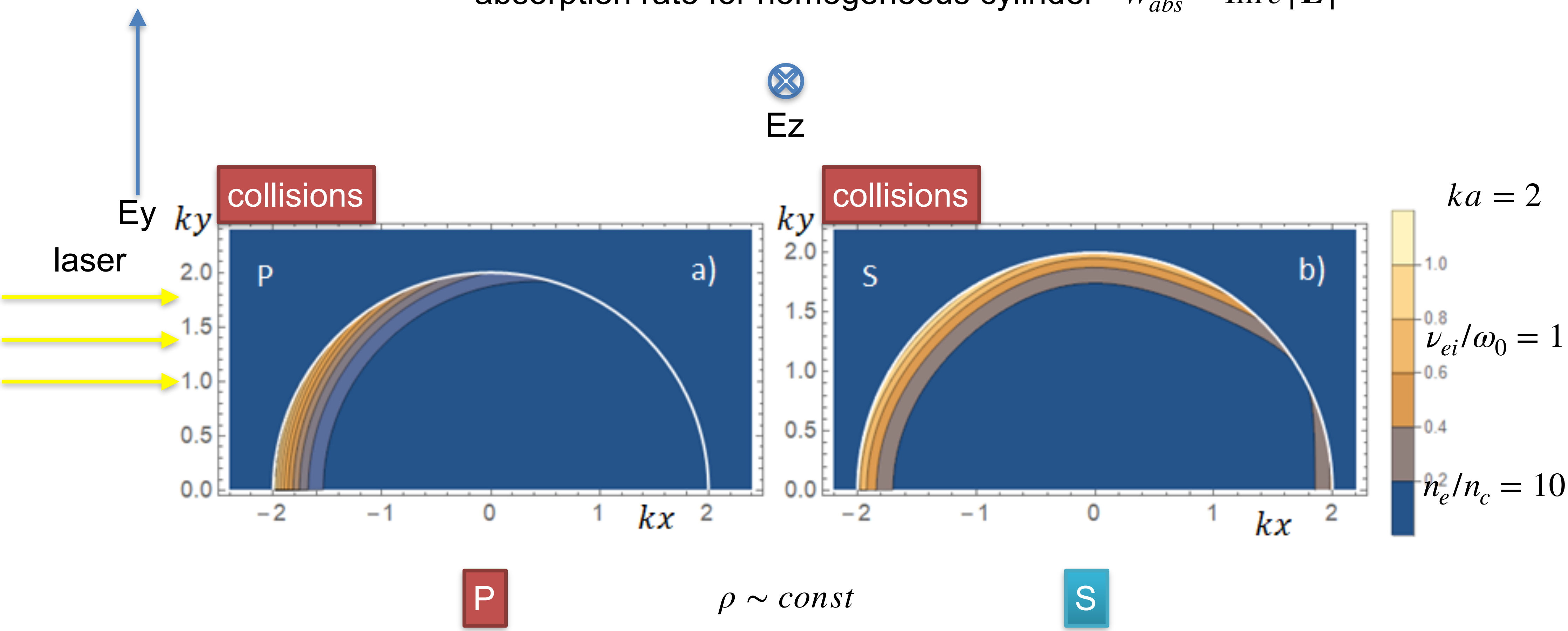
$$\sigma = Q_{abs} \cdot \sigma_{geom}$$

We calculate scattering & absorption efficiency factors

Q_{sca} Q_{abs}

Theoretical results: absorption rate

absorption rate for homogeneous cylinder $W_{abs} = \mathrm{Im}\,\epsilon\,|\mathbf{E}|^2$



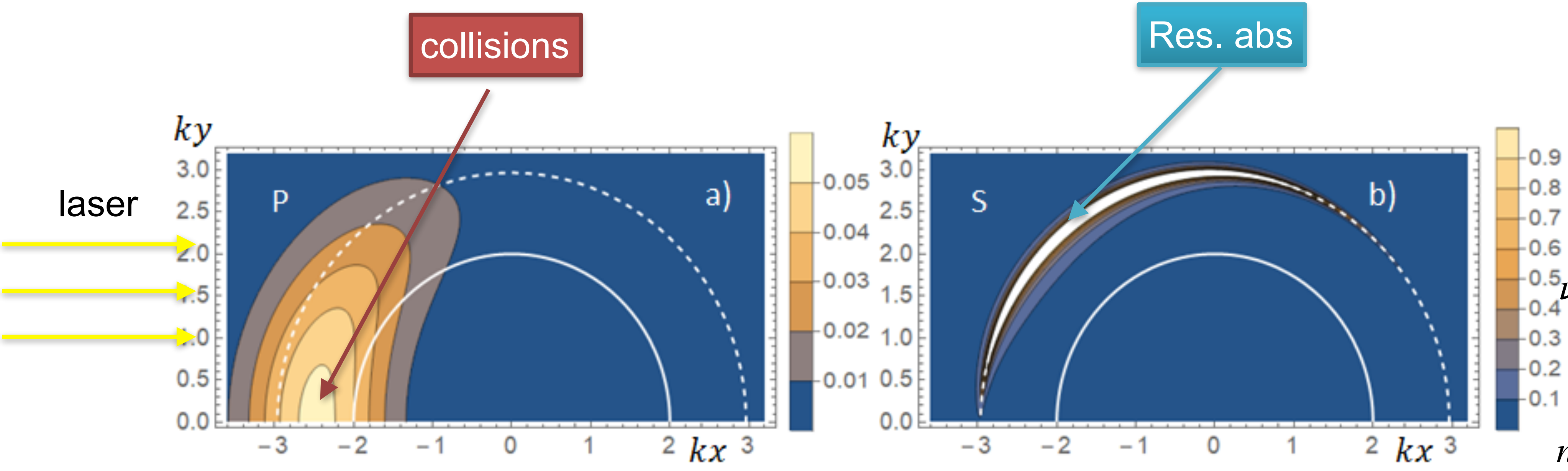
$\rho \sim const$

for both S- and P-pol cross section of absorption depends weakly on the laser polarization

absorption in this case is proportional to the electron-ion collision frequency

Theoretical results: absorption rate

absorption rate for inhomogeneous cylinder $W_{abs} = \mathrm{Im}\,\epsilon\,|\mathbf{E}|^2$



$ka = 2$

$\nu_{ei}/\omega_0 = 1$

$n_e/n_c = 10$

P

S

$\rho \sim \exp[-(r/a)^2 \ln 2]$

Res. absorption works at any angle of incidence for S-pol

in S-pol case: Collisional absorption + resonance absorption

does not depend on the imaginary part of dielectric permittivity i.e. collisional frequency

Efficiency factors: dependence on the cylinder radius

$ka = 2$

$$\sigma = Q_{abs} \cdot \sigma_{geom}$$

homogeneous

$\rho \sim const$

$Q_{abs,P} = 0.3$

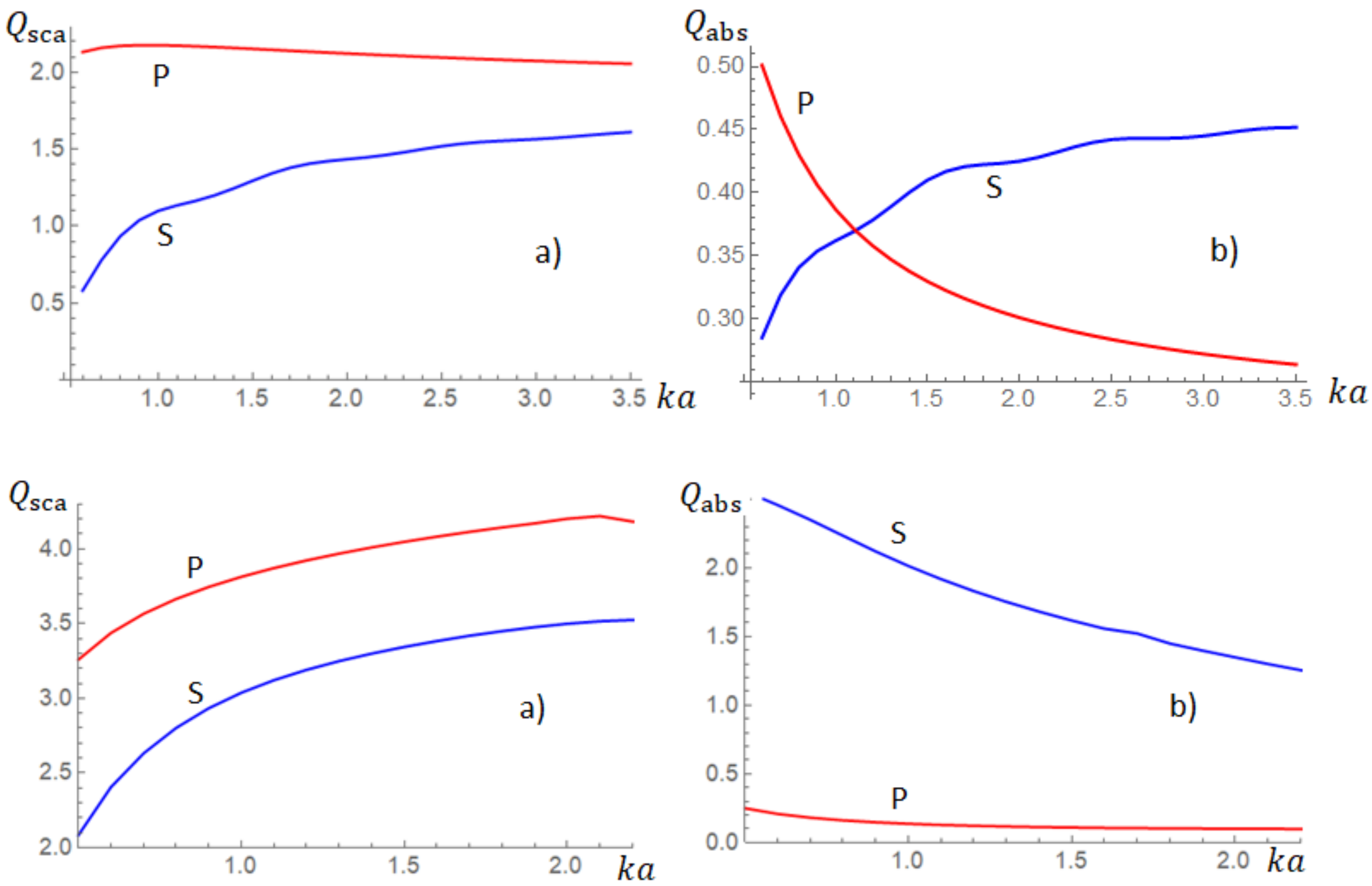
$Q_{abs,S} = 0.4$

inhomogeneous

$\rho \sim \exp[-(r/a)^2 \ln 2]$

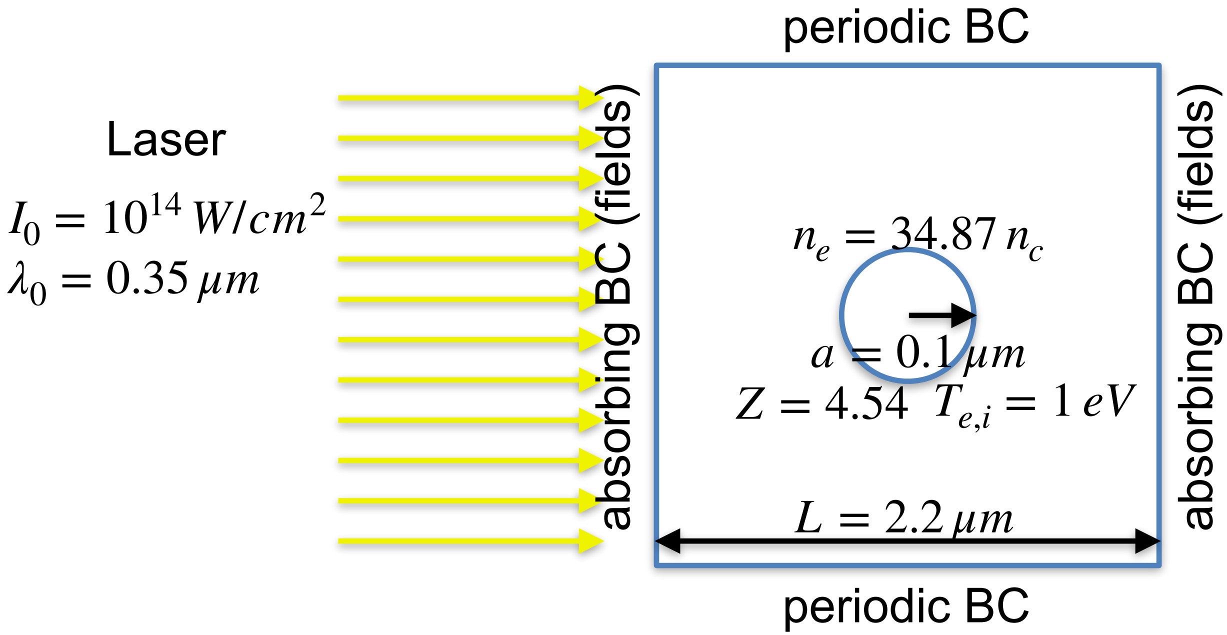
$Q_{abs,P} = 0.3$

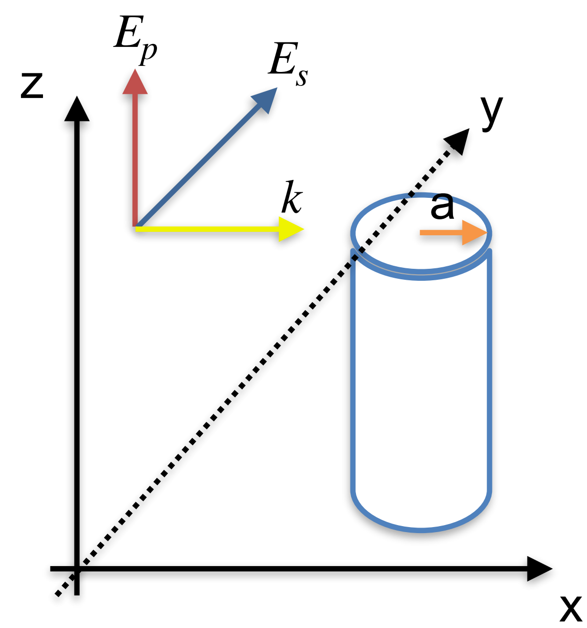
$Q_{abs,S} = 1.5$



radial inhomogeneity of the cylinder changes the absorption rate even in the case of large collision frequency

Simulation model





We used collisional PIC 2D simulations (SMILEI)

Initial density profile in our simulation is const.

extend theory to arbitrary radial density profile
profile on a cylinder of radius $k \cdot a$

$$\rho \sim \exp[-(r/a)^p \ln 2]$$

Ep: p-polarisation

Es: s-polarisation

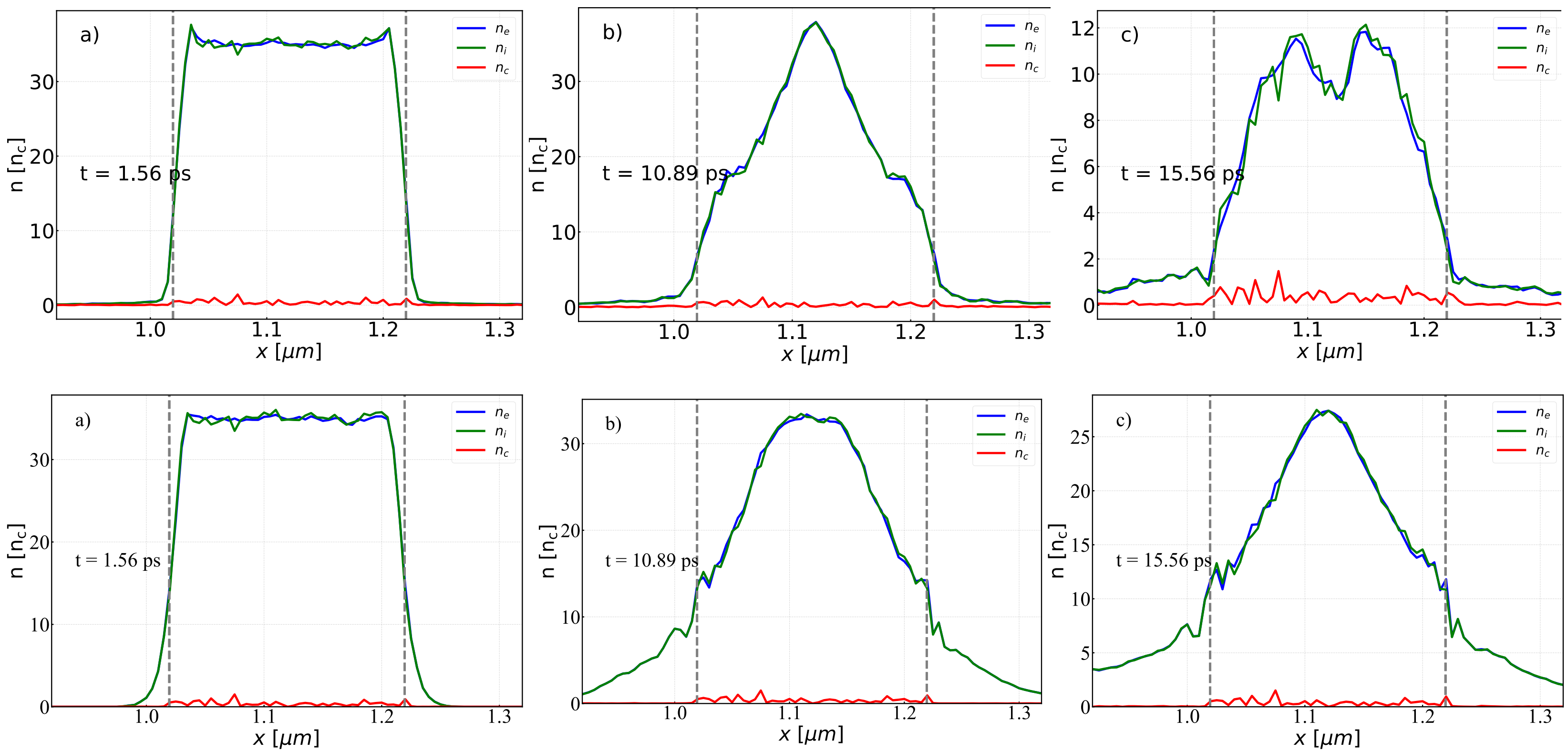
Motivation:

1. check the theoretical model of absorption
2. understand the variation of the cylinder density and temperature with time
3. characterize the ablated plasma and homogenization time

Density profiles

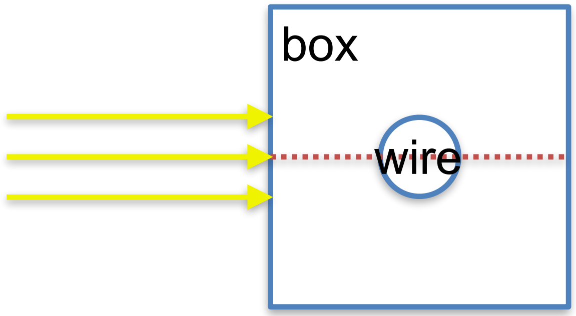
S

P



dashed line is the position of the cylinder

$$n_c = |Z \cdot n_i - n_e|$$



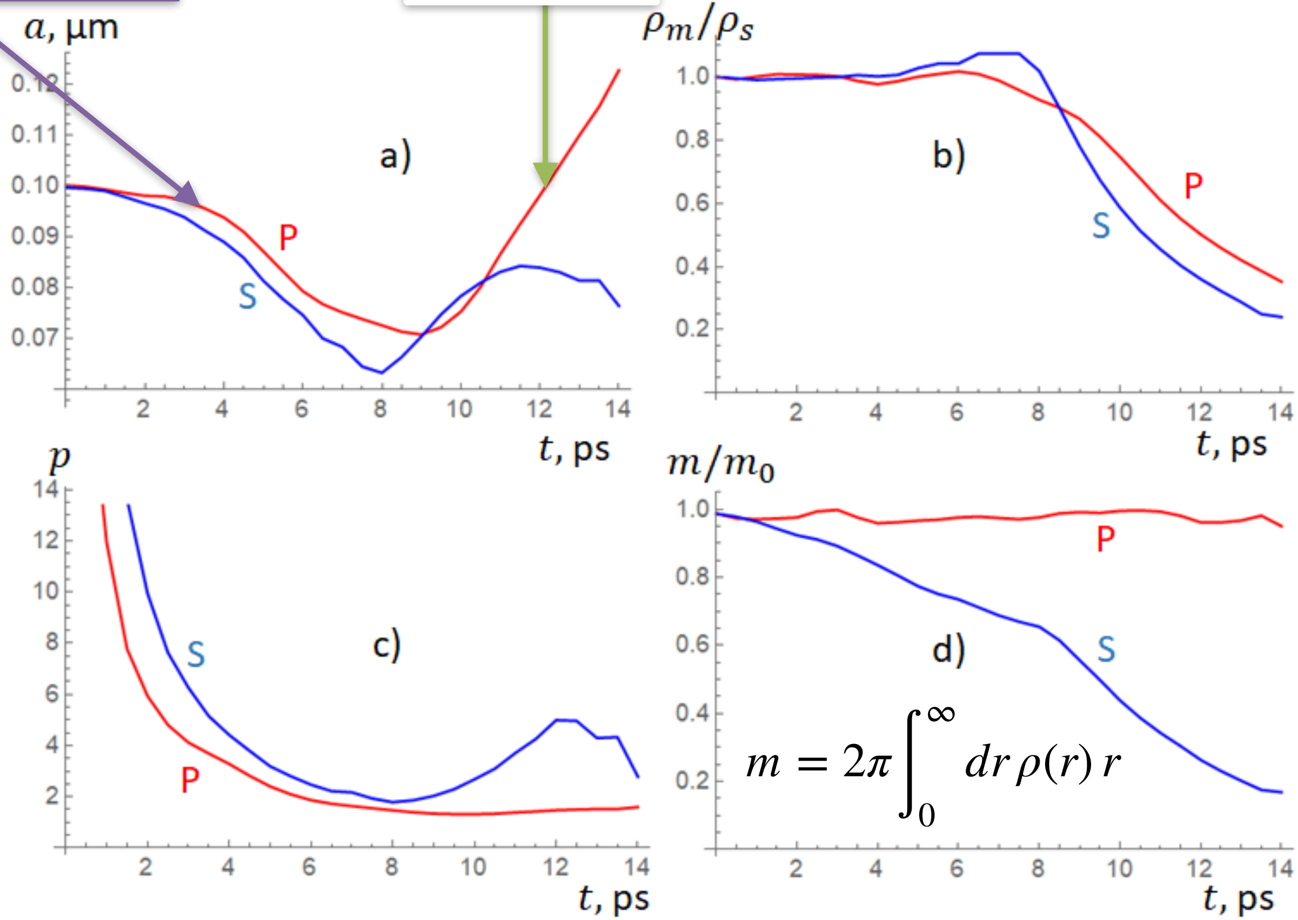
1. faster expansion for S and slower for P
2. bell-shaped profile: exponential parametrization applies
3. approximately quasi-neutral expansion

$$\rho(r) = \rho_c \exp[-(r/a)^p \ln 2]$$

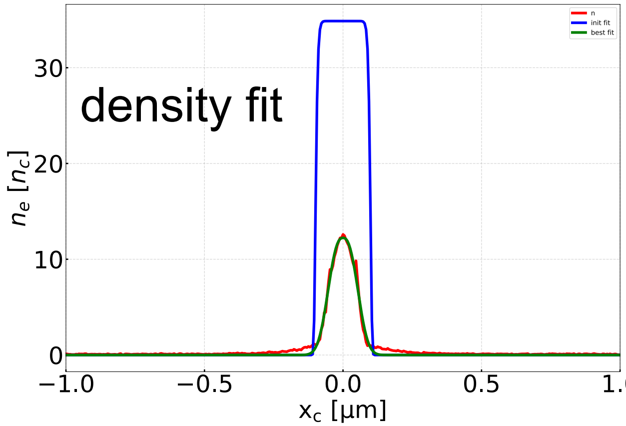
Parametrization of the density profile in the cylinder

rarefaction wave

expansion



ablation dominates for S-pol



model:

$$\rho(r) = \rho_c \exp[-(r/a)^p \ln 2]$$

$$a = a(t),\ p = p(t),\ \rho_c = \rho_c(t)$$

dominance ablation for S-pol all the time, dominance of expansion for P-pol
two expansion phases: rarefaction wave for rho = constant and expansion after 8ps

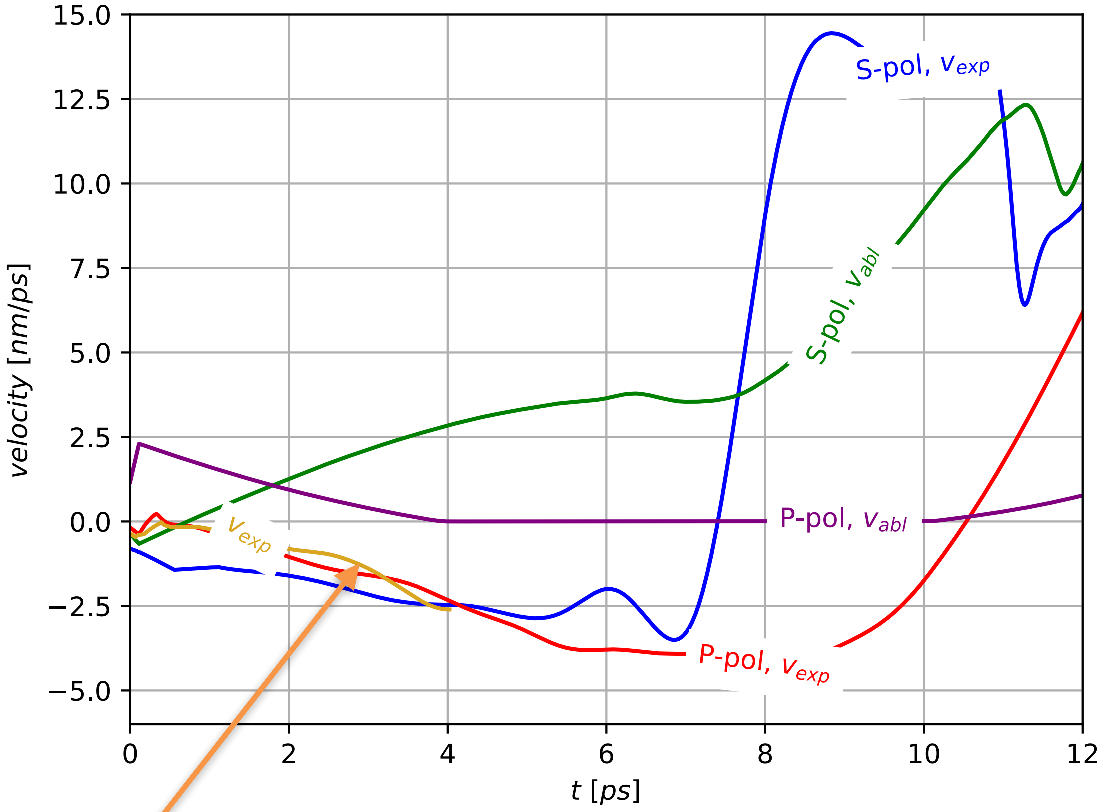
Ablation/expansion velocity

ablation dominates for S-pol

$$v_{\rm abl} = -\frac{\dot{m}_c}{2m_c}a \qquad v_{\rm exp} = v_{\rm abl} + \dot{a}$$

thermal ablation, Phys. Fluids 25, 1644 (1982).

almost zero ablation for P-pol



1. dominance ablation for S and expansion for P
2. two expansion phases: rarefaction and expansion
3. characteristic time of rarefaction is ~8ps

expansion competes ablation at later stage

$$\tau_h \simeq \frac{a_0}{v_{\rm abl}} \simeq 30 \text{ ps} \quad \text{S}$$

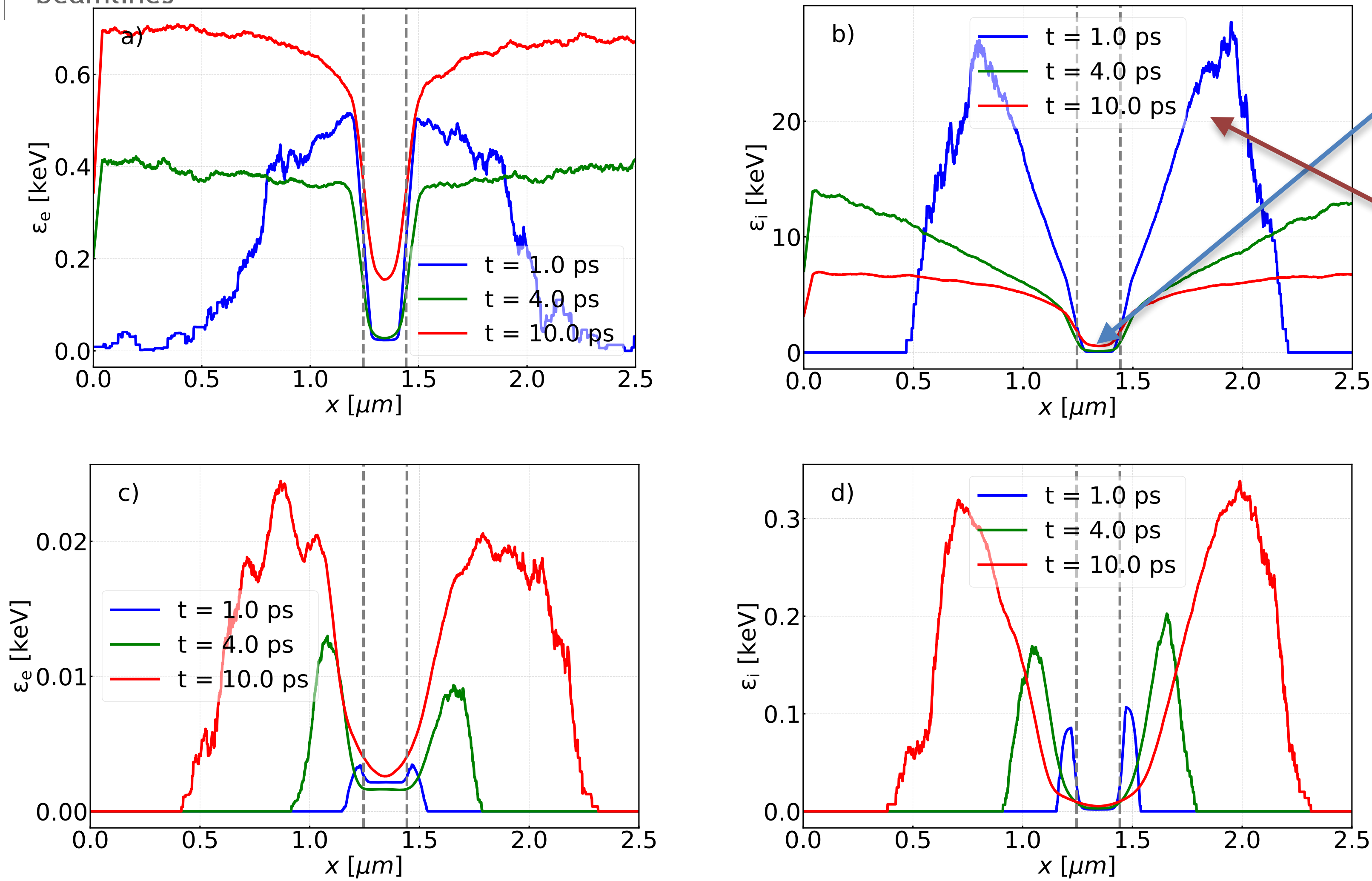
$$\tau_h \simeq \frac{l_{\rm pore}}{v_{\rm exp}} \simeq 100 \text{ ps} \quad \text{P}$$

expansion without laser coincides with P-pol case → poor absorption, cold core

Electron and ion energy partition

S

P



cold center

hot ablated plasma

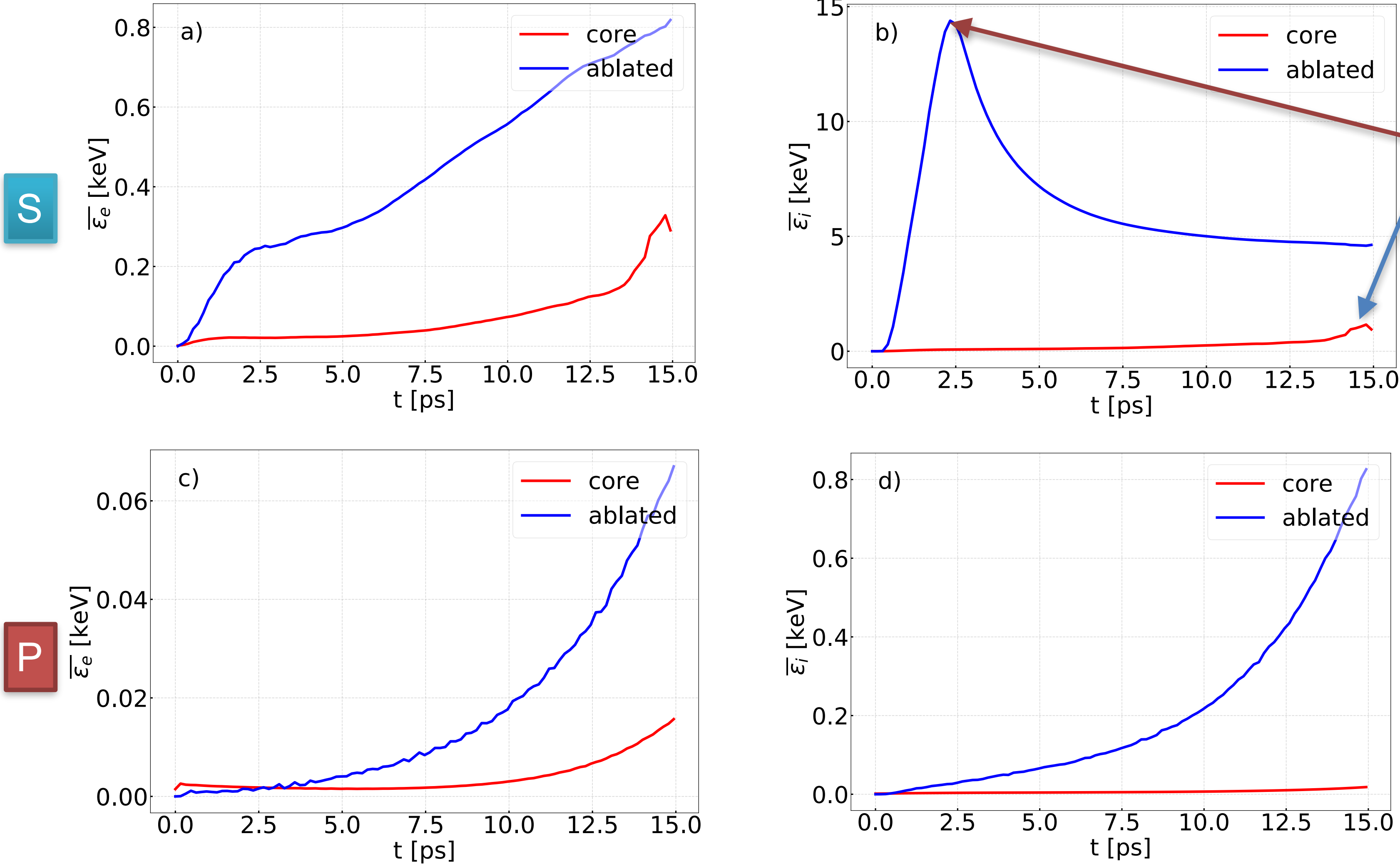
ablation process dominates

much less energy is absorbed in P-pol case

electrons have smaller average energy than ions

ions are accelerated via electrostatic ablation process

Electron and ion energy evolution



cold core

hot ablated plasma

ablation process dominates

very slow bulk heating: surface energy absorption, suppressed heat transport inside the cylinder

much less energy is absorbed in P-pol case

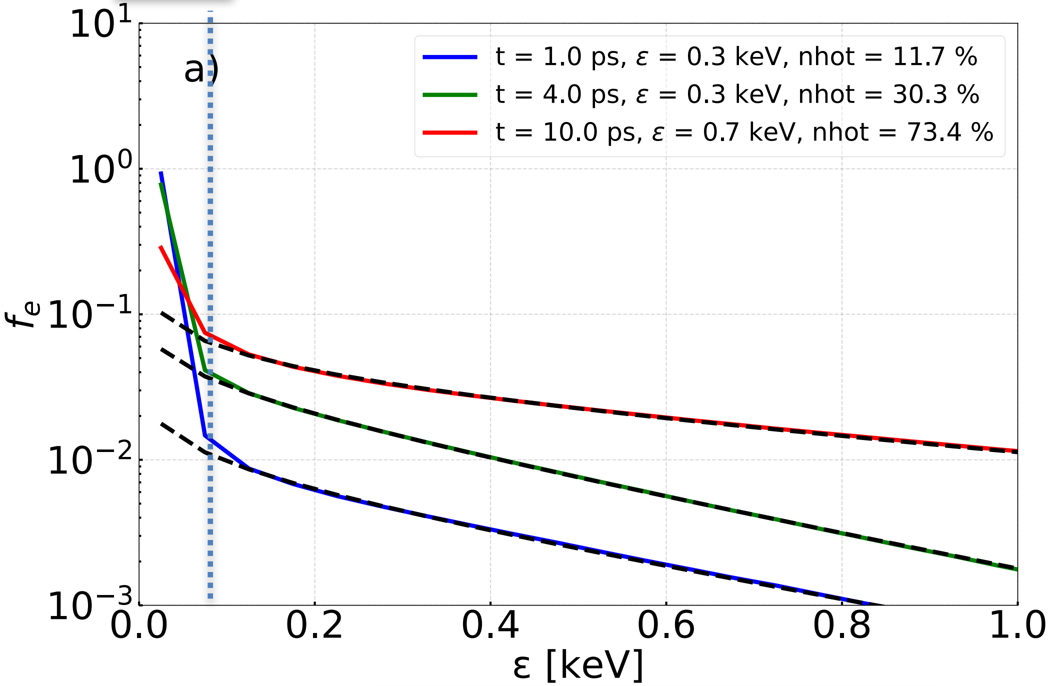
electrons have smaller average energy than ions

ions are accelerated via electrostatic ablation process

Particle energy distribution

core

electrons



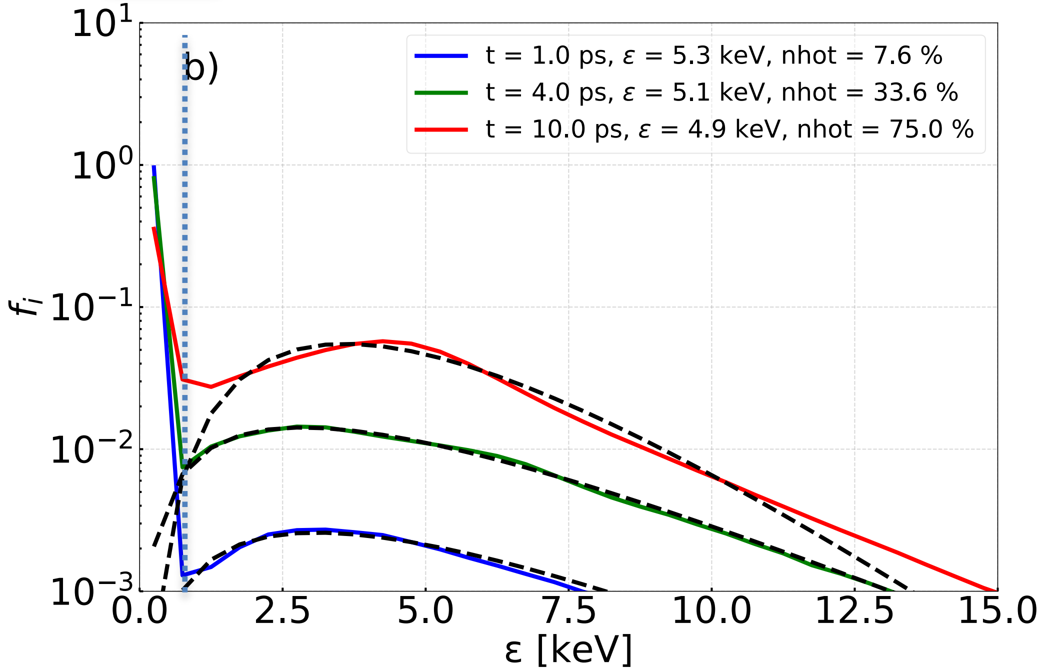
ablated plasma, ~0.7 keV

$$f_h(\varepsilon) = \frac{n_h}{T_h^{k+1}\,\Gamma(k+1)}\,\varepsilon^{k_h}\exp\left(-\frac{\varepsilon}{T_h}\right)$$

S

core

ions



ablated plasma, ~4.9 keV

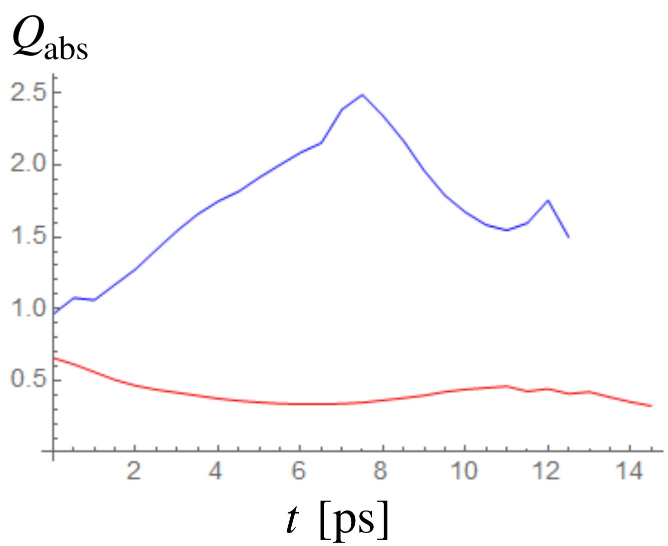
ions are not yet thermalized on such a short time scale: large amount of energy is still in the ion radial flow

energy balance in the pore: reflected+transmitted+absorbed=1

$R = f_{\text{back}} Q_{\text{sca}} 2a/L \qquad T = 1 - (Q_{\text{abs}} + f_{\text{back}} Q_{\text{sca}}) 2a/L$

Polarization	Reflection	Transmission	Absorption	Q_{abs}	$f_{\text{back}} Q_{\text{sca}}$
S	6%	82%	12%	1.32	0.66
P	10%	88%	2%	0.22	1.1

TABLE II. Energy balance in the simulation averaged over a time interval 7 – 15 ps.



from simulation:

$f_{\text{abs}} = 12\,\%$

$Q_{\text{abs,S}} = 1.3$

from theory:

$Q_{\text{abs,S}} = 1.5$

$$f_{\text{abs}} = \frac{2a\, Q_{\text{abs}}}{L} \cdot 100\,\% \simeq 13\,\%$$

Summary

- The laser absorption efficiency in foams strongly depends on the shape of the structure and it's orientation with respect to the laser polarization
- In S-pol case there are two mechanisms of absorption: collisional absorption and resonance absorption, if there is a density gradient (no res absorption if there is no density gradient)
- Only collisional absorption in P-pol case at normal incidence
- Ablation process dominates in the S-pol case, slow expansion in the P-pol case
- Laser energy is transferred mainly to the ions via electrostatic ablation process: energy partition electrons/ions = 2/3

$$\bar{\varepsilon}_i \simeq 5\,keV$$

cross-section of process

$$\sigma = Q_{abs} \cdot \sigma_{geom}$$

$$Q_{abs,P} = 0.4$$

$$Q_{abs,S} = 1.5$$

inhomogeneous cylinder

absorption-expansion parameters are used in the hybrid micro-macro model (L. Hudec, O8 S2)

Thank you
for your attention!