Italian National Agency for New Technologies, Energy and Sustainable Economic Development

High power laser irradiation of low-Z porous media: numerical simulations and experiments

MATTIA CIPRIANI
C.R. Frascati | FSN-FUSPHY-SAD

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In collaboration with
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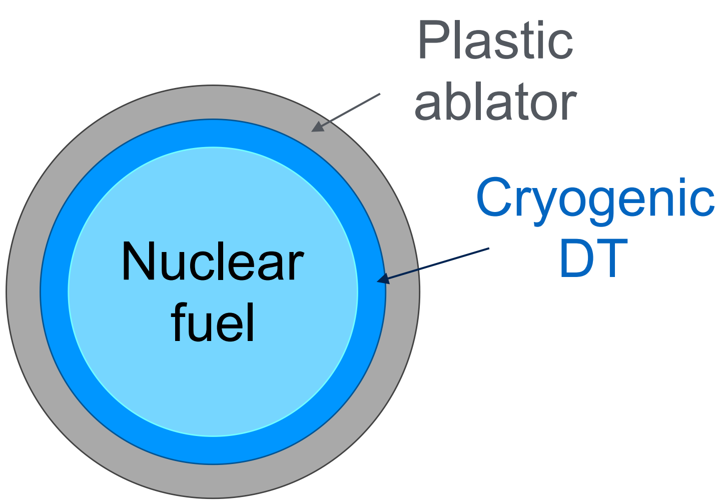
[2]*ENEA, Fusion and Technologies for Nuclear Safety Department, Frascati (Rome), Italy*

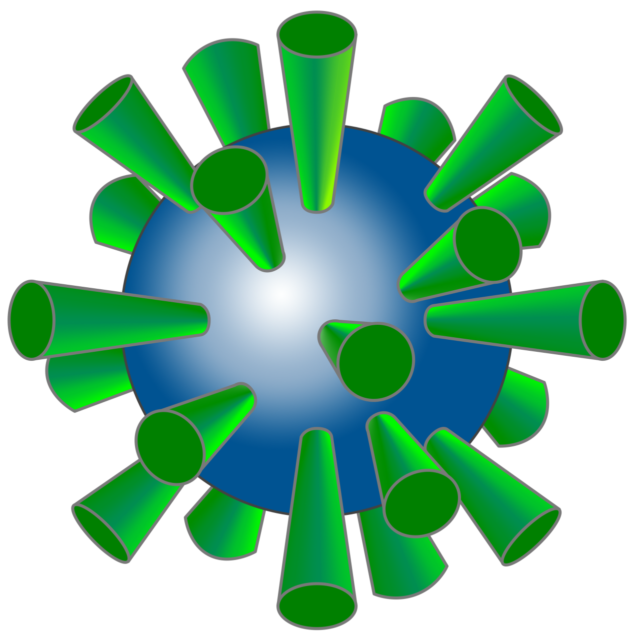
Plan of the talk

- Introduction
  - Direct drive Inertial Confinement Fusion
  - Foams and their features
- Numerical simulations:
  - A code for foams: MULTI-FM
  - Numerical simulations for overcritical foams
- Experiments at ABC on overcritical foams with large pores
  - Evidence of ablation loading increase due to foams
  - Measurement of hydrothermal wave speed at ABC and simulations
- Simulations and experiments with subcritical foams with small pores
  - Experiments at GEKKO XII and PALS and simulations
- Conclusions and Future developments

Introduction

Inertial Confinement Fusion (ICF)
Nuclear fuel ⇨ Deuterium-Tritium (DT) mixture
Fusion target compressed by action of high power laser beams





For the direct drive approach the fusion capsule is irradiated from all direction by many laser beams

Problem: uniform irradiation is crucial but difficult to achieve

Porous materials or foams can help to **smooth laser irradiation inhomogeneities** and to **improve laser absorption on the target**

And much more

- Increase pressure on the shockwave
- Laser-to-X-rays conversion
  - Doped foams
  - Metallic foams
  - …

Porous materials or foams

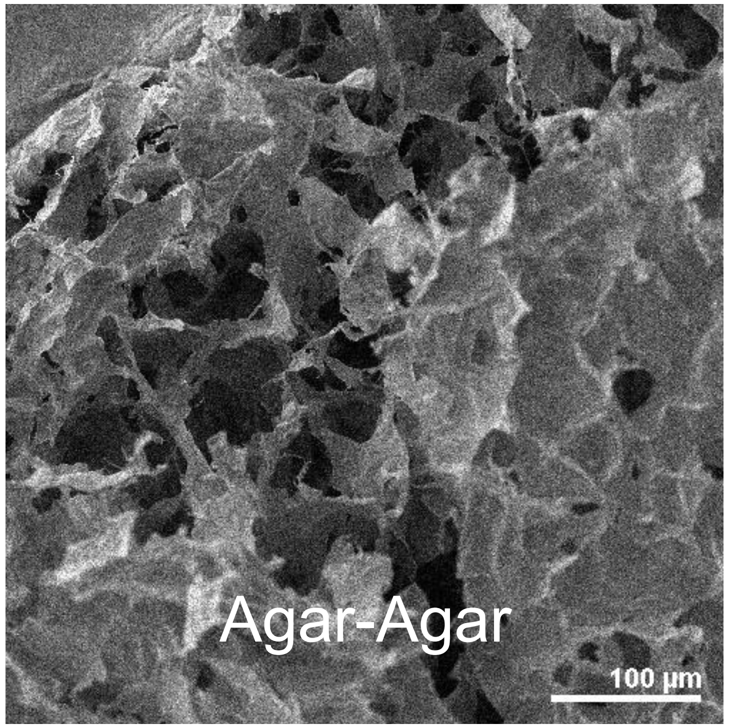
Porous materials have a stochastically distributed membrane or a filamentous structure, constituted by solid parts and large voids

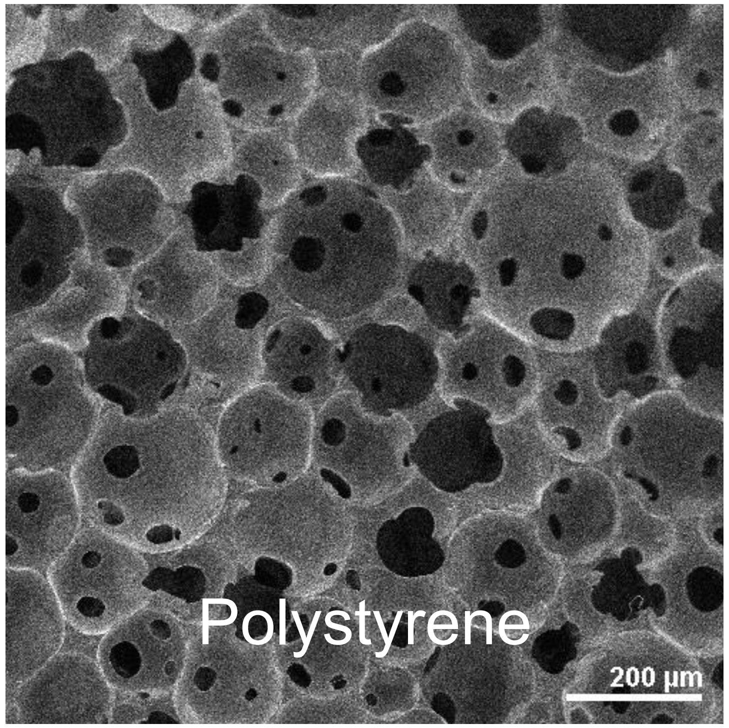
Average density: few mg/cm^3 $\longrightarrow$ several hundreds mg/cm^3

Thus → Subcritical and overcritical foams are available

Large amount of experimental data to formulate a model for the laser produced plasma from these materials

Examples

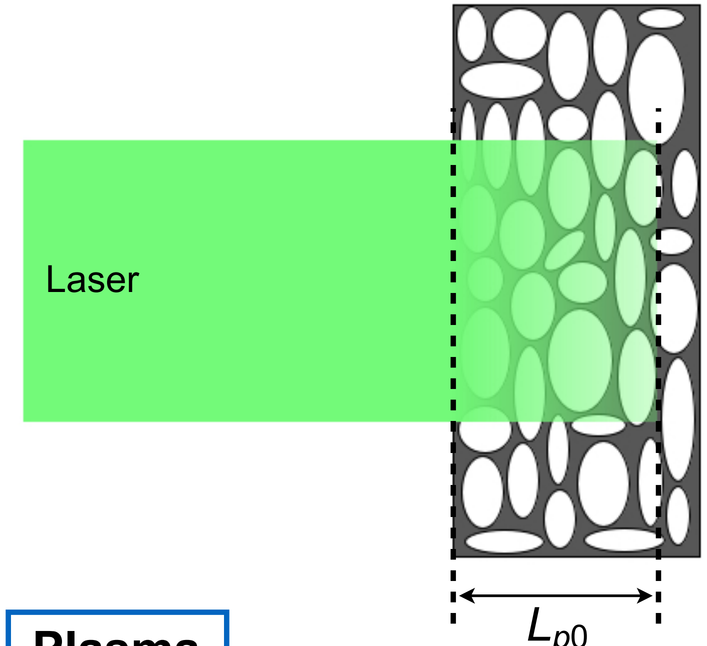




Laser absorption in foams

The solid elements are heated by the laser and the expanding flows of matter start to fill the pores
In this initial phase the laser penetrates into the target up to the geometric transparency length L_{p0}

Initial pore size: δ_0
Initial solid parts thickness: b_0



$$L_{p0} = \frac{\pi^2}{2}\frac{\rho_s}{\rho_p} b_0$$

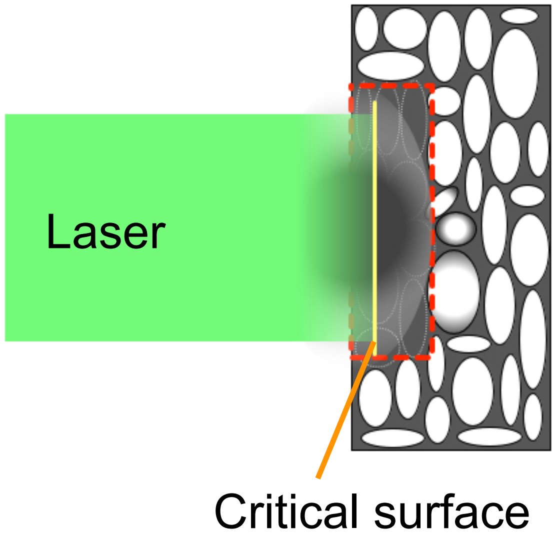
ρ_s : solid parts density
ρ_p : foam average density

Plasma Homogenization

OVERCRITICAL FOAMS

$\rho_p > \rho_{cr}$

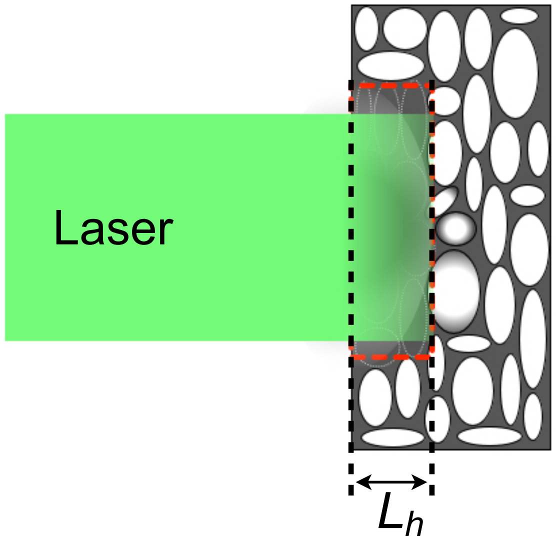
The critical surface is formed in the homogenized plasma inside the target



SUBCRITICAL FOAMS

$\rho_p < \rho_{cr}$

The absorption length reaches the minimum L_h with homogeneous plasma



A dedicated code for foam simulation

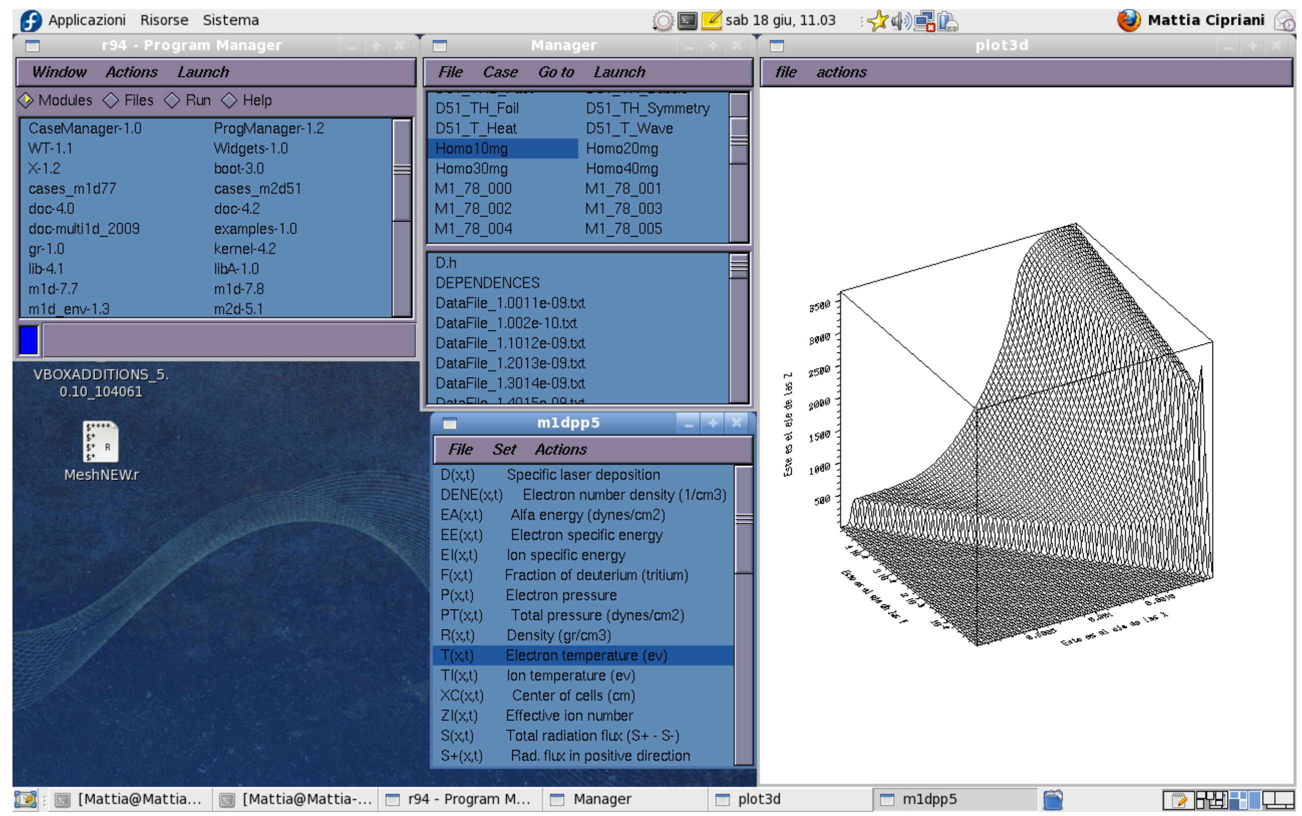
[**Mattia Cipriani** et al., *Laser Part. Beams* **36**, 121 (2018)]

Simulate the behavior of foams by a specifically designed numerical code

Starting point: **MULTI hydrodynamic code** [R. Ramis et al., *Comp. Phys. Comm.* **49** 475 (1988)]

Why 1D-MULTI:

- Freely available
- Tested in detail, very good documentation
- Also 2D version available



Newly developed code: **MULTI-FM** (foam modeling), 1D code especially developed to simulate foam materials

Other important attempt: **modified PALE code**

2 dimensional code, limited to closed small-pores subcritical foams

[J. Velechovsky et al., *Plasma Phys. Control. Fusion* **58** 095004 (2016)]

Good quantitative agreement with the known experiments about subcritical foams

Fundamental assumptions

The main parameter for foam modeling is the **degree of homogenization** of the laser-created plasma

Effects of plasma homogenization

[S.Yu. Gus'kov et al., *Quantum Electronics* **27** 696 (1997)]
[S.Yu. Gus'kov et al., *Quantum Electronics* **30** 191 (2000)]

- Determines the depth of laser absorption (transparency length L_p)

  The more the plasma is homogeneous, the shorter the absorption depth

- Determines the efficiency for heat conduction

  The more the pores are filled, the more the electronic heat conduction is effective

- Determines the response of the target to pressure gradients

  The more the pores are filled, the more the mechanical action can be transmitted through the homogenizing plasma

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MULTI-FM implementation: laser absorption

Strategy: Effective absorption via effective absorption coefficient

The absorption coefficient is [S.Yu. Gus'kov, **Mattia Cipriani** et al., *Plasma Phys. Control. Fusion* **57** 125004 (2015)]

$$K_p(x,t) = \frac{\delta_0}{b_0 L_{p0}} \left\{ \frac{1}{\left[\left(1 - \frac{b_0}{\delta_0}\right)\left(1 - 2\int_0^t \frac{dt'}{\tau_0(x,t')}\right)\right]^{1/2}} - 1 \right\}$$

$$L_{p0} = \frac{\pi^2}{2}\frac{\rho_s}{\rho_p} b_0$$

$$\tau_0 \propto 1/T(x,t)^{5/2}$$

which is valid for $0 < t < t_h$, where t_h is the time of total homogenization

The time of total homogenization t_h is determined by the following formulas

Subcritical foams

$$2\int_0^{t_h(x)} \frac{dt'}{\tau_0(x,t')} = 1 - \left[\frac{1 - \left(\frac{\rho_p}{\rho_{cr}}\right)^{4/5}}{1 - \left(\frac{\rho_p}{\rho_s}\right)^{4/5}}\right]$$

Overcritical foams

$$2\int_0^{t_h(x)} \frac{dt'}{\tau_0(x,t')} = 1$$

MULTI-FM implementation: laser absorption

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The degree of homogenization of the plasma is determined by this factor

In the code define

$$\mathrm{IsFoam}(x_i, t_h) = 1 - H(x_i, t_n)/H_C$$

x_i is the position of the numerical cell and t_n the time step of the simulation

$$H(x_i, t_n) = 2\int_0^{t_n} \frac{dt'}{\tau_0(x_i, t')}$$

$$H_C = \begin{cases} 1 & \rho_p \geq \rho_c \\ \dfrac{1 - \left(\dfrac{\rho_p}{\rho_{cr}}\right)^{4/5}}{1 - \left(\dfrac{\rho_p}{\rho_s}\right)^{4/5}} & \rho_p < \rho_c \end{cases}$$

$\mathrm{IsFoam}(x_i, t_h) =$

1 — Completely **inhomogeneous** plasma

Homogenization

0 — Completely **homogeneous** plasma

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- Determines the response of the target to pressure gradients

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MULTI-FM implementation: Heat conduction

The heat conduction is affected by the homogenization process of the foam plasma

The effect is approximated by the formula

Original formula in MULTI

$$\text{Heat flux} \longrightarrow \quad q(x_i,t_n) = -\eta(x_i,t_n)\overbrace{\left[\chi(x_i,t_n)\frac{\partial T_e(x_i,t_n)}{\partial x}\right]}$$

$$\eta(x_i,t_n) = 1 - \mathrm{IsFoam}(x_i,t_n)$$

Conductivity

MULTI-FM Simulation
Only heat conduction

OVERCRITICAL FOAM

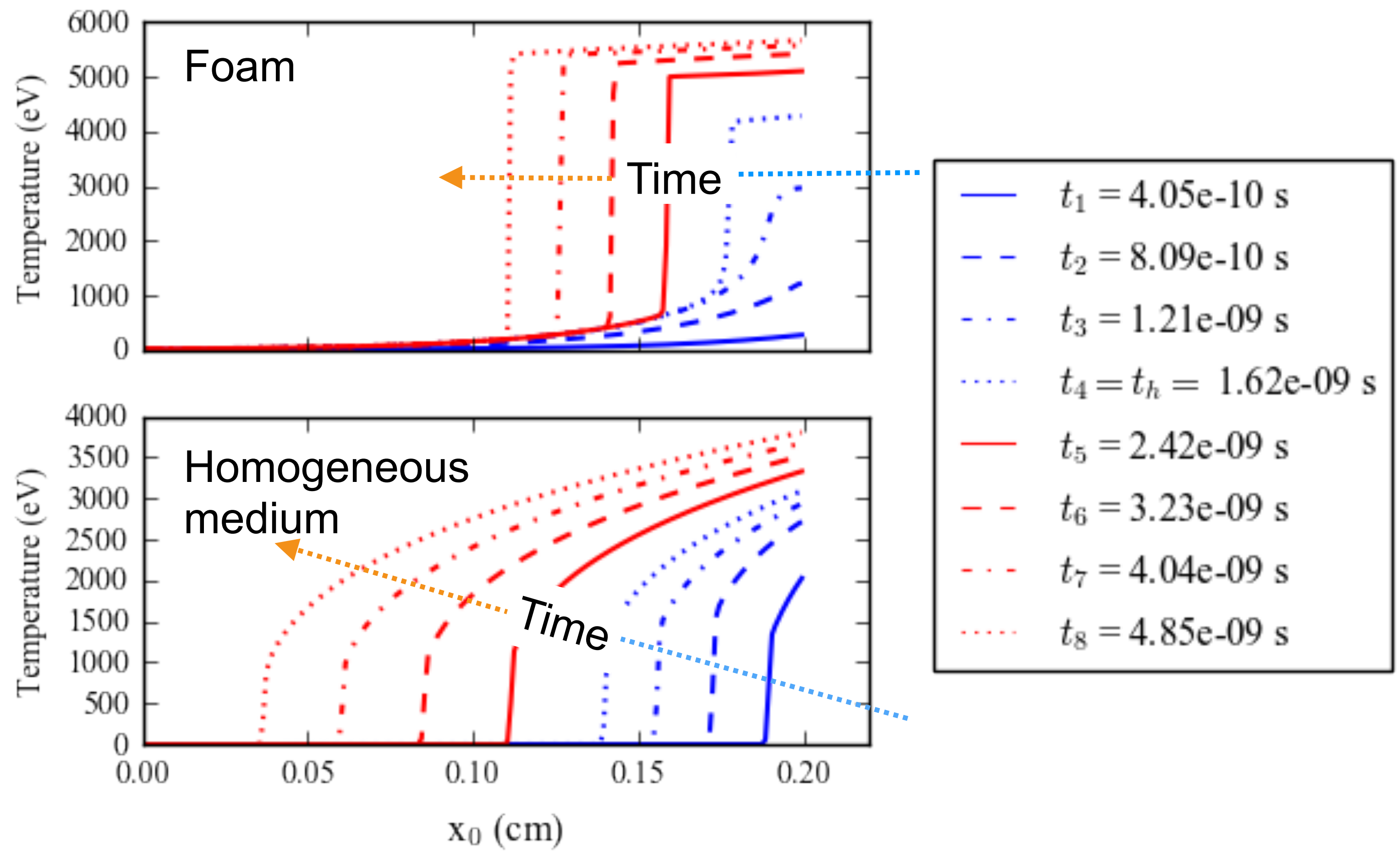
Parameters:

$$\rho_p = 10\ \mathrm{mg/cm^3}$$

$$\delta_0 = 40\ \mu m$$

$$\lambda_L = 1054\ \mathrm{nm}$$

Note:
The “**Homogeneous medium**” is a homogeneous medium with the same density and chemical composition of the foam



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MULTI-FM implementation: response to pressure gradients

The response to pressure gradients in the homogenization region is affected by the homogenization process of the foam plasma

The effect is approximated by the formula

$$\frac{\partial}{\partial t} v(x_i, t_n) = -\eta(x_i, t_n) \frac{\partial}{\partial m} P(x_i, t_n) \qquad \eta(x_i, t_n) = 1 - \mathrm{IsFoam}(x_i, t_n)$$

MULTI-FM Simulation - Only hydrodynamics

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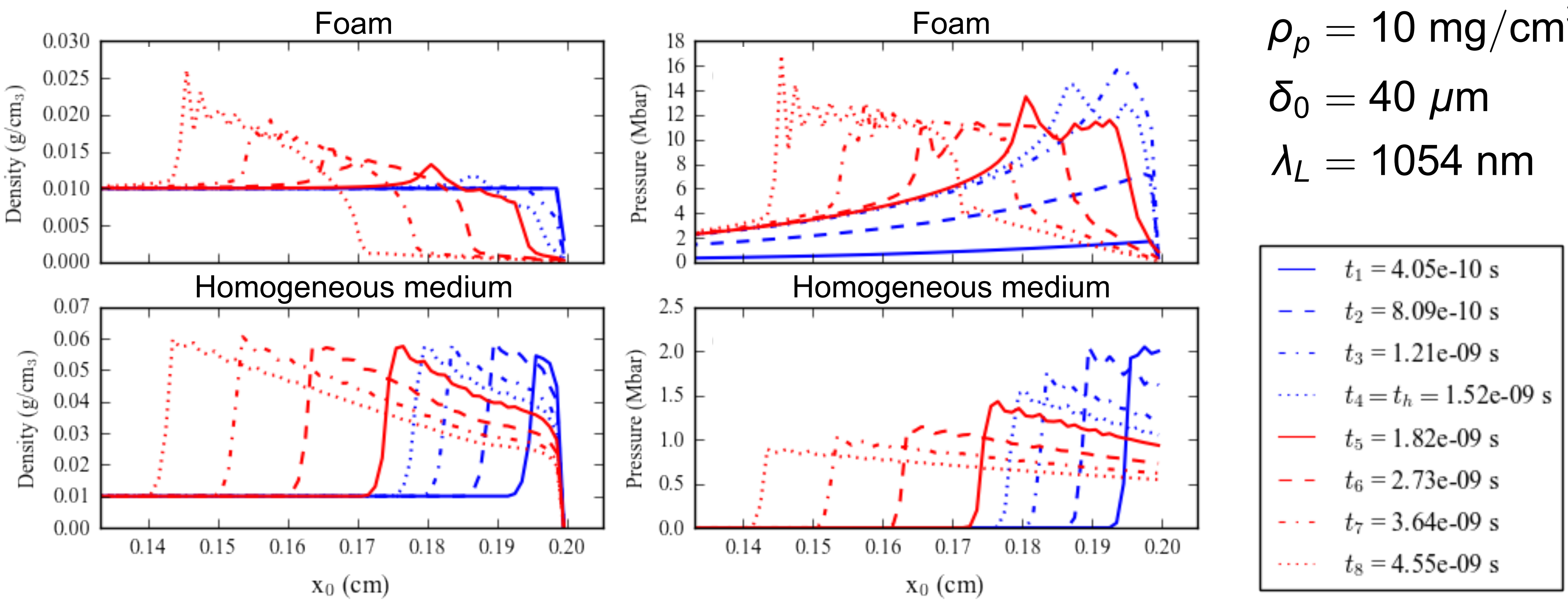

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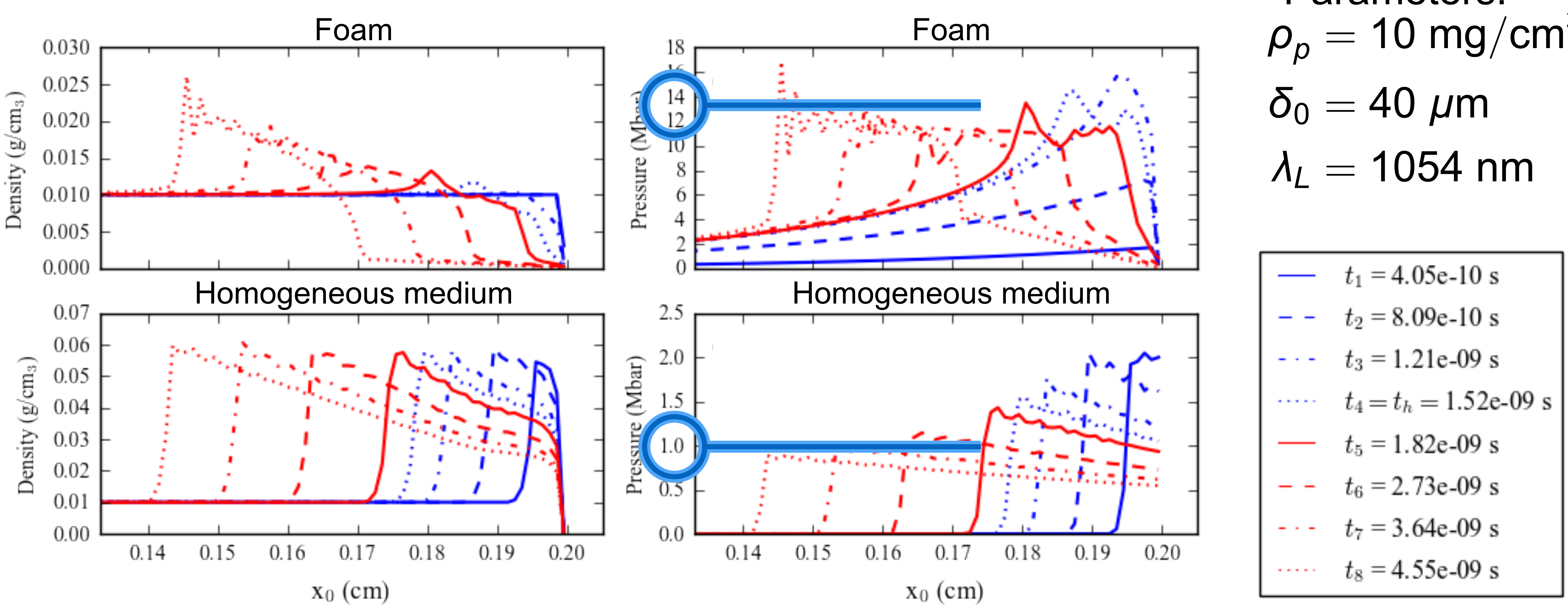

Overcritical foam

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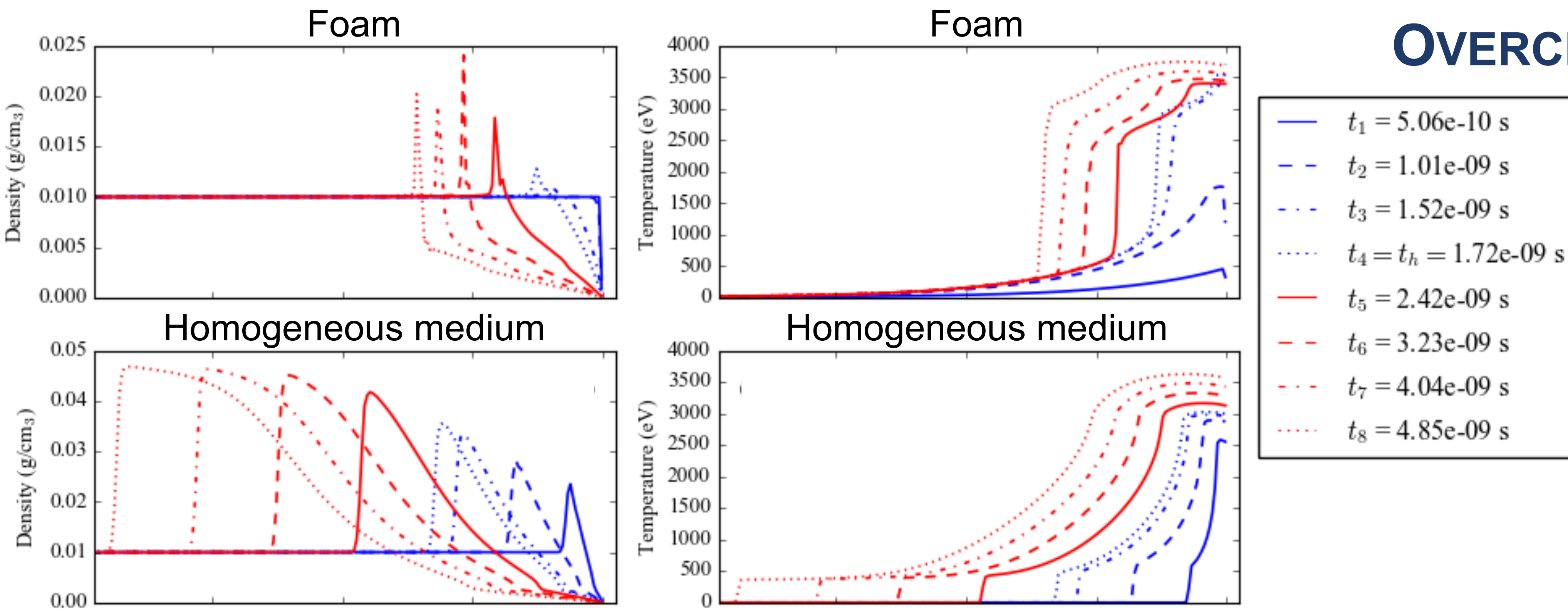
Complete simulation: Large pore foam



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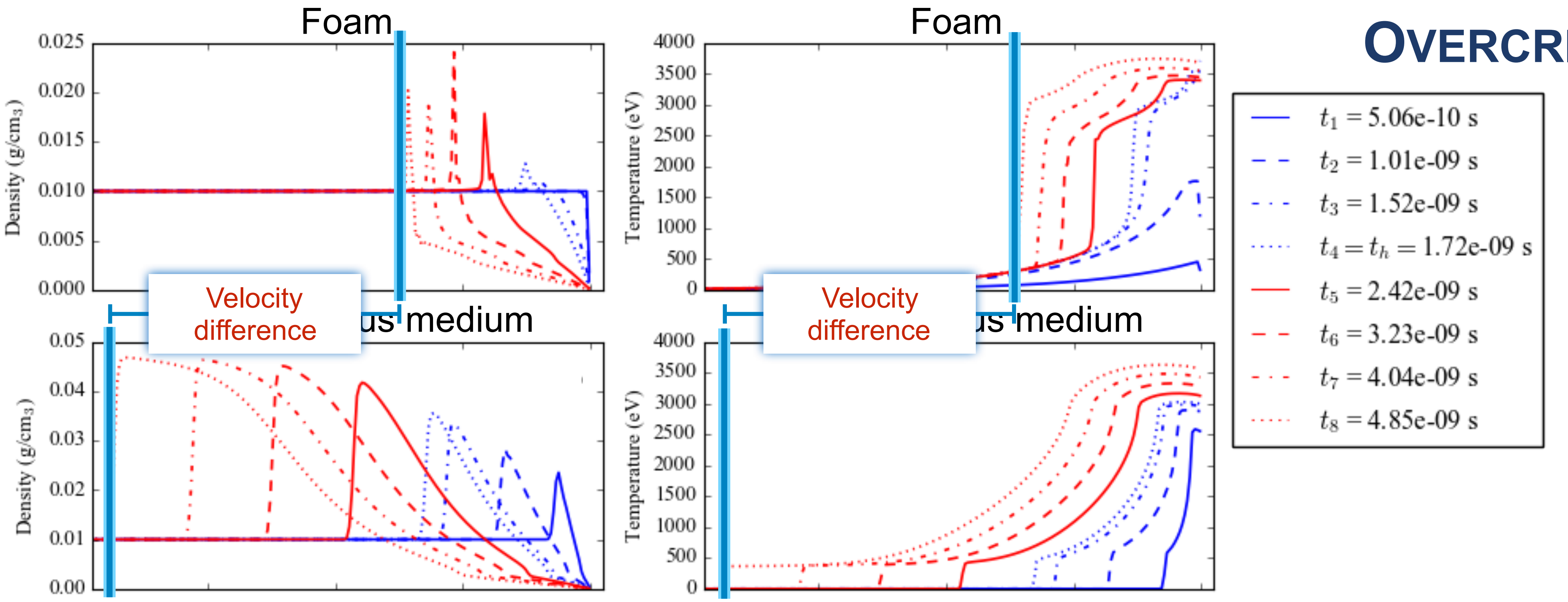

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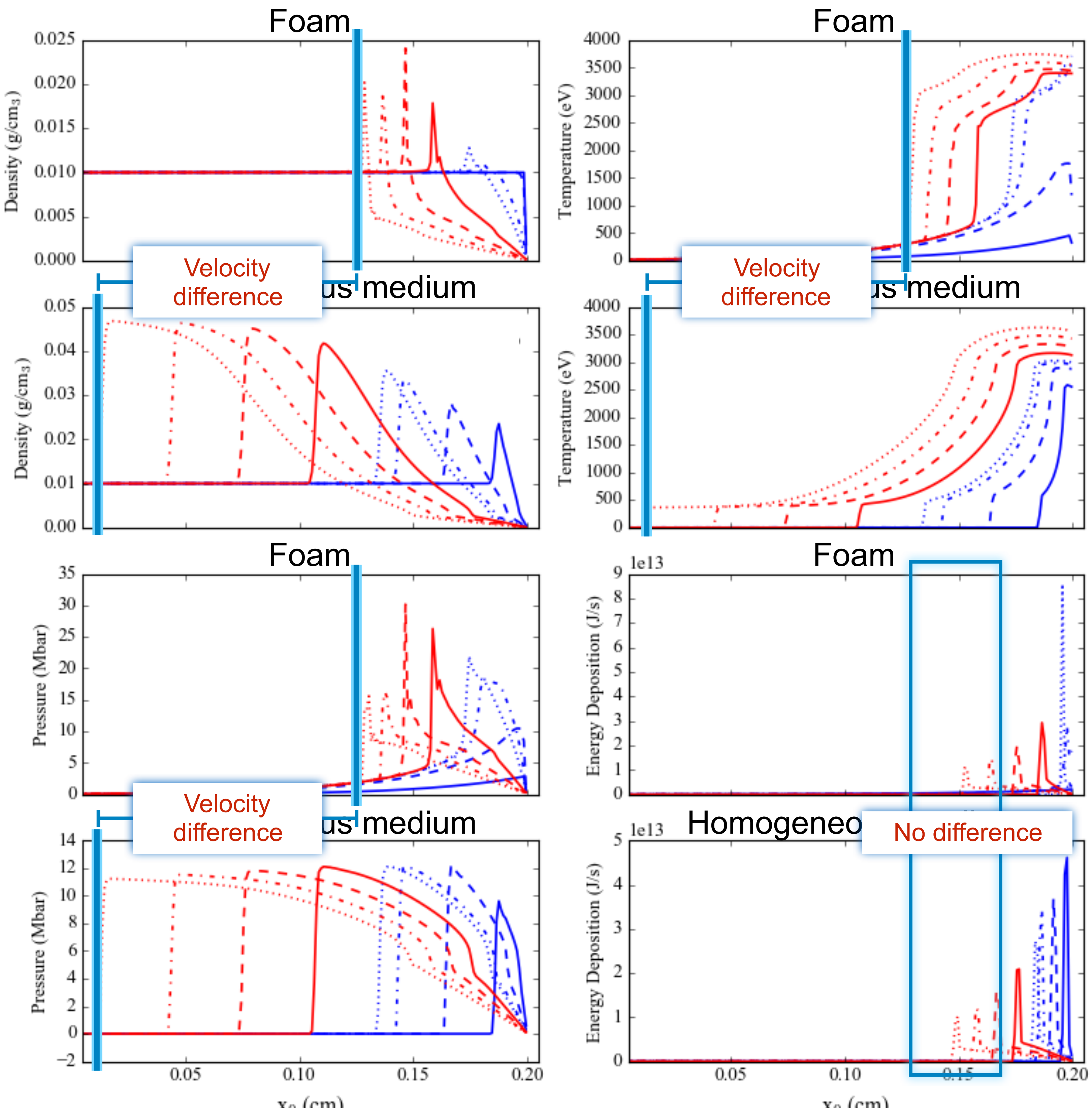

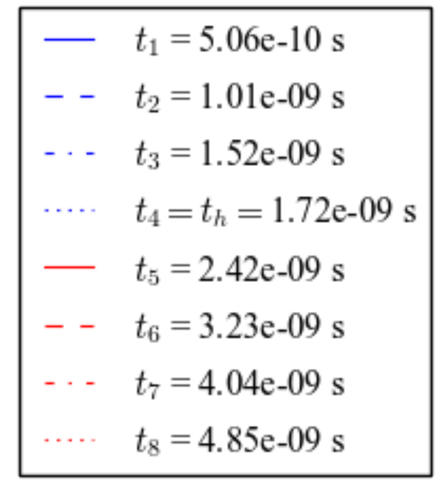

OVERCRITICAL FOAM

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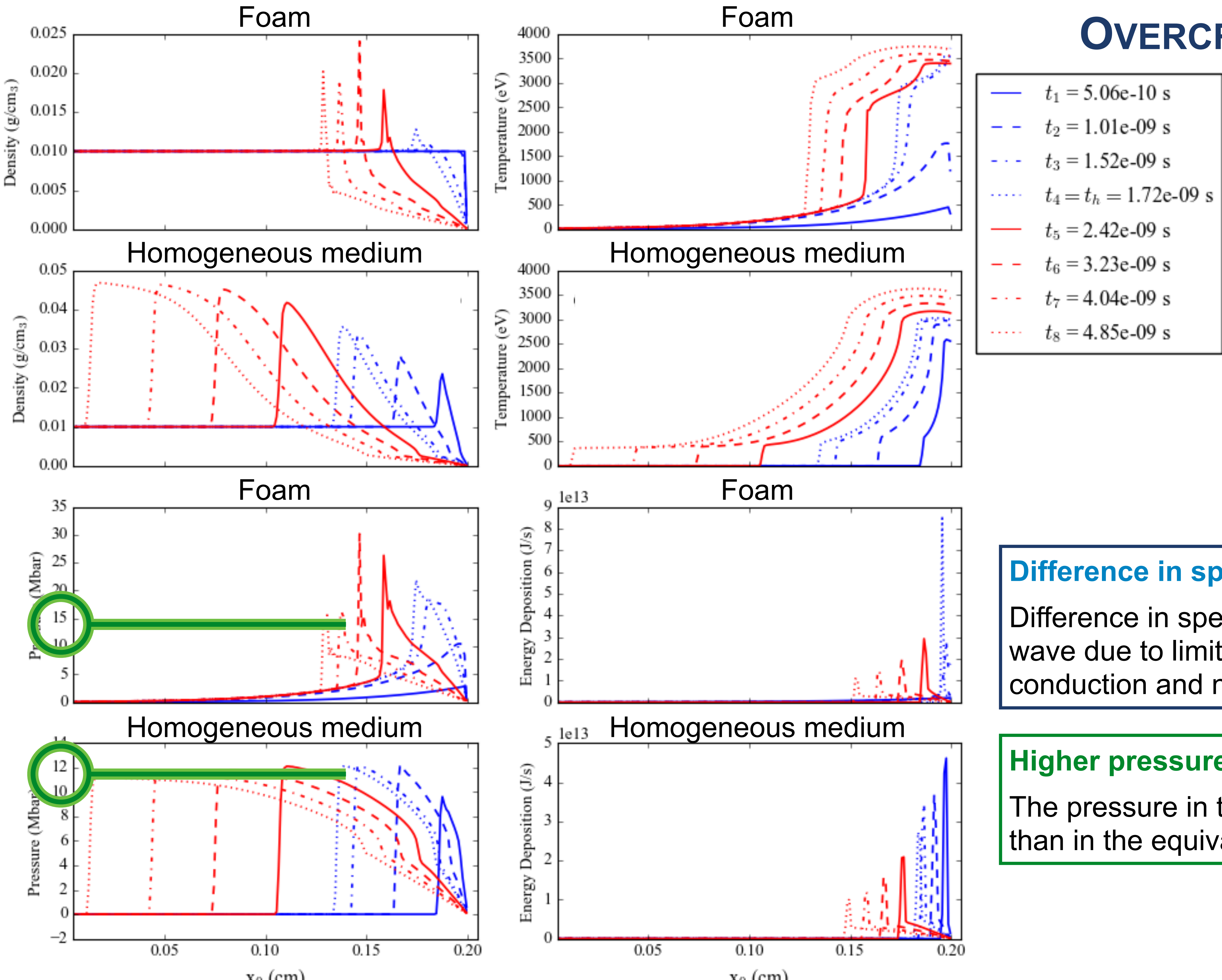
Difference in speed:

Difference in speed of the hydrothermal wave due to limitation on the heat conduction and not to absorption features

Complete simulation: Large pore foam



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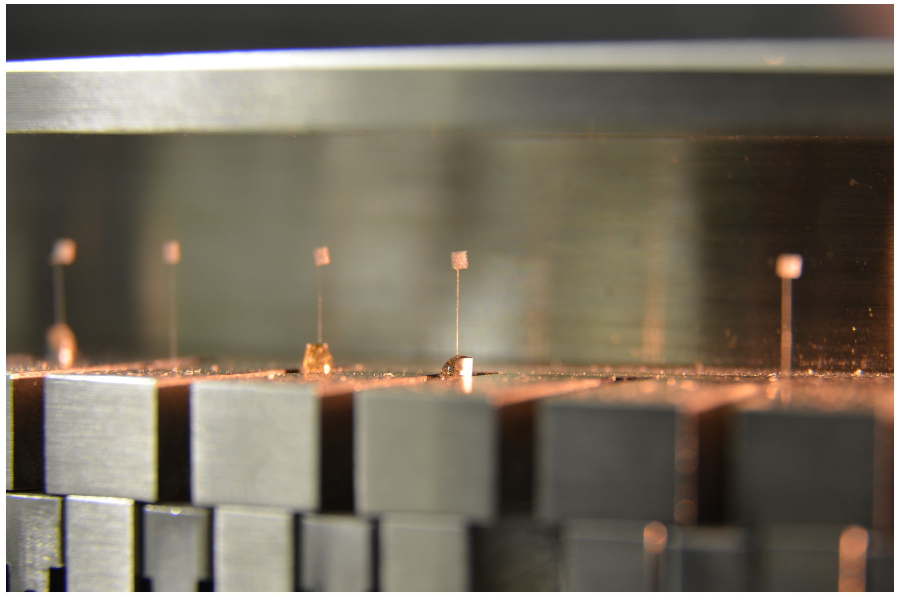
Higher pressure:

The pressure in the foam target is larger than in the equivalent homogeneous target

ABC laser at ENEA Frascati

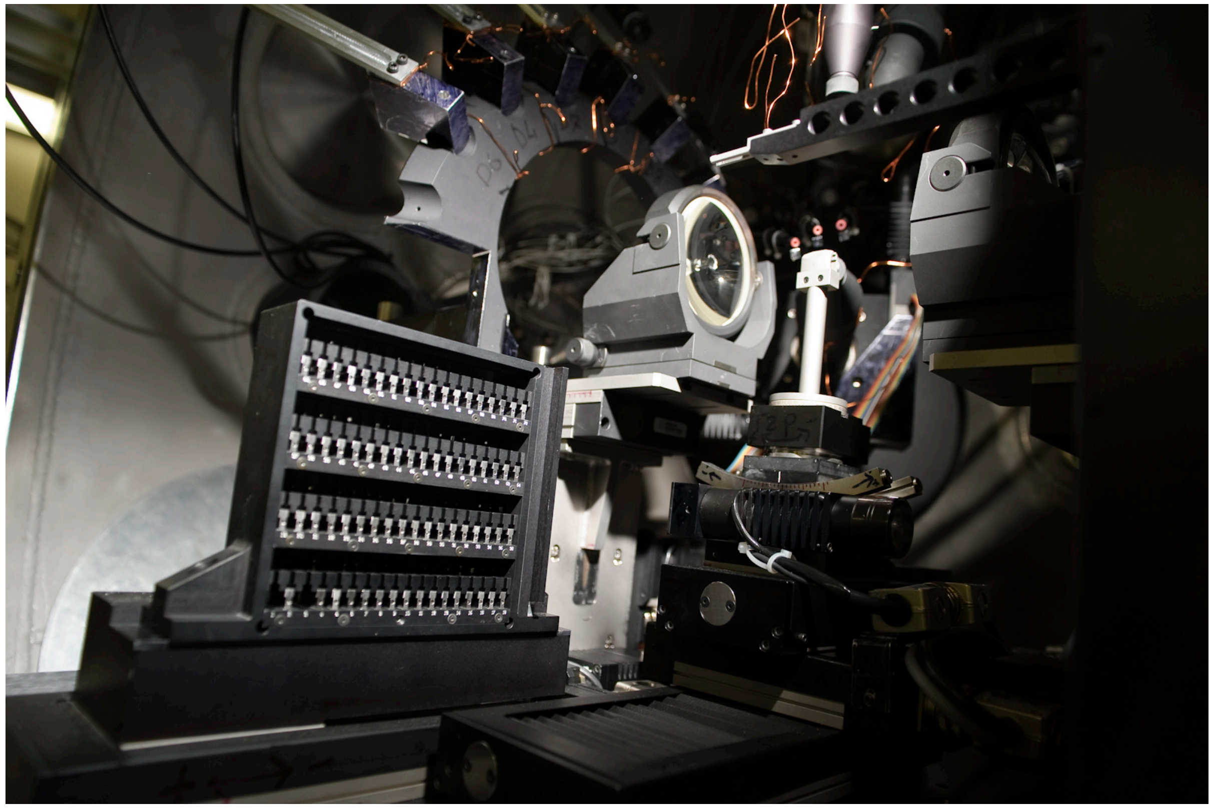
ABC is at **ENEA CR Frascati**

- Neodimium-phosphate glass laser
- Two counter propagating beams
- Up to 100 J in 3 ns per beam
- Up to 10^{15} W/cm^2 intensity



Targets

Laser room



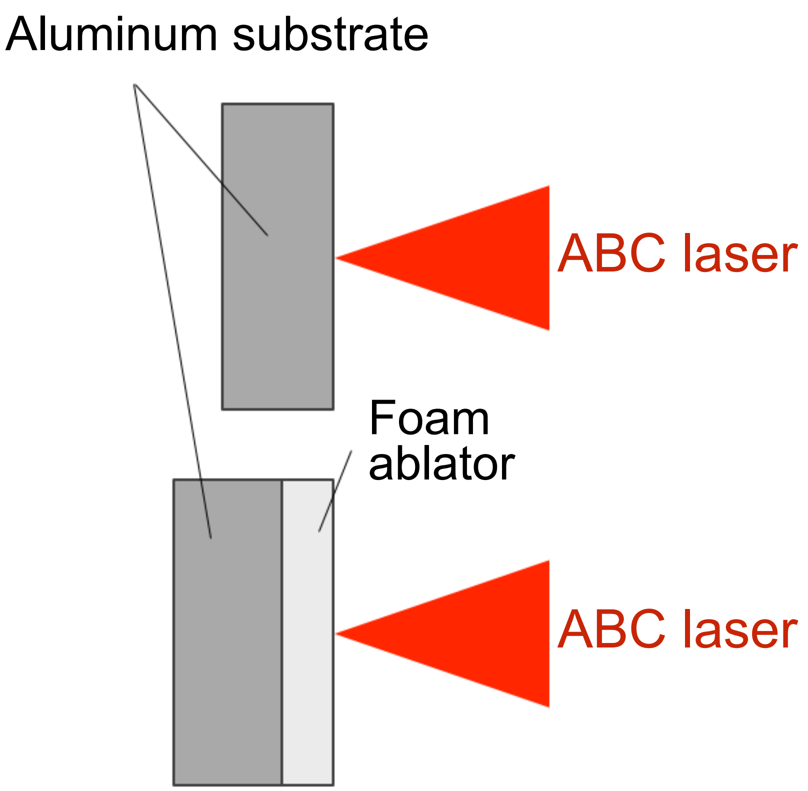
Internal of the experimental chamber

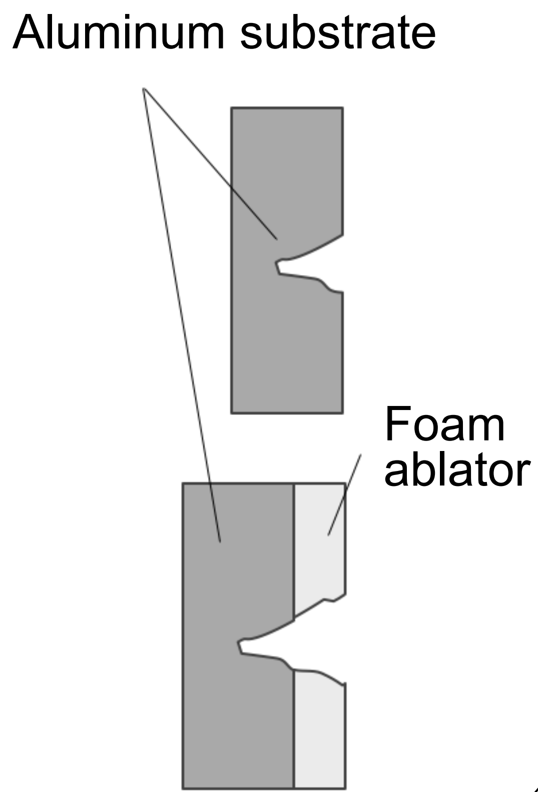
Ablation loading: energy transfer via crater volume

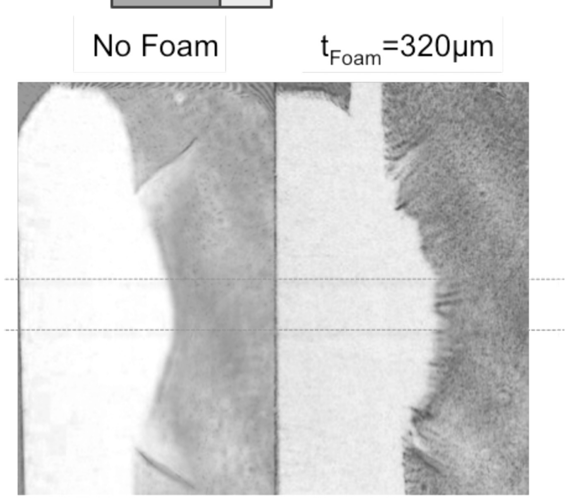
[R. De Angelis et al., *Phys. of Plasmas* **22** 072701 (2015)]

Experiment at **ABC**: thick aluminum substrate irradiated with and without a foam cover

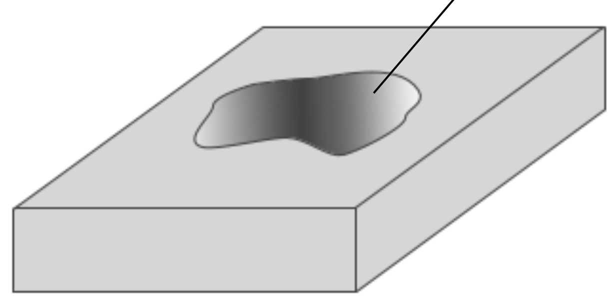
⇨ Measure the change in **ablation loading** and **energy transfer**

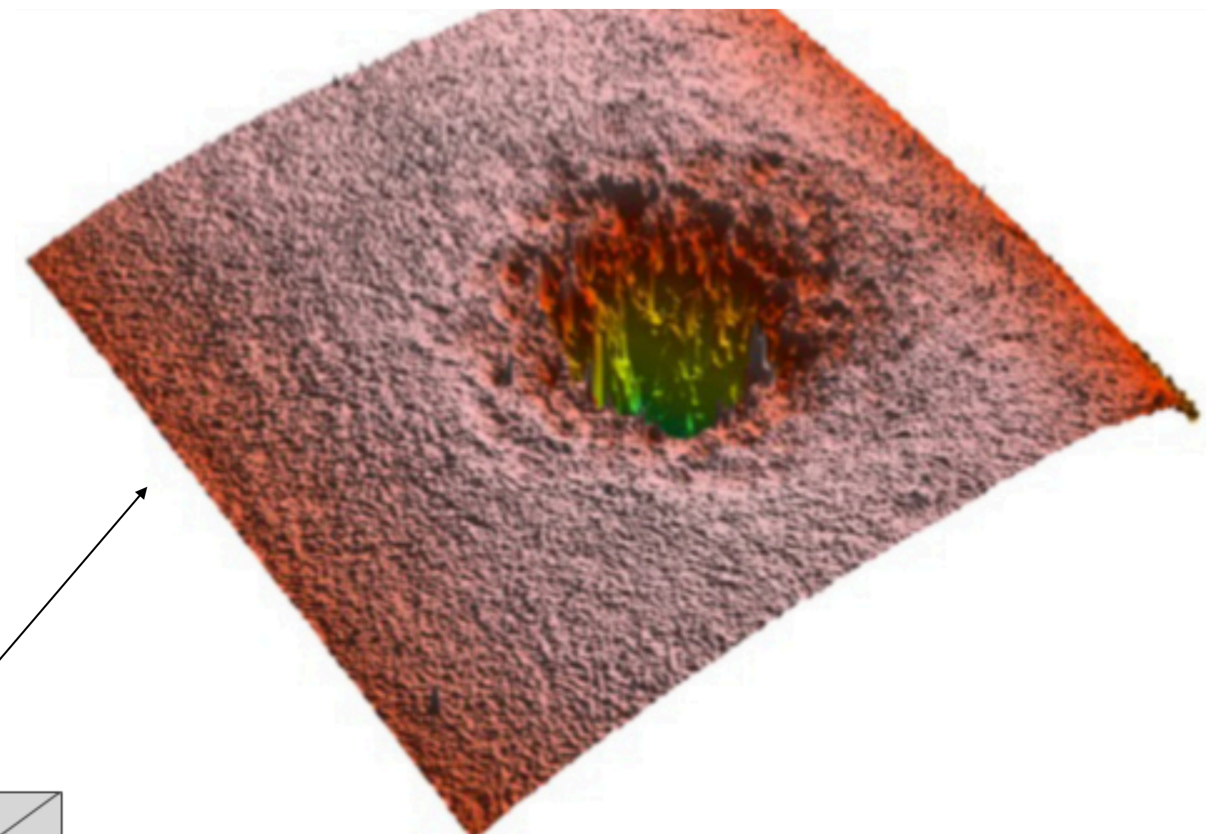






Shadowgraphy





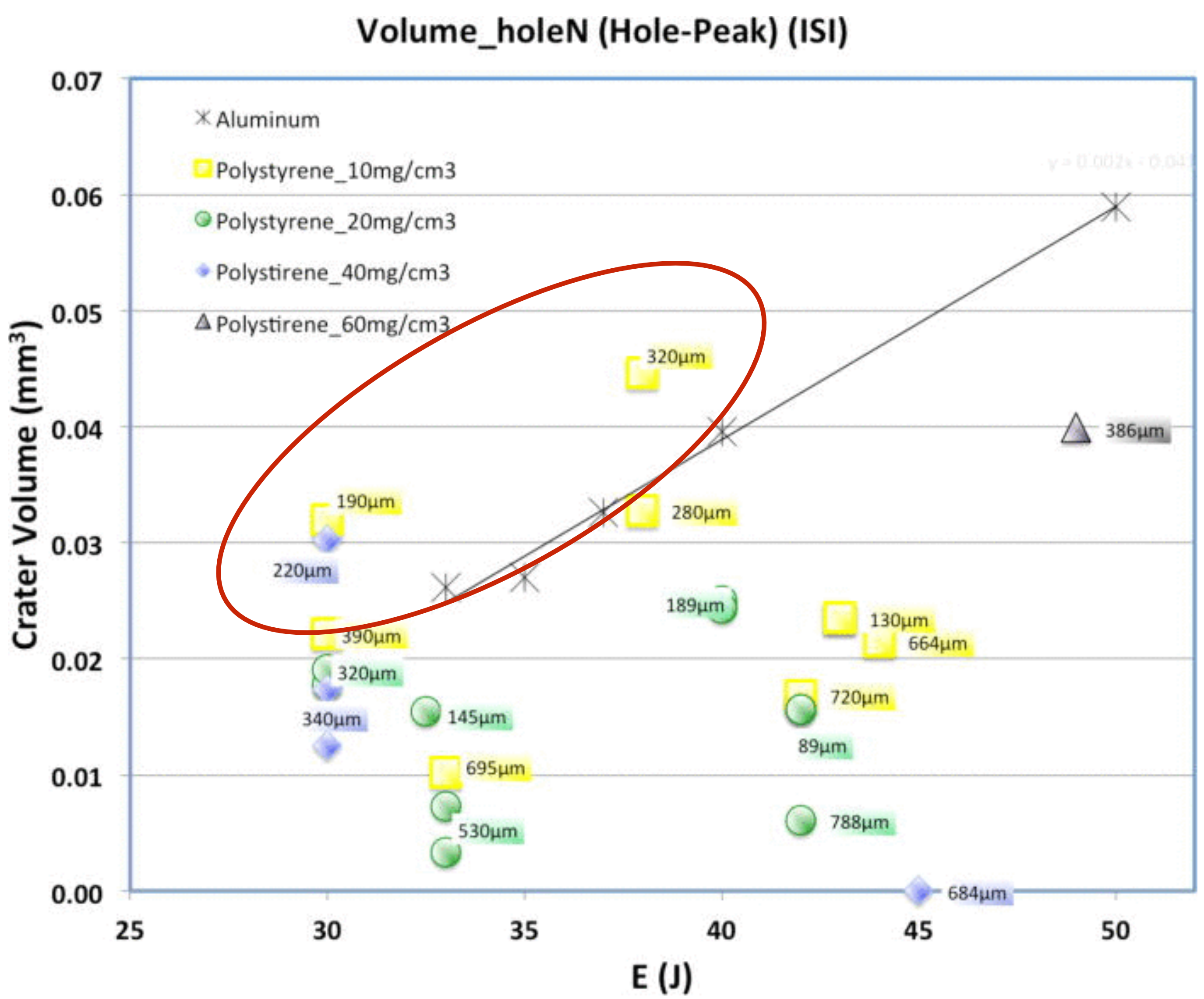
Confocal microscope image (shot #1117)

The crater volume is related to the amount of laser energy transferred to the material

Ablation loading: energy transfer via crater volume

[R. De Angelis et al., *Phys. of Plasmas* **22** 072701 (2015)]

The results suggest for given laser energy **optimal combinations** of thickness and density at which the **energy transfer is more efficient**



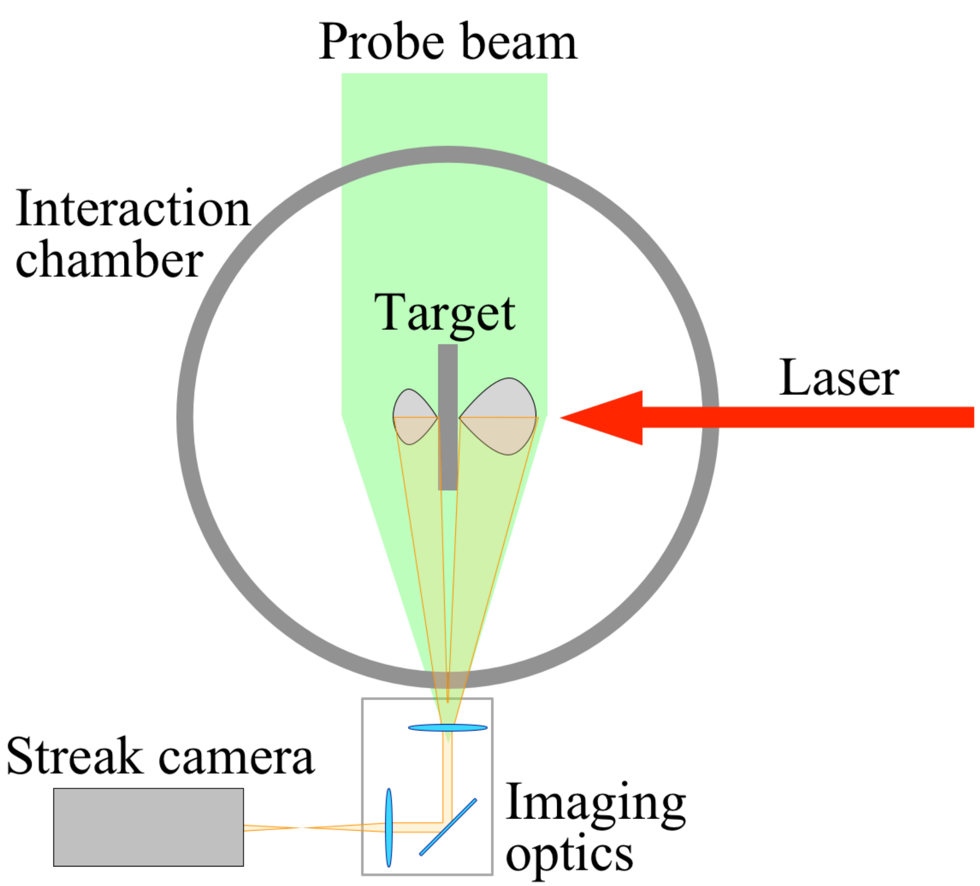
To be investigated in the near future with MULTI-FM simulations

Hydrothermal wave speed: measurements at ABC

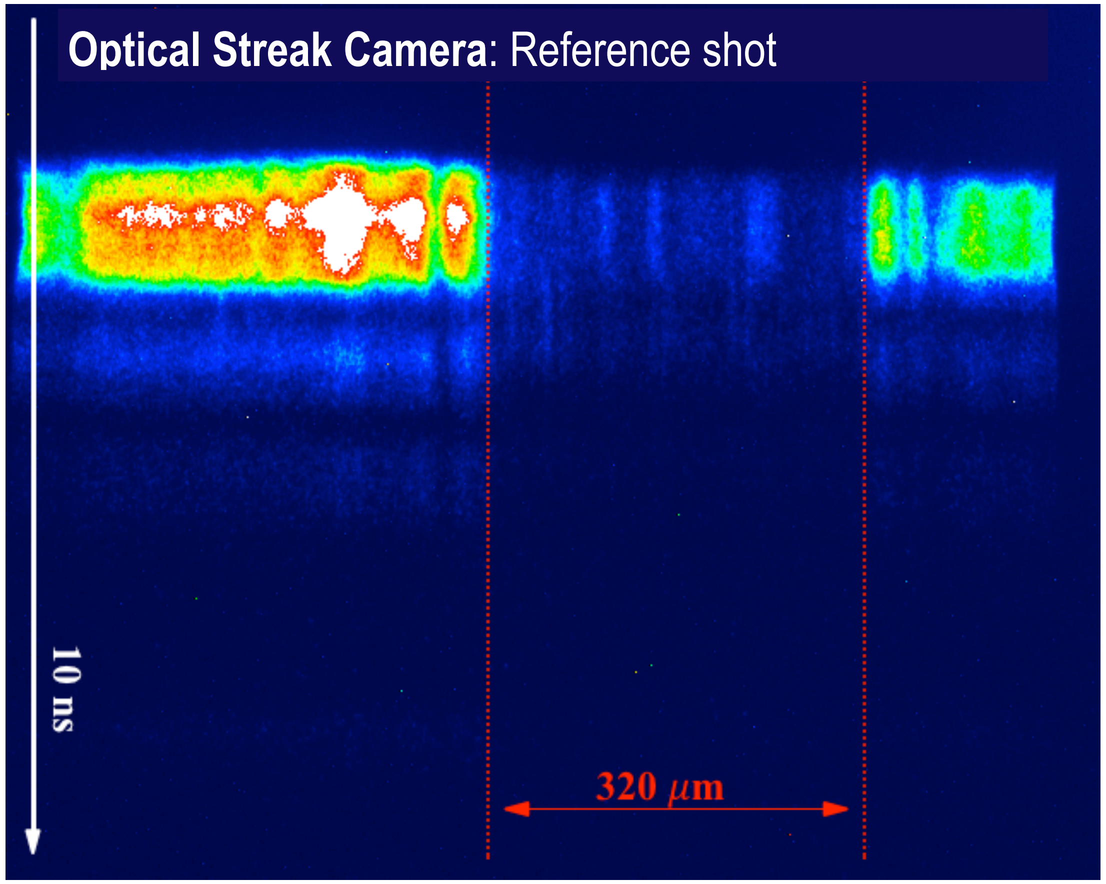
[**Mattia Cipriani** et al., *Phys. Plasmas* **25** 092704 (2018) - Editor's Pick]

Experiments at ENEA ABC installation on overcritical foams:

The speed of the hydrothermal wave in the foam measured via optical streak camera images



Experimental setup



$I = 2 \cdot 10^{14} \mathrm{W/cm^2}$

Thickness $= 320\ \mu m$

$t_L = 3$ ns, $\sin^2$ time profile

$\rho_p = 10\ \mathrm{mg/cm^3}$

$\delta_0 = 40\ \mu$m

$\lambda_L = 1054$ nm

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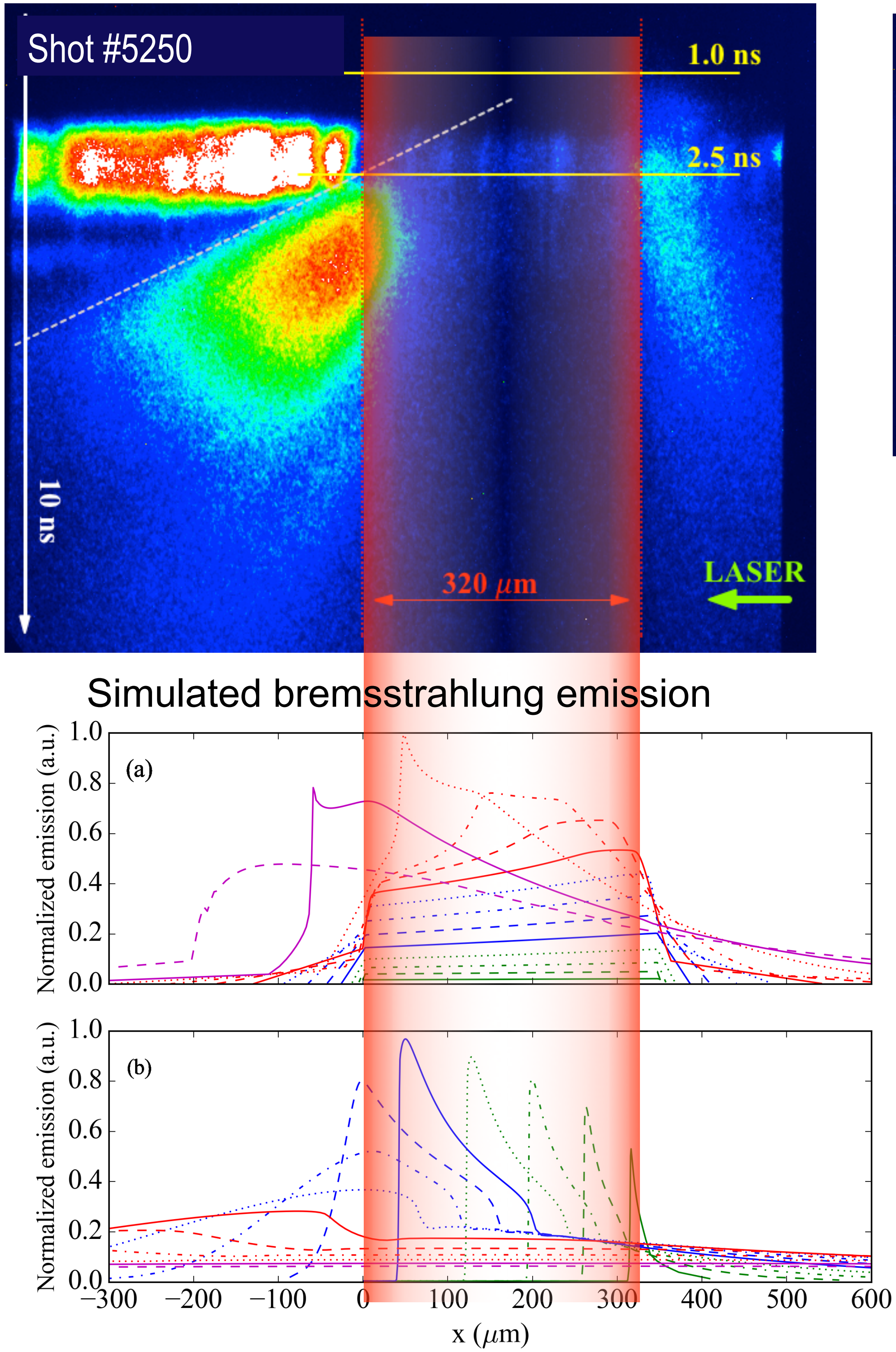

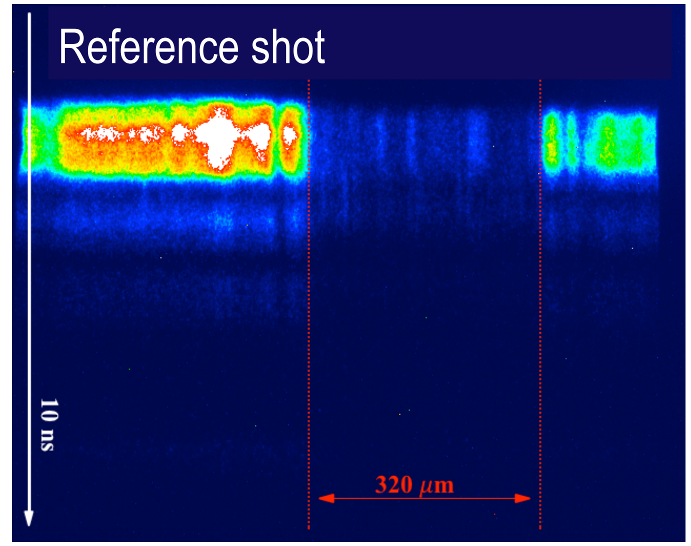

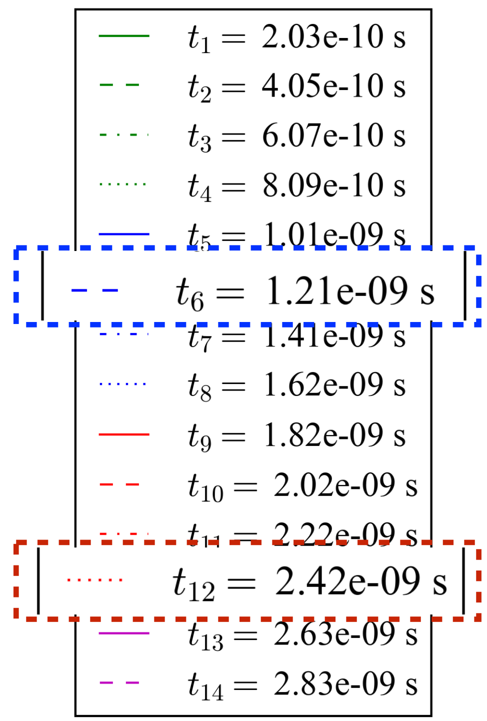

ENEA ABC Results

Shot #5251

Overcritical foam

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$t_L = 3$ ns, $\sin^2$ time profile

$\rho_p = 10\ \mathrm{mg/cm^3}$

$\delta_0 = 40\ \mu m$

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Homogeneous medium
Speed of the wave: 264 μm/ns

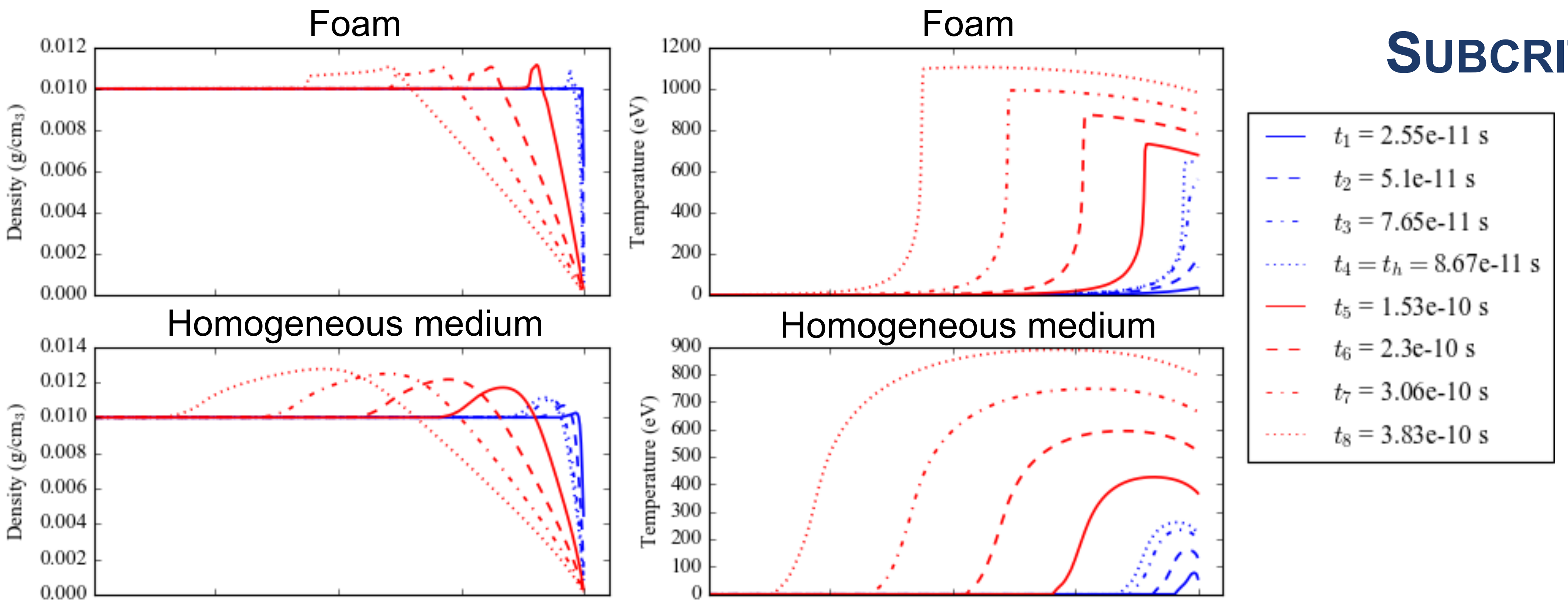
Foam medium
Speed of the wave: 132 μm/ns

Experimental result
Speed of the wave: (130 ± 40) μm/ns

Speed of the hydrothermal wave:

Good agreement between simulations and experiments at ABC

Complete simulation: Small pore foam



SUBCRITICAL FOAM

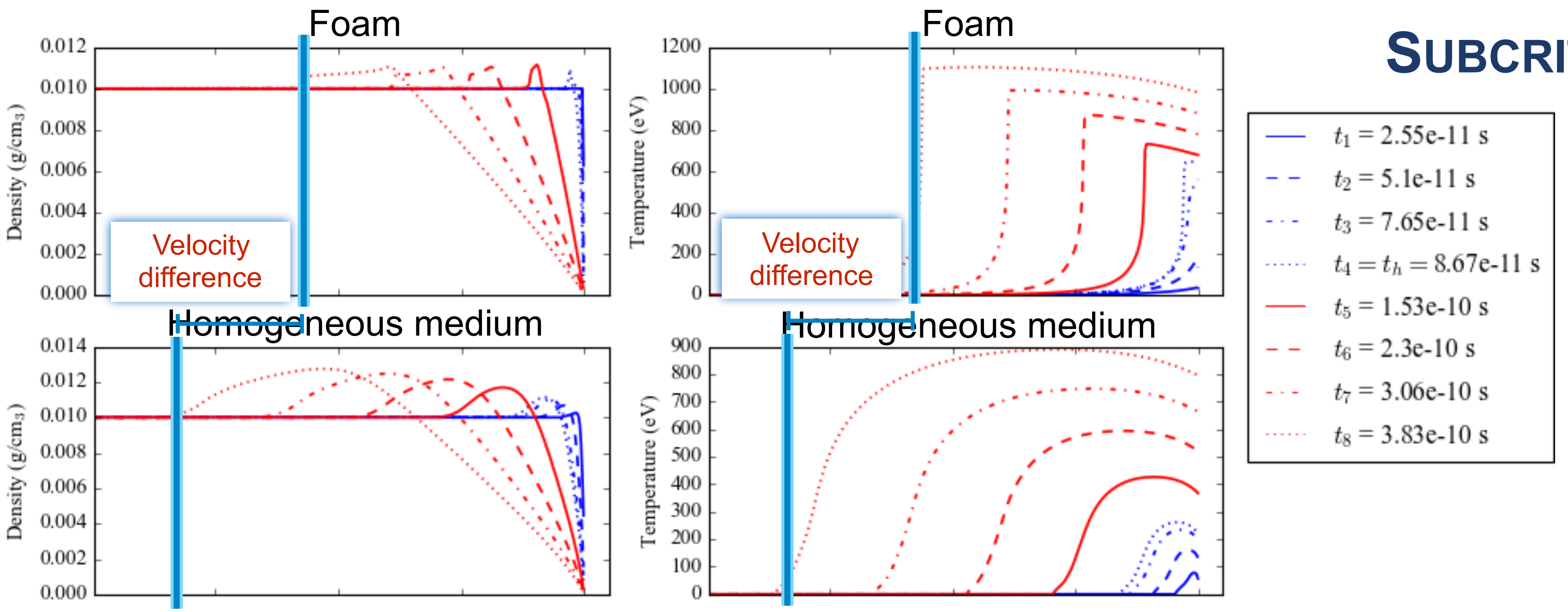
Parameters:

$\rho_p = 10\ \mathrm{mg/cm^3}$

$\delta_0 = 1\ \mu\mathrm{m}$

$\lambda_L = 351\ \mathrm{nm}$

Complete simulation: Small pore foam



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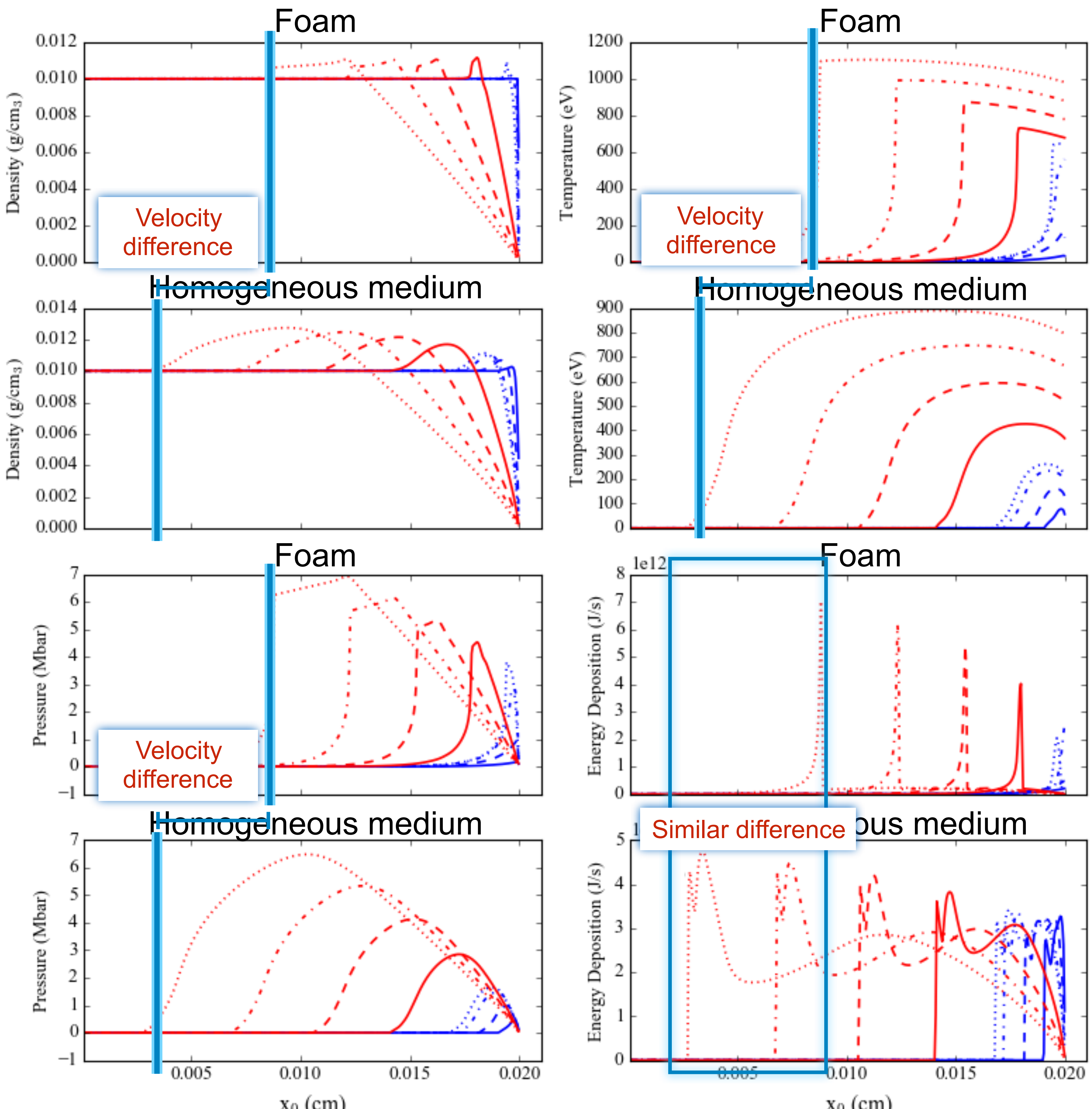

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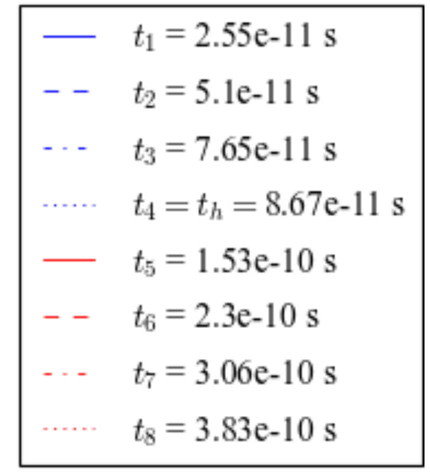

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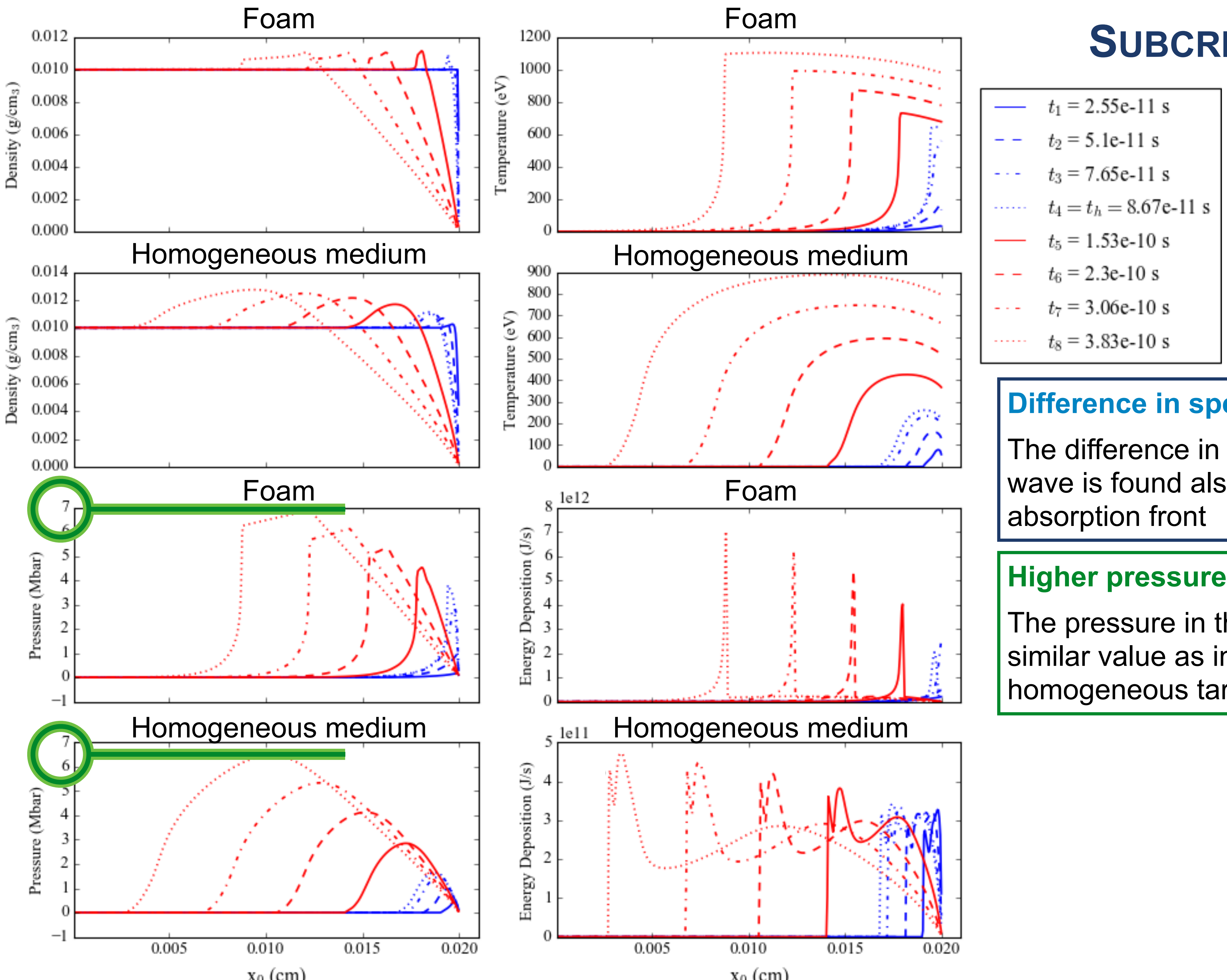
The difference in speed of the hydrothermal wave is found also in the speed of the absorption front

Complete simulation: Small pore foam



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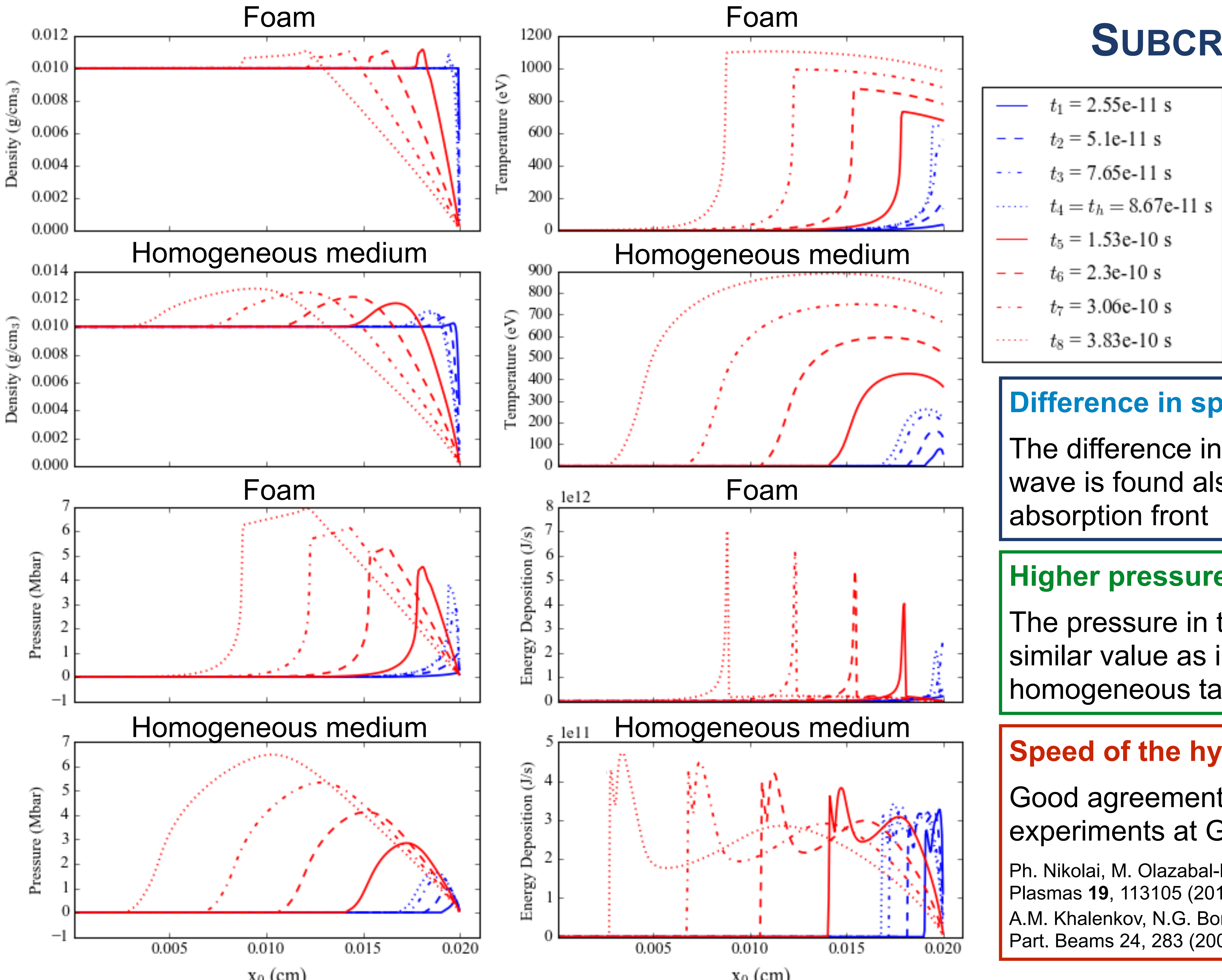

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Higher pressure:

The pressure in the foam target has a similar value as in the equivalent homogeneous target

Speed of the hydrothermal wave:

Good agreement between simulations and experiments at Gekko-XII and PALS

Ph. Nikolai, M. Olazabal-Loume, S. Fujioka et al, Physics of Plasmas **19**, 113105 (2012)
A.M. Khalenkov, N.G. Borisenko, V.N. Kondrashov et al, Las. Part. Beams 24, 283 (2006)

Complete simulation: Small pore foam

GEKKO-XII Results

[Ph. Nikolai et al., *Physics of Plasmas* **19** 113105 (2012)]

Parameters of the experiment

$$\rho = 10\,\text{mg/cm}^3$$
$$\delta_0 = 1\,\mu\text{m}$$
$$\tau_L = 3.4\,ns$$
$$I_L \simeq 3 \cdot 10^{14}\text{W/cm}^2$$

Measured hydrothermal wave speed

$$v_{w,exp} = 290\,\mu\text{m/ns}$$

Homogeneous medium hydrothermal wave speed

$$v_{w,sim} = 660\,\mu\text{m/ns}$$

MULTI-FM hydrothermal wave speed

$$v_{w,sim} = 490\,\mu\text{m/ns}$$

Complete simulation: Small pore foam

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PALS Results

[A.M. Khalenkov et al., *Las. Part. Beams* **24** 283 (2006)]

Parameters of the experiment

$\rho = 9\,\text{mg/cm}^3$

$\delta_0 = 1\,\mu\text{m}$

$\tau_L = 320\,ps$

$I_L \simeq 7 \cdot 10^{14}\text{W/cm}^2$

Measured hydrothermal wave speed

$$v_{w,exp} = 330\,\mu\text{m/ns}$$

Homogeneous medium hydrothermal wave speed

$$v_{w,exp} = 990\,\mu\text{m/ns}$$

MULTI-FM hydrothermal wave speed

$$v_{w,exp} = 740\,\mu\text{m/ns}$$

PALE hydrothermal wave speed

$$v_{w,exp} = 500\,\mu\text{m/ns}$$

Conclusions

The foam features have been implemented in the MULTI-FM code

- Volume laser absorption
- Low efficiency for heat conduction
- Low efficiency in responding to pressure gradients

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- Low efficiency in responding to pressure gradients

These are the main reasons for the slow down of the hydrothermal wave

- **Main physical result**: The pressure in the (overcritical) foam is larger than in an equivalent homogeneous medium

The foams have been studied experimentally at ABC

- The ablation loading efficiency is increased by using a foam as ablator
- The speed of hydrothermal wave propagation has been measured by optical diagnostics and is in good agreement with MULTI-FM simulations

Future developments

Future simulative developments:

- Improve the simulations for small-pores subcritical foams
- Simulate foam + substrate configurations as the ones used in many experiments
- Improve the approximations with better modeling
- Do the same implementation in a 2D code (such as MULTI-2D)

Future experimental developments:

- Improve the knowledge on ablation loading efficiency with other dedicated experiments
- Use additional diagnostics in hydrothermal wave speed measurements, such as X-ray streak camera…

The End

Thank you
for your attention

Contacts

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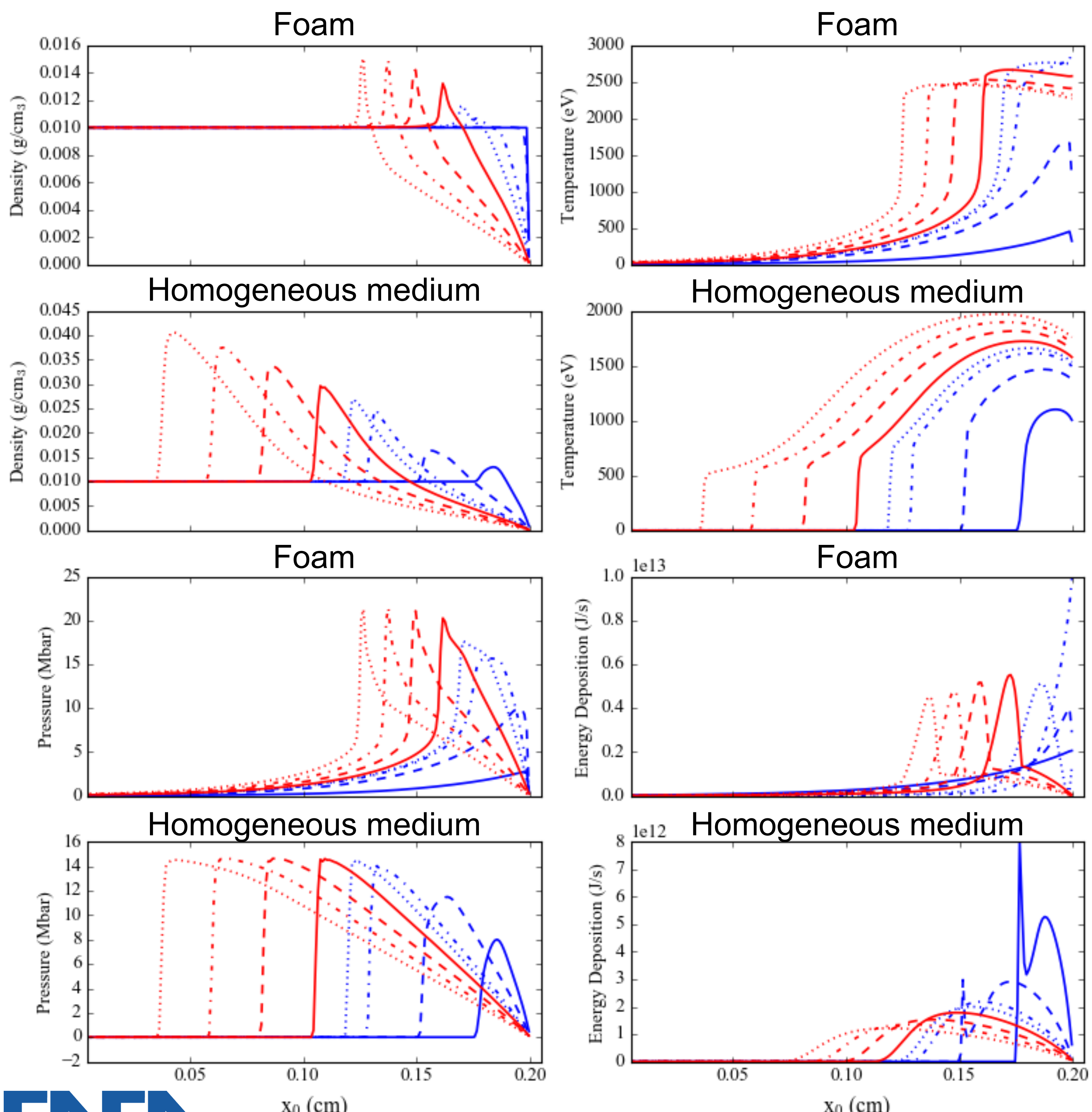
Backup

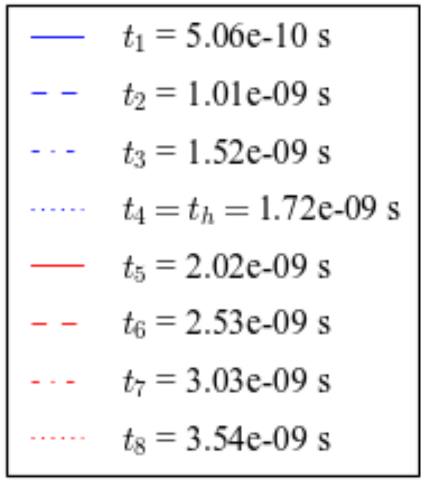
Backup slides

Complete simulation: Large pore foam

Complete simulation: Large pore foam



SUBCRITICAL FOAM



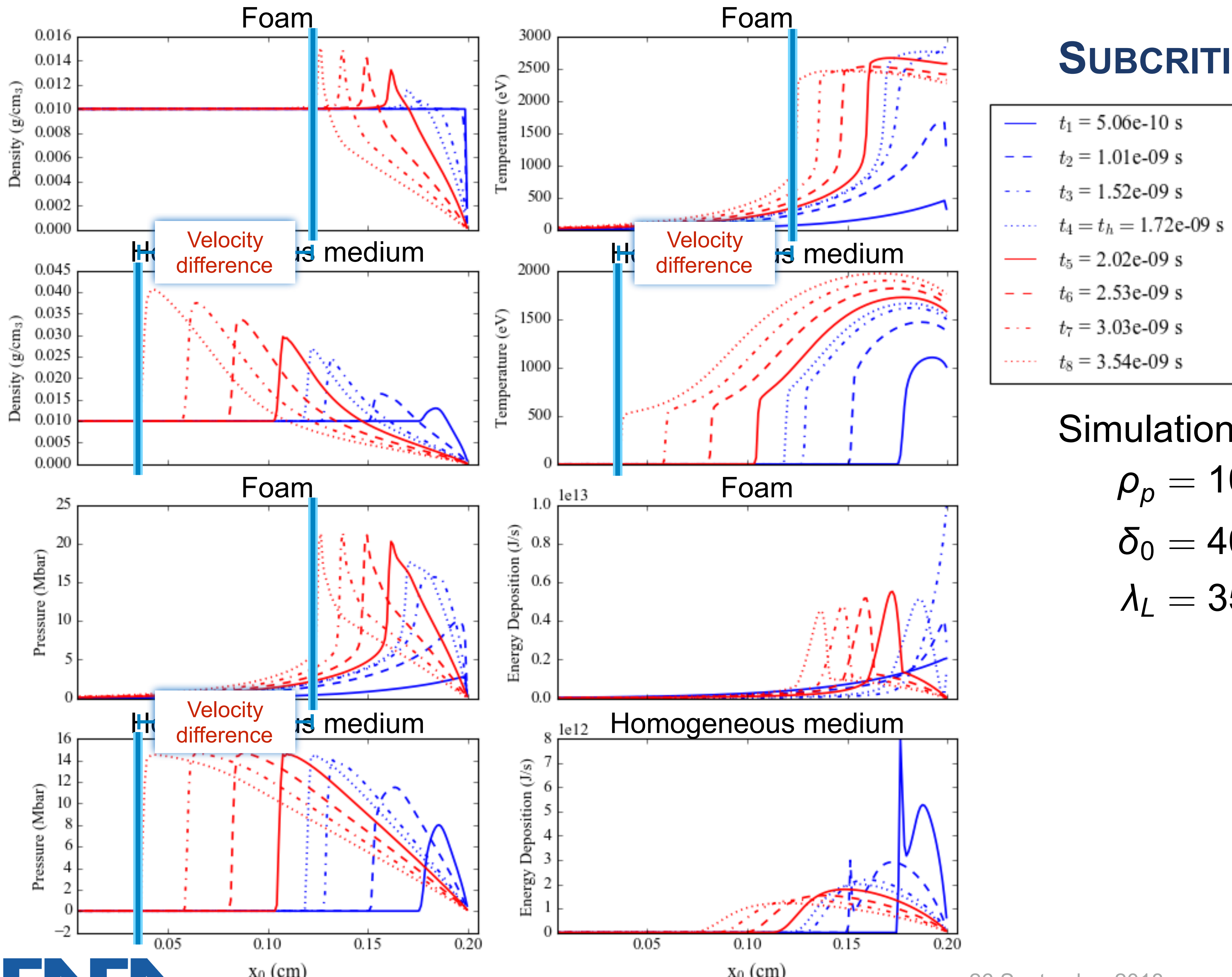
Simulation parameters:

$$\rho_p = 10 \text{ mg/cm}^3$$

$$\delta_0 = 40\ \mu\text{m}$$

$$\lambda_L = 351 \text{ nm}$$

Complete simulation: Large pore foam



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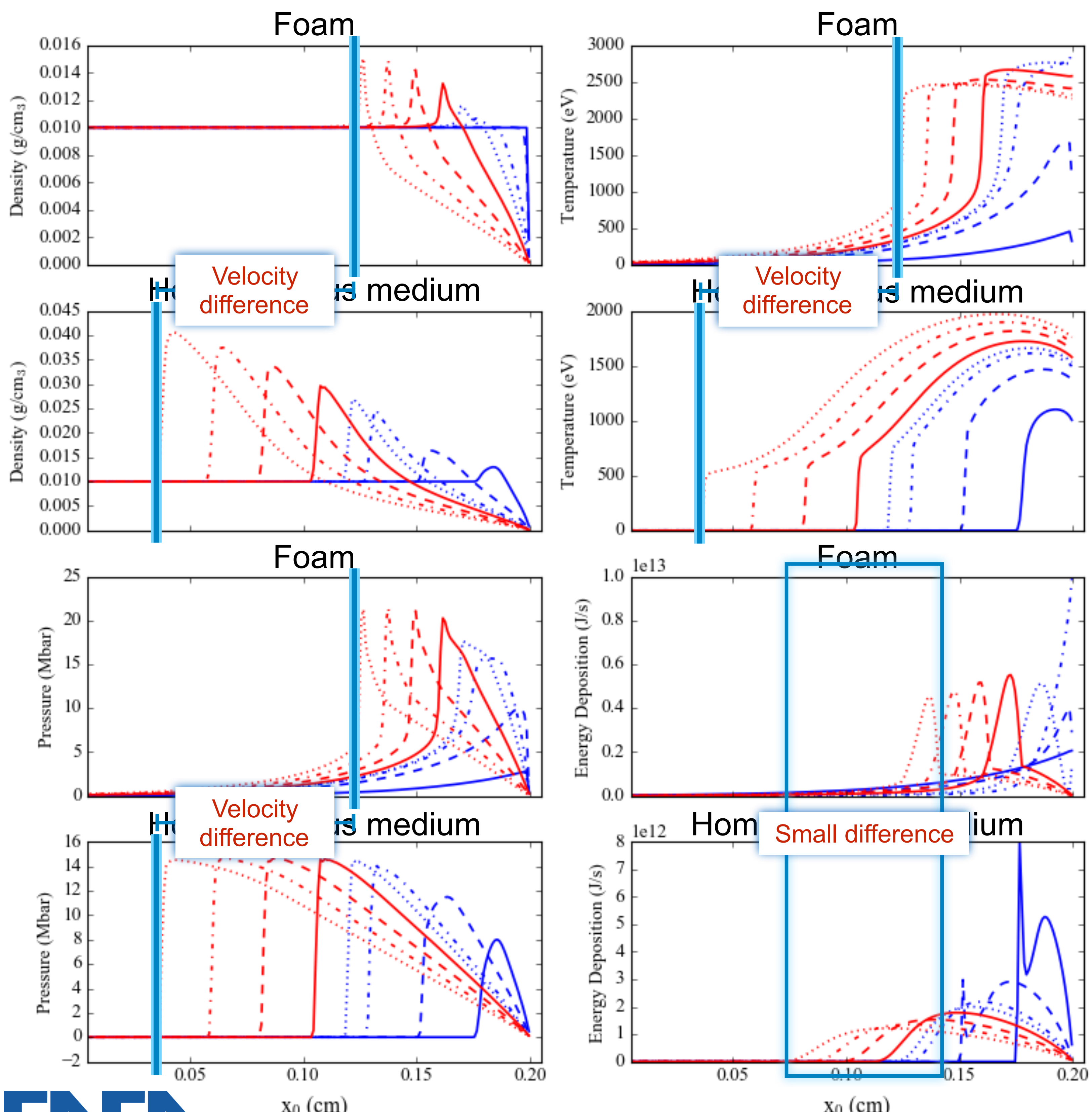
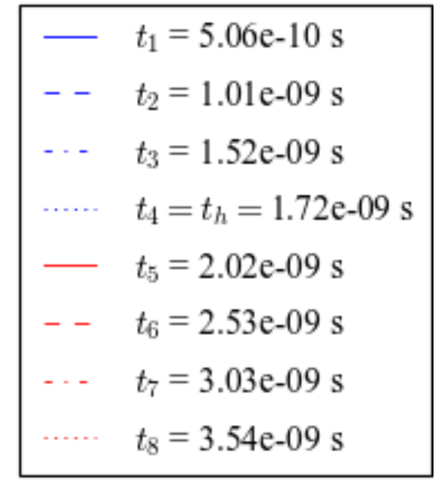


Subcritical foam



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Conclusion:

The difference in speed of the hydrothermal wave is mainly due to limitation on the heat conduction and not to absorption features

Complete simulation: Small pore foam

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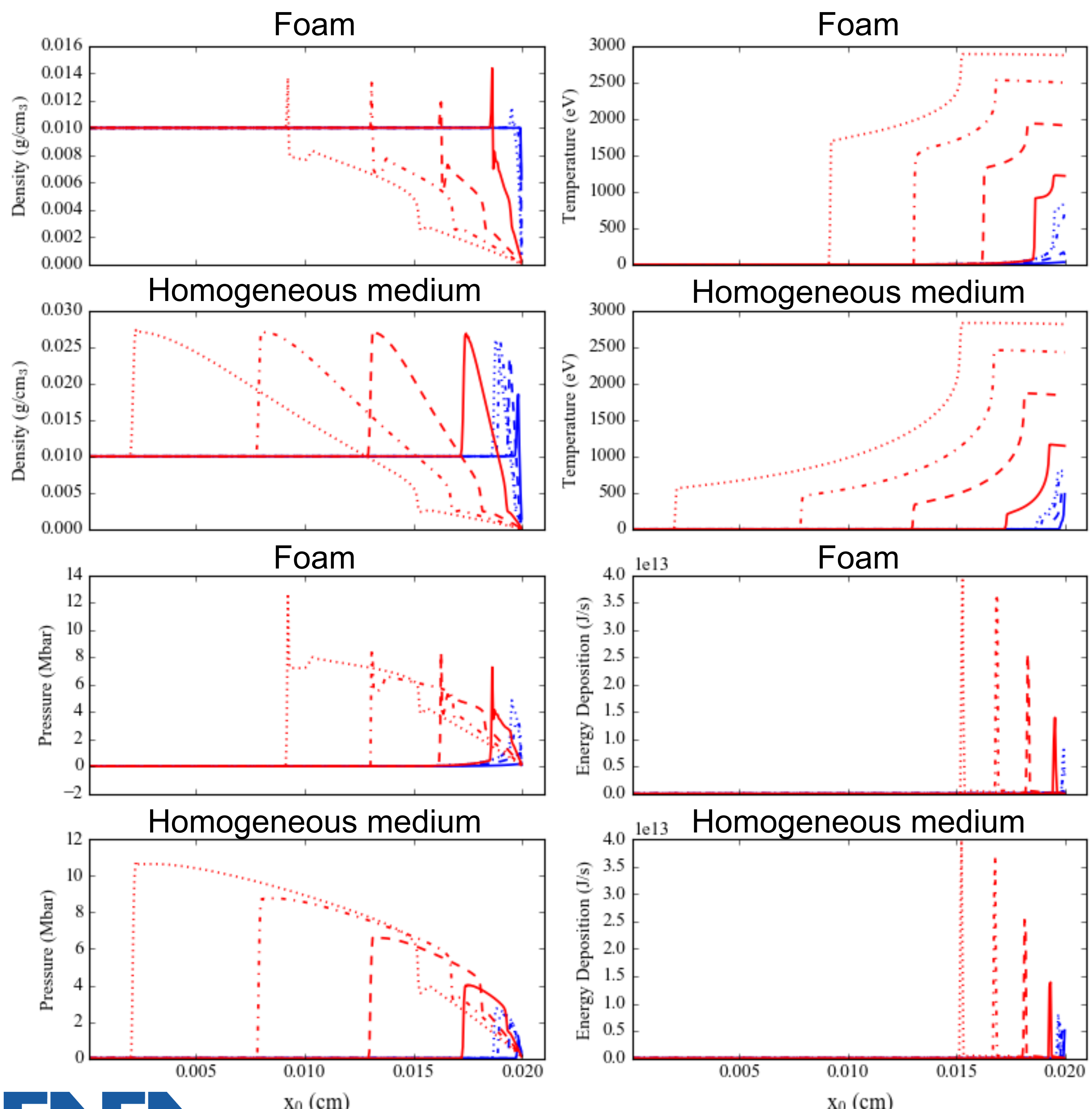
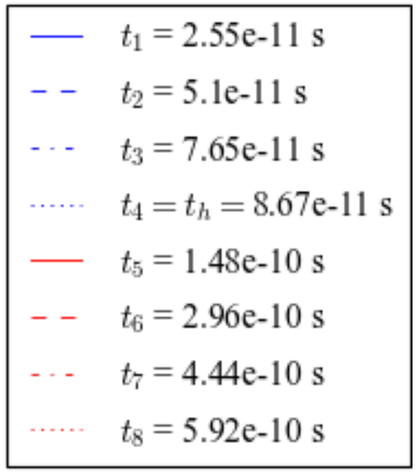


OVERCRITICAL FOAM



Simulation parameters:

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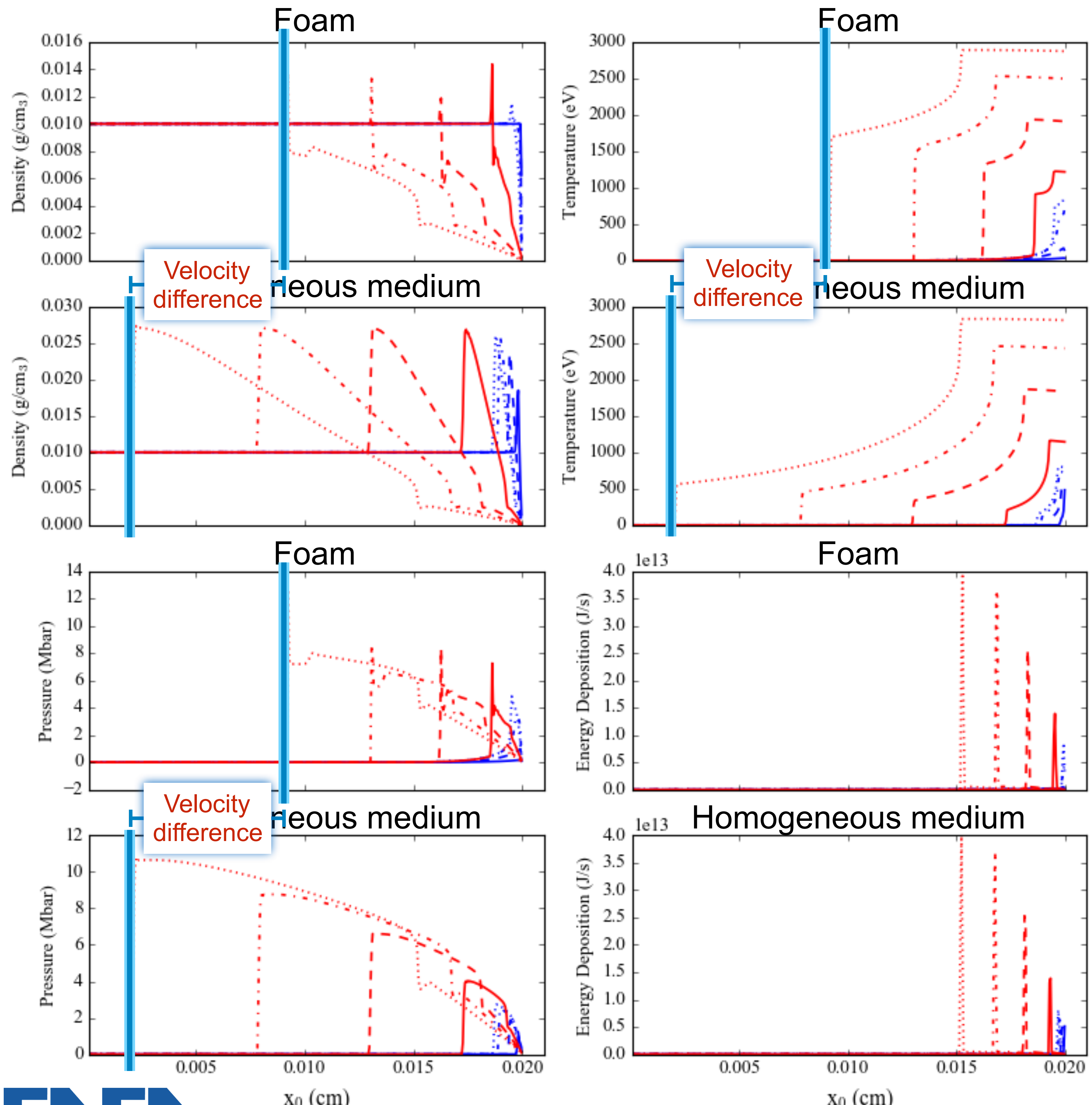
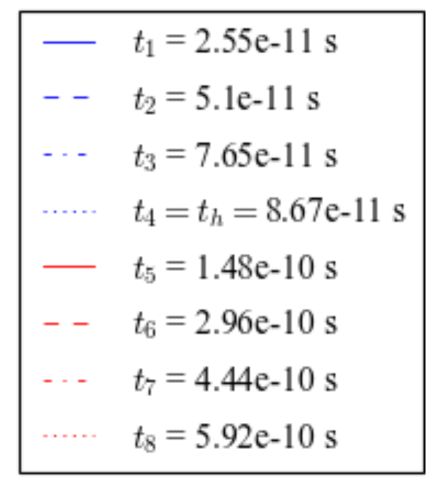
$$\delta_0 = 1\ \mu\text{m}$$

$$\lambda_L = 1054\ \text{nm}$$

Complete simulation: Small pore foam



OVERCRITICAL FOAM



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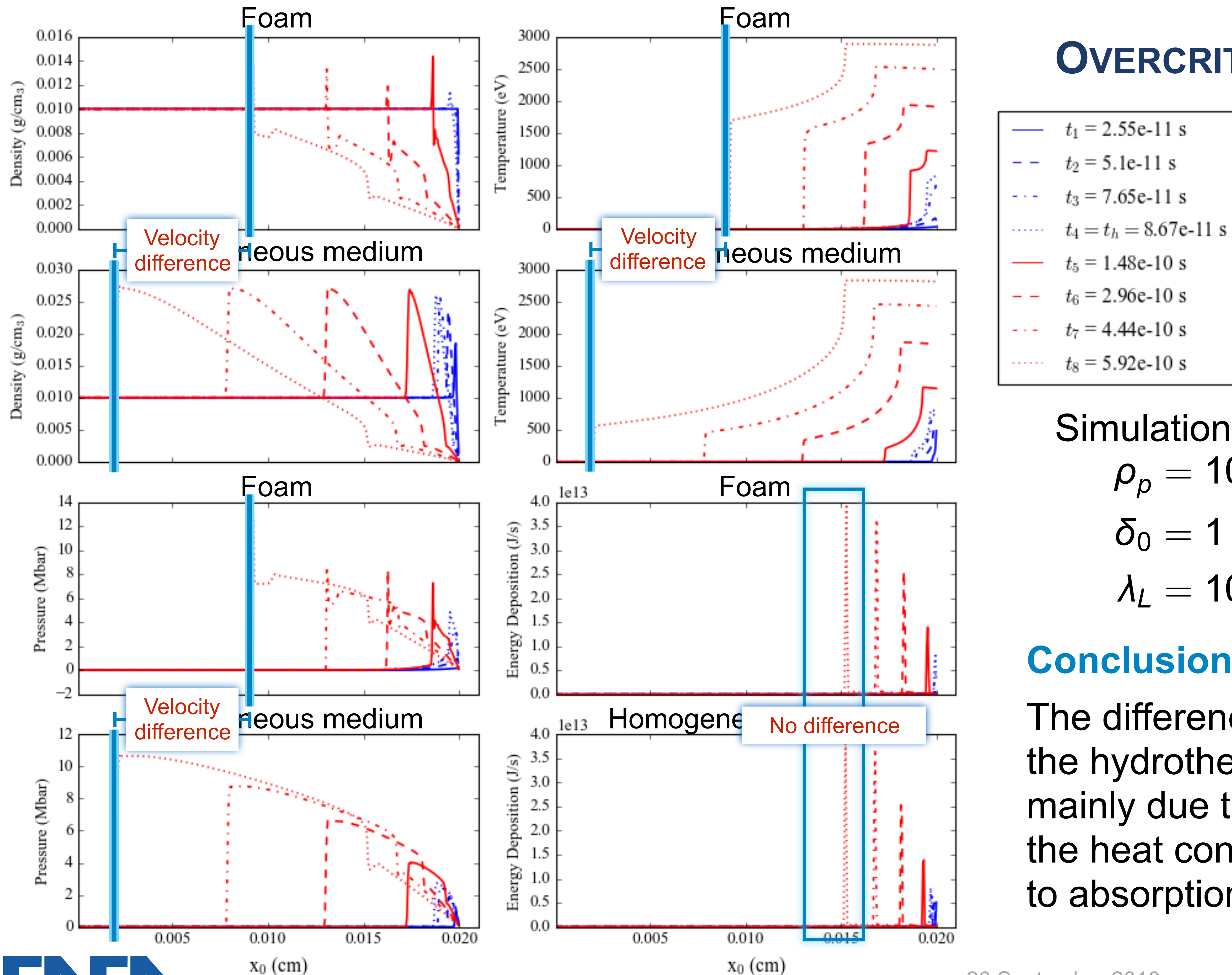

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