STUDY OF PROCESSES IN POLYMER TARGETS UNDER HIGH-ENERGY IMPACT

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Relevance

Materials:

- Polymers;
- Composites.

Application area:

- Aerospace industry;
- Nuclear and thermal power engineering;
- Pipeline transport.

Benefits:

- Strength;
- Weight.

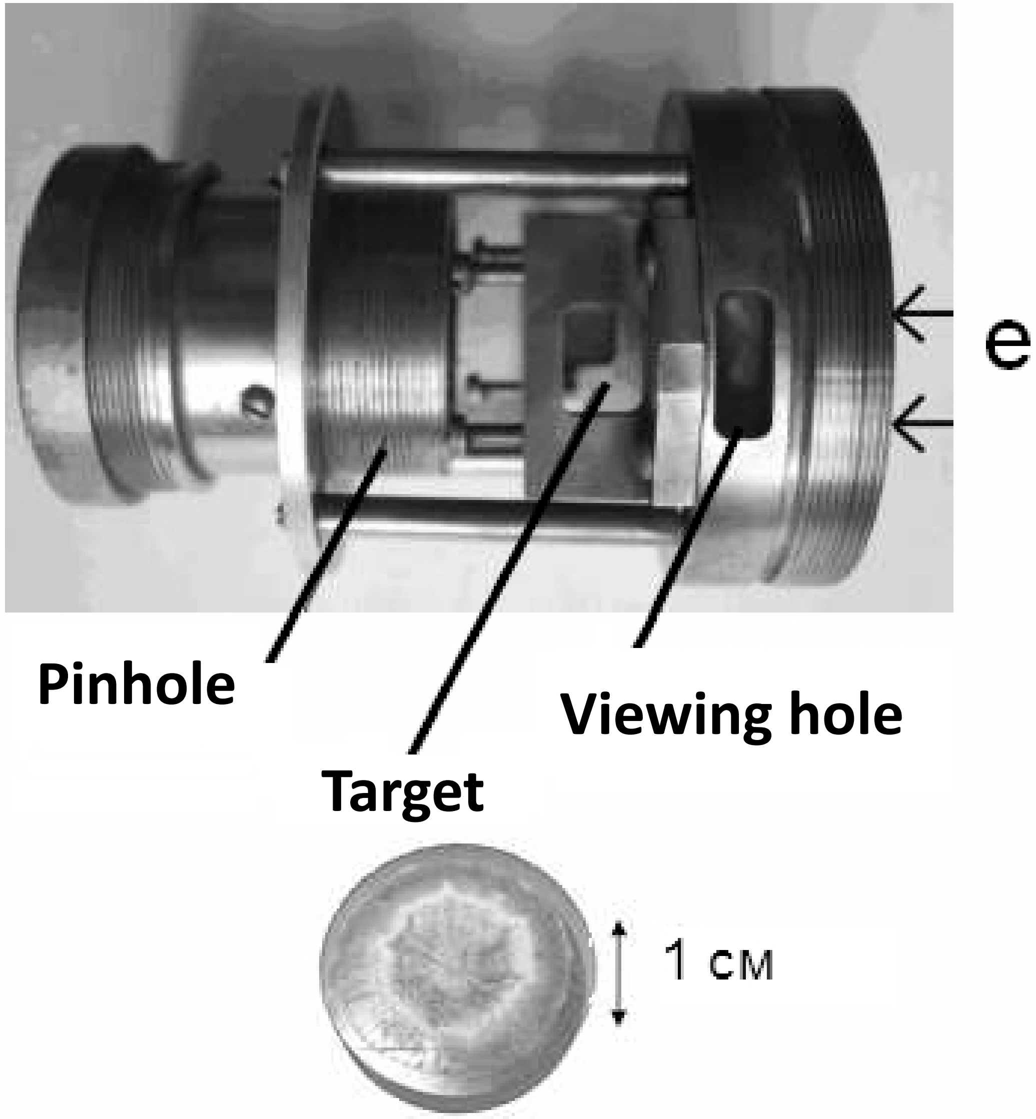
Problems:

- Insufficient accuracy of experiments;
- Limited opportunities for experimentation.

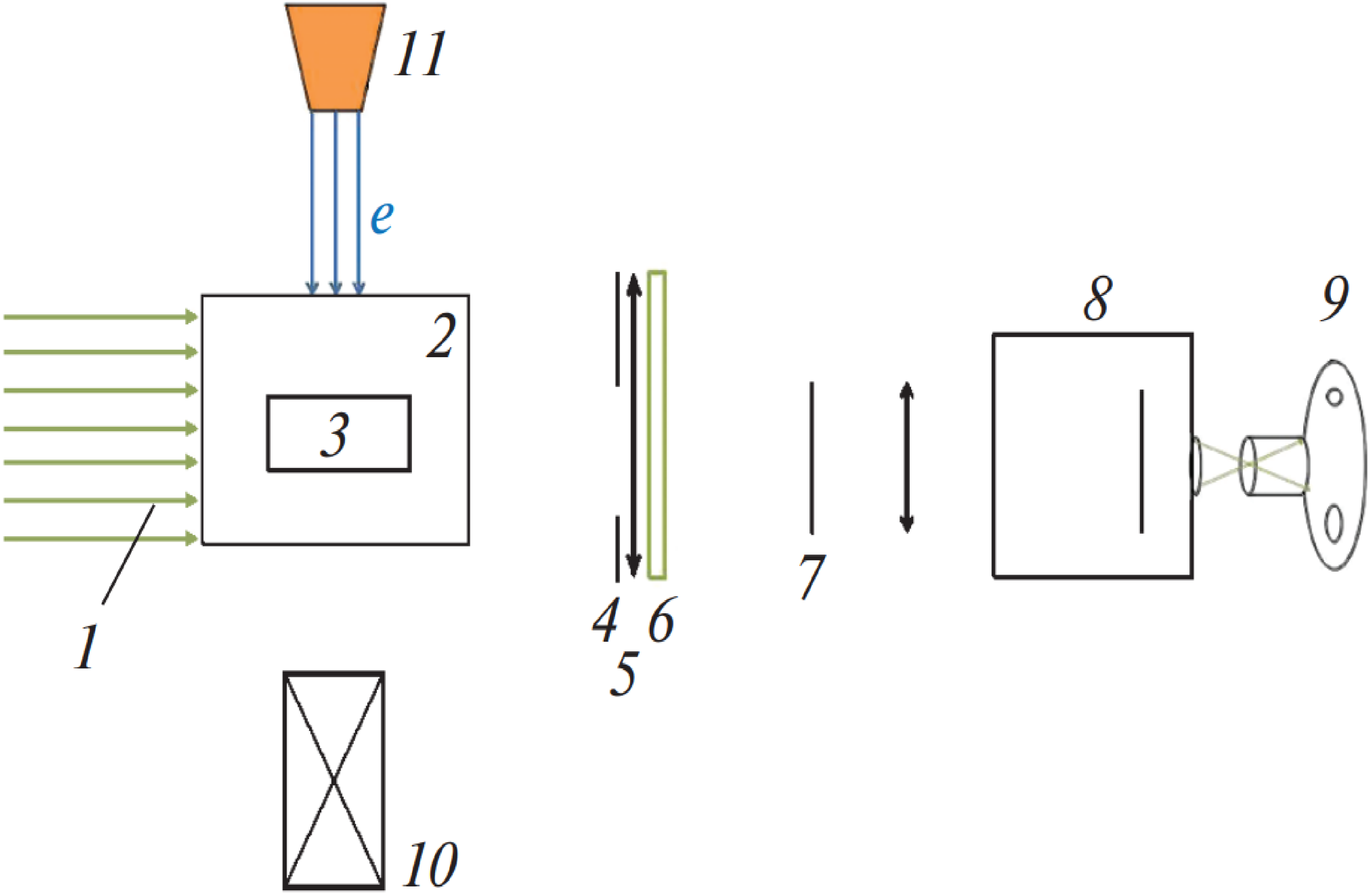
Experiment parameters

1. Beam current: 20–45 kA;
2. Duration: 100–150 ns ;
3. Fluence: 240 –1000 J/cm^2;
4. Electron energy: 200-500 keV.

Experiments were carried out on high current electron accelerator “Kalmar” (National Research Center “Kurchatov Institute”, Moscow, Russia).

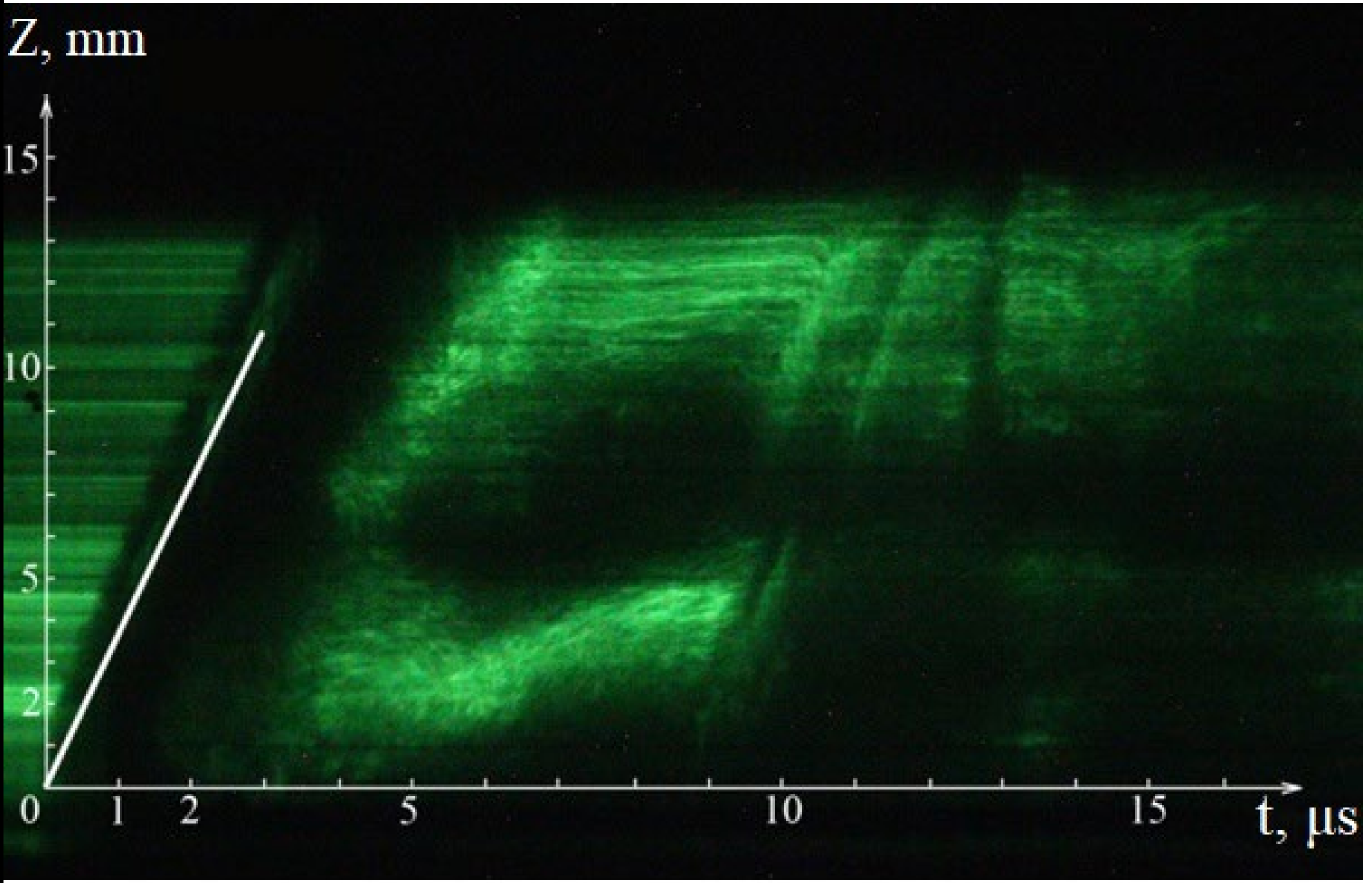


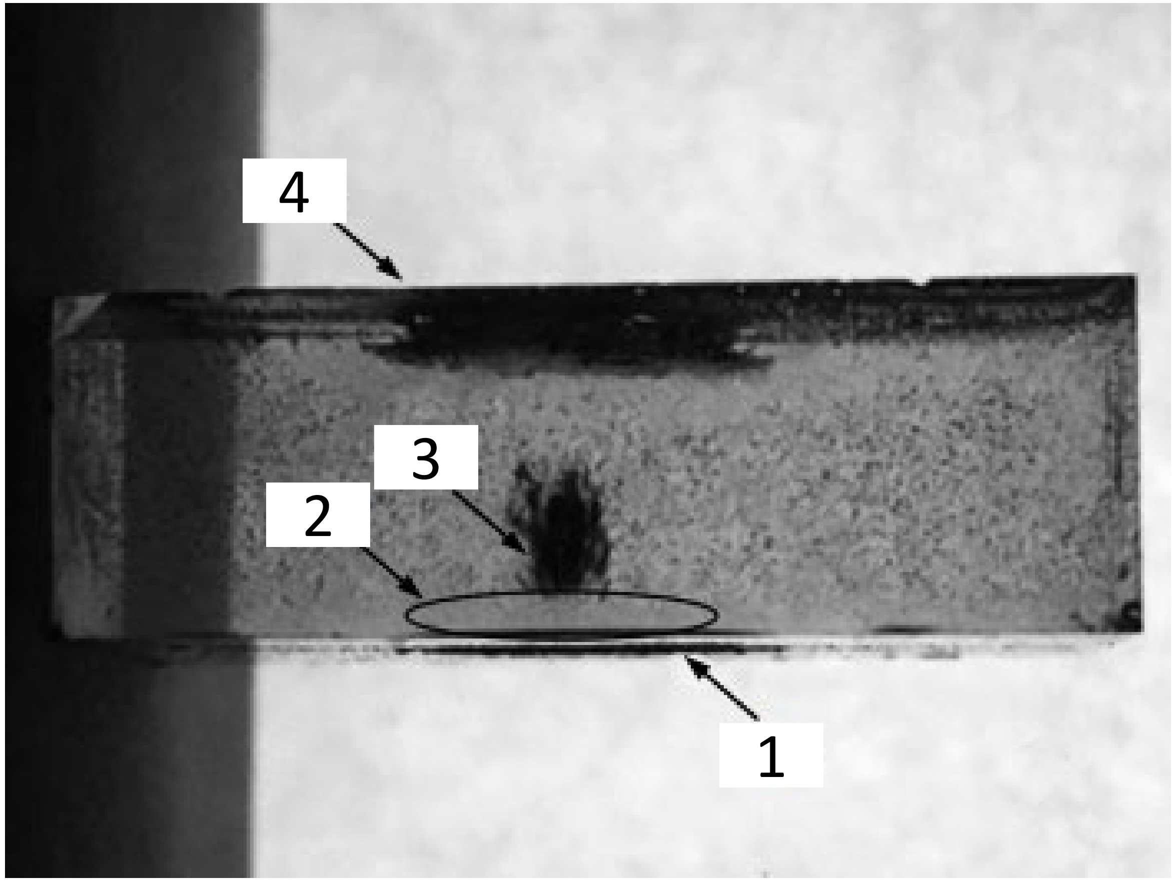
Scheme of the experiment



1 – laser beams,
2 – sample,
3 – shock wave region,
4 – slit diaphragm,
5 – objective,
6 – green light filter,
7 – time analyzing slit,
8 – electron optical camera,
9 – camera,
10 – pinhole,
11 – cathode.

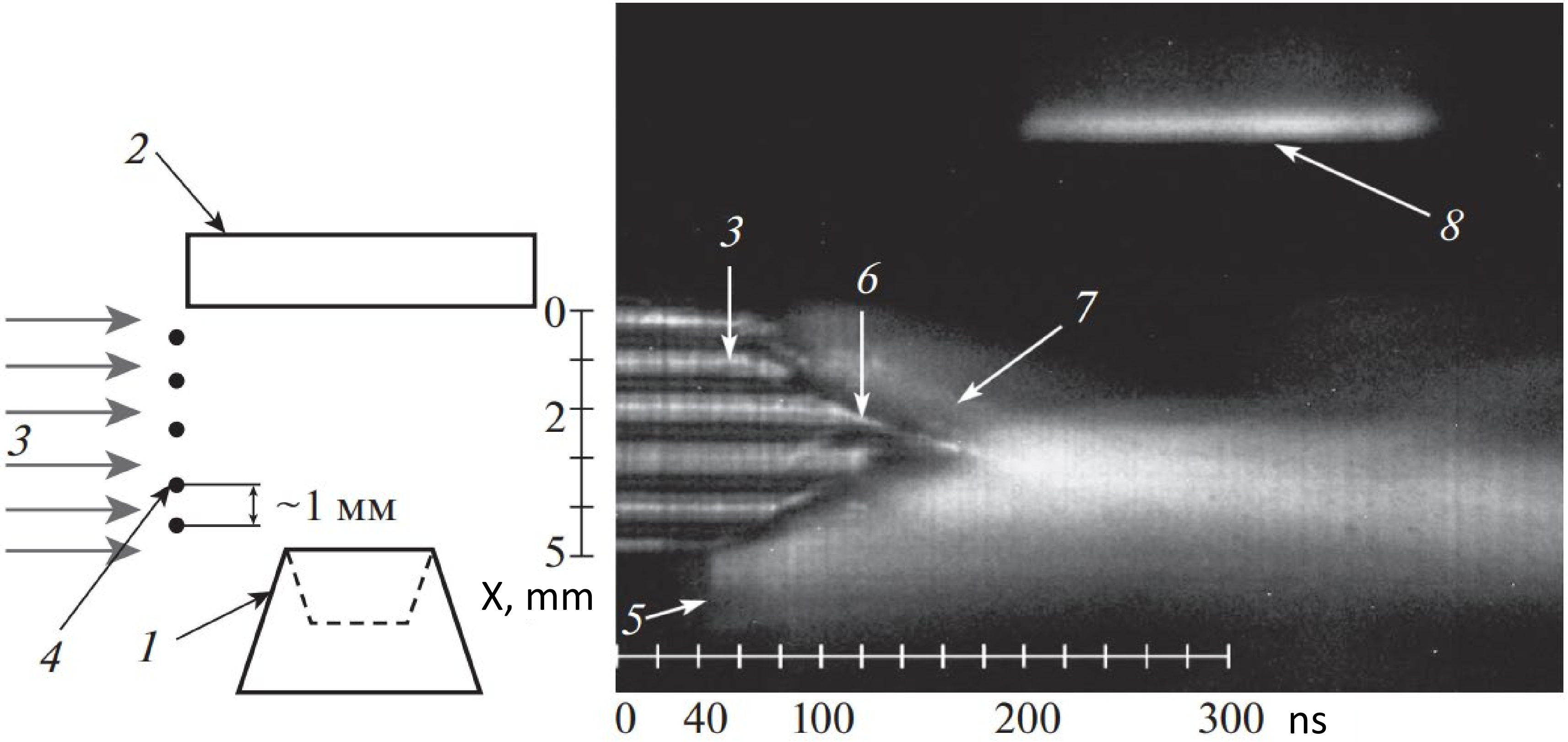
Experiment results





1) Demidov B. A., Kazakov E. D., Kalinin Y. G., Krutikov D. I., Kurilo A. A. , Orlov M. Yu., Strizhakov M. G., Tkachenko S. I., Chukbar K. V., and Shashkov A. Yu. Instrum Exp Tech 63, 370–374 (2020). doi:10.1134/S0020441220030094

Experiment results



2) Kazakov E.D., Kalinin Y.G., Krutikov D.I., Kurilo A.A., Orlov M.Yu., Strizhakov M.G., Tkachenko S.I., and Shashkov A.Yu. *Plasma Phys. Rep*. 47, 803–813 (2021). doi:10.1134/S1063780X21080067

Chronogram of a shadow laser image of a diode gap with spatial modulation of laser radiation caused by a grid on the input window; on the left is the geometry of the diode: 1 – cathode; 2 – anode; 3 – laser radiation; 4 – modulating grid on the input window; 5 – plasma intrinsic radiation from the side surface of the cathode, 6 – the area of the density gradient of the diode plasma, 7 – the area of “weak” glow of the diode plasma, 8 – the radiation of the synchro-impulse of the LED.

Mathematical model

Gas dynamic model:

$$\frac{\partial}{\partial t}\rho + \nabla(\rho\vec{w}) = 0;$$

$$\frac{\partial}{\partial t}\rho w_i + \sum_k \frac{\partial}{\partial x_k}\mathbf{\Pi}_{ik} = 0;$$

$$\mathbf{\Pi}_{ik} = \rho w_i w_k + P\delta_{ik};$$

$$\frac{\partial}{\partial t}\left(\rho E + \frac{1}{2}\rho w^2\right) + \nabla\vec{q} = 0;$$

$$\vec{q} = \left(\rho E + \frac{1}{2}\rho w^2 + P\right)\vec{w};$$

$$P = P(\rho, E).$$

Elastic-plastic model:

$$\frac{d\rho}{dt} + \rho\nabla_i v^i = 0;$$

$$\rho\frac{dv_i}{dt} = F_i + \nabla_j\sigma_i^j;$$

$$\rho\frac{dE}{dt} = \sigma^{ij}\dot{\varepsilon}_{ij} - \nabla_i q^i + Qs;$$

$$\dot{\varepsilon}_{ij} = \frac{1}{2}\left(\nabla_i v_j + \nabla_j v_i\right); \qquad q^i = -\aleph\delta_{ij}\nabla_j T;$$

$$\frac{dD_{\sigma ij}}{dt} + 2G\dot{\lambda}D_{\sigma ij} = 2G\left(\dot{\varepsilon}_{ij} + \frac{1}{3\rho}\frac{d\rho}{dt}\delta_{ij}\right) - 3\alpha K\left(T - T_0\right)\delta_{ij};$$

$$\sigma_{ij} = -P + D_{\sigma ij}\Psi + \left(\left(3\eta - 2\mu\right)\dot{\varepsilon}\delta_{ij} + 2\mu\dot{\varepsilon}_{ij}\right)\Psi;$$

$$\dot{\lambda} = \frac{3}{2\sigma_T^2}\sigma^{ij}\dot{\varepsilon}^{(p)}_{ij};$$

$$P = P\left(\rho, E\right);$$

Mathematical model

1. Criterion of maximum stresses

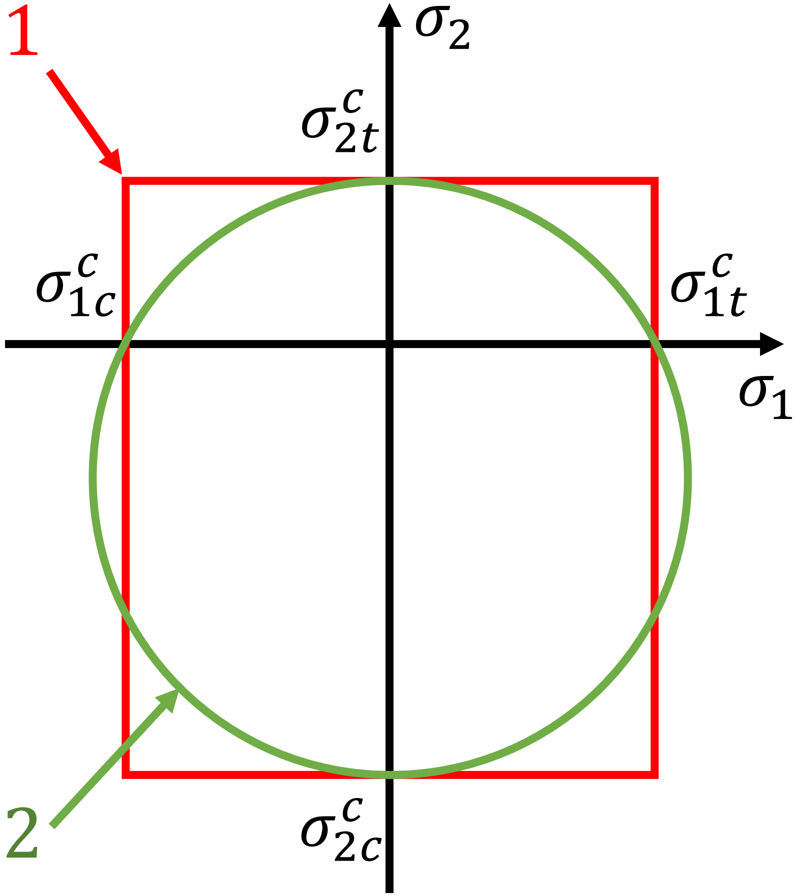
$$\left(\left|\frac{\sigma_1}{X}\right|,\left|\frac{\sigma_2}{Y}\right|,\left|\frac{\sigma_3}{Z}\right|,\left|\frac{\sigma_{12}}{S}\right|,\left|\frac{\sigma_{13}}{R}\right|,\left|\frac{\sigma_{23}}{Q}\right|\right)_{\max} \le 1$$

2. The quadratic Mises-Hill criterion

$$F(\sigma_{22}-\sigma_{33})^2+G(\sigma_{11}-\sigma_{33})^2+H(\sigma_{22}-\sigma_{11})^2+2L\sigma_{23}^2+2M\sigma_{31}^2+2N\sigma_{12}^2\le 1;$$

$$F=\frac{1}{2}\left(\frac{1}{(\sigma_2^c)^2}+\frac{1}{(\sigma_3^c)^2}+\frac{1}{(\sigma_1^c)^2}\right);\qquad G=\frac{1}{2}\left(\frac{1}{(\sigma_1^c)^2}+\frac{1}{(\sigma_3^c)^2}+\frac{1}{(\sigma_2^c)^2}\right);$$

$$H=\frac{1}{2}\left(\frac{1}{(\sigma_2^c)^2}+\frac{1}{(\sigma_1^c)^2}+\frac{1}{(\sigma_3^c)^2}\right);\ L=\frac{1}{2\left(\tau_{23}^c\right)^2};\ M=\frac{1}{2\left(\tau_{31}^c\right)^2};\ N=\frac{1}{2\left(\tau_{12}^c\right)^2}.$$



The method of dynamic control of changes in the aggregate state

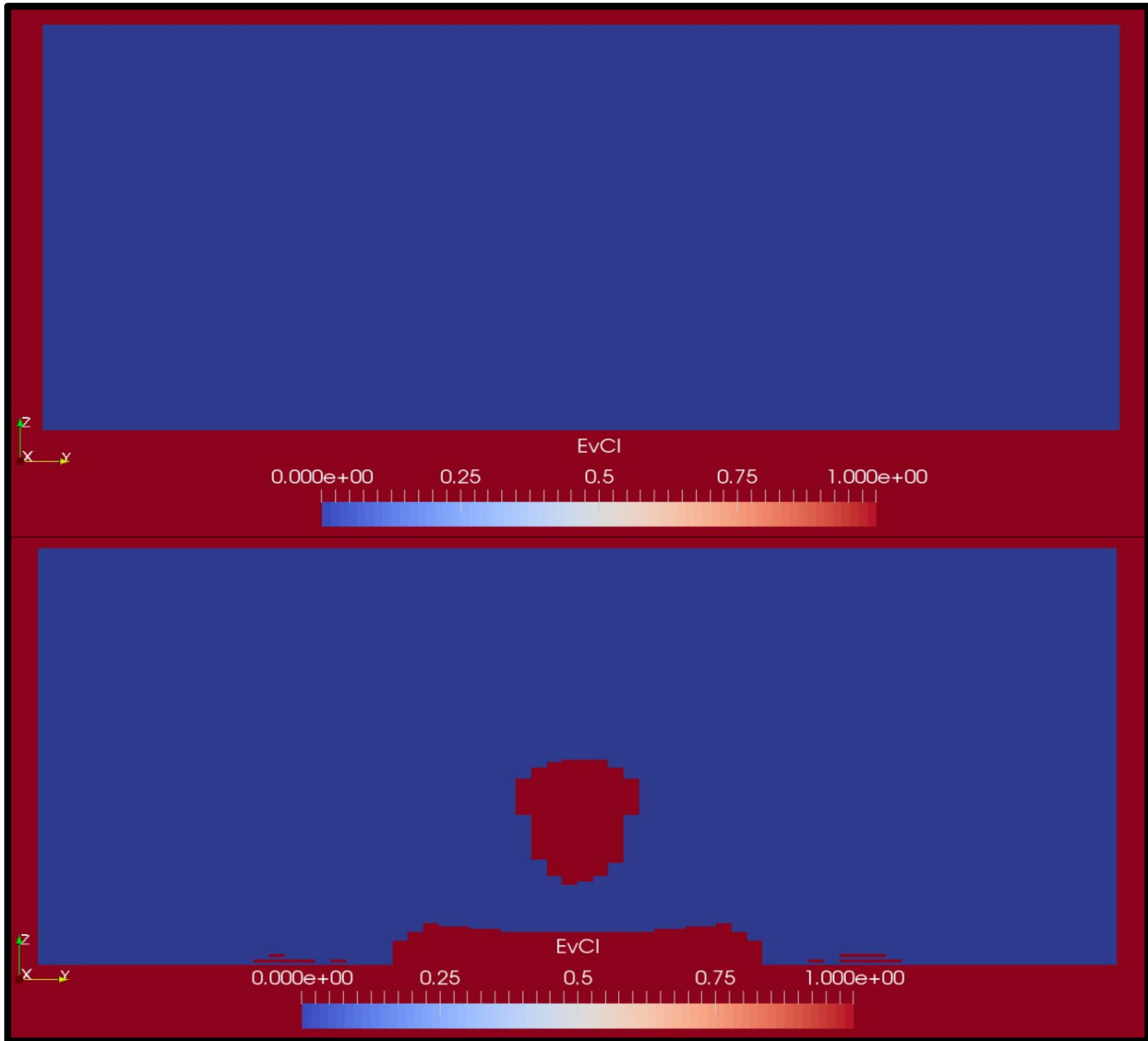
Criterion of aggregate state:

$$\Psi = \begin{cases} 1, \rightarrow E \geq L_S \mid \Sigma \geq \sigma_{np}; \\ 0, \rightarrow E < L_S \,\&\, \Sigma < \sigma_{np}. \end{cases}$$

Behavior of the mathematical model:

$$\sigma_{ij} = -p + D_{\sigma ij}\Psi + \left(\left(3\eta - 2\mu\right)\dot{\varepsilon}\delta_{ij} + 2\mu\dot{\varepsilon}_{ij}\right)\Psi.$$

The areas of volumetric destruction work exclusively for compression.



Simulation results

The effect of a relativistic electron beam on a polymer material

The cylindrical shape sample is made of epoxy resin, diameter 3.5 cm, thickness 1.5 cm.
Exposure parameters: source – electron beam, fluence – 600 J/cm2, duration of exposure – 100 ns.

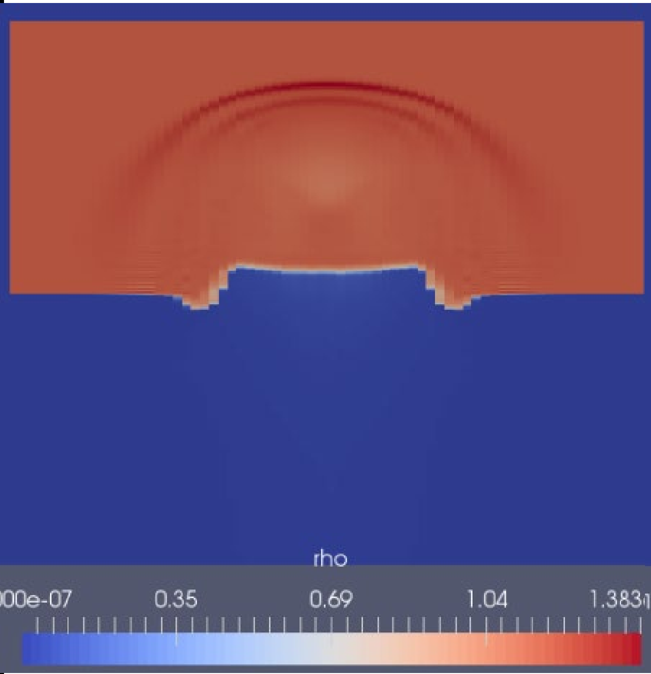


Fig. 1 – density field in g/cm^3, at a time of 3.5 microseconds.

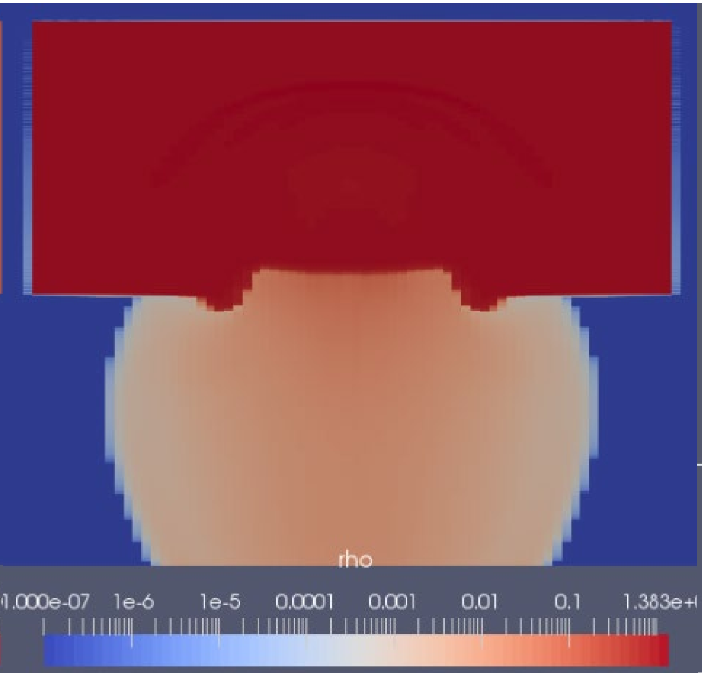


Fig. 2 – density field in logarithmic scale g/cm^3, at the time of 3.5 microseconds.

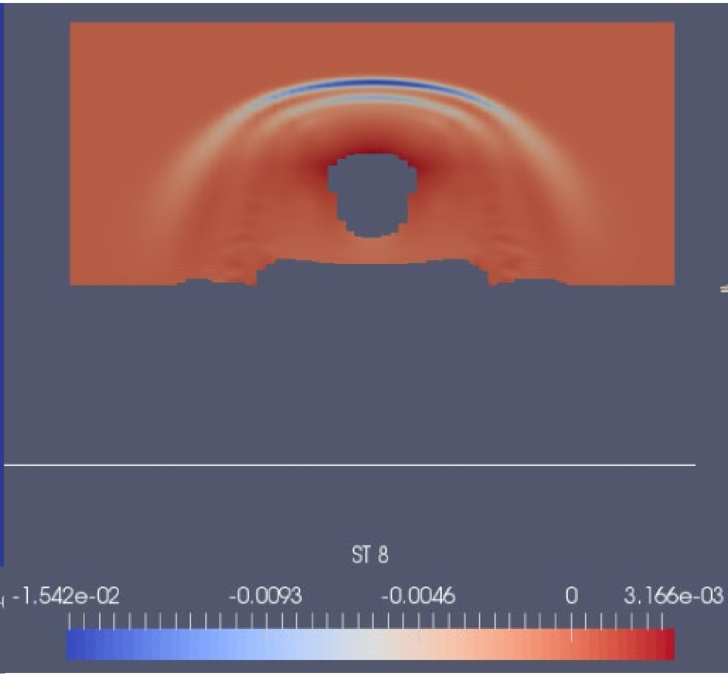


Fig. 3 – The Szz component of the stress tensor in Mbar, at a time of 3.5 microseconds.

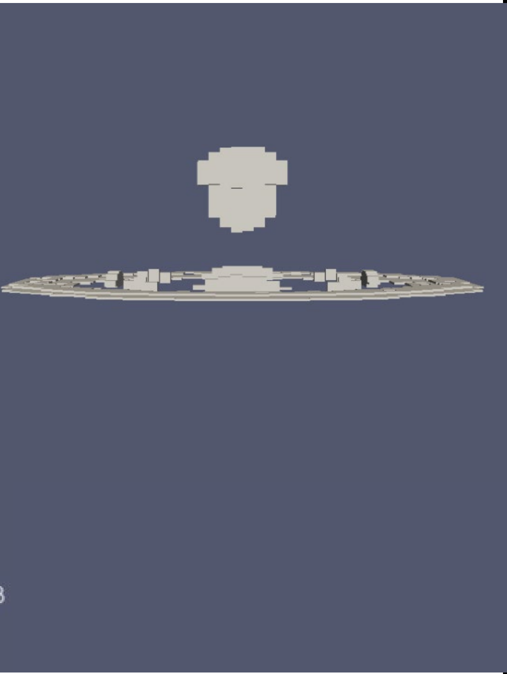
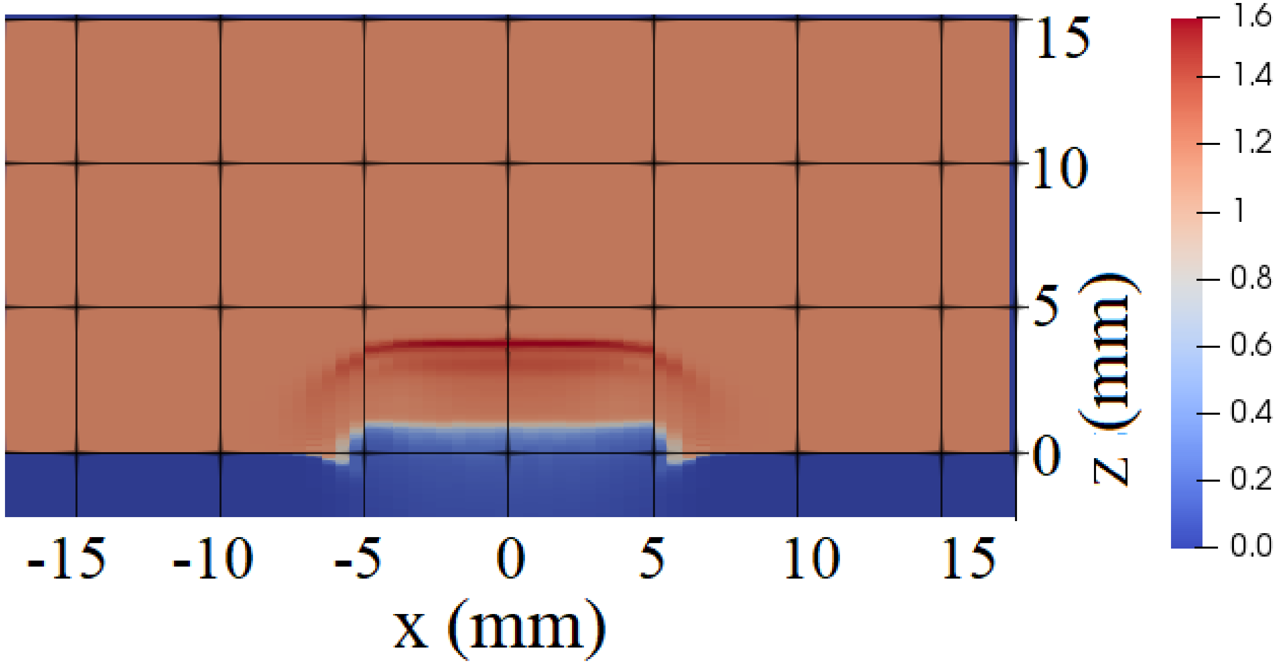
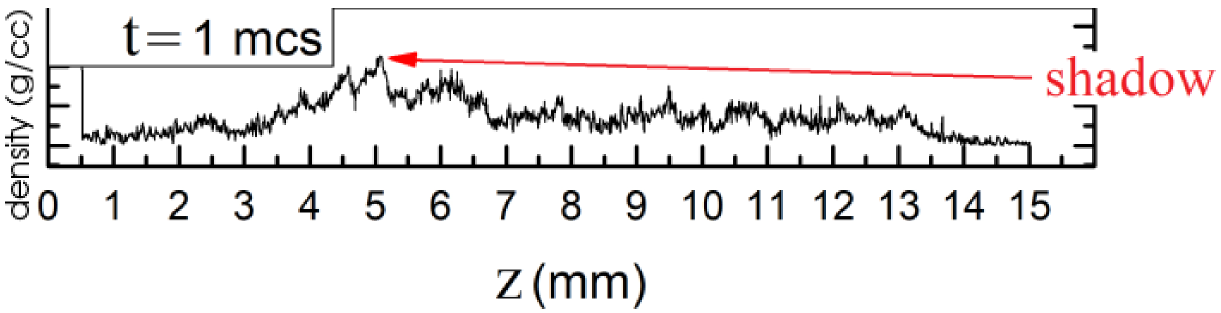


Fig. 4 – Volumetric destruction, at the time of 3.5 microseconds.

Simulation results

3) Boykov D. S., Olkhovskaya O. G., and Gasilov V. A. *Math Models Comput Simul*, 14, No. 4, 599–612 (2022) DOI: 10.1134/S2070048222040044





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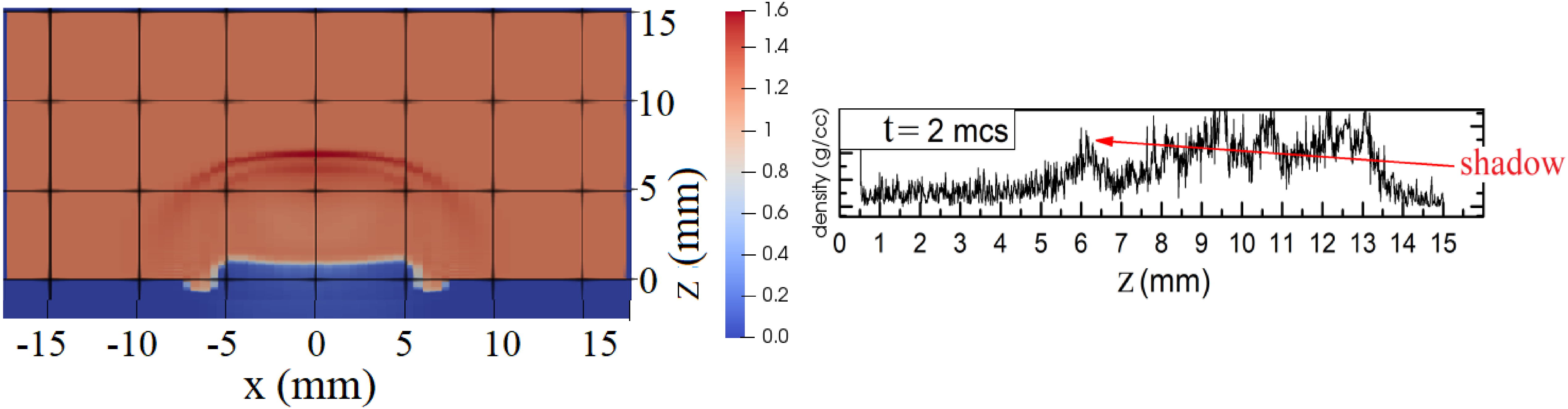

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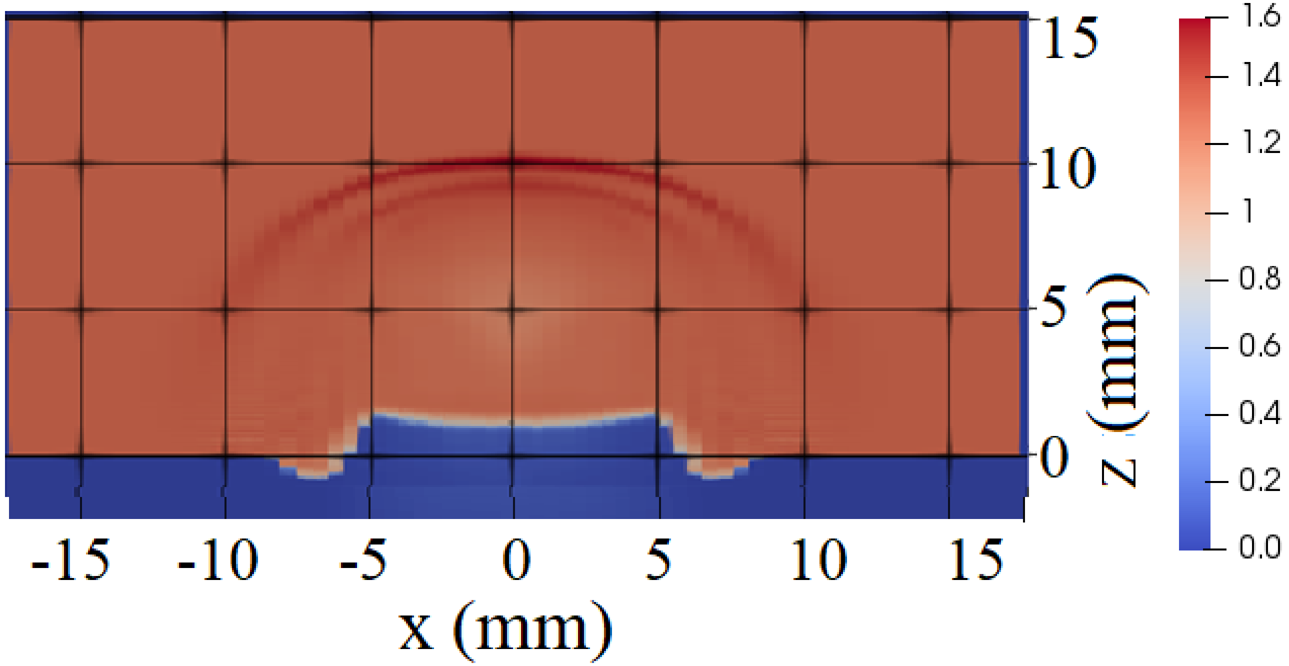

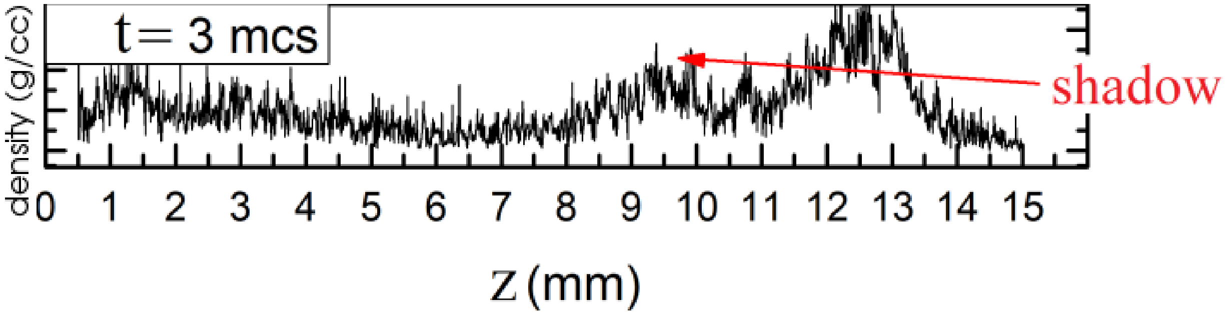

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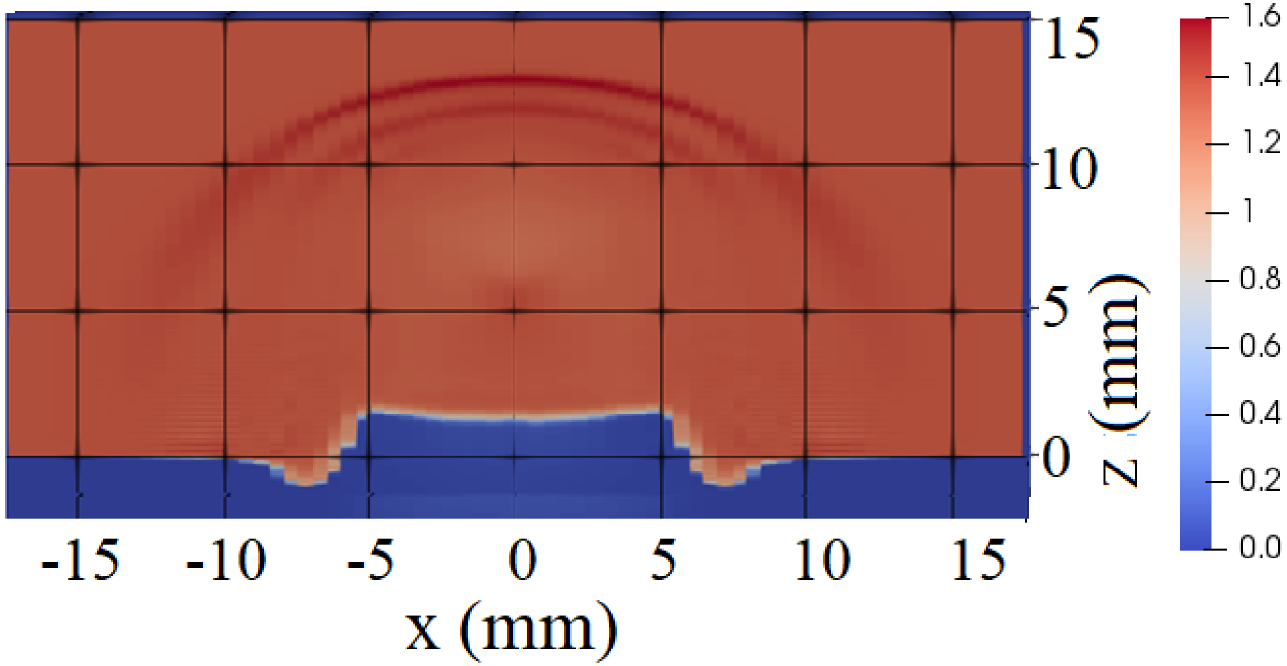

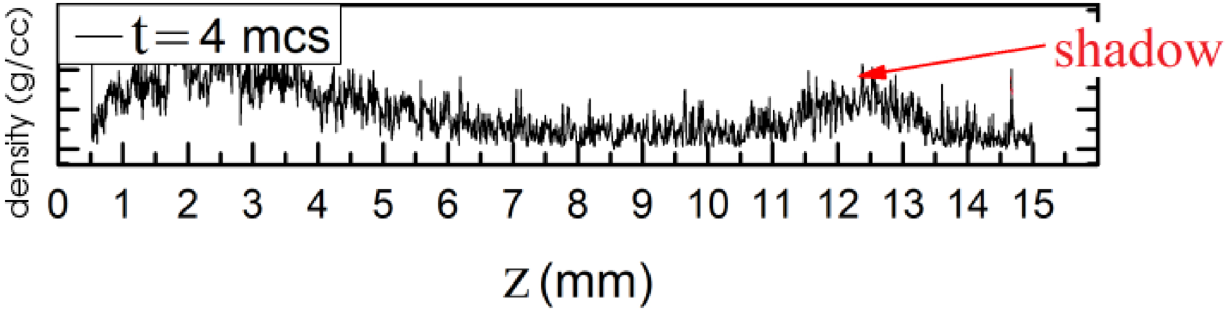

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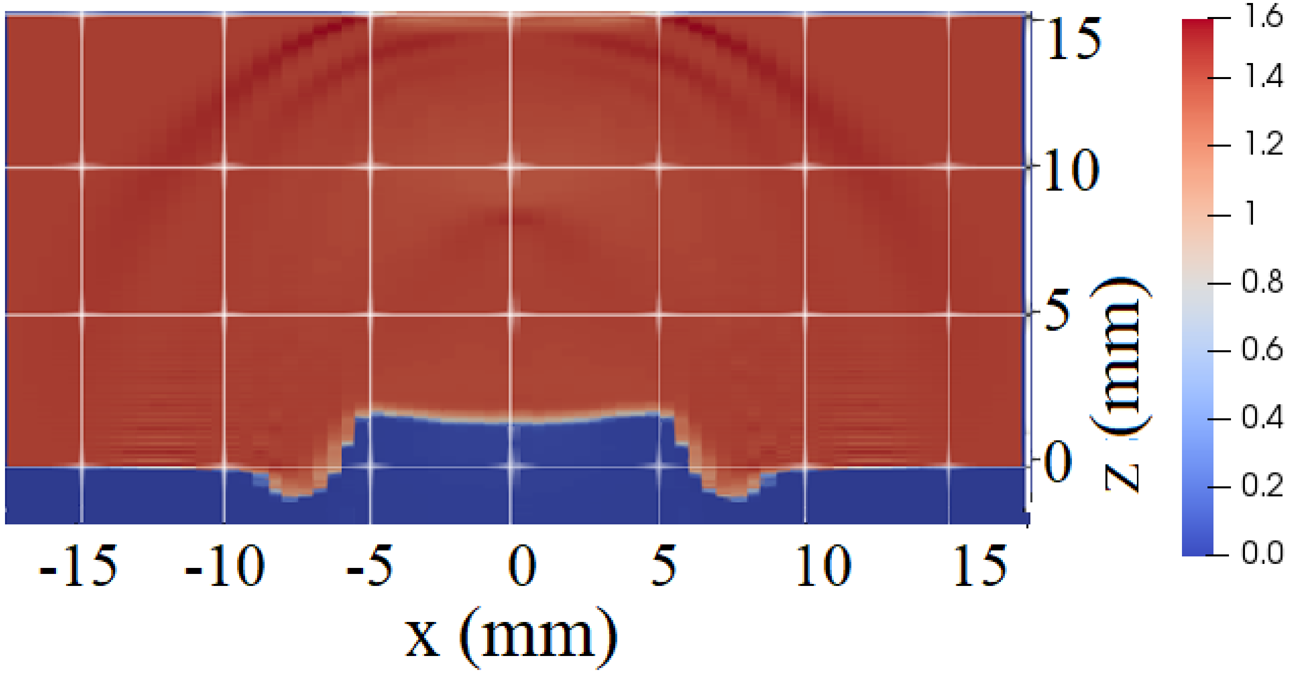

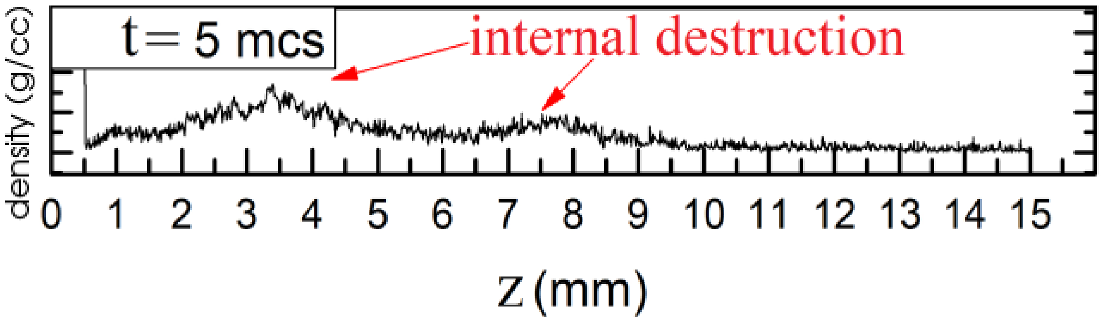

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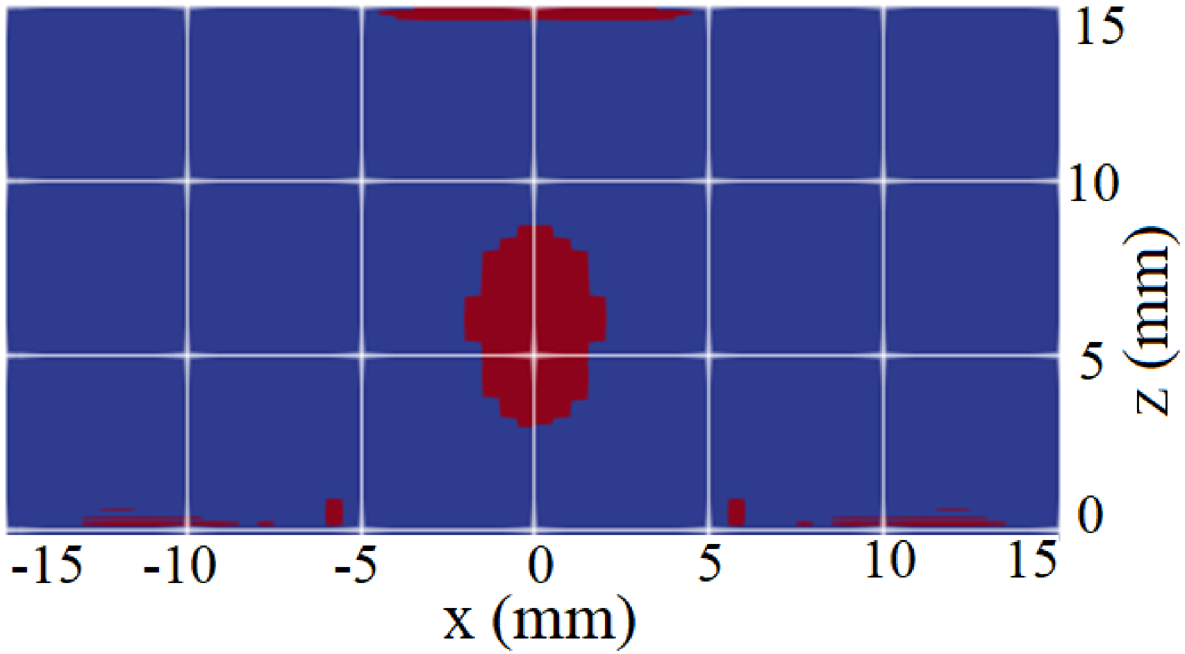

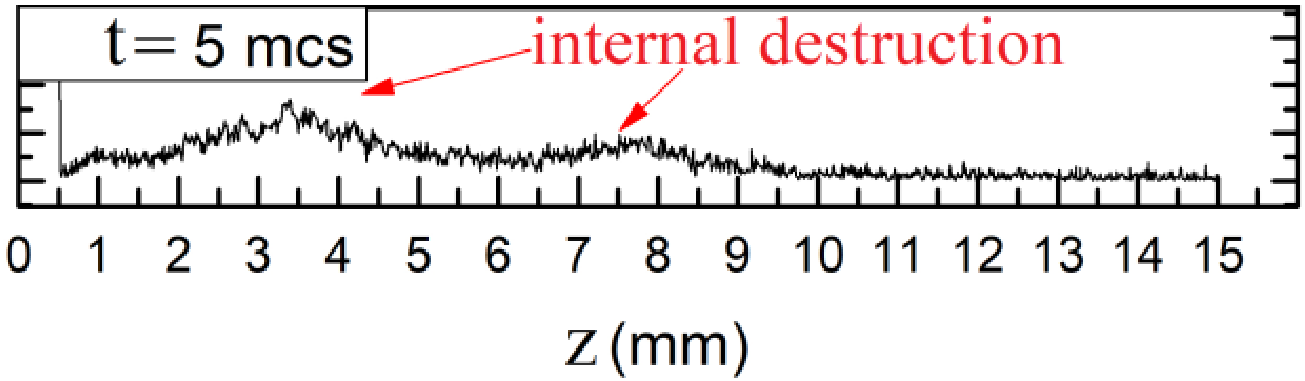

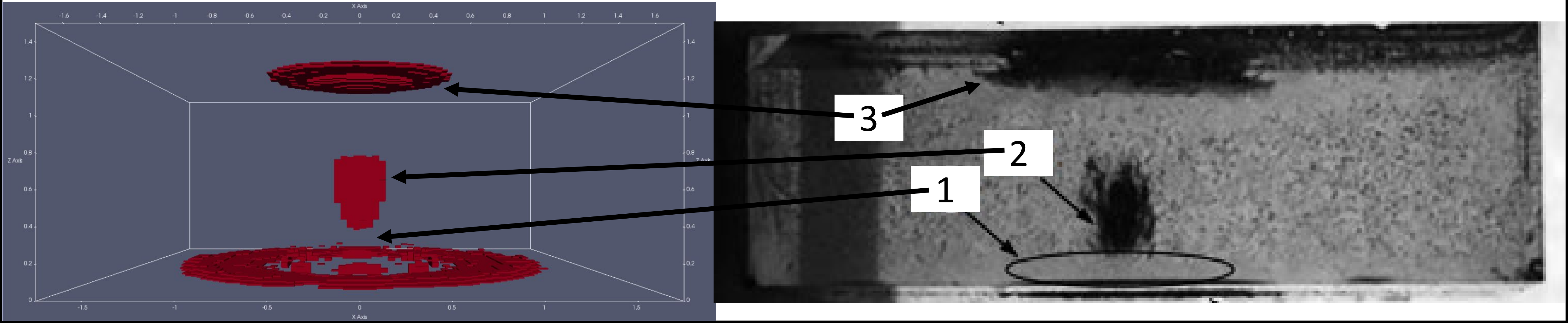

Conclusion

- We have investigated a sample of epoxy resin exposed to 600 J/cm^2 REB. Laser shadow chronogram allowed observation of the wave processes in the material and estimation of the compression wave parameters. The wave pattern in epoxy resin appeared to be comparable but not identical with that obtained for Plexiglas. Brittle fracture in the volume of the target and spallation on its rear surface took place.
- End-to-end computer model was developed to support these experiments. The model included the action of the REB on the target front surface resulted in the evaporation of the substance and formation of a pressure pulse, gasdynamic phenomena in the diode gap, and elastoplastic phenomena in the solid target, leading to destruction in the unevaporated matter. Wave processes in a target are essentially non-one-dimensional, and require 3D simulation in the case of non-cylinder sample. Appropriate modeling of this complex multiphysics problem is based on high resolution numerical methods as well as on high performance computing. The implemented computer models are verified by experimental data. Comparison of simulation results with experimental data is used to test the applied models of volumetric fractures and spallations in brittle solids, and to validate wide-range equations of state. The developed software can be used for numerical stress-strain analysis of various structural units loaded by strong pulsed forces and/or energy fluxes.