Modeling of target deformations due to pre-pulse with debris analysis

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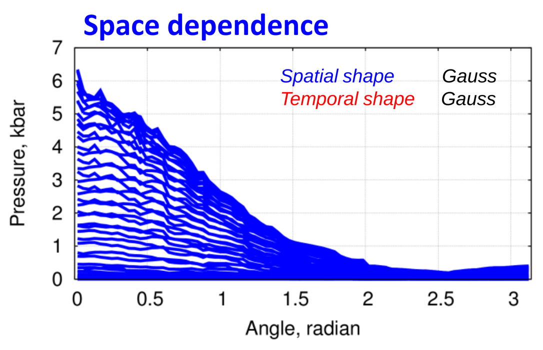
Objective

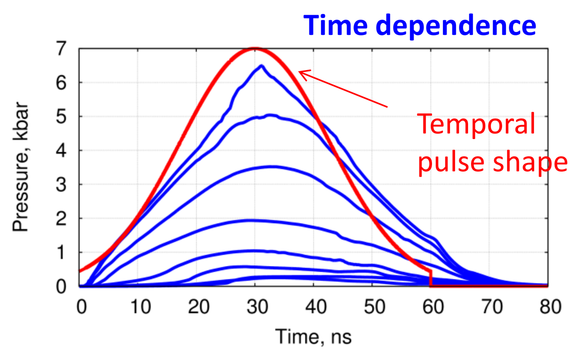
The main goal of the work is to investigate time/space/size fragment distributions during the process of target deformation due to laser pre-pulse.

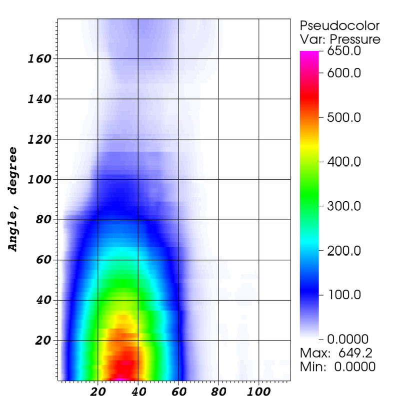
- *fragments distribution over size;*
- *mass distribution over angle;*
- *axial and radial velocity distribution over fragments mass;*

RZLINE code → modeling of laser-target interaction, plasma formation

An example for analytically defined laser pulse



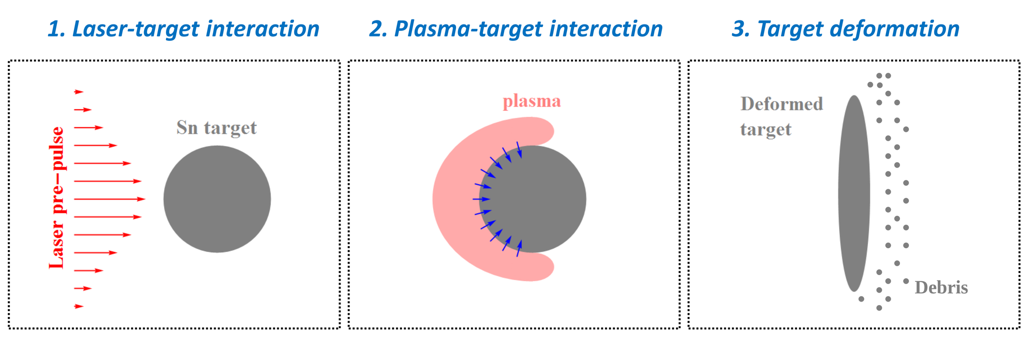




Power balance from RZLINE	
Reflection of laser light , %	**49**
Laser light, missing the droplet, %	**23**
Fast ions (>1keV), %	**17**
Number of evaporated atoms-ions, %	**2.7**

RZLINE ablation pressure distribution is critical for the droplet dynamics (hole formation, debris, elongation velocity etc.).

Modeling approach



RZLINE code → modeling of laser-target interaction, plasma formation

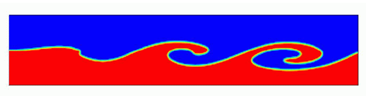
Calculation of plasma ablation pressure at the target surface

OpenFOAM code → hydrodynamics modeling of liquid target deformation

Separate modeling of plasma processes and target hydrodynamics
- *Limitation: small target deformation within laser pulse duration*
- *Radiation fluxes ≤ 10^{11} W/cm²*

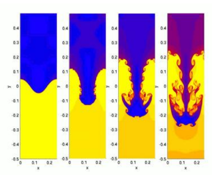
Instabilities leading to fragmentation of the droplet

Kelvin–Helmholtz



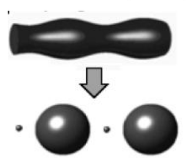
can occur when there is velocity shear in a single continuous fluid, or where there is a velocity difference across the interface between two fluids.

Rayleigh–Taylor



is instability of an interface between two fluids of different densities which occurs when the lighter fluid is pushing the heavier fluid.

Plateau–Rayleigh



explains why and how a falling stream of fluid breaks up into smaller packets with the same volume but less surface area. It is related to the Rayleigh–Taylor instability and is part of a greater branch of fluid dynamics concerned with fluid thread breakup.

Mullins, B. J. and Mead-Hunter, R. and King, A. J. C. 2012. Simulating Plateau-Rayleigh instability and liquid reentrainment in a flow field using a VOF method http://espace.library.curtin.edu.au/R?func=dbin-jump-full&local_base=gen01-era02&object_id=189025

Shock waves

can cause spallation of the droplet material in different directions

3D Hydrodynamics description

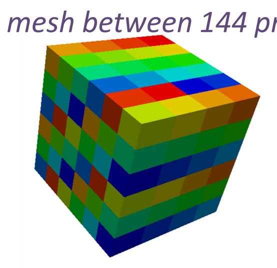
- + Volume of Fluid method
- + Two phases (Liquid and Gas)
- + Immiscible fluids
- + Isothermal
- + Viscosity
- + Compressibility

Regular hydrodynamics

- + Surface tension
- + Crushing/merge of droplet(s)
- + Ideal gas equation of state for surrounding gas and constant speed of sound for liquid droplet
- + Surrounding plasma influence through ablation pressure from RZLINE code

Specific

Partition of the mesh between 144 processors

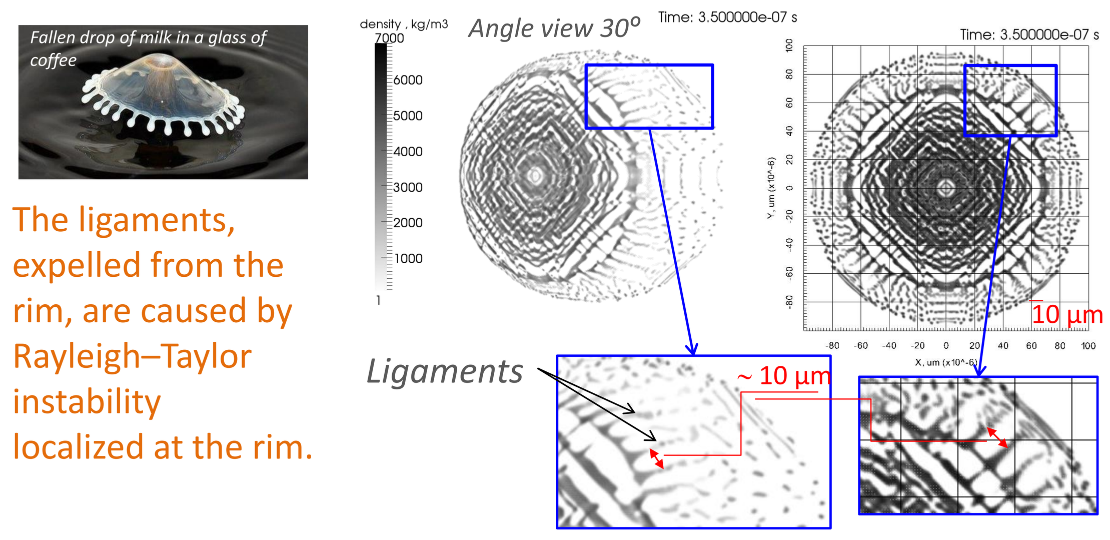


Calculation volume – 200x200x200 μm
Cubic cell with side – 0.5 μm

Open∇FOAM®
http://www.openfoam.com/

OpenFOAM – free to use 3D simulation software library with extensive CFD and multi-physics capabilities

Droplet fragmentation: ligament formation

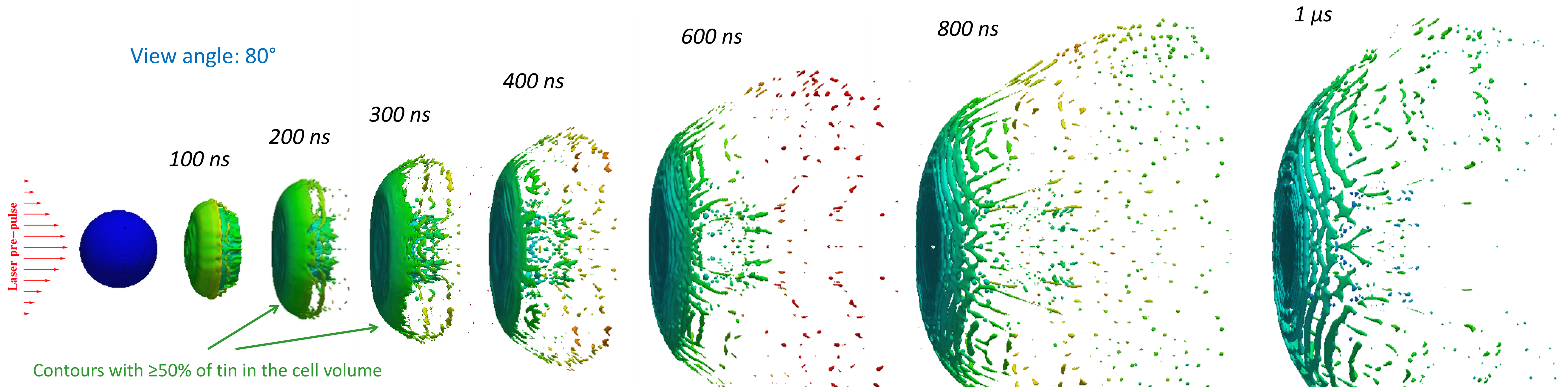


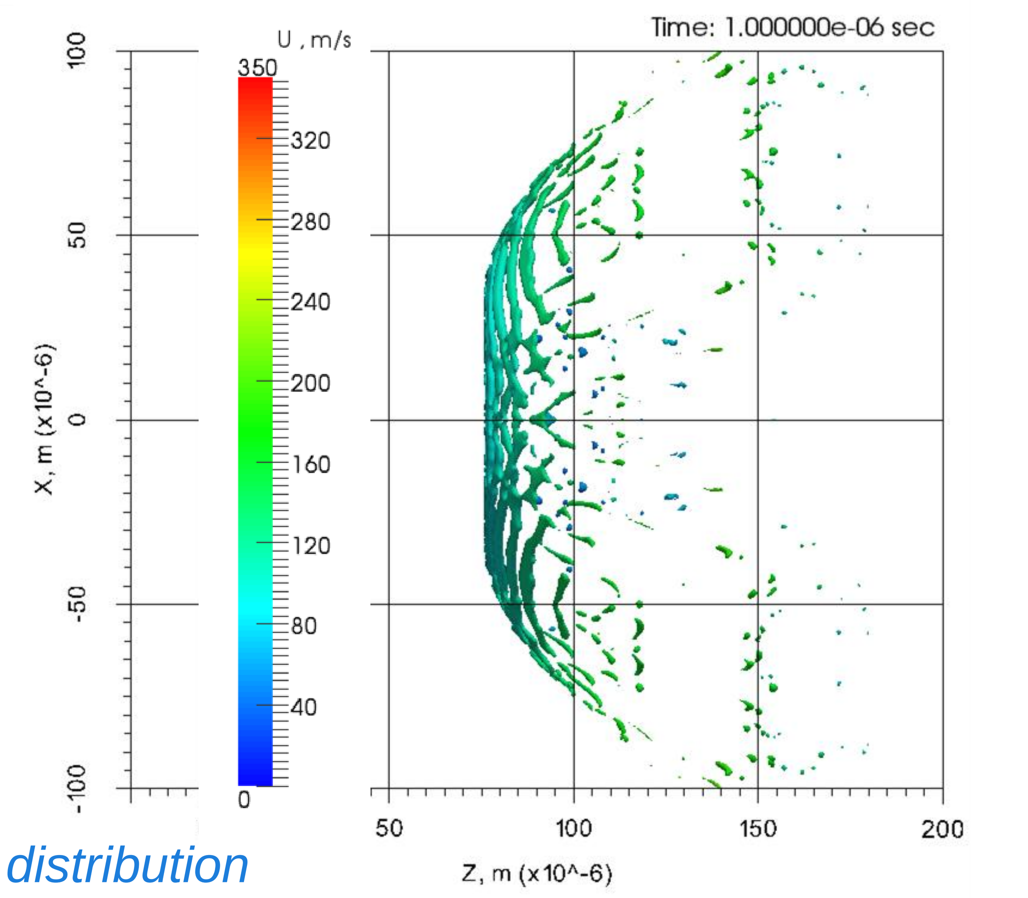
The ligaments, expelled from the rim, are caused by Rayleigh–Taylor instability localized at the rim.

References

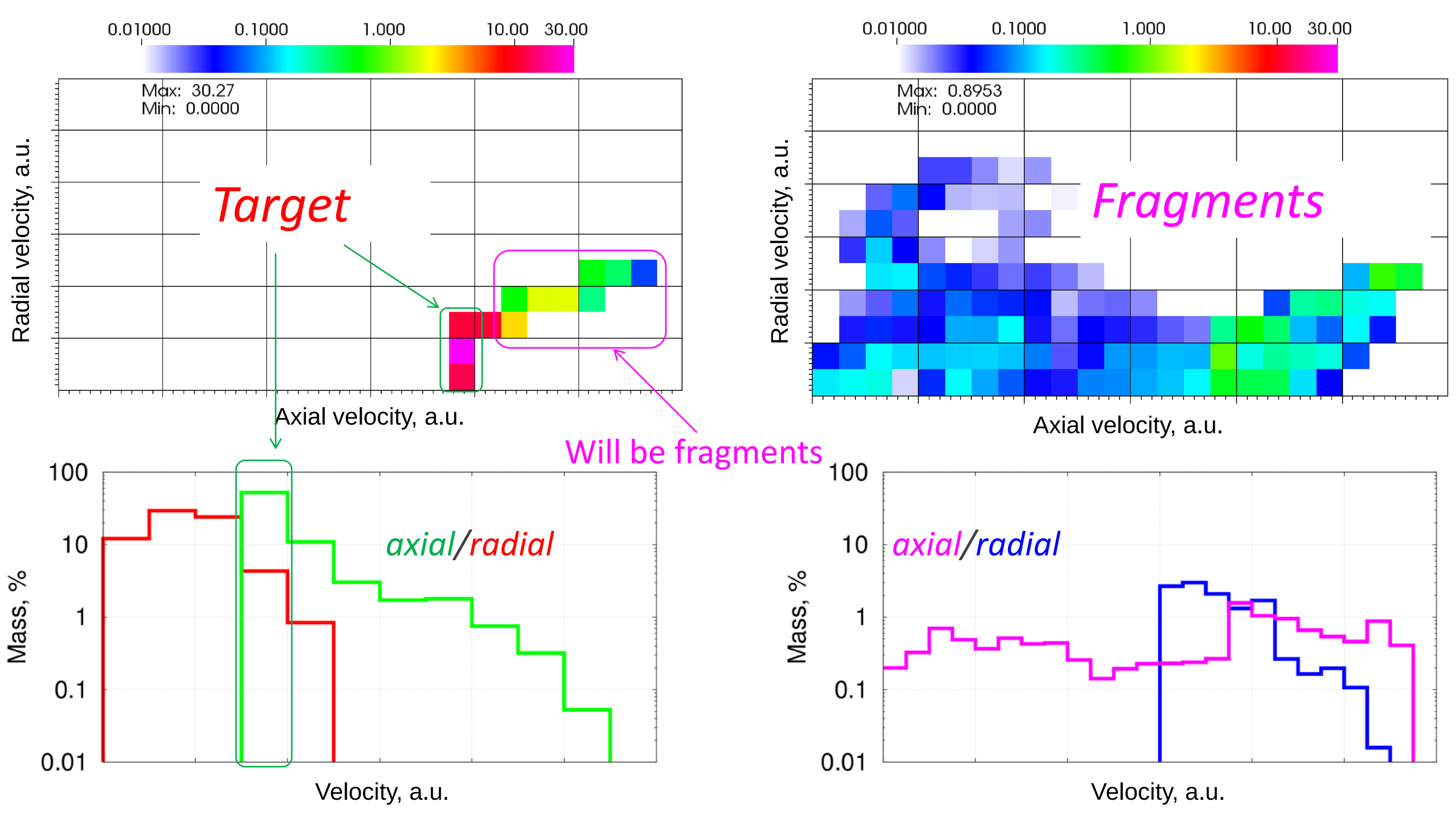
E. VILLERMAUX and B. BOSSA (2011). Drop fragmentation on impact. Journal of Fluid Mechanics, 668, pp 412-435 http://dx.doi.org/10.1017/S002211201000474X

Pringuey, Thibault Roland Christophe Maurice. Large eddy simulation of primary liquid-sheet breakup https://www.repository.cam.ac.uk/handle/1810/244655

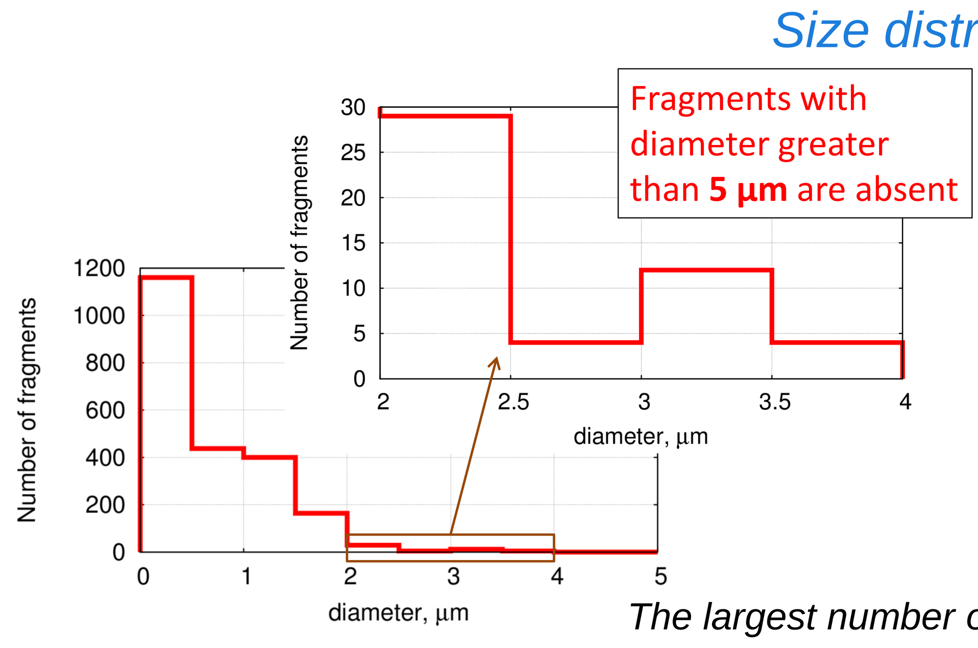


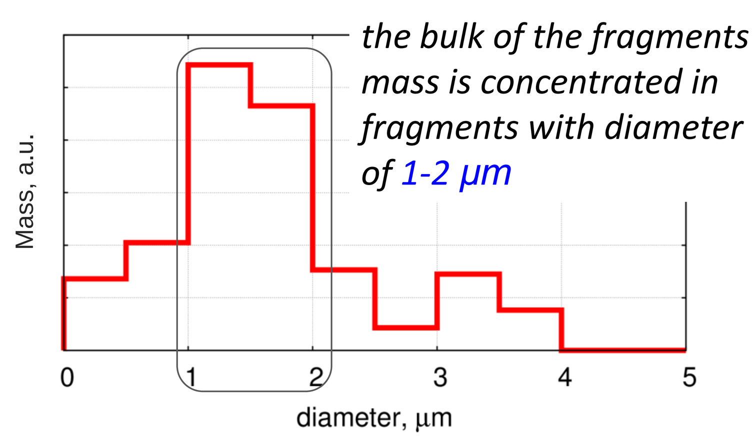


Mass and velocity distributions



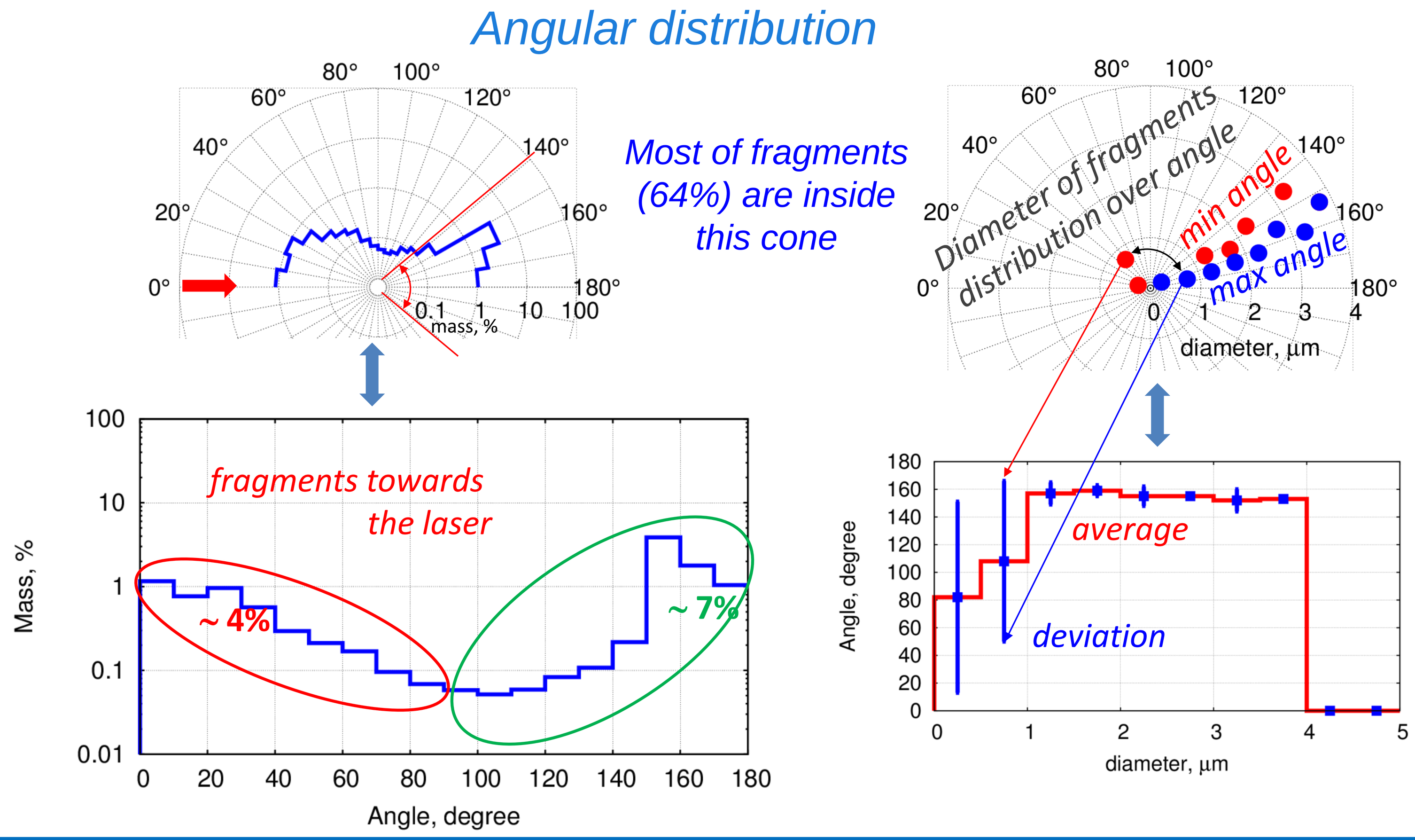
Size distribution



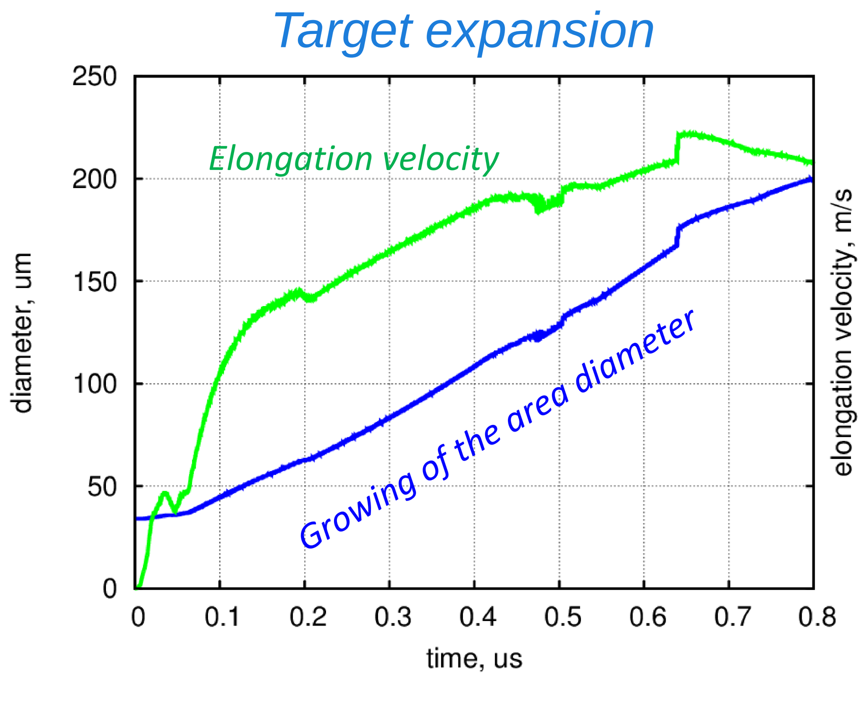


The largest number of fragments have diameter in the range of 0 – 2 μm
Fragments diameter can be up to 4 μm

Angular distribution



Target expansion



All simulations have been performed on the KIAM RAS K-100 Scalable GPGPU-based Hybrid Computing System

http://www.kiam.ru/MVS/resourses/k100.html

Conclusions

- *A combination of RZLINE & OpenFOAM describes key characteristics of droplet expansion after pre-pulse:*
  - ✓ *Shape formation, fragmentation*
  - ✓ *Elongation (expansion) velocity*
  - ✓ *Angular mass distribution of fragments*
  - ✓ *Fragments distribution over size*
  - ✓ *Velocity distribution of fragments*
- *The model allows to study the impact of pulse shape on target formation and debris distribution.*

*The study is a result of hard work of many people and teams at **ISAN**, **KIAM** and **ASML**.*
Special thanks to Harry Kreuwel and ASML team for stimulating discussions and experimental validation of the model.