РОССИЙСКИЙ ФЕДЕРАЛЬНЫЙ ЯДЕРНЫЙ ЦЕНТР ВНИИЭФ

The use of high power lasers for studying rheological properties of substances

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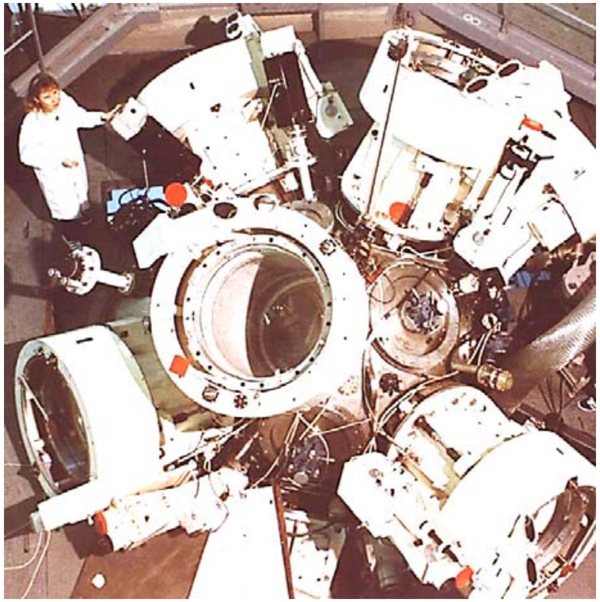
XIII Zababakhin's Scientific Hearings International Conference
Snezhinsk, Russia, 20 - 24 March, 2017

Annotation

- ✓ Statement and results of laser experiments at RFNC-VNIIEF laser facilities on studying rheological properties of various substances are discussed.
- ✓ Main attention is devoted to experiments at low flows of laser radiation (LR) when relatively low intensity shock waves are generated within the target. The shock wave attenuation dynamics and spalls generation are investigated.
- ✓ The laser method simulating preventive nuclear explosion destructive effect on dangerous asteroids is considered.
- ✓ In laser experiments with stony asteroid micro models the criteria for chondrites asteroids effective destruction at contact nuclear explosion were defined.

"ISKRA-5" laser facility

"ISKRA-5" building appearance



12-beam spherical chamber
$\varnothing$ 2 m

12 – beam photo-dissociative Iodine laser with $\lambda = 1.315\ \mu m$;
Laser energy at first harmonics is up to 30 kJ
Pulse duration – 0.4 ns
Power – up to 100 TW

"LUCH" laser facility

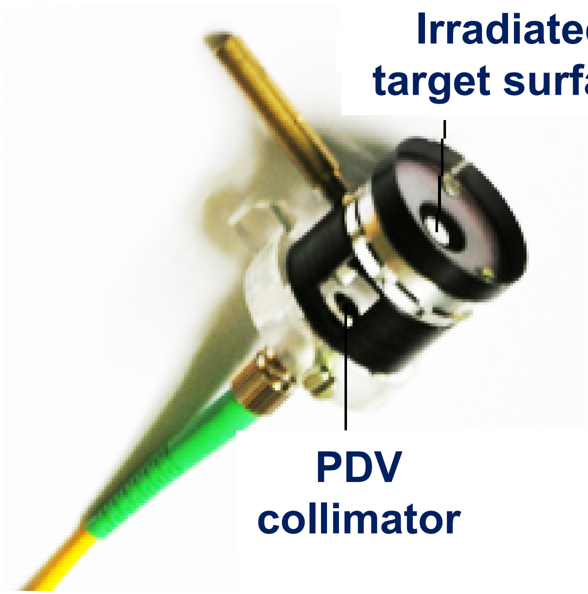
Solid-state ND laser λ= 1.054 μm
Amplification channels – 4
Beam – 20x20 cm
Duration – 2-4 ns
Channel energy – 3-3.3 kJ
Energy in 2ω – 2kJ
Operates more than 15 years

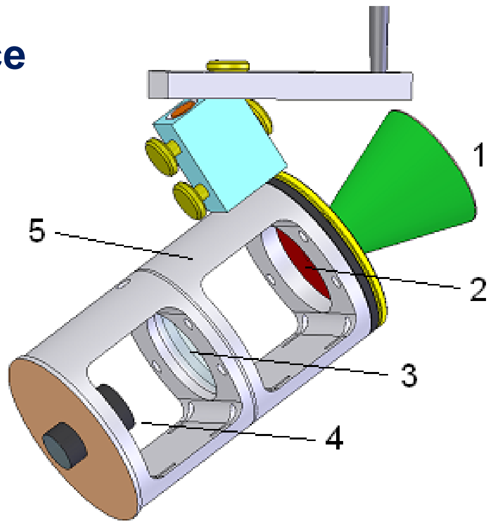
4-channel amplifying module

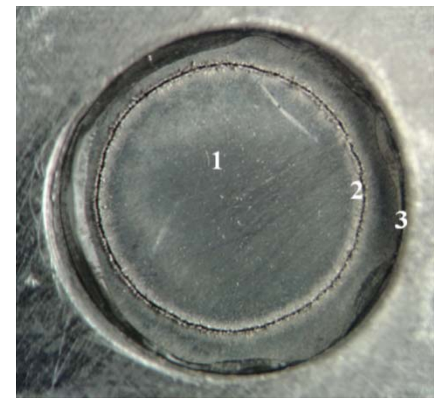
General directions of research

- Equations of state for various substances at pressures up to 70 MBar
- Soft XR mean free paths at temperatures up to 50 eV
- Soft X-radiation transport
- Gas dynamics instabilities and turbulent mixing
- Laser radiation transport within closed cavities
- LR absorption and reflection at flows $10^{11} – 10^{14}$ W/cm^2
- Methods of increasing laser radiation symmetry
- Magnetized plasma physics
- Physics of laser fusion targets of direct exposure
- Physics of laser fusion X-ray targets
- Non-equilibrium processes within inverted corona laser targets
- Processes at moderate laser radiation flows

Rheological properties study of various substances at “LUCH” facility







Target unit and draft photo

1 – high-power laser radiation beam;
2 – irradiated target backside;
3 – protective screen for collimator;
4 – PDV collimator;
5 – target unit case

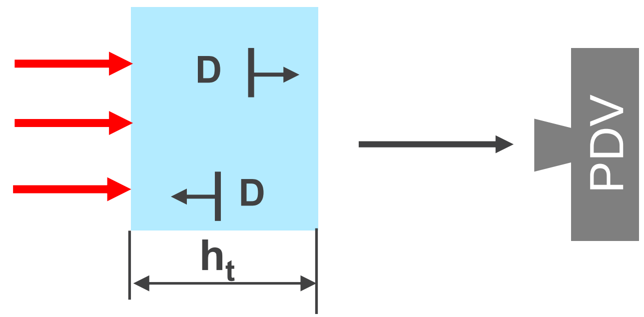
Photo of target backside surface initial state

1 – polished target surface;
2 – circular groove, reducing edge effect at spallation;
3 – border of aperture within the case

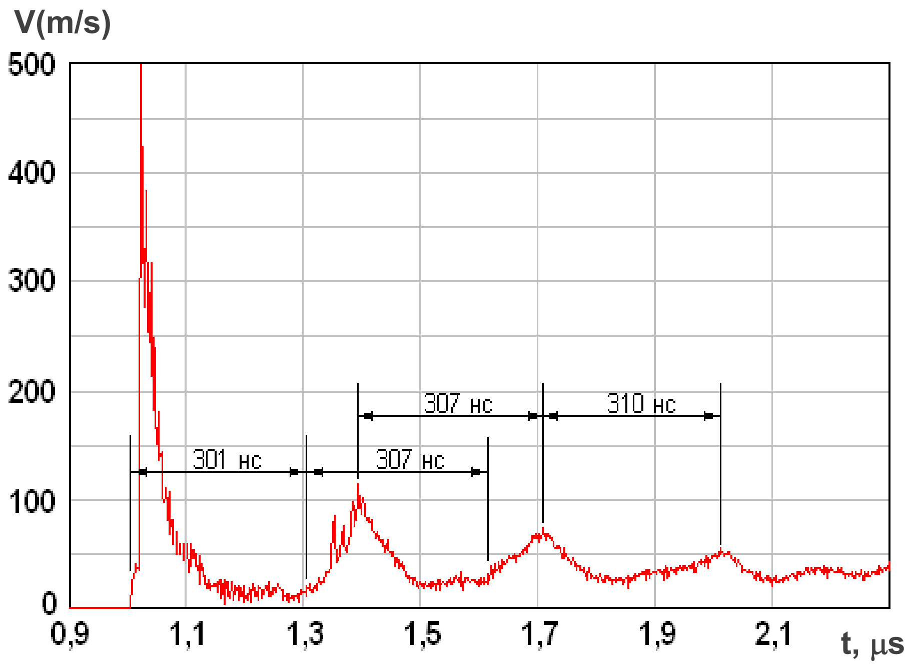
Photon Doppler Velocimetry (PDV) – laser optical - heterodyne method for velocity detecting.

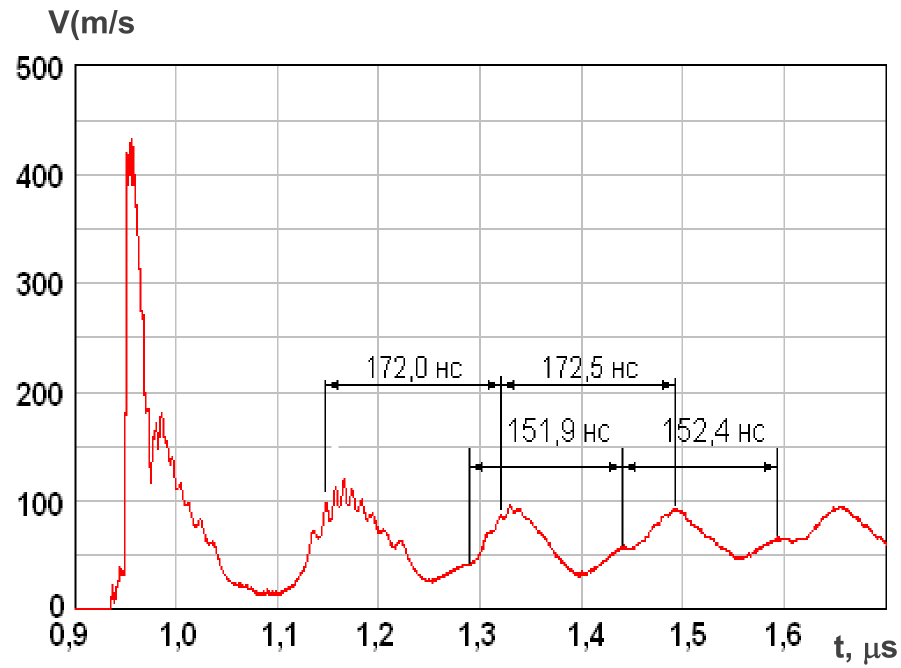
Acoustic waves in alloy AL1060
(no spalls)

h_t = 975 ± 1 μm
Q_{LR} = 107 ± 16 J
τ_{LR} = 5.0 ± 0.3 ns
S_{LR} = 9.5 ± 0.9 mm^2
τ = 308.5 ± 2 ns
D = 6.32 km/s



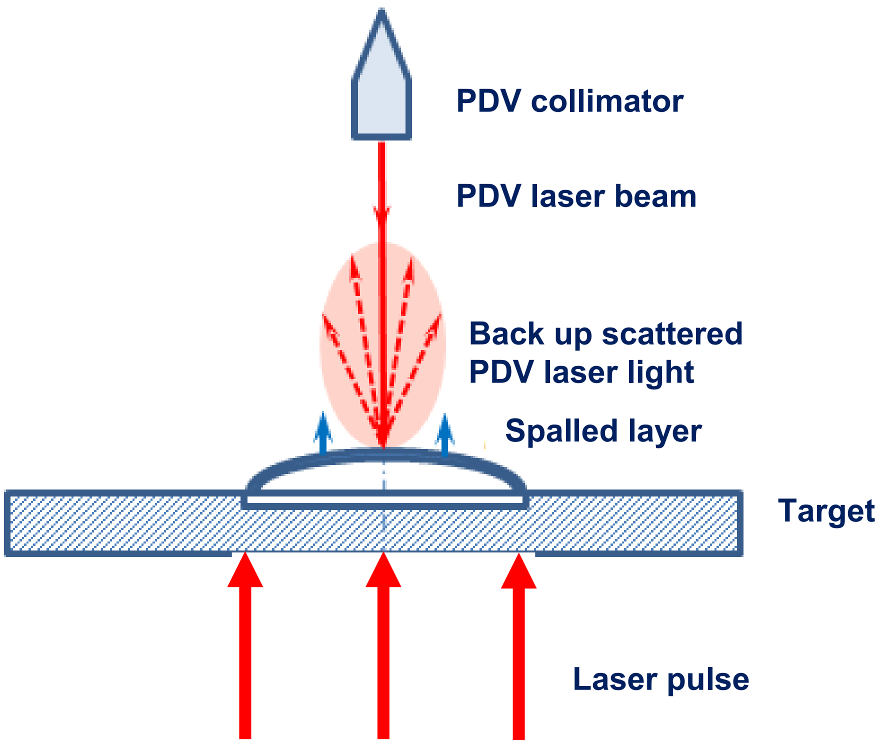
h_t = 515 ± 1 μm
Q_{LR} = 86 ± 13 J
τ_{LR} = 4.5 ± 0.1 ns
S_{LR} = 9.5 ± 0.9 mm^2
τ = 172.2 ± 1 ns
D = 5.98 km/s





Velocity of AL1060 flat target back surface vs time.
Attenuation of low shock (acoustic) waves.

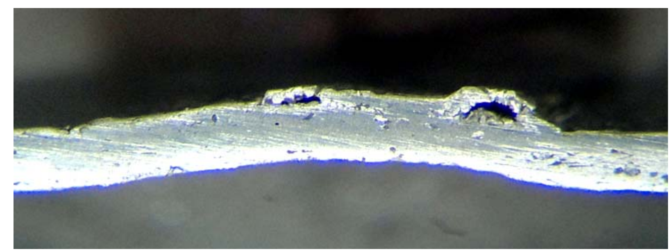
Spalls in AL1060 alloy
(Experiments at “LUCH” facility)



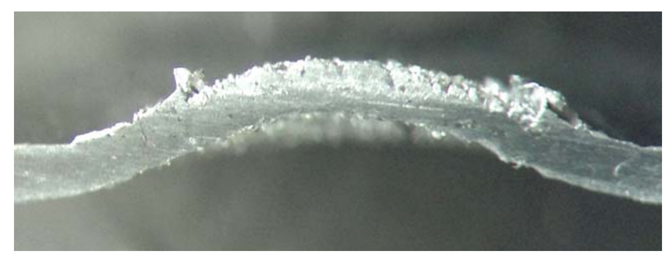
“LUCH” facility experimental layout
(flat liner)

Target cross-section photos

no spalls

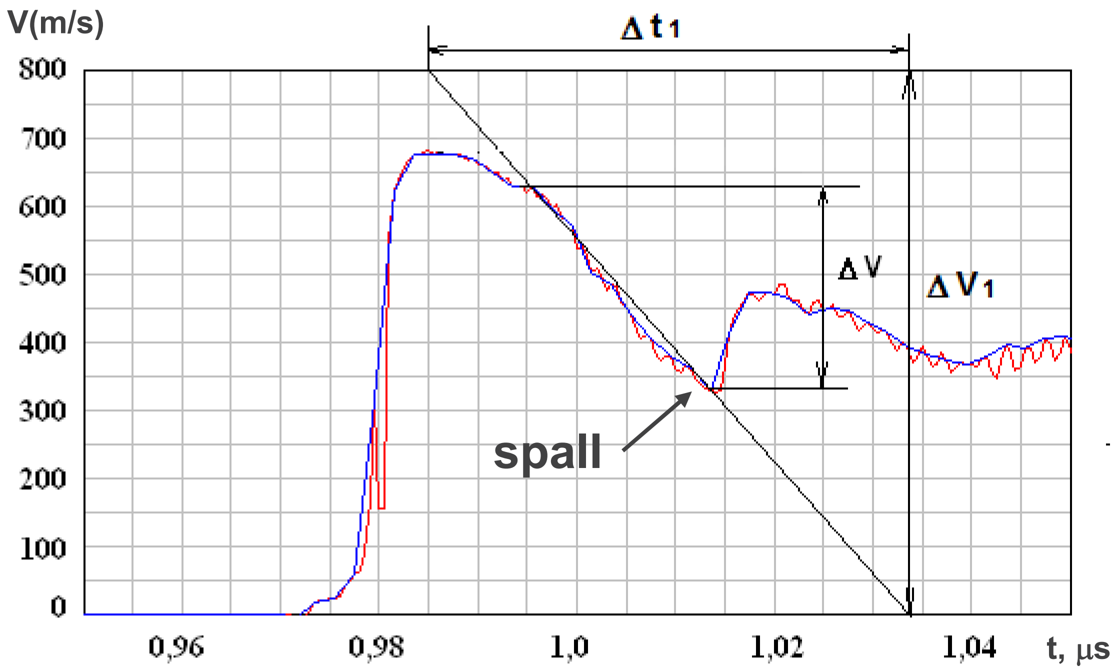


Concealed spalls



Complete spall

Target back surface velocimetry
(spalls)



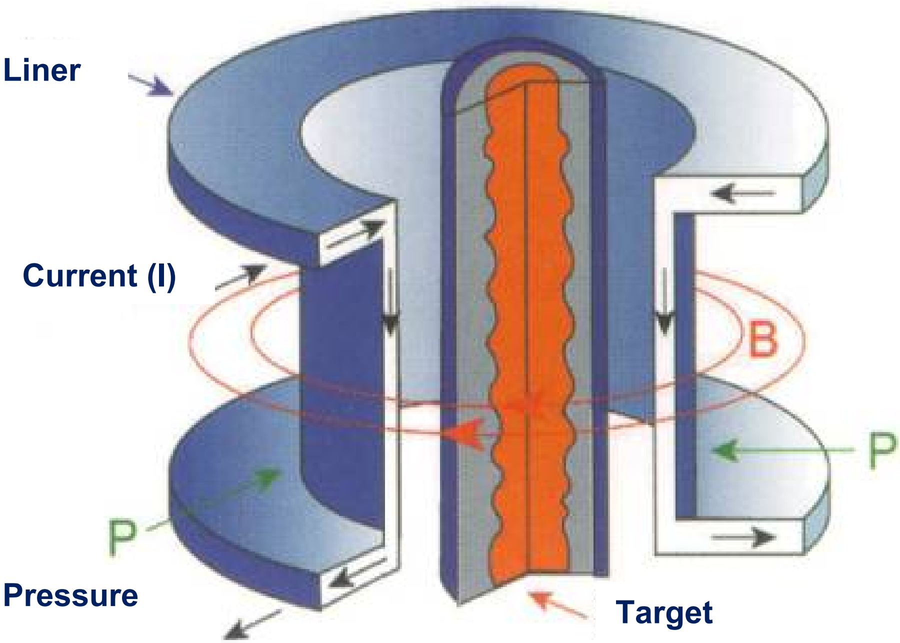
Influence of averaging interval in Hilbert transform on results of PDV oscillogram numerical processing :

$\Delta\tau$ = 125 ps – red; $\Delta\tau$ = 2000 ps – blue; $d\varepsilon/dt = -0.5 \cdot dv/dt/D$.

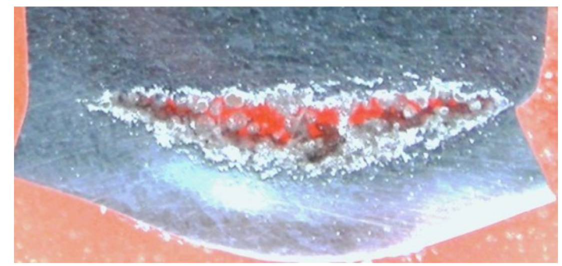
Spalls in AL1060 alloy
(electro physical experiments with magneto-cumulative generator)

Cylindrical liner

Loading scheme



Spall origin



Complete spall

ДОКЛАДЫ АКАДЕМИИ НАУК, 2013, том 448, № 3, с. 285–288

ФИЗИКА

УДК 539.4

ИССЛЕДОВАНИЕ РЕОЛОГИЧЕСКИХ СВОЙСТВ АЛЮМИНИЯ С ПРИМЕНЕНИЕМ ВЗРЫВОМАГНИТНЫХ ГЕНЕРАТОРОВ

© 2013 г.   В. А. Васюков, А. М. Глыбин, П. В. Дудай, В. И. Дудин, А. А. Зименков, В. А. Иванов, А. В. Ивановский, А. И. Краев, А. И. Кузяев, С. С. Надежин, А. А. Петрухин, А. Н. Скобелев, О. А. Тюпанова, W. L. Atchison, D. B. Holtkamp, A. M. Kaul, R. E. Reinovsky, G. Rodrigues, L. J. Tabaka, C. L. Rouscalp, J. B. Stone, D. M. Oro, M. Salazar, J. R.Griego, J. R. Payton, D. T. Westley

Представлено академиком Р.И. Илькаевым 30.03.2012 г.

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Aluminum alloys strength properties
(comparison of the results)

Purpose: extension of experimental data range on various material properties

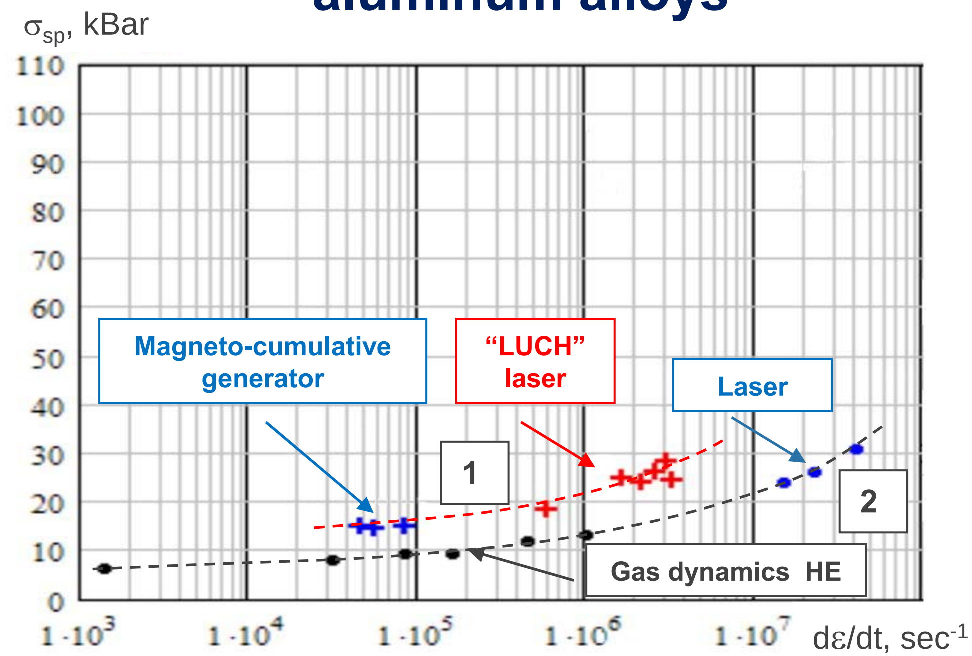
Methods: laser pulse and electro physical loading of liners, made from materials under consideration

Particular features: mutual verification of the methods, scale factor, enhanced range of effective parameters

Current stage: working-out of methods and their optimization

Expected results: creating of experimental material properties database for pulse processing techniques

Spall strength measurement for aluminum alloys



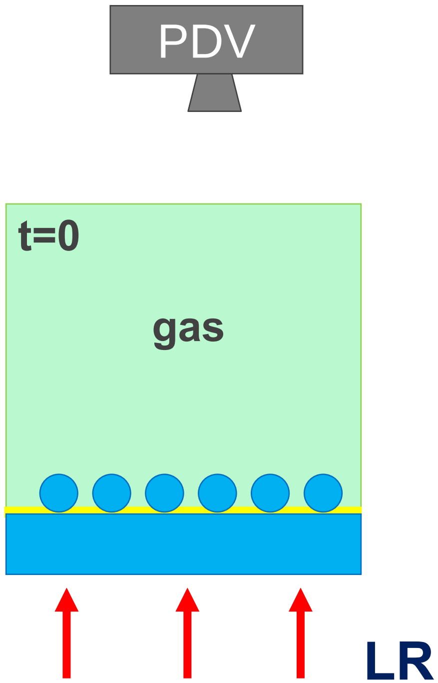
Deformation rate

1 – nano-dispersed aluminum AL1060.

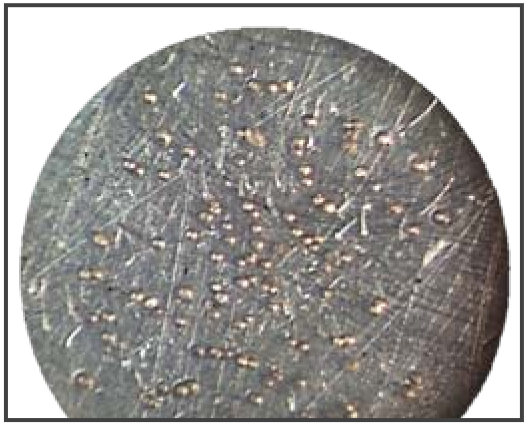
2 – aluminum alloy AMг6M –

A.I.Bushman, G.I.Kannel, A.L.Ni, V.E.Fortov " Thermal physics and dynamics of intensive pulse actions", Chernogolovka,1988.

PDV technique calibrating at “LUCH” facility experiments



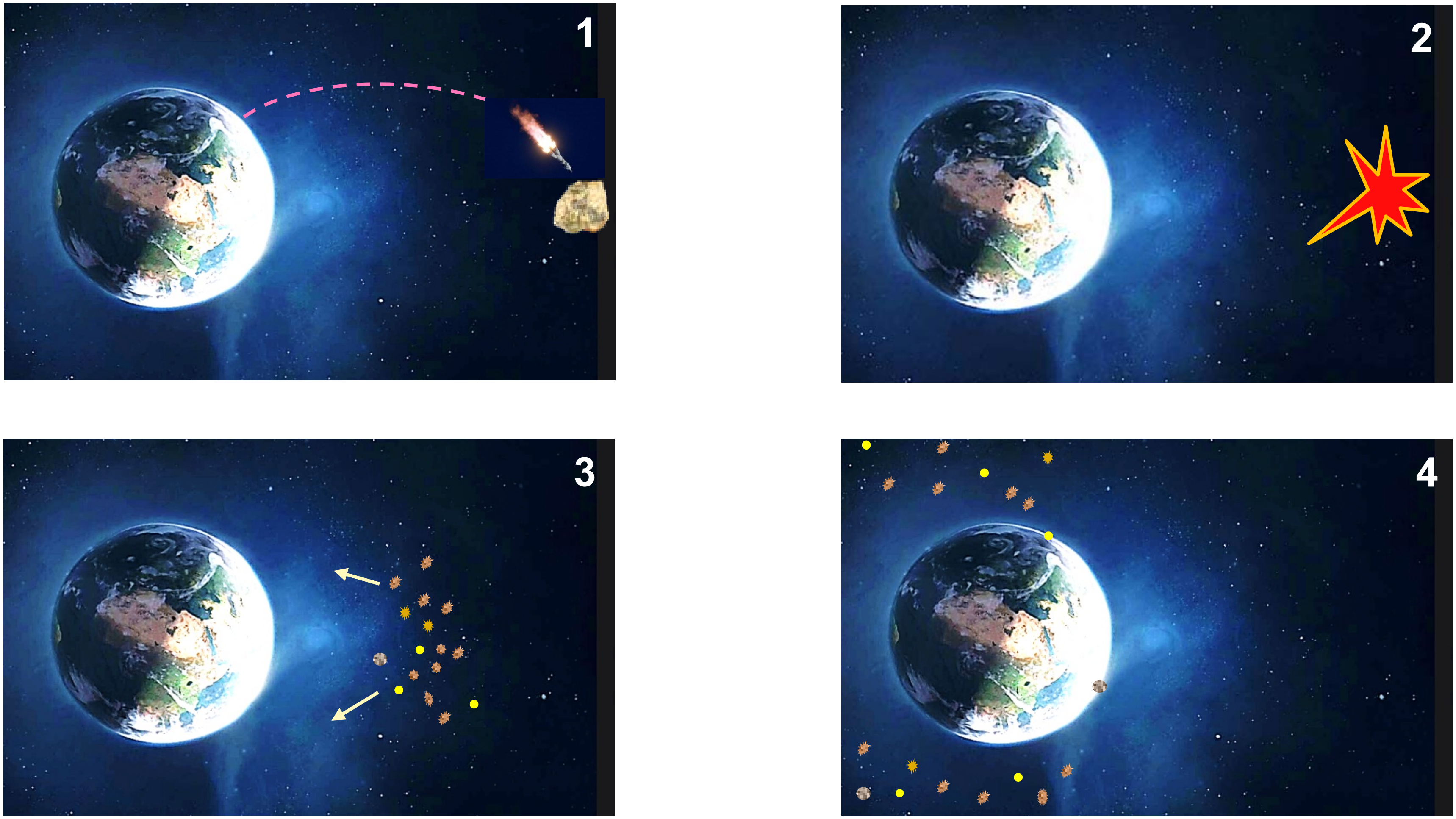
Experimental layout



Lead target with small spheres (experimental sample)

Small spheres deceleration in gas (ø ~ 100μm); $\Delta p<\sigma_{sp}$

Asteroid safety



Asteroid is disintegrated under nuclear explosion with small fragments, scattering wide apart . Catastrophe is prevented.

Asteroid safety
(on navigation)

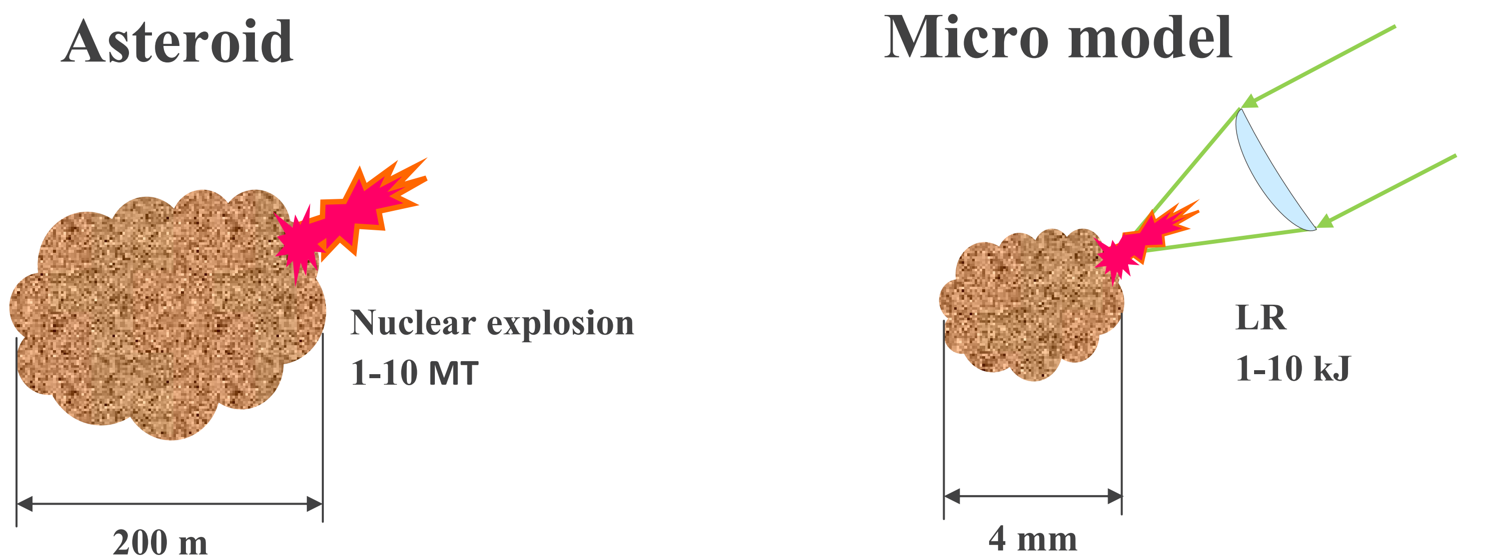
Estimation of nuclear protection conditions:

- When velocity of asteroid fragments at its disintegration is V_{fr}~ 10 m/s and Asteroid - Earth typical approaching velocity is V_{ast}~ 20 km/s, it is necessary to carry out nuclear explosion at distance $L= RV_{ast}/V_{fr}$~ 13 Mln. km to deviate fragments on safe distance, which is more than Earth radius R_{Earth}= 6400 km.
- For asteroids with 200 m in diameter self gravity of fragments is negligible, if its velocities V_{fr} are greater than 1 m/s.
- The rocket must start $t = L/V_r$~ 15 days before asteroid arrival at point of explosion with velocity V_r~ 10 km/s.
- At that moment the asteroid will be at the distance $L_1 = L(V_{ast} + V_r)/V_r$ ~ 39 Mln. km from the Earth.
- For more accuracy Kepler orbits must be used.
- High navigation accuracy should be provided during the whole flight period to ensure controlled effect of danger elimination.

Asteroid safety

- The method, simulating high-power nuclear explosion destructive effect on asteroids, is introduced and realized. It is based on physical and geometrical similarity concept.
- It is proposed to replace real asteroid of hundreds meters in diameter by its scale model, fabricated from the similar substance with the similar physical properties and having a few mm in diameter.
- Nuclear explosion energy release (in megatons) on the asteroid surface should be replaced by laser energy pulse release (hundreds J) on small area of the scale model surface.
- Hydrodynamic effects and processes of spallation will be physically similar both in full-scale and model scale tests, when explosion (laser pulse) energy to asteroid (model) mass ratios are approximately equal.
- On "ISKRA-5" and “LUCH” laser facilities the criteria for stony asteroid destruction at contact nuclear explosion were experimentally estimated using physical similarity principle.

Asteroid safety

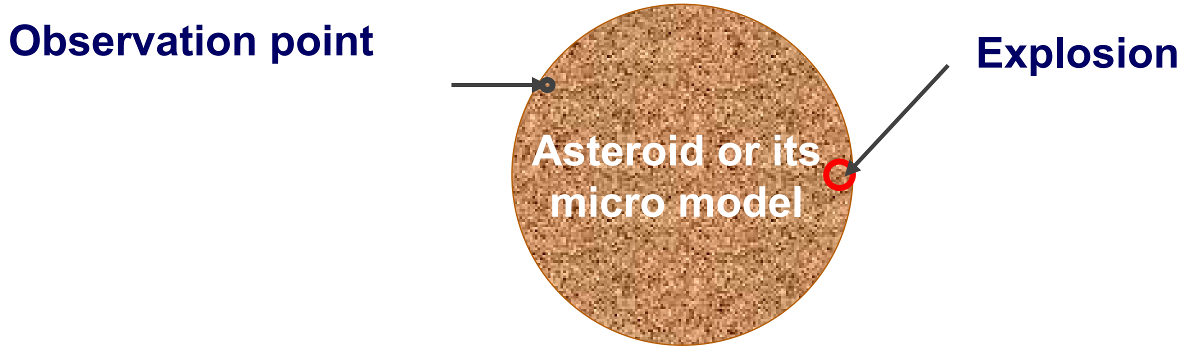


Large stony asteroids (80-90% from total number) are breakable and have low destruction threshold (0.05-0.1 kBar). It lets us hope on their effective splitting with the help of nuclear explosion.

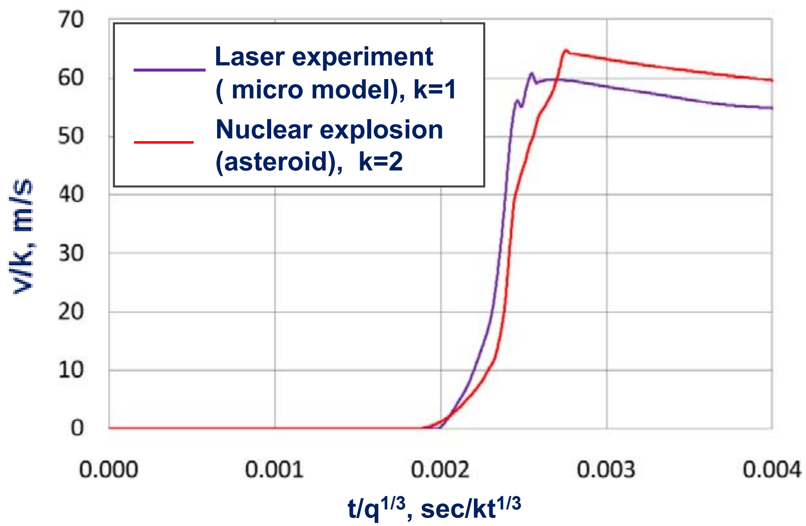
Equality of effecting energy to object mass ratios is key criterion of the physical similarity of processes in both full-scale and model scale tests.

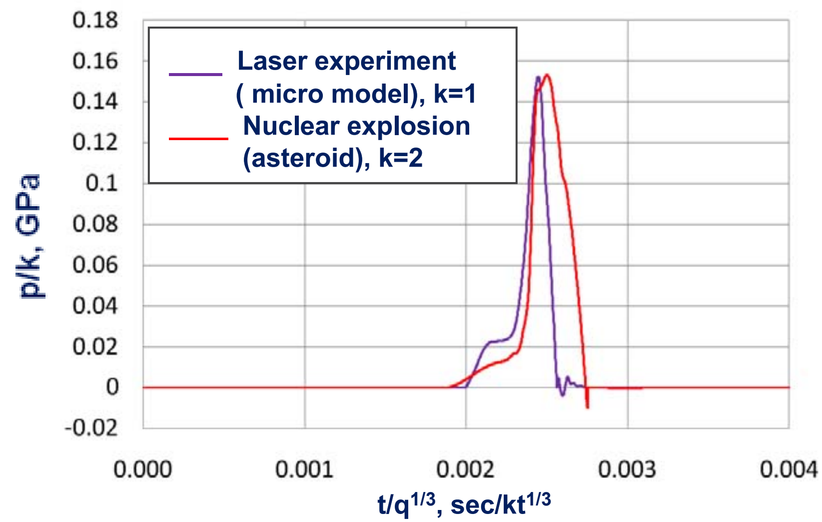
Asteroid safety

(2D – calculation similarity confirmation)



Calculation layout





The example of mass velocity and pressure dependence on normalized time at the presented observation point (kt – kilotons).

Asteroid safety

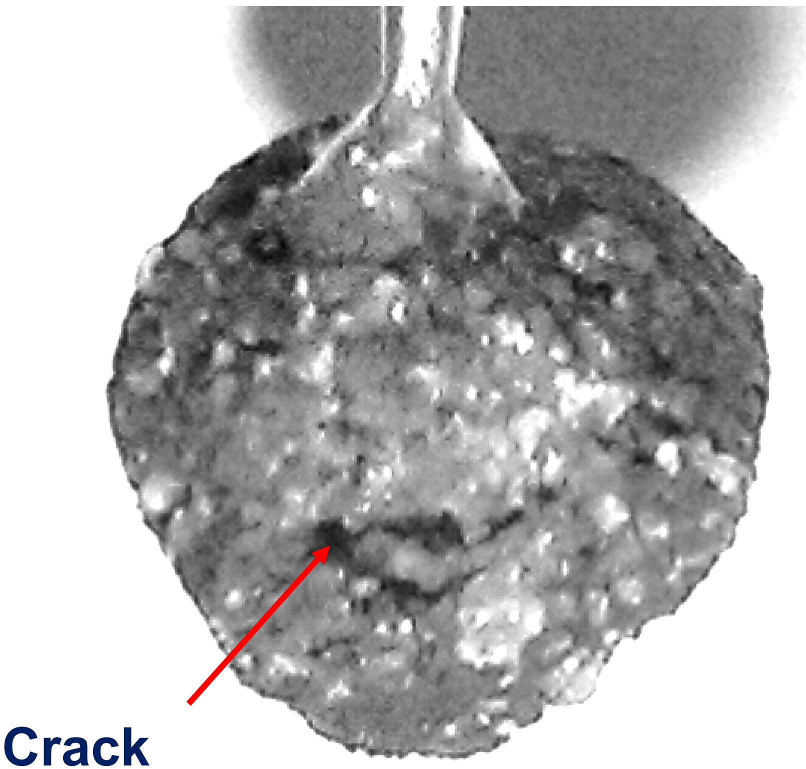
Chelyabinsk asteroid fragment
Mass ~ 0.5 tons
(initial mass ~ 10000 tons)

Stony asteroid micro model,
manufactured at VNIIEF,
Mass ~ 1 gram.

Asteroid safety
(laser simulation, "ISKRA-5")

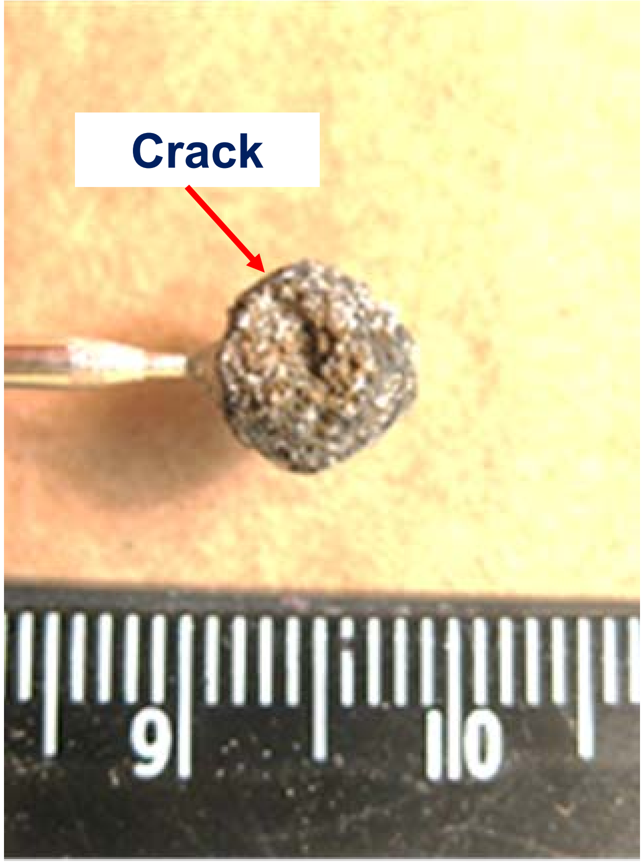
Photos of target ∅ 8 mm at "ISKRA-5" laser experiment (at destruction threshold)

Before experiment



After experiment

Asteroid safety
(laser simulation, "ISKRA-5")



Target ∅ 8 mm after experiment.

Fragments of target ∅ 4 mm, gathered after experiment.

Asteroid safety
(on artificial asteroid manufacturing)

1. Artificial chondrite: chemical composition

SiO_2 – 40%
FeS – 6%
MgO – 26%
Fe_2O_3 – 18%

2. Initial materials splitting up ranges:1-20-800 μm.

3. A few sets of mini asteroids with different compression strength σ are manufactured :

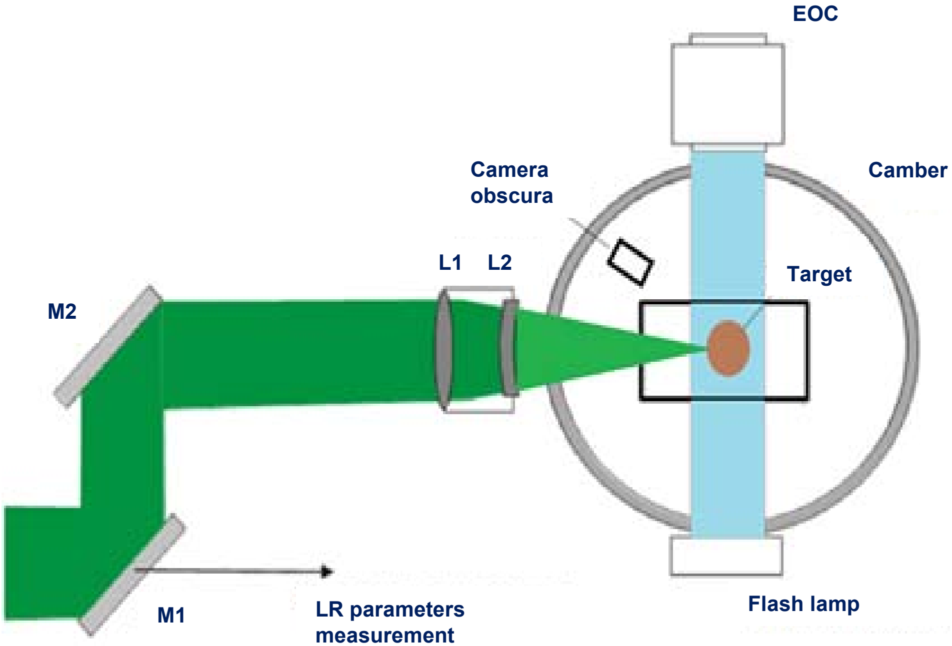
63 Bar
225 Bar
900 Bar
1341 Bar

4. Maximal tension strength is 10 times less, accordingly.

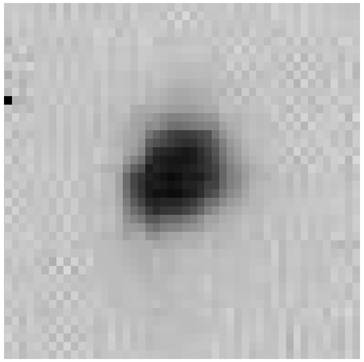
Typical diagram of artificial asteroid material sample compression

Maximal tension strength σ_{sp} = 6,3 MPa (63 Bar), and deformation ε_{sp} = 5,5 %.

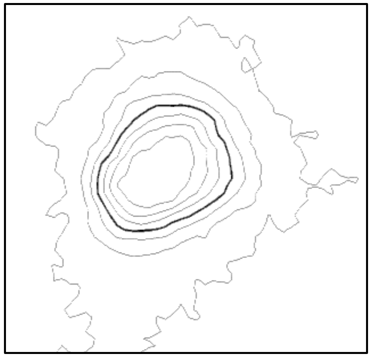
Asteroid safety
(Experiments at “LUCH” facility)



a)



b)



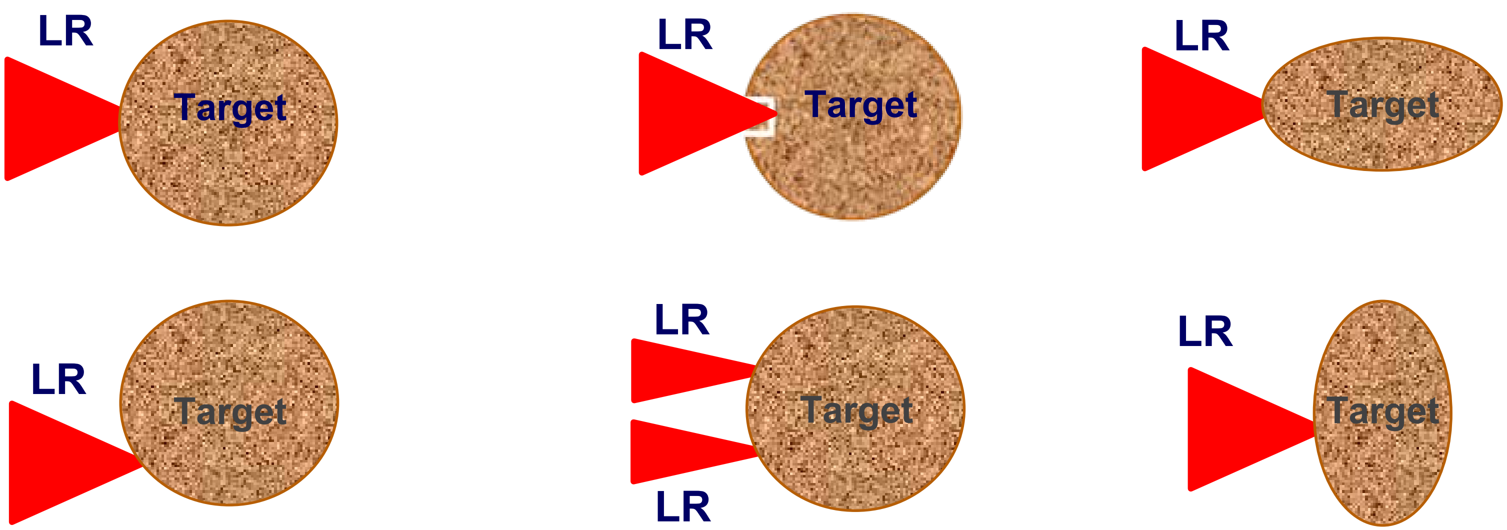
Experimental set-up layout :
M1, M2 – mirrors, L1, L2 – lenses,
EOC – Electron Optical Converter.
λ=0.527 μm, E_{las}= 100 ÷ 500 J,
$\tau_{0,5}$ = 1.4 ÷2.2 ns.

Typical “LUCH” experiment:
a)X-ray camera obscura photo of the laser spot.
b) X - ray intensity distribution isolines. d_{eff} =129 μm.

Asteroid safety
(variation of parameters)

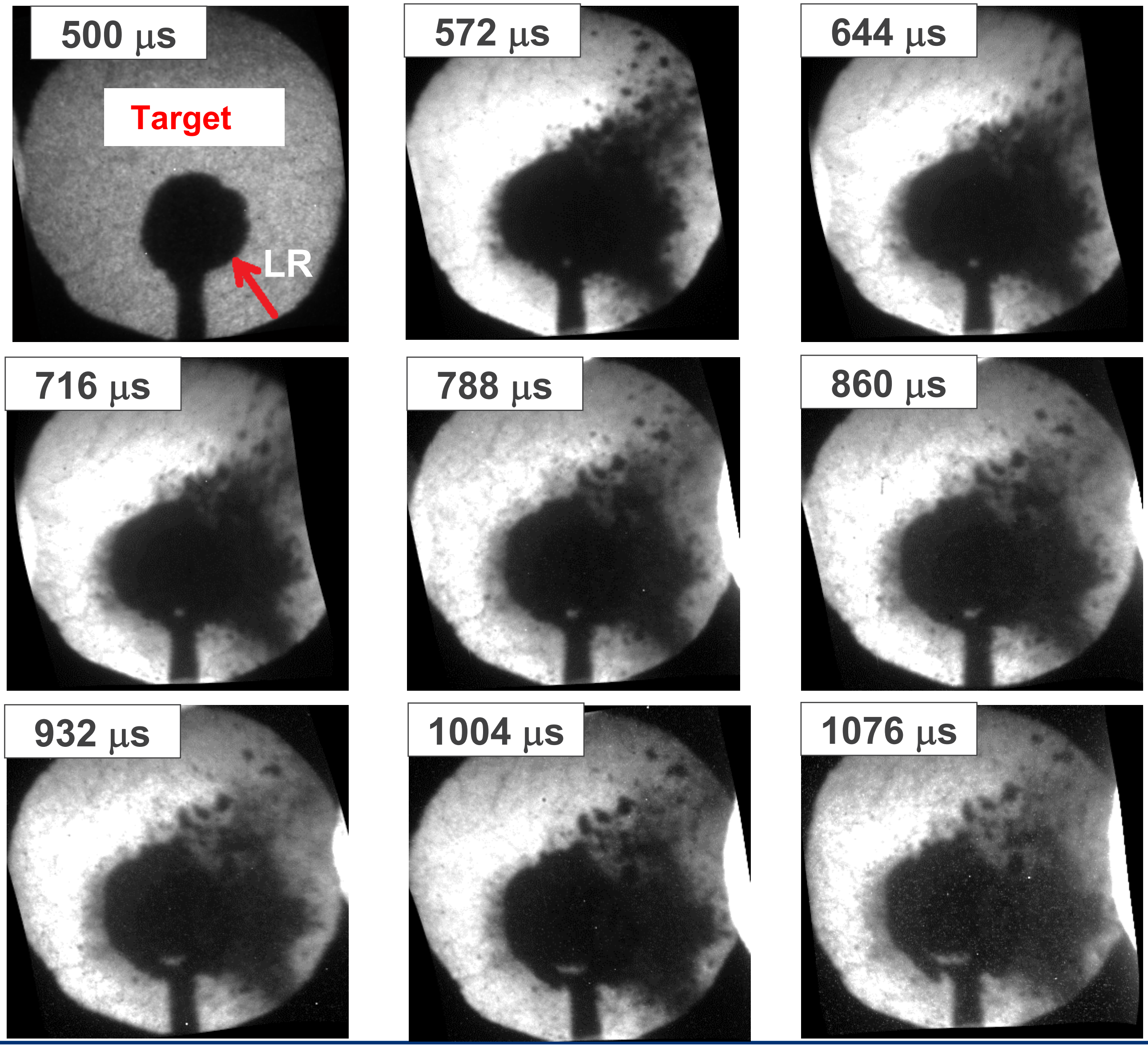
To determine the criteria for asteroids effective destruction at nuclear explosion the following laser experiments were carried-out :

- **With variation of mini asteroids size and shape**
- **With variation of the substance heterogeneous structure**
- **With micro models having different compression strength**
- **With the natural chondrite asteroid substance**
- **With variation of energy release place**
- **With imitation of nuclear explosion in a cavity**



Asteroid safety

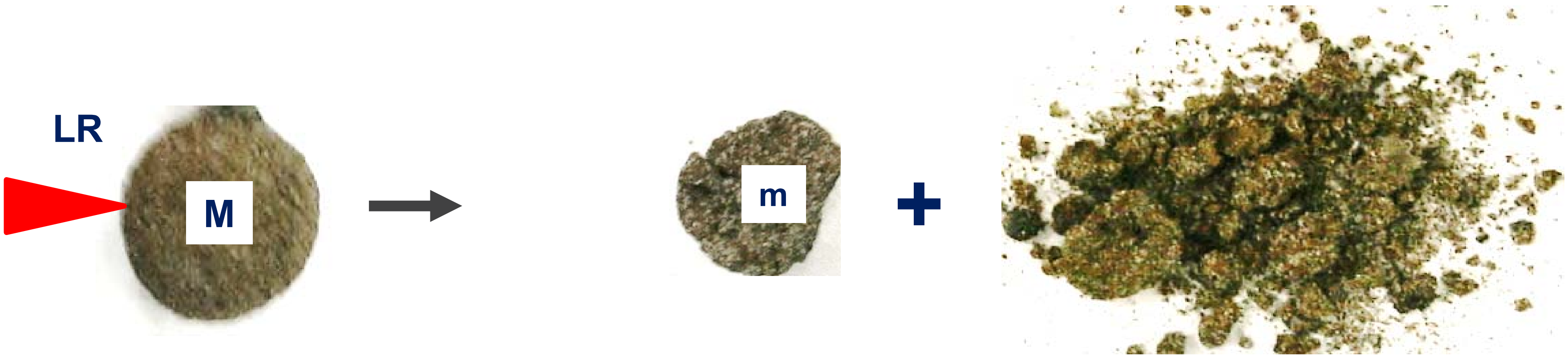
(target fragments dispersion at "LUCH" facility)



Typical dynamics of target fragments dispersion. Experiment 05.02.15. Start of shooting – 500 μs after target irradiation.

Asteroid safety
(“LUCH”, sphere, σ=225 Bar)

29.09.2015 E/M= 500 J/g. Partial destruction. Backside super large fragment m= 0.35·M.



23.09.2015 E/M= 750 J/g. No super large fragments.

Asteroid safety
(“LUCH”, sphere, σ =1341 Bar)

21.07.2015 E/M= 740 J/g. Partial destruction. Backside super large fragment m= 0.75·M.

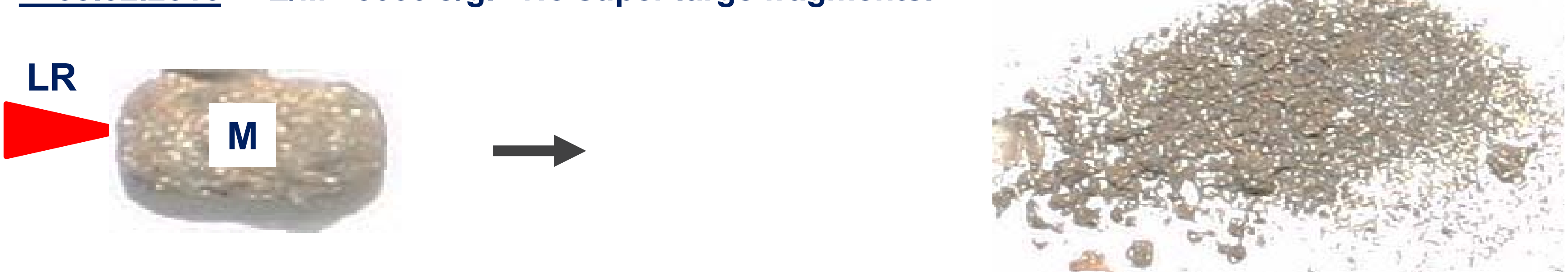
22.07.2015 E/M= 1100 J/g. No super large fragments.

Asteroid safety
("LUCH", ellipsoid σ =225 Bar)

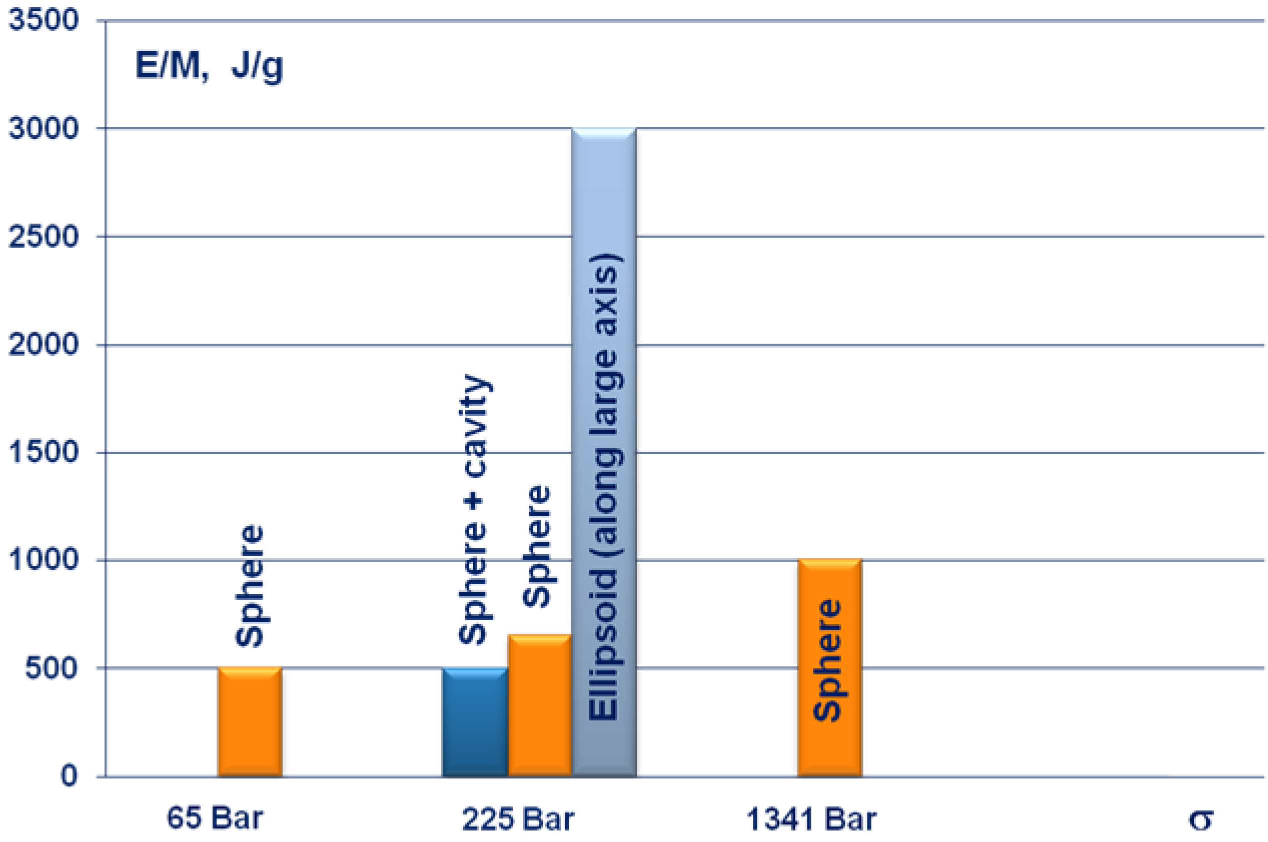
22.01.2016 E/M= 1300 J/g. Partial destruction. Backside super large fragment m= 0.45·M.

03.02.2016 E/M= 2900 J/g. Partial destruction. Backside super large fragment m= 0.23·M.

03.02.2016 E/M= 3000 J/g. No super large fragments.



Asteroid safety
(“LUCH” facility experimental summary)



Dependence between asteroid micro model destruction criterion and compression strength.

Asteroid safety

- The direct numerical calculations confirmed quantitatively the existence of similarity.
- Stony asteroid effective destruction takes place at nuclear explosion energy to mass ratio more than

E/M = 1000 ÷ 3000J/g.

- Laser experiments results converted into full-scale conditions demonstrate that nuclear explosion with energy ~ 6 Mт destructs effectively 200 m diameter stony asteroid.
- Effective destruction threshold rises for ellipsoid-shape asteroids.
- Typical velocity of macroscopic fragments is the same both in full-scale and model cases. Fragments velocities were about V_{fr} ~ 4.5 ÷ 15 m/s.

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Thank you for your kind attention!