Transmission of laser radiation with a wavelength of 0.438 μm and intensity of (3--7)·10^{14} W/cm^2 through undercritical plasma from polymer aerogels

N.G.Borisenko, A.A. Akunets, A.M.Khalenkov, D.Klir[1], V.Kmetik[2], E.Krousky[3], J.Limpouch[1], K.Masek[3], Yu.A.Merkuliev, V.G.Pimenov[4], M.Pfeifer[3], I.Ullshmidt[2].

Lebedev Physical Institute, Moscow, Russia,

ngbor@sci.lebedev.ru

[1]*Czech Technical University, Czech Republic*

[2]*Institute of Plasma Physics, Czech Republic*

[3]*Institute of Physics, Czech Republic*

[4]*Zelinsky Organic Chemistry Institute, Russia*

Abstract

The velocities of energy transport in undercritical plasma of polymer aerogel with and without copper nanoparticles were measured. Transmission of laser light through targets of different thicknesses as submicron three-dimensional polymer networks with densities below the critical value ($0.13 \div 0.52 N_{cr}$) for a wavelength of 0.438 μm and intensity of $(3 \div 7) \cdot 10^{14}$ W/cm^2 at a half-height pulse duration of 0.32 ns was studied. The transfer of a heating laser radiation was registered on the rear side of the target. It ranged from the level of about 0.5% for the thickness of a low-density layer of 400 μm and density of 9 mg/cm^3 (mass per unit square of 0.36 mg/cm^2) up to 50÷60% for the thickness of 100 μm and density of 2.25 mg/cm^3 (mass per unit square of 0.02 mg/cm^2). The time dependences of the optical emission from the rear side of the targets were measured. They are indicative of the plasma dynamics in two-layer targets (polymer foam on Al foil) and enable the estimation of the absorption depth for the laser light in undercritical plasma.

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OUTLINE

- Introduction.
- Target development
- Characterization of plastic aerogel with nanoparticles
- Basic/differential plasma properties study: transparency of undercritical aerogel
- Application
- Conclusion

ICF target – a means of plasma science and technology

From target design to target fabrication: estimate, create, measure

Aerogel target + nanoparticles

Necessary scale ρ, F, I, d…	+	+	+
Fluctuations and accuracy	?	+	+
Admixtures	?	+	+

Is target developed then? NO!

- **Apply it in plasma experiment**
- **Analyze for predicted and/or new physics**
- **Verify target specifications**
- **Meet new requirements through fabrication development**
- **Measure plasma basic/deferential properties**

Get a relevant target !

Method of heat-and-flow smoothing for non-uniform energy distribution

Powerful laser radiation speckled structure causes plasma instabilities and shell-fuel mixing. For uniform energy distribution the foam of undercritical density is proposed on the target to convert light to heat-and-shock in the essential volume of corona. The laser energy input improves. The small-scale instabilities and the viscous dissipation of those are initiated, the interplay of relaxation and dissipation processes was shown to produce homogenization [Gus'kov, 1998].

Method of dynamic plasma phase plate (DPPP)

A separate highly transparent thin foam foil across the laser beam path was proposed and tested in VNIIEF, Sarov (Federal Institute of Experimental Physics). Relatively large cells and thin structural elements were requested.

Thin and non-stable plasma network acts as a phase plate, but has no drawback of the stationary RPP of having permanent phase pattern.

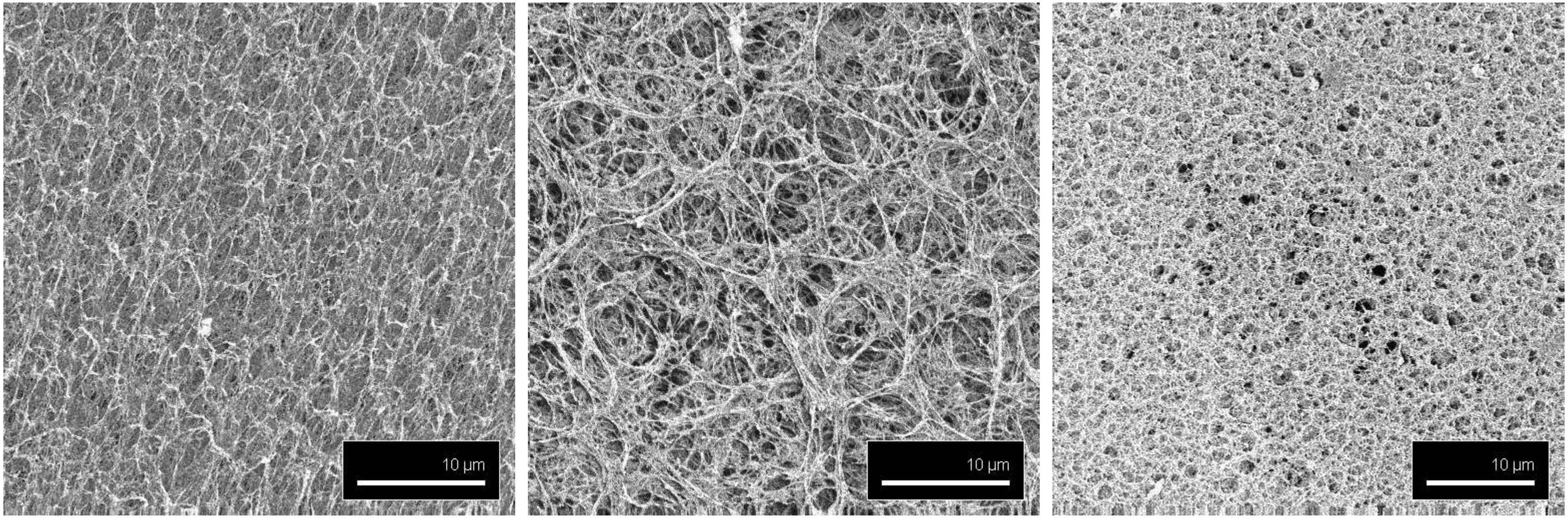
New goals for aerogel targets fabrication

- High-Z nanoparticles dopant with different boiling temperatures for increasing uniform compression.
- Steps in density profile ranging from subcritical (2 mg/cc) to 100 mg/cc for increased hydrodynamic efficiency of targets.
- Layers with density gradient for experiment on equation-of-state of the matter.
- Concentration wave of high-Z nanoparticles in aerogel layer for increasing target efficiency, and/or for x-ray converter.

Production of TAC (Triacetate Cellulose) aerogel (3-D Network)

- TAC chemical synthesis (see posters of V.G. Piminov)
- Strong transparent gel formation of 0.1-0.2 mass % from thermally induced gelation/crystallization system in mixed (chloroform and methanol) solvent.
- Vessels are surface treated by fluoro-organo-silicon Ftorsam-39 (supplied by the Zelinskii Institute of Organic Chemistry) to ensure hydro-and-oleo phobic properties. Uniform thickness foam layers realized.
- *Cu*-loaded TAC for aerogel with average cluster size of 50 nm (specific surface when in powder 23.6 m^2/g) Silica-organic modifier preserves the aerogel structure from deterioration during the loading procedure.
- Samples of gel layers bathed in methanol for aging.
- Supercritical drying using CO_2 as usual.

Polymer TAC aerogels of different density



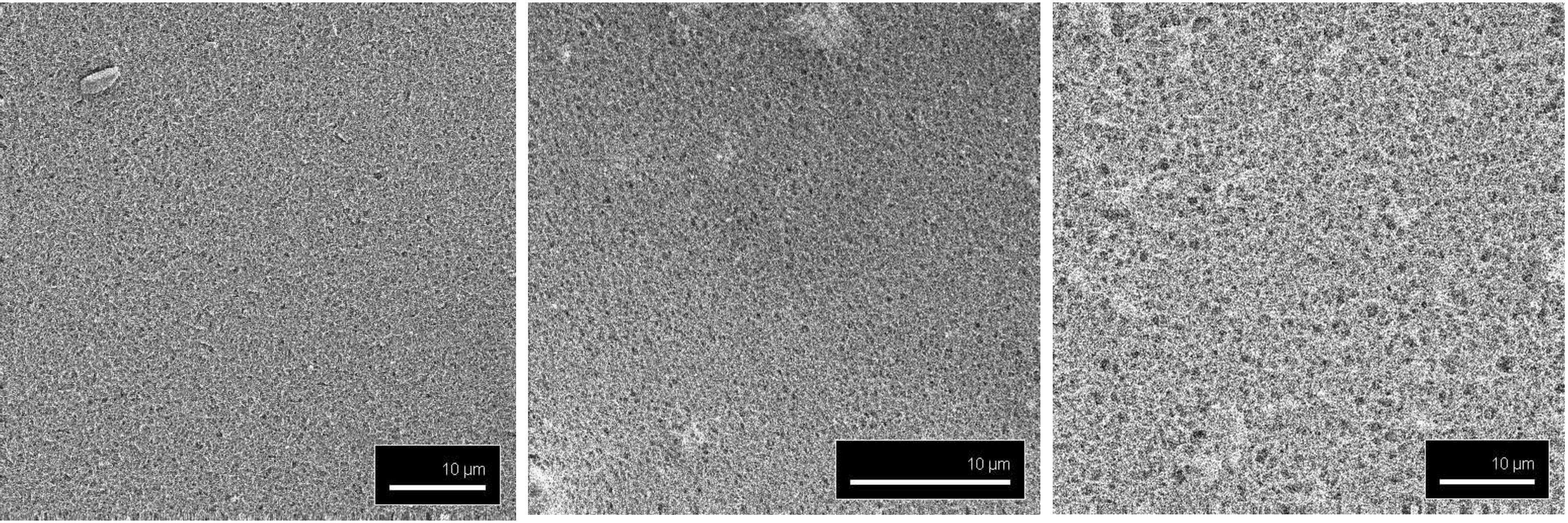
SEM pictures: from left to right TAC 1 mg/cc, 2 mg/cc and 5 mg/cc. Scale–10µm.

A.M. Khalenkov, N.G. Borisenko, et al. Experience of microheterogeneous target fabrication to study energy transport in plasma near critical density. // Laser & Particle Beams, 2006, Vol. 24, pp. 283-290.

N.G. Borisenko, et al. Regular 3-D networks with clusters for controlled energy transport studies in laser plasma near critical density. // Fusion Sciences and Technology, 2006, V. 49, #4, pp. 676-685.

N.G. Borisenko, et al. Intensive (up to 1015 W/cm2) Laser Light Absorption and Energy Transfer in Subcritical Media with or without High-Z Dopants. AIP Conference Proceedings, 2006, Vol. 849, pp. 242-246.

Polymer TAC 3D-nets with and without Cu nanoparticles



TAC structure of 10 mg/cc (SEM) from left to right: without Cu, with Cu nanoparticles of 10% by weight and of 20% by weight. Scale – 10 μm. Synthesis in IOCh 01/19/2005

A.M. Khalenkov, N.G. Borisenko, et al. Experience of microheterogeneous target fabrication to study energy transport in plasma near critical density. // Laser & Particle Beams, 2006, Vol. 24, pp. 283-290.

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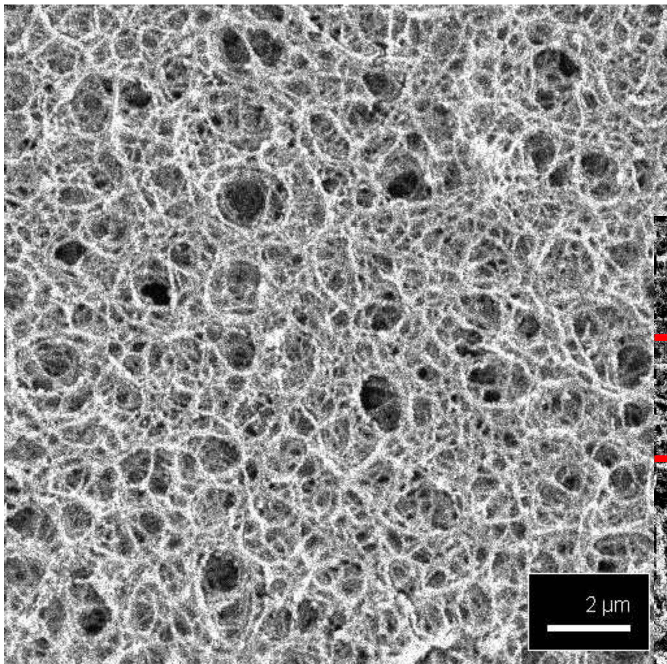
N.G. Borisenko, et al. Intensive (up to 10^{15} W/cm^2) Laser Light Absorption and Energy Transfer in Subcritical Media with or without High-Z Dopants. AIP Conference Proceedings, 2006, Vol. 849, pp. 242-246/

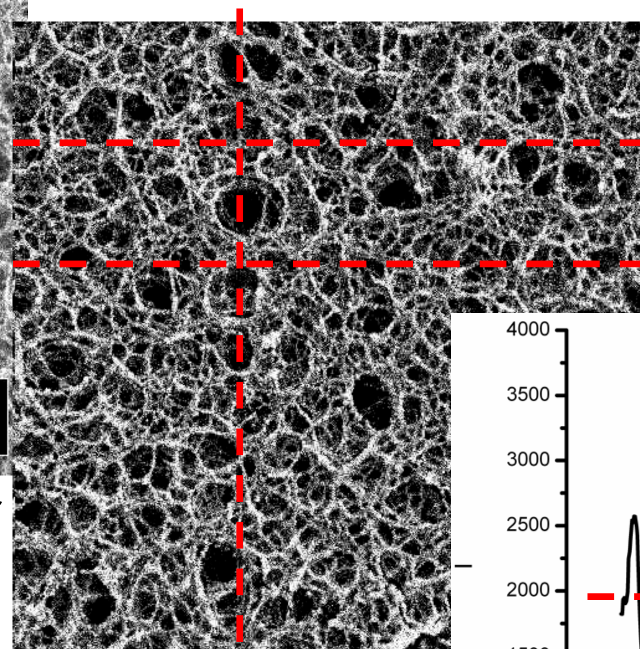
Average pore size

Computer procedure of 3-D network analysis to measure the cell size and fiber diameter

TAC of 10 mg/cc done Jan 15 ,2005, average fiber distance (pore size) ≈ 1.5 μm



Initial SEM image, scale bar 2 μm



Scanned intensity line ready for cell and fiber mathematical restoration

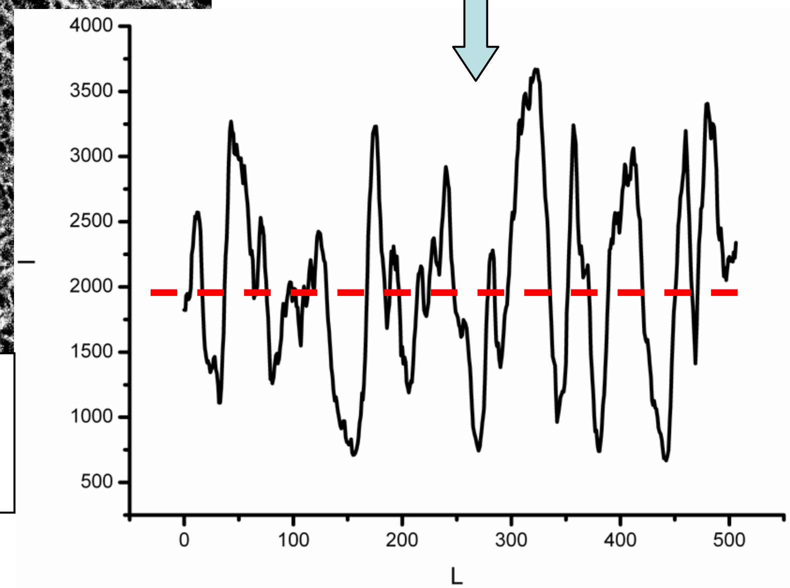
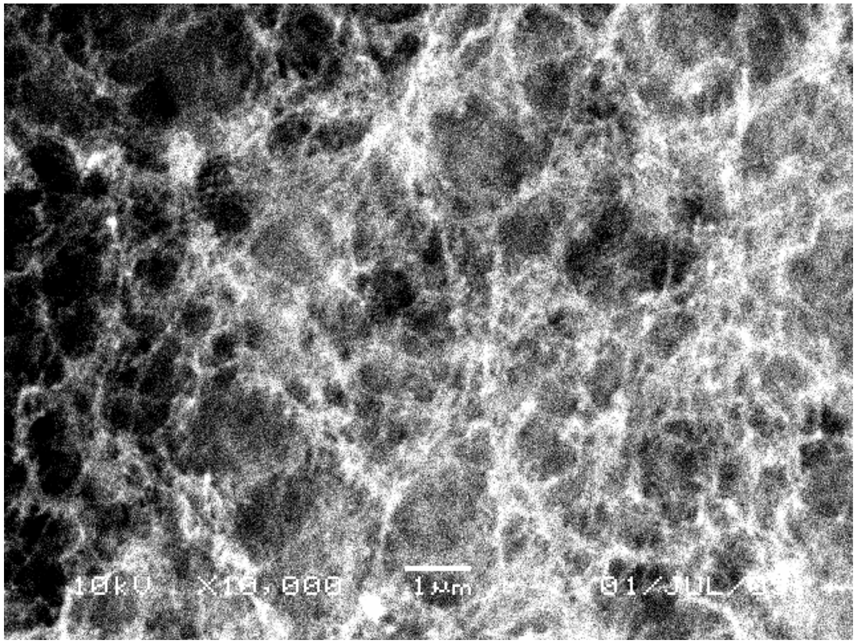
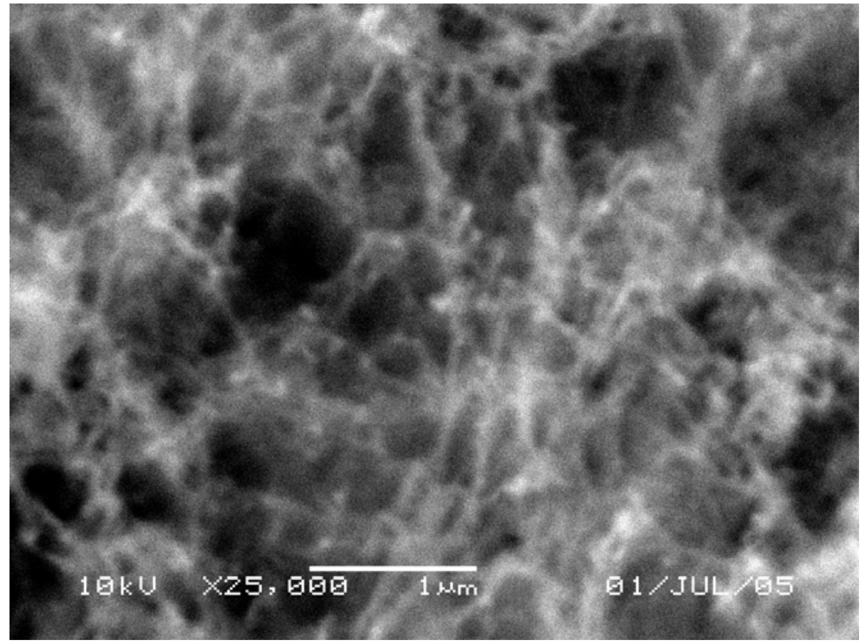


Image processed: denoised, illumination and contrast equalized, intensity scanning done along the red lines

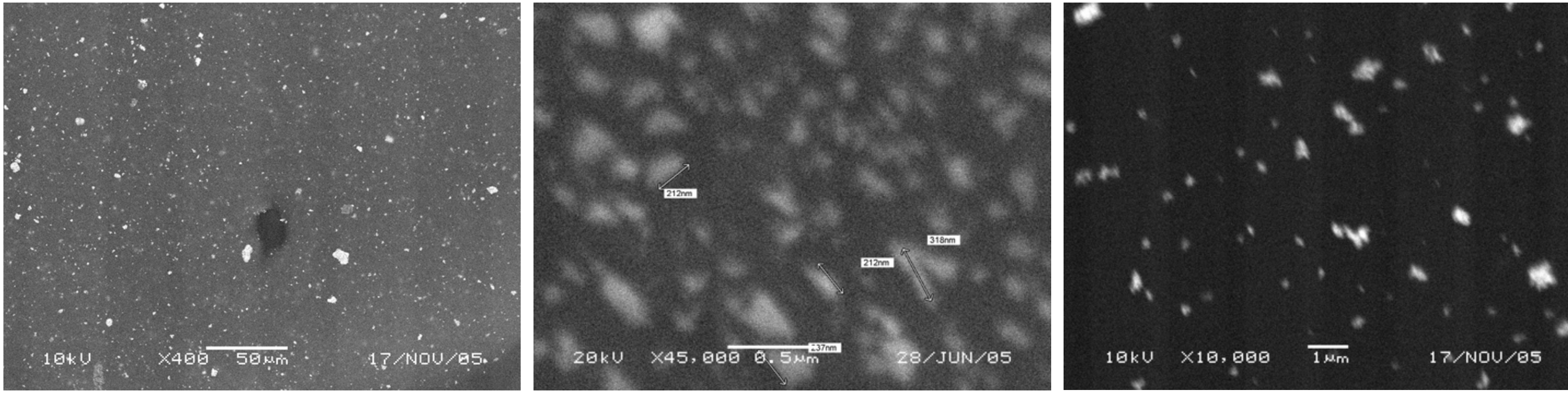
Structure by SEM photos: TAC 3D-networks depend on coating.



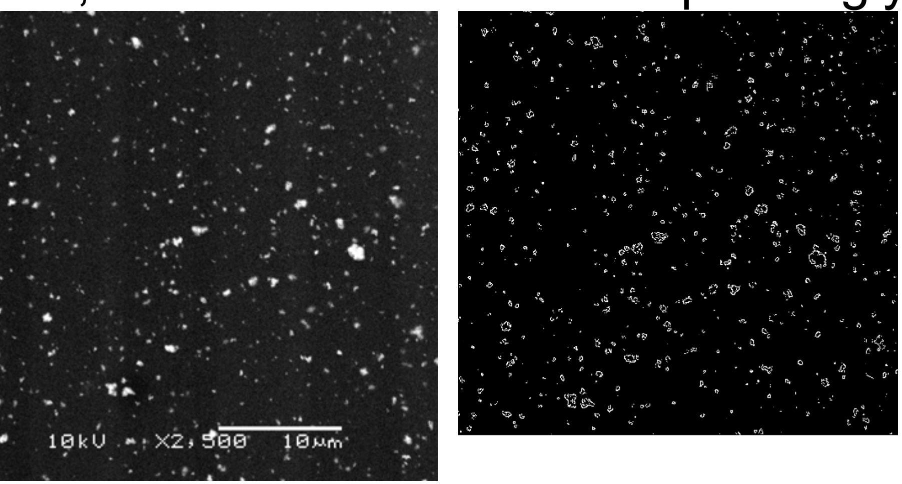


2 SEM images of TAC 5 mg/cc with 20-nm carbon coating. Scale bar is 1 μm. Gold visualizes rougher structure with larger inter fiber distances, thin details are lost

SEM monitoring of Cu-particles



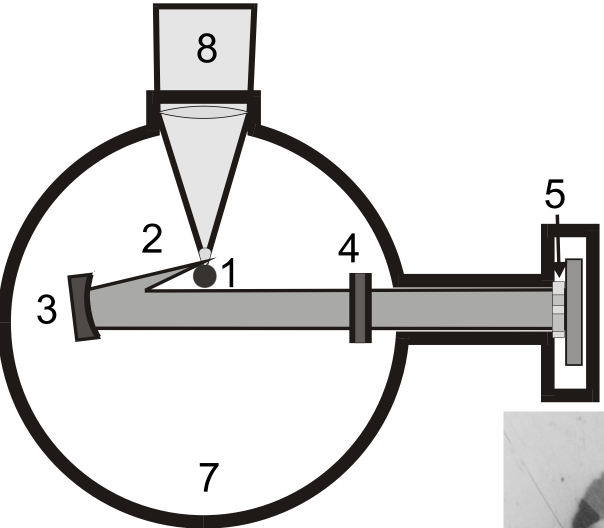
SEM in poor vacuum for submicron Cu particles and agglomerate visualization in X-ray self emission of Cu. TAC film+15wt% Cu. Bars equal 50, 0.5 and 1 micron correspondingly.



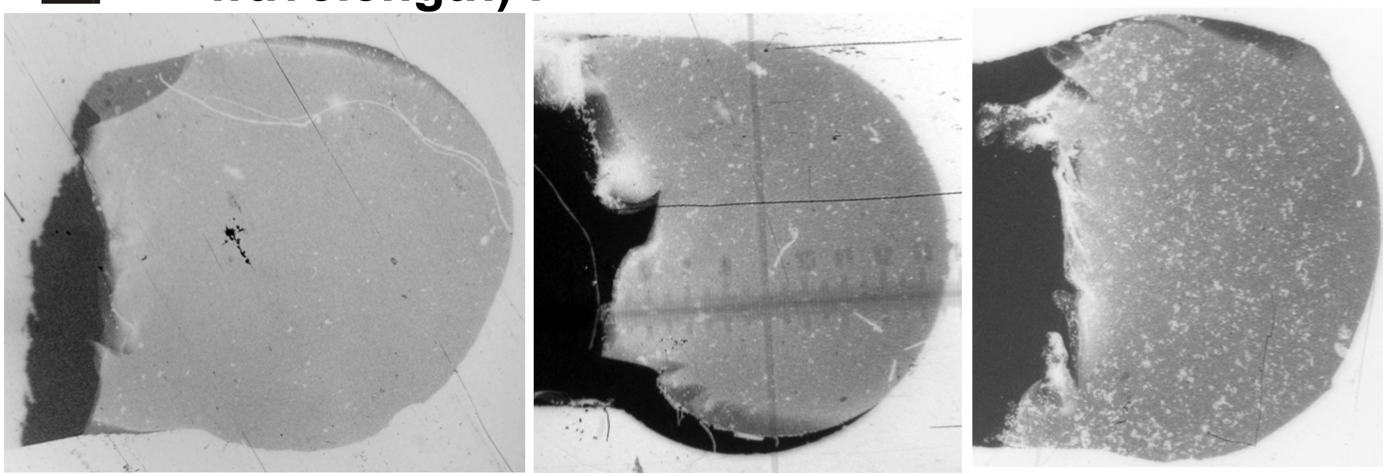
The images with no conductive material on the surface of the layer; dark area in the center is due to damage of the low-density layer by electrons.

TAC film with Cu-particles in it (bar 10 µm): left – SEM picture, and right picture – numerically processed one for automatic particle and agglomerates counting. Software of LPI. **High-Z particles near the surface are clearly visible**

Plasma backlighting+multilayered mirrors (x-ray and EUV) for monitoring of plastic aerogel



Experimental scheme for monochrome X-ray (4.5nm, 286eV) imaging :
1- Massive renium target; 2- plasma cloud; 3- multi-layered X-ray normal-incidence mirror Co/C; 4- Sc/C filter on the polyimide film; 5- aerogel; 6- X-ray film UF-4 (Russian); 7- vacuum chamber; laser light (0.53 µm wavelength) .



3 soft X-ray transmission images of TAC with thickness 0.3 mm and density 10 mg/cc. From left to right – pure TAC, TAC with 10% Cu by weight, TAC with 20% Cu by weight (70 µm between long scale marks). High-Z particles are clearly seen in the volume

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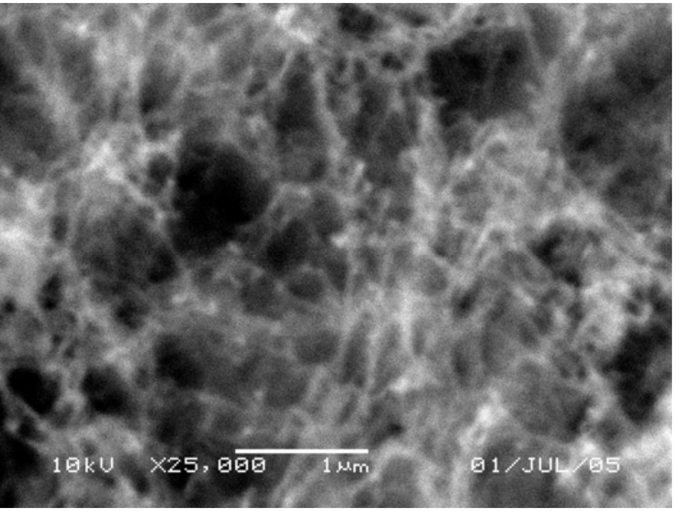
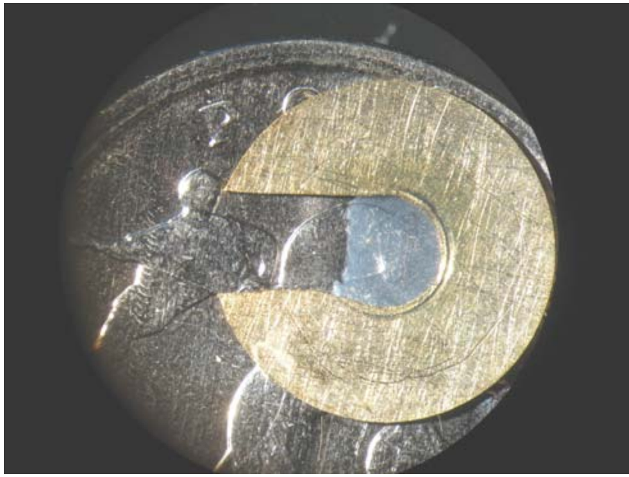
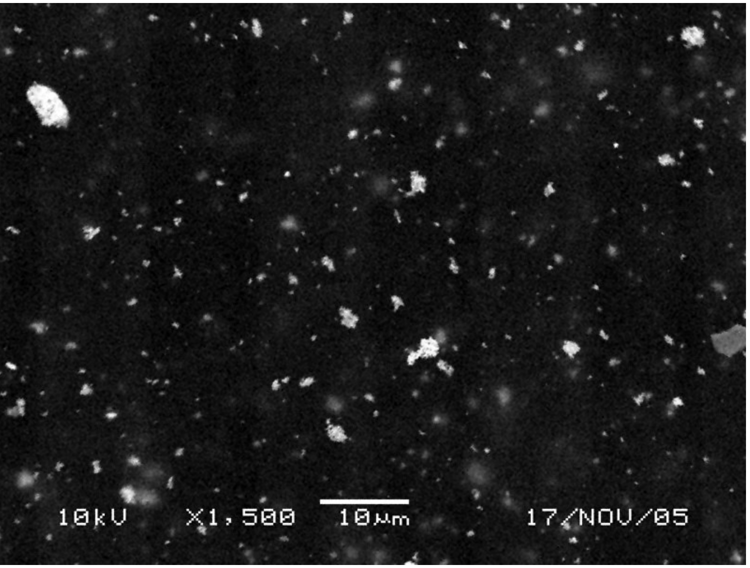
Aerogel layers of density-independent structure



Density fluctuations <1% in the focal area Ø 300 µm



TAC 10 mg/cc 300 µm on the kopeik



Similar structure in the range 50 down to 1 mg/cc, inter fiber distance 0.4- 1.8 µm, diameter 0.05 µm, fiber density 0.2 g/cc

TAC+Cu (15% mass) 10 mg/cc, Cu particles 40 nm, concentration $5 \cdot 10^{12}$ cm^{-3}, 3% nanoparticles agglomerated

Developed target should be studied in plasma experiment!

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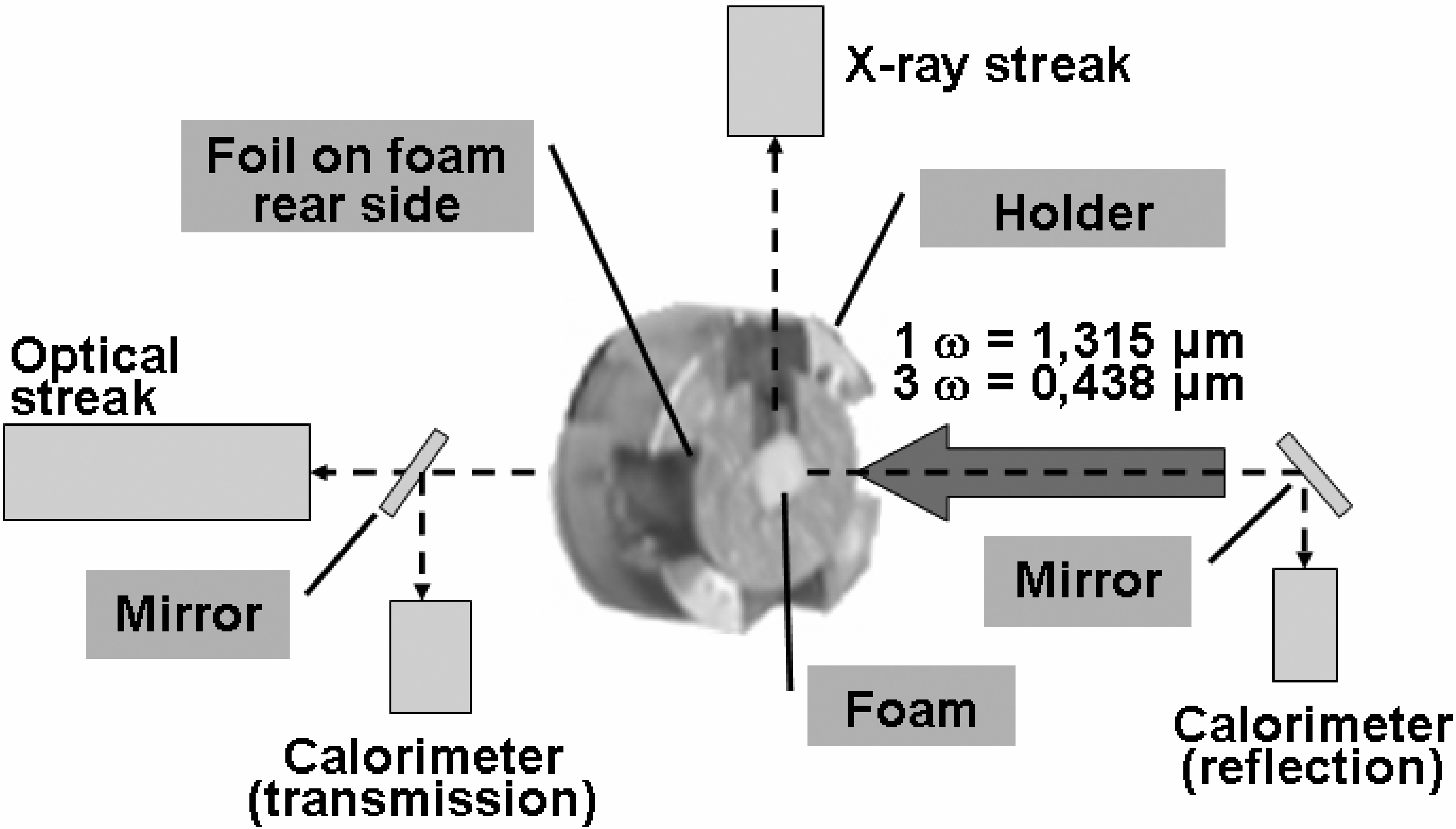
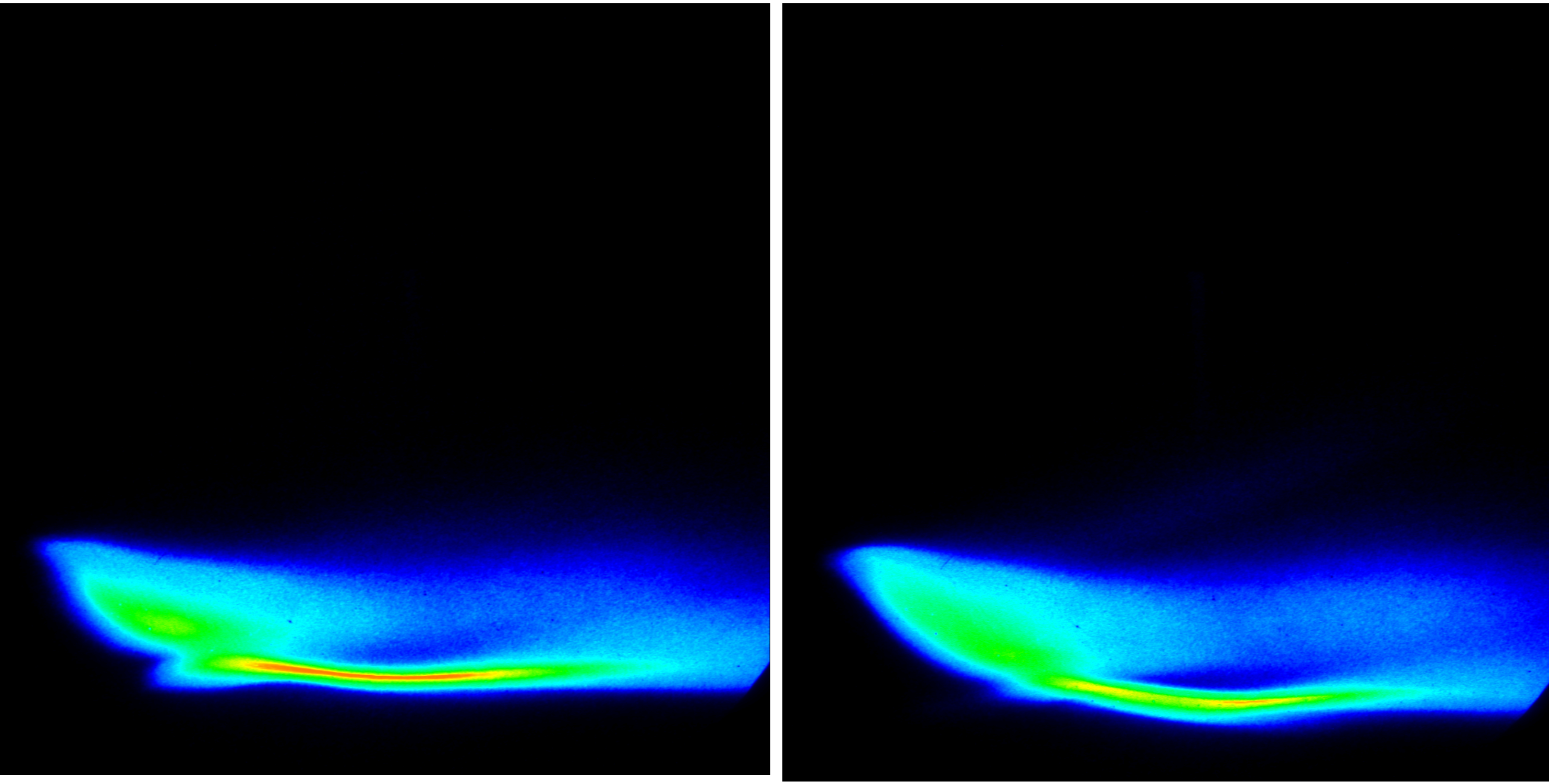
Diagnostic scheme of PALS

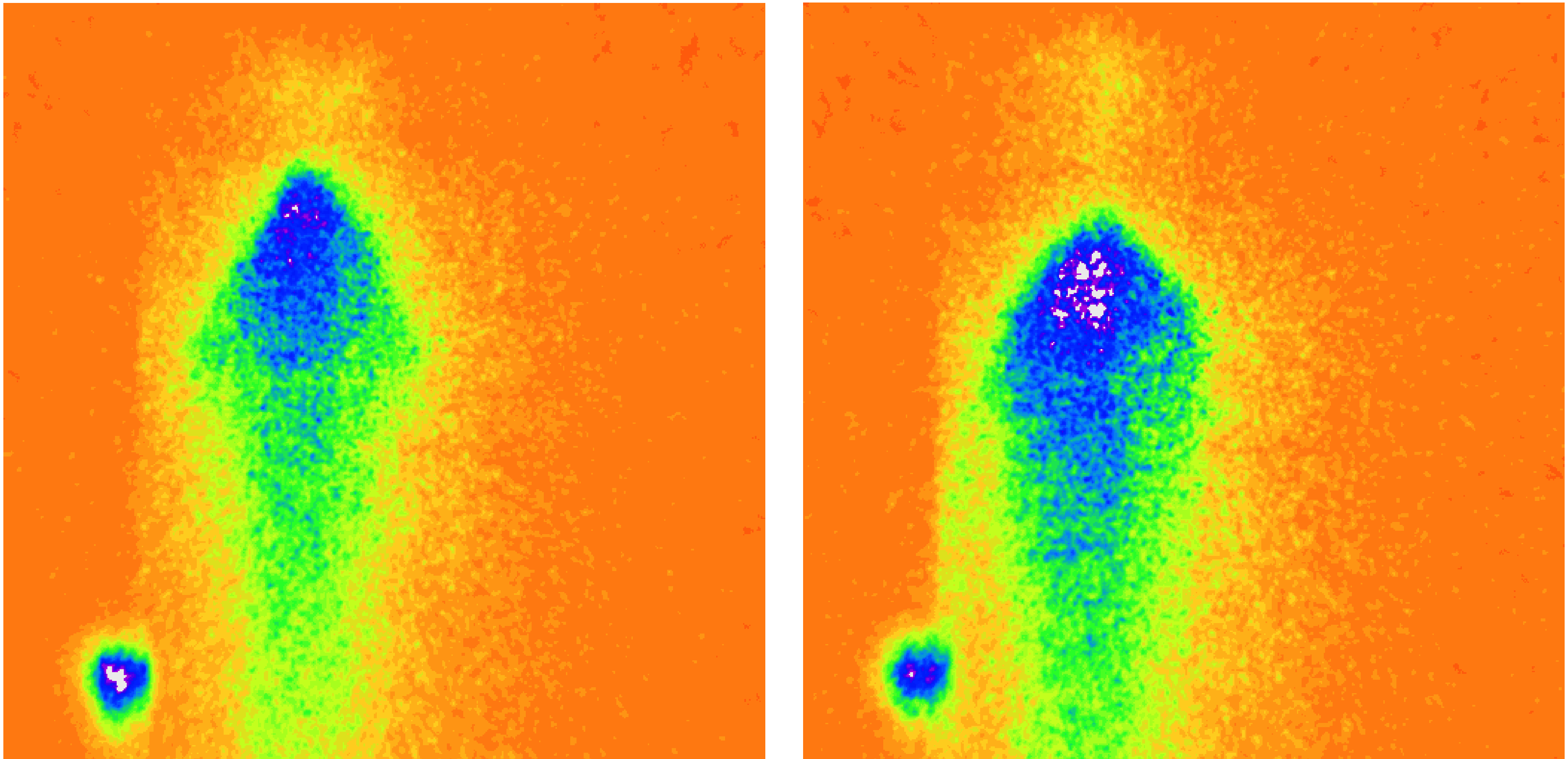


With stable laser performance and well characterized 3-D networks similar data are reliably reproduced due to uniform target structure



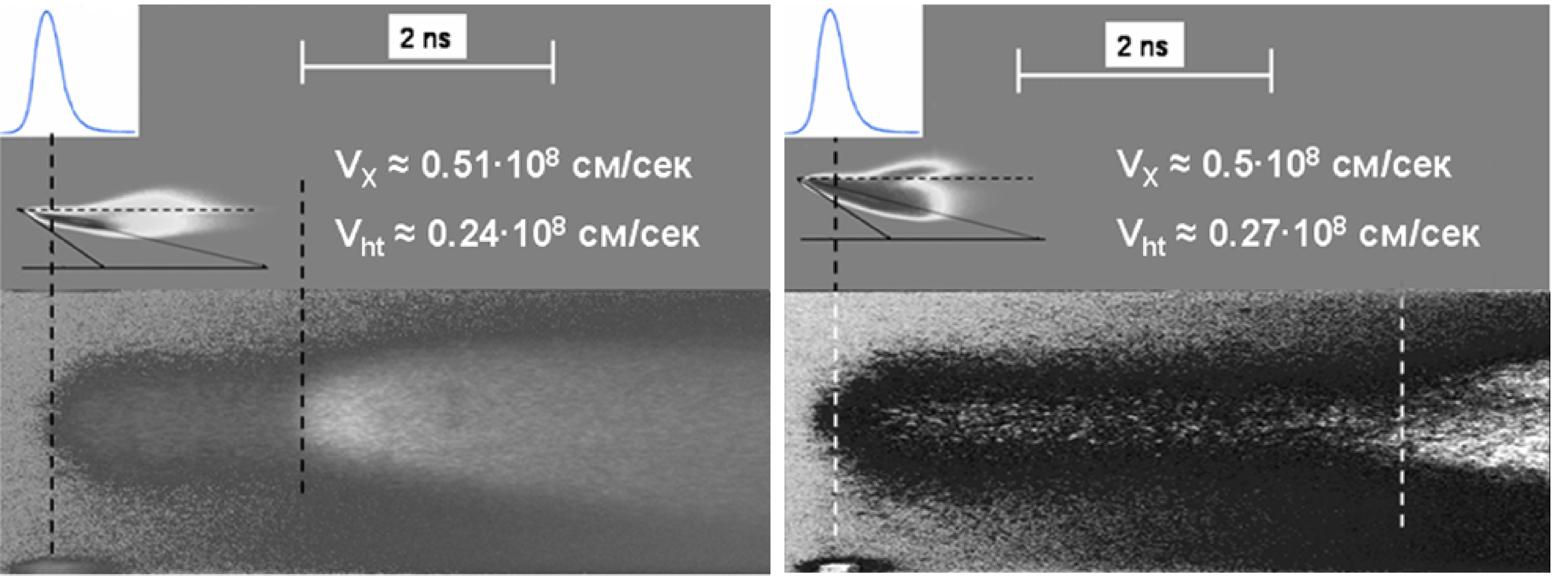
Shots #28233 and #28236 EL=165 J, TAC density 4.5 mg/cc, x-ray streak camera, time on the horizontal axis flows from the left to the right. The whole frame duration is 2 ns, laser light from above, the vertical spatial range is 2 mm. PALS iodine laser 3ω shots are reported from here on.

2006 PALS (Prague, Czech) experiments



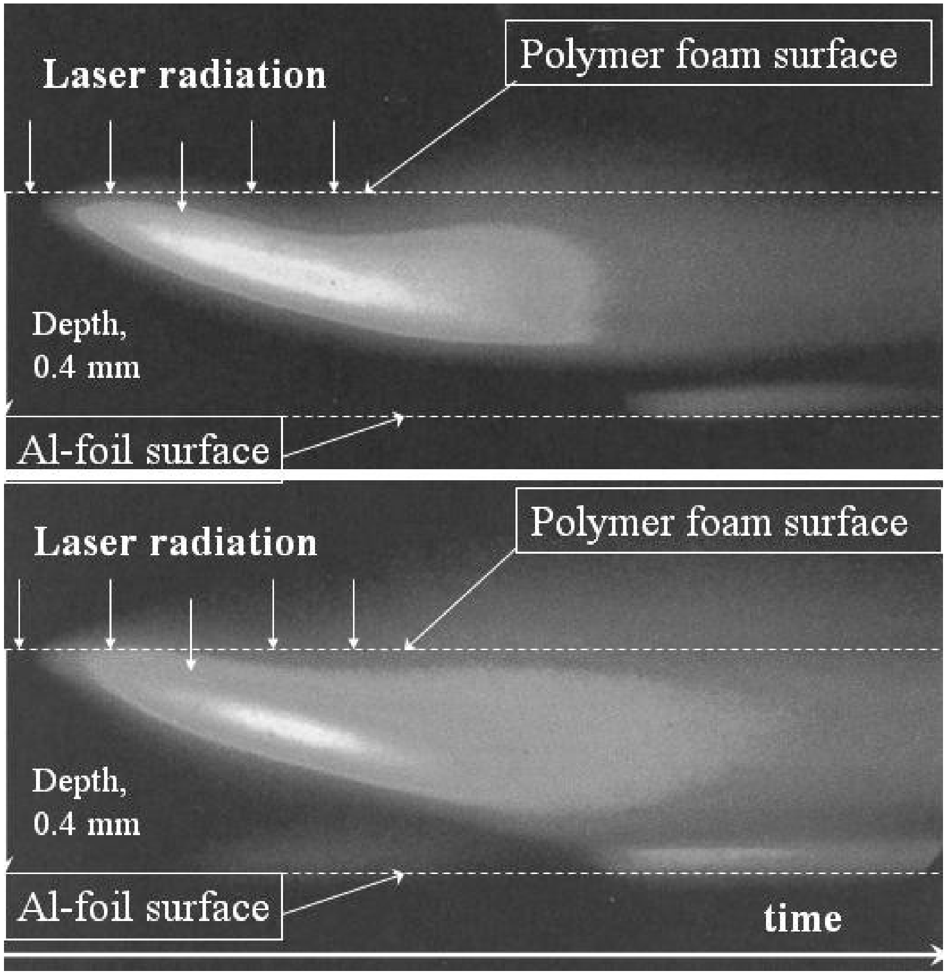
Foam-and-foil laser illuminated targets. Optical streak camera images for TAC foams of 9 mg/cc 450 µm thick covered with Al-foil of 5 µm (done in 2005 and repeated in 2006) . **Time axis directed downwards, the total time recorded - 5.2 ns. Full frame in horizontal directions equals to 2mm spatial range. Separate spot on the left shows laser pulse delayed for 5 ns. Iodine laser 3ω shots 30225, E_L= 52,2 J and 30226 E_L= 50,5 J.**

X-ray streak images show almost no effect of Cu-nanoparticles concentration on the velocities of energy transport measured in plasma in the course of laser pulse duration. Whereas after pulse termination the optical streak-camera registers an essential time delay in the start of optical intensive emission from Al-foil on the foam's rear side

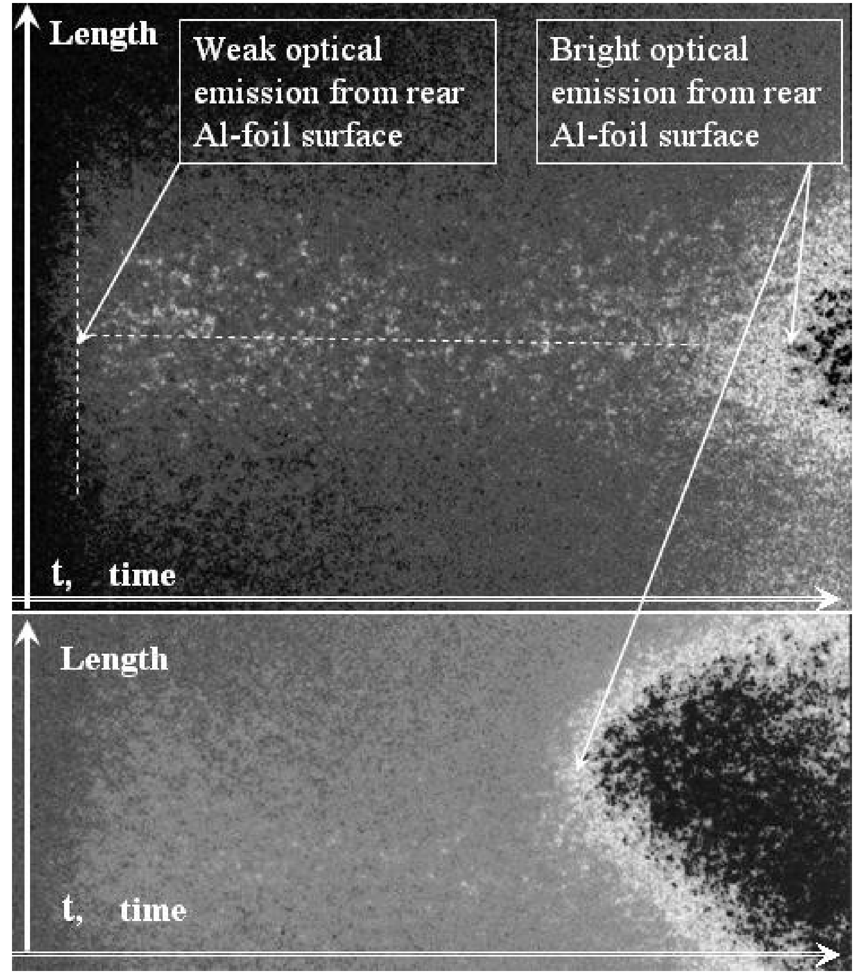


Upper streak images are x-ray, lower are optical. The left set corresponds to shot # 28207, E_L=157 J, 3 ω, TAC target 9.1 mg/cc; the right set corresponds to shot # 28211, E_L=158 J, 3 ω, TAC target 9.1 mg/cc including 9.9wt% Cu . In both shots the foam targets 400µm thick are covered with 5-µm Al foil on the rear side. Time increases from left to the right, velocities in cm/s. Vertical dashed lines show the time delay of intensive optical light arrival.

Cu added (top) – no Cu (bottom) comparison



X-ray emission streak-images for TAC-aerogel targets with density 9 mg/cc: top – with Cu-nanoparticles (shot #28220); bottom - without additives (shot #28205).

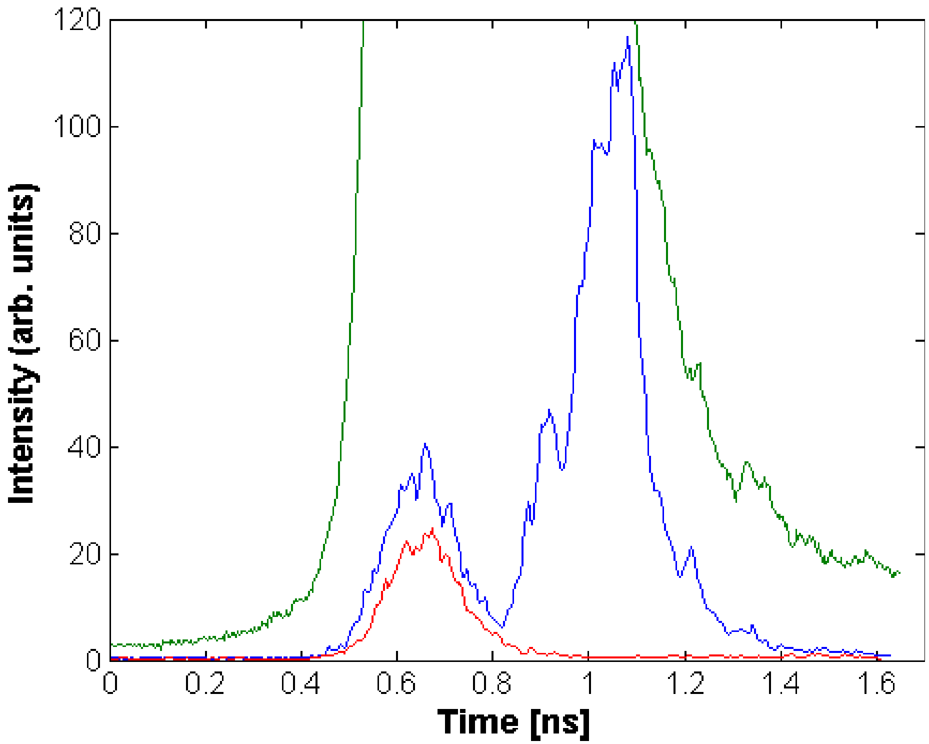


Comparison to Al-foils optical emission for TAC-aerogel targets with density 9 mg/cc: top – with Cu-nanoparticles (shot #28213); bottom - without additives (shot #28214).

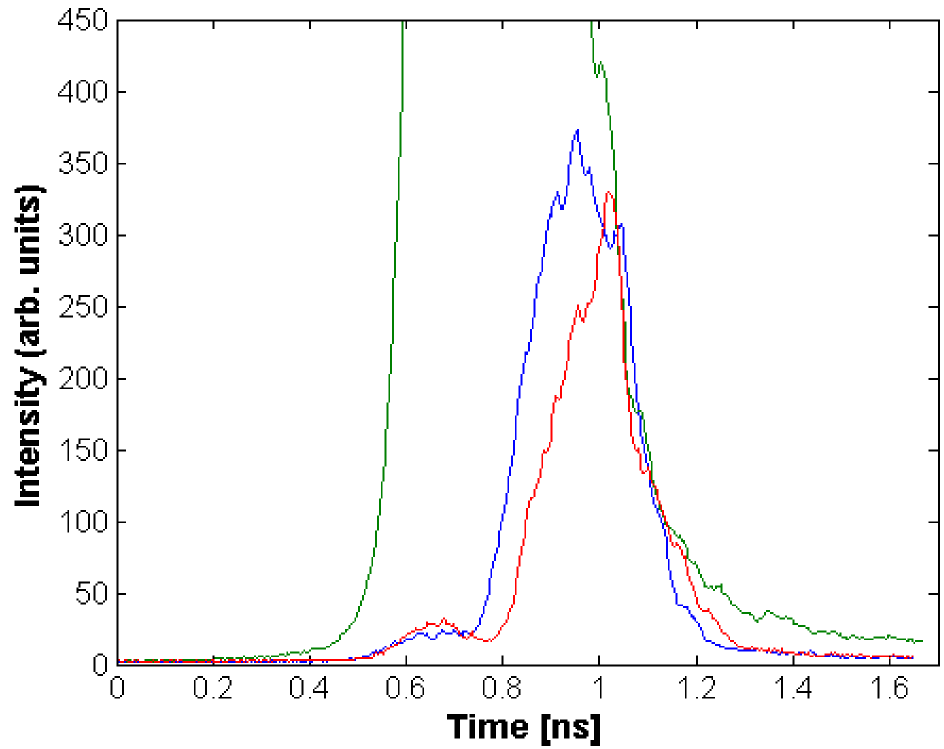
Energy registered on the rear side of the target - undercritical plasma (calorimeter)

↓ Density \ thickness →	400 μm	200 μm	100 μm
$(6\text{-}8)\cdot10^{14}$ W/cm^2			
9 mg/cm^3	0-3%	6.2%	13%
4.5 mg/cm^3	8,7%	21%	45%
2.25 mg/cm^3	27%	49%	
$(3\text{-}4)\cdot10^{14}$ W/cm^2			
4.5 mg/cm^3	7%	15%	37%
2.25 mg/cm^3	17%	29%	57%

Optical signal intensity via time on the rear side of the aerogel target

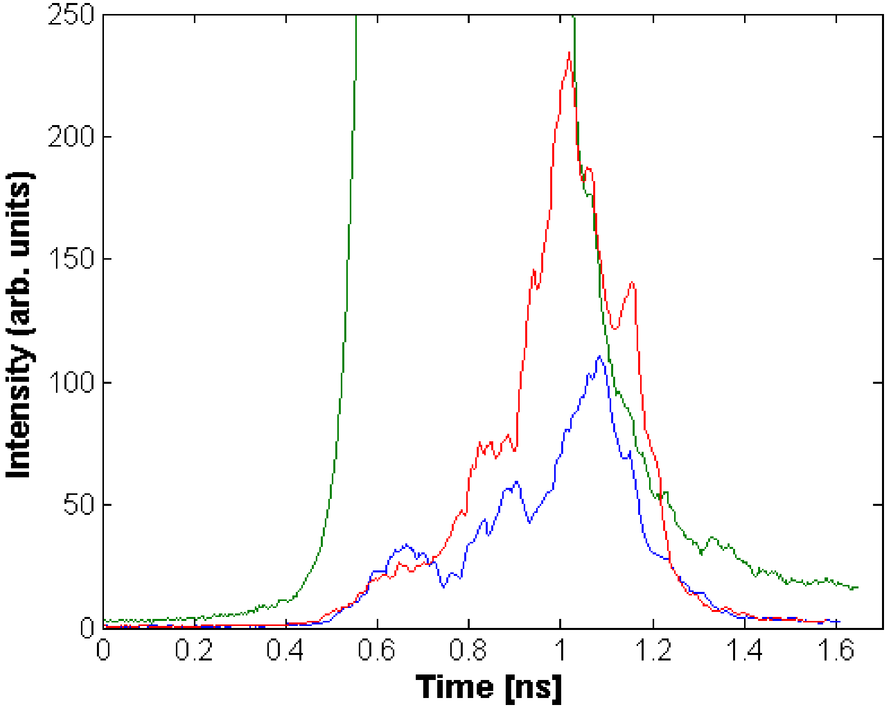


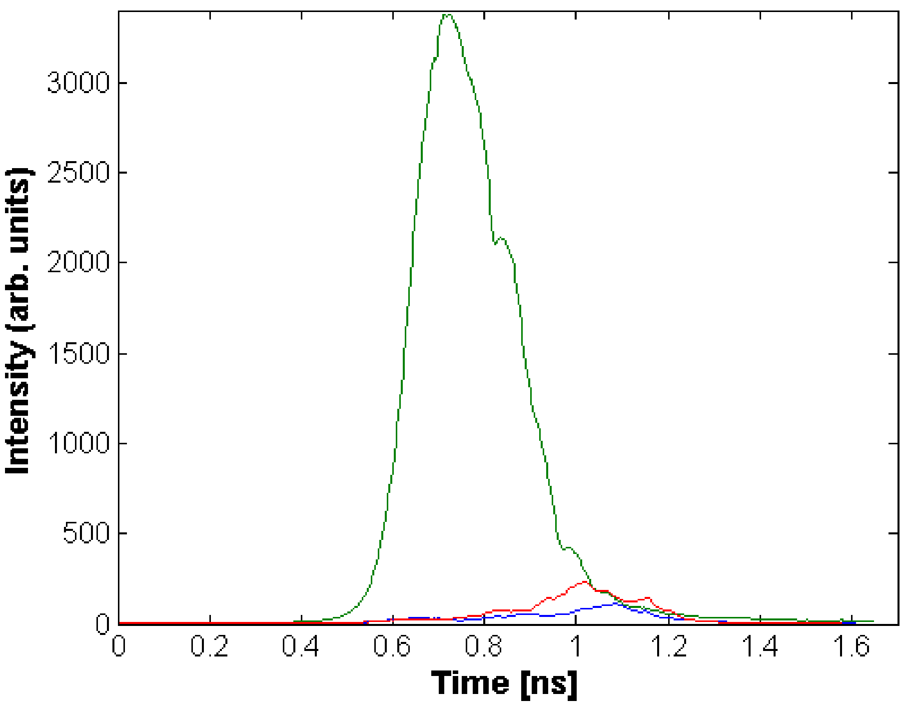
9 mg/cm³ – 200 μm (245), 4.5 mg/cm3 – 400 μm (251), (255) no target



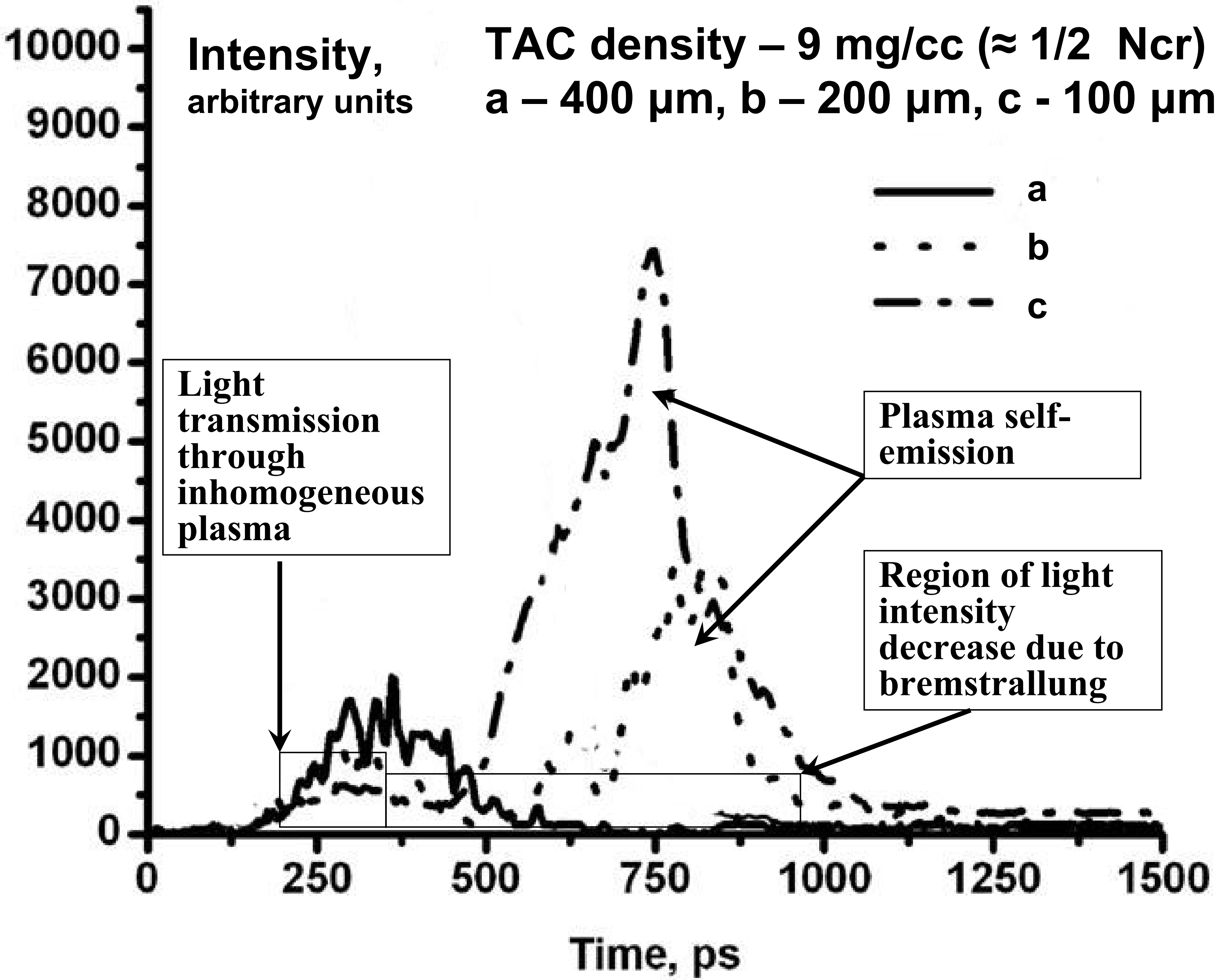
9 mg/cc – 100 μm (263 и 264). (255) no target

Optical signal intensity via time on the rear side of the aerogel target





4.5 mg/cc 400 μm . №30247 и 30248



Intensity,
arbitrary units
TAC density – 9 mg/cc (≈ 1/2 Ncr) :
a – 400 µm, b – 200 µm, c - 100 µm
a
b
c
Light transmission through inhomogeneous plasma
Plasma self-emission
Region of light intensity decrease due to bremstrallung
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
0
250
500
750
1000
1250
1500
Time, ps

Light transmission through inhomogeneous plasma

Laser induced inhomogeneous → homogeneous plasma formation from 3D polymer network with (micron distance between fiber and 0.05-0.1 μm fiber diameter) was observed by laser light transmission at high intensity (6-8)·10^{14} W/cm^2 during first 100-150 ps of laser pulse.

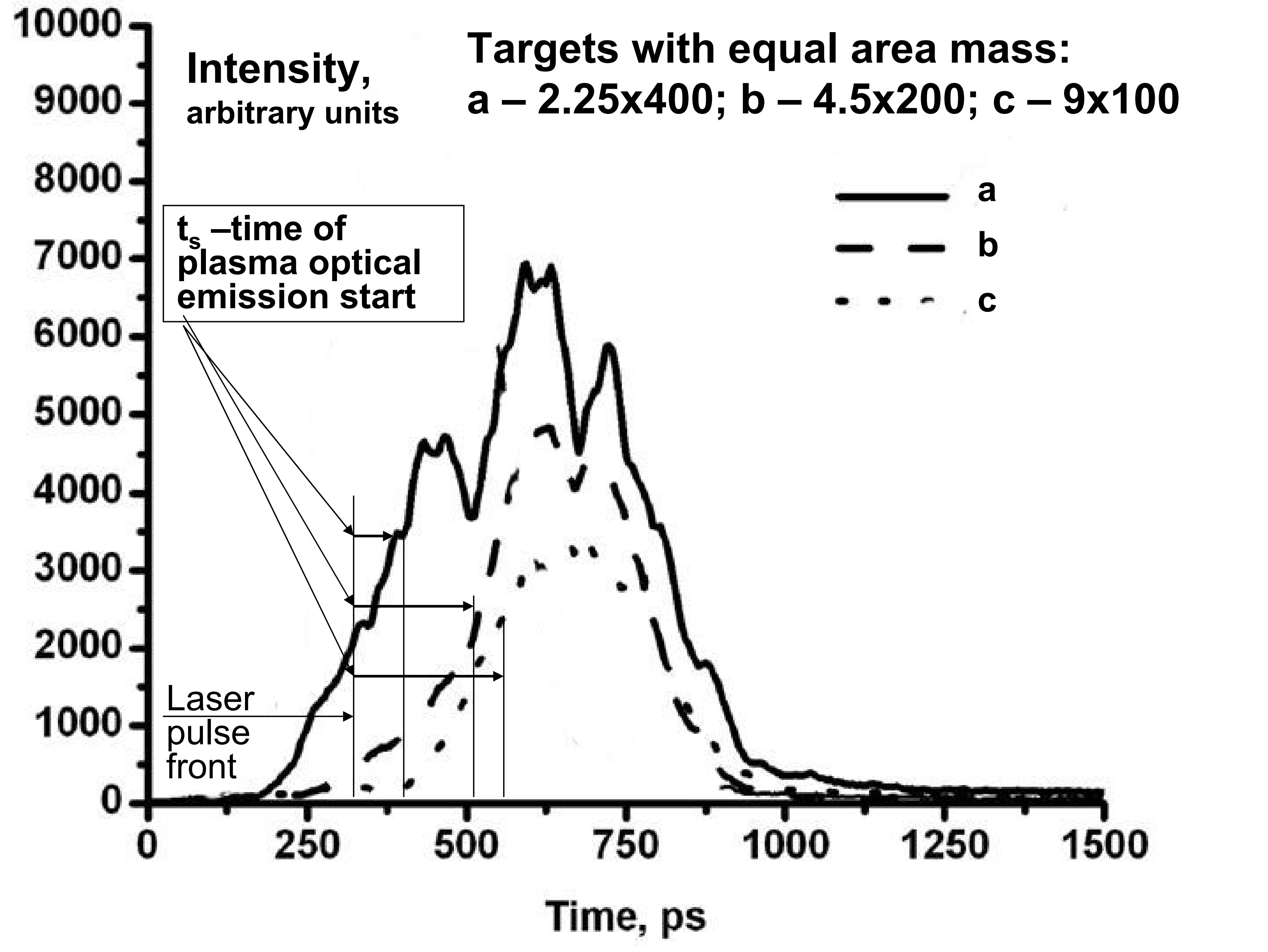
Ionization wave in 9 mg/cc plasma covers the distance 40-70 μm (20-50 distance between fiber) during 150-200 ps and forms homogeneous plasma layer which weakens laser irradiation.

Theoretical calculation of homogenization time gives the time from 30 ps to 80 ps, but does not take into account the densification wave movement.

Up to now the laser light transmission through inhomogeneous plasma has no correct theoretical explanation.

Transmitted laser energy on the rear side of the target relative to the energy delivered into the aerogel

↓ density \ thickness →	400 µm	200 µm	100 µm	Optical loss distance
$(6\text{-}8)\cdot 10^{14}$ W/cm^2				
9 mg/cc (1/2 N_{cr})	<0.3%	3,2±0.6%	15±3,5%	55 µm
4.5 mg/cc (1/4 N_{cr})	5.5±1%	21±4.5%	50±12%	135 µm
2.25 mg/cc (1/8 N_{cr})	28±5%	55±10%		320 µm
$(3\text{-}4)\cdot 10^{14}$ W/cm^2				
4.5 mg/cc (1/4 N_{cr})	5±1%	17±4%	42±9%	120 µm
2.25 mg/cc (1/8 N_{cr})	19±3%	34±5%	67±12%	240 µm



Intensity,
arbitrary units
Targets with equal area mass:
a – 2.25x400; b – 4.5x200; c – 9x100
a
b
c
t_s –time of plasma optical emission start
Laser pulse front
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
250
500
750
1000
1250
1500
Time, ps

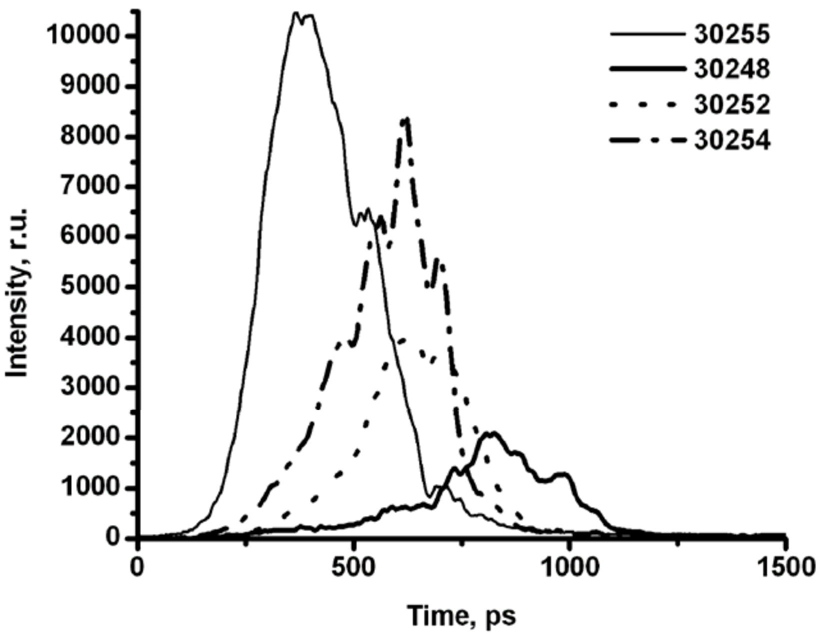
Delay of plasma self-emission on the rear side of the target

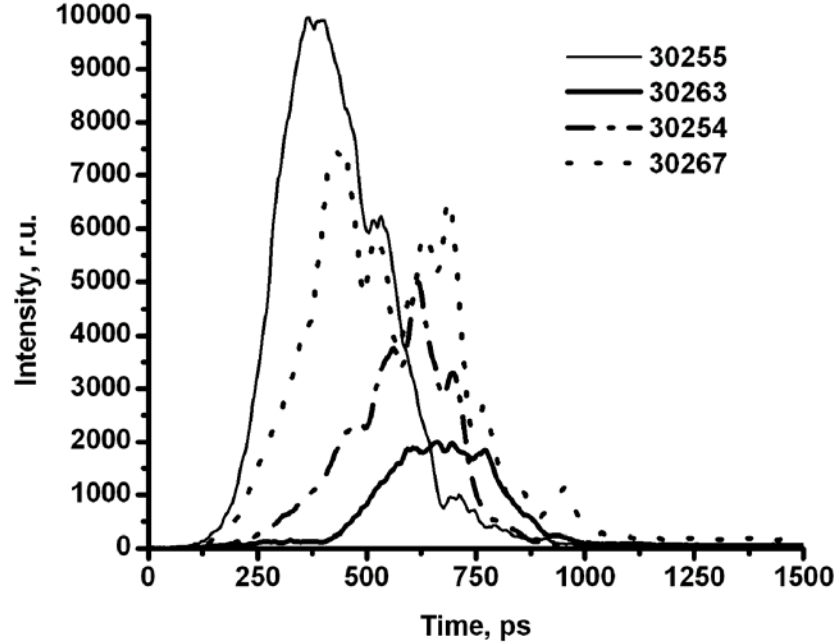
↓ Density \ thickness →	400 μm	200 μm	100 μm
(6-8)·10^{14} W/cm^2			
9 mg/cc		0.61 ns	0.3 ns
4.5 mg/cc	0.54 ns	0.26 ns	0.14 ns
2.25 mg/cc	0.25 ns	0.12 ns	0.05 ns
(3-4)·10^{14} W/cm^2			
4.5 mg/cc	0.67 ns	0.35 ns	0.16 ns
2.25 mg/cc	0.34 ns	0.15 ns	0.07 ns

Velocities estimated from optical signal delays in comparison to those measured from x-ray streak

	3ω, transmission 2006		2005 3ω		
	V_{pf}, 10^7 cm/s	E_L J	X-ray streak V_X, 10^7 cm/s	V_{ht}, 10^7 cm/s	V_{opt}, 10^7 cm/s
TAC 4,5 mg/cc	7,5±1,6	170	8,7±1,5 (E≈170 J)	4,6±0,7	3,6±0,5
	6±2	80	3,7±1 (E≈100 J)	2,0±1	2,4±1
TAC 9 mg/cc	3,3±1,0	170	5,1±1,1 (E≈160 J)	2,4±0,5	2,0±0,3
			3,9±1 (E≈100 J)	2,4±1	0,9±0,5
TAC 2,25 mg/cc	16±4	170			
	12,5±4	80			

Optical streak-images on the rear side of the foam target, no Al foil, for laser light wavelength 0.438 nm and maximum intensity $1.2 \cdot 10^{15}$ W/cm^2





Left picture – E_L=170 J, 3ω, TAC density 4.5 mg/cc, shot #30248 – 400 μm, shot #30252 - 200 μm, shot #30254 - 100 μm, shot #30255 without target

Right picture - TAC layer with thickness 100 μm: E_L=80 J, 3ω, shot #30267 density 2.25 mg/cc and E_L=170 J, 3ω, shot #30254 density 4.5 mg/cc, shot #30263 density 9 mg/cc, shot #30255 without target

Time scale horizontal (ps), intensity profiles in arbitrary units, but normalized to shot #30255 intensity. **Less signal for thicker foam and for denser layer**

Application

- Energy transport are studied in low-density materials of various structure (open and closed cells, different cell sizes, etc.) with “Mishen” laser (Target) in TRINITI, Troitsk, Moscow region.
- Dependence of neutron yield on structure and density of deuterated target on laser “Neodim” in TsNIIMASh, in Moscow region.
- Experimental comparison of “thermal” method of heat-and-flow smoothing by volume-structured material and of “optical” method of a separate dynamical plasma phase plate on “Iskra-5” in VNIIEF in Sarov.
- Equation-of-state studies on laser “Luch” in VNIIEF, Sarov.
- Influence of dopants in low-density materials on energy transport on laser “Kanal” in LPI in Moscow.
- Effective compression of spherical targets in cylindrical and quasispherical liners on Z-pinch of “Angara-5” installation
- The soft X-ray transmission imaging based on laser illuminated x-ray source in conjunction with parallel beam selection by x-ray mirrors verified the aerogel has <1% density variations in the interaction volume.

Conclusion

- Aerogels with 1µm open pores, density down to 1.0 mg/cm^3 and target-to–target repeatability are developed.
- The efficiency of soft X-ray (λ = 4.5 nm, E = 286 eV) monitoring of target parameters was shown, including high-Z dopants.
- Laser light transmission is measured through undercritical plasma of 0.52, 0.26, 0.13 N_{cr} and different thicknesses.
- Wide areal mass range (0.32-0.02mg/cm^2) allowed to isolate: light transition through non-homogeneous plasma, laser extinction in underdence plasma and plasma self-emission.

Conclusion 2

- The starting time of plasma self-emission coincides with the time of x-ray emission front to reach the rear surface of aerogel plasma.
- Characteristic distances for exponential optical extinction are measured for 0.438 μm and average intensities $(6\text{-}8)\cdot 10^{14}$ W/cm^2 и $(3\text{-}4)\cdot 10^{14}$ W/cm^2 in the undercritical densities of 1/2, 1/4 and 1/8 of critical one.


Borisenko
N.G.