Laser targets and diagnostics in the era of validation experiments

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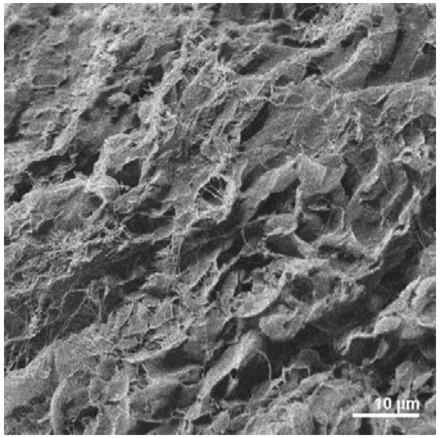
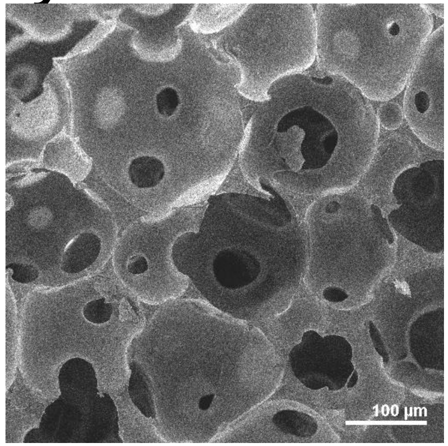
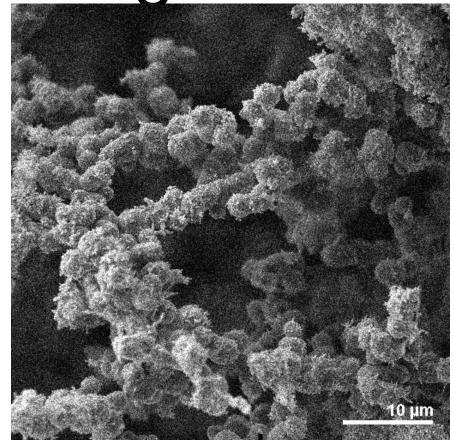
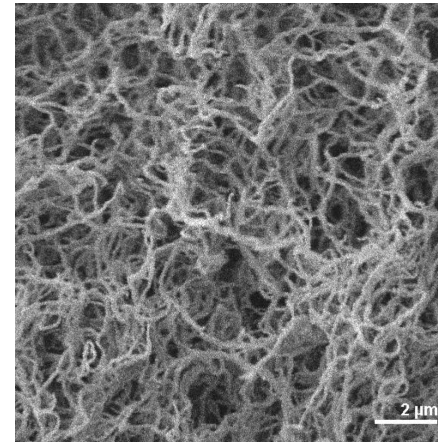
1. Introduction. Various foam layers for targets and different requirements to the foam structures.
2. What we must prove? Smoothing effect and structure imprint absence. Is that all? Various groups find new effects to study (laser radiation transmission through turbulent plasma, pressure amplification, subcritical plasma density oscillation, etc.)
3. A lot of foam target parameters. Methods for parameter measurements wanted.
4. New results and proposals of validation experiments.
5. Conclusion.

Low-density materials heterogeneous structures









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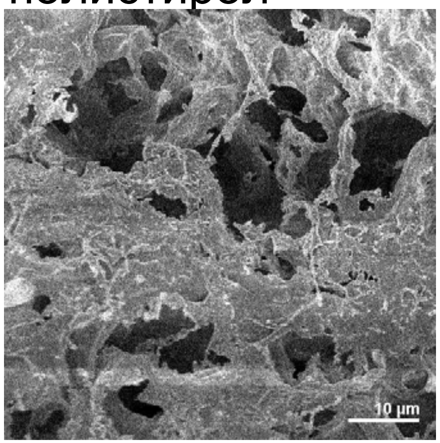
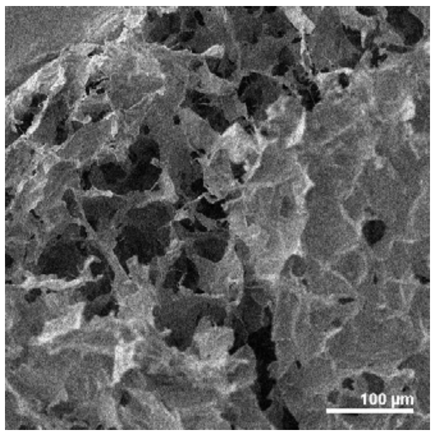
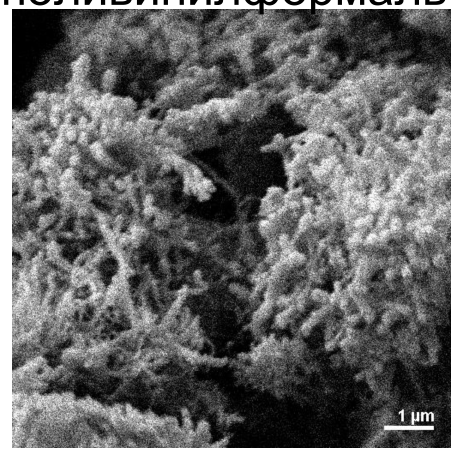
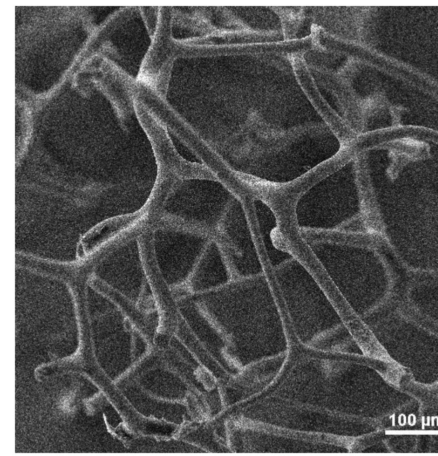
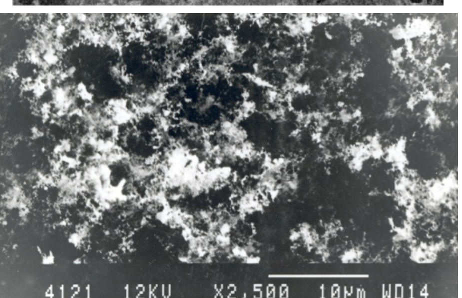


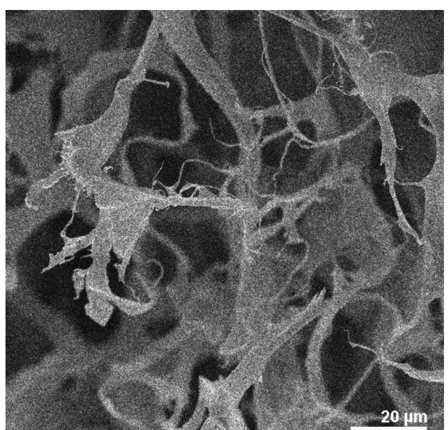


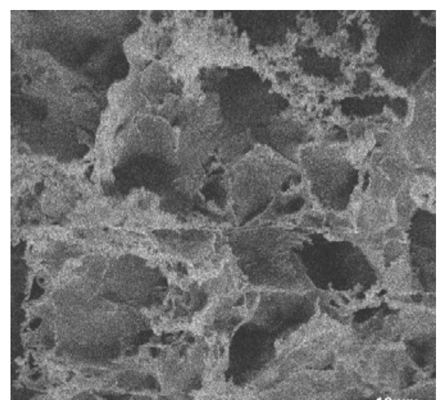


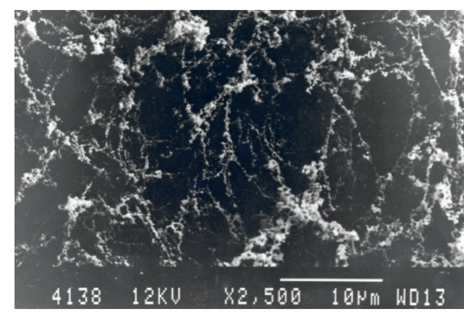


Морская губка



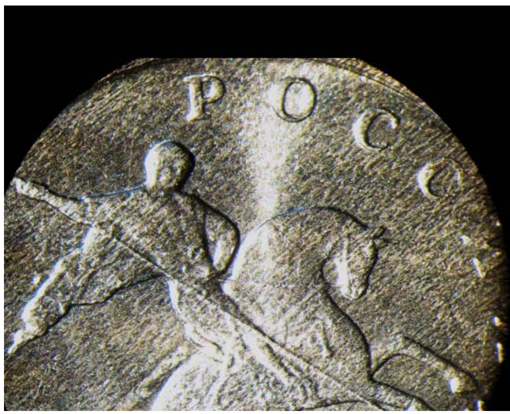






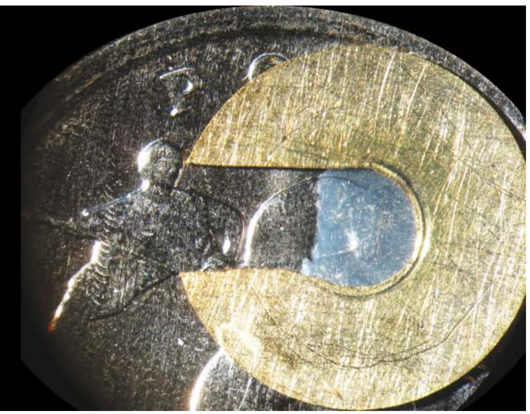
TAC foam: 3-D network (open-pores polymer aerogel)

- Regular microstructure, size-and-structure repeatability
- Micrometer pores and submicron fiber thickness
- Average density of as low as 1 mg/cc
- Thick layers are optically transparent – the target components could be mounted

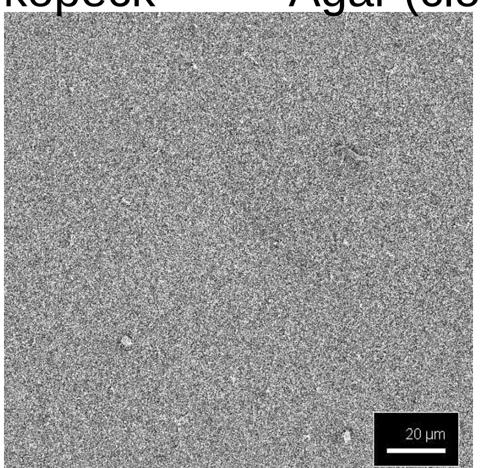


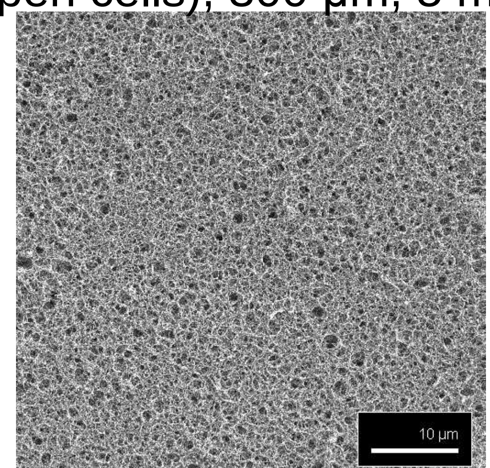
1 kopeck

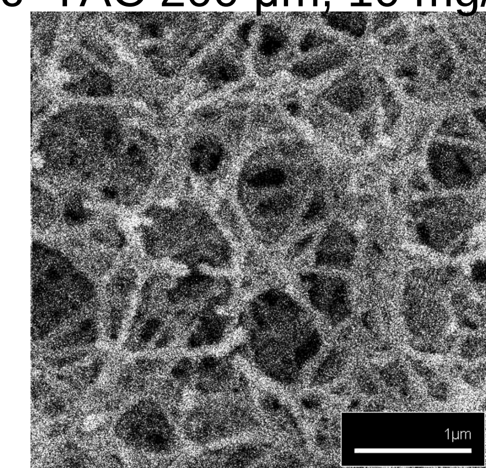
Agar (close-open cells), 300 µm, 5 mg/cc



TAC 200 µm, 10 mg/cc

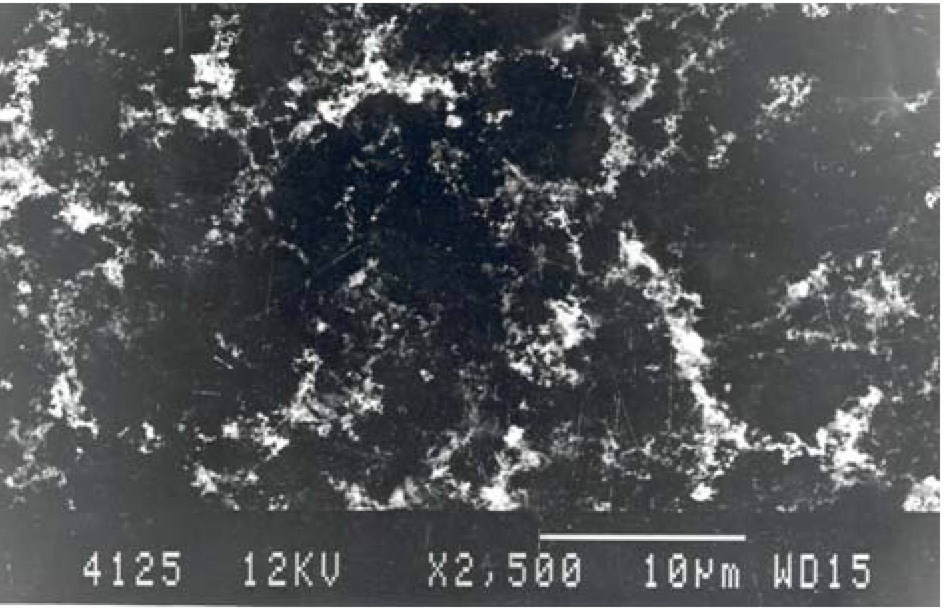


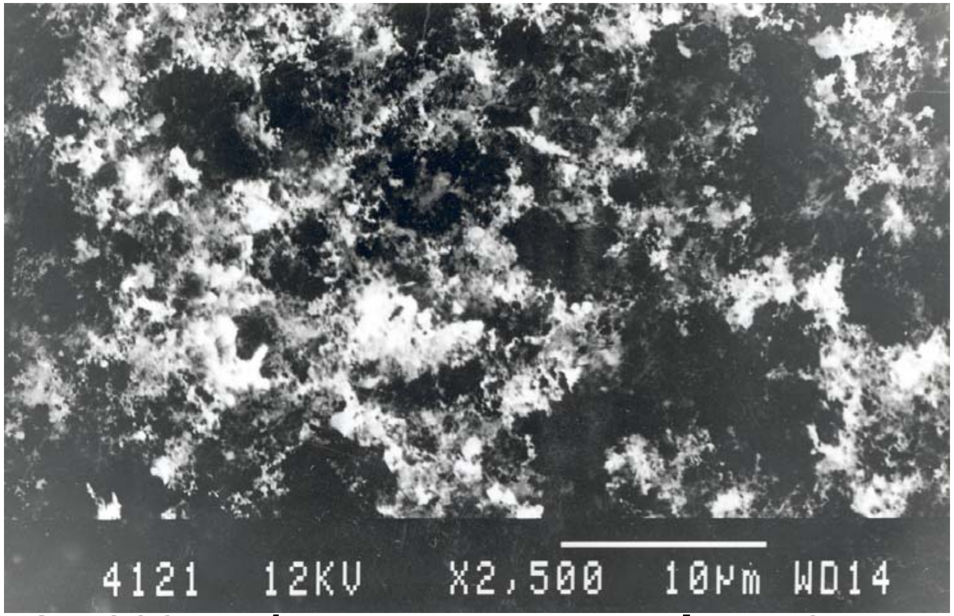




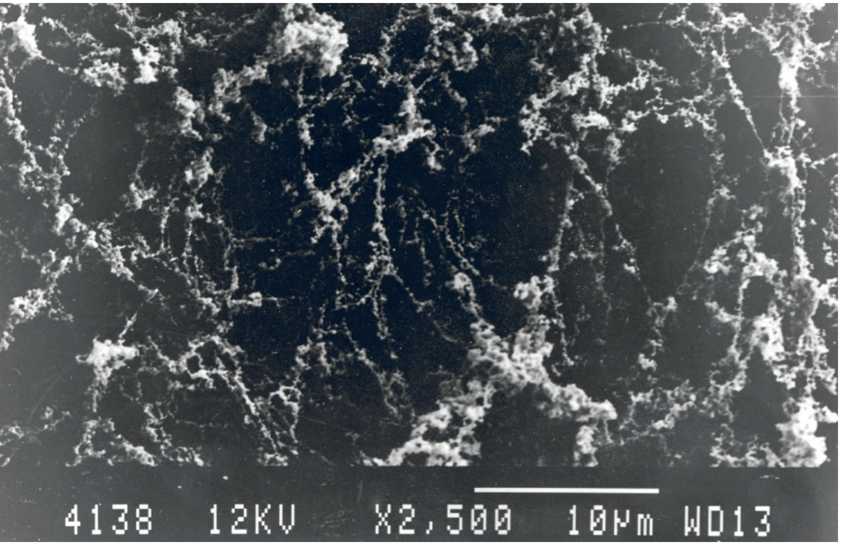
TAC microstructure SEM, bars equal to 20;10;1 µm correspondingly

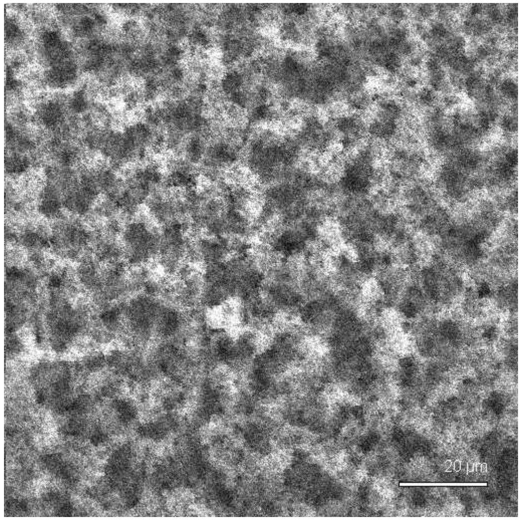
Metal foams – metal smog layers

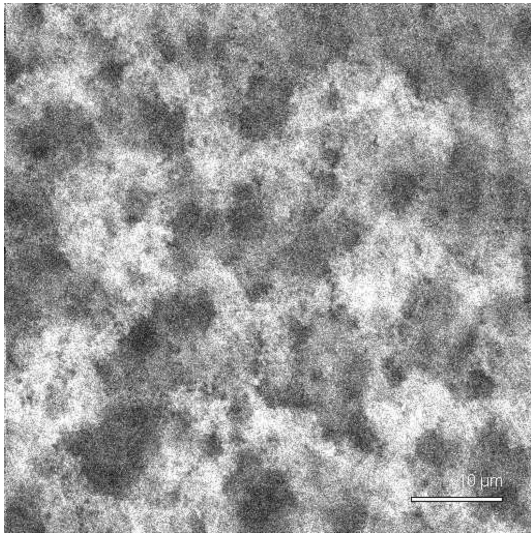




Cu-layer with density 30 mg/cc **Cu 200 mg/cc** **scale – 10 µm**







Au layer with density 200 mg/cc, scale – 10µm. **Sn** scales – 20 and 10 µm

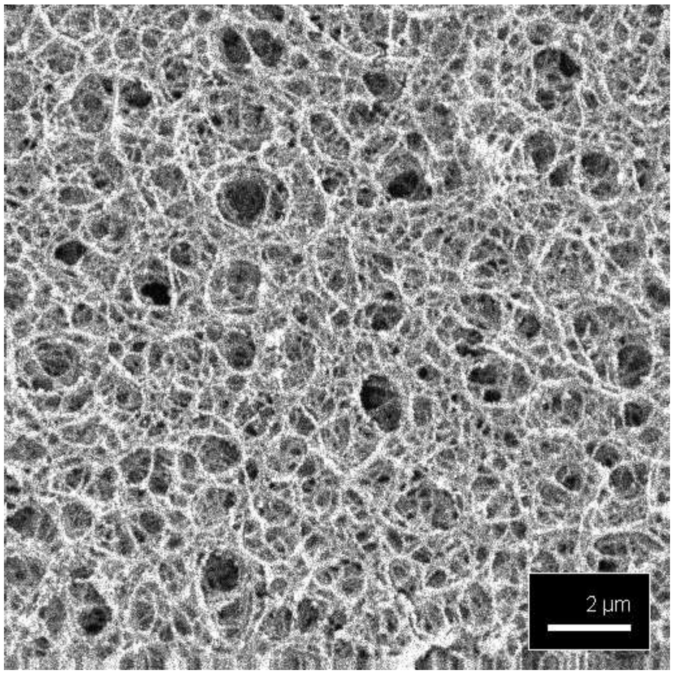
Motivation for new low-density materials fabrication (and measurement!)

- High-Z nano-dopants with different boiling temperatures for increasing uniform compression (microturbulent plasma life-time control).
- Multilayer structure of density ranging from subcritical (2 mg/cc) to 100 mg/cc for increased hydrodynamic efficiency of targets.
- Density gradient for pressure multiplication in EOS exp.
- Concentration wave of high-Z dopant in the layer for increased target efficiency.
- Optimal structure (fiber distance and diameter, layer dimensions) for plasma random phase plate.
- High-Z low-density x-ray converter of indirect targets.
- High-Z low-density layer for the converters of ps-laser radiation to β-particles beam at the fast ignition.
- Predeuterated (or DT) materials for neutron ignition sources.

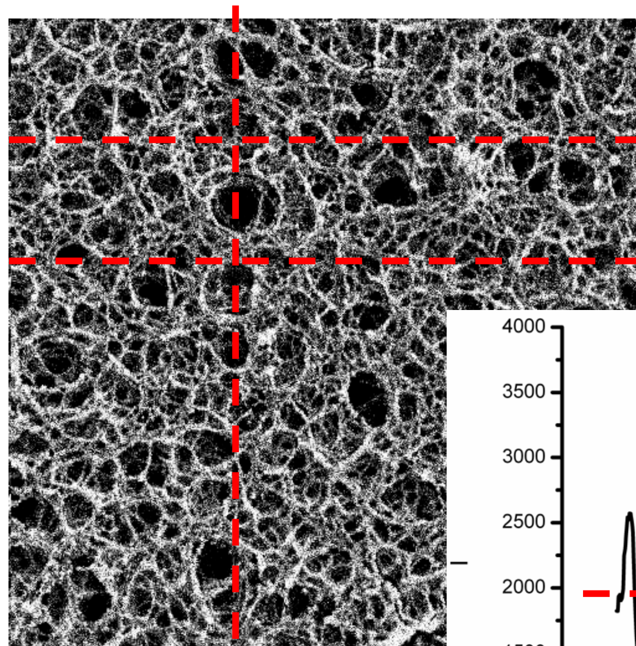
Average pore size and fiber diameter

Computer procedure of 3-D network analysis to measure the cell size and fiber diameter [*Nikitenko A.I.*]

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

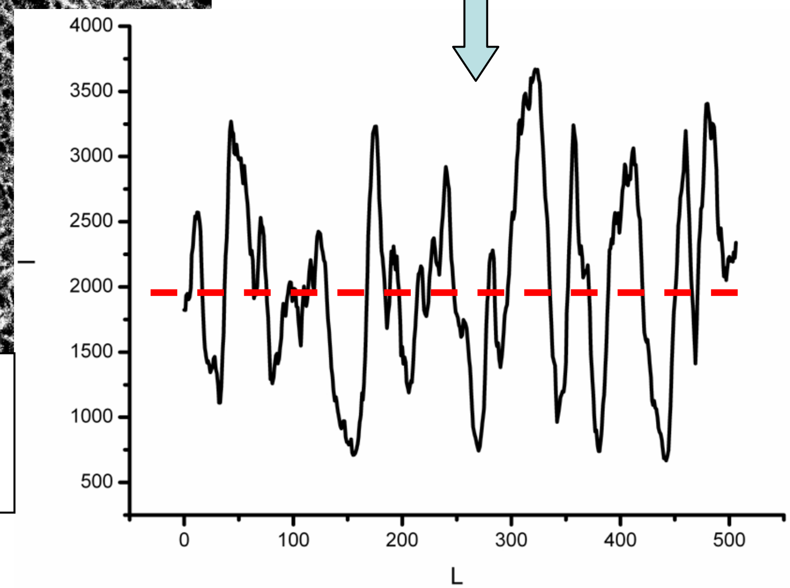
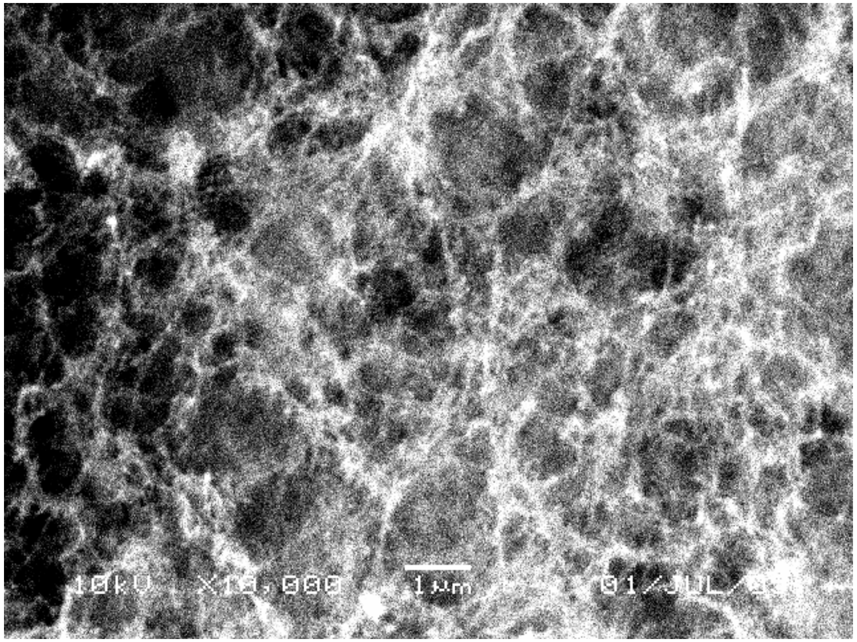
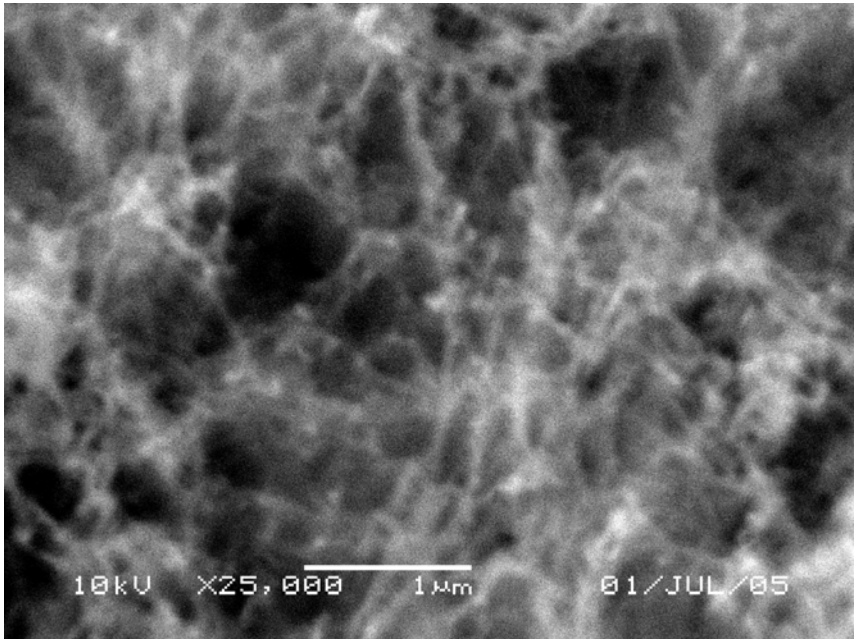


Image processed: denoised, illumination and contrast equalized, intensity scanning done along the red lines

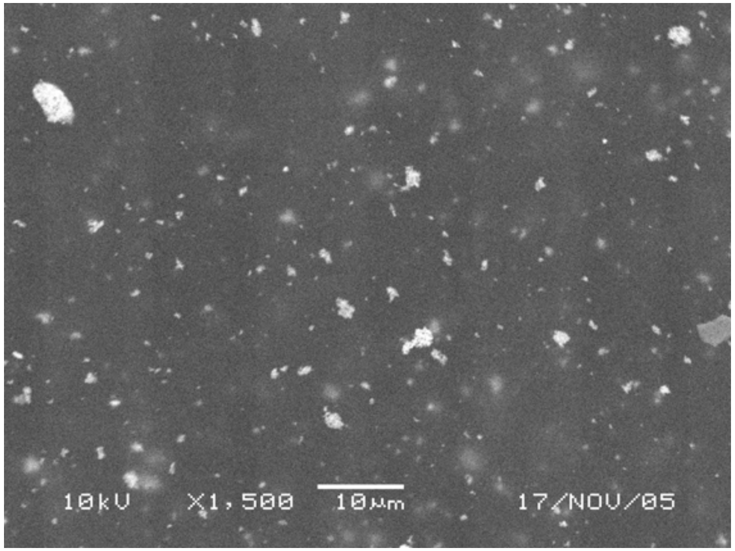
SEM photos of TAC 3D-networks dependent on coating.





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

Nanoparticles agglomerates and size distribution



TAC, 10 mg/cc, 15wt% Cu,
Lebedev Physical institute, 2005

At low gel concentration the UDP high-Z admixtures tend to agglomerate. So the additional effort is necessary for uniform heavy particles distribution.

Centrifugal separation

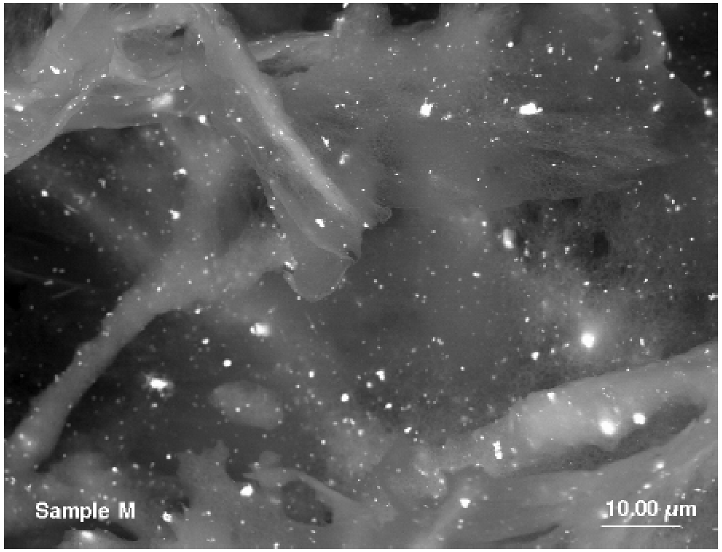
→ Eliminate large particles

Dispersion

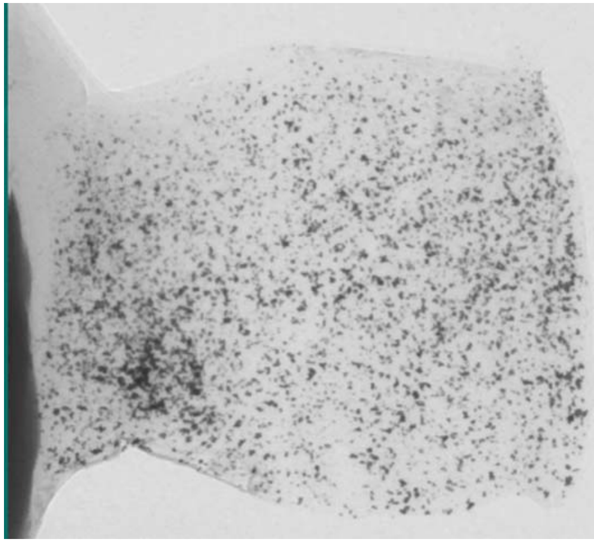
→ High-power ultrasonic dispergators

Appretes

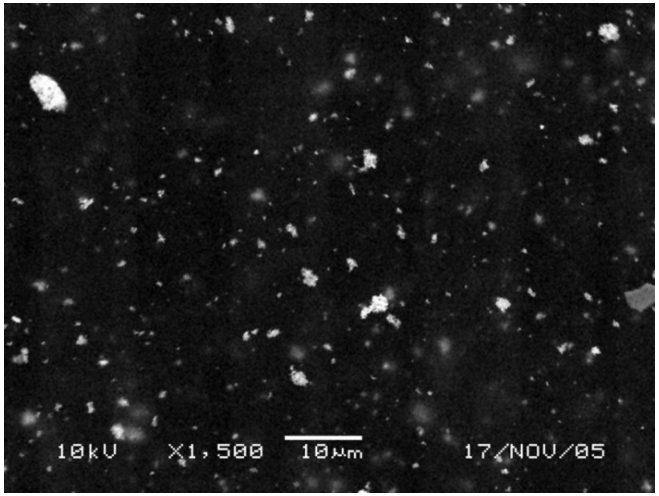
→ UDP particles treated with different hydro-oleophobic chemicals



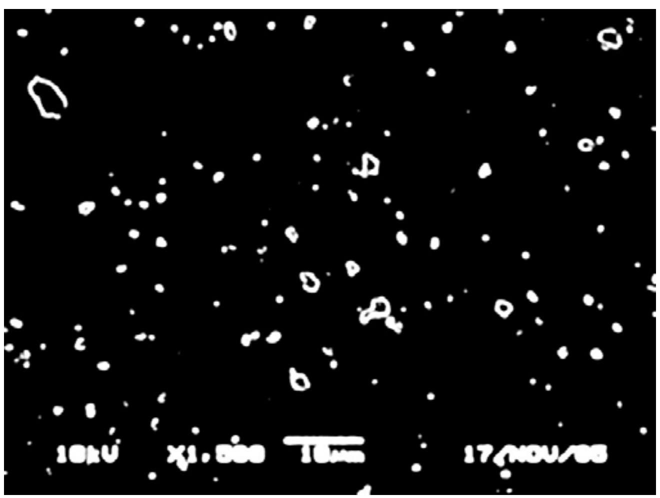
K. Youngblood, (Schafer, Sandia, США)
15 TFM report, 2003, пена TPX 14 мг/см^3


F. Lewis,AWE UK, 15 TFM report, 2003,
Au clusters in foam of 50 mg/cc

Verifying chemical composition and size of nanoparticles



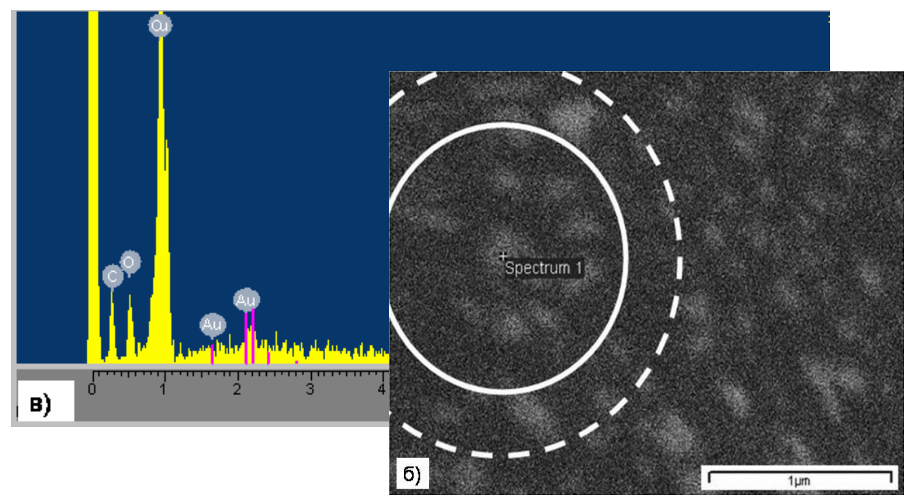
Low density TAC 10 mg/см^3 with embedded, 15% Cu particles, the image prepared for counting



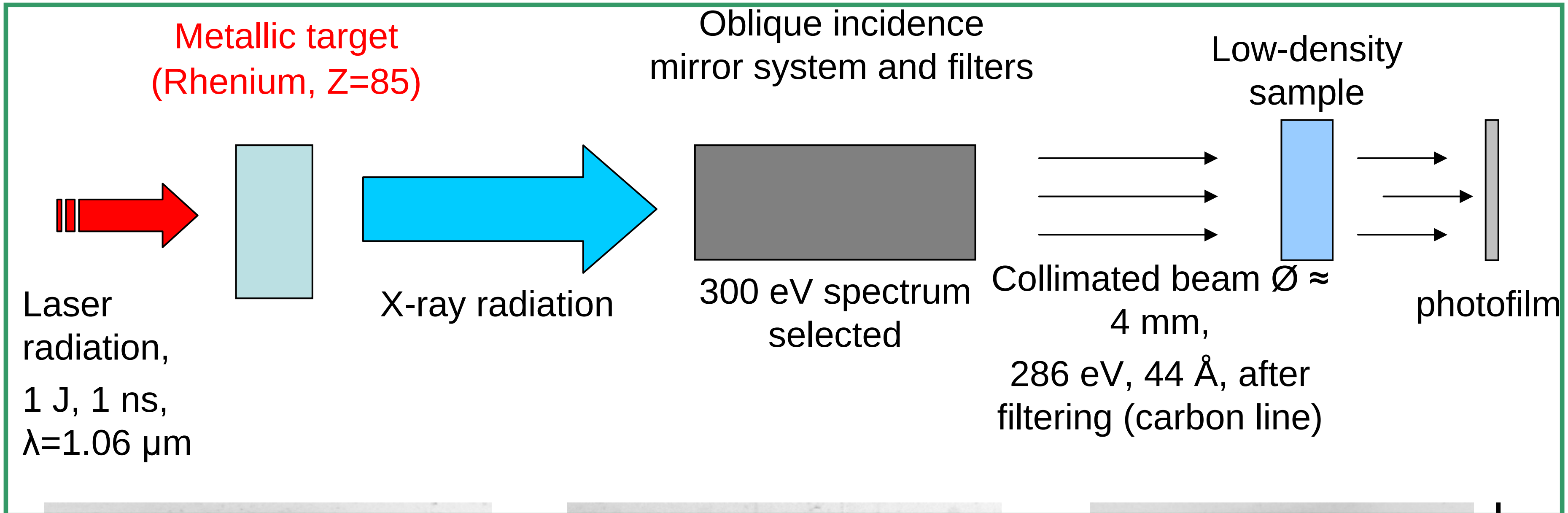
The same frame processed and counter-ready

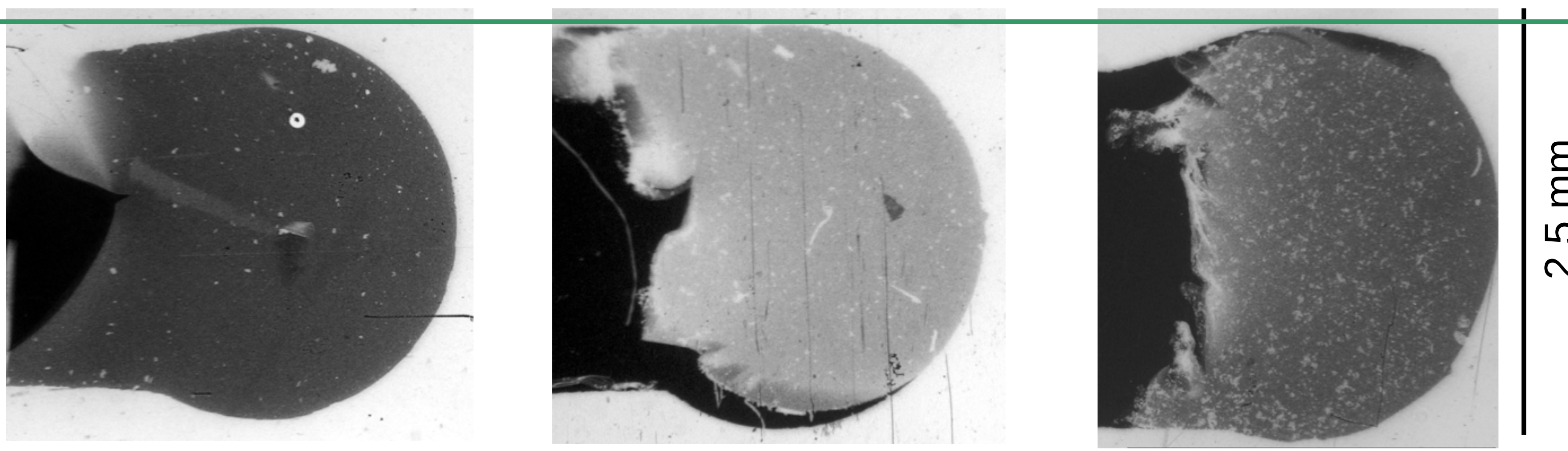
Material contrast SEM in low vacuum (~ 1 Pa), <u>no conducting layer deposited</u> + software processing for automatic agglomerates counting

High-Z additive in TAC analyzed with Au deposition, Cu 50 нм is detected



4.4 nm x-ray source for 3D low-density target monitoring





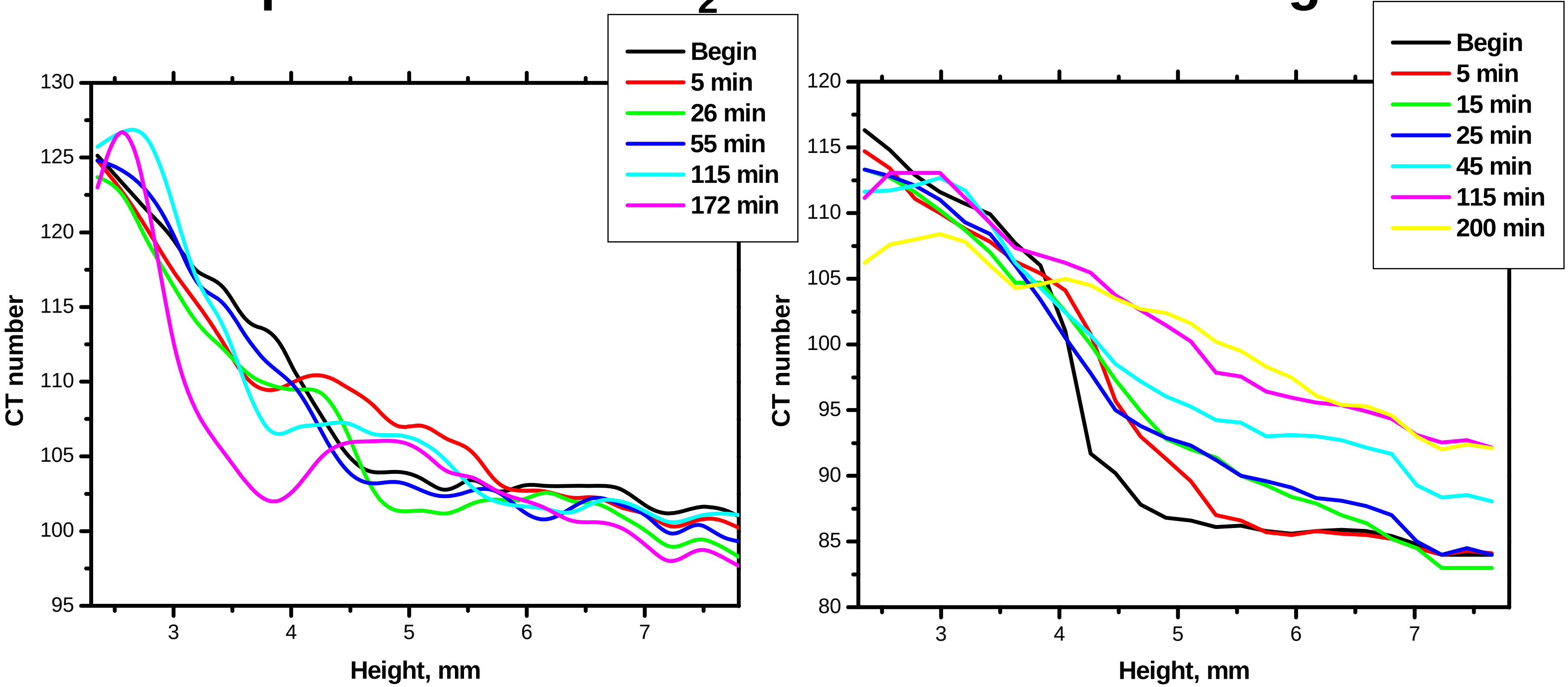
TAC 4.5 mg/cc

TAC10 mg/cc, 10% Cu

TAC 10 mg/cc, 20% Cu

300 μm thick layers

Dependence of SiO_2 concentration via height



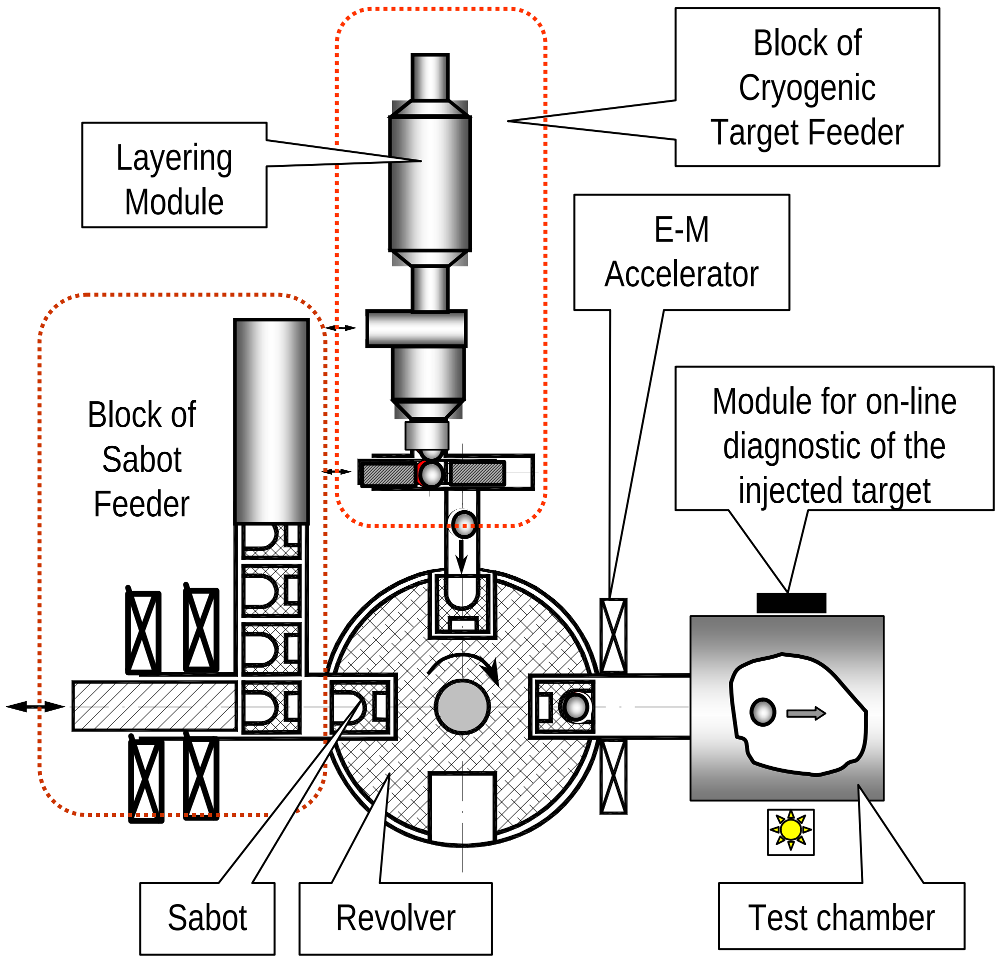
Dependences of count tomography (CT) numbers via height of TEOS solution (in the tube) during gel growth at various time after TEOS solution is placed on catalyst for two start concentrations: left – 0.5 basic solution, right – 0.25 basic solution. SiO_2 concentration can be found from comparison on CT number in table with SiO_2 concentration. Tomography during synthesis of silica polymer for aerogel with density gradient!

N.G. Borisenko, A.A. Akunets, I.A. Artyukov, K.E. Gorodnichev, Yu.A. Merkuliev. X-ray tomography of the growing silicagel with density gradient. // Fusion Science and Technologies. 2009, V. 55, No4, May, pp. 477-483.

Foams of different chemical systems and structures are proposed depending on the necessities of laser experiment.
Begun in cooperation with INEOC and conducted together with Zelinskiy institute (both belonging to RAS) during recent years the works with cellulose triacetate resulted in undercritical plastic aerogels used in experiments on different laser facilities for 3ω, 2 ω , and 1ω laser light.
In contrast the higher densities of foams are fabricated from other chemical materials: deuterated PE, RF resin, beryllium deuteride and others.
The targets produced in Russia with declared parameters similar to those produced in Scotland by W. Nazarov from differing polymers and independent technology routes proved to possess similar structure from the point of view of laser light interacting with them. From time to time such targets met in the one and same laser experiments on PALS, LULI or LIL facilities and produced results supporting each other and thus verifying the measured phenomena. **Cu dust** Our foam components also participated in the shots of PHELIX and UNILAC in Germany and KANAL, ISKRA 5, LUCH, MISHEN and NEODIM in Russia.
The targets with density gradient are now under development in LPI. These are continuously grown in silicagel in the course of its synthesis. The gradient formation dynamics is measured by 3-D tomography right in gel substance. The achieved gradient in supercritically dried samples is reported to be 1 $g \cdot cm^{-3}/cm$, which is still too low for pressure multiplication in laser shots.

TARGET SUPPLY SYSTEM IS ONE OF THE BUILDING BLOCKS OF IFE REACTOR. OPERATIONAL PRINCIPLE IS THE FST-PRINCIPLE: HIGH REP RATE OPERATION WITH FREE-STANDING TARGETS

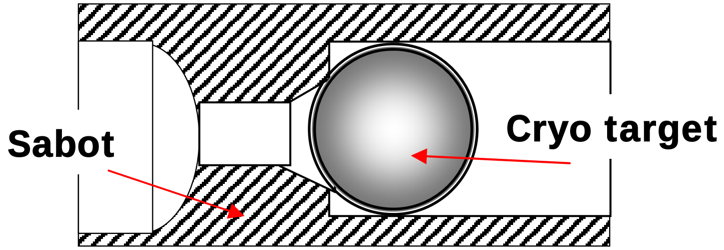
The technologies to operate with free-standing targets at each production step (fuel filling, layering, target characterization and injection) are under development in in the Cryogenic Group of TTL over the last 20 years.



[I.E.Osipov et al. IFSA-2001]

❑ TARGET SUPPLY SYSTEM BASED ON THE FST-PRINCIPLE

- High rep-rate producing the reactor-scaled cryogenic targets
- Repeatable assembly of the target & sabot
- Target & sabot acceleration
- Target injection and on-line diagnostics



ASSEMBLY TO BE ACCELERATED

Driver and fuel (size and cost, requirements)

1. **Fundamental contradiction between size & cost of fuel (target) and driver (laser) of Laser Fusion.**

	Driver	Targets
Quantity	1	10^{11} in 30 years
Volume per unit	$3 \cdot 10^{6}$ m^3	10^{-7} m^3
Cost per unit	10^{10}\$	0.1\$

2. **Second contradiction between mostly fixed laser system and fully variable target construction for different applications of Laser Fusion, between the requirements to laser (driver) and targets constructions**

During past 40 years all conditions, which driver cannot fulfill, went to targets construction additional strict requirements! (DT-solid sphere + strictly profiled laser pulse → shell target + simple laser pulse; laser radiation nonuniformity → indirect target; etc.).

This is why validation experiments with targets will always be necessary.

Indirect targets are beyond our present consideration, because we believe they must give way to the direct ones in Laser Fusion

Validation experiments

Similar plastic aerogels (regular open-cell foams or 3-D networks) of TMPTA (Nazarov) & TAC (Borisenko) used to smooth the radiation nonuniformities at different powerful lasers, perform other physical processes in microheterogeneous plasma as well, which are essential for the energy transfer models.

Large dynamic range of registration characterized both optical and X-ray streak-camera images. Their processing shows the weak heating of metal-foil on the rear of the aerogel to appear long before the main heat arrives by thermal conductivity and hydrodynamic waves.

Measured light transmission through the microheterogeneous plasma and the non-linear optical effects help to explain how the solid foil is heated through the aerogel.

The analysis of already published experiments on PALS and LIL is done in order to extract the additional information from signals only several-fold higher than the noise.

The processes important for the energy balance were studied in these experiments:

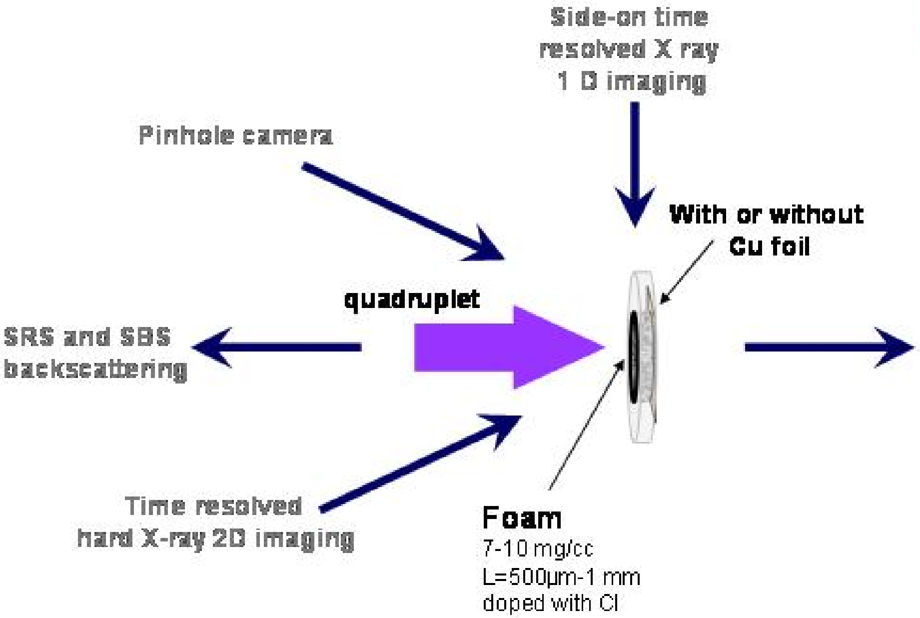
1- laser light diffusion through microturbulent plasma in the vicinity of the critical plasma density and light transmittance via target density and thickness;

2 – part of laser pulse energy transferred into SRS, SBS, harmonics and so on;

3 – heating of Al (Cu)-foil (shell) by passed and by converted radiation, which result in the material flux meeting and slowing down the main heat-and-material wave in the low-density matter.

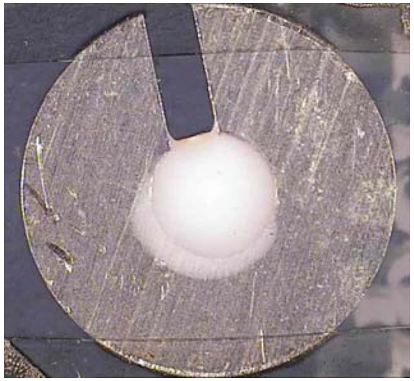
LIL laser diagnostic scheme

The LIL experiment



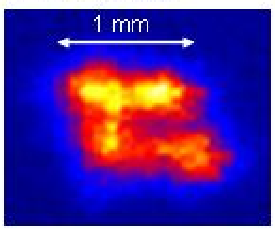
LASER

- 10 kJ of 351 nm light
- 2.7 ns square pulse
- minimum SSD level (< 1 Å)
- 1 mm spot size
- 3×10^{14} W/cm² on target

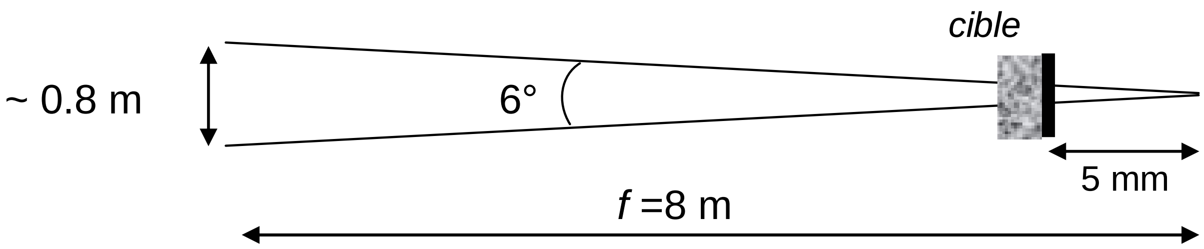


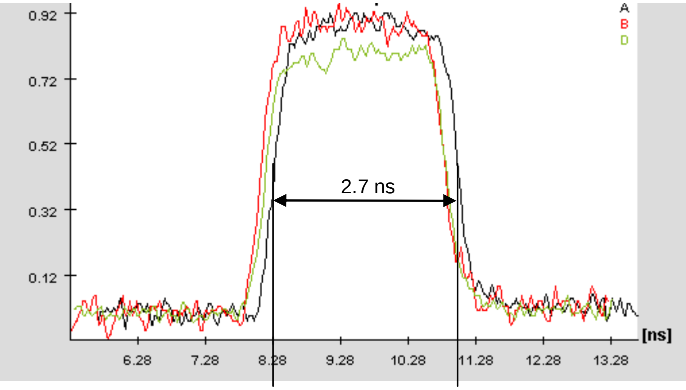
Transmitted beam diagnostic
- absolute power
- angular distribution

Laser focal spot

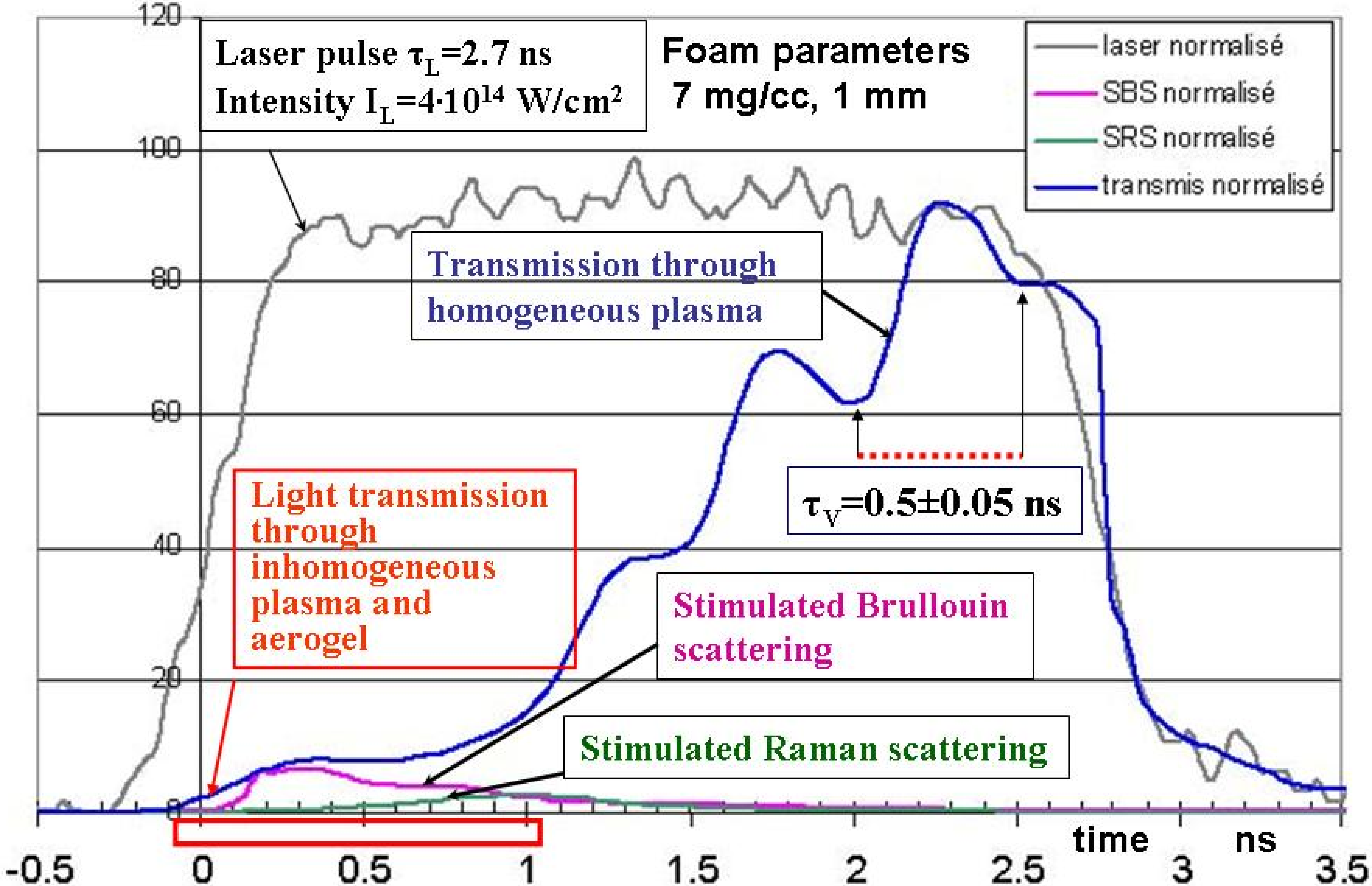


→ visualization of the ionization front
→ measurement of the foam ionization energy budget
→ foam effect on laser backscattering
→ validation of the foam smoothing effect

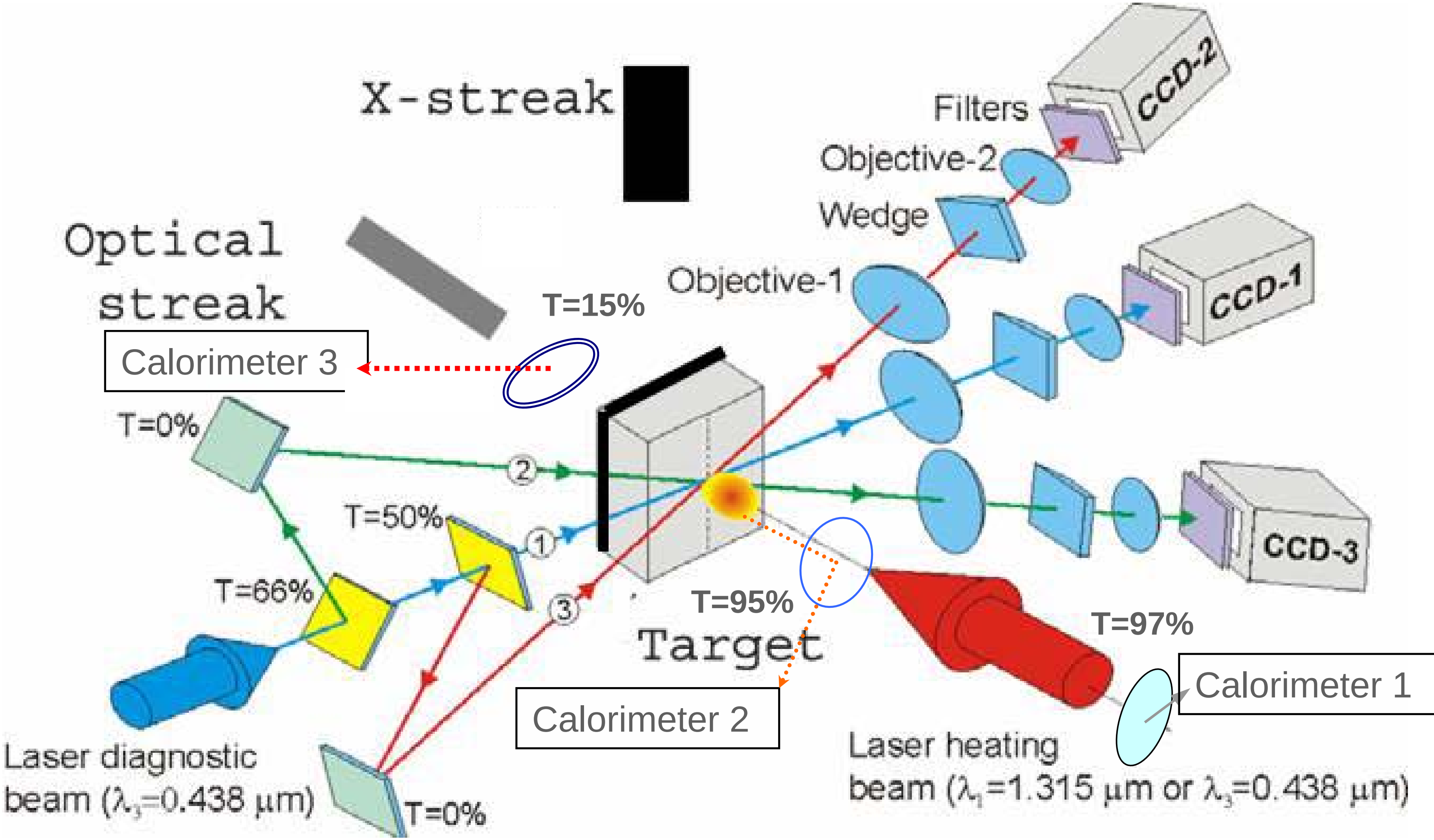




Laser radiation transmission through undercritical aerogel.

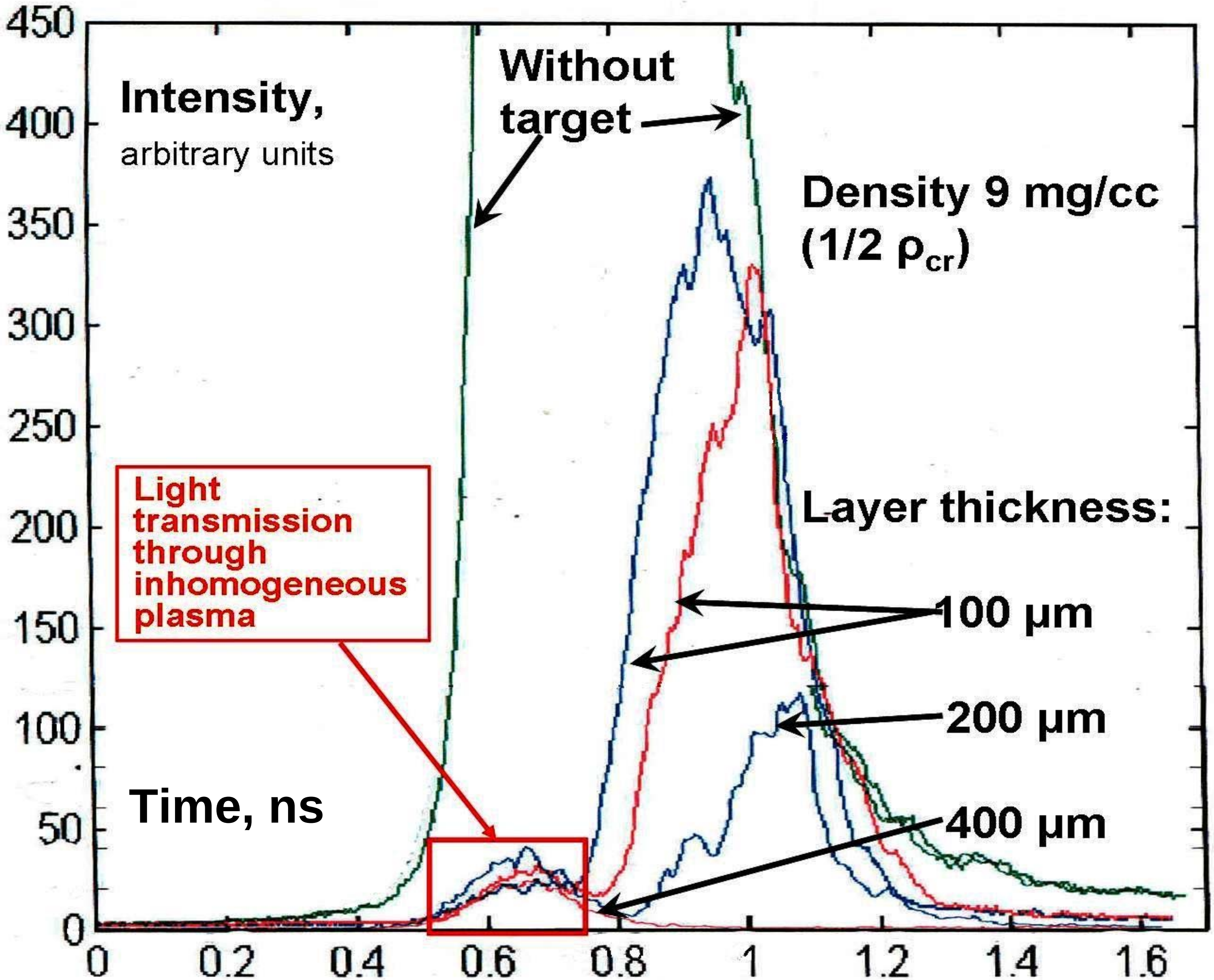


Normalized signals from laser, transmission of laser radiation, stimulated Bruillouin scattering, stimulated Raman scattering. (LIL 2007 experiment)

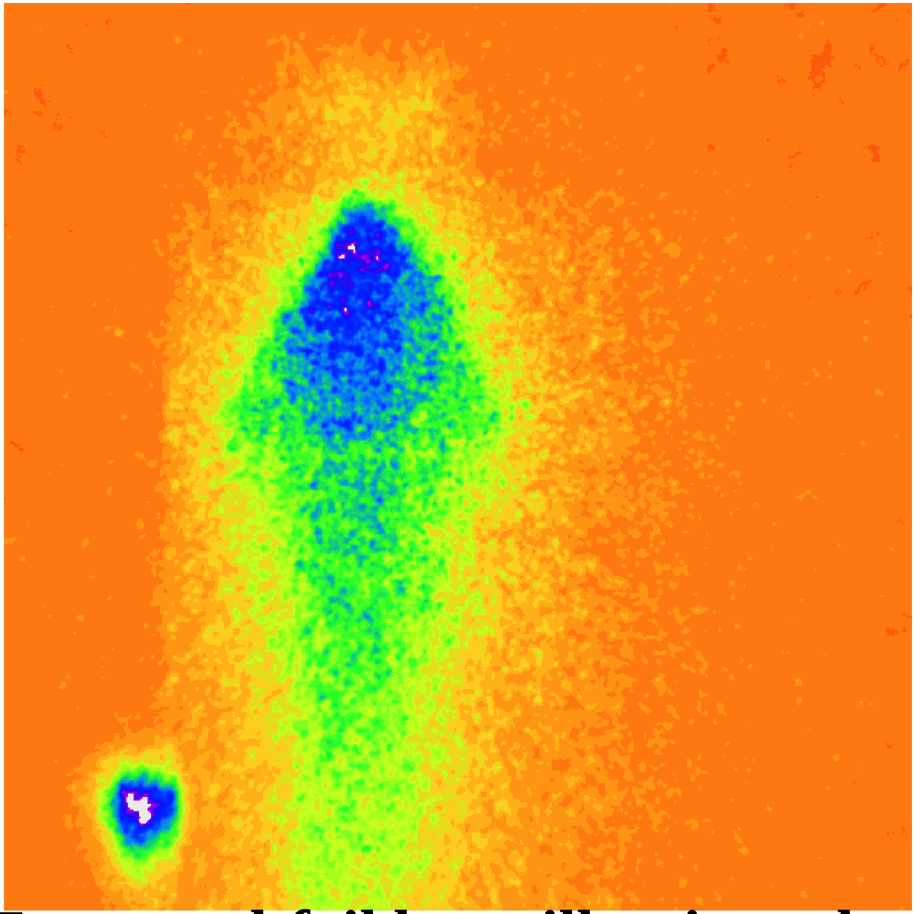


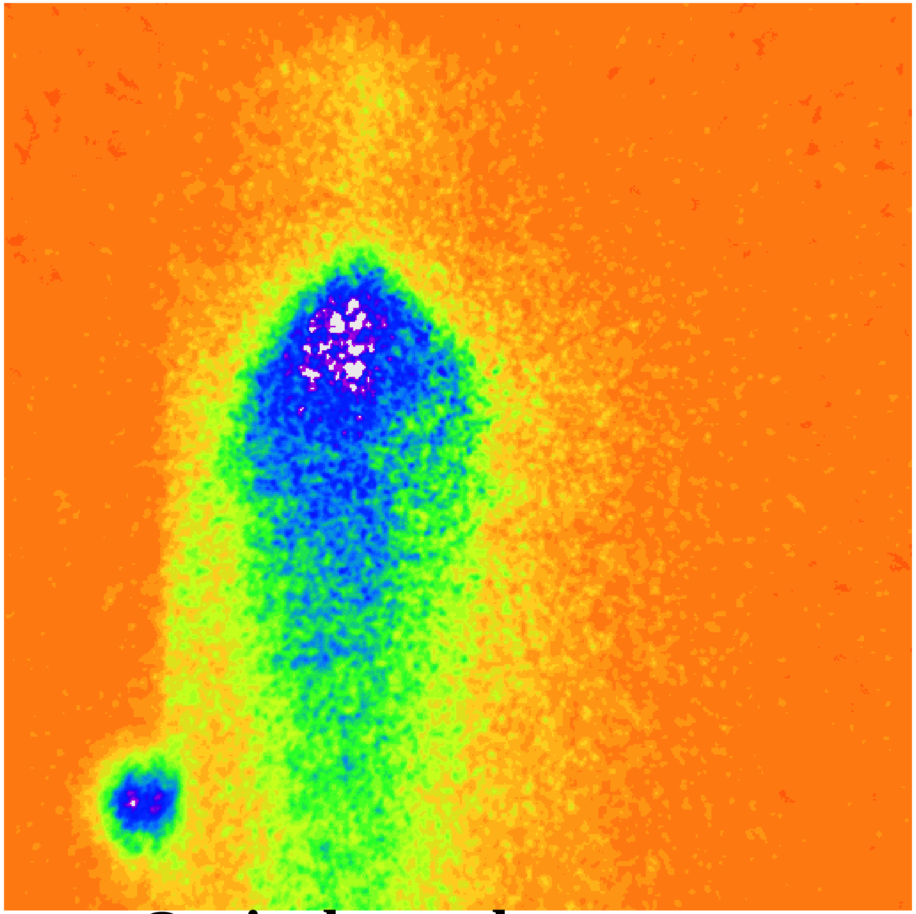
PALS irradiation and diagnostic scheme

Continued: the same density, varied thickness of target



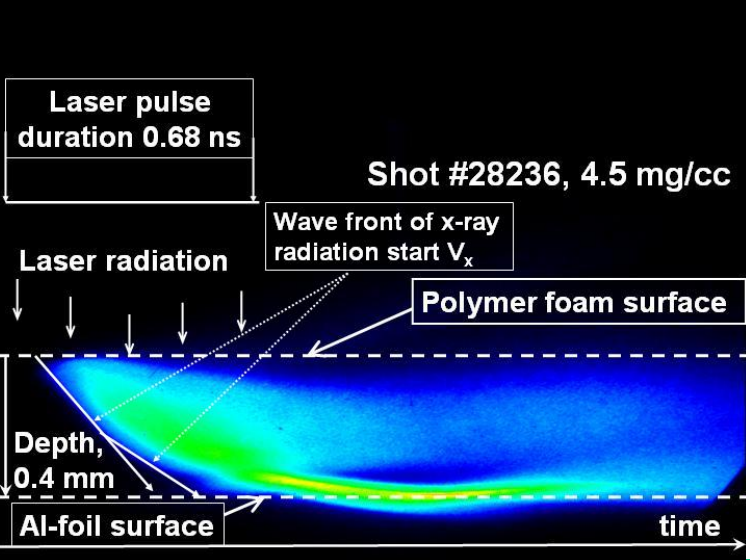
PALS experiments repeatability



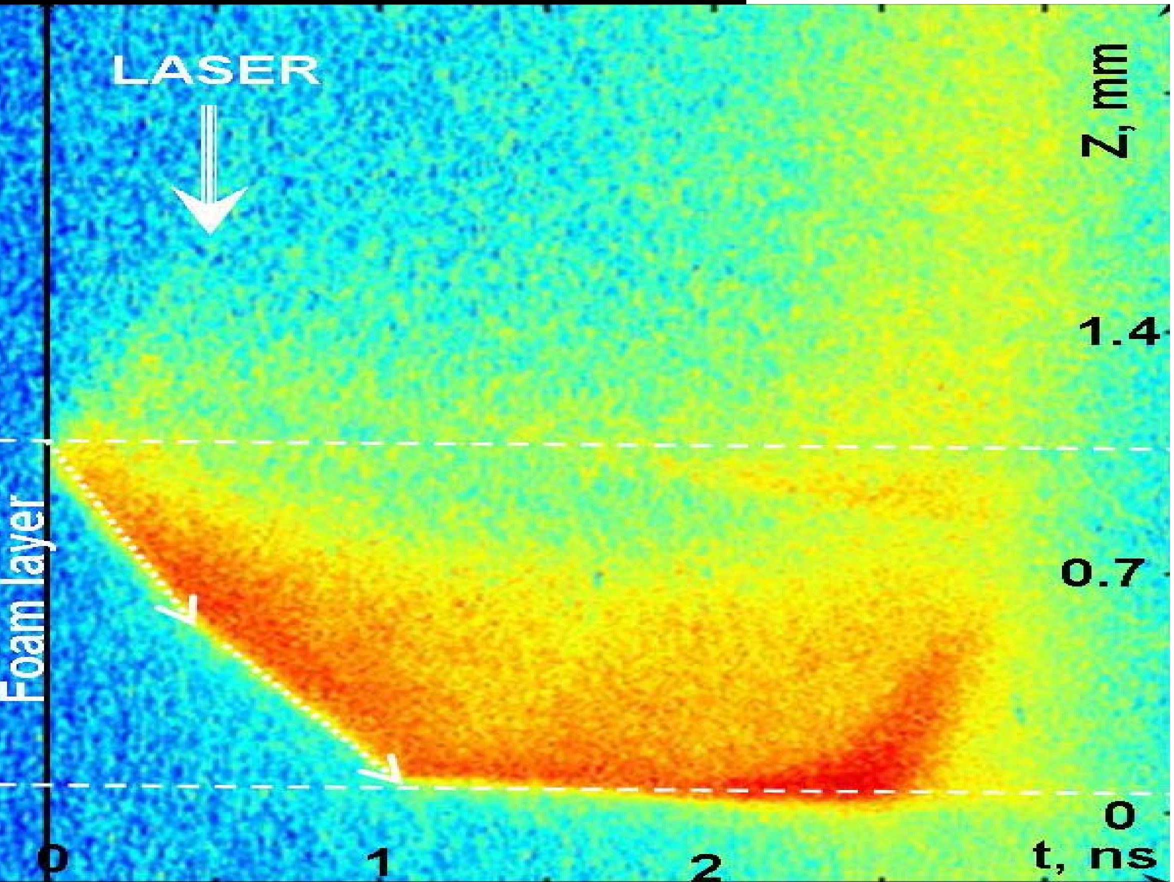


Foam-and-foil laser illuminated targets. Optical streak camera images for TAC foams of 9 mg/cc 450 μm thick covered with Al-foil of 5 μm (done in 2005 and repeated in 2006) . **Time axis directed downwards, the whole time period recorded - 5.2 ns. Full frame in horizontal directions equals to 2mm spatial 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.**

PALS x-ray streak- image in comparison with LIL data



Polymer – TAC +Al foil (1/4 critical density, LPI)

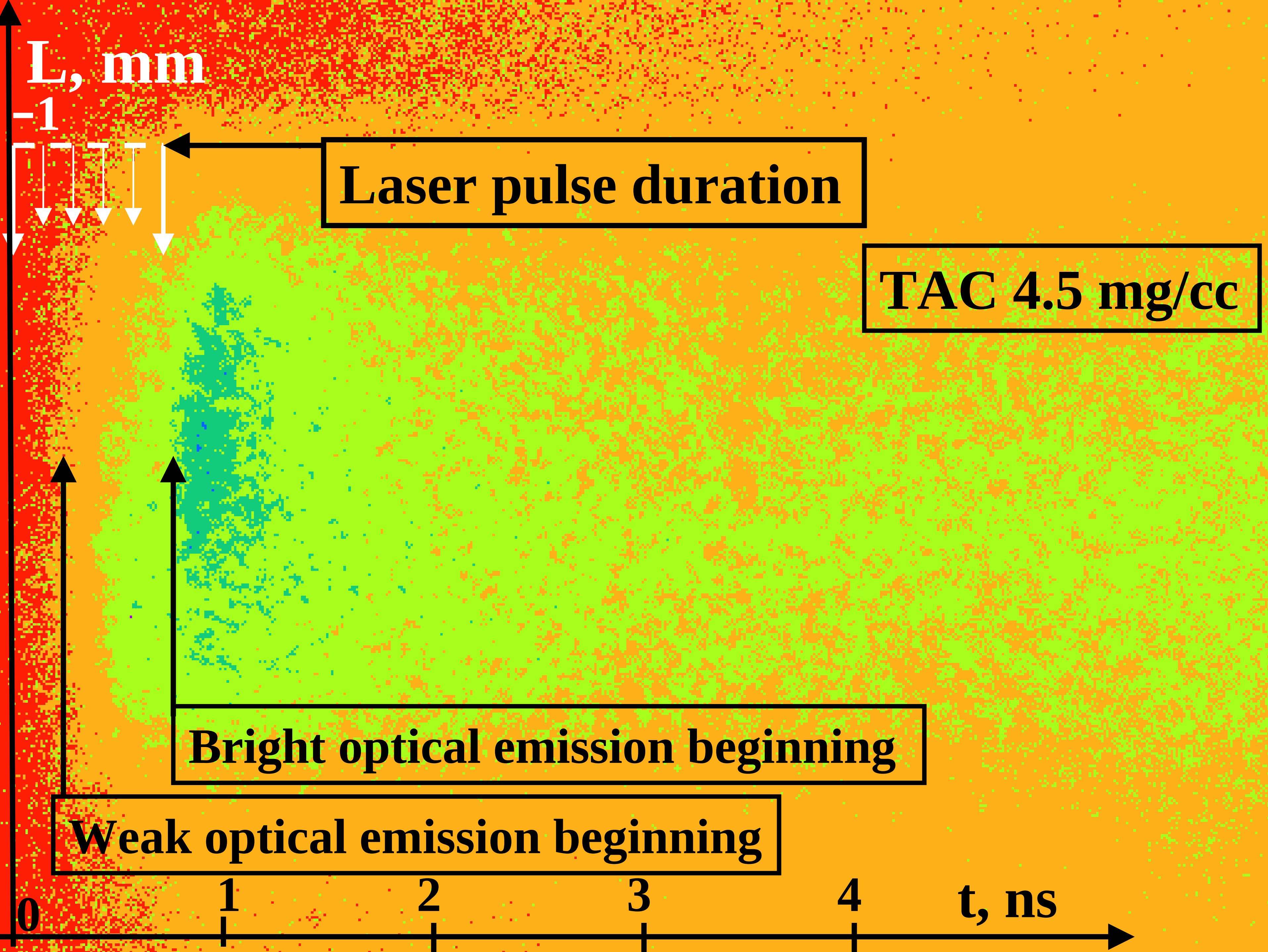


Polymer - TMPTA +Cu foil (10 mg/cc, W.NAZAROV)

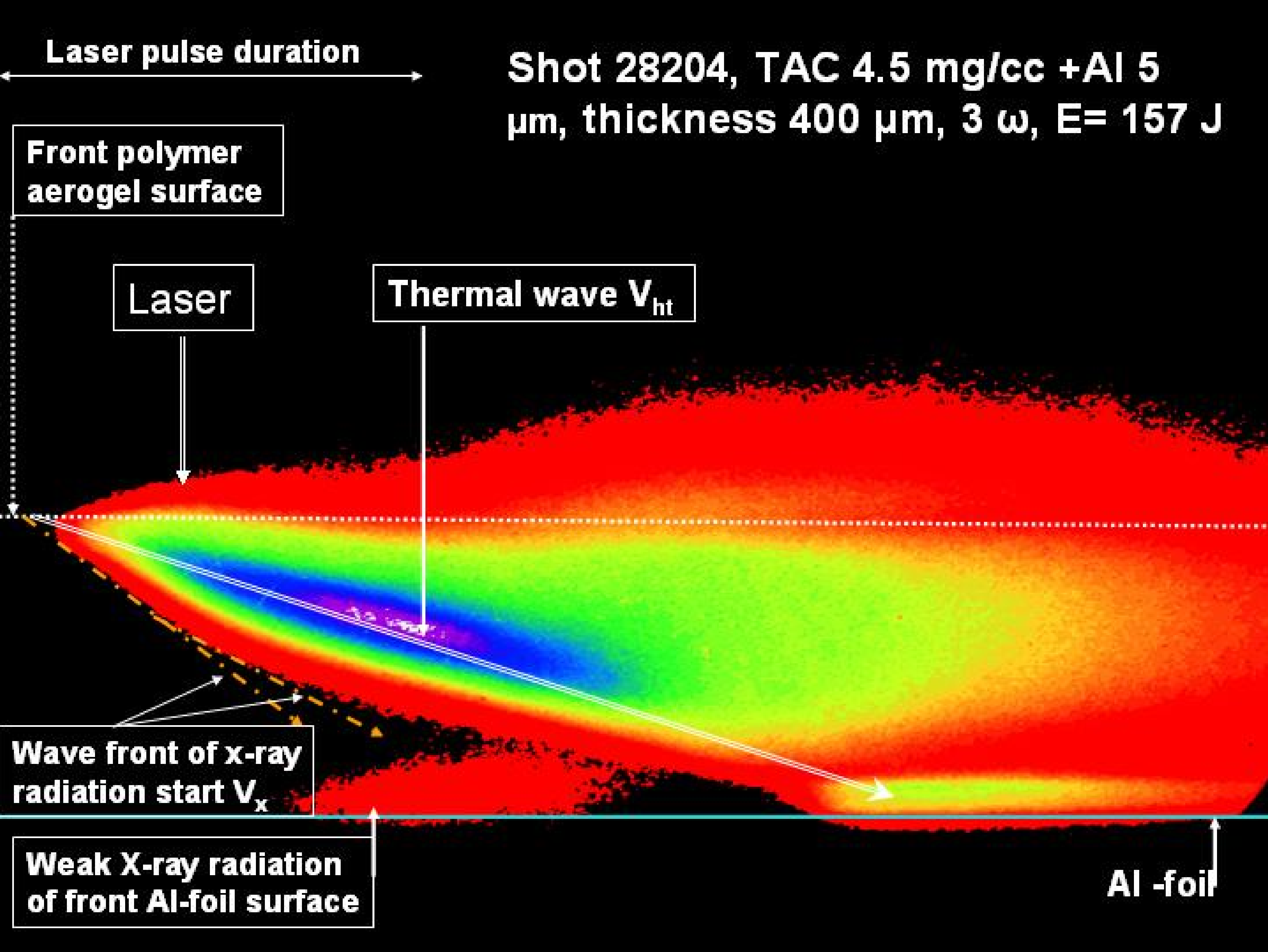
both scales match

Similar laser radiation fluxes give the similar changes of ionization front velocities

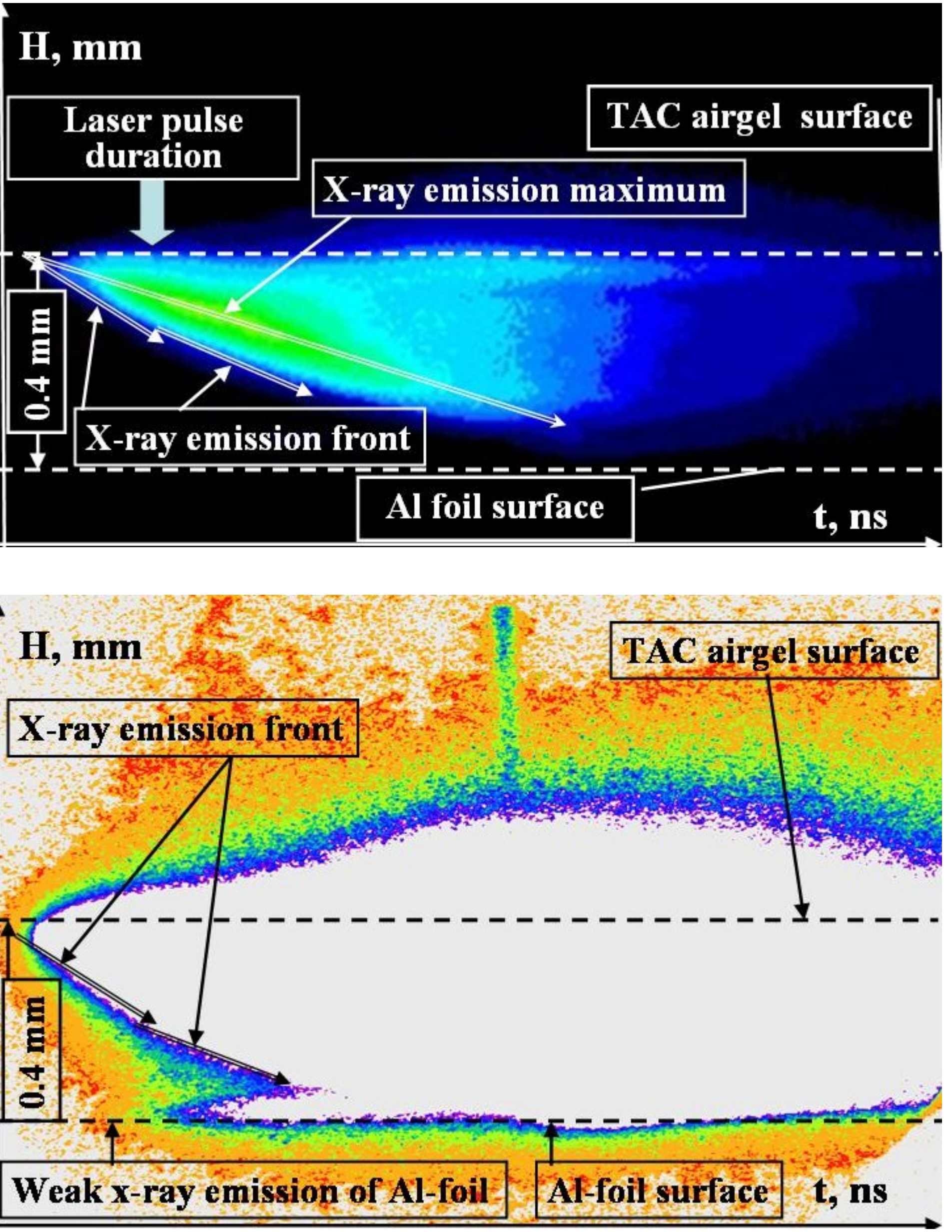
Repeatability of target performance with different facilities, time and country!



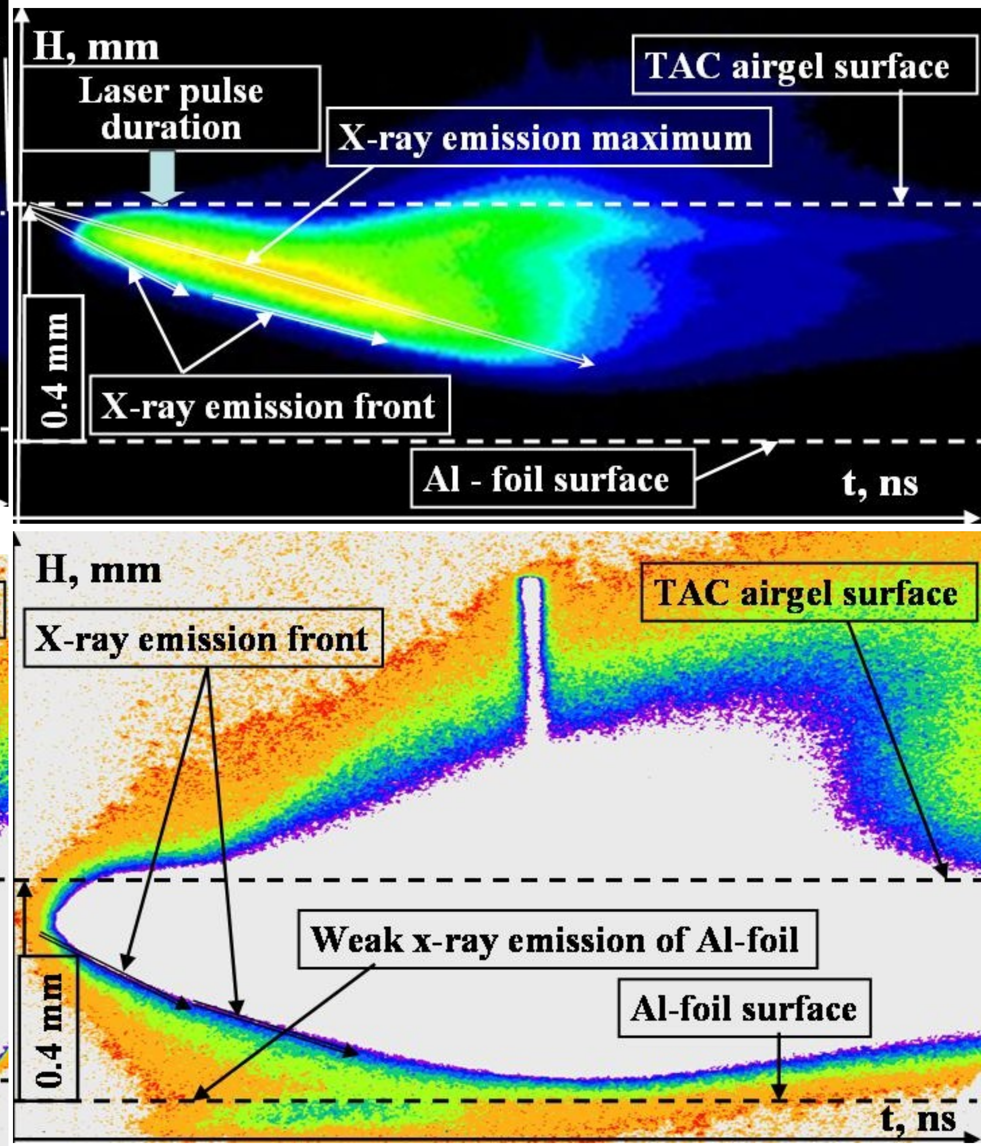
L, mm
–1
Laser pulse duration
TAC 4.5 mg/cc
Bright optical emission beginning
Weak optical emission beginning
0
1
2
3
4
t, ns


Laser pulse duration
Shot 28204, TAC 4.5 mg/cc +Al 5 µm, thickness 400 µm, 3 ω, E= 157 J
Front polymer aerogel surface
Laser
Thermal wave V_ht
Wave front of x-ray radiation start V_x
Weak X-ray radiation of front Al-foil surface
Al -foil

Bright and weak signals from X-ray streak-camera

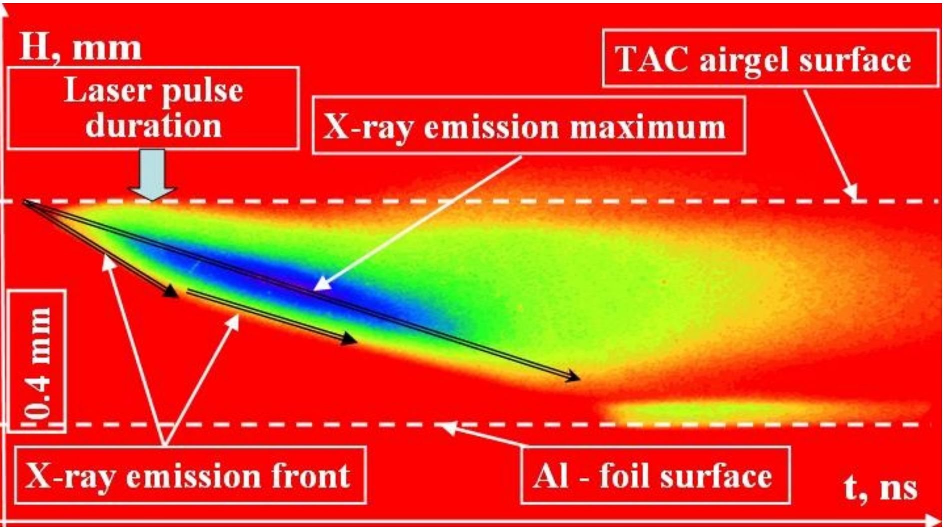


28232, TAC 9.1 mg/cc **1/4 ncr**, 400 μm

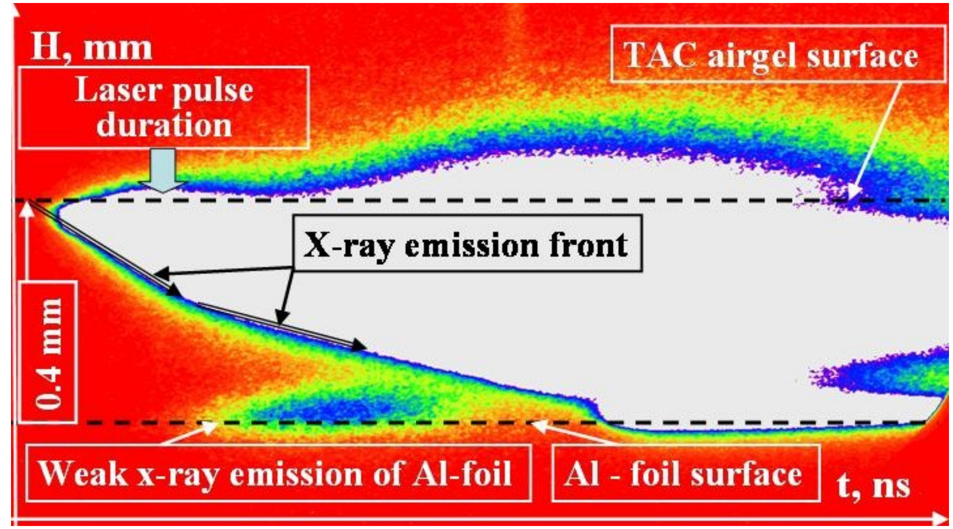


28231, 9.1 mg/cc, 0.9 TAC +0.1Cu, 400 μm

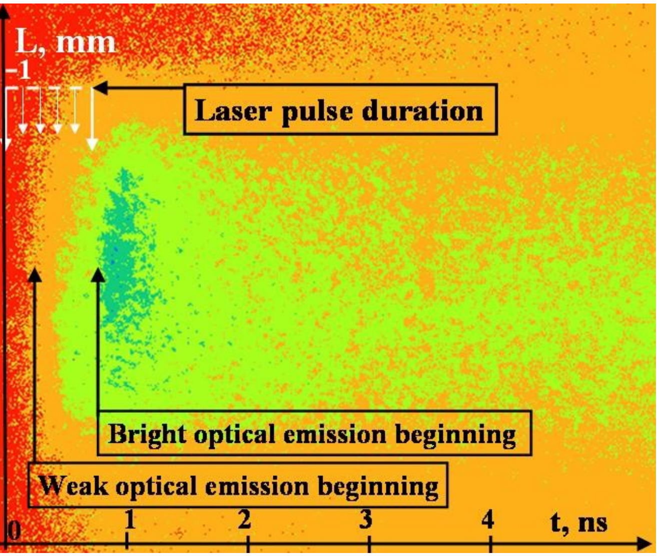
Weak signals of Al-foil emittance prior main heat arrival



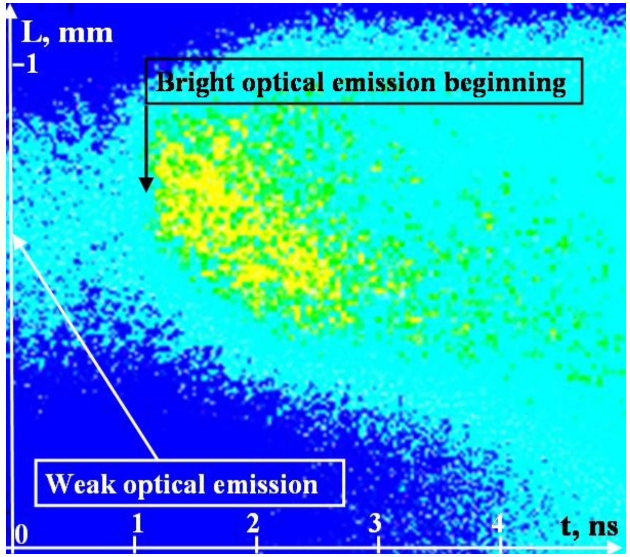
28204, TAC 4.5 mg/cc, 400 μm



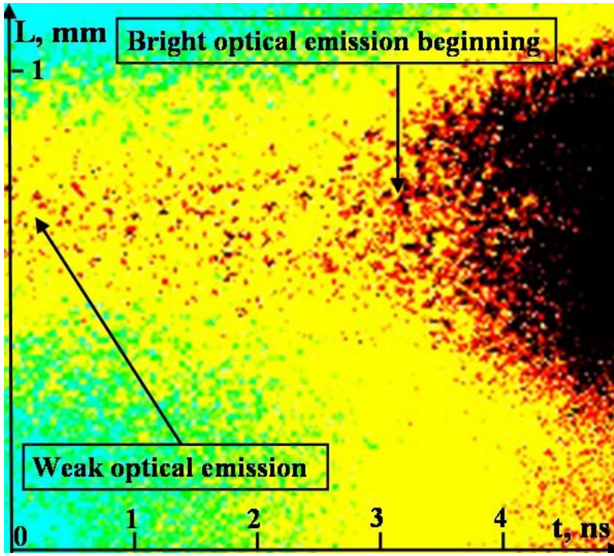
28204, TAC 4.5 mg/cc, 400 μm усилен в 30^x



28204, 4.5 mg/cc, 400 μm
усилен в 8x



28232, 9.1 mg/cc, 400 μm
усилен в 8x



28231, 9.1 (TAC&Cu) mg/cc,
400 μm, усилен в 8x

Shots comparison from PALS and LIL

The processes important for the energy balance were studied in these experiments:

1- laser light diffusion through microturbulent plasma and aerogel in the vicinity of the critical plasma density and light transmittance via target density and thickness;

2 – part of laser pulse energy transferred into SRS, SBS, harmonics;

3 – heating of Al (Cu)-foil (shell) by passed and by converted radiation, which result in the material flux meeting and slowing down the main heat-and-material wave in the low-density matter;

4 - special computer data processing of the images from large dynamic range (12-14 bit in black-and-white) streak cameras in X-rays and in the visible range was applied. It proved the weak preheat of the metal substrate long before the main shock and heat arrive to it through aerogel.

Results from third harmonic radiation lasers of PALS and from second harmonic of LIL : laser on light transmission through microheterogeneous plasma match each other.

Weak signals from x-ray and optical streak-cameras are recorded.

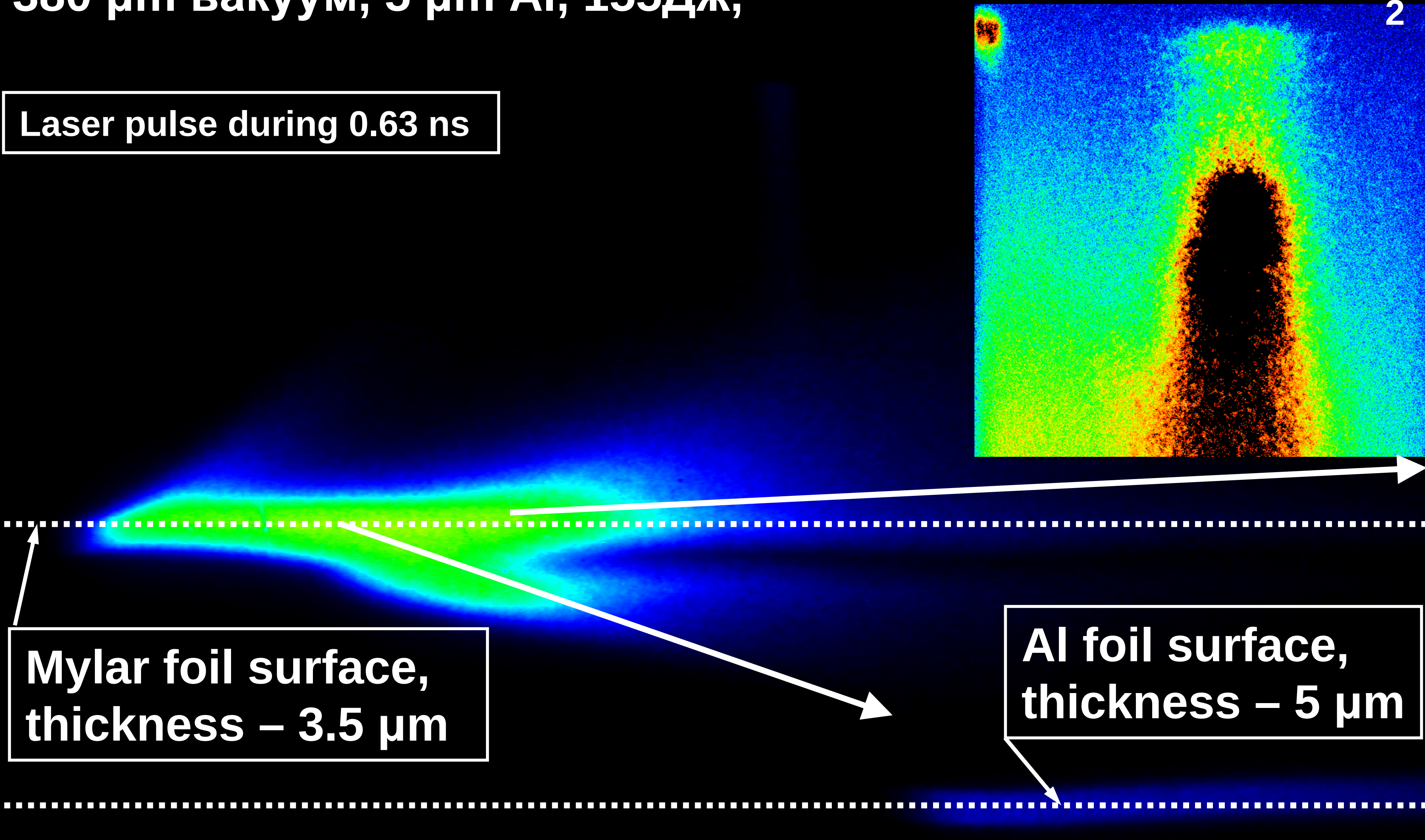
Results from basic frequency of PALS and of MISHEN on previous heating of Al-foils through aerogel/plasma are consistent to each other.

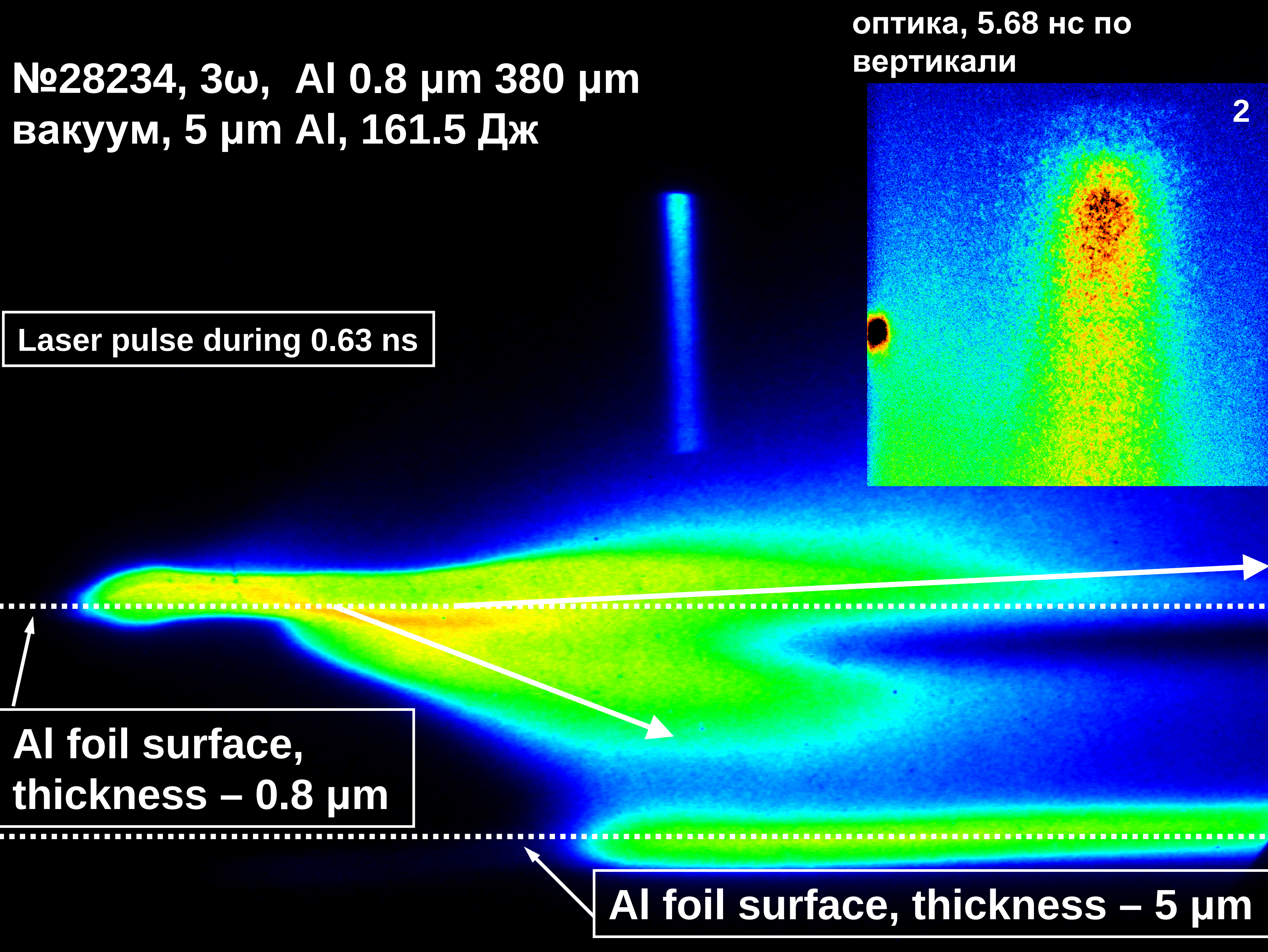
Results from PALS and from LIL on plasma formation velocity in two-layers (aerogel + metal foil) targets coincide.

Plasma jet flight through aerogel with copper nanoparticles is slower than without additives

№28221, 3ω, Mylar 40нм Al+3.5 μm, 380 μm вакуум, 5 μm Al, 155Дж,

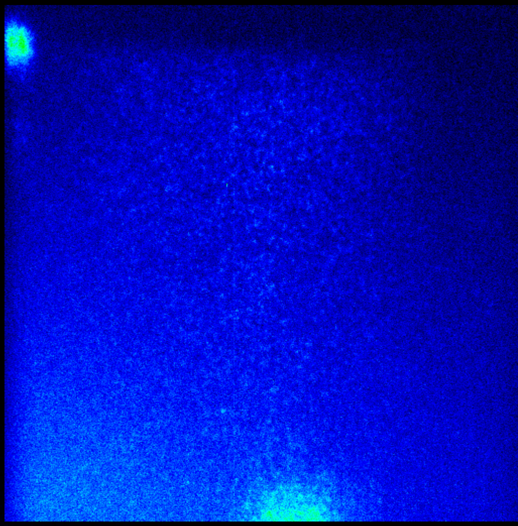
оптика, 5.68 нс по вертикали

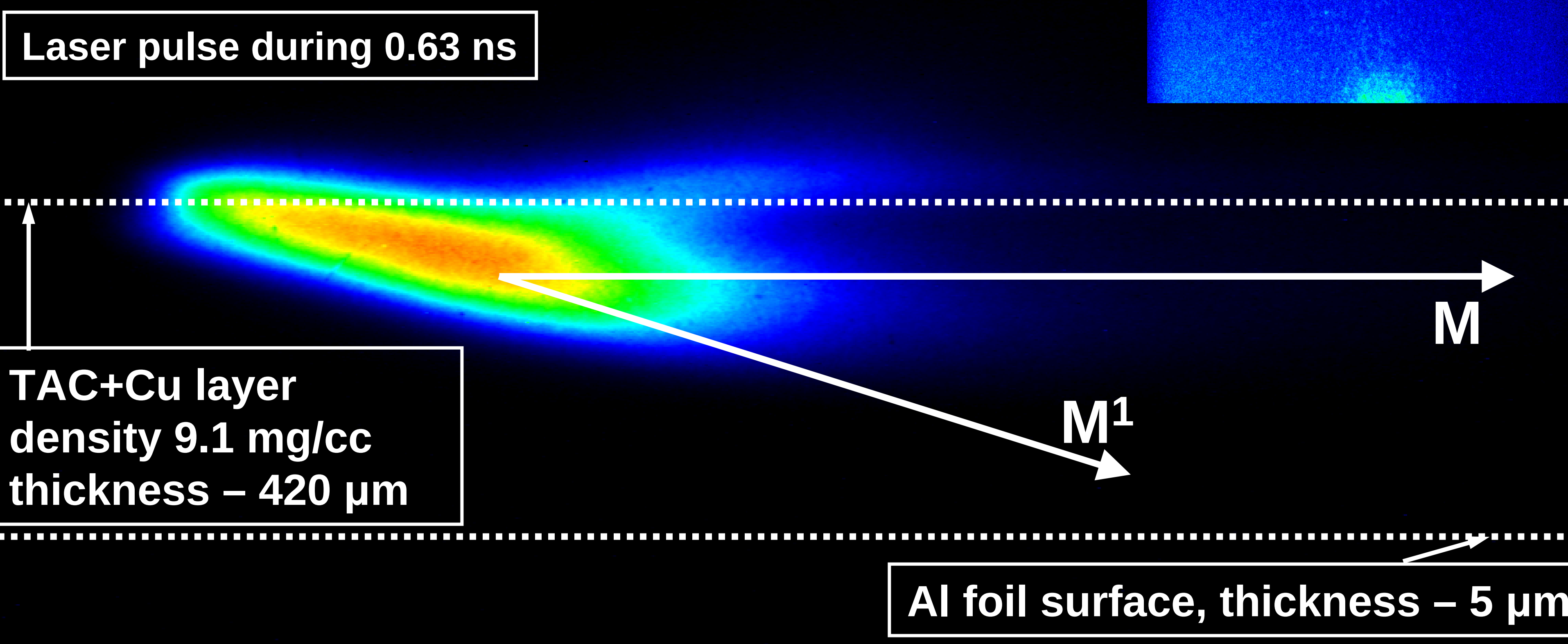



№28234, 3ω, Al 0.8 μm 380 μm
вакуум, 5 μm Al, 161.5 Дж
оптика, 5.68 нс по
вертикали
2
Laser pulse during 0.63 ns
Al foil surface,
thickness – 0.8 μm
Al foil surface, thickness – 5 μm

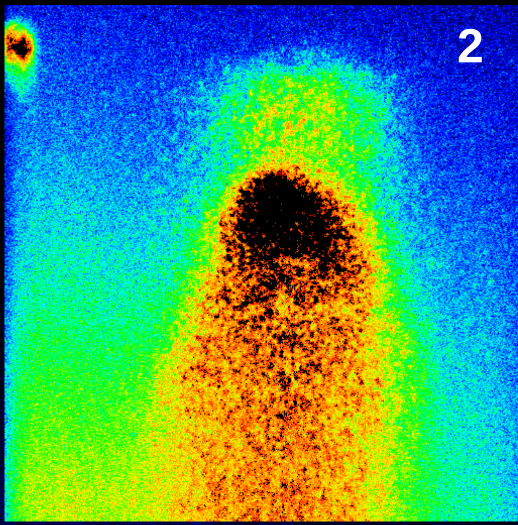
№28208, 3ω, 156 Дж, ТАЦ+Cu 9.1 мг/см3, 420 μm, Al, 5 μm, рентген 2 нс

оптика, 5.68 нс по вертикали



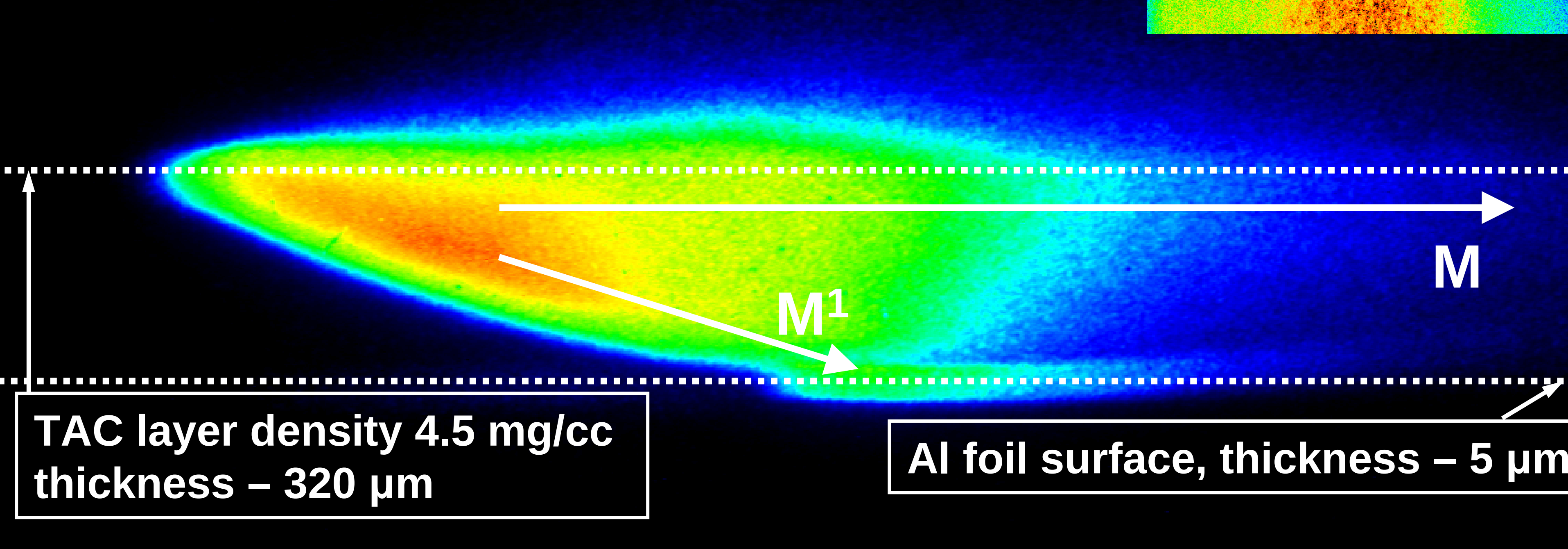


оптика, 5.68 нс по вертикали



№28215, 3ω, 102 Дж, ТАЦ 4.5 мг/см3, 320 μm, Al, 5 μm, 1 рентген 2 нс

Laser pulse during 0.63 ns

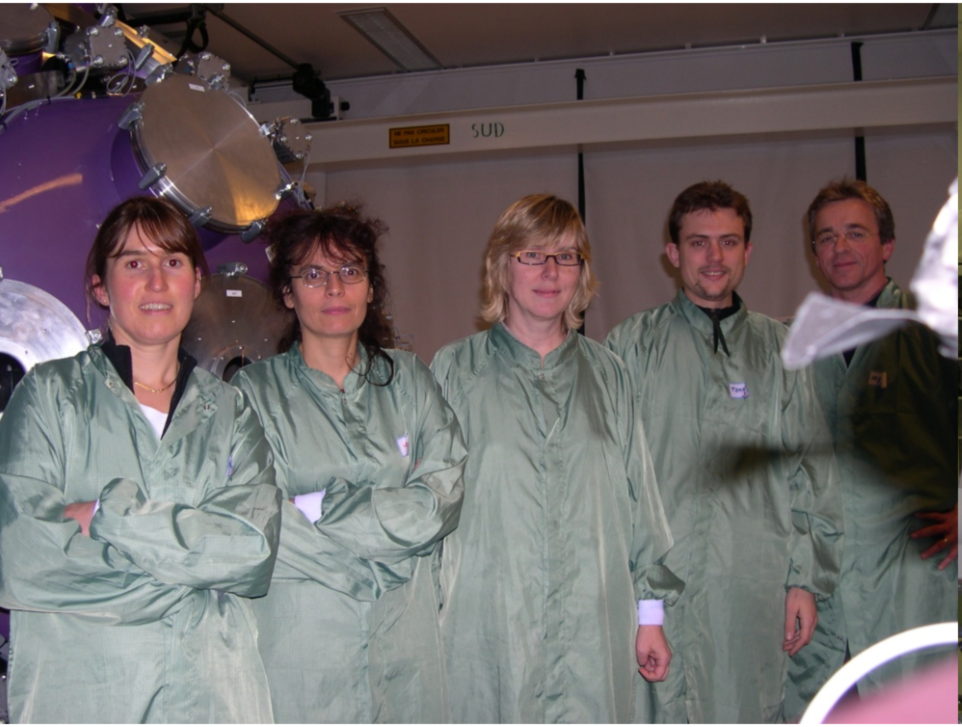


Acknowledgements

PALS: D. Klir, V. Kmetik, E. Krousky, J. Limpouch, K. Masek, M. Pfeifer, J. Ullschmied et al.

LULI: S. Depierreux, C. Labaune, D.T. Michel, C. Stenz, V. Tassin, et al.

LIL: S. Depierreux, C. Labaune, D.T. Michel, C. Stenz, M. Grech, S Huller, P. Nicolai, D. Pesme, W. Rozmus, C. Meyer, P. Di-Nicola, R. Wrobel, E. Alozy, P. Romary, G. Thiell, G. Soullie, C. Reverdin, B. Villette.



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Conclusion

1. During past 40 years all conditions, which driver cannot fulfill, went to targets construction additional strict requirements. This is why validation experiments with targets will always be necessary.
2. Though target fabrication techniques are different for different projects each of them results in such “by-products” as new fundamental knowledge, laboratory astrophysics, material constants at extreme conditions and others, which are worth studying themselves.
3. Target creation is a highly integrated research field, with cross-links to atomic, nuclear, laser, solid-state and plasma physics. Interesting and difficult and in many respects challenging.