The radiation yield in different spectral ranges from low density structured laser plasma with different high z-admixture

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Topics

- Laser plasma - Radiation source
- Energy balance: main processes
- Radiation sources: ICF physics (hohlraum), diagnostics, material sciences, technology - EUV lithography source
- Requirements: target designs
- Experimental results
- Theoretical models and simulation
- Conclusion

Abstract

The laser radiation has low entropy, and, thus, may be effectively converted into the radiation of a more hard range. The problem is to find particular schemes for different tasks. The competing processes under the laser plasma heating are the plasma thermal radiation and the plasma expansion - the conversion of the laser pulse energy into the plasma kinetic energy. The efficiency of the two mentioned processes depends on the density and size of plasma, and may be effectively controlled by these two parameters: a decrease of density and an increase of the target size enhance the efficiency of radiation. The radiation spectrum depends on the plasma conposition and the heavy admixtures concentration in the plasma. In the last two years in laser irradiation of the target researches the scientists have been deeply involved in studying of the energy transformation and transfer (including the radiation) processes in low-density structured foam-like media with an addition of different (in particular, heavy) elements.

It has been found experimentally that under laser irradiation of a foam-line target with the heavy ion admixture it is possible to produce the radiation with the efficiency close to 50%.

This report concerns a theoretical basis and the experimental results related to the problem.

Effective Conversion of Laser Radiation into Plasma Self-emission

(G.A.Vergunova, V.B.Rozanov, Kvantovaya Elektronika, v.19, N3. 263-265, 1992)

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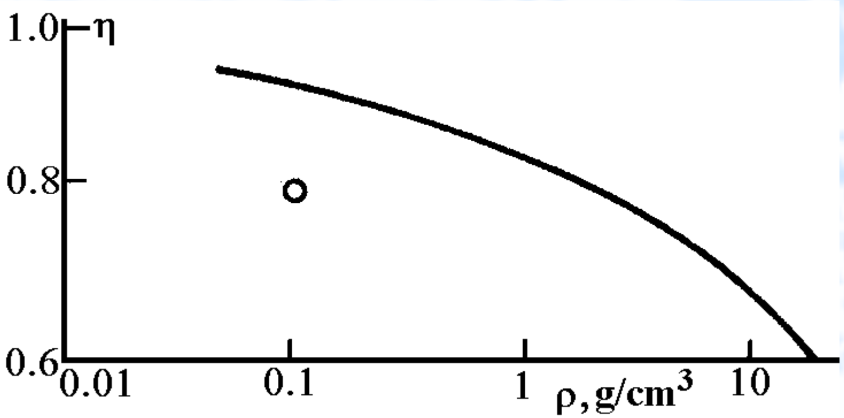
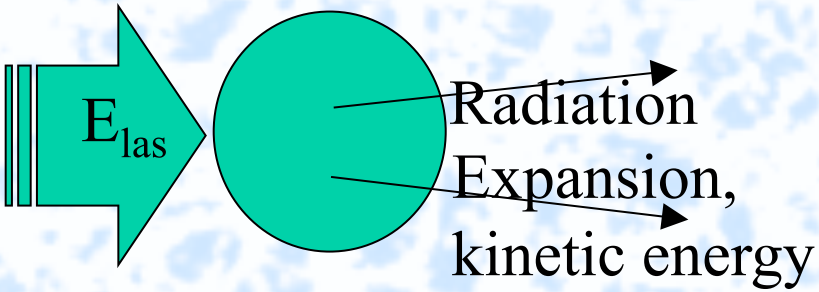
Target density influence
Optic-transparent plasma





E_{las}

Radiation
Expansion,
kinetic energy

Coefficient of laser radiation conversion in plasma self-emission,

λ=1.06μm, τ=4ns, $q_{las}=10^{13}$ W/cm^2.

$E_{las} = N\varepsilon = 4\pi R^2 q_{las}\tau_{las} = 4\pi R^3/3\cdot n\varepsilon$,

N - total number of particles in the target, ε - energy per particle,

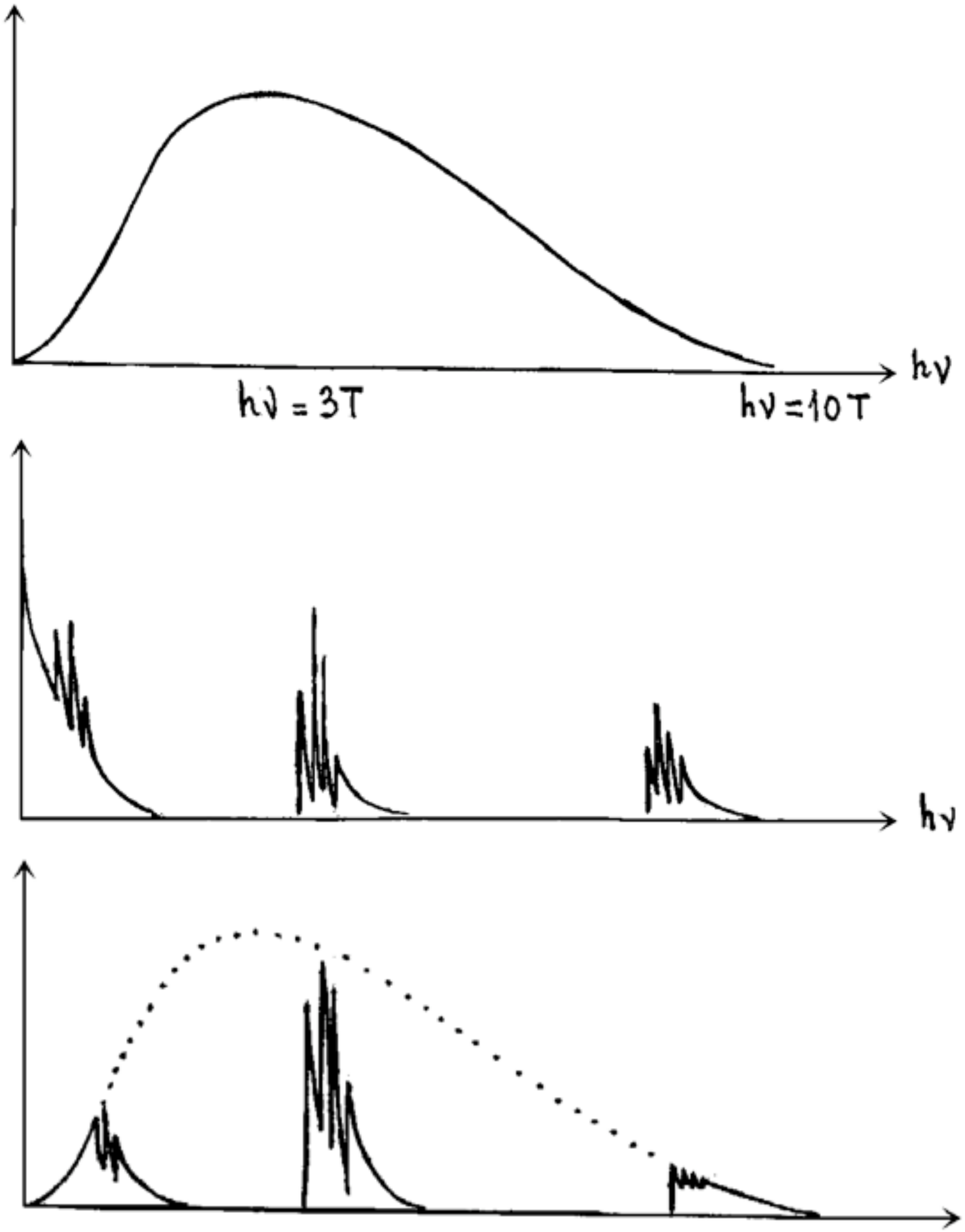
$\tau_{rad} = n\varepsilon/j$, j - emissivity, n - density

$\tau_{exp} = R/c_s$, R - target radius, c_s - sound velocity

High efficiency radiation conversion condition: $\tau_{rad} < \tau_{exp}$

or $jR/c_s \sim \varepsilon n$

K-electrons radiation (1)



Low entropy laser radiation:

$dE_{las} = TdS$

dS is small,

$T \sim h\nu$ is high

Black body radiation:

$$S_{\nu,eq} = \frac{2\pi h\nu^3}{c^2}\frac{\nu^3}{\exp\left(\frac{h\nu}{kT}\right)-1}$$

K-electrons radiation (2)

Atoms	Ti	Cu	Ge	Kr	Zr	Ag
Z	22	29	32	36	40	47
hν, keV	6.6	11.3	13.8	17.6	21.8	30

Emissivity of the plasma (Bremsstrahlung + photorecombination):

$$J = 4.85\cdot 10^{-24}\, z\,\overline{z^2}\, n_i^2 T_e^{1/2}\left(2.4 I/T_e + 1\right)\frac{\mathrm{erg}}{\mathrm{cm^3 s}}$$, T_e - keV

Opacity: $J = \int j_\nu d\nu$ $j_\nu = \kappa_\nu I_{\nu,eq}$ $I_{\nu,eq}$ - black BR intensity

K-electrons radiation $^{(3)}$

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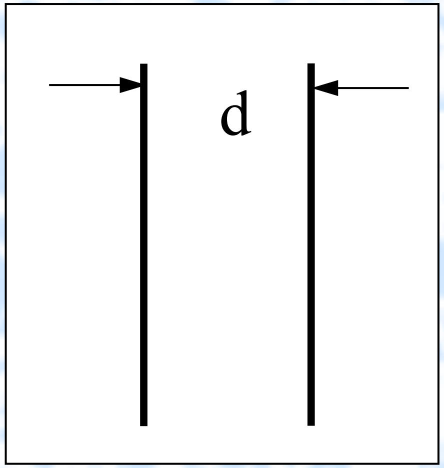
Plane target:

$\tau_\nu = d/l_\nu = \kappa_\nu$ – optical thickness

Photons escape probability:

$$W_\nu^{(1)} = \frac{1}{\tau_\nu}\left[\frac{1}{2} - \int_1^\infty \exp(-x\tau_\nu)\frac{dx}{x^3}\right]$$

$$S_\nu^{(1)} = 4\pi j_\nu W_\nu^{(1)}\frac{d}{2} = \pi I_{\nu,eq}\left[1 - 2E_3(\tau_\nu)\right]$$



Spherical target:

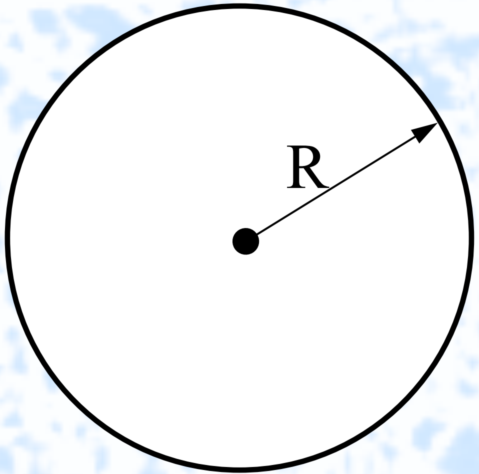
$x_\nu = 2R/l_\nu = \kappa_\nu 2R$ – optical thickness

Photons escape probability:

$$W_\nu^{(3)} = \frac{3}{x_\nu}\left[\frac{1}{2} - \frac{1}{x_\nu}\left(\frac{1}{x_\nu} - \left[1 + \frac{1}{x_\nu}\right]e^{-x_\nu}\right)\right]$$

$$S_\nu^{(3)} = 4\pi j_\nu W_\nu^{(3)}\frac{R}{3}$$

If R = 1.4d $\quad \dfrac{|S_\nu^{(1)} - S_\nu^{(3)}|}{S_\nu^{(1)}} < 7\%$



K-electrons radiation (4)

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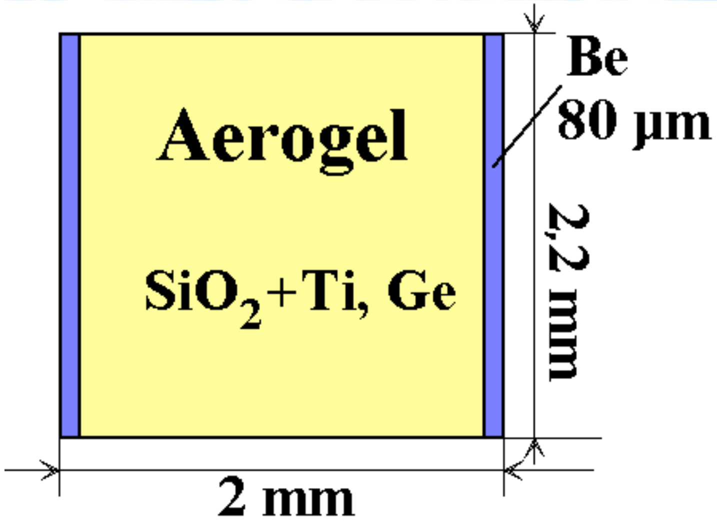

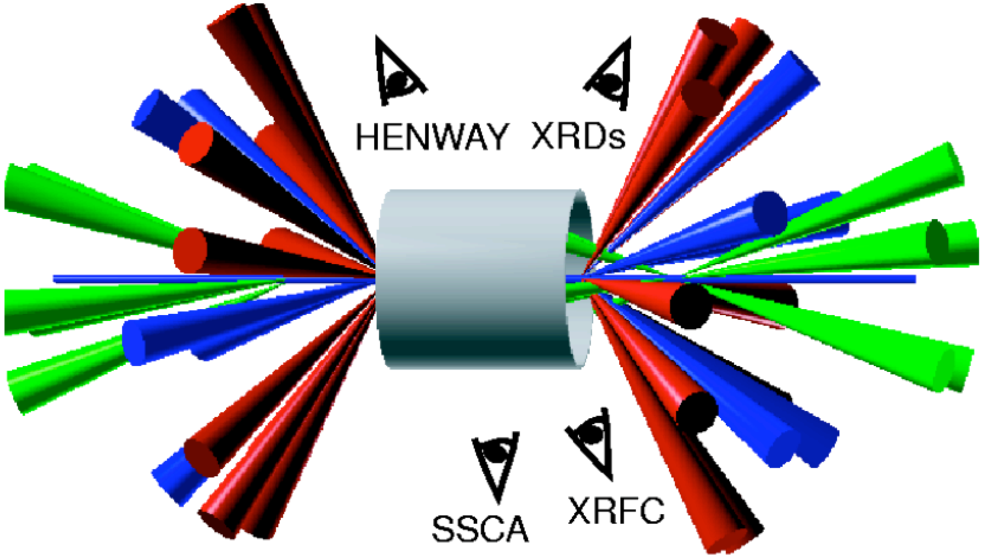

$E_L = 7 – 14 – 20$ kJ, 3ω, $\tau_L = 1$ ns (square form)

$I_L = (1.7 – 8)10^{15}\cdot W/cm^2$ (Omega laser, LLE)

Aerogel: $\rho = (3.1 – 6.5)$ mg/cm^3

Ti at. 3% Ge at. <20%

Ti: $4.67 < h\nu < 5$ keV Output 1.9%·14.5 kJ = 290 J

Ge: $10 < h\nu < 13$ keV Output 1 – 3%·20 kJ = 200 – 600 J

$h\nu < 2$ keV Output ~50% ≈ 10 kJ

* M.Tobin et al., ECLIM 29, 2006, Madrid, Spain

* K. Fournier et al., Phys.Rev.Lett., **v.92,** 165005 (2004)

K-electrons radiation (5)

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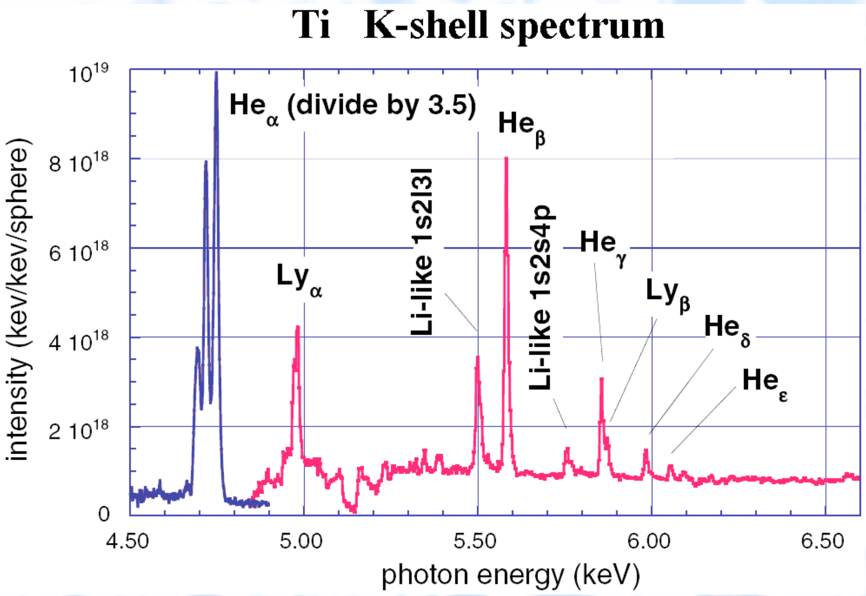

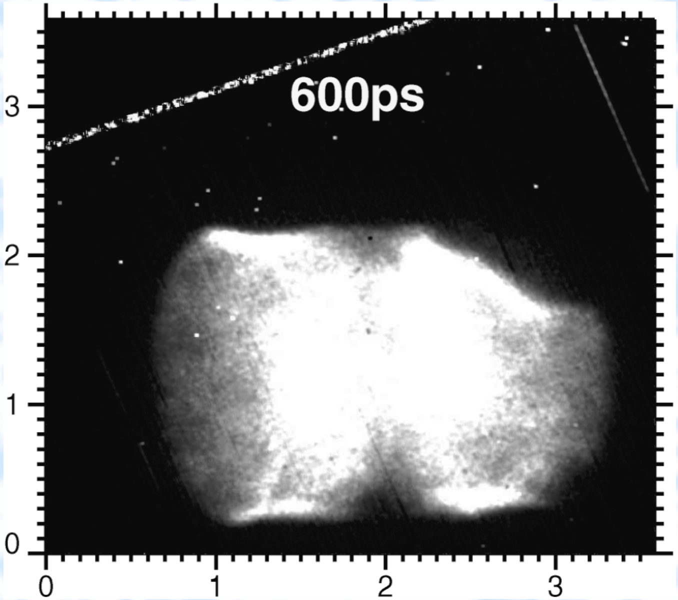

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Requirements for properties of the radiation sources

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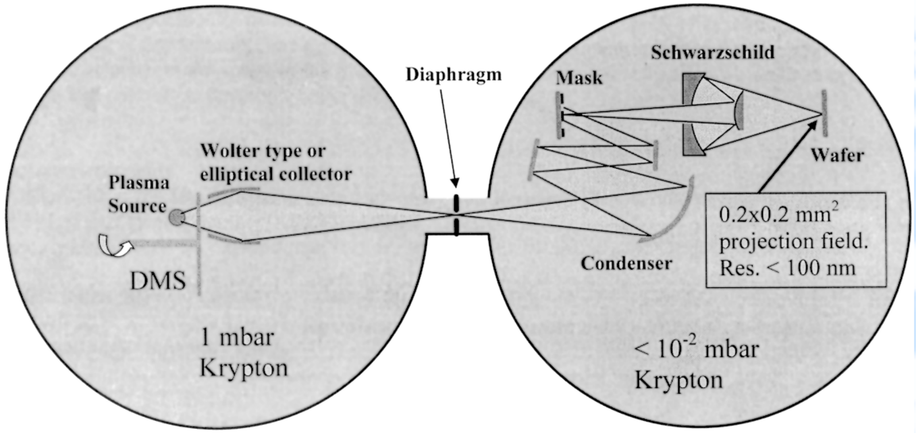
Soft x-ray source for scientific investigation and technology application (including biological objects investigation and material sciences):

- Spectral range hν ~ 50eV - 20 keV
- High efficiency
- Single shot and repetition rate modes
- Stable, efficient and clean source
- Soft x-ray source requirements (LPI, TRINITI)

Requirements for properties of the radiation sources

EUV litography source:

- Spectral range 13 - 14 nm
- Repetition rate mode. Average power $P_{h\nu}$ in the intermediate focus in the 2% bandwidth around 13.5 nm - 100W
- Efficiency in the useful band ~ 2%
- Lifetime of optic system about ~ 1 year
- Debris mitigation problem
- EUVL prototype of the FIRB project (ENEA, Frascati, S.Bollanti, F.Flora et al)



EUV-source

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Requirement:

100 W, 30000 hours lifetime

Single shot:

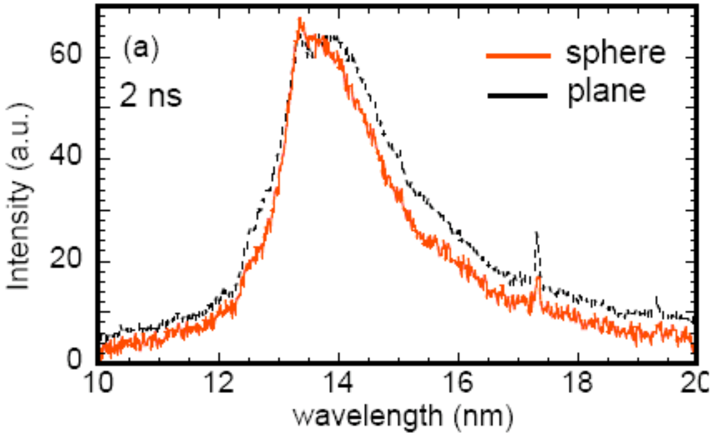
$\tau_L = 2$ and 8 ns

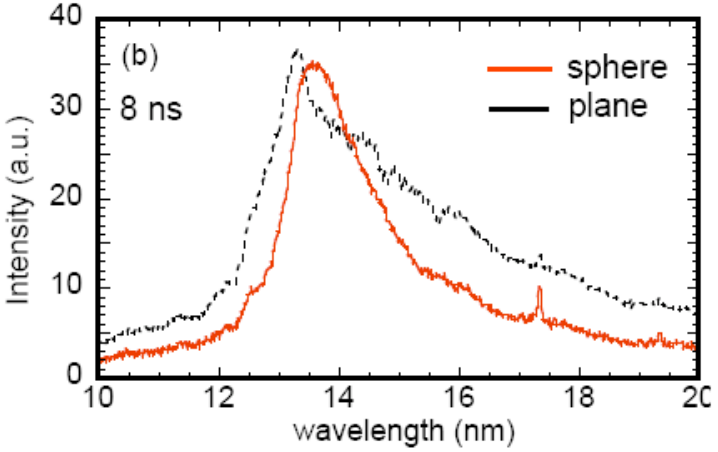
$I_L = 10^{10} – 5 \cdot 10^{11}$ W/cm^2

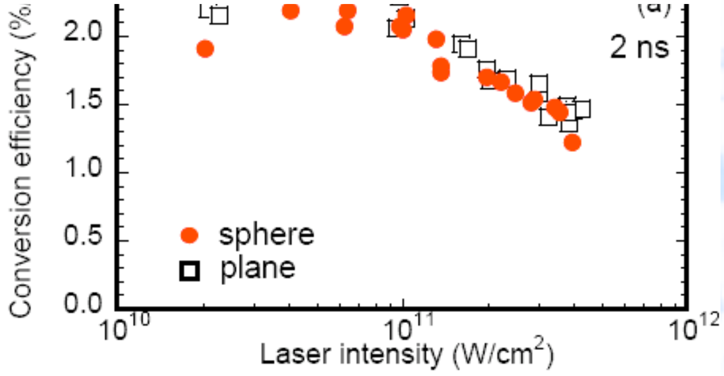
$\eta \approx 2\%$

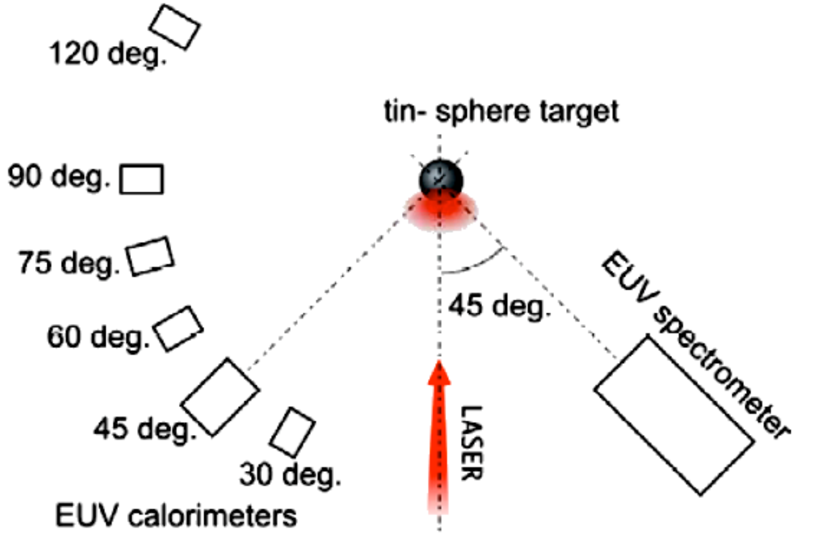
Rep. rate 10 Hz

$\eta \approx 0.2\%$









Experimental arrangement.

Target physics. Main Relations⁽¹⁾

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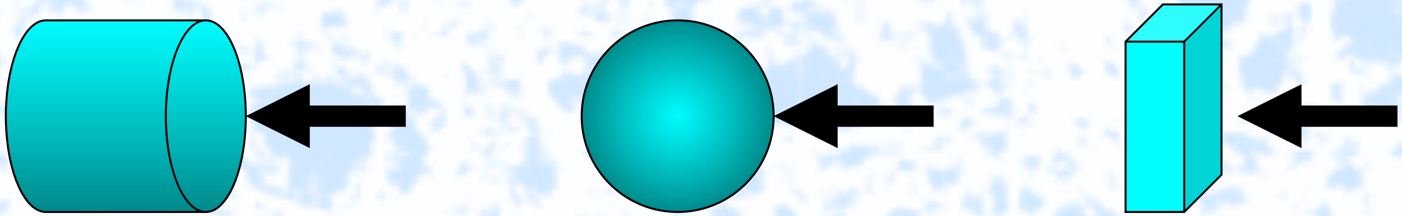
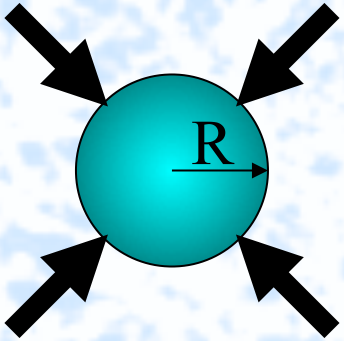
- We will use one-side irradiation of cylindrical (spherical, plane) target.





- Simple model: Spherical target,
  Symmetrical irradiation
- $P_L = E_l \nu$, ν - repetition rate, single shot - E_L
- $E_L = 4\pi R^2 q_L \tau_L$, $E_L = N\varepsilon$, q_L - laser intensity, τ_L - laser pulse duration
- $N = R^3 n \cdot 4\pi/3$ - total number of atoms in the target, n - particles density
- $\varepsilon = \varepsilon_T + \varepsilon_{ion} + \varepsilon_{kin}$ - energy per particle

Target physics. Main Relations$^{(2)}$

- $\kappa R >= 1$ Laser radiation absorption condition
- $\tau_{exp}=R/c_s$, c_s- sound velocity, τ_{exp}- time of expansion, transition of laser energy into kinetic energy
- $\tau_{rad}=n\varepsilon/j$, j- emissivity (erg·cm^3/s) integrated over spectrum, τ_{rad} - time of the laser energy transition into radiation energy
- $\tau_{rad}< \tau_{exp}$ Condition of high efficiency of radiation
- $j\ \tau_{exp}/(n\varepsilon)= \eta_{rad}$ - efficiency of radiation
- Spectral range of radiation depends on the spectral emissivity j(hν), density n and plasma temperature T

Target physics. Main Relations$^{(3)}$

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Important parameters of the problem:

- P, E_L, ν, q_L, τ_L, ε, τ_{rad}, τ_{exp}, n, T, $j = \int j(h\nu)dh\nu$
- Examples: $P_{h\nu} = 100W$, $\eta_{h\nu} = 2\%$, $P_L = 5 \cdot 10^3 W = E_L \nu$,

  $\nu = 100$, $E_l = 50J$ **- OR -** $\nu = 10000$, $E_l = 0.5J$

- What is better for high efficiency? There are wide fields for optimization between parameters indicated above.

- The targets made of low density foams with heavy elements dopants (clusters) give good possibilities to choose appropriate condition for high efficiency laser energy transformation into radiation energy in EUV of soft x-ray ranges.

- The foam targets have additional possibilities to solve the debris problem

Simulation DIANA 1D

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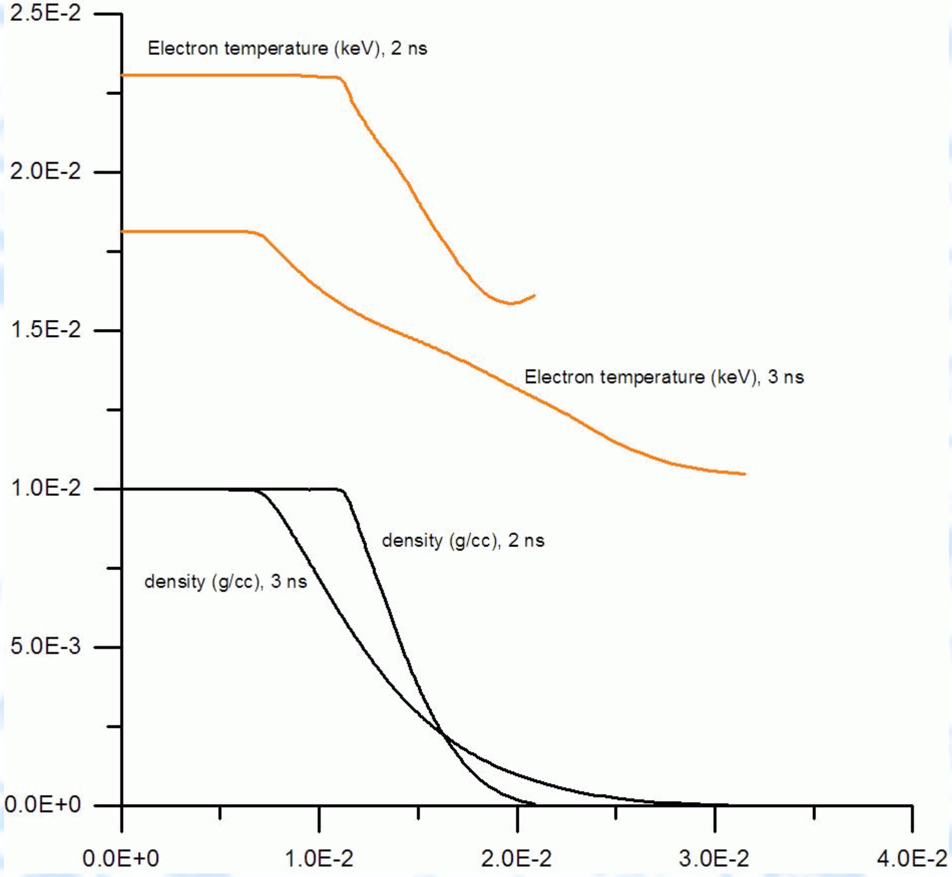
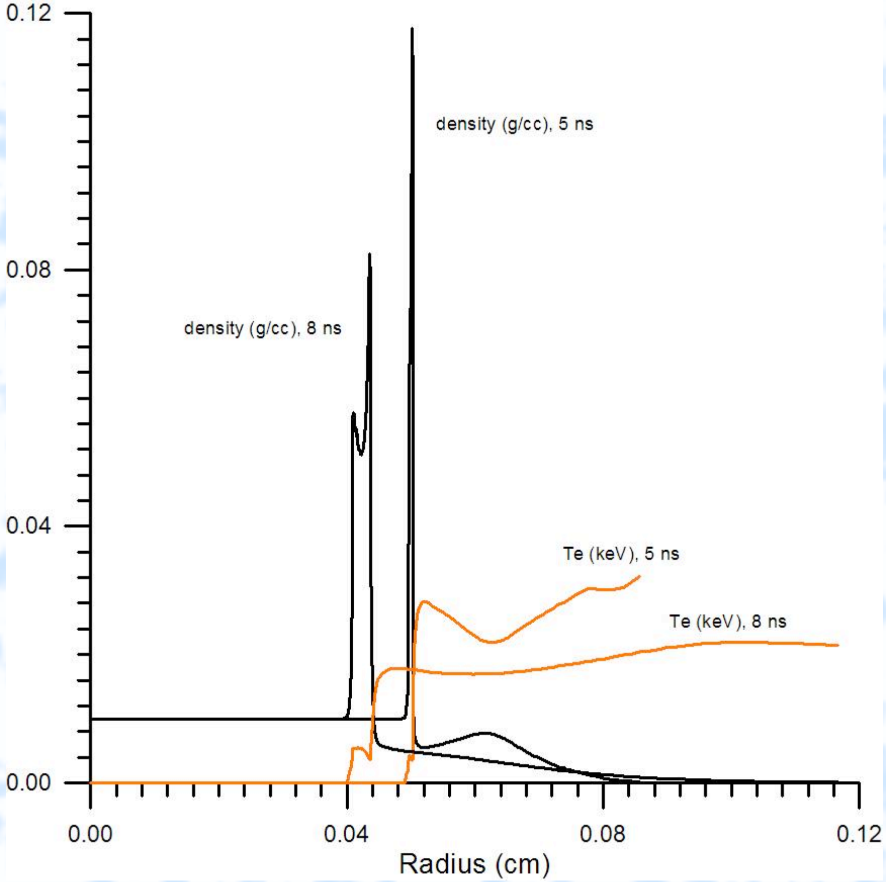
Homogeneous media (LPI, IMM, 2006)

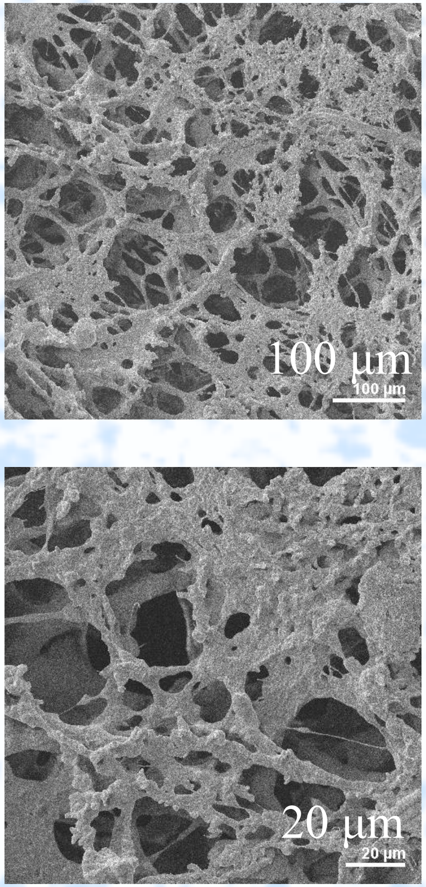
$E_L=0.5J\ I_L=10^{11}$ W/cm^2
$E_R=23\%$

$E_L=50J\ I_L=10^{11}$ W/cm^2
$E_R=53\%$

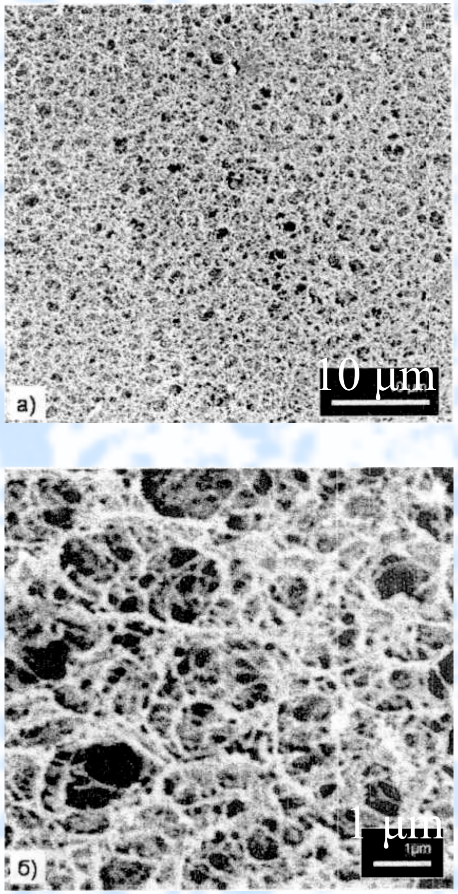




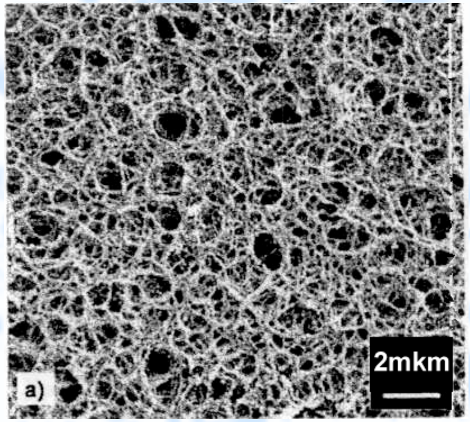
Foams



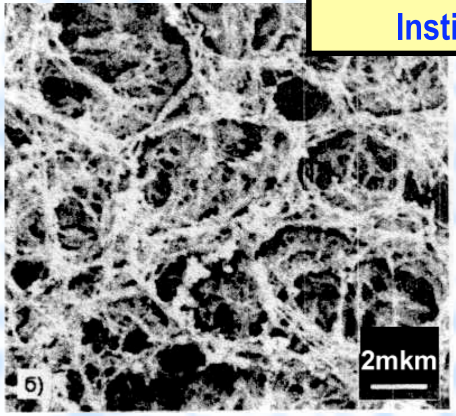
Polystyrene +NaCl



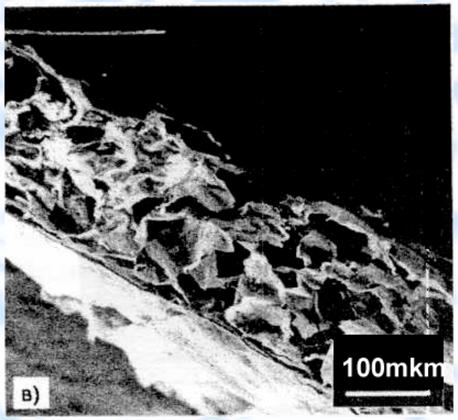
TAC 4.5mg/cm^3



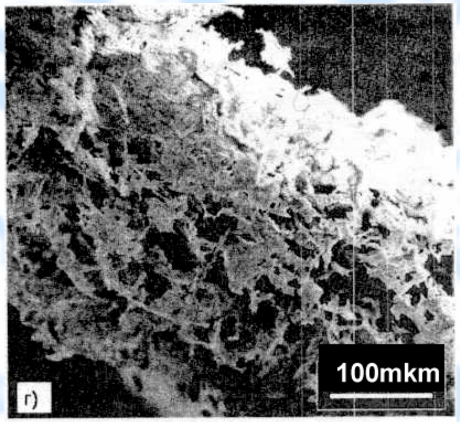
TAC
9.1mg/cm^3



TAC + 9.9%Cu
9.1mg/cm^3



agar
20mg/cm^3



agar 10mg/cm^3+
SnO_2 10mg/cm^3

TAC foam structure

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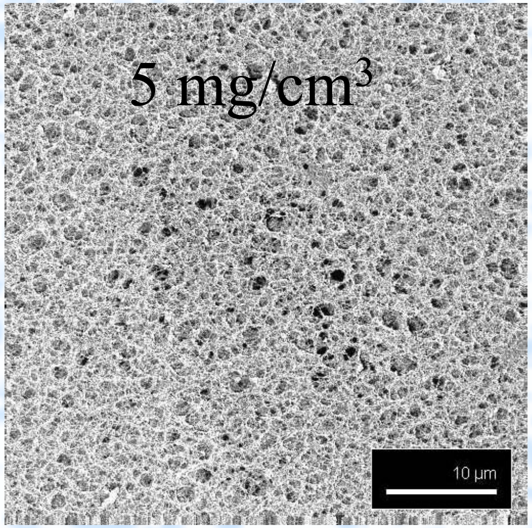
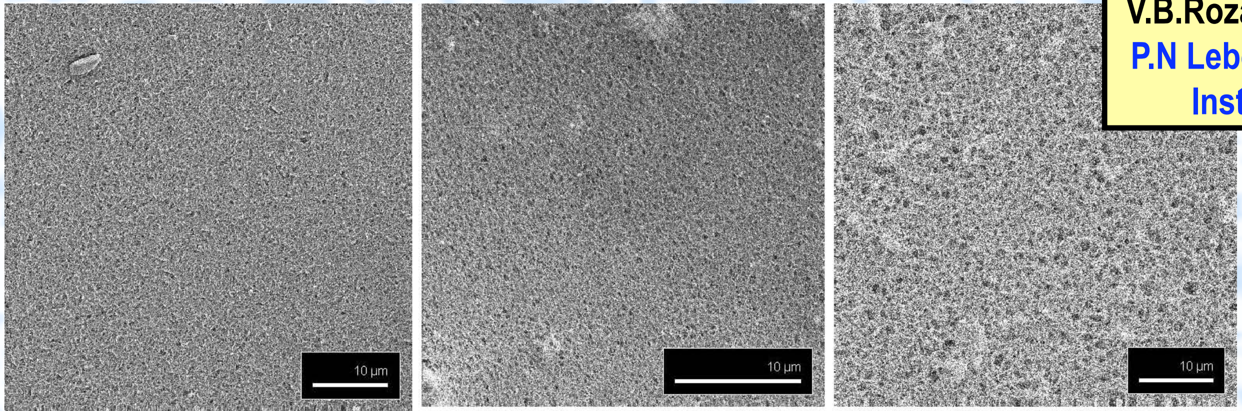
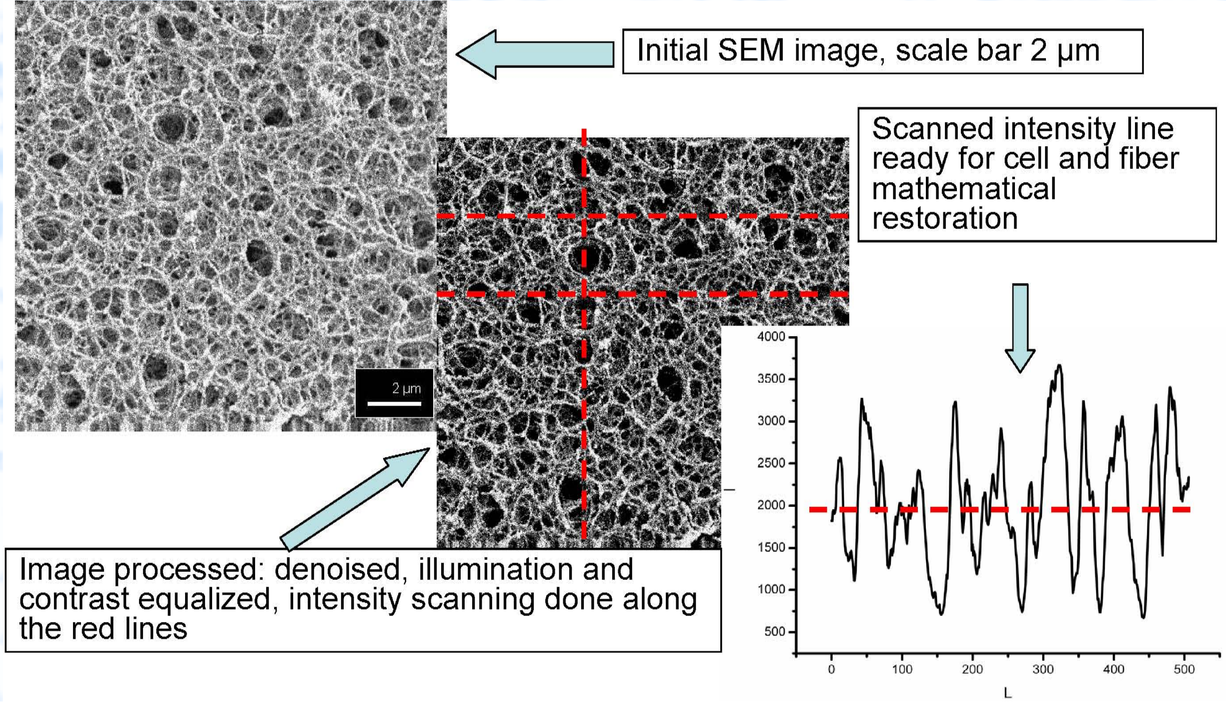




TAC structure of 10 mg/cc (SEM) from left to right: without Cu, with Cu nanoparticles of 10% by weight and of 20% by weight. Scale – 10 µm. Synthesis in IOCh 01/19/2005



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

Foam parameters

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PALS : TAC - $C_{12}H_{18}O_8$

$\lambda_{1\omega}$ = 1.315 μm, $N_{e\ cr\ 1\omega} = 0.6\cdot 10^{21}$ 1/cc	$\lambda_{3\omega}$ = 0.438 μm, $N_{e\ cr\ 3\omega} = 5.4\cdot 10^{21}$ 1/cc

Targets: TAC on 5 μm Al

ρ_1=4.5 μg/cc;

ρ_2=9.1 μg/cc;

ρ_3=9.1 μg/cc – TAC + 9.9% Cu

For $\lambda_{1\omega}$ TAC targets are overcritical:

For $\lambda_{3\omega}$ TAC targets are undercritical:

LIL: TMPTA - $C_{15}H_{20}O_6$

$\lambda_{1\omega}$ = 1.05 μm, $N_{e\ cr\ 1\omega}$ = 1021 1/cc	$\lambda_{3\omega}$ = 0.351 μm, $N_{e\ cr\ 3\omega}$ = 9·1021 1/cc

TMPTA foam 900 μm 6.5 μg/cc

For $\lambda_{3\omega}$ TMPTA targets are undercritical

- A.M. Khalenkov, N.G. Borisenko,et al.Experience of microheterogeneoustarget fabrication to study energy transport in plasma near critical density. // Laser & Particle Beams, 2006, **24**, pp. 283-290.
- N.G. Borisenko, et al. Regular 3D networks with clusters for controlled energy transport studies in laser plasma near critical density. // Fusion Sciences and Technology, 2006, **49**, #4, pp. 676-685.
- N.G. Borisenko, et al. Intensive (up to 1015W/cm2) Laser Light Absorption and Energy Transfer in SubcriticalMedia with or without High-Z Dopants. AIP Conference Proceedings, 2006, **849**, pp. 242-246/

Radiative characteristics of different plasmas for radiation near 13-14 nm: Xe,Sn,O ... (1)

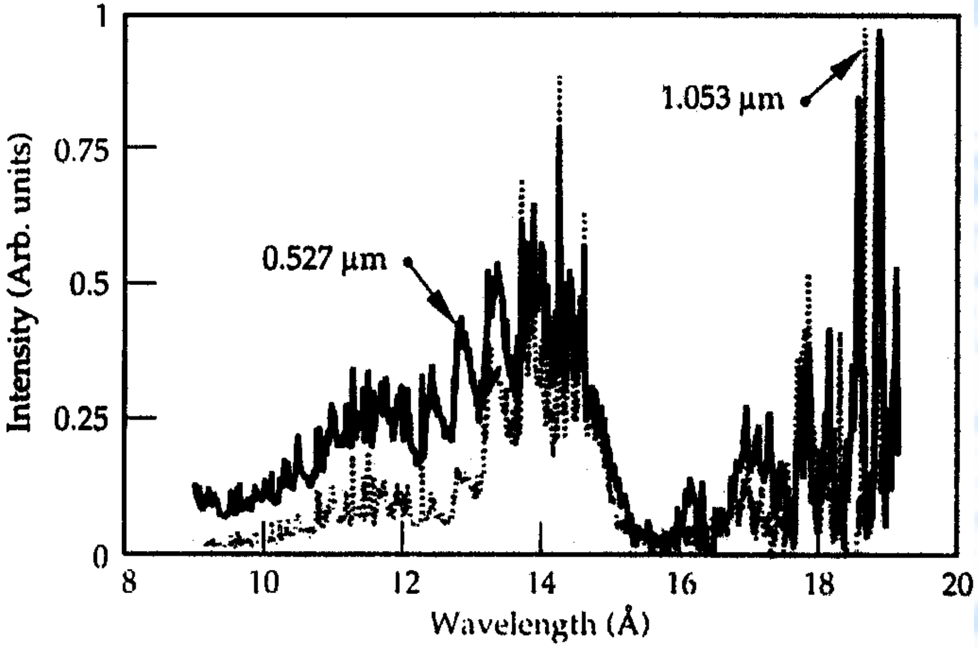
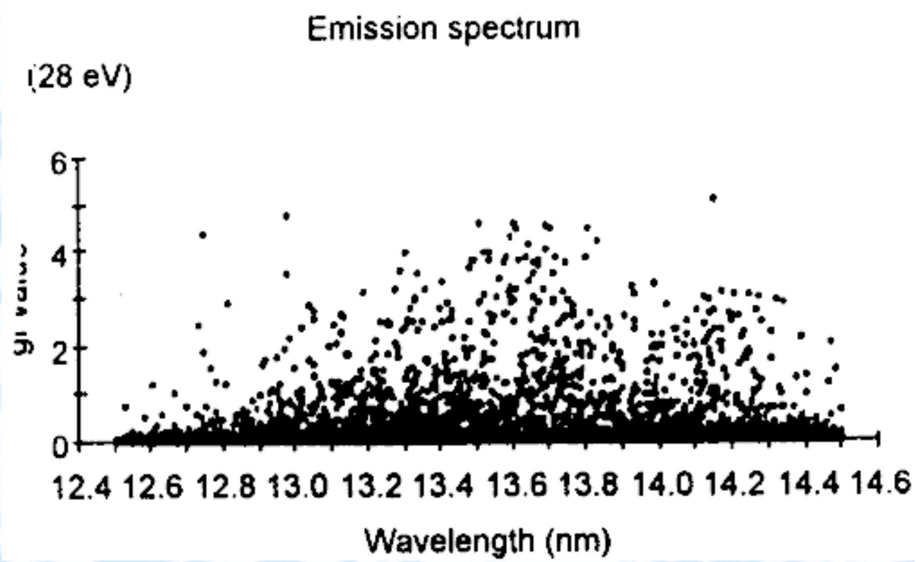


FIGURE 9. Comparison of x-ray spectra from solid Xe measured from plasmas produced with 1.053-µm (dashed line) and 0.527-µm (solid line) laser light. (20-07-0695-1659pb01)

Solid Xe experiments, 1995 (UCRL)



Sn, T-28 eV simulation, 2003 (Dublin Univ.)

Radiative characteristics of different plasmas for radiation near 13-14 nm: Xe,Sn,O ... (2)

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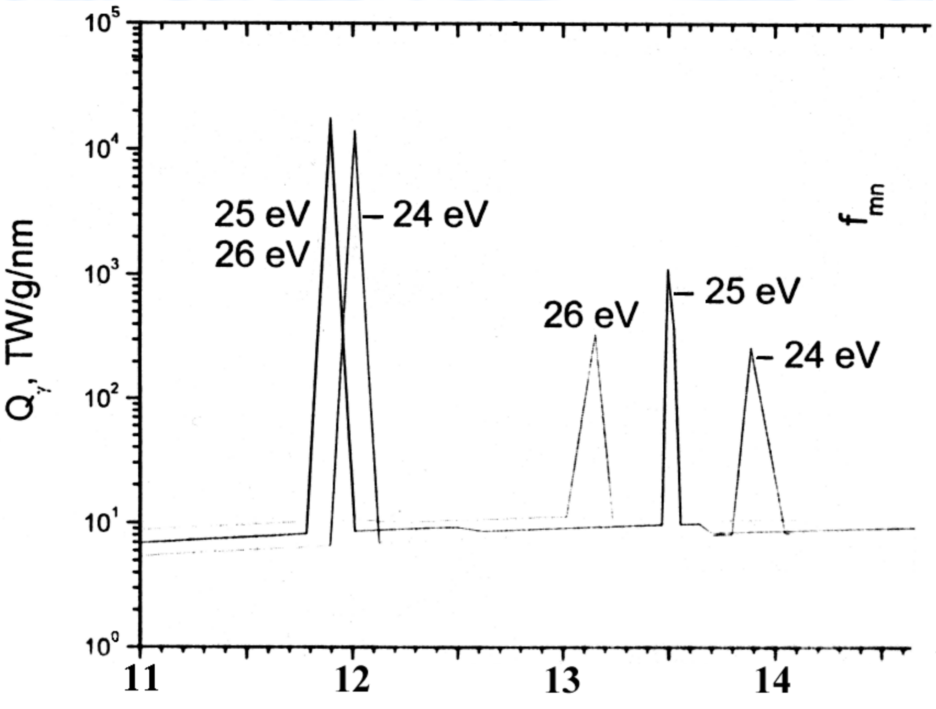
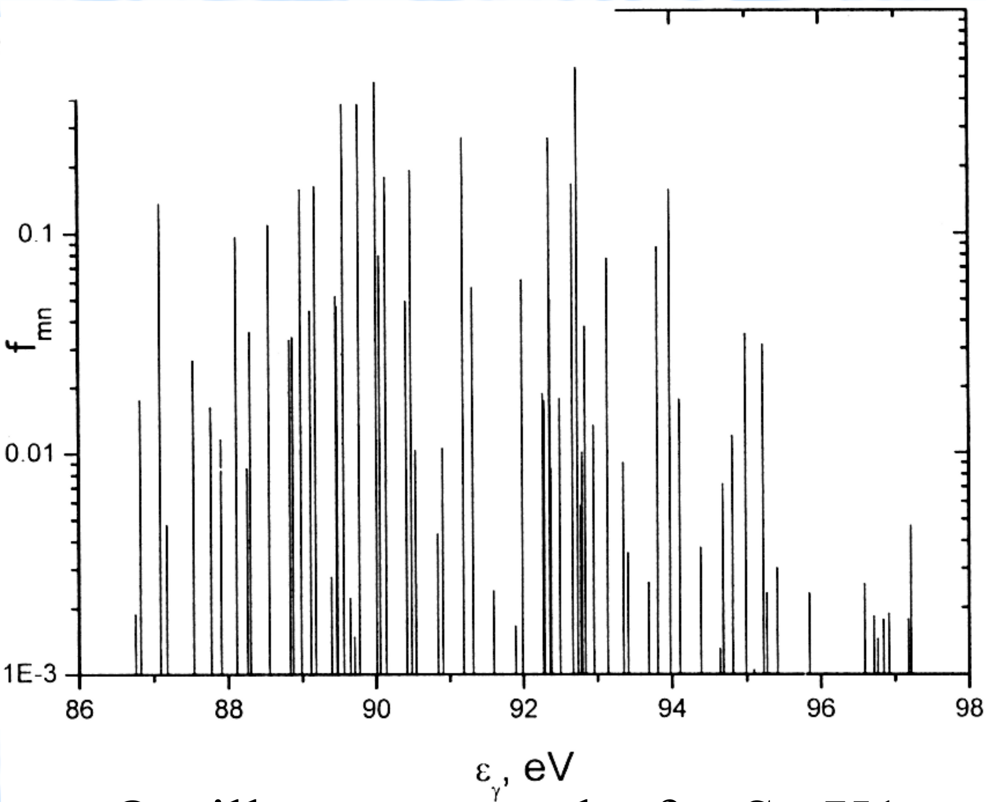


Sn, simulation of emissivity



Oscillators strengths for Sn X1

Radiative characteristics of different plasmas for radiation near 13-14 nm: Xe,Sn,O … (3)

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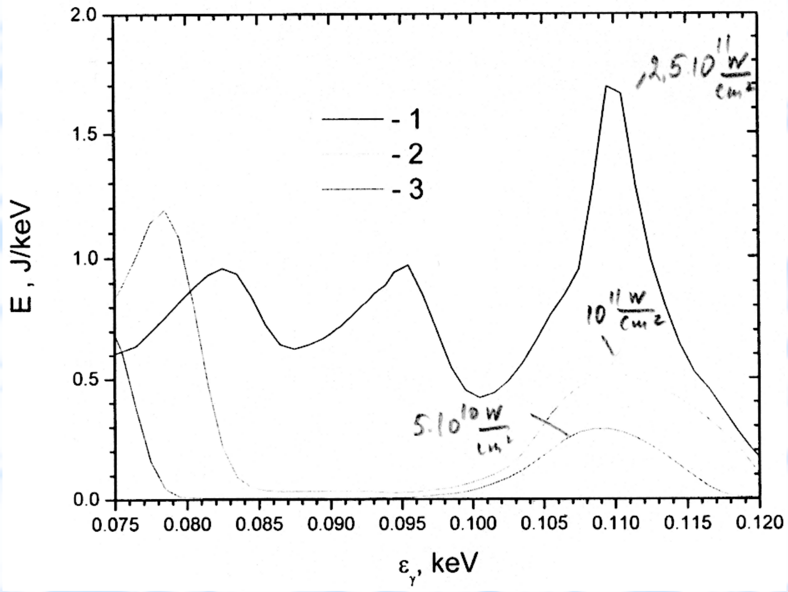
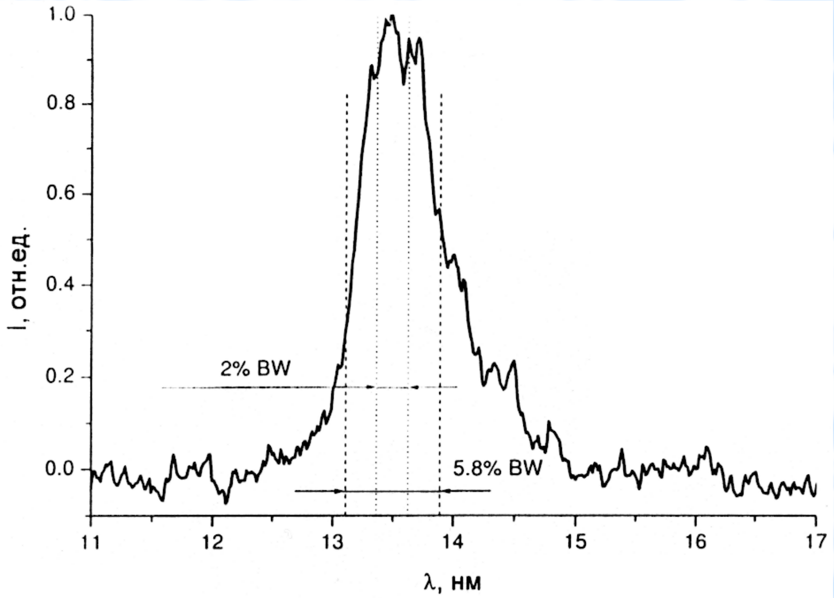


The spectrum of radiation from foam target with 10% addition (on density) of Sn. Simulation for different laser intensity irradiation. Spectral efficiency in 2% BW is 5%. (RFNC-VNIIEF, Sarov, 2006)



The radiation spectrum of Sn target under CO_2 laser irradiation, intensity ~ 10^{11}W/cm^2 (TRINITI, 2005)

Radiative characteristics of plasma

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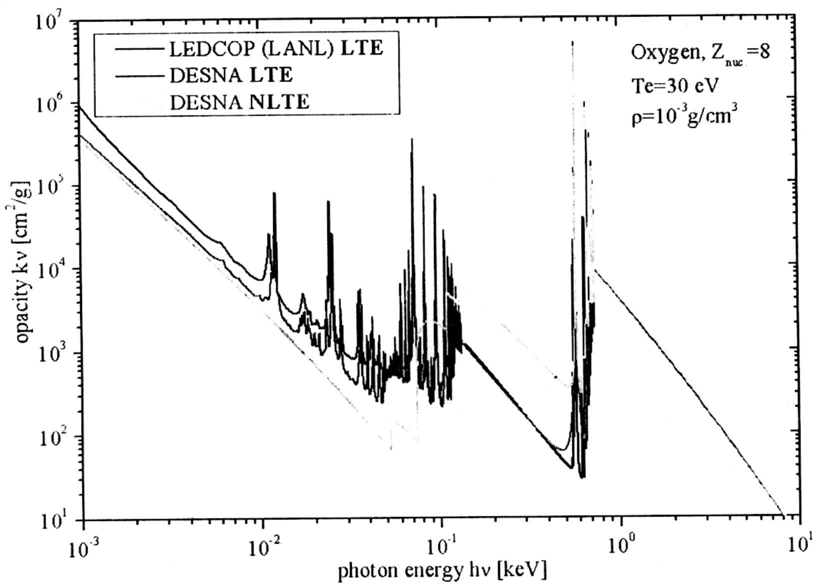
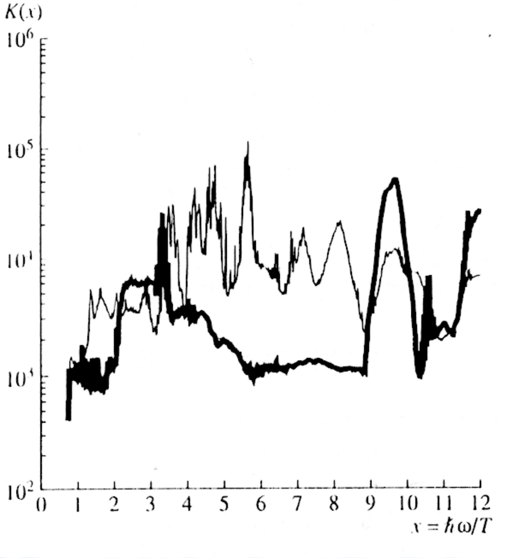
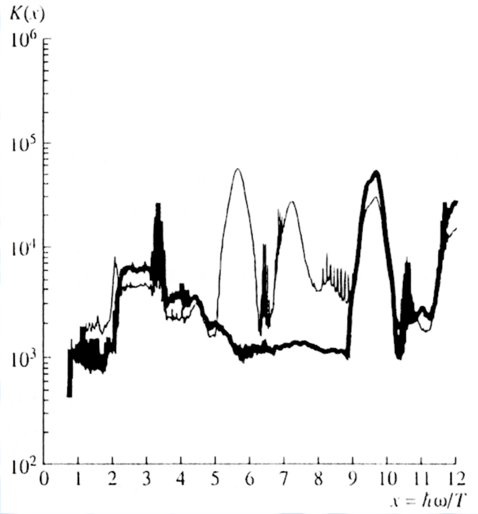






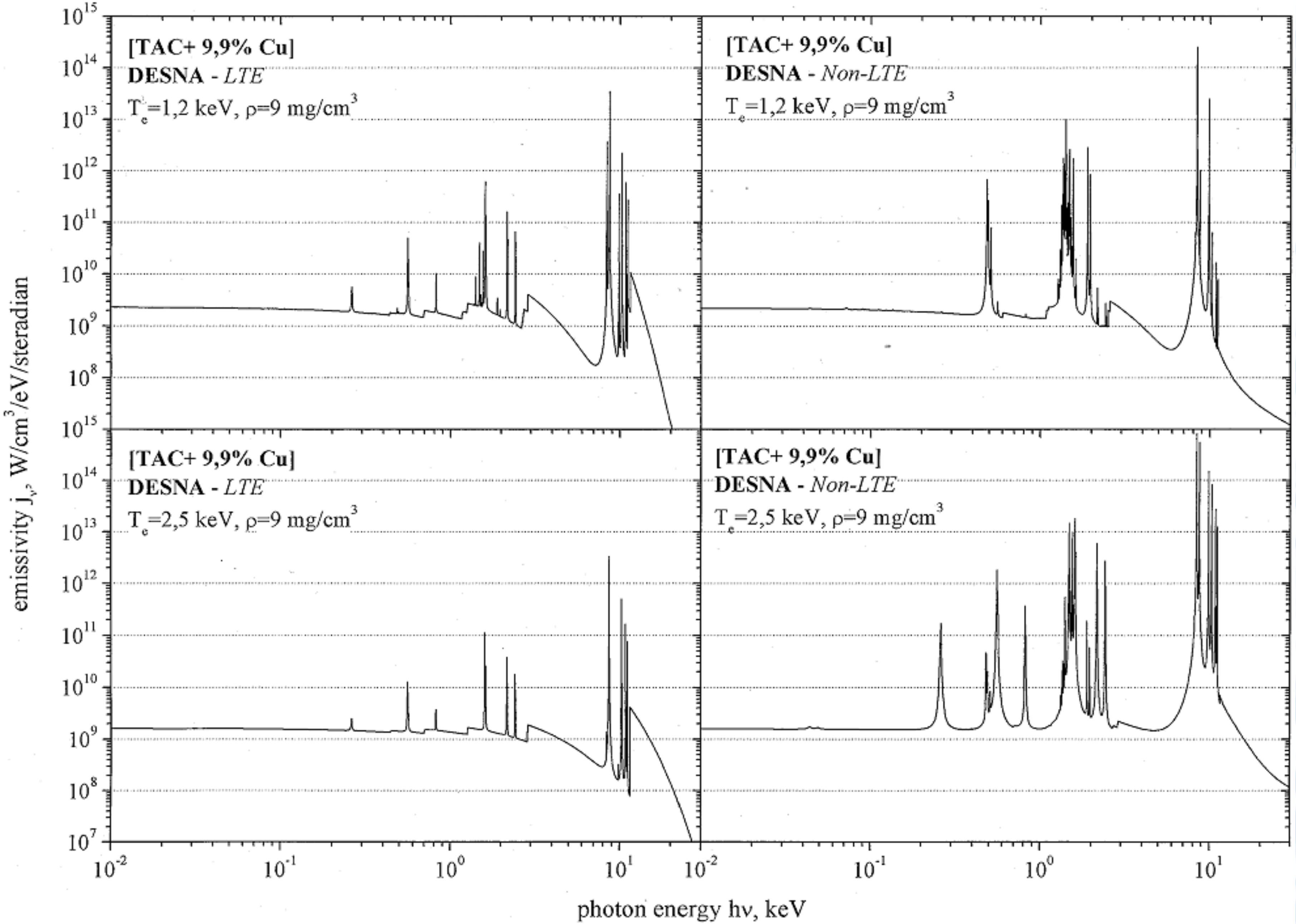
Au:W:Gd:Pr:Ba:Sb Au:Gd

T=250eV, 1g/cm^3. (N.Orlov)

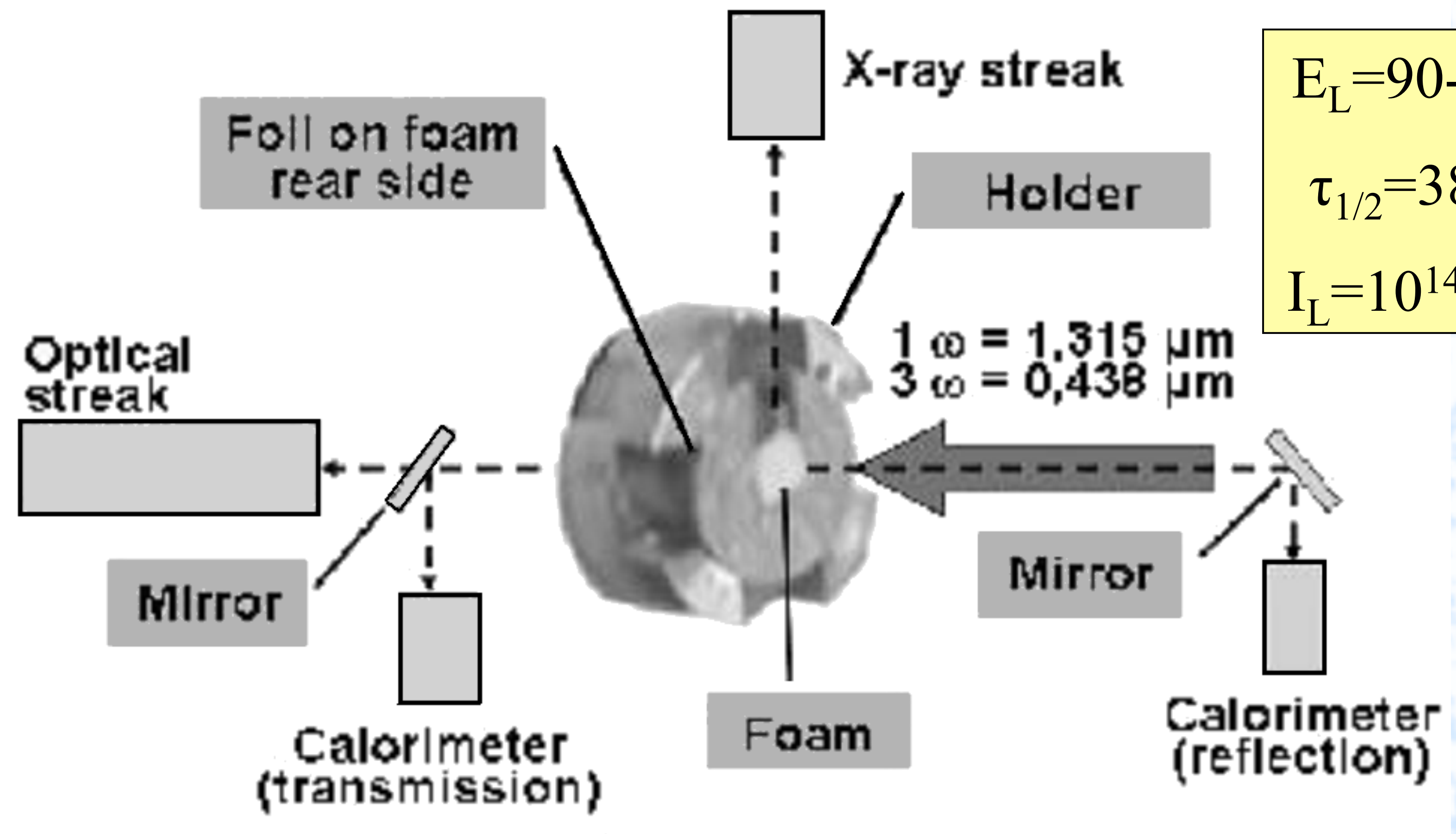
for Oxygen radiation near 13-14 nm (DESNA code - P.N.Lebedev Institute, 2006)

for radiation in the range hν~100 - 500 eV

Plasma spectral emissivity



PALS experiment scheme



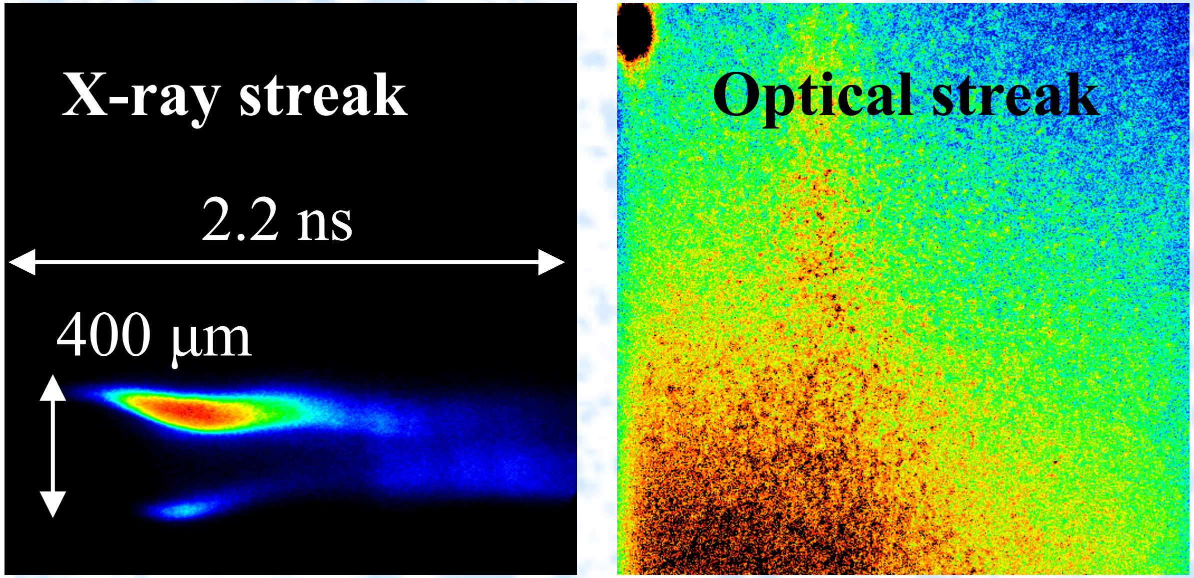
E_L=90-170J

$\tau_{1/2}$=380ps

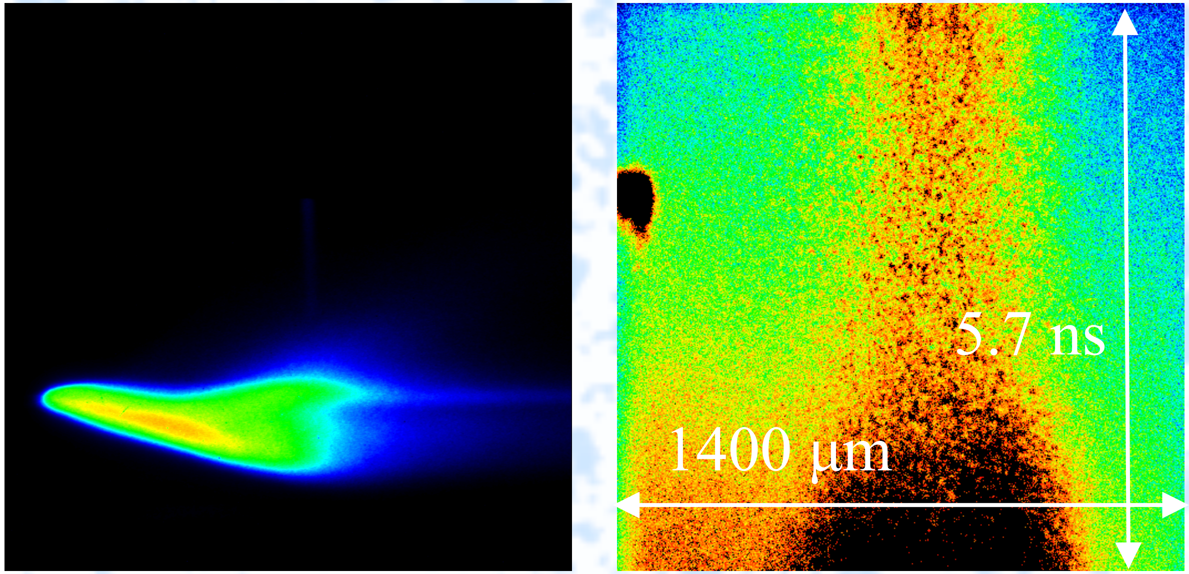
I_L=10^{14}-10^{15}

- Energy transfer in low-density porous targets doped by heavy elements, *V. Rozanov, D. Barishpoltsev, G. Vergunova, S. Gus'kov, N. Demchenko, I.Ya. Doskoch, E. Ivanov, E. Aristova, N. Zmitrenko, J. Limpouch, D. Klir, E. Krousky, K. Masek, V. Kmetik, J. Ullschmied,* ***J. Phys.: Conf. Ser.*****, 112,** 022010 (2008)

PALS experiments (1)
Foam target



Focus: **300 µm in front**
Incid.Energy: **173 J**
Frequency: **1ω, 1.315µm**
Foam type: **TAC**
Density: **9.1 mg/cm^3**
Thickness: **400 µm**
Foil**:** Al, 5 µm



Focus: **300 µm in front**
Incid.Energy: **166.4 J**
Frequency: **3ω**
Foam type: **TAC+Cu(9.9%)**
Density: **9.1 mg/cm^3**
Thickness: **400 µm**
Foil**:** Al, 5 µm

PALS experiments $^{(2)}$
Foam target

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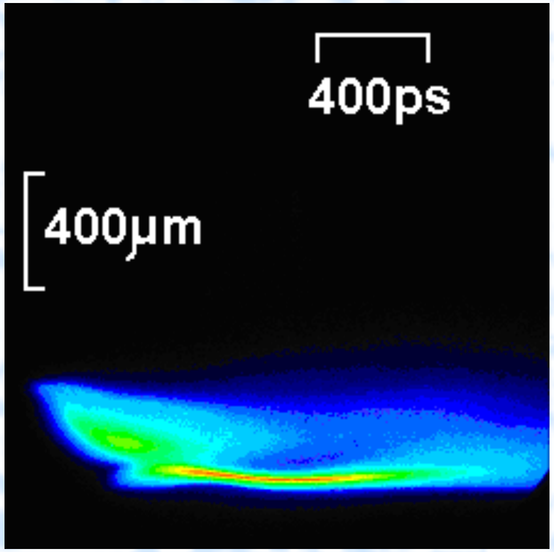
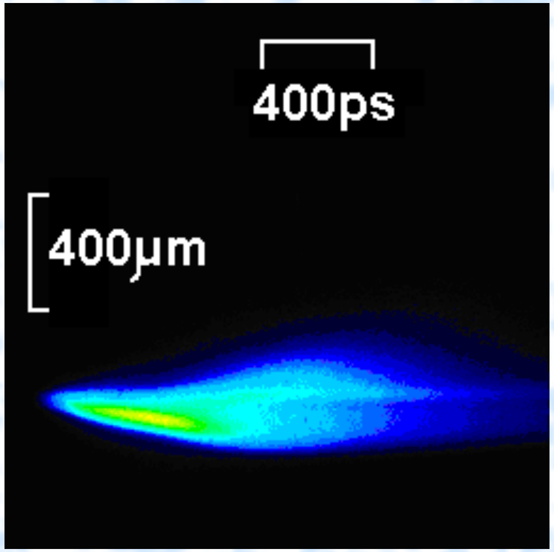


a



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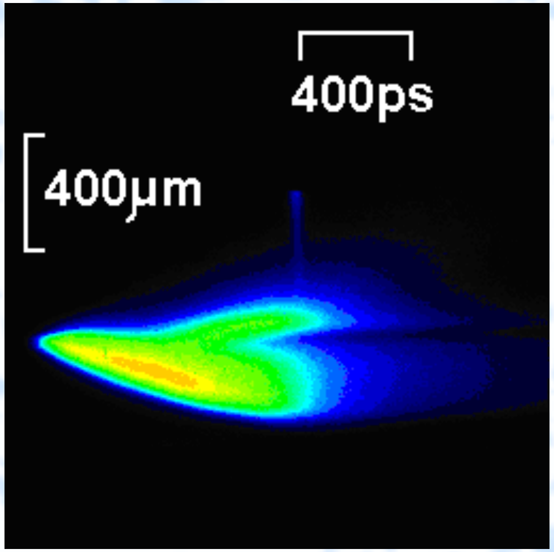

c

PALS experiments:

E_L~150 J, λ_3=0.454μm

$I_L=3\cdot10^{14}$

TAC, 400μm + Al, 5μm

a) ρ=4.5 mg/cm^3

b) ρ=9.1 mg/cm^3

c) ρ=9.1 mg/cm^3 + 9.9%Cu

PALS experiments (3)
TAC 4.5 mg/cm^3, 1ω

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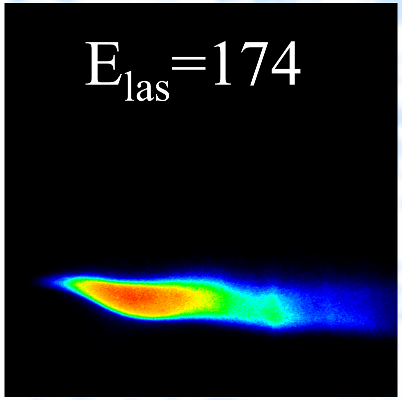
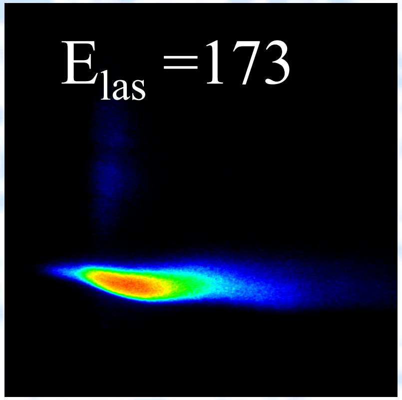
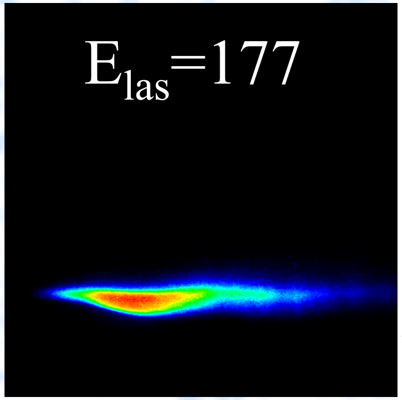
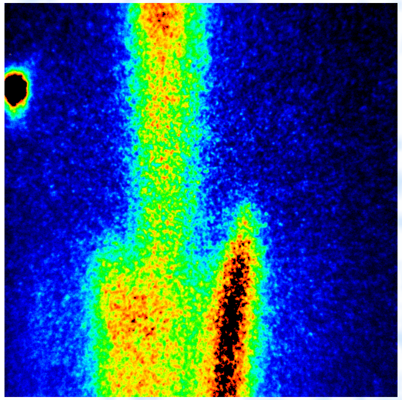
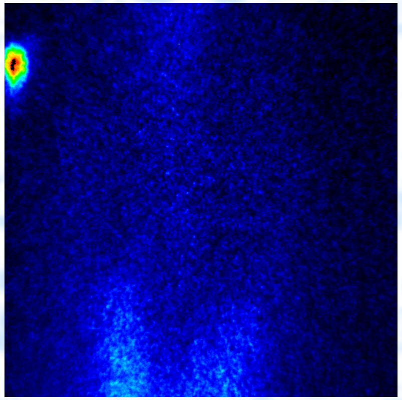
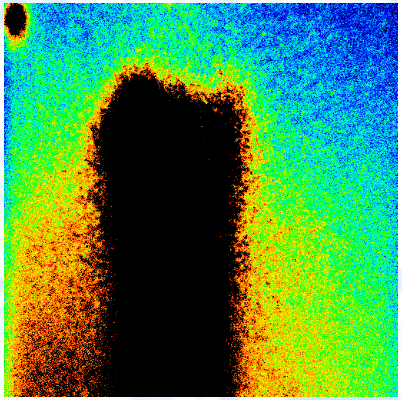


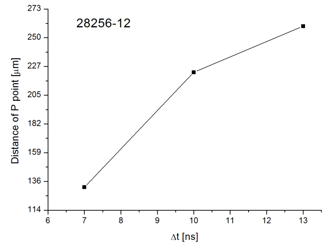


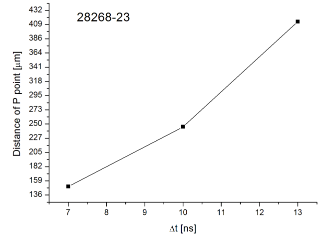


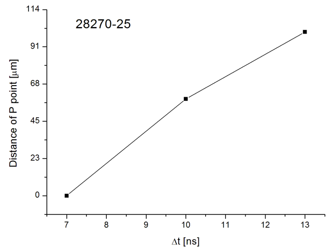


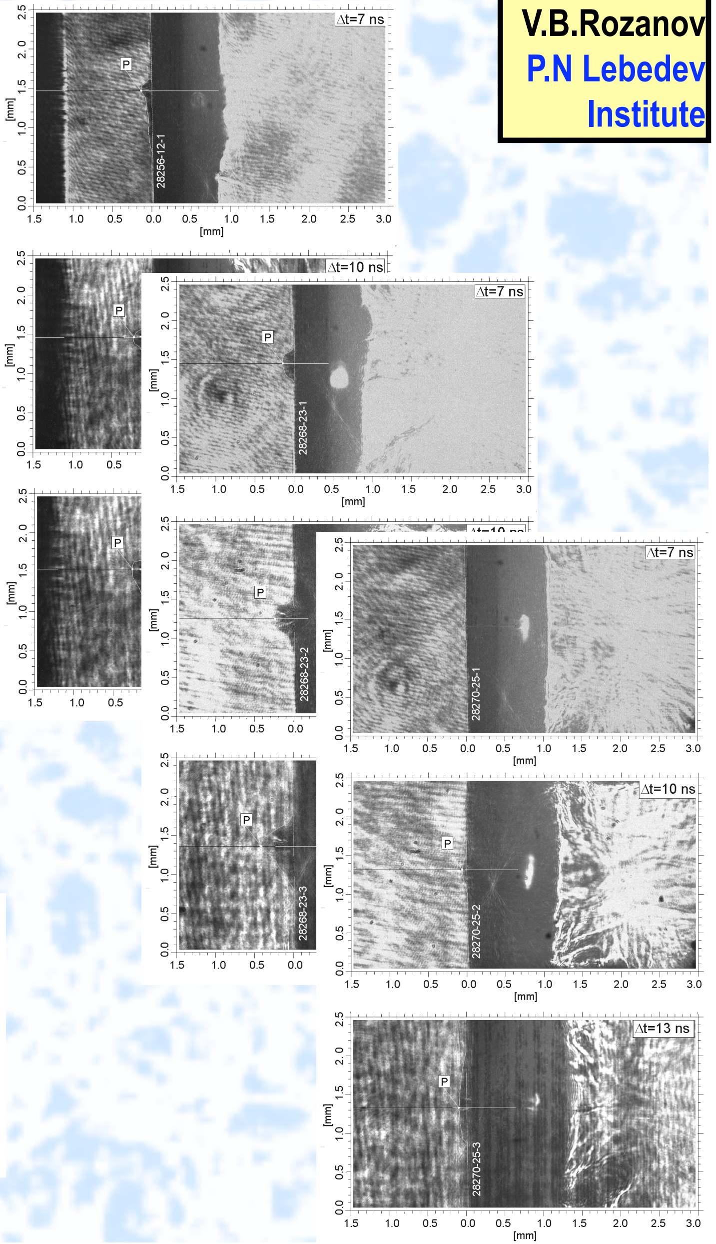






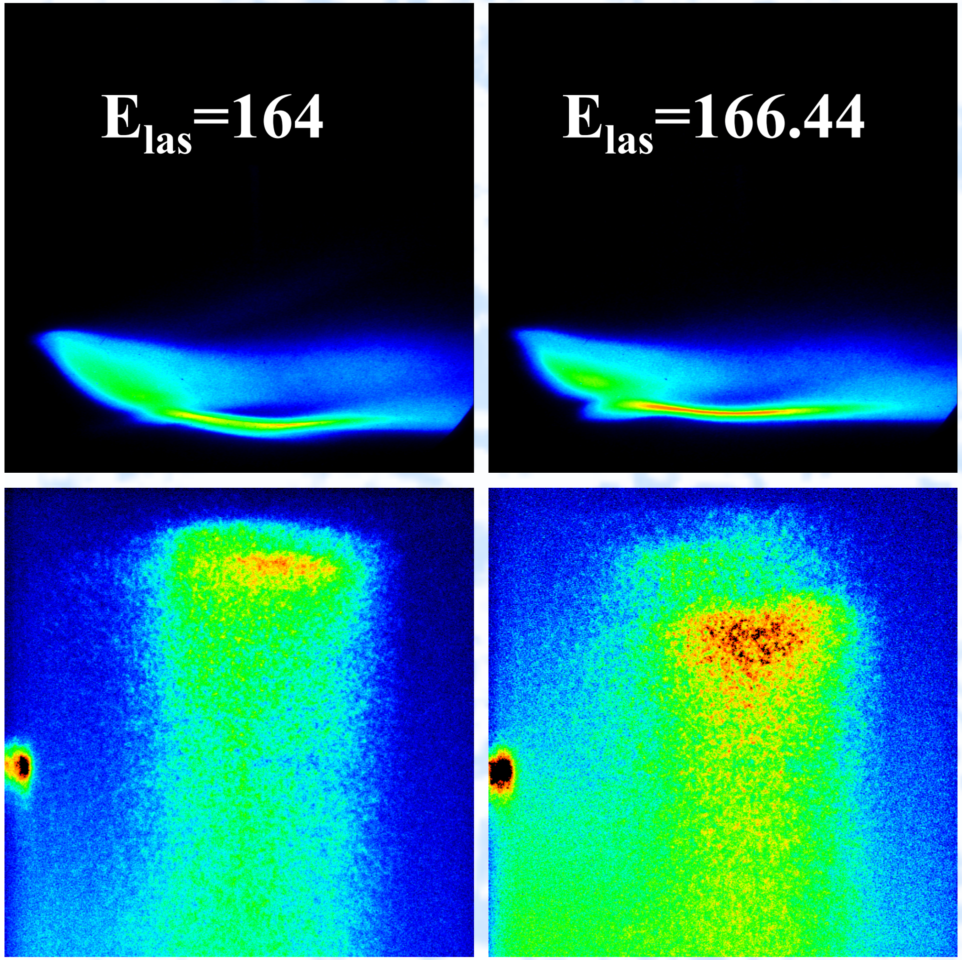




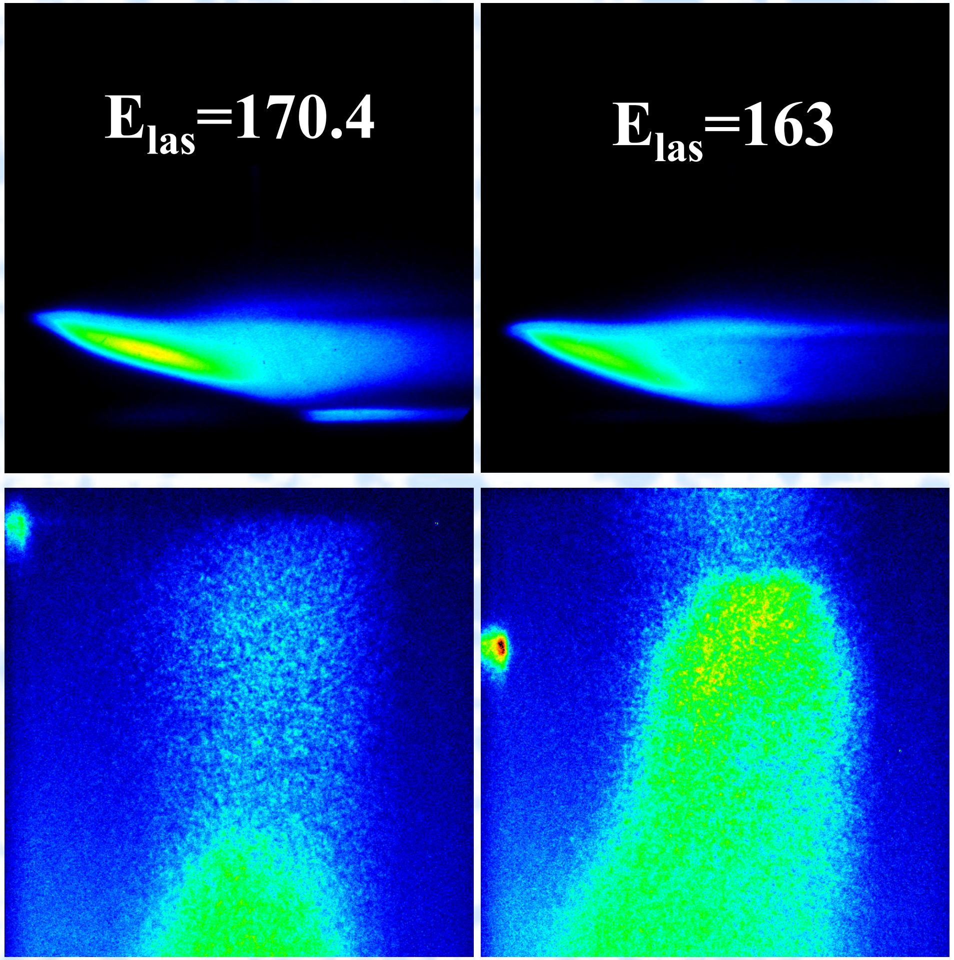


PALS experiments (4)

TAC 4.5 mg/cm^3, 3ω



TAC 9.1 mg/cm^3, 3ω



PALS experiments ⁽⁵⁾
TAC+Cu 9.1 mg/cm³, 1ω

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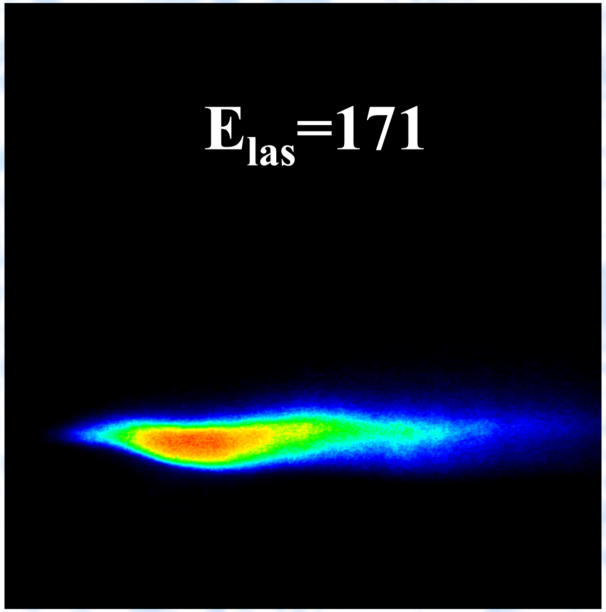

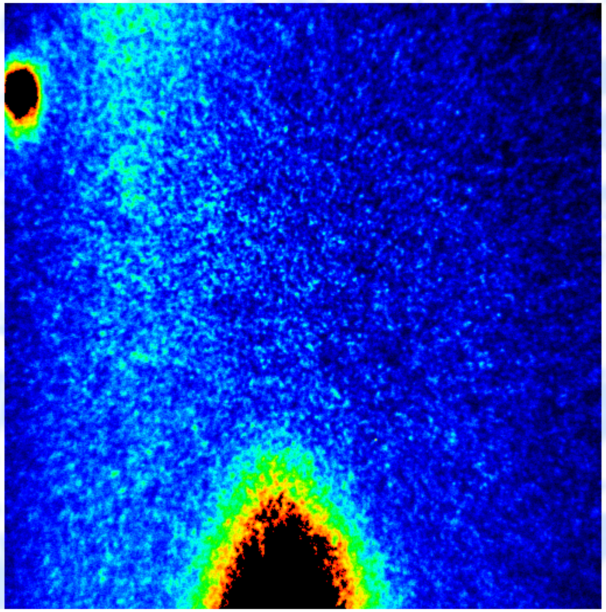

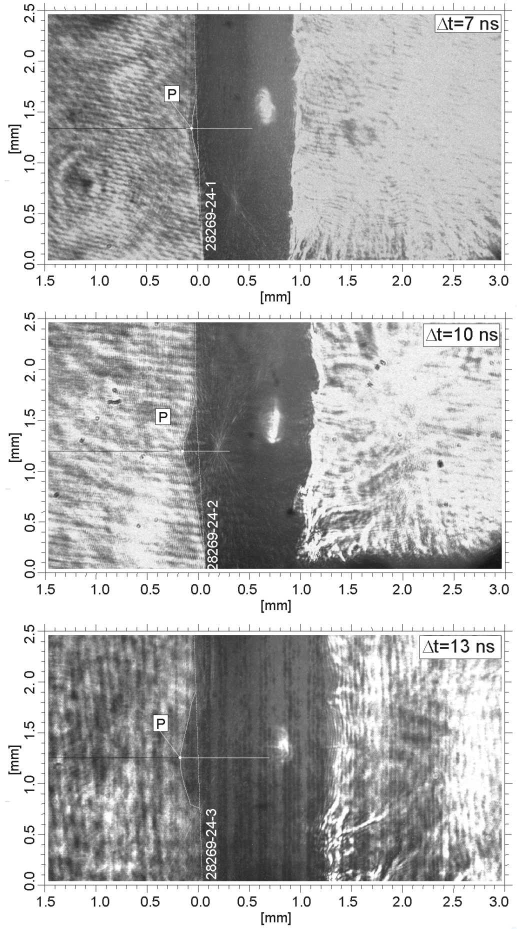

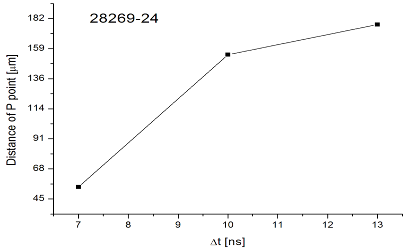

Experiment (TRINITI, 2004)

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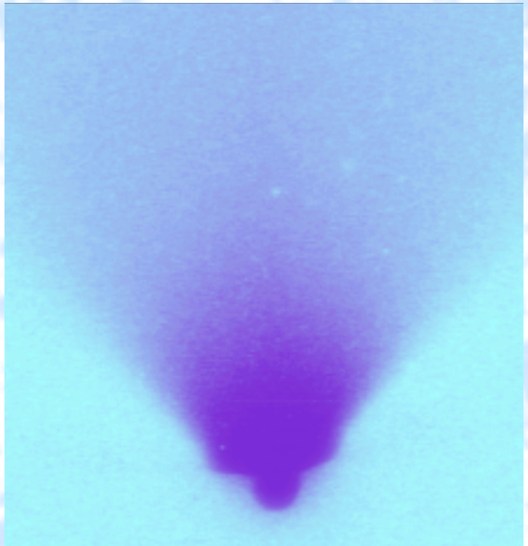
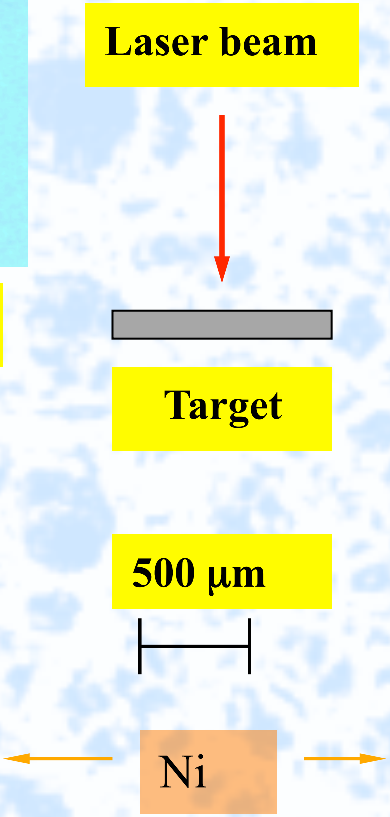


Ni foil, d=0.6 μm

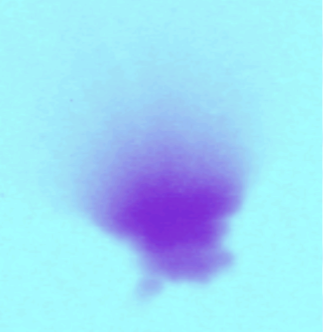


Laser beam

Target

500 μm

Ni



Agar, d=300 μm, ρ=2 mg/cm^3

Agar (d=300 μm, ρ=2 mg/cm^3) with Ni foil (d=0.6 μm) at the rear surface

Agar (d=300 μm, ρ=1 mg/cm^3) doped by CuCl$_2$ (ρ=1 mg/cm^3) with Ni foil (d=0.6 μm) at the rear surface

Simulation: LATRANT 2D

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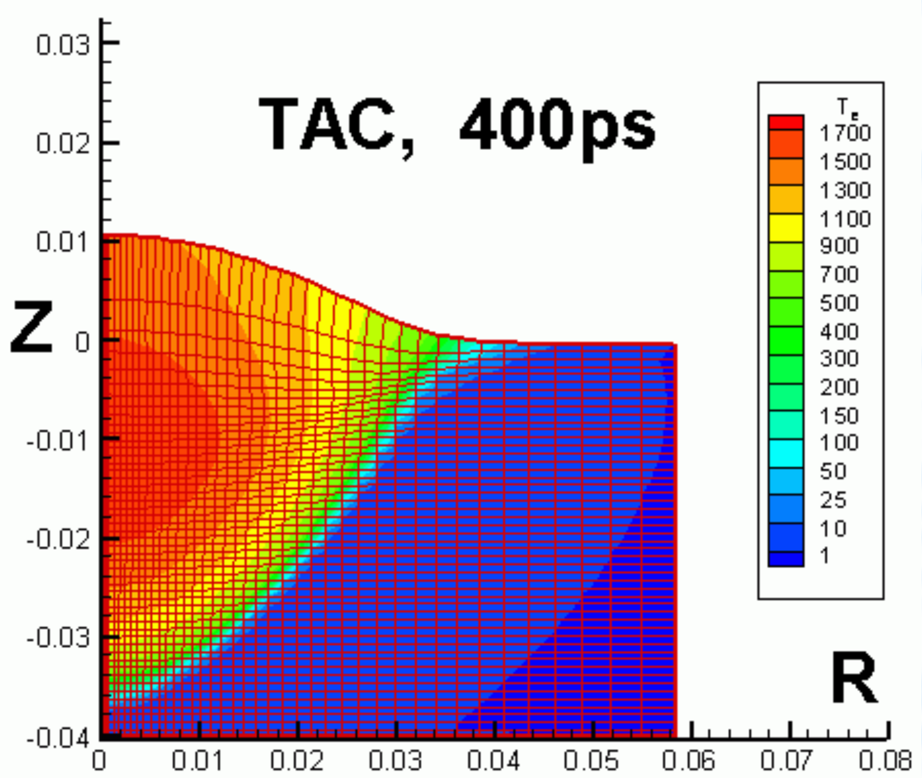
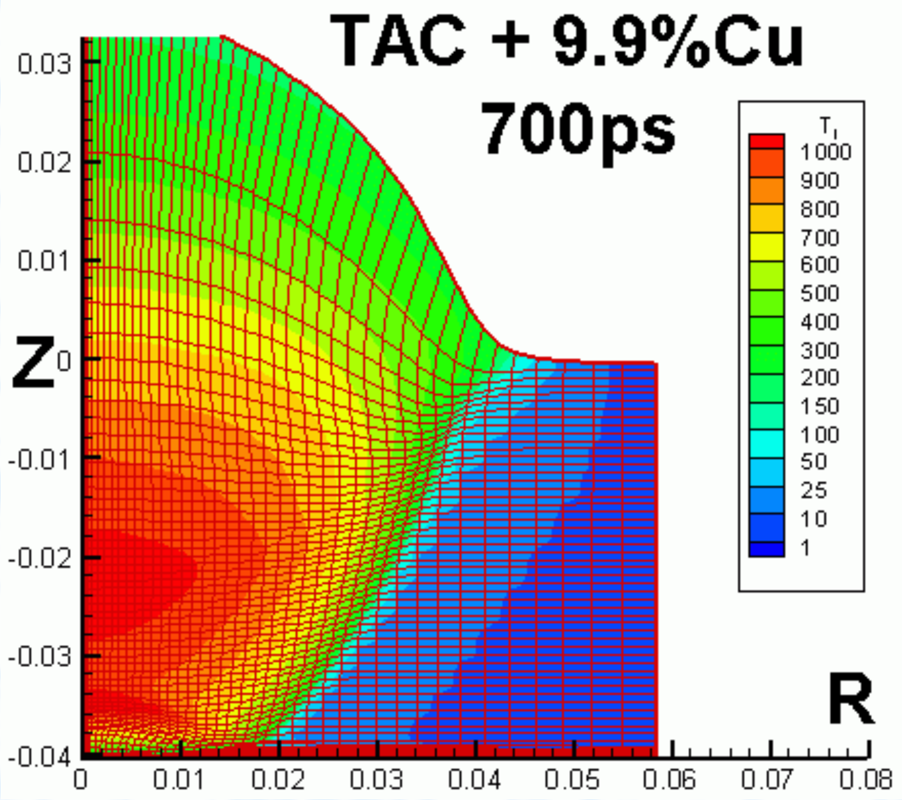
Homogeneous media radiation transport

(LPI, IMM, 2006)





Simulation: LATRANT 2D

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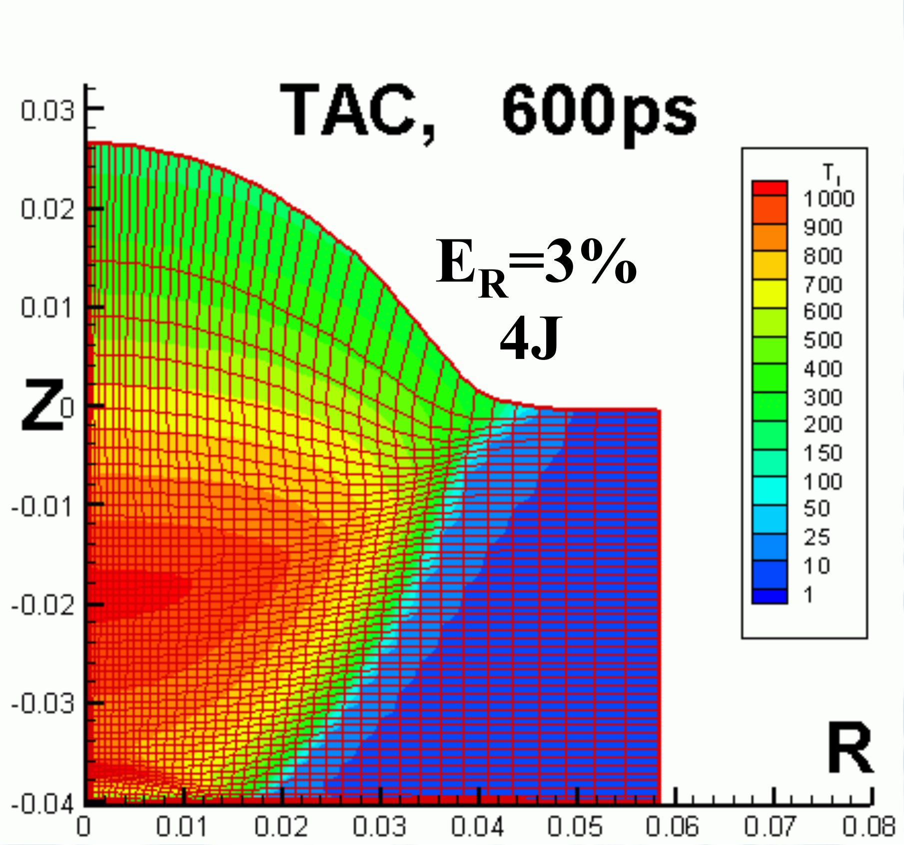
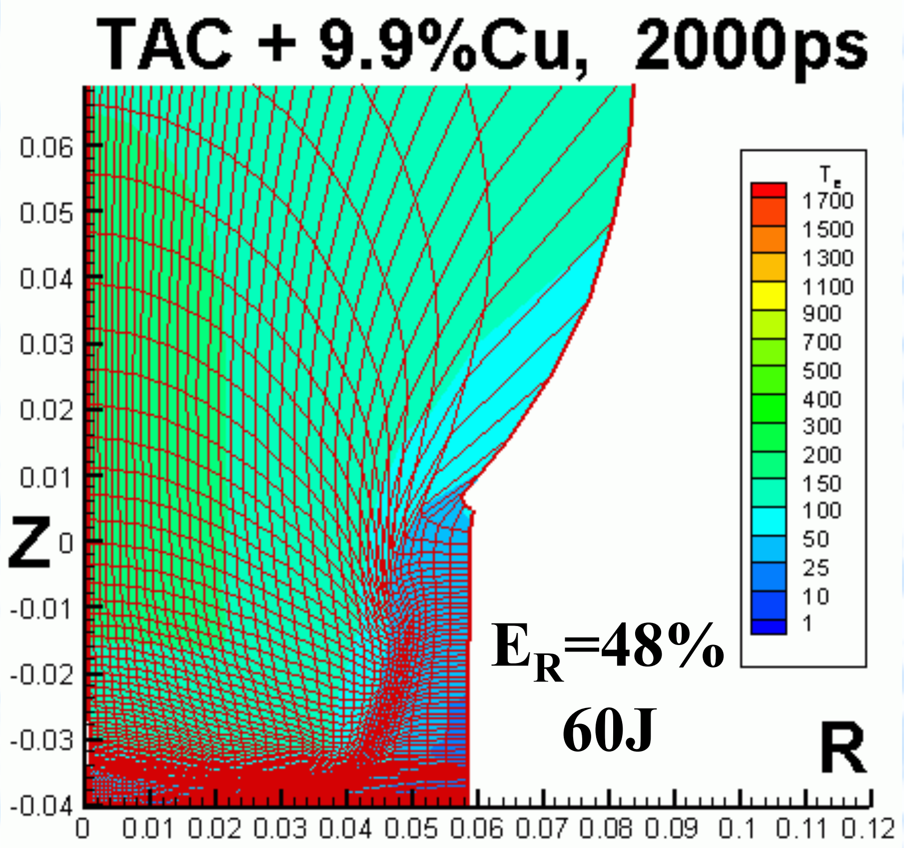
Homogeneous media radiation transport

(LPI, IMM, 2006)





Theoretical model for PALS experiment (1)

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Institute

Includes:

- Strong point explosion model:

$$R = \left[\frac{75}{16\pi}\frac{(\gamma-1)(\gamma+1)^2}{(3\gamma-1)}\right]^{1/5}\left(\frac{Et^2}{\rho}\right)^{1/5}$$

- After the end of the laser pulse the plasma behaves like a homogeneous medium, and its further evolution corresponds to the strong point explosion model. The Al foil optical emission allows one to estimate the plasma energy, which turns to be essentially smaller than the laser pulse energy

- Heat wave velocity (x-ray streak) depends on electron heat conductivity (we can choose the flux limiter value)

- Laser energy reflection strongly depends on electron heat conductivity rate: low rate heat conductivity → high reflection level

Theoretical model for PALS experiment (2)

- Effective equation of state of the foam (relaxation):

- The life time of dense structures is limited by the ion viscosity

- EOS for Al:

ρ/ρ_0	p (Mbar)	T, ^{0}K	D, km/s	U, km/s
1.39	0.56	1300	8.6	2.4
1.55	0.99	3000	10.2	3.6
1.7	1.53	5600	11.8	4.8

PALS RAPID simulation (1)

E_{las} ~ 100 J, **λ = 1.315 μm**

τ_{las} = 0.38 ns at $1/2q_{max}$ for 1ω ; **τ_{las} = 0.32 ns at $1/2q_{max}$ for 3ω**

$q_{las} = 3.6\cdot10^{14}$ W/cm²

Target: **TAC-foam (380 μm) + Al (5 μm)**

Foam density: **4.5 mg/cm³ and 9.1 mg/cm³**

Simulation:

Hydrodynamic code RAPID, 20 thin solid layers separated by low-density gas. Average density equals to foam density. Flux-limited electron thermal conductivity:

$$W_e = \frac{W_{Sp} W_{max}}{W_{Sp} + W_{max}}$$, where W_{Sp} -- Spitzer flux,

$$W_{max} = f n_e T_e (T_e / m_e)^{1/2}$$ -- limiting flux, f – flux limiter.

PALS RAPID simulation (2)

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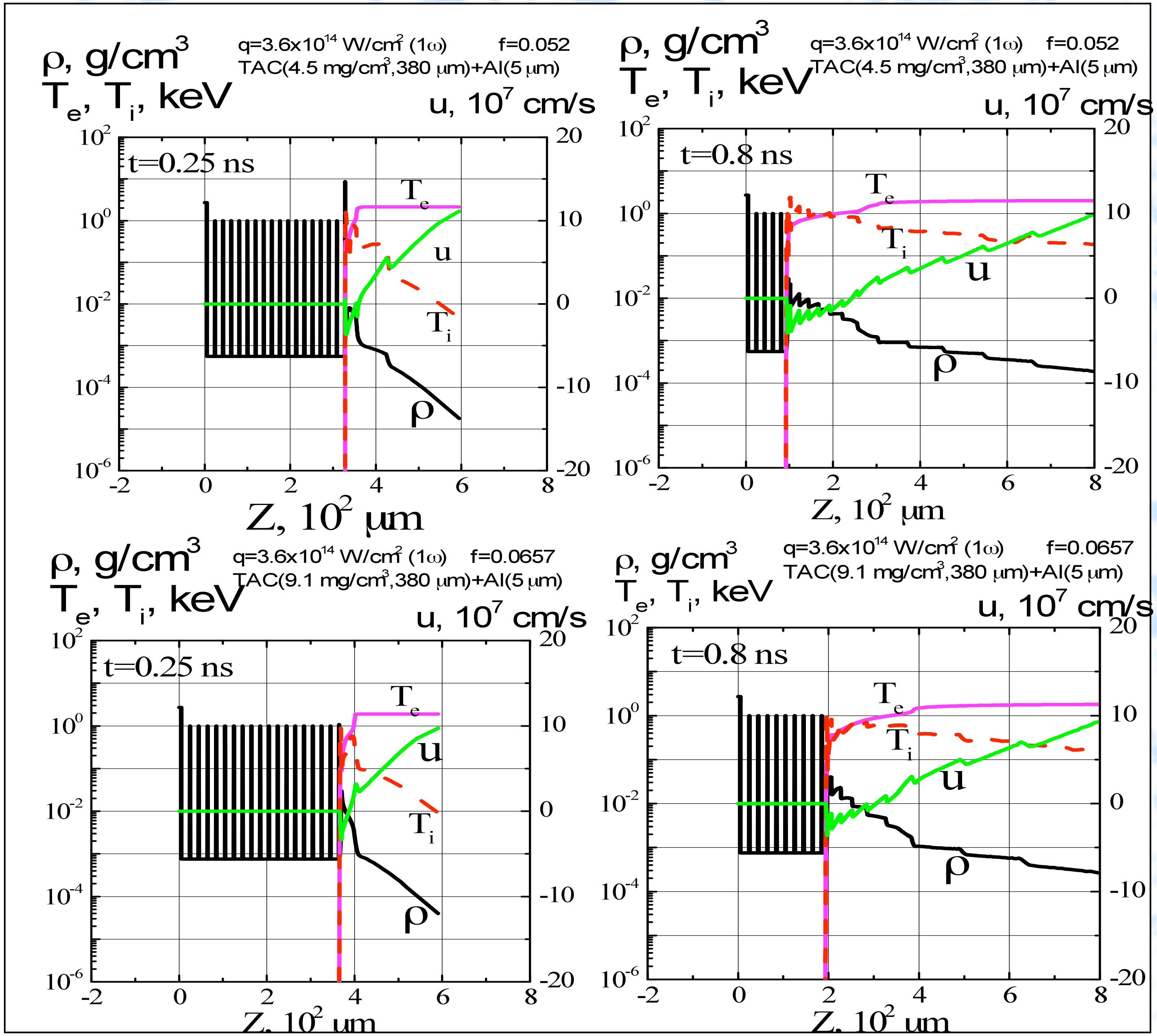

f = 0 .052

f = 0.0657

PALS RAPID simulation$^{(3)}$

	4.5 mg/cm^3	9.1 mg/cm^3
1ω	$v_f = 3.25 \cdot 10^7$ cm/s $q=3.6 \cdot 10^{14}$, $f=0.052$, $d_a=0.136$ $q=1.8 \cdot 10^{14}$, $f=0.0675$, $d_a=0.233$	$v_f = 2.5 \cdot 10^7$ cm/s $q=3.6 \cdot 10^{14}$, $f=0.0657$, $d_a=0.159$ $q=1.8 \cdot 10^{14}$, $f=0.0864$, $d_a=0.274$
3ω	$v_f = 8.7 \cdot 10^7$ cm/s $q=3.6 \cdot 10^{14}$, $f=0.0403$, $d_a=0.606$ $q=1.8 \cdot 10^{14}$, $f=0.0616$, $d_a=0.815$	$v_f = 5.04 \cdot 10^7$ cm/s $q=3.6 \cdot 10^{14}$, $f=0.027$, $d_a=0.686$ $q=1.8 \cdot 10^{14}$, $f=0.09$, $d_a=0.920$

v_f – average velocity of thermal wave front (experimental value). Table shows the flux limiter values *f* which provide in simulations the experimental values of velocity v_f. δ_a – simulated value of absorption efficiency (collisional absorption).

1D Hydrodynamic code RAPID include Maxwell equations for heating radiation, the hydrodynamical equations with electron thermal conductivity, the model of the absorption takes into account inverse bremsstrahlung, and anomalous and resonance absorption.

- Yu.A.Afanas’ev, E.G.Gamalii, N.N.Demchenko, O.N.Krokhin, and V.B.Rozanov. Teoretical study of the hydrodynamics of spherical targets taking the refraction of the laser radiation into account, *Zh.Eksp. Teor.Fiz.* **79**, 837-849, 1980. *Sov. Phys.JETP* **52** (3), 1980
- S.Yu.Gus'kov, N.N.Demchenko, V.B.Rozanov, R.V.Stepanov, N.V.Zmitrenko, A.Caruso, C.Strangio. Symmetric compression of 'laser greenhouse' targets by a few laser beams, *Quantum Electronics*, **33**(2003)

PALS RAPID simulation(4)

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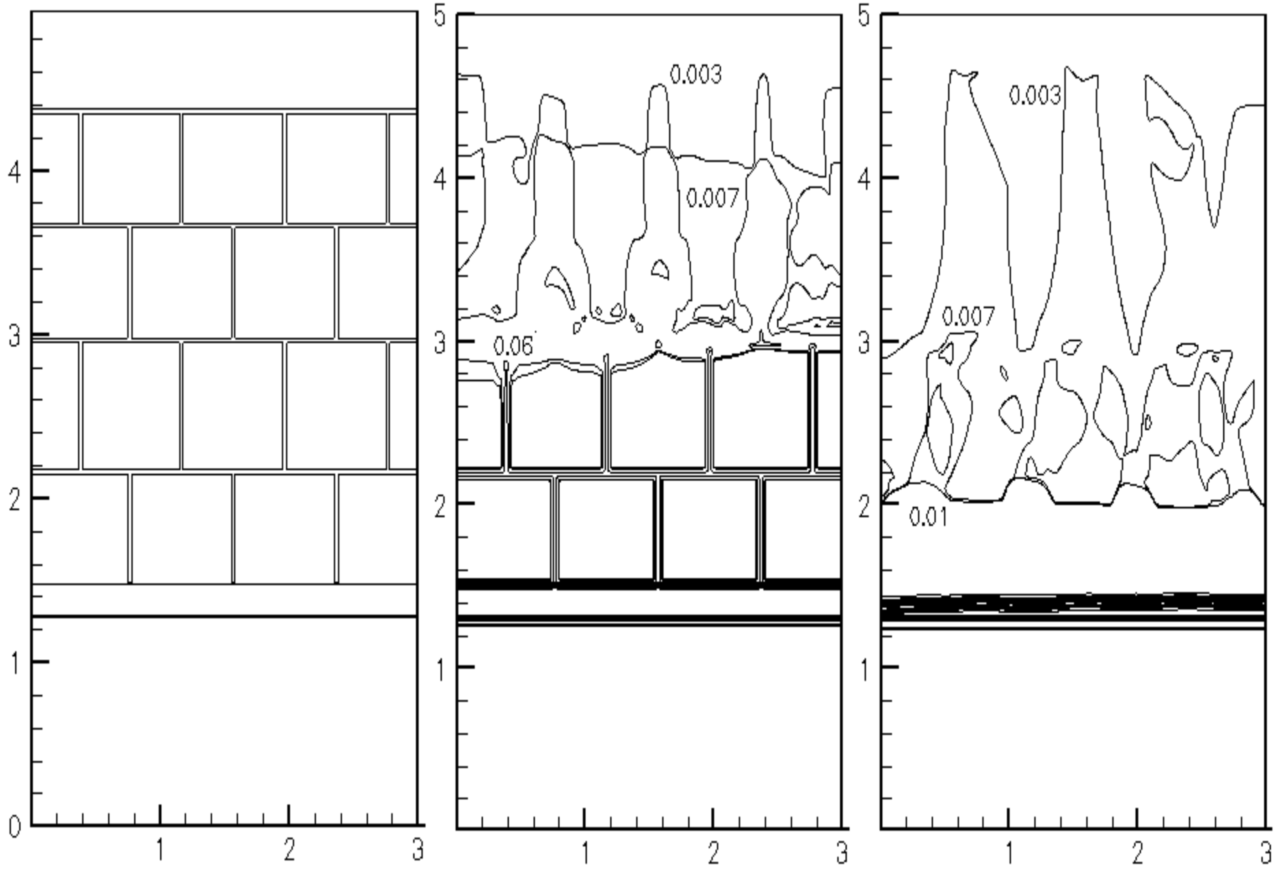
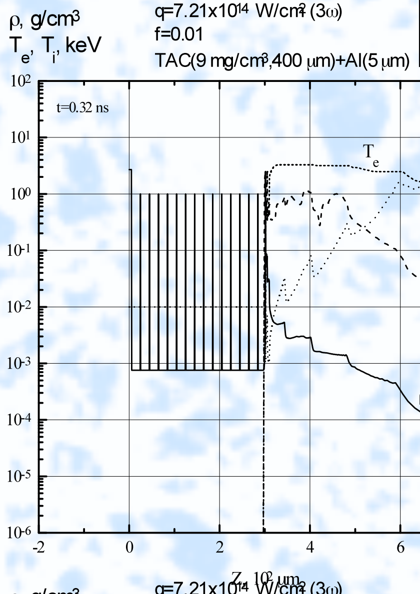
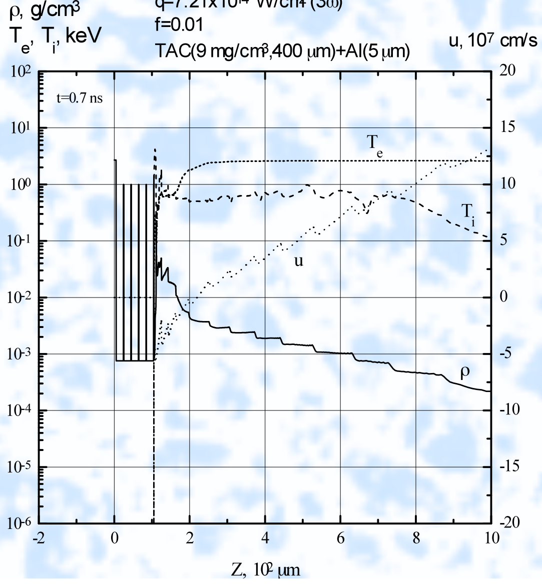
NUTCY 2D, RAPID 1D codes:

laser-irradiated structured media

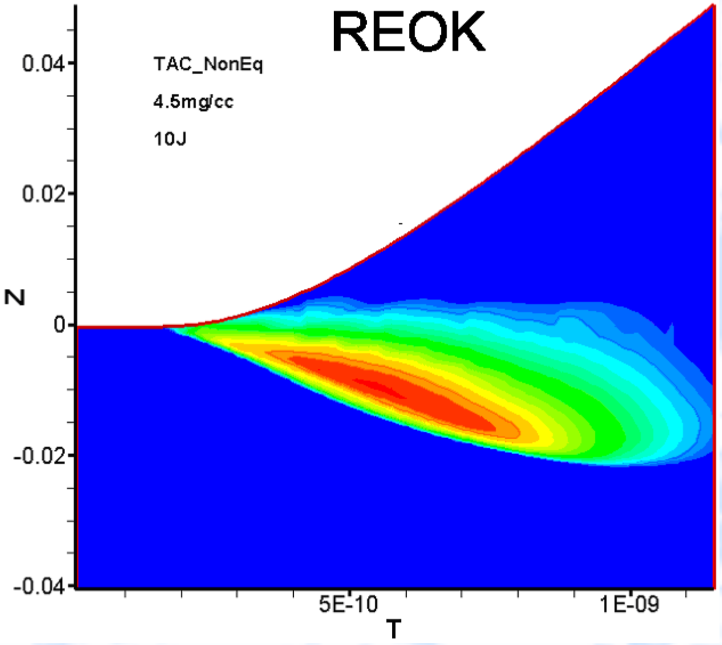
(LPI, IMM, 2006)

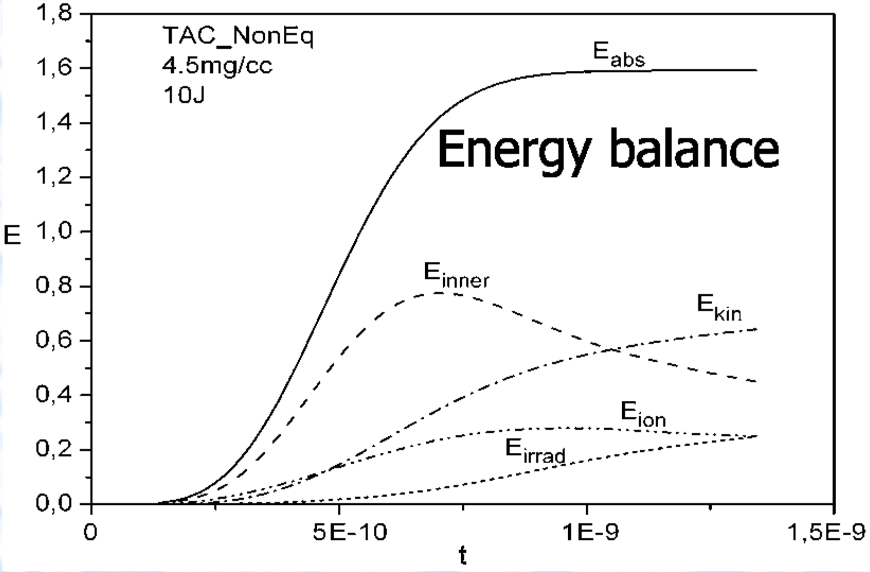


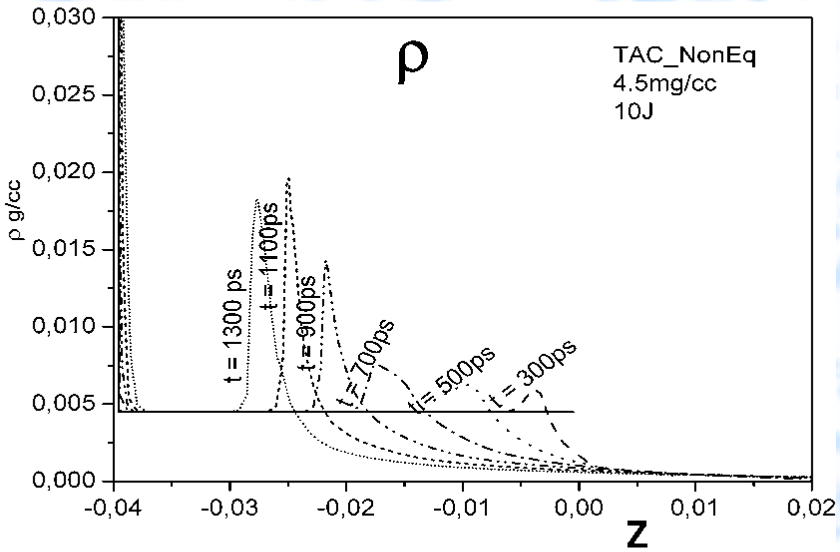


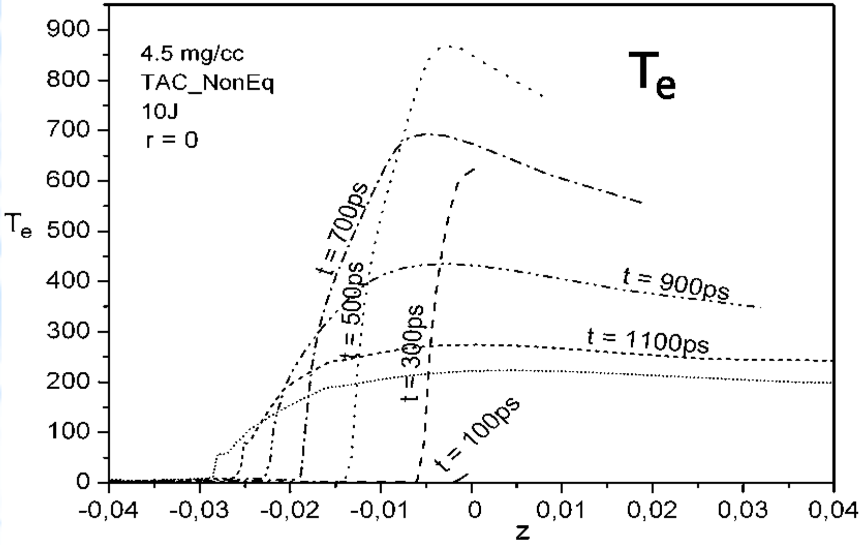


PALS Numerical simulations(5)
TAC 4.5 mg/cm^3, 1ω, 10J, r=0









PALS Numerical simulations(6)
TAC 9.1 mg/cm^3, 1ω, 10J

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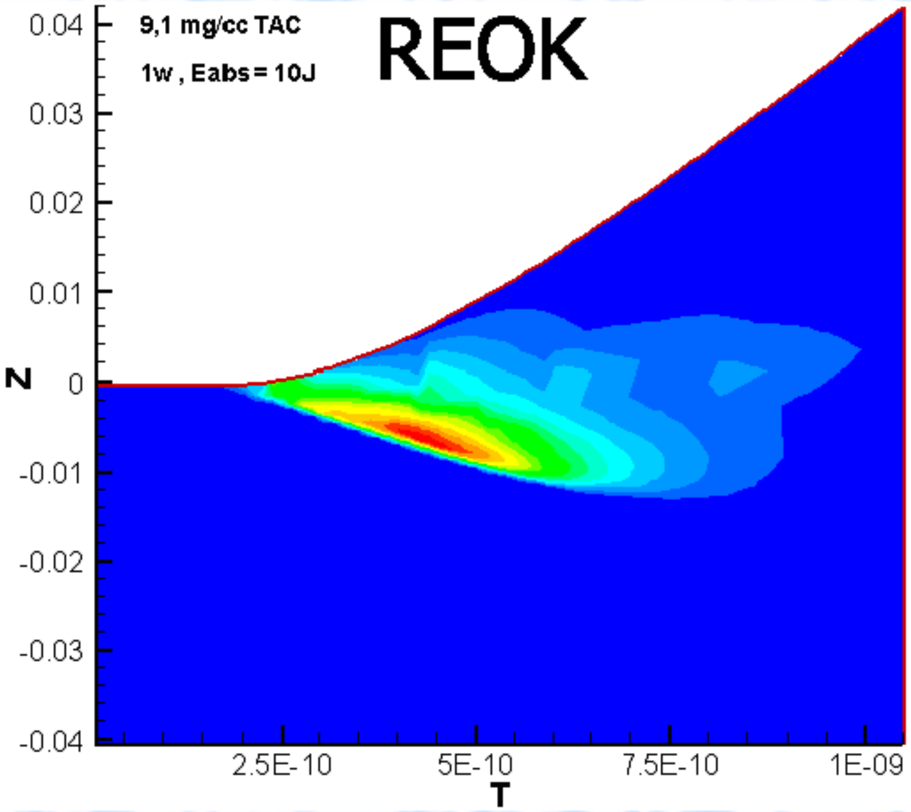

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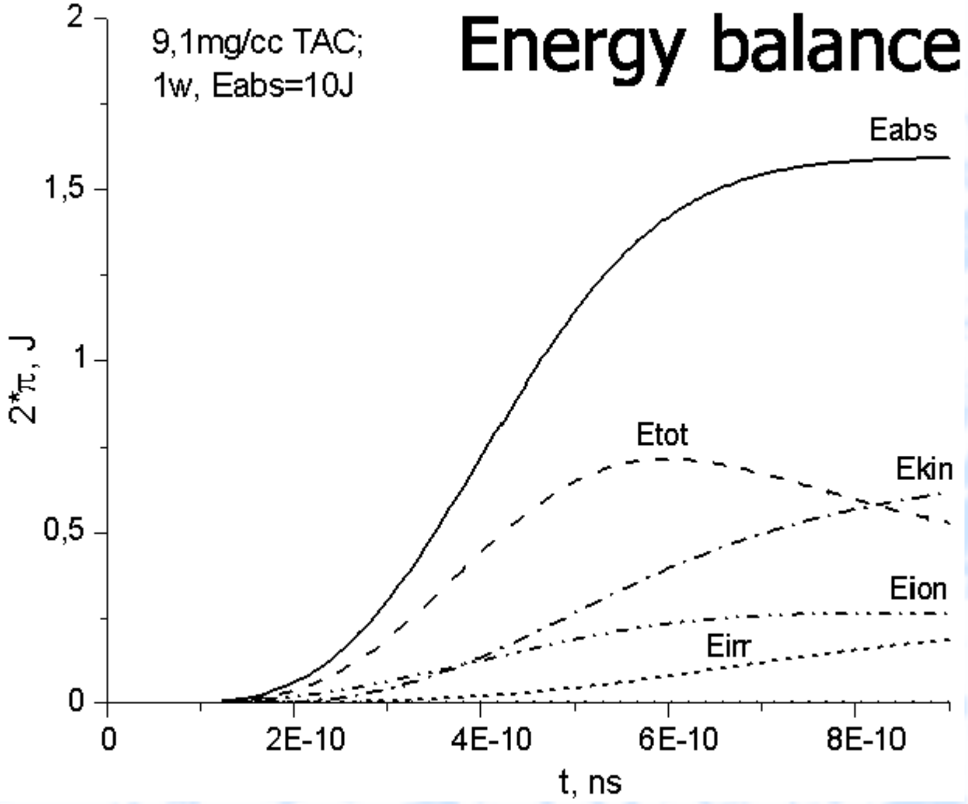

Energy balance

PALS Numerical simulations⁽⁷⁾
TAC 4.5 mg/cm³, 3ω, 30J

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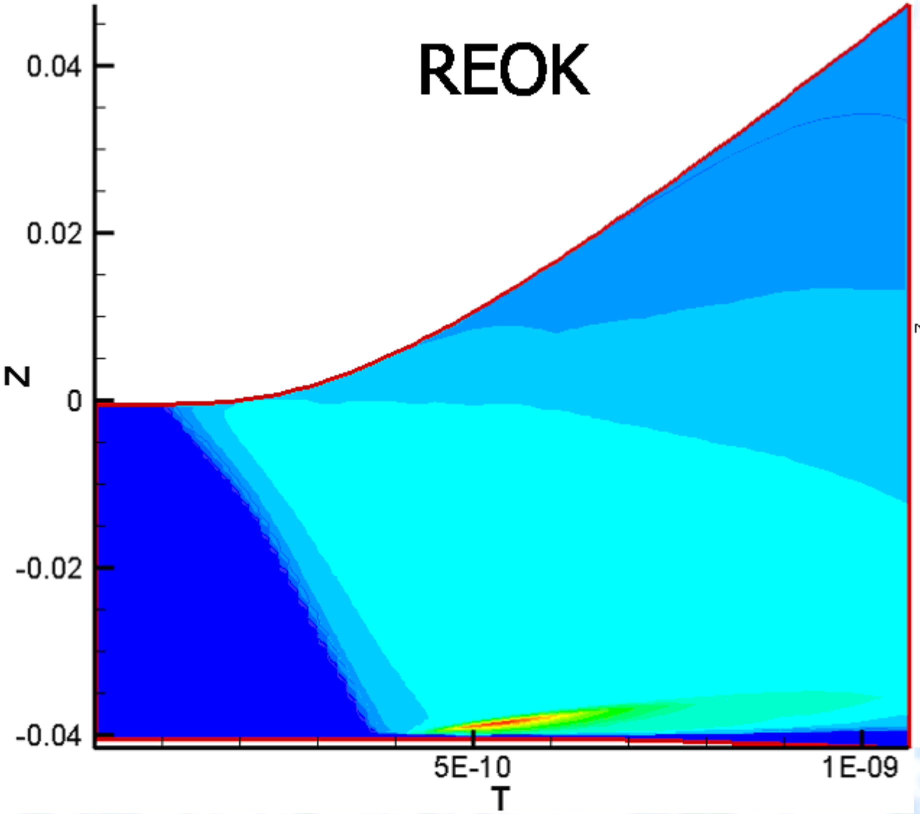
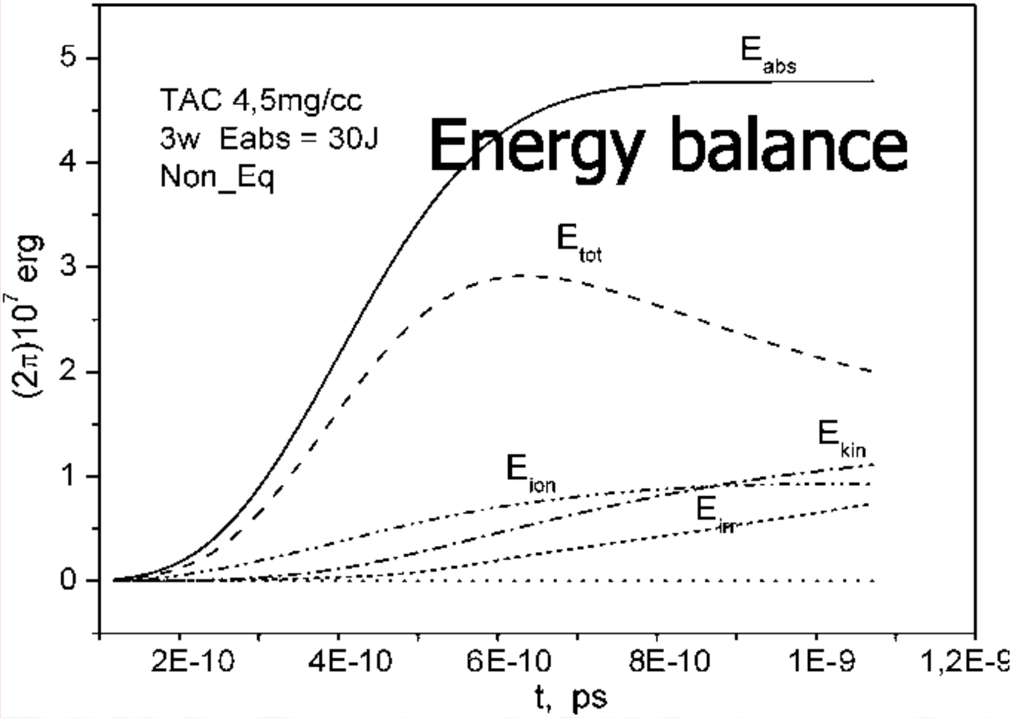
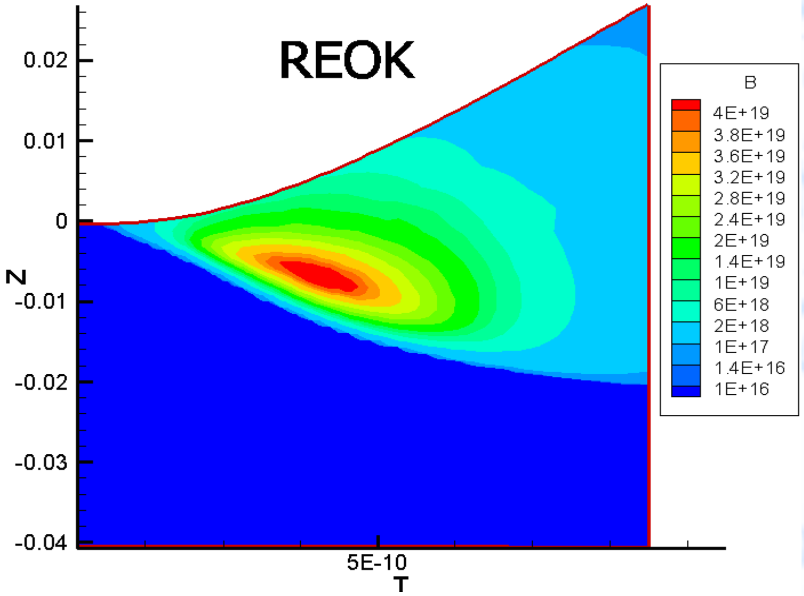
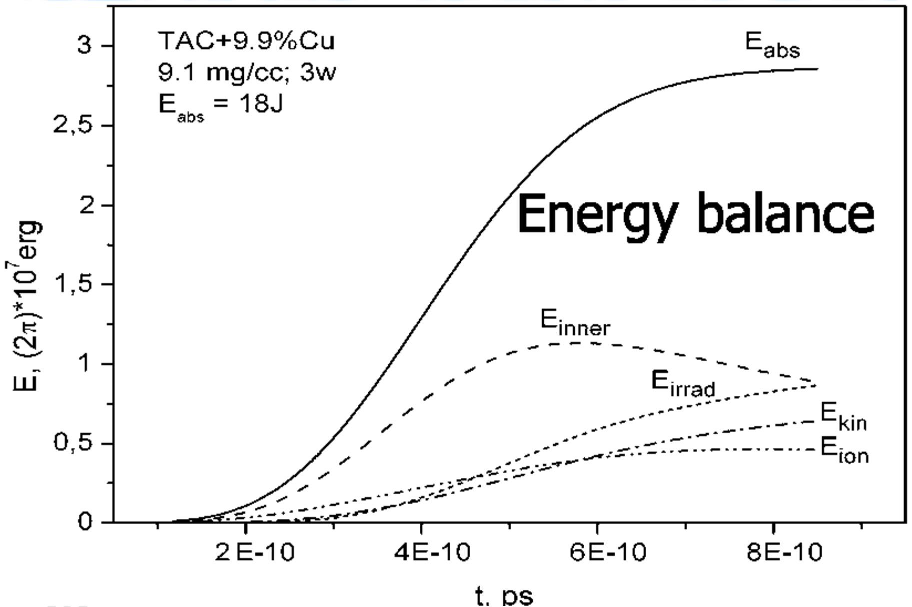
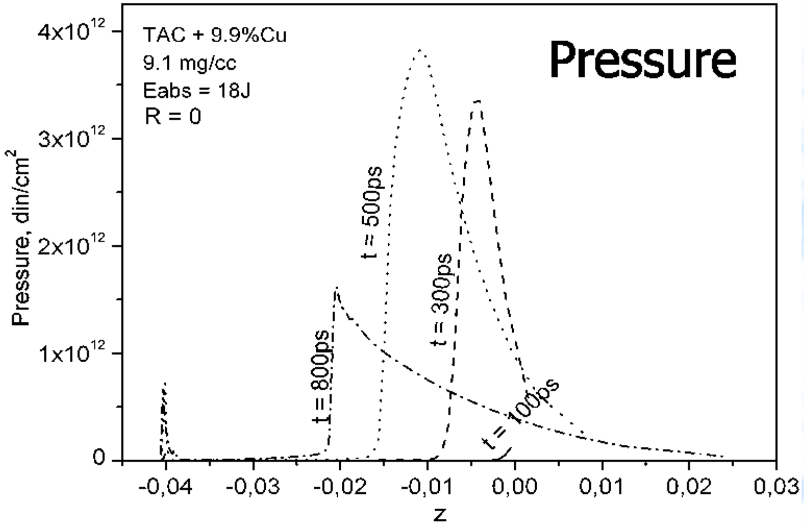


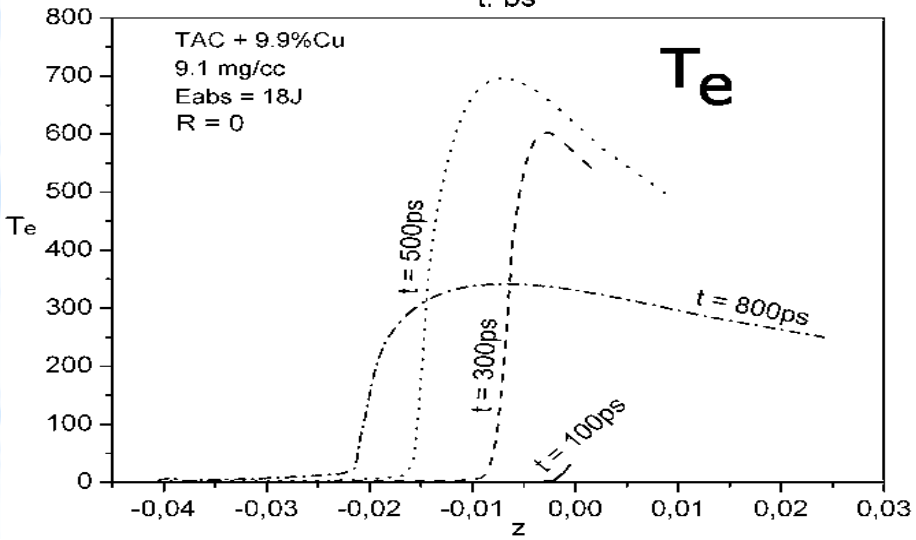


PALS Numerical simulations(8) TAC +Cu 9.9% = 9.1 mg/cm^3, 3ω, 18J, r=0









LIL experiments (1)

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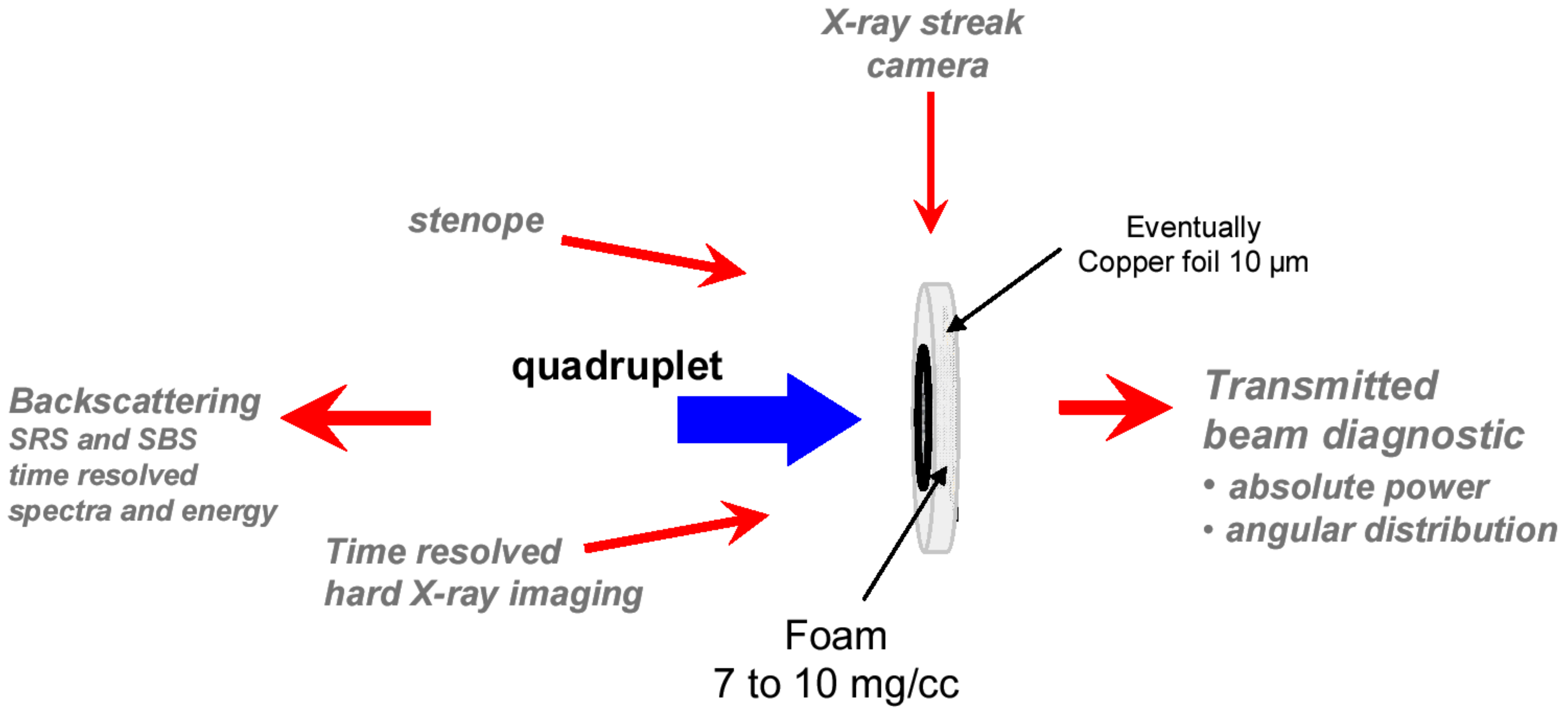
$E_{las} \sim 10$ kJ, **$\lambda = 0.351\ \mu m$**

$\tau_{las} = 2.5$ ns at $1/2q_{max}$ **$q_{las} = 4 \cdot 10^{14}\ W/cm^2$**

Target: **TMPTA-foam (900 μm)**

Foam density: **6.5 - 10 mg/cm^3**



X-ray streak camera

stenope

Eventually
Copper foil 10 µm

quadruplet

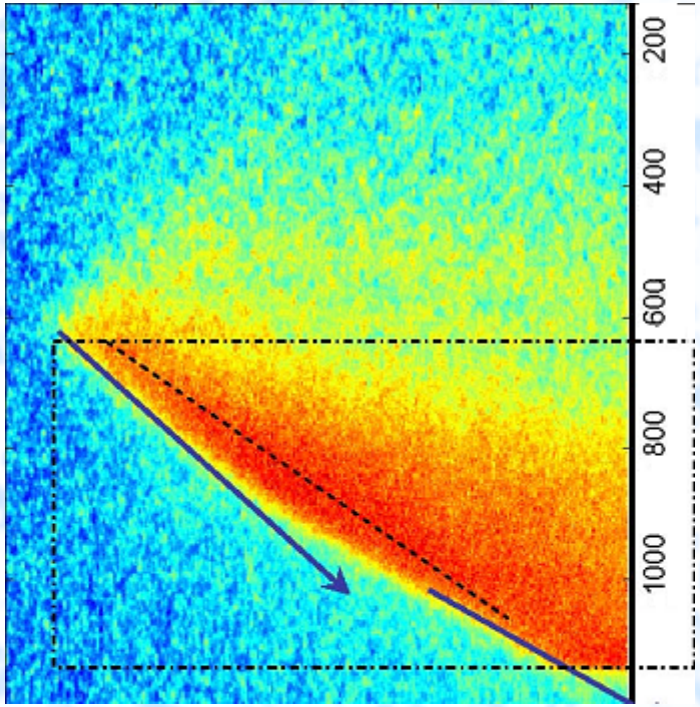
Backscattering
SRS and SBS
time resolved
spectra and energy

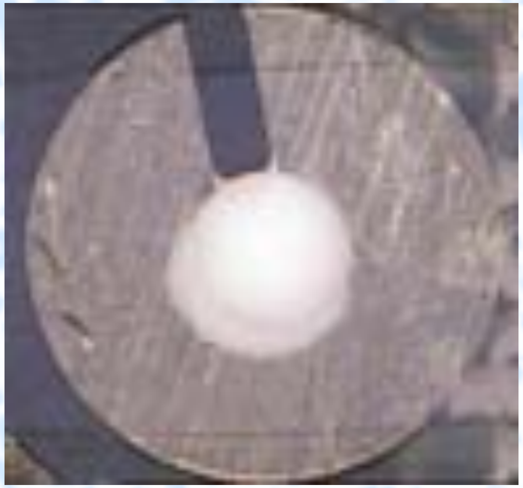
Transmitted beam diagnostic
- ***absolute power***
- ***angular distribution***

Time resolved hard X-ray imaging

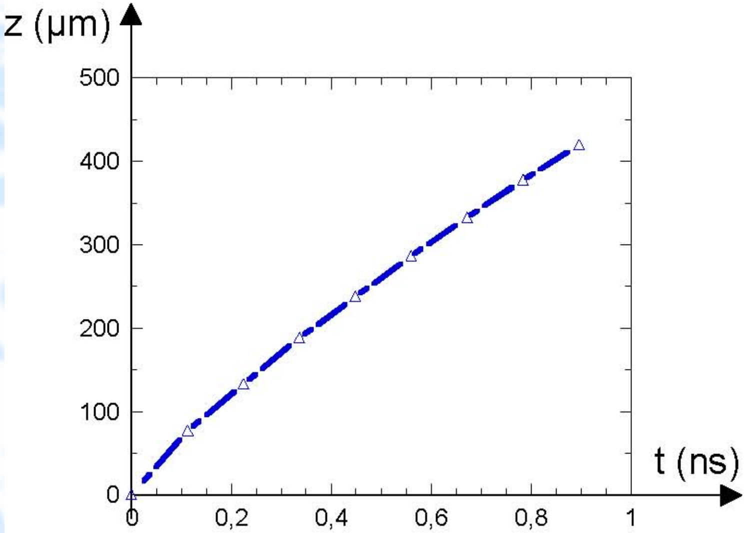
Foam
7 to 10 mg/cc

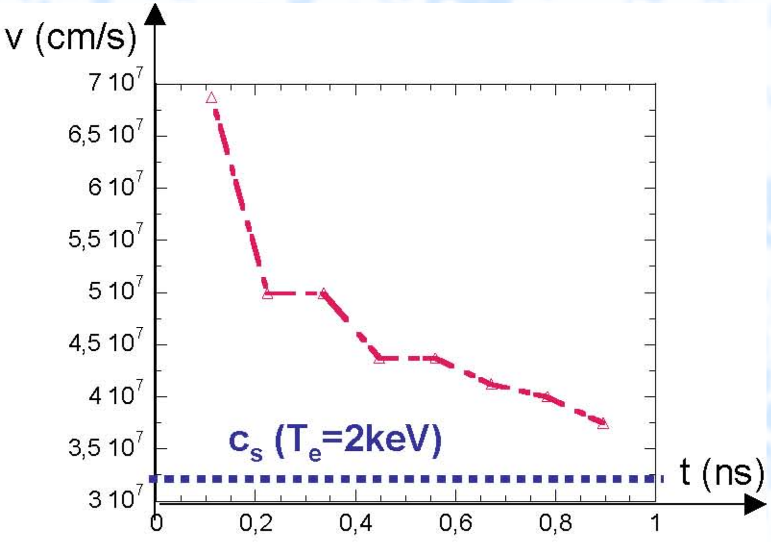
LIL experiments $^{(2)}$





LIL target photo





LIL experiments (3)

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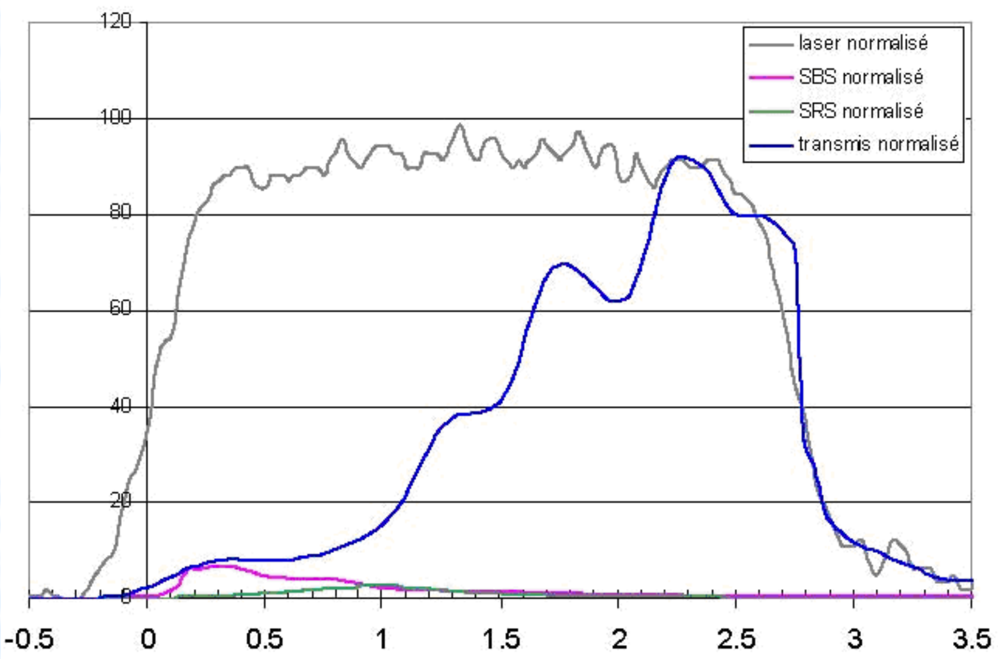

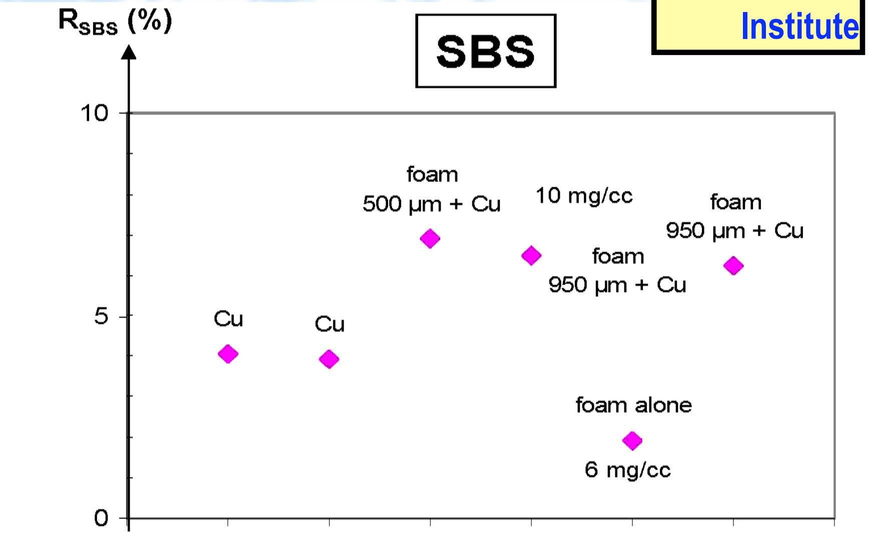

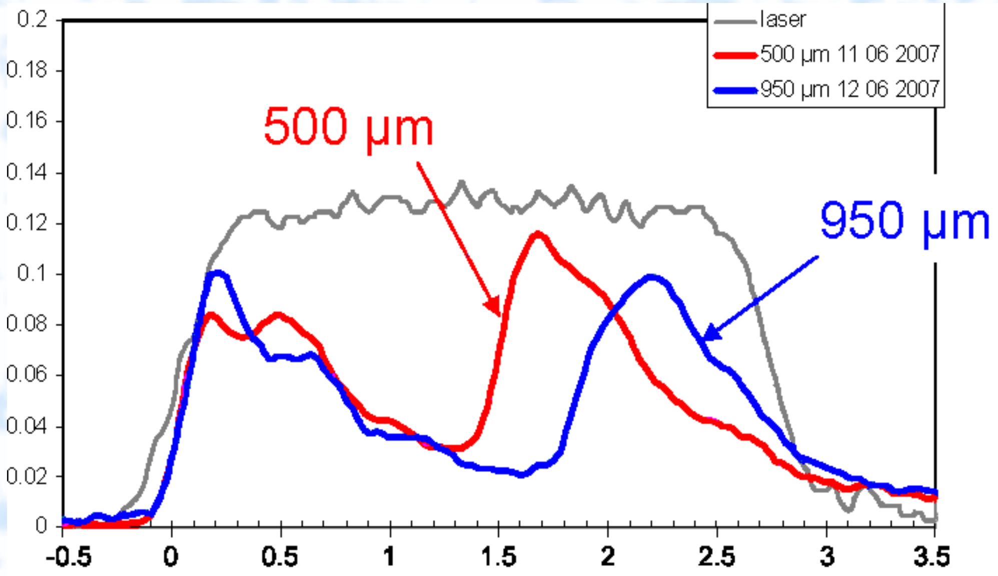

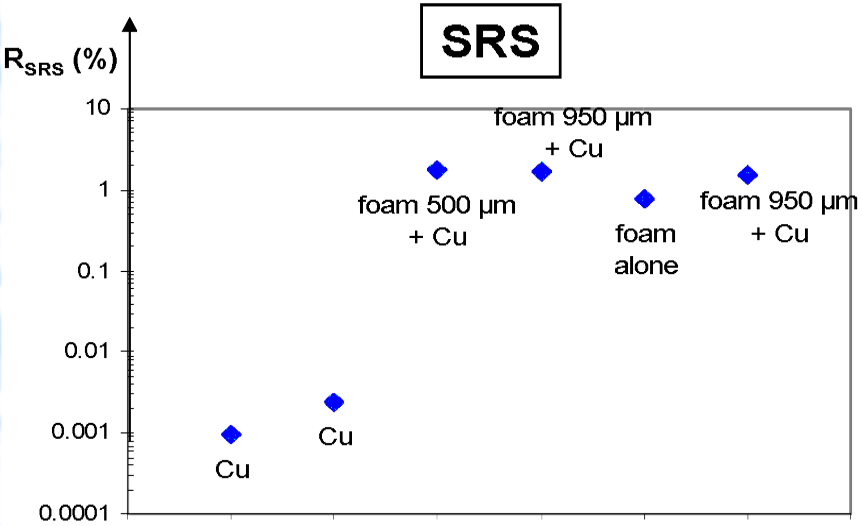

LIL experiments (4)

simulation by code CHIC-2D

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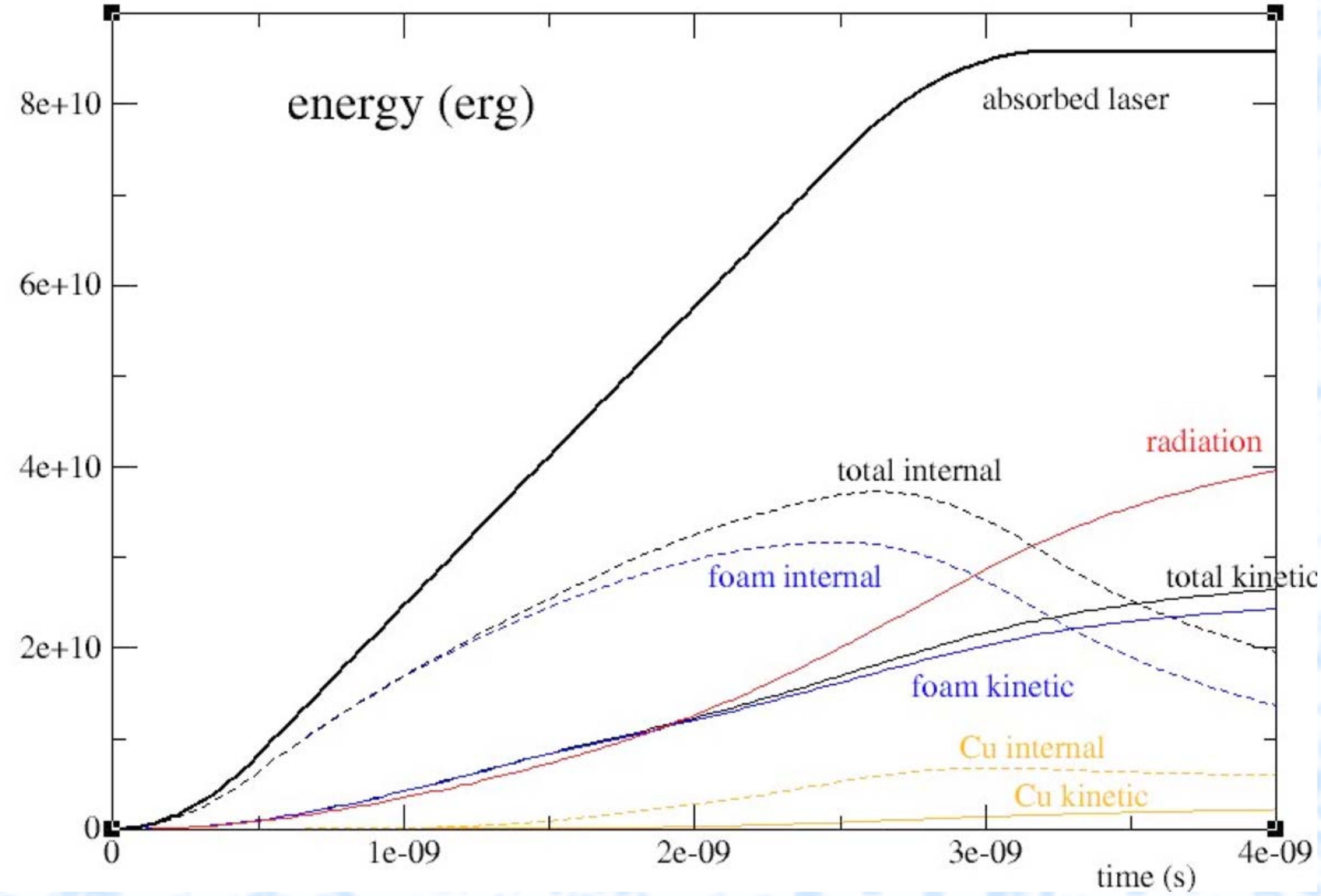
(10mg/cc, 950microns)



LIL experiment simulation (1)

$E_{las} \sim 10$ kJ, $\lambda = 0.351$ μm

$\tau_{las} = 2.5$ ns at $1/2q_{max}$

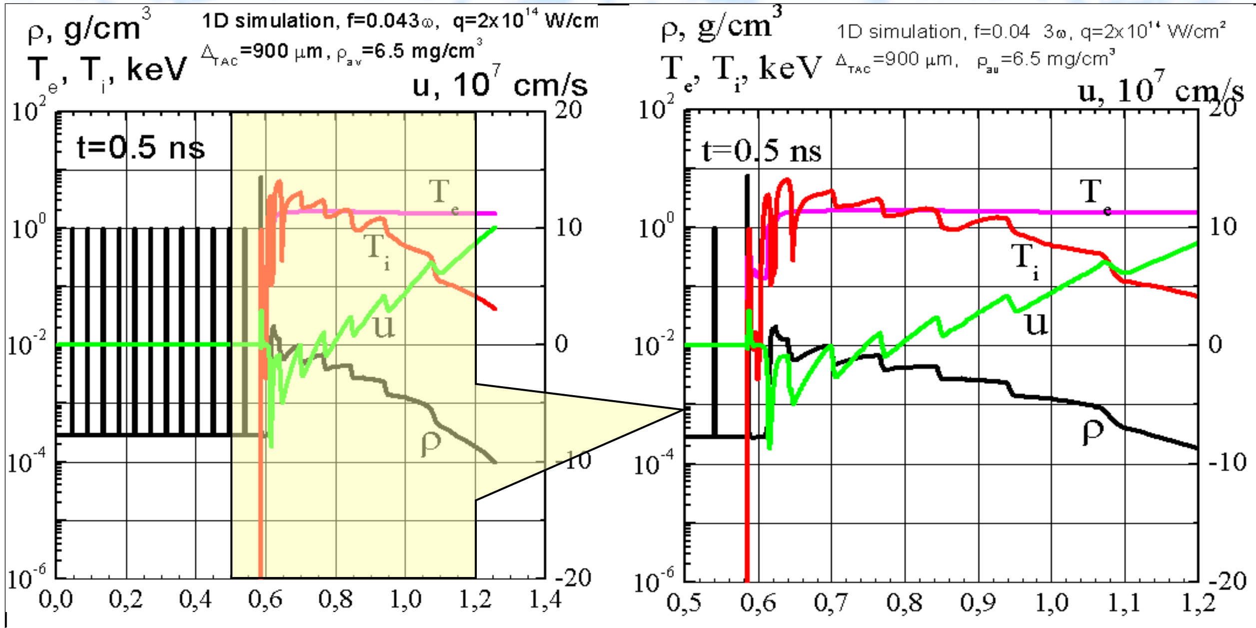
$q_{las} = 4 \cdot 10^{14}$ W/cm^2

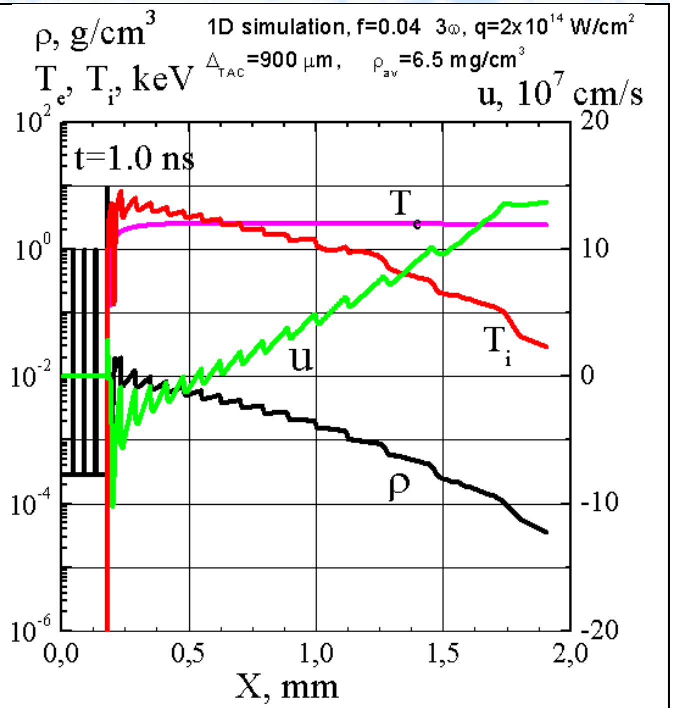
Target: **TAC-foam (900 μm)**
Foam density: **6.5 mg/cm^3**

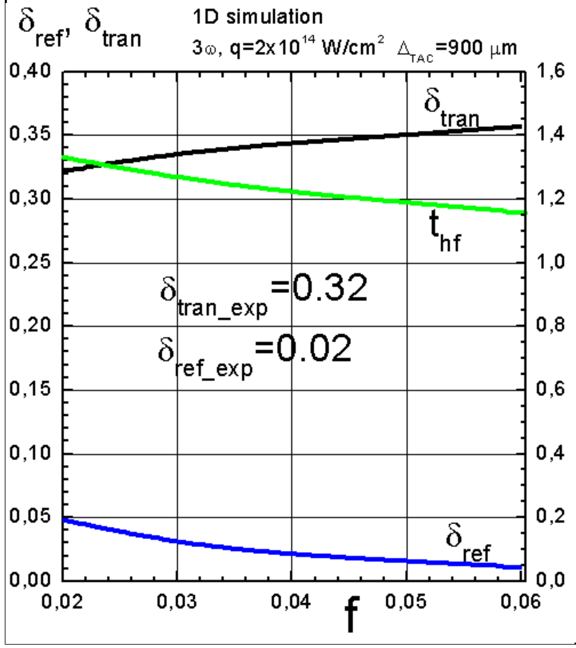
Simulation:

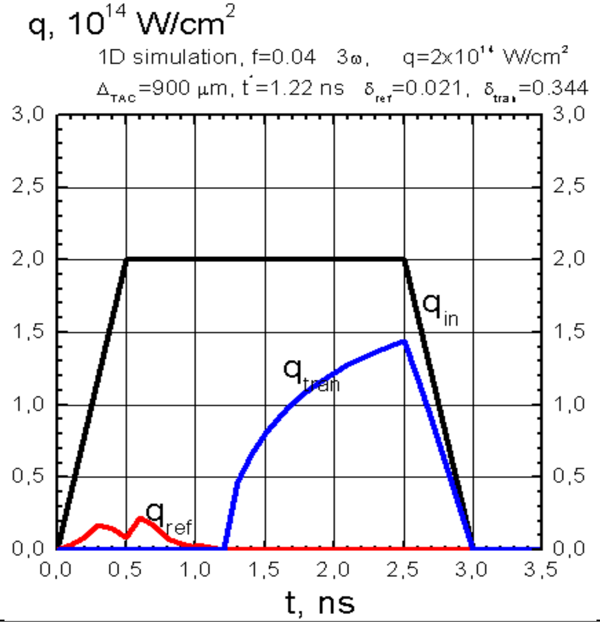
1D simulations were performed for incident laser flux 2x10^{14} W/cm^2 because part of energy is losed due to transport in transverse direction.

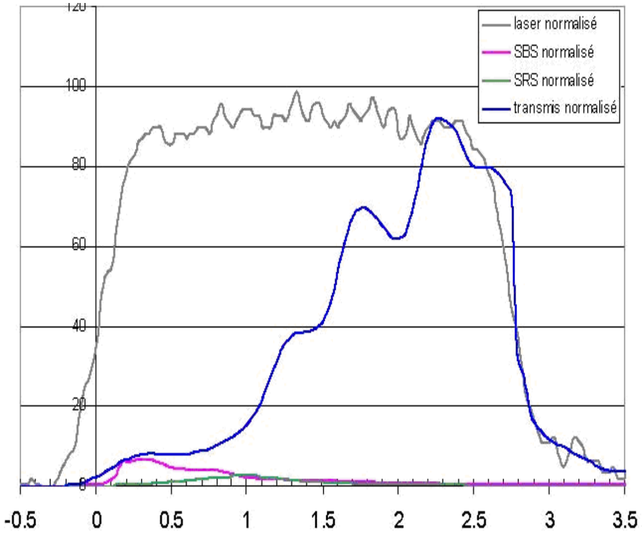
LIL RAPID simulation (2)











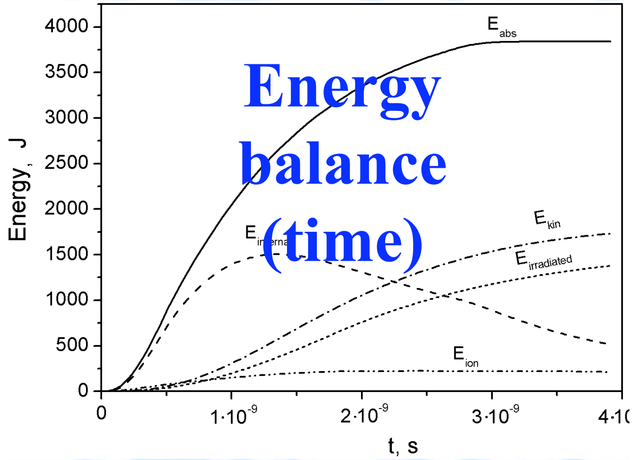
LIL experiment simulation$^{(3)}$
2D LATRANT

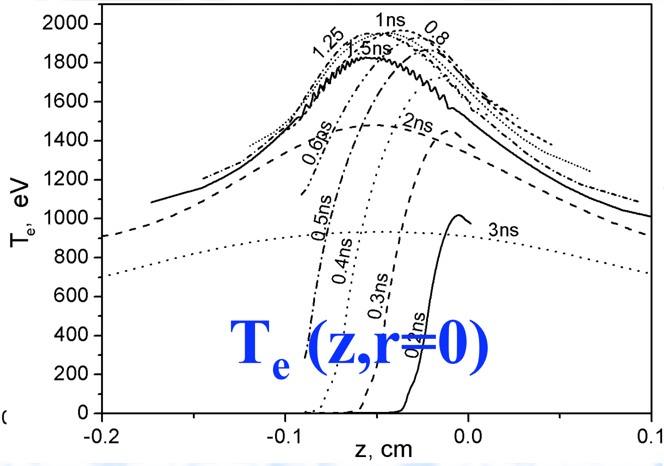
V.B.Rozanov
P.N Lebedev Institute

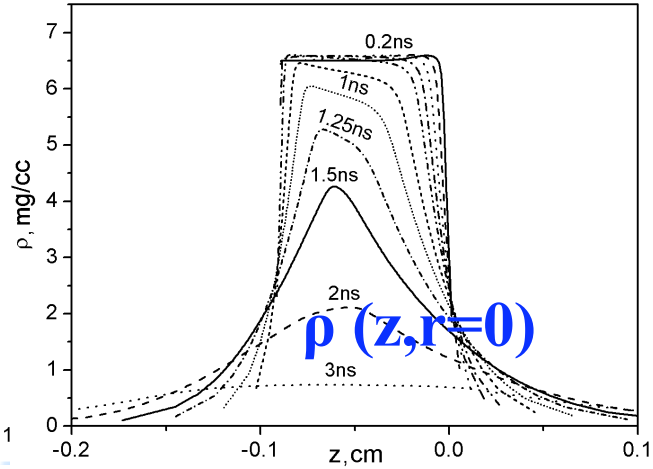
ILP3: E_{las} = 8 kJ,   λ = 0.351 μm

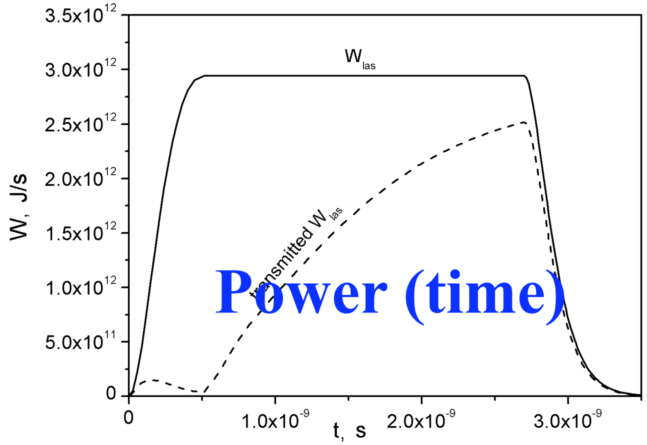
τ_{las} = 2.7 ns at $1/2q_{max}$

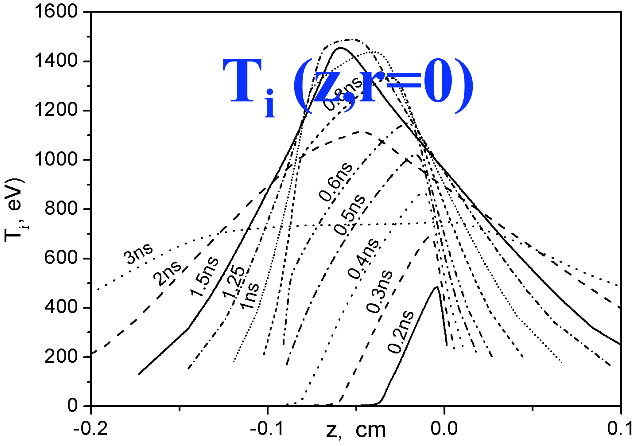
Target: **TMPTA ($C_{15}H_{20}O_6$)-foam, 900 μm**   Foam density: **6.5 mg/cm^3**

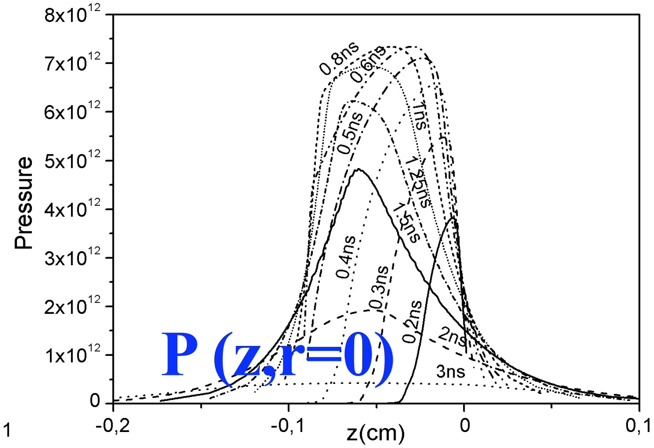












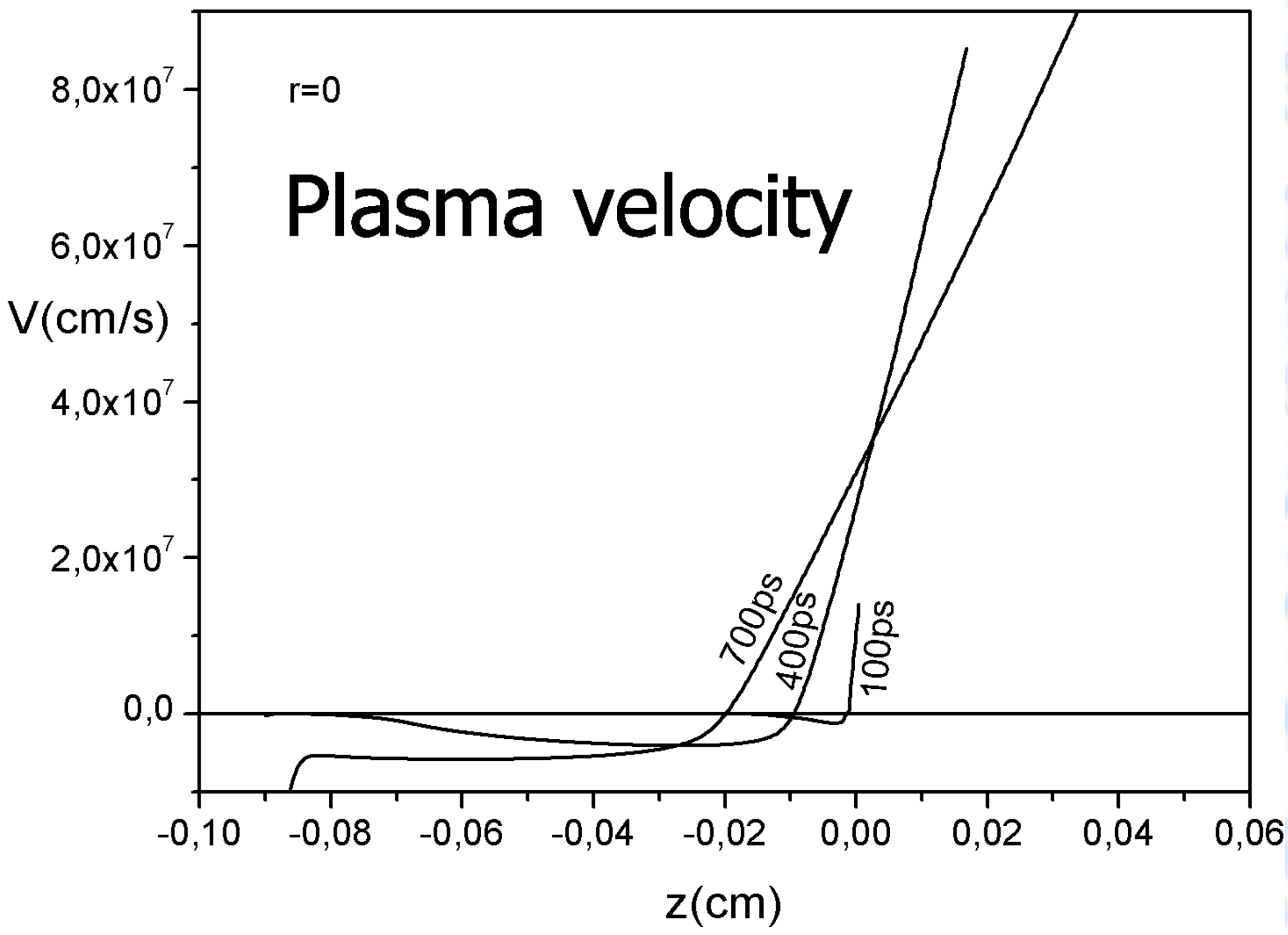
LIL experiment simulation(4)
2D LATRANT

V.B.Rozanov
P.N Lebedev
Institute

ILP3: E_{las} = 8 kJ, λ = 0.351 µm

τ_{las} = 2.7 ns at $1/2q_{max}$

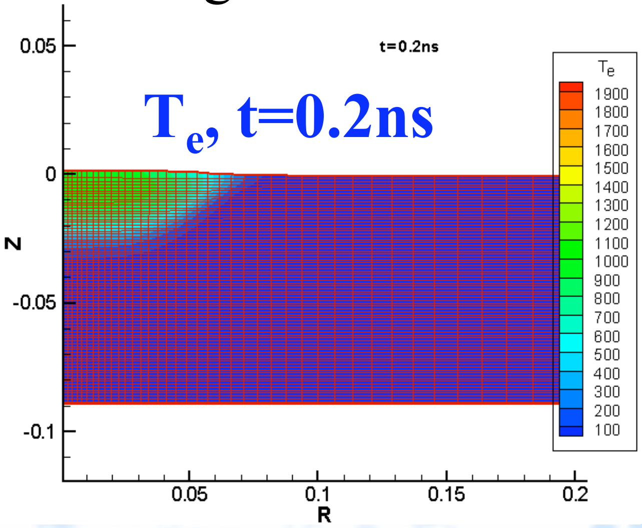
Target: **TMPTA ($C_{15}H_{20}O_6$)-foam, 900 µm** Foam density: **6.5 mg/cm^3**

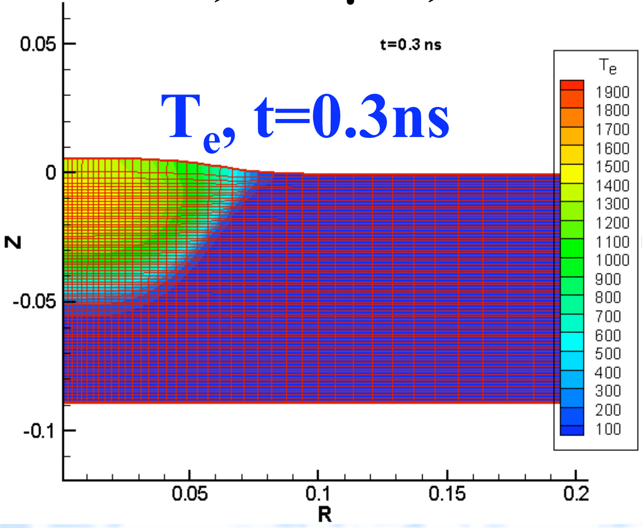


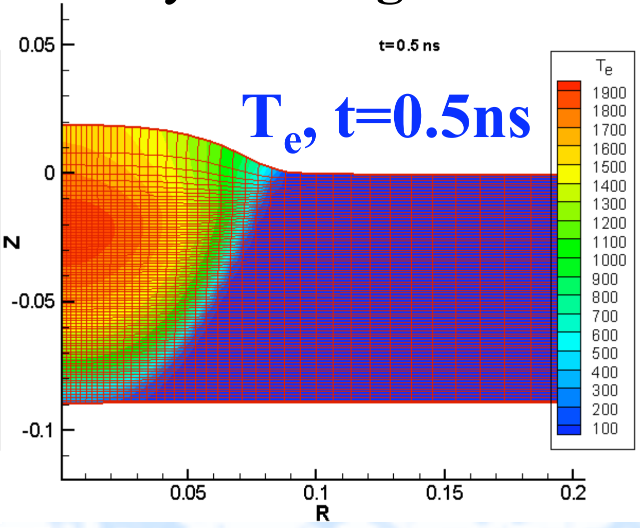
LIL experiment simulation$^{(5)}$
2D LATRANT

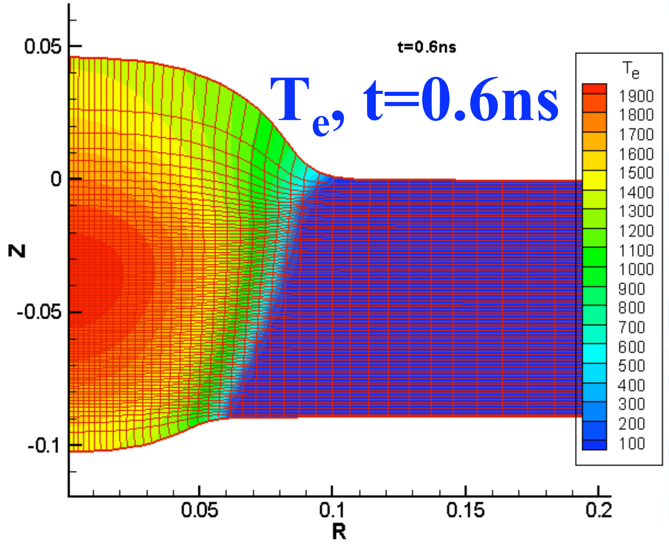
ILP3: E_{las} = 8 kJ, λ = 0.351 µm τ_{las} = 2.7 ns at $1/2q_{max}$

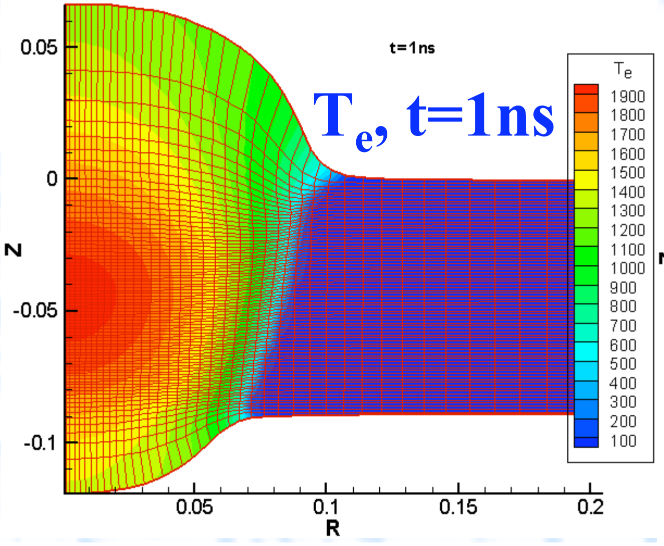
Target: **TMPTA-foam, 900 µm,** Foam density: **6.5 mg/cm^3**

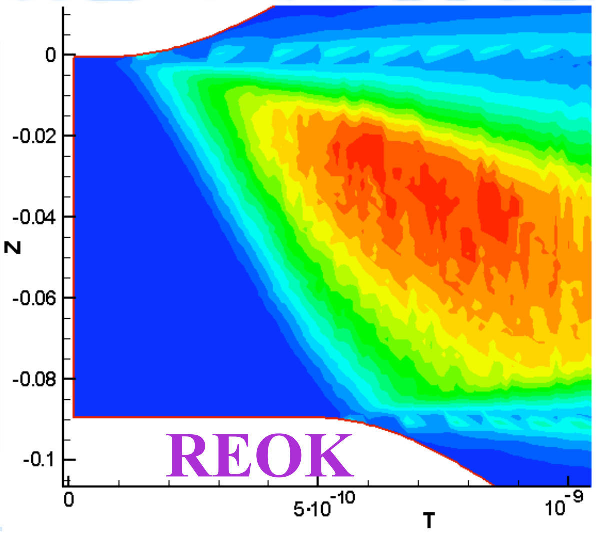












LIL: x-ray emissivity simulation in 2D LATRANT

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TMPTA: Non-LTE integral emissivity

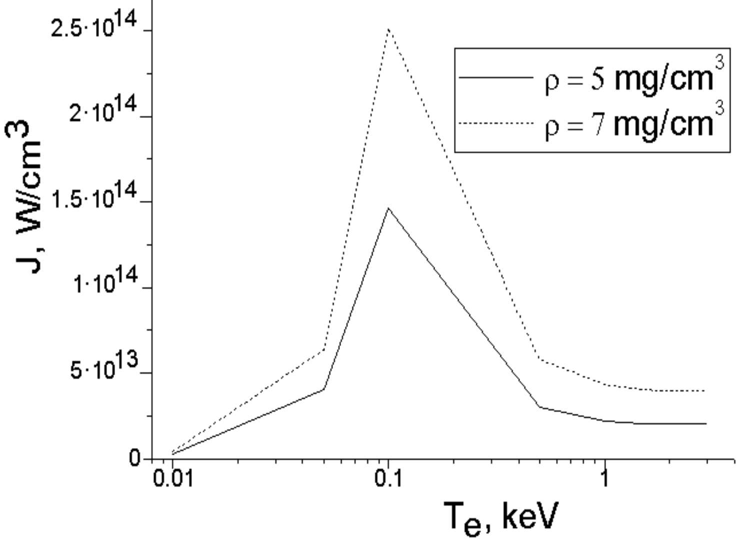
	ρ, g/cm^3							
T_e, keV	0.005	0.007	0.010	0.015	0.030	0.050	0.100	1.000
0.01	$2.65\cdot10^{12}$	$3.98\cdot10^{12}$	$6.08\cdot10^{12}$	$9.46\cdot10^{12}$	$2.08\cdot10^{13}$	$3.85\cdot10^{13}$	$8.68\cdot10^{13}$	$2.67\cdot10^{15}$
0.05	$2.01\cdot10^{13}$	$3.63\cdot10^{13}$	$6.64\cdot10^{13}$	$1.27\cdot10^{14}$	$3.62\cdot10^{14}$	$7.37\cdot10^{14}$	$1.82\cdot10^{15}$	$3.18\cdot10^{16}$
0.10	$4.8\cdot10^{13}$	$9.31\cdot10^{13}$	$1.91\cdot10^{14}$	$4.17\cdot10^{14}$	$1.53\cdot10^{15}$	$3.76\cdot10^{15}$	$1.17\cdot10^{16}$	$2.29\cdot10^{17}$
0.50	$2.72\cdot10^{13}$	$5.37\cdot10^{13}$	$1.09\cdot10^{14}$	$2.43\cdot10^{14}$	$9.57\cdot10^{14}$	$2.6\cdot10^{15}$	10^{16}	$7.65\cdot10^{17}$
1.00	$2.18\cdot10^{13}$	$4.27\cdot10^{13}$	$8.67\cdot10^{13}$	$1.93\cdot10^{14}$	$7.6\cdot10^{14}$	$2.07\cdot10^{15}$	$8.07\cdot10^{15}$	$7.01\cdot10^{17}$
1.50	$2.11\cdot10^{13}$	$4.01\cdot10^{13}$	$8.14\cdot10^{13}$	$1.82\cdot10^{14}$	$7.18\cdot10^{14}$	$1.97\cdot10^{15}$	$7.7\cdot10^{15}$	$6.94\cdot10^{17}$
2.00	$2.07\cdot10^{13}$	$3.95\cdot10^{13}$	$8.04\cdot10^{13}$	$1.8\cdot10^{14}$	$7.11\cdot10^{14}$	$1.95\cdot10^{15}$	$7.68\cdot10^{15}$	$7.07\cdot10^{17}$
2.50	$2.04\cdot10^{13}$	$3.96\cdot10^{13}$	$8.06\cdot10^{13}$	$1.8\cdot10^{14}$	$7.14\cdot10^{14}$	$1.97\cdot10^{15}$	$7.76\cdot10^{15}$	$7.25\cdot10^{17}$
3.00	$2.05\cdot10^{13}$	$3.99\cdot10^{13}$	$8.11\cdot10^{13}$	$1.82\cdot10^{14}$	$7.21\cdot10^{14}$	$1.99\cdot10^{15}$	$7.85\cdot10^{15}$	$7.41\cdot10^{17}$

Balance: Theoretical estimation

E_{abs} = **5.2 kJ** : **3.3 kJ** on heating + ionization T_e=2keV, ρ=6.5mg/cm^3, X-ray emission - 100J/ns

Where is energy?

2D simulation X-ray: **1.7kJ**



CONCLUSION

- Low and medium density laser plasma (0.001-0.1 g/cm^3) with high Z admixture is the effective source of radiation in the spectral range 0.01-20 keV

- It was demonstrated, that
  - efficiency >50% for $h\nu \leq 2$ keV
    1-3% for $h\nu \approx 5$-10 keV
    2% for $13.3 < \lambda < 13.7$ nm
  - radiation energy ≈10 kJ for $h\nu \leq 2$ keV (hohlraum situation ~10^6 J)
    100-500 J for $h\nu \approx 5$-10 keV

- E_{rad}=10 kJ corresponds to $N_\gamma = 6 \cdot 10^{19}$ $h\nu \approx 1$ keV
  τ_L=1 ns $(4\pi)^{-1}(dN_\gamma/dt) \approx 5 \cdot 10^{27}\ (s \cdot str)^{-1}$
  E_{rad}=500 J corresponds to $N_\gamma = 3 \cdot 10^{17}$ $h\nu \approx 10$ keV
  τ_L=1 ns $(4\pi)^{-1}(dN_\gamma/dt) \approx 2 \cdot 10^{25}\ (s \cdot str)^{-1}$

- These results open new possibilities in diagnostics, material and biomedical sciences, technology, X-ray laser physics.

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3. S.Yu. Gus'kov, et al., Proc. of SPIE, 4424, 332-335, 340-347, 2001.
4. S.Yu. Gus'kov, et al., JETP, 81(2), 296, 1995.
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7. LLE Review, 102, 67, 2005
8. I. G. Lebo, et al., Las. Part. Beams, 22(3), 267, 2004.
9. V. Rozanov, et al., J. Phys.: Conf. Ser., 112, 022010, 2008

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PALS Numerical simulations (1) TAC 4.5 mg/cm^3, 1ω, 50 J, LATRANT code, 20 layers, r=0

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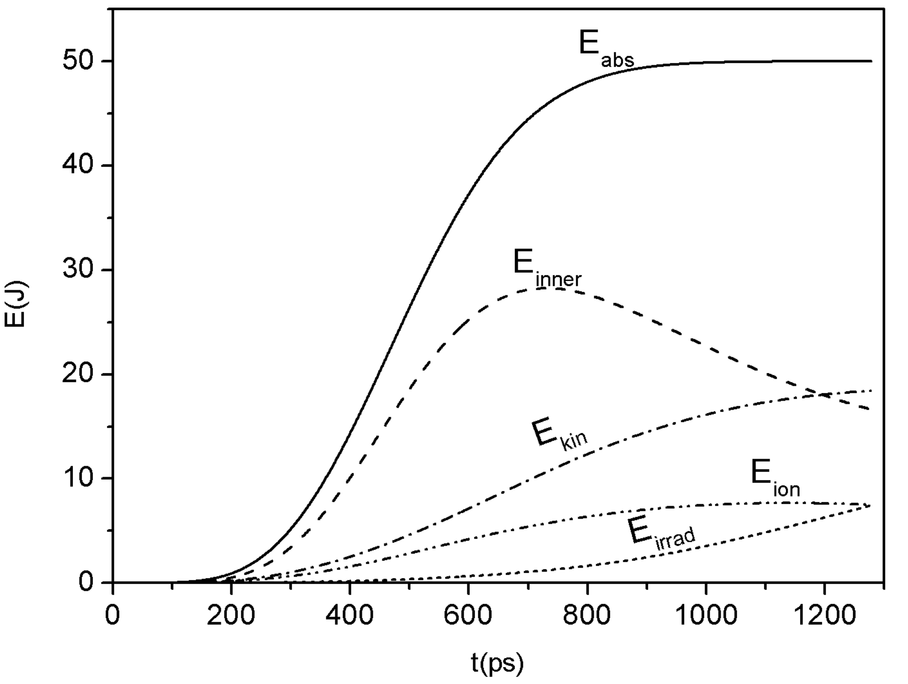

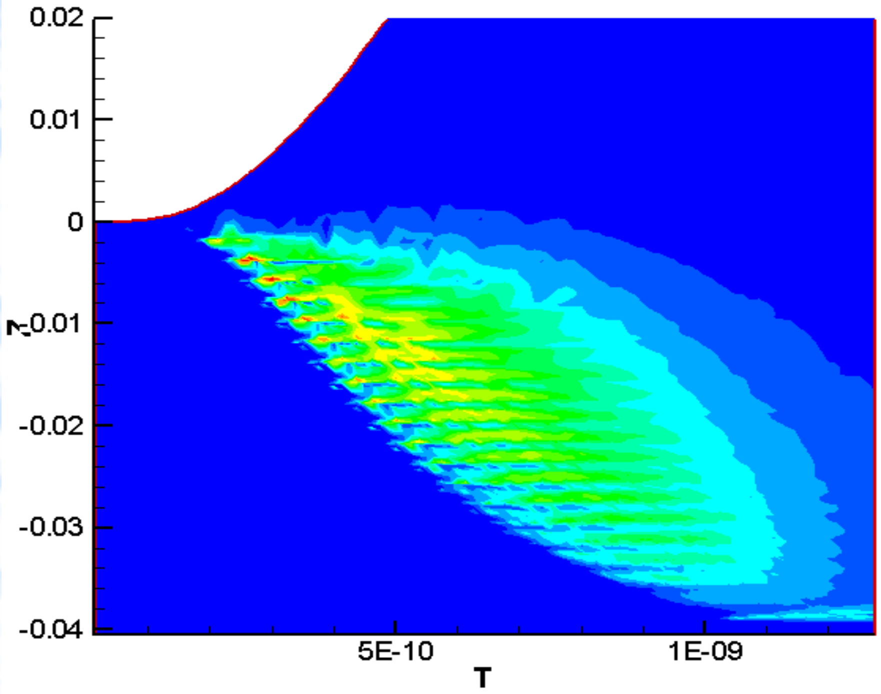

Energy balance **REOK data**

LATRANT takes into account radiation transport in multigroup approach and gas dynamics according to an improved Lagrangian difference scheme (E.N.Aristova, A.B.Iskakov. LATRANT: two-dimensional radiative Lagrangian gas dynamics for ICF problems, Matematicheskoe modelirovanie, v. 16 (2004), №3, p.63-77

PALS Numerical simulations (2) TAC 4.5 mg/cm³, 1ω, 50 J, 20 layers, r=0

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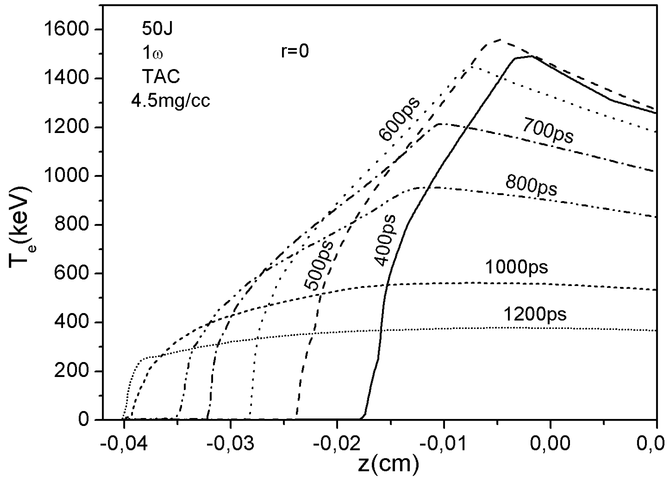
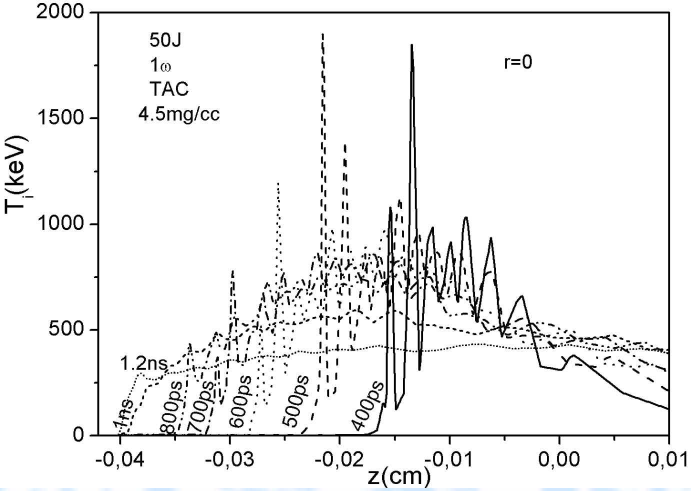
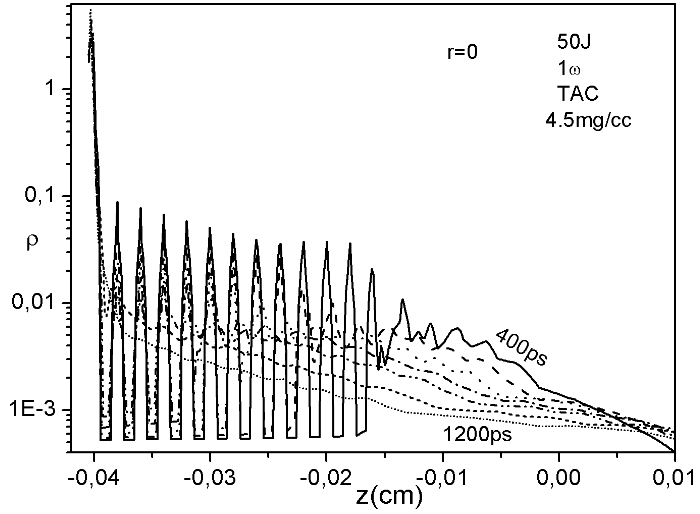


← Electron

Ion →

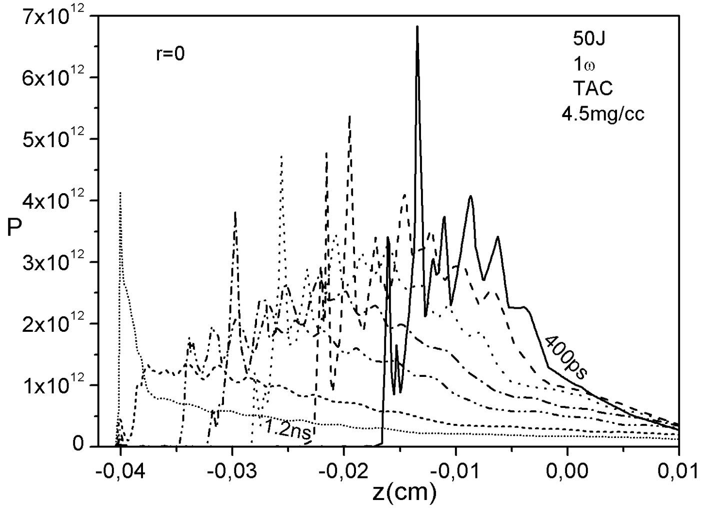
temperatures





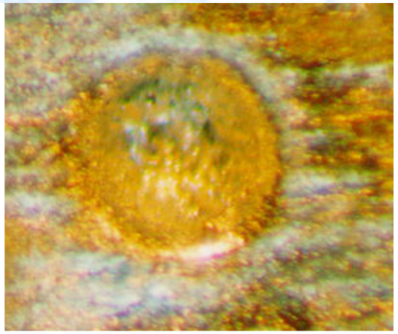
← Density

Pressure →

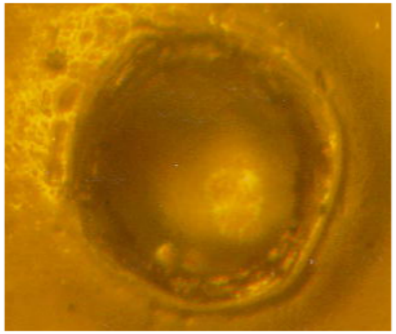


Debris problem

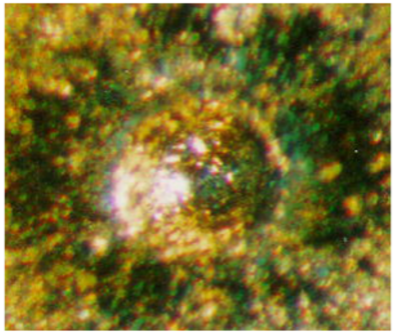
Al

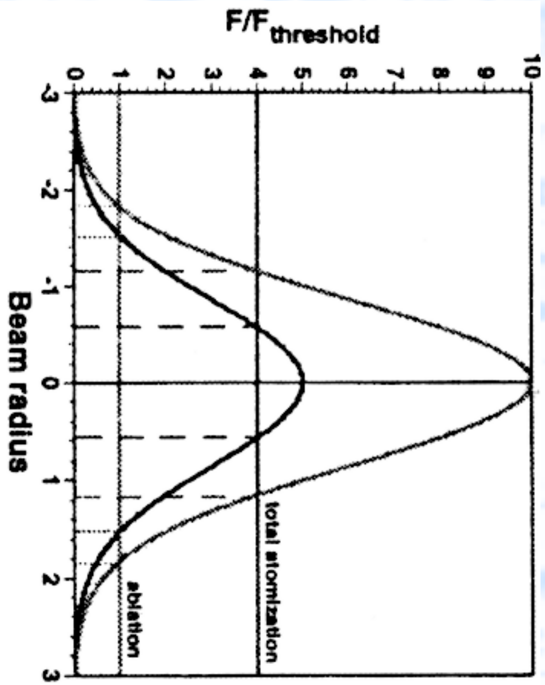


(CH)$_n$



Ti





Atomization/ ablation thresholds for short laser pulse

(E.G.Gamaly et al, 2004)

Experimental results for

E_L=4-20 J, R_L=100μm, τ=1ns

(LPI, “Kanal” facility, 2001)