About target structure in laser plasma experiments

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Outline

In early high-power irradiation experiments on low-density targets the structure was reported to have slight if any influence on the major results. Further the distinct unpredicted effects appeared to be connected with initial solid structure, especially when the diagnostic means achieved higher resolution and accuracy.

Polymer aerogels, unlike many other low-density materials (foam, dust, nano-snow) have a net-like structure, consisting of macromolecular fibers and globules. That means they are highly regular as regards their spatial structure, so high repeatability was demonstrated in interaction experiments with polymer aerogel targets. However we yet have definite molecular structure in the polymer before irradiation.

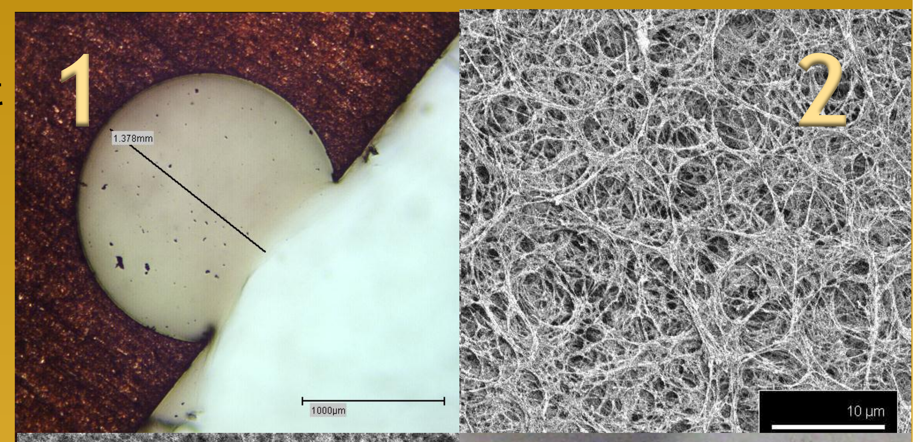
Should we take into account or neglect a molecular structure for plasma effects?

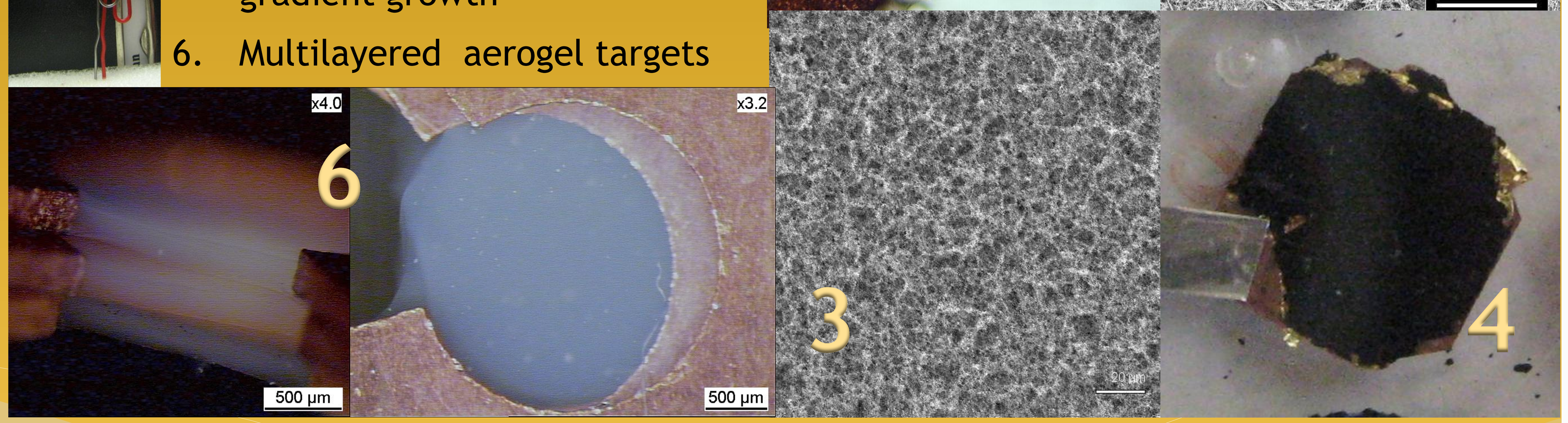
Below we consider the initial phase of soft x-rays to rapture molecular bonds, then atomic structure to estimate if those could be visualized in plasma.

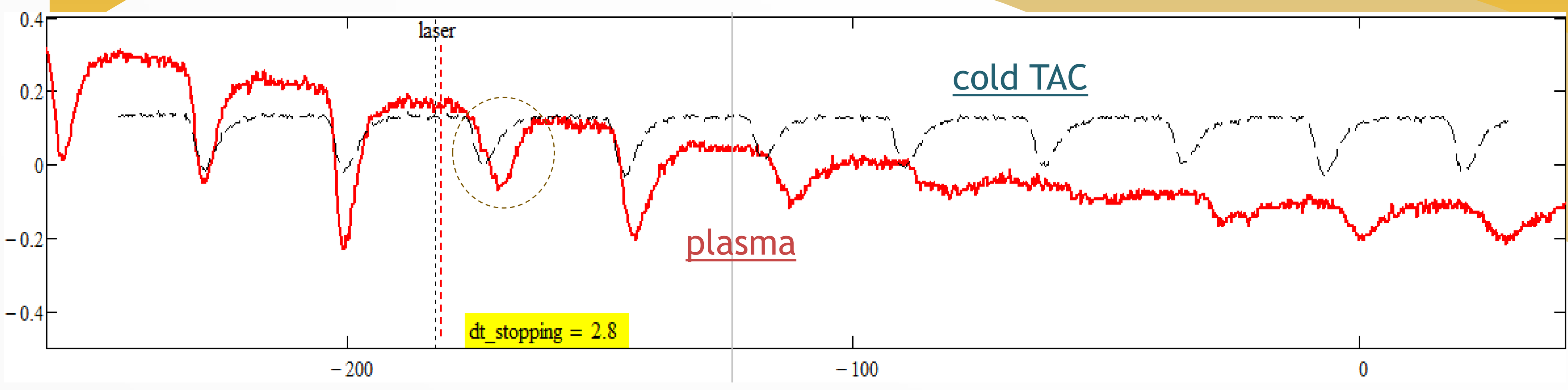
Low-density targets:

[1,2]

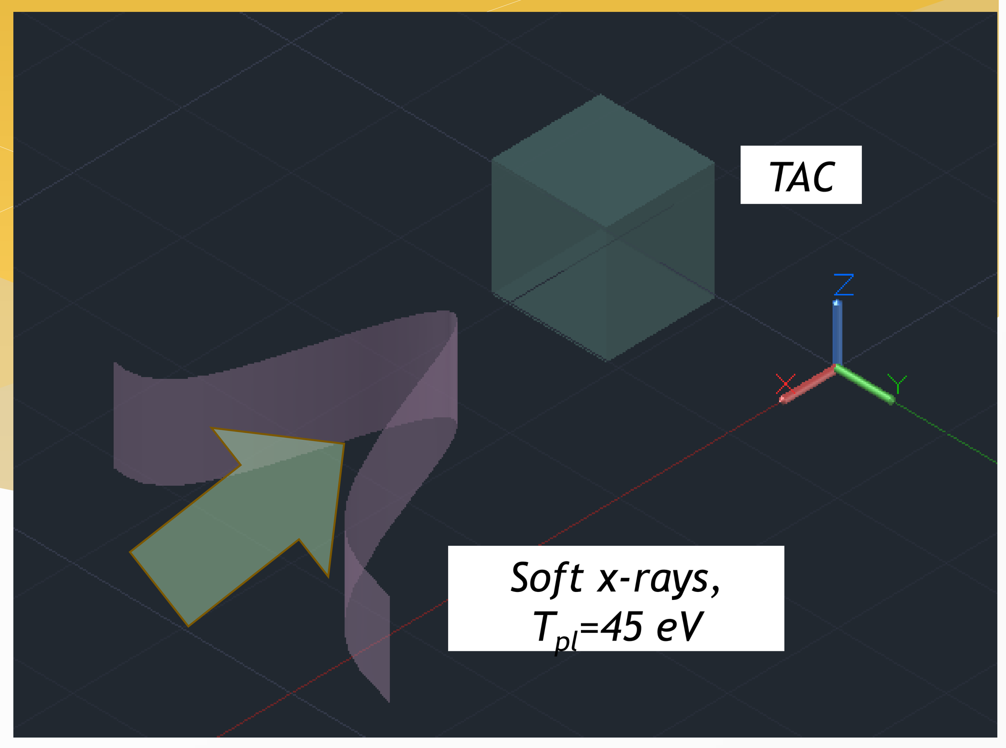
1. Polymer (plastic) aerogel target
2. SEM image of polymer aerogel
3. SEM image of *Au* nano-snow
4. Metal nano-snow target
5. Silica -polymer gel with density gradient growth
6. Multilayered aerogel targets



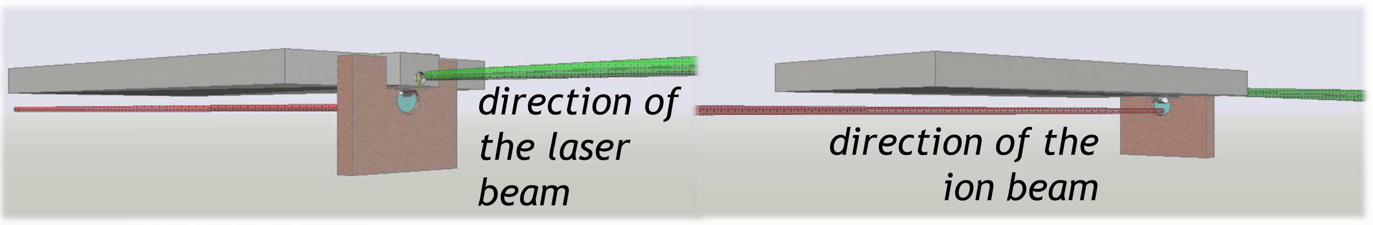


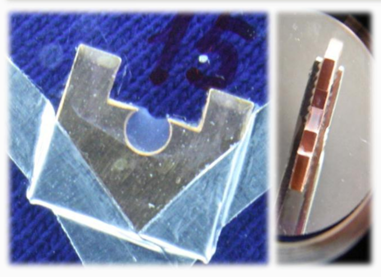


The TAC foam was irradiated with soft x-rays from the *Au* hohlraum. The incoming energy from the PHELIX laser system was converted with 80% efficiency into Planckian-like spectrum with T_{pl}=45 eV **[5]**. The laser pulse parameters were 150 J within 1 ns, which means up to 120 J of the blackbody internal energy.

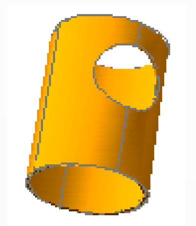


Combination experiments on PHELIX laser together with UNILAC heavy ion beam in GSI (2011-2012) showed unpredicted results. On early times of aerogel irradiation, a decrease of ion stopping power of the target in comparison with ion stopping in cold target was observed. Further increase of ion stopping power occurs due to ion scattering on plasma hot free electrons. **[3 - 6]**

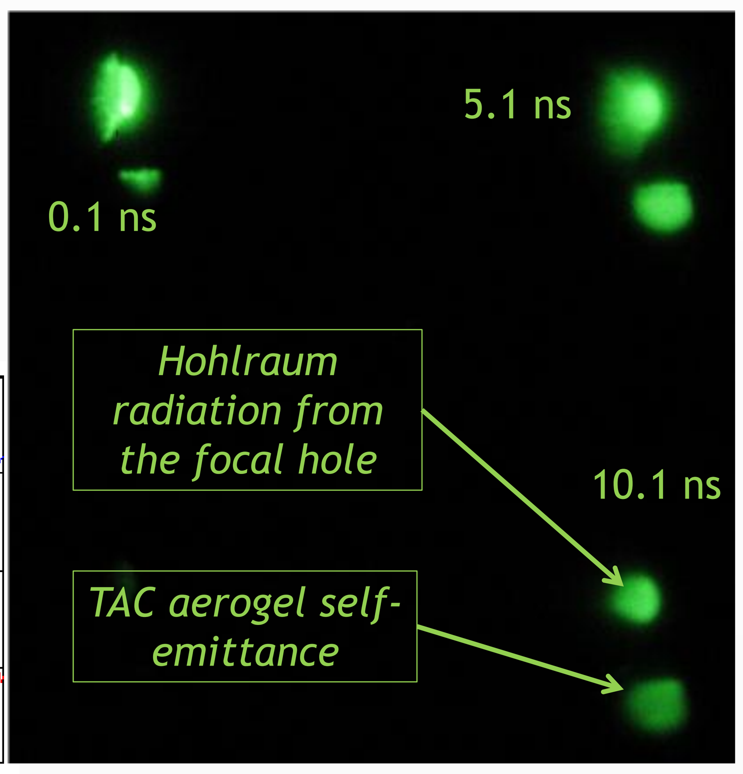


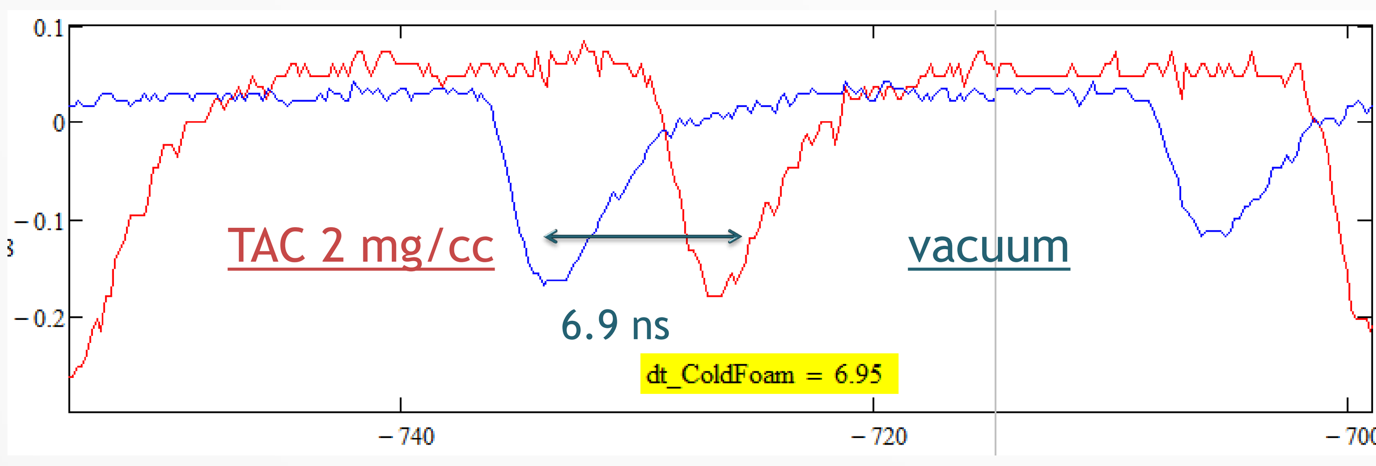


2 mg/cc TAC aerogel



Hohlraum (Au 12.5 mkm).





$$(1)\ u(\omega,T)=\frac{1}{\pi^2c^3}\frac{\hbar\omega^3}{\exp\left({}^{\hbar\omega}/_{kT}\right)-1}\qquad w(T)=\int_0^\infty u(\omega,T)d\omega=\frac{\pi^2(kT)^4}{(\hbar c)^3}\approx$$
$$\approx \mathbf{5.3\cdot 10^{21}}\ {}^{\boldsymbol{eV}}/_{\boldsymbol{cm^3}}$$

A blackbody with fixed internal energy will cool, irradiating by Stefan-Boltzman law:

$$(2)\ -\frac{dW}{dt}=s\cdot\sigma T^4\qquad W=aT^4\cdot V=\sigma T^4\frac{4V}{c}\ (3)$$

$$(4)\ -\frac{dW}{dt}=\frac{16\sigma V}{c}T^3\frac{dT}{dt}\qquad \sigma Ts=-\frac{16\sigma V}{c}\frac{dT}{dt}\ (5)$$

$$(6)\ -\frac{dT}{T}=\frac{c}{16L}dt\qquad T=T_0\cdot\exp\left(-{}^{ct}/_{16L}\right)\ (7)$$

So the time of the source “death” may be estimated by:

$$(8)\ -\frac{dW}{dt}=\frac{c}{4L}W\qquad W=W_0\cdot\exp\left(-{}^{ct}/_{4L}\right)\ (9)$$

Here W_0 is 120 J – total blackbody energy. Now we estimate cooling time (down to 1/e of initial energy) as: $t\approx 5\cdot 10^{-9}s$, which is capable with x-ray diode data.

We consider no losses which is possible due to hohlraum construction. Energy flux is irradiated only from the bottom of the cylinder, directly onto the polymer. Within early times of x-ray – polymer interaction we can consider blackbody (hohlraum) spectra stable and temperature and irradiated energy constant because of rather slow thermal changes.

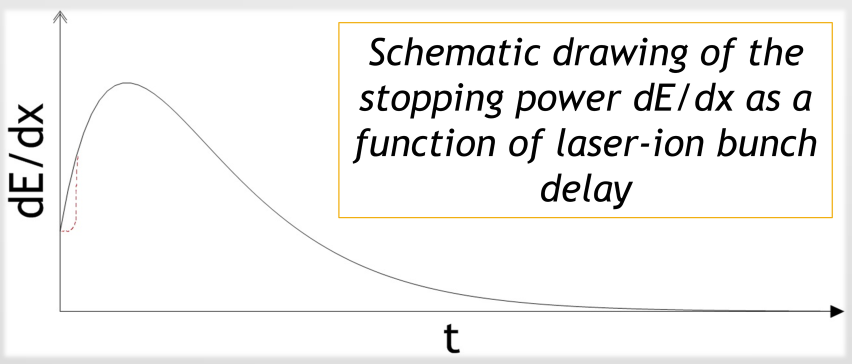
$$(10)\ E_{Pl}=\frac{c}{4}w\cdot s\cdot t\approx 10^{20}t\ [eV],\qquad t \text{ in } [ns]$$

In GSI TAC polymer aerogels of 2-3 mg/cc density were used. Such densities lead to subcritical electron densities in plasma, so we may consider the substance transparent. TAC is chemically written as $[C_{12}H_{16}O_8]_n$, with average element mass 8 a.u. Each monomer has 38 molecular bonds, several of which are double. Average bond strength in such polymer is 130-200 kcal/mol which means 5-8 eV per atom. Now we can recalculate density (2 mg/cc) of the initial target into bonds “concentration” and estimate energy and time for molecular structure dissolving:

$$(11)\ \rho=\frac{M}{V}=\frac{m_{av}N_{bond}}{V}\qquad n_{bond}=\frac{N_{bond}}{V}=\frac{\rho}{m_{av}}\approx 1.3\cdot 10^{20}[1/cc]\qquad (12)\ E{\sim}n_{bond}\cdot\varepsilon_{av}\cdot V\approx 2\cdot 10^{19}[eV]$$

Comparing E from (12) with source energy E_{Pl} from (10), we get $t\approx 2\cdot 10^{-1}[ns]$ – lower-bound for time period for molecules dissolution in the 2 mg/cc TAC polymer target. Strong back scattering of the laser beam energy to the focal hole and extremely energetic (up tp 800 eV) γ-photons emitted into the foam during the laser pulse duration are negligible for TAC ionization process. Weak Planckian-like radiation onto the aerogel compensate neglected energy losses from the hohlraum. As a result we may have visible ion stopping decrease within around 1-2 nanoseconds after laser beam arrival on the hohlraum. This effect may be explained by different ion-scattering mechanisms in plasma and in solid structures. Initial aerogel structure is stable and complicated and is formed with molecular, Van der Waals and hydrogen bonds. So as the target temperature rises, polarization interaction with the whole structure is replaced with scattering on plasma free electrons. Polarization interaction force decreases with structure mobility increase.

Ion scattering on non-structured carbon and hydrogen plasma targets was reported in [7,8]. The single-track interaction model is valid there and energy losses predictably increase together with electron density. Cross-section simulations or experiments for diatomic molecular ions are to be performed further (ex: *C*=*C*, *C*-*O*).



Schematic drawing of the stopping power dE/dx as a function of laser-ion bunch delay

Conclusions

The indirect irradiation of polymer aerogels by PHELIX laser beam converted into soft x-rays provides milder conditions for target polymer transition into plasma. Primary atomic physics estimations show that times and energies for such transition are capable to produce the bunch shift. Continuous probing of the target by high-energy bunch-structured ion beam is considered, so on the early times of interaction the complex transient disintegration process is not over. Further studies and strict calculations are needed to include spatial structure influence and the main transient process into the model.

References:

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