Advanced Additive Manufacturing of Foams for High-Power Laser Interactions at ELI Beamlines

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RG50 Workshop, 23rd June 2023

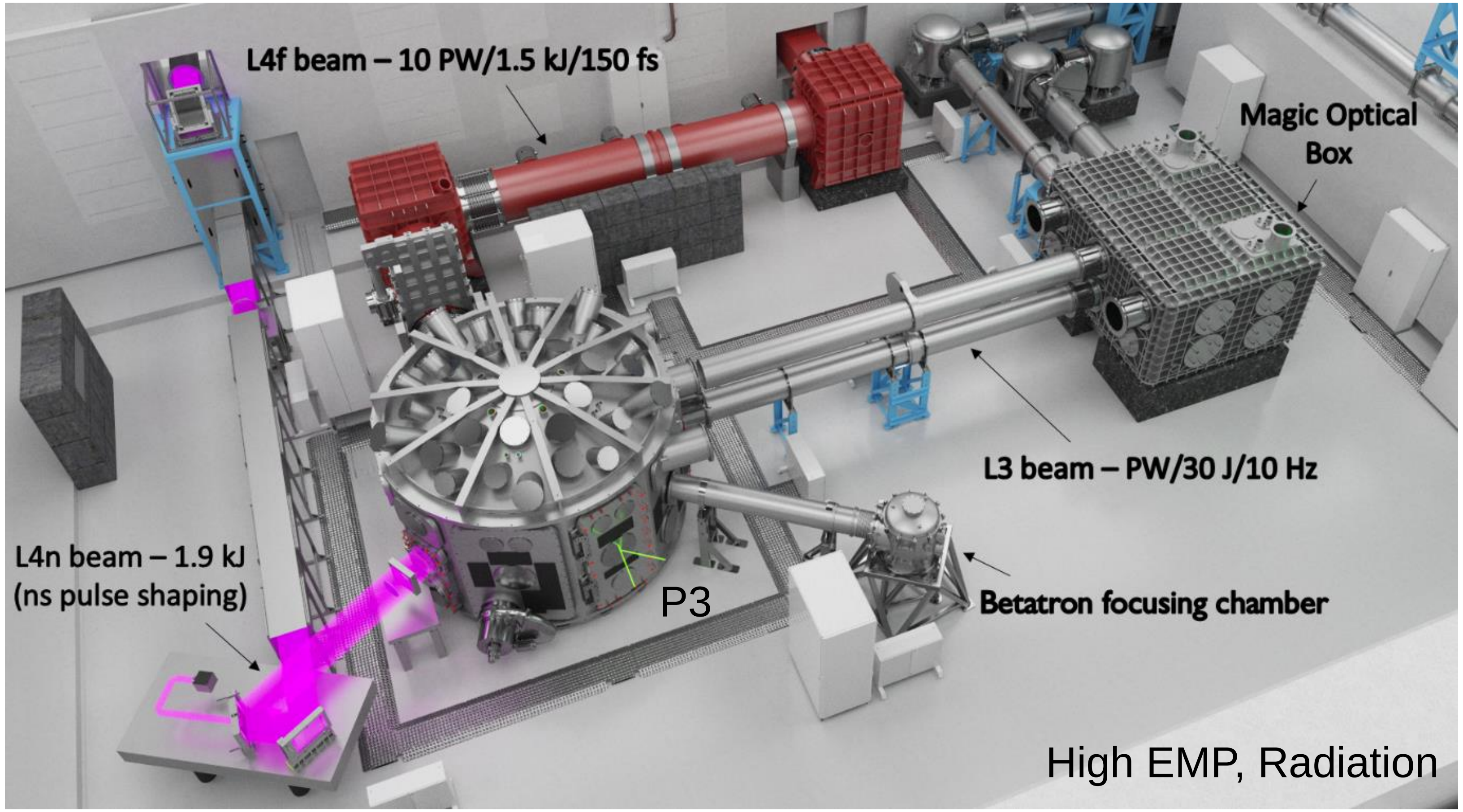
FZU Institute of Physics of the Czech Academy of Sciences
The Czech Academy of Sciences

The E3 experimental hall is aimed at the study of plasma physics and ultra-high intensity interactions

P3 = Plasma Physics Platform

It will receive high-power high-rep-rate lasers:

- L3(HAPLS) – 1PW (30J, 30fs, 10 Hz) - currently 450 TW at 3.3 Hz
- L4f(ATON) – 10PW (1.5kJ, 150fs) – 1 per 2-3 minutes, can be also used in ns configuration (L4n, currently being commissioned)
- L2(DUHA) – 80TW (2J, 25 fs, 50 Hz)



50 m^3, fast pumping/venting times if needed

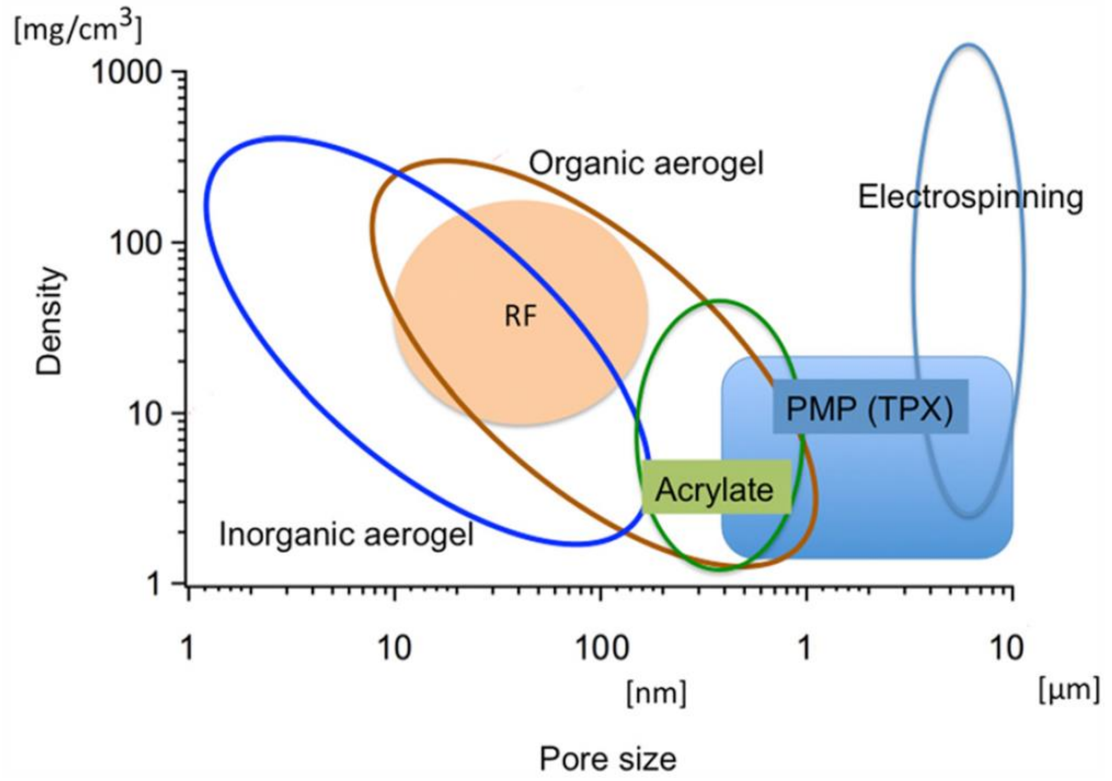
Currently mostly fusion and astrophysics research.

The P3 Experimental Platform – a tour inside the chamber

- Users can take a tour inside the experimental chamber
  - Useful for a general view of what is possible inside the chamber.
  - Centimeter precise measuring tools are also available.

https://my.matterport.com/show/?m=fkP3VjGbYyq

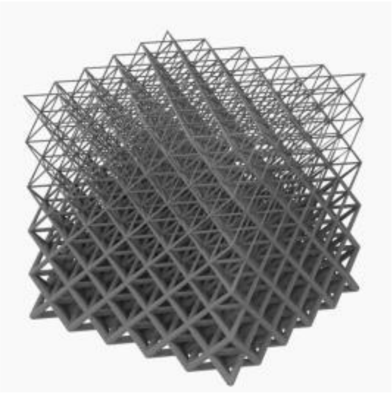
- Low density solid targets have to be inhomogeneous/porous - they have to contain spaces inside
- Various structures are possible - closed, semi-closed, open cells, (foil and fiber-like structures)
- Generally small pores are required, sub-μm scale
- Lower density → larger pores
- Polyacrylates – TMPTA $C_{15}H_{20}O_6$ by W. Nazarov
- Proprietary UV-curable photoresists for AM manufacturing
- Targets may be doped with higher Z elements, either homogeneous dispersion or clusters



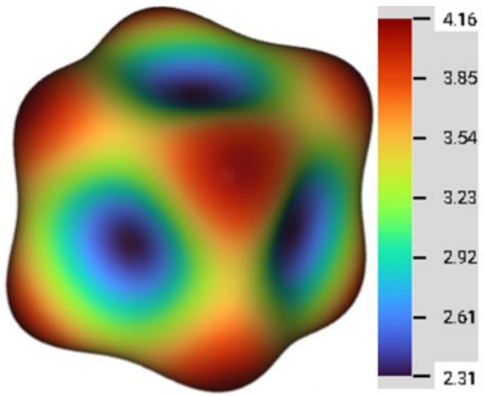
Parameters of various low density materials
K. Nagai *et al*., Phys. Plasmas **25** (2018) 030501

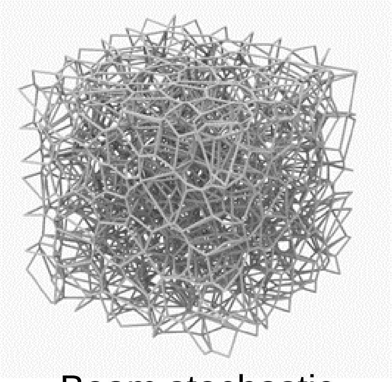
3D Additive Manufactured Targets

- Advantages
  - Full control over the structure/geometry
  - Wide range of target designs
  - Structural stability
- Various low density (~8.5 mg/cm^3) targets designed and tested for stiffness and stress
- Beam periodic octet truss selected for printing and first experiments
  - Cylindrical shape (1000 μm diameter, 600 μm depth) with a supporting but hollow frame

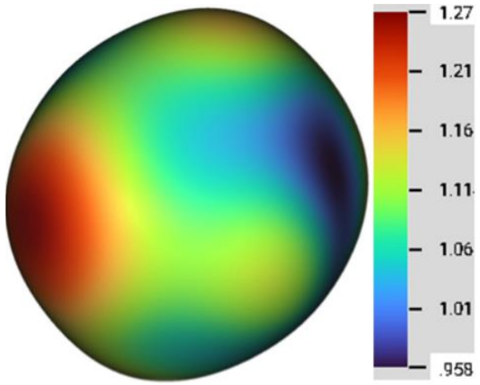


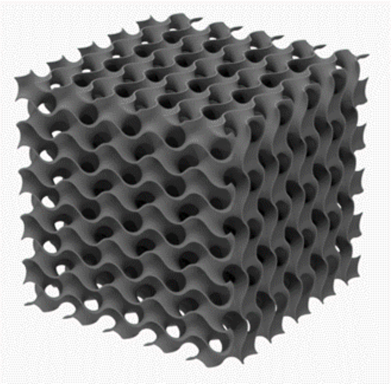
Beam periodic



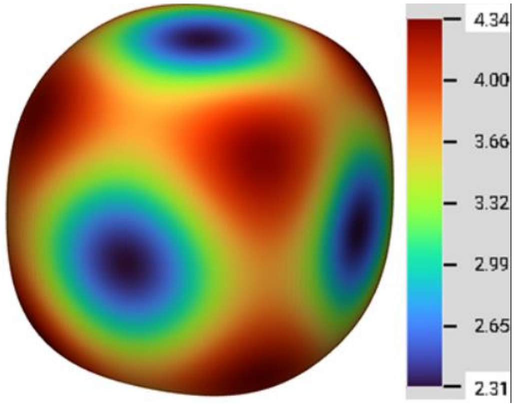


Beam stochastic





TMPS



Stiffness test results [MPa]

with T. Wiste, O. Maliuk, K. Chadt

in collaboration with Institute of Photonics and Electronics, Prague.

J. Appl. Phys. 133, 043101 (2023); doi: 10.1063/5.0121650

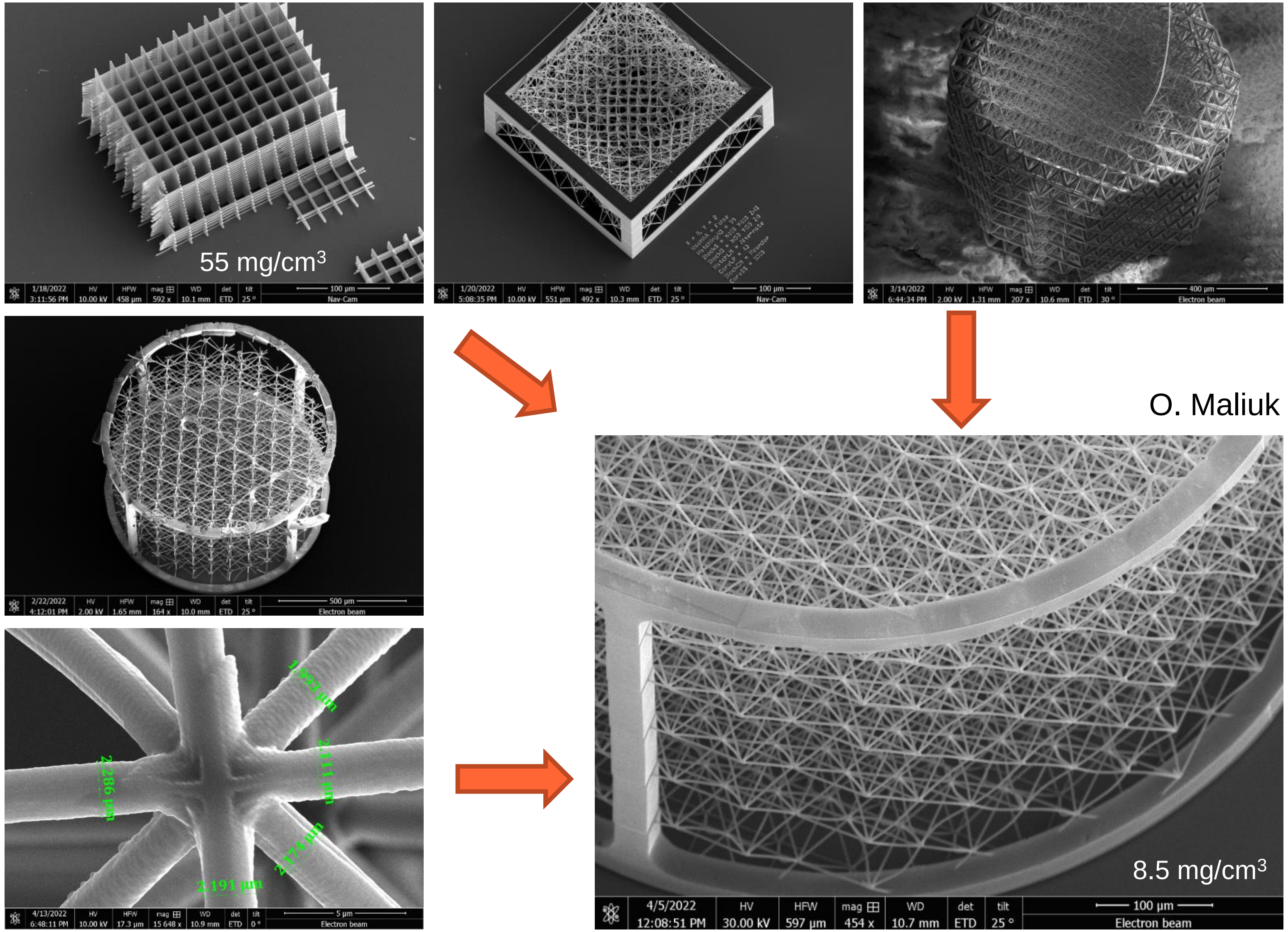
Nano-scale 3D Printer (@ UFE, Prague)

- Nanoscribe Photonic Professional GT2
  - Two-Photon Polymerization Laser Lithography (2-PP LL)
    - fs-class laser, ~MHz
  - IP-Dip2 resin (Nanoscribe GmbH)
  - 63x objective (NA 1.4, Carl Zeiss) – corresponding to approx. 200 x 200 x 600 nm^3 “ellipsoidal” building blocks
  - Dip-in-Laser Lithography (DiLL) mode
  - Block sizes were cubes with a side of 100 μm with offset of 2 μm in the horizontal plane and 3 μm in the vertical direction.
  - Aver. 25 mW power (50% of nominal) to avoid overexposure
- The new generation of Nanoscribe printers can achieve optical quality surfaces through energy variation when printing the building blocks (Quantum X, roughness R_a down to 5 nm).

O. Maliuk

In collaboration with Institute of Photonics and Electronics, Prague

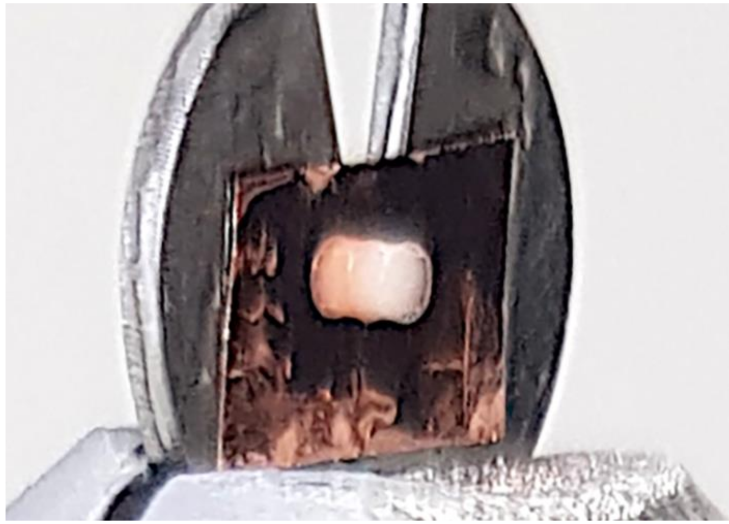
- Gaining printing know-how was the most demanding part of the fabrication process
  - complemented by optimization of structure (fillets, frames, …)
- The targets had to be directly printed on an 8 µm thick copper foil for experimental purposes.
  - Risk of resin overexposure (mitigated by printing on the less finished and more light-diffusive side of the foil, lower power)
- Print was developed in Propylene glycol methyl ether acetate (PGMEA, 30 min) then washed in IPA (60 min).
- Dry structures cured via UV-light (2 min).

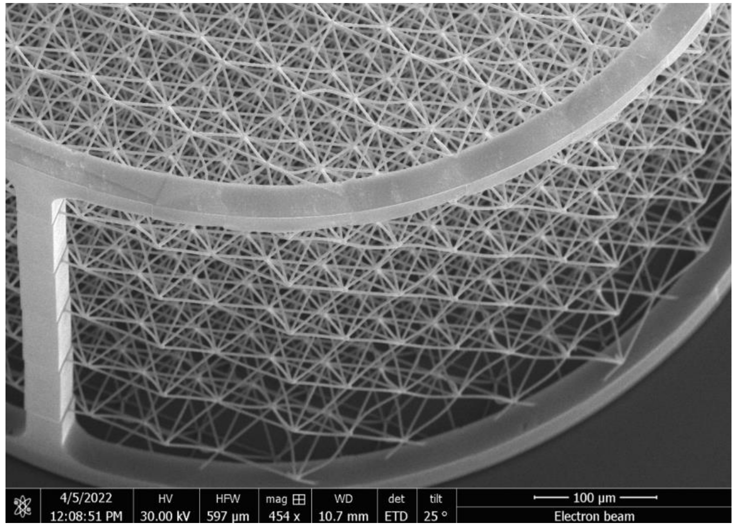


eli beamlines

Experiments at Prague Asterix Laser System (PALS)

- We used 3rd harmonics of the PALS laser (λ = 438 nm), around 180 J energy per pulse, one shot per 30 minutes
- Compared to graphene foams and TMPTA aerogels
  - critical density ~ 18 mg/cm^3, all targets used were underdense
- Diagnostics:
  - soft x-ray streak camera for measuring the velocity of ionization front propagation
  - time integrated x-ray spectroscopy for measuring electron and ion temperatures
  - hard x-ray imager for measuring Kα emission produced by hot electrons in copper

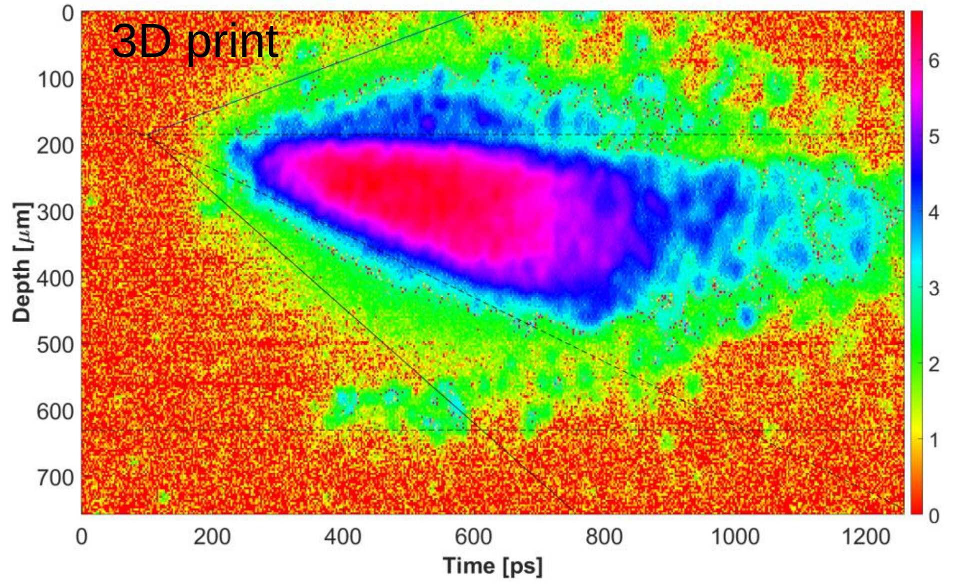




Publication in progress

X-ray streaks

- The measured **hot electron yield** was comparable to bare copper foil and much greater than for other targets. The hot electron spot was much broader than for other targets
- 3D graphene targets were used for interaction experiment for the 1st time. Due to complicated spatial structure, the **speed of ionizing heat wave** lower than in TMPTA of higher density.
- Chlorine doped plastic TMPTA aerogel was used in order to have possibility to derive ion and electron temperature from the emission spectra. The measured **ion temperatures** are approximately **3-times higher** than electron temperatures.
- For 3D printed foam the expansion is bigger and starts inside when best focus is inside the target



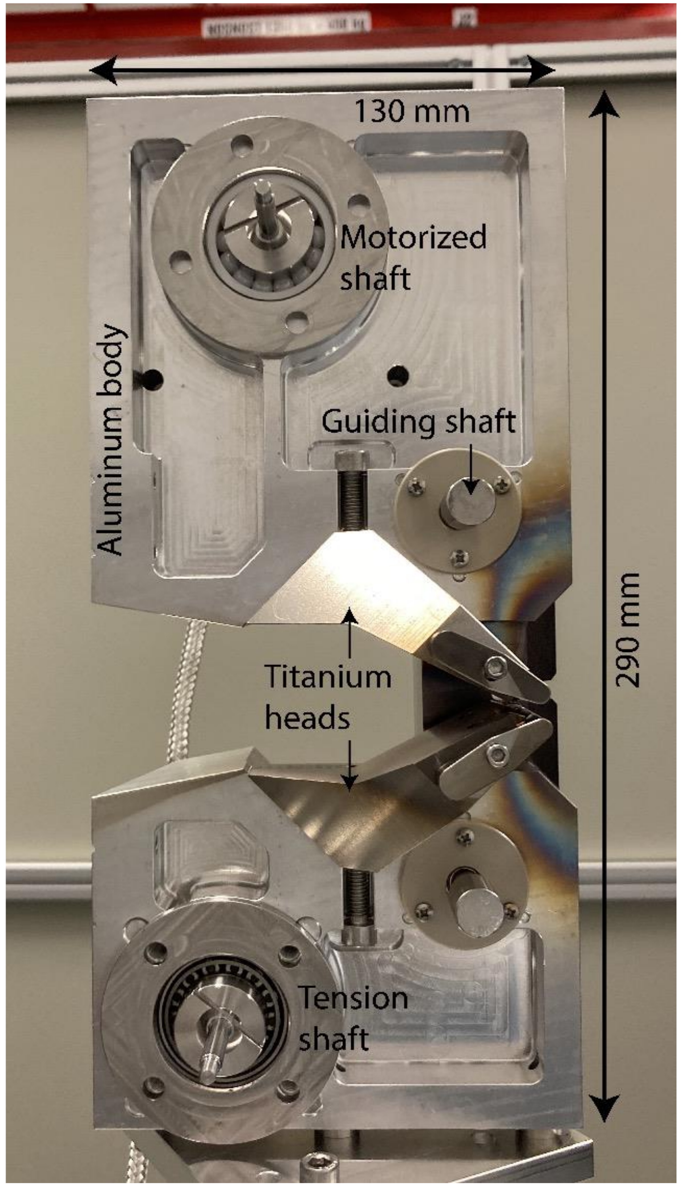
shot 489
3D-print, 180 J, 284 ps, focus on surface, max. X-ray = 765

Plotted logarithm of X-ray yield
(only photons >~ 1.5 keV get through the detection channel)

J. Limpouch @ *ECLIM2022*

Tape Target System

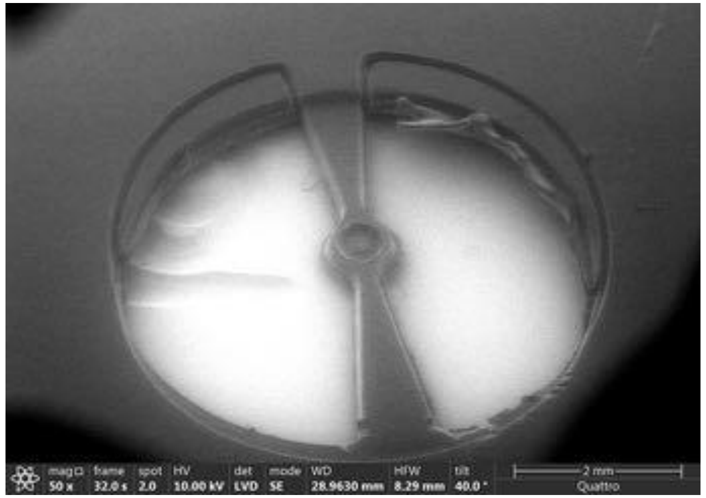
- An in-house developed tape target systems allows to shoot for several hours without the need to break the vacuum
  - A stepper motor pulls the tape from the magazine,
  - while tape tension is controlled by a magnetic brake.
    - A basic tension shaft, before an upgrade
  - Tested up to 7 cm/s in real shooting conditions
- The system can be used in both single shot and burst modes
  - In single shot mode, the stepper motor keeps tension on the target through its holding torque.



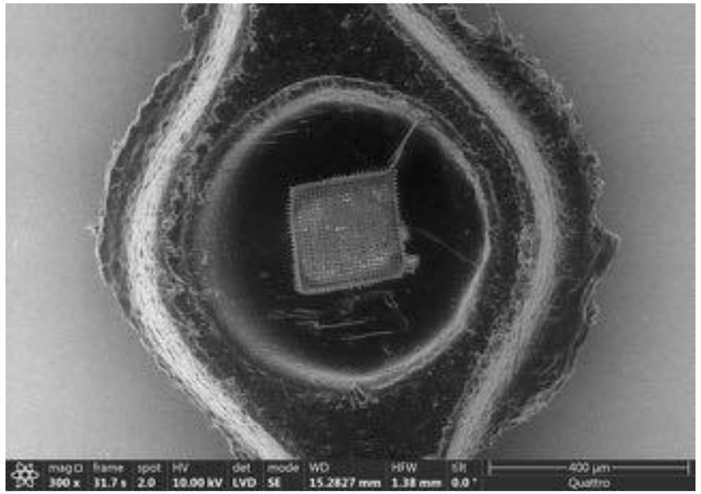
F. Condamine et al. Review of Scientific Instruments **92**, 063504 (2021)

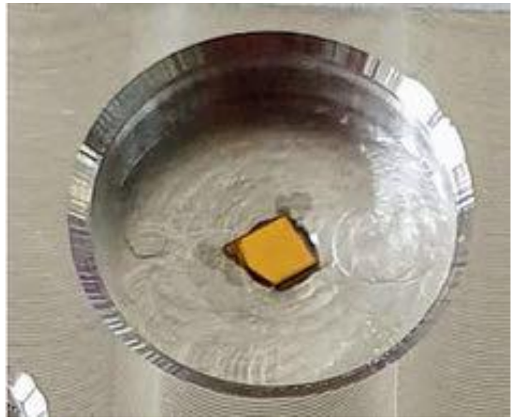
High Rep-rate Tape Target System – Future Perspectives

- Next step is to broaden our high repetition rate tape target capabilities to allow the use of sophisticated tapes
  - Such as foams, dots, multilayers etc.
- There is a couple of ways how to approach that
  - Direct 3D printing/coating onto plastic tapes
  - inserting pre-prepared targets into thick tapes
- The number of targets is large
  - We shot 1000s in bursts in a day or two
  - Others of magnitude more for continuous shooting at 10 Hz



Courtesy General Atomics, collab. with ELI BL



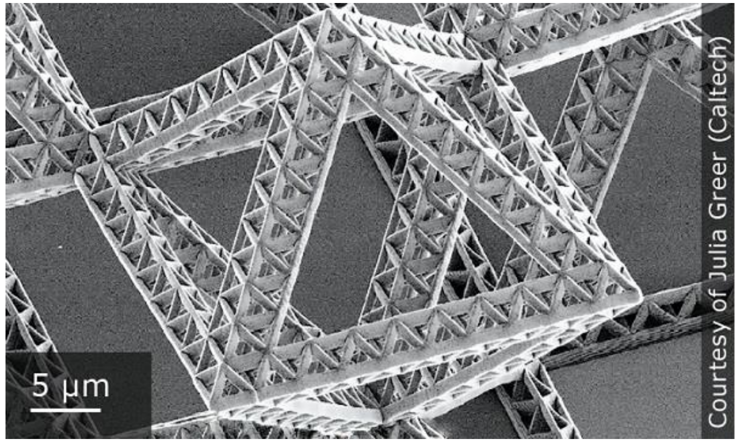


Multilayer target example

beamlines

Future Perspectives

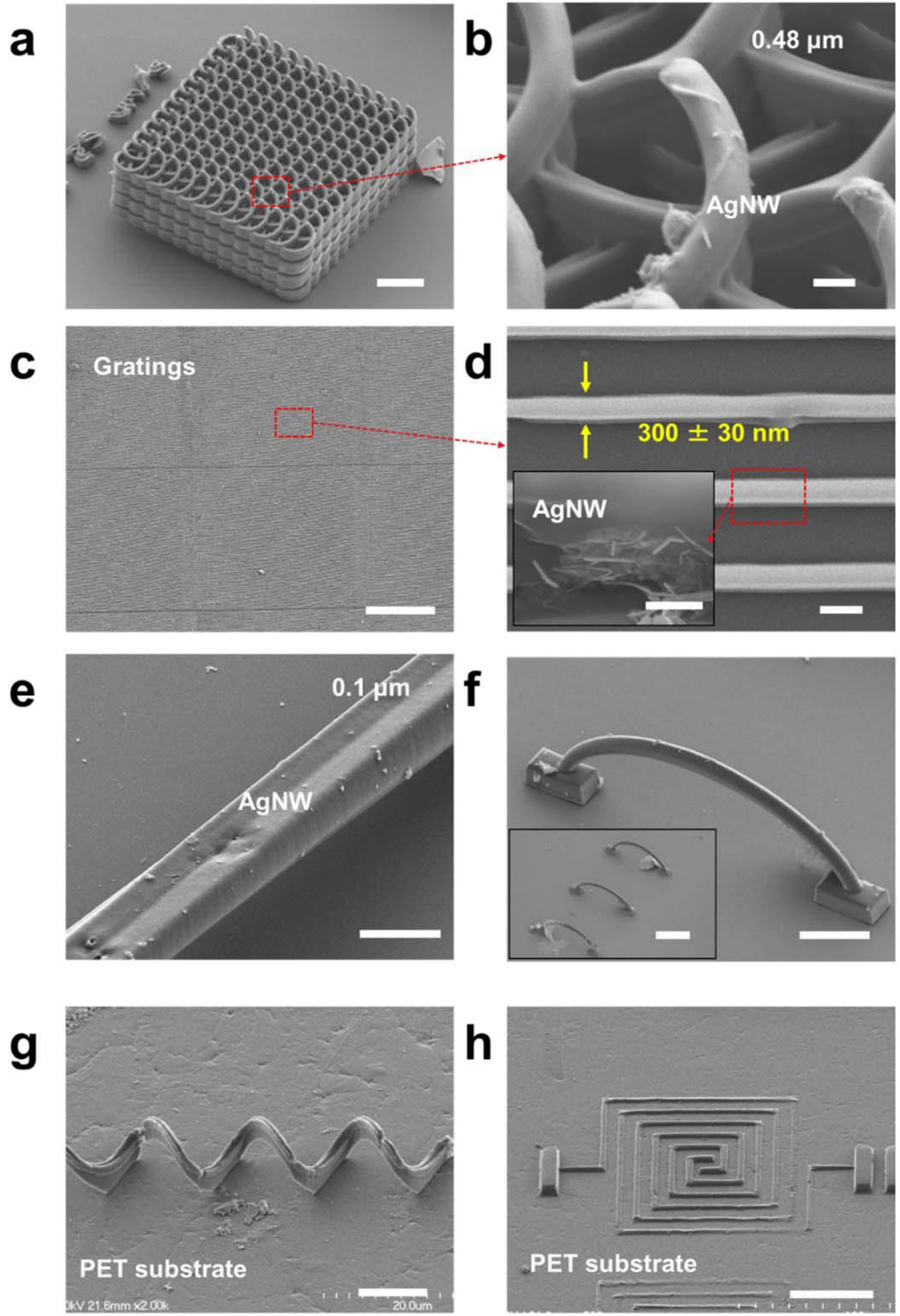
- Different geometries investigated
  - minimal surfaces (e.g. gyroid) rather than beams
  - structured beams
- Doping (e.g. chlorine, aluminum, C-nanotubes)
  - a couple of ideas on doping, chlorine in particular - not tested yet
- Adequate detailed simulations are needed
- Other than low density foams targets
  - customized targets for gamma generation
  - the new generation of printers allows for optical quality of surfaces



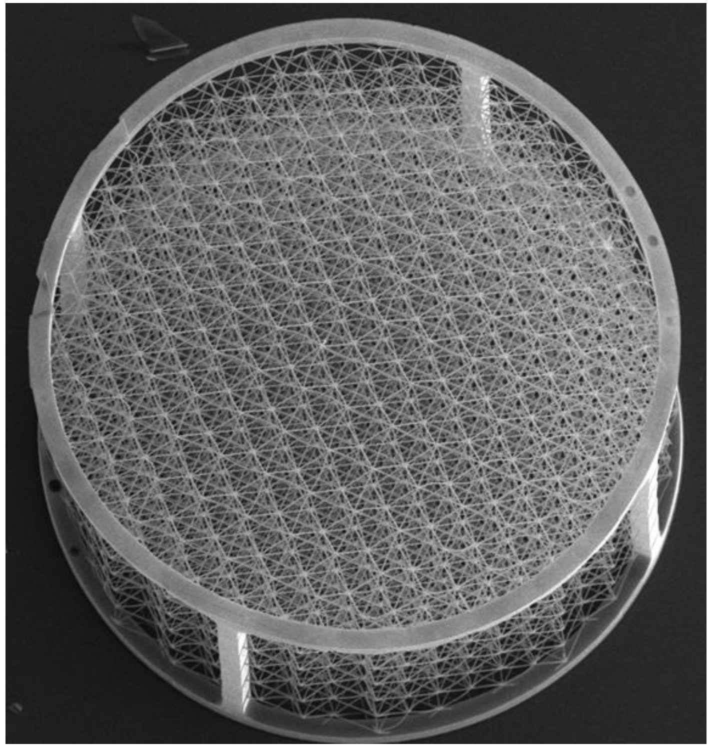
Nanoscribe Quantum X shape
Surface roughness (R_a) down to 5 nm

Carbon nanotubes (CNT)

- Conductive composite structures
- Ying Liu et al, Int. J. Extrem. Manuf. 1 (2019) 025001 (15pp) - *Precise assembly and joining of silver nanowires in three dimensions for highly conductive composite structures*



- At the P3 platform, we have developed and successfully tested AM targets (3D printed)
- There is a wide range of ideas and possible future improvements
- In-house designed high repetition rate Tape Target System was successfully tested up to 3.3 Hz and 450 TW and high mechanical stability was demonstrated
- Merging high repetition rate systems and sophisticated targets is an exciting and challenging future task



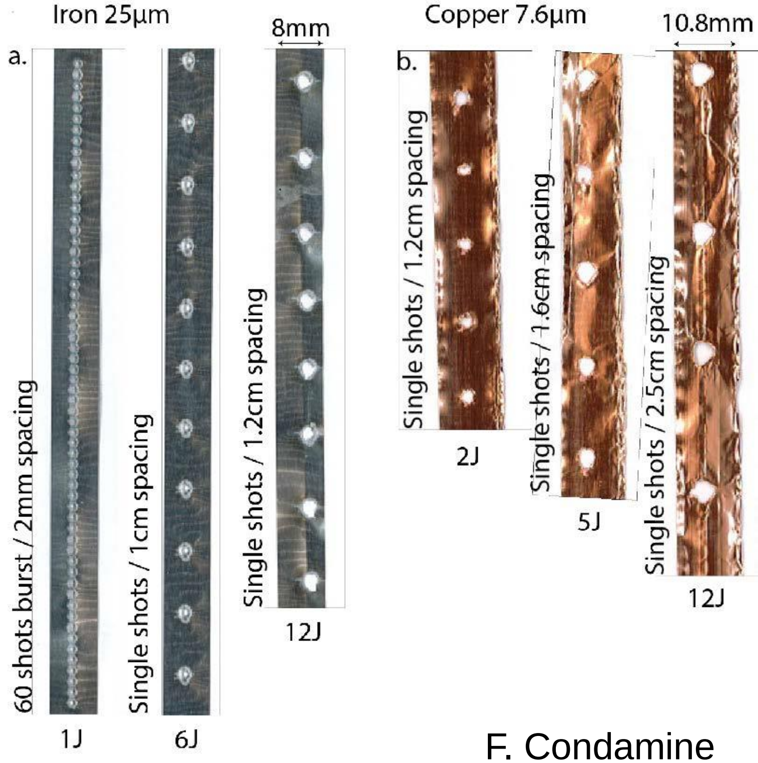
BACKUPS

- All elements at direct proximity of the interaction point are easily interchangeable
  - Two titanium heads are used to position the target
  - Designs can be customized upon a user request
- The design of the aluminum body gives a 300° angle of view for diagnostics
- Large slit at the center to shoot the laser from the rear side
  - The slit has an opening angle adapted to our f/3 OAP
  - Very convenient to place diagnostics close to the target
- A secondary slit gives view on the target from the side
  - More space to put diagnostics in the equatorial plane
  - Convenient for symmetrical diagnostics

F. Condamine at TARG5 (2021, Dresden)

Tape Target System Commissioning

- Commissioned at HAPLS (ELI BL)
  - 450 TW, 3.3 Hz or single shots, (12 J, 27 ns) @ 810 nm
  - Short focal length 75 cm, FWHM of the FS 5 µm
  - The below numbers correspond to status before HAPLS and Tape Target upgrades
- Kα yield stability 6.6 % (25 µm Fe), 10.6 % (7.6 µm Cu)
- EMP stability of 3.3 % (Fe), 4.7 % (Cu)
  - Handy tool to see also slow variations in laser-plasma stab.
- Tape stability also measured directly with a microscope
  - RMS of 8.6 µm for 15 µm Fe (before brake upgrade)
  - Significant improvement after the magnetic brake upgrade – RMS is never worse than ~4 µm, even for a narrow and thin copper tape



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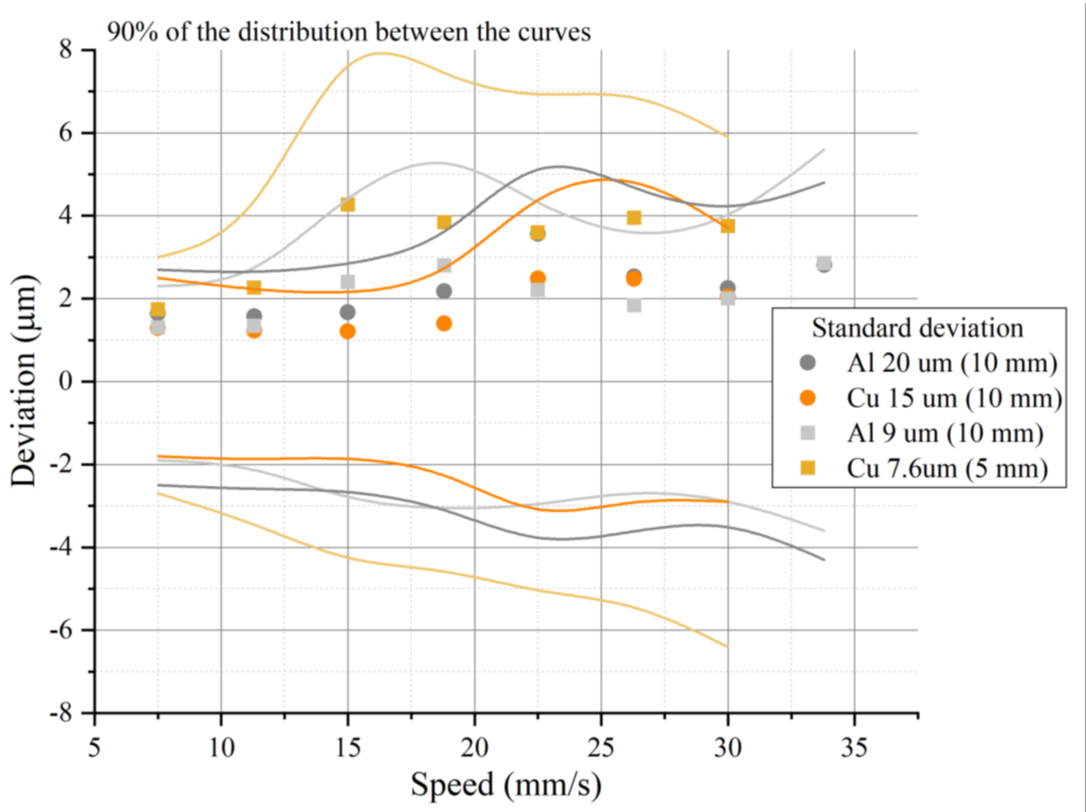

TMPTA aerogel foam structure