Advancements in double-layer target production for enhanced laser-driven ion acceleration

ERC-2014-CoG No. 647554
ENSURE

Davide Orecchia

Dresden, 26/10/2021

NanoLab

Overview

Introduction

Experimental campaigns and motivations

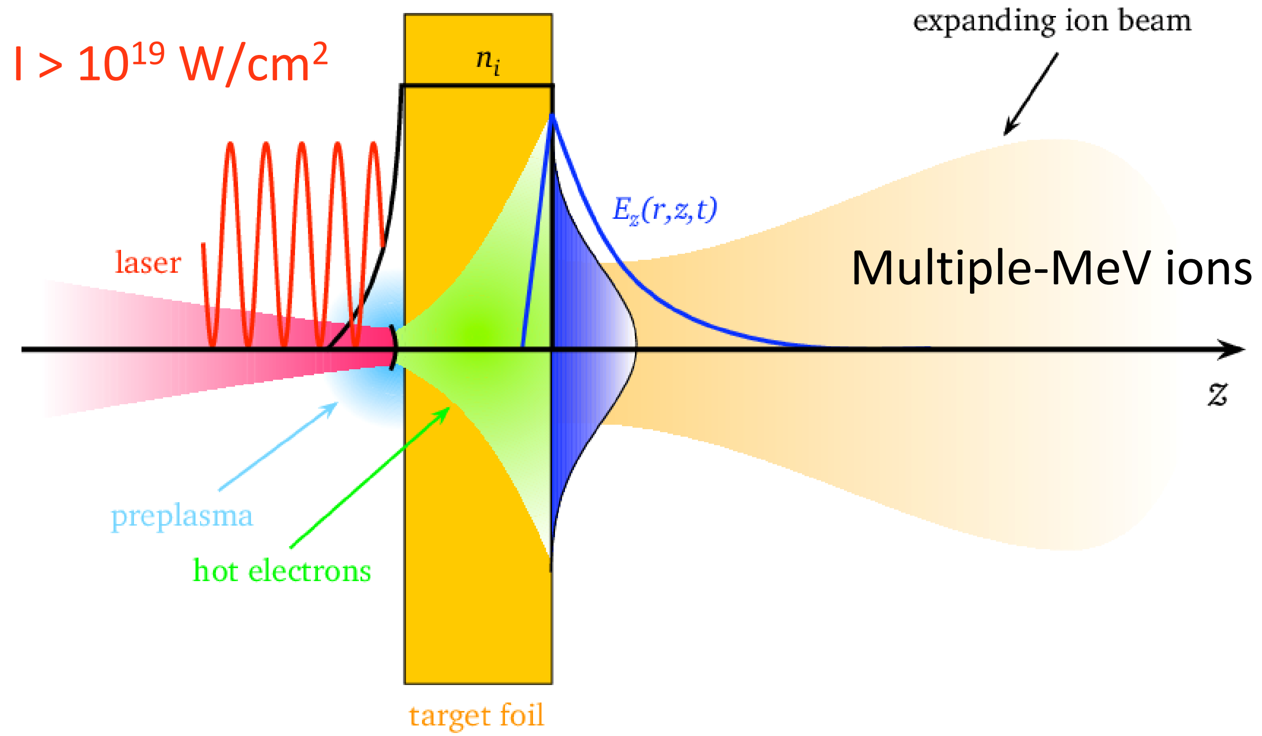
Freestanding Double Layer Target (DLT) production

Particle In Cell (PIC) simulations

Conclusion and perspectives

Laser-driven ion sources

A. Macchi et al., Reviews of Modern Physics, 85.2 (2013)



M. Roth and M. Schollmeier, CERN Yellow Reports (2016)

TNSA ⇩ Solid targets

Applications:

- Material analysis
- Medical applications and radiobiology
- Radioisotope and neutron production
- Fast ignition in inertial confinement fusion

10s TW Class Lasers

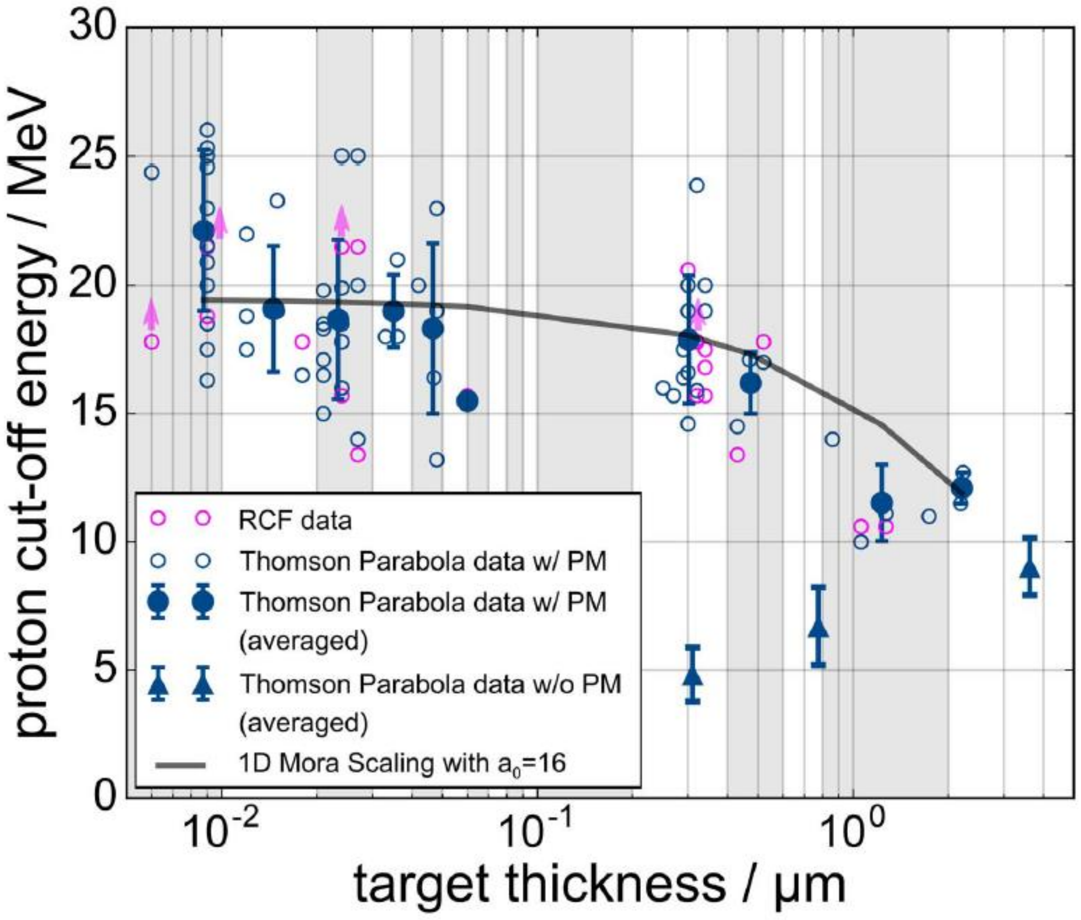
- Compact system
- High repetition rate

100s TW and PW Class Lasers

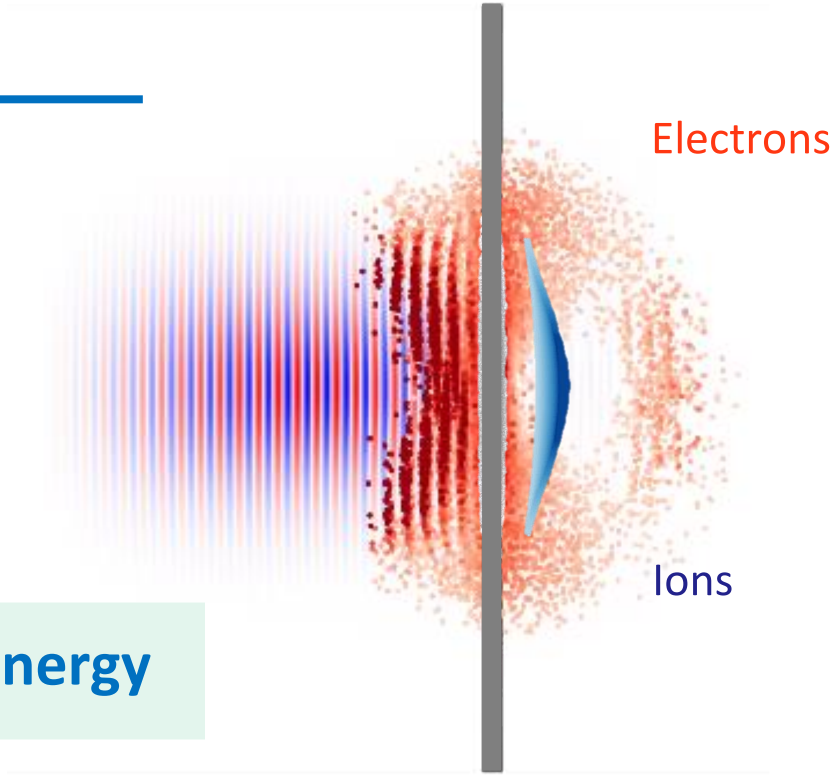
- Higher ion energies
- More ions accelerated

The target is the key

Enhanced laser-driven acceleration: thin targets



P. L. Poole et al., New Journal of Physics 20.1 (2018)

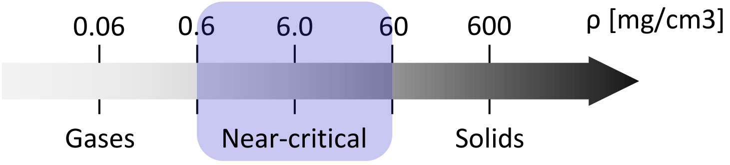


2× proton energy

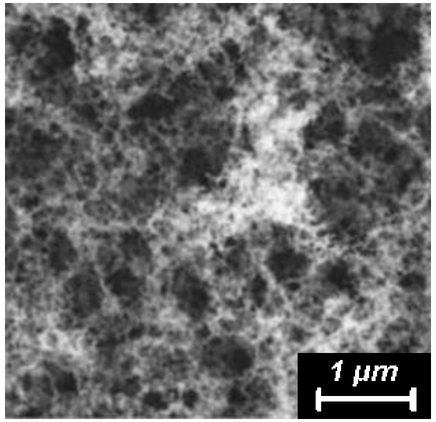
$t \sim 100s\ nm\ \div\ \mu m$

Thinner targets ⇨ Higher ion energies

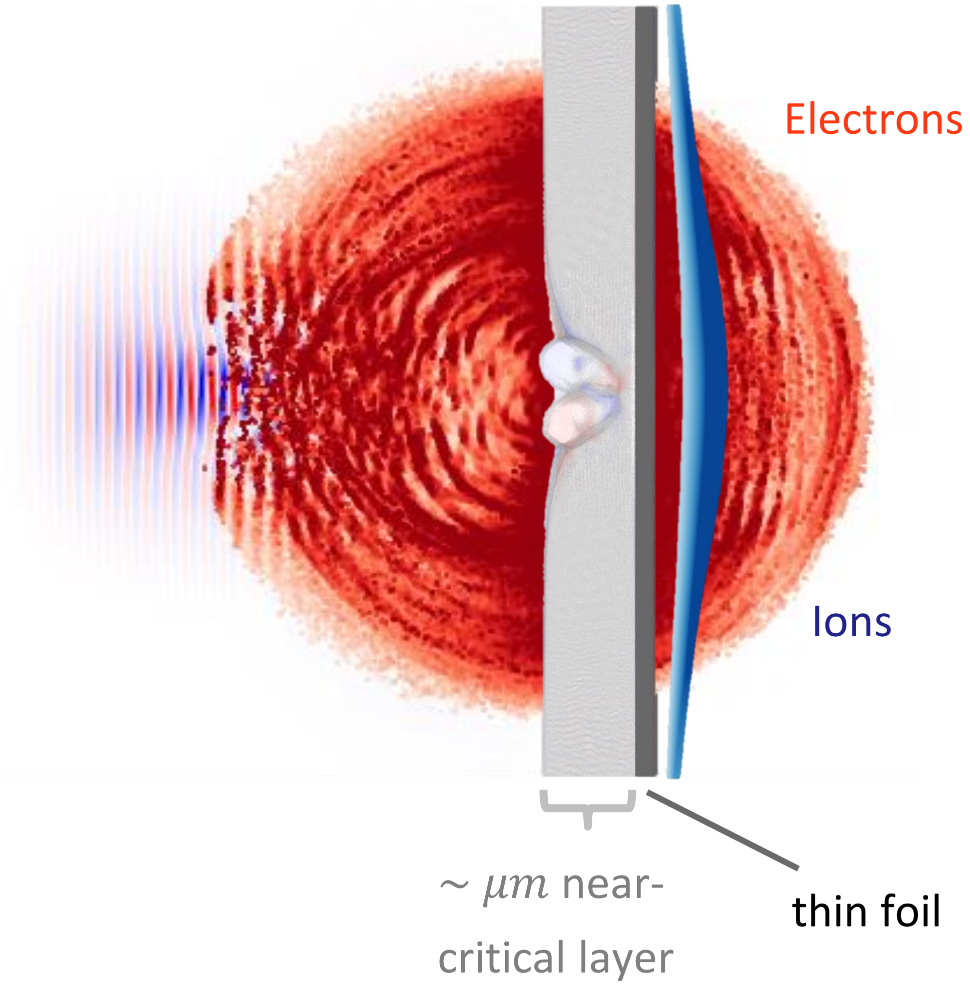
Near-critical Double Layer Targets (DLT)



Carbon foams



Enhanced laser-plasma coupling through a **near-critical layer**

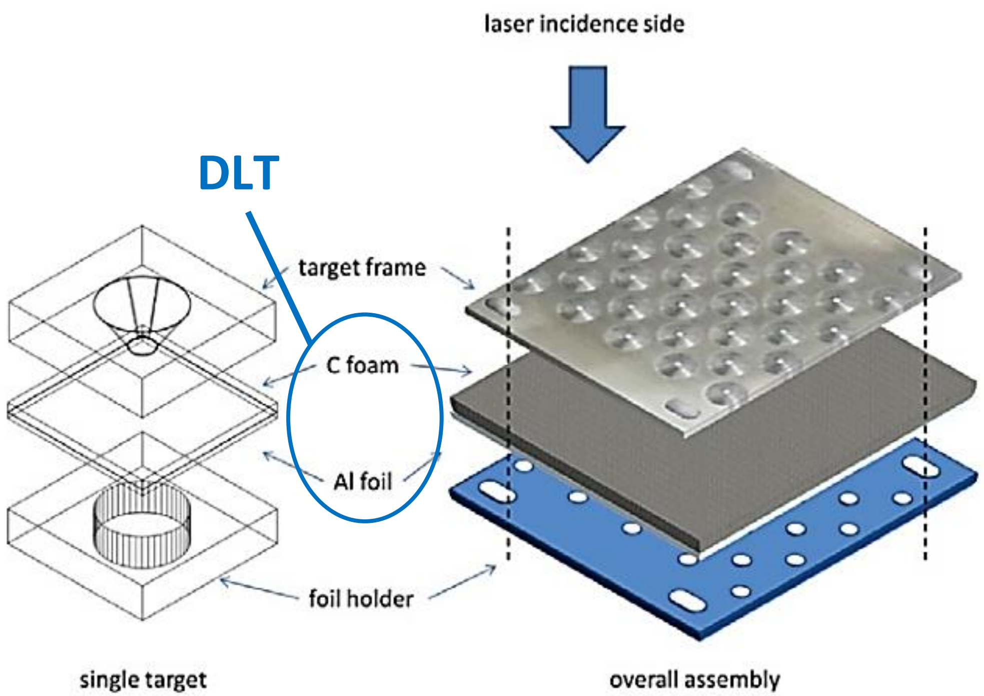


Near-critical Double Layer targets (DLT)

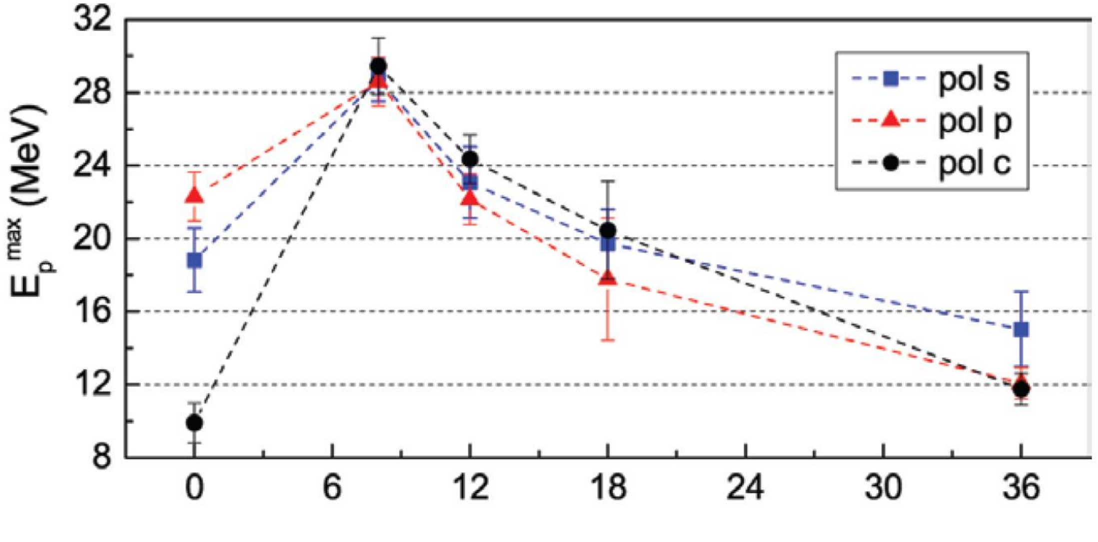
M. Passoni et al., Phys. Rev. Accel. Beams 19.6 (2016)

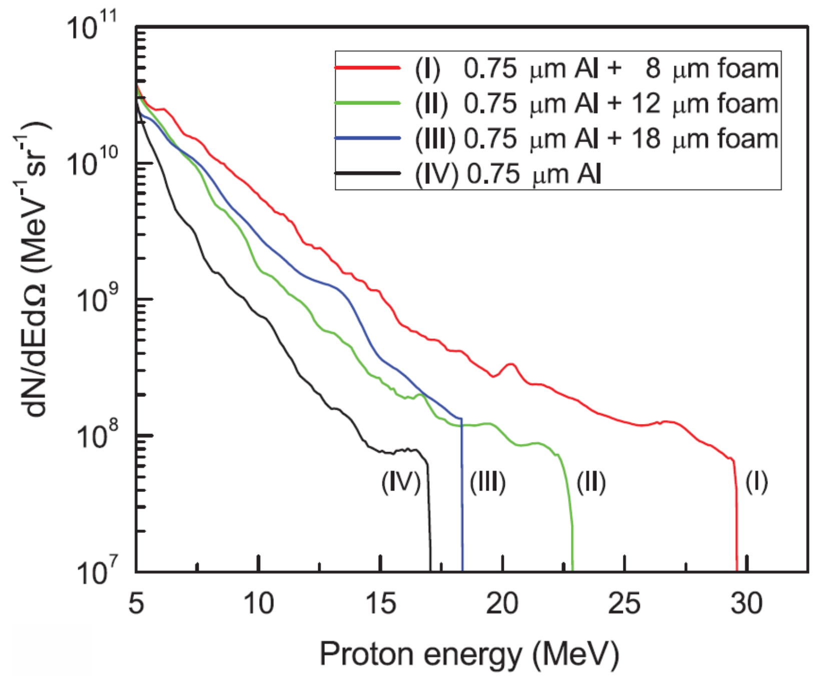
DLT experimental campaign @ CoReLS, IBS

I. Prencipe et al., Plasma Physics and Controlled Fusion 58.3 (2016)



- 100 TW class laser
- 30° incidence
- Thinner foam 8 µm

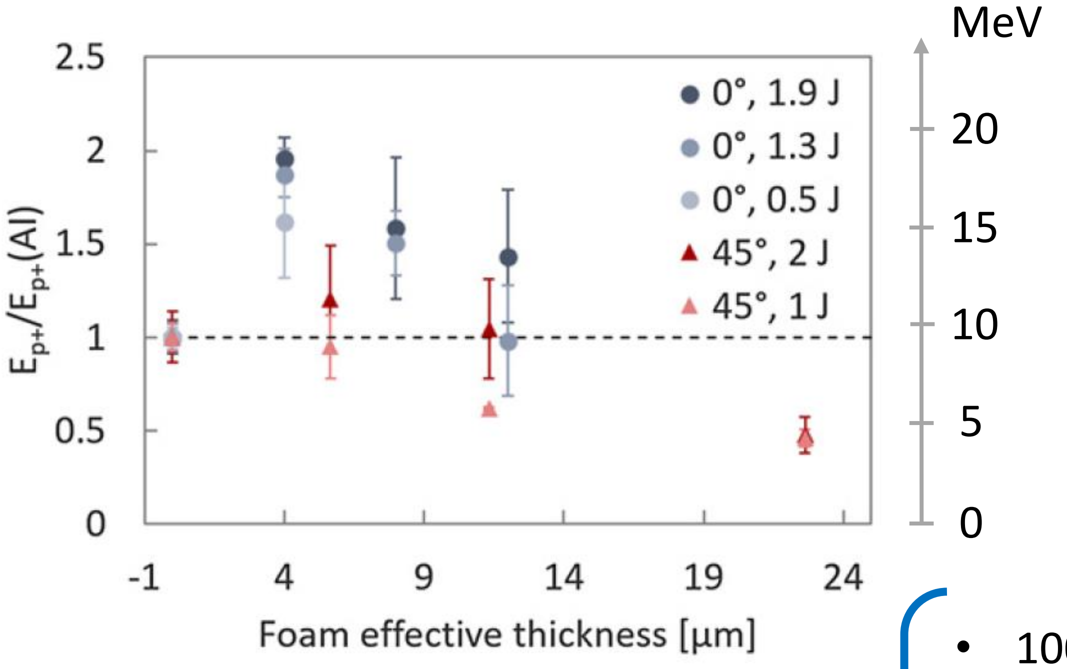


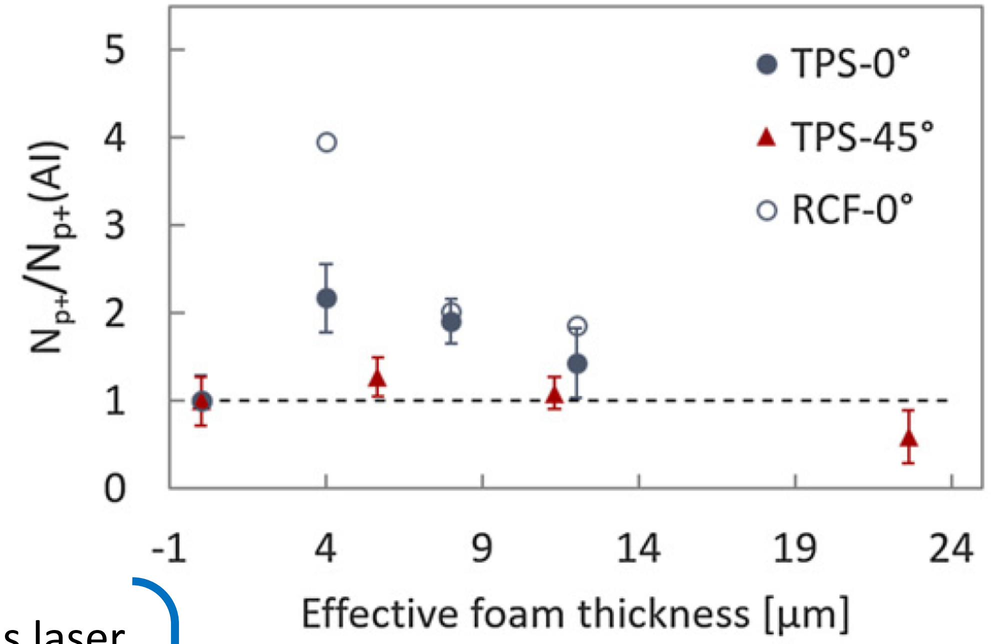


30% more energy**, polarization independent**

I. Prencipe et al., New Journal of Physics 23.9 (2021)

Effect of laser incidence and foam thickness





100% more proton energy

- 100s TW class laser
  - 0° incidence
- thinner foam 4 μm

4× proton number

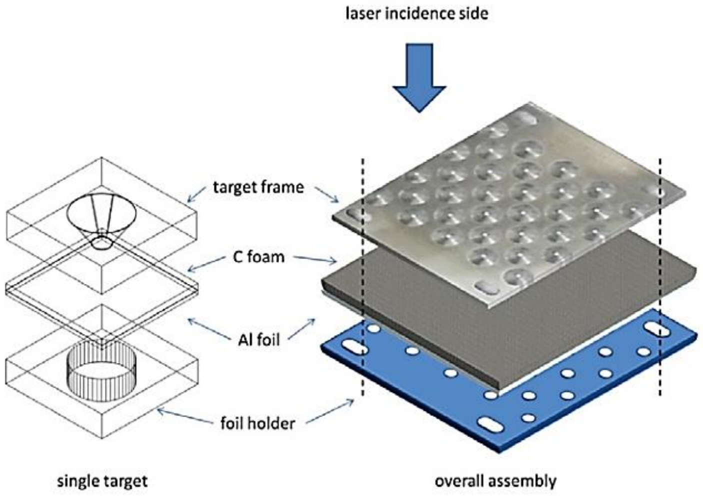
Features of the **foam layer** are **pivotal**

Targetry

The **experimental results** justify the interest in **target development**

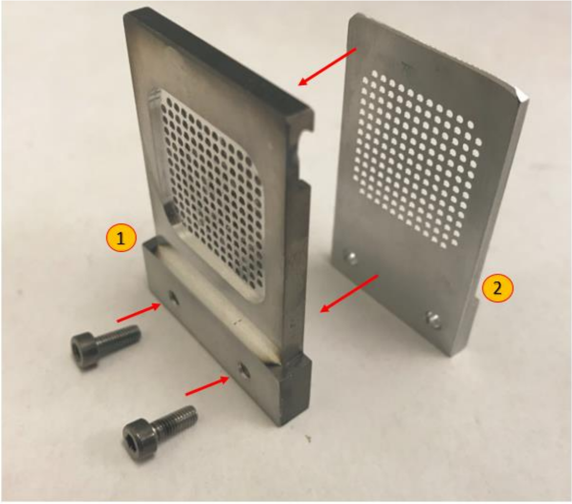
Substrate grown directly on the target holder

- Tunable thickness (100s $nm \div \mu m$)
- Thickness uniformity (light-tight)
- **High reproducibility** among holes
- Freedom in material choice



Standard substrates

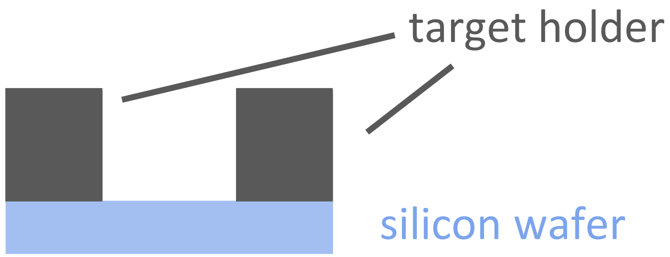
- High thickness **uncertainty** (±30%)
- Limited available thickness
- Not light-tight
- Prone to wrinkles and deformation while handling



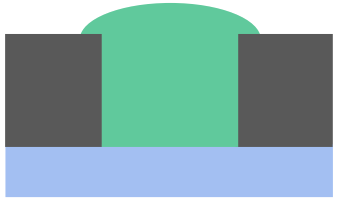
SourceLAB Laser Plasma Technologies

Freestanding DLT production

1



2



Hole filling with **sacrificial material**

3

Removal of the silicon wafer

4

Film deposition (**magnetron sputtering**)

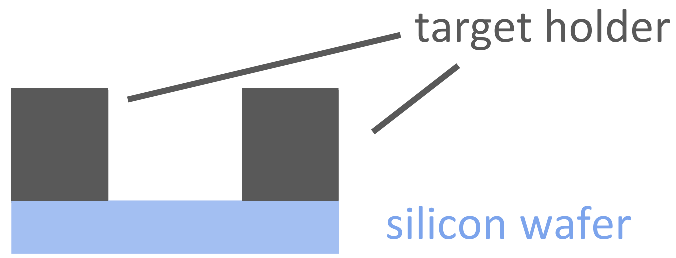
5

Removal of the filling material

6

Carbon foam deposition (**PLD**)

Holder preparation

1


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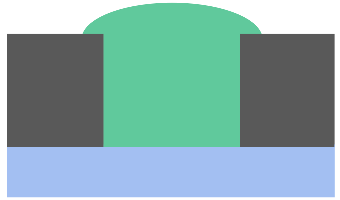

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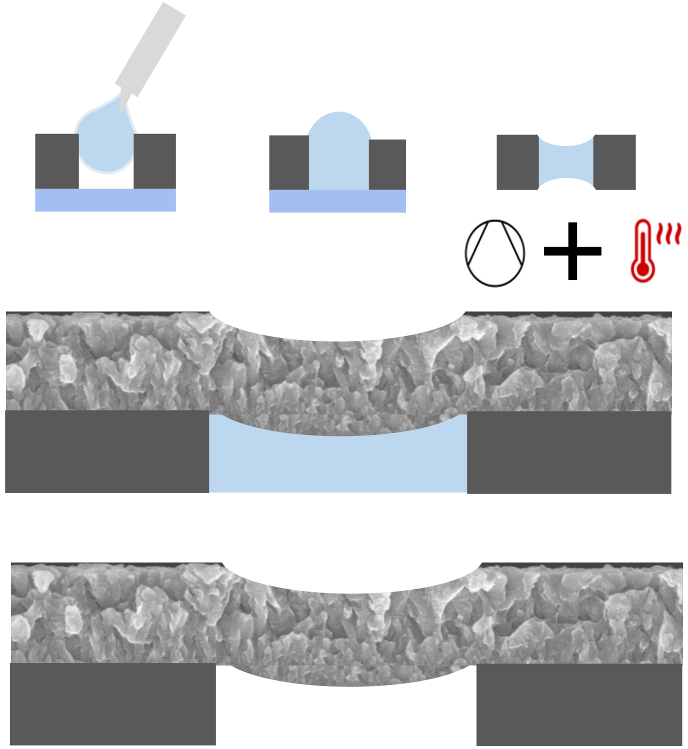
Choice of the filling material

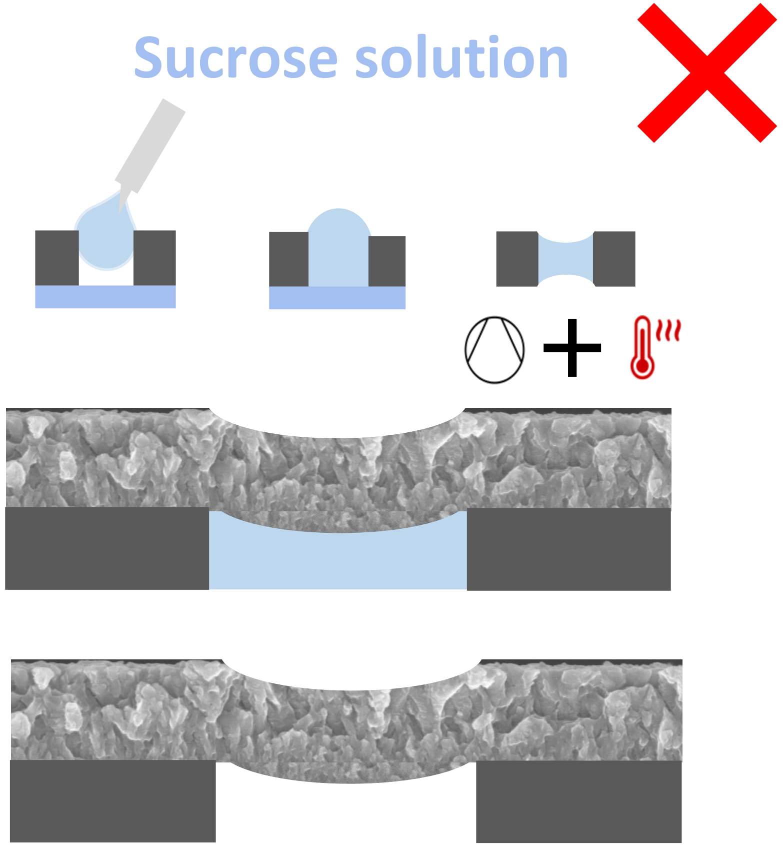
Sucrose solution



- Soluble in water ✓
- Crystalline ✗
- Shrinks during crystallization (concave surface) ✗

Choice of the filling material

Sucrose solution



- Soluble in water ✓
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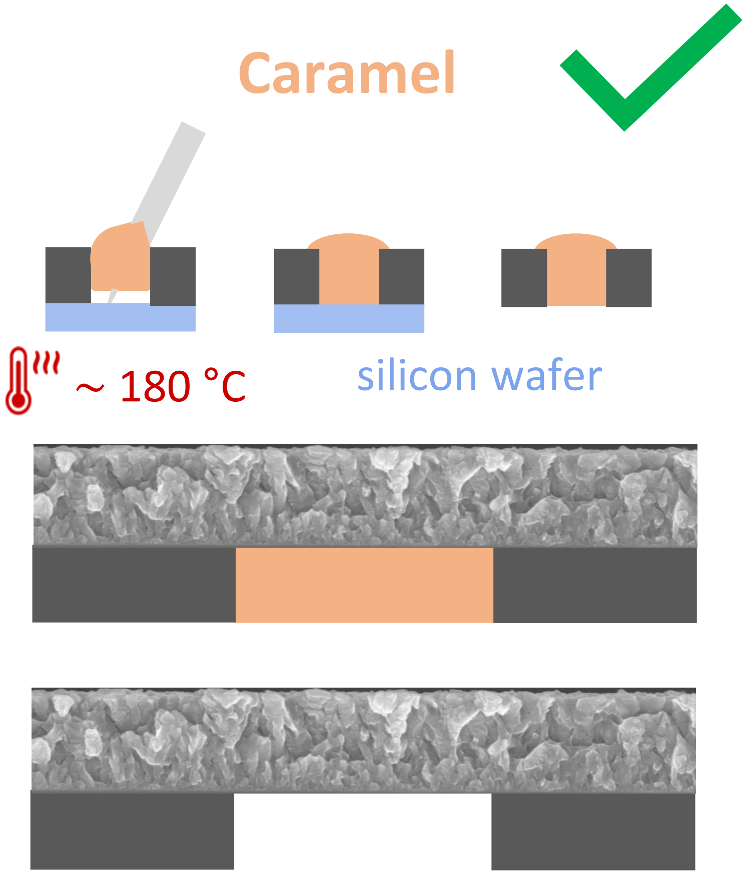
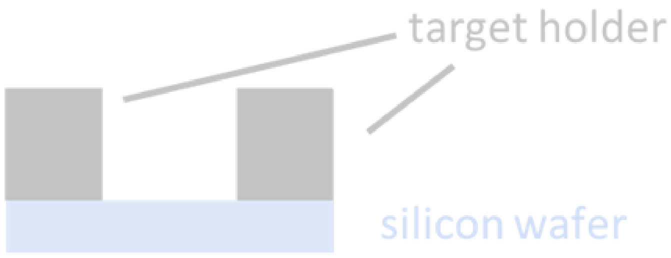
Caramel

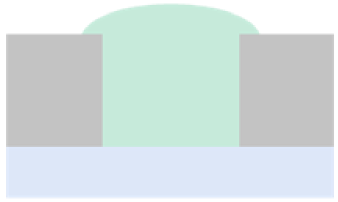


- Soluble in water ✓
- **Amorphous** ✓
- Planar uniform surface ✓

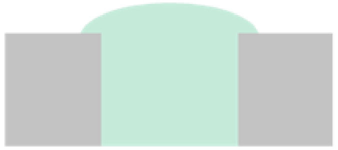
DLT substrate production



①

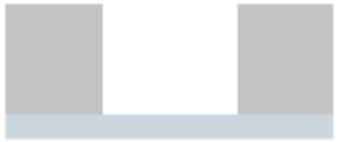


② Hole filling with **sacrificial material**

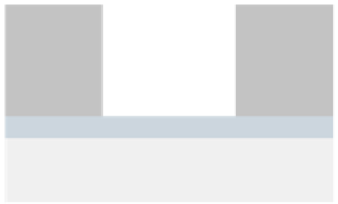


③ Removal of the silicon wafer

④ **Film** deposition (**magnetron sputtering**)

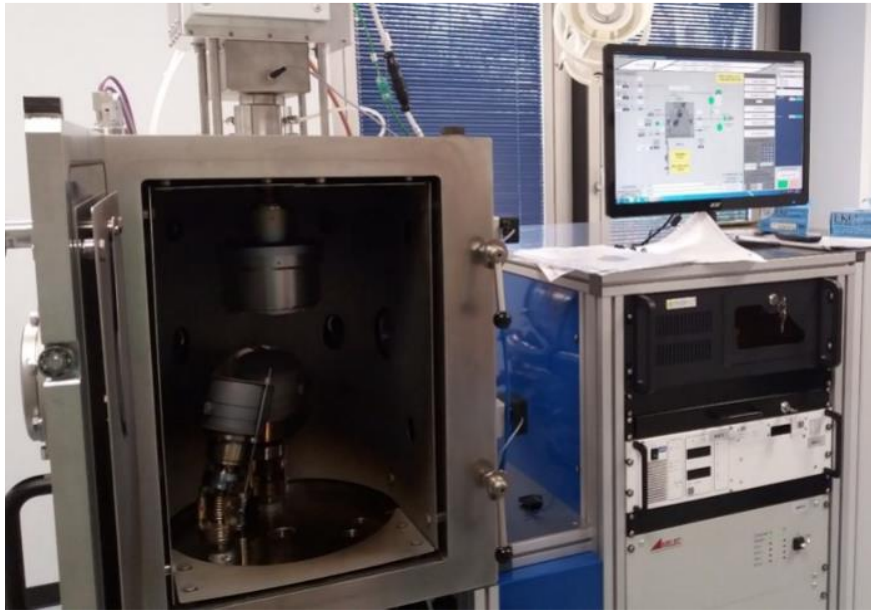


⑤ Removal of the filling material



⑥ **Carbon foam** deposition (**PLD**)

Magnetron sputtering



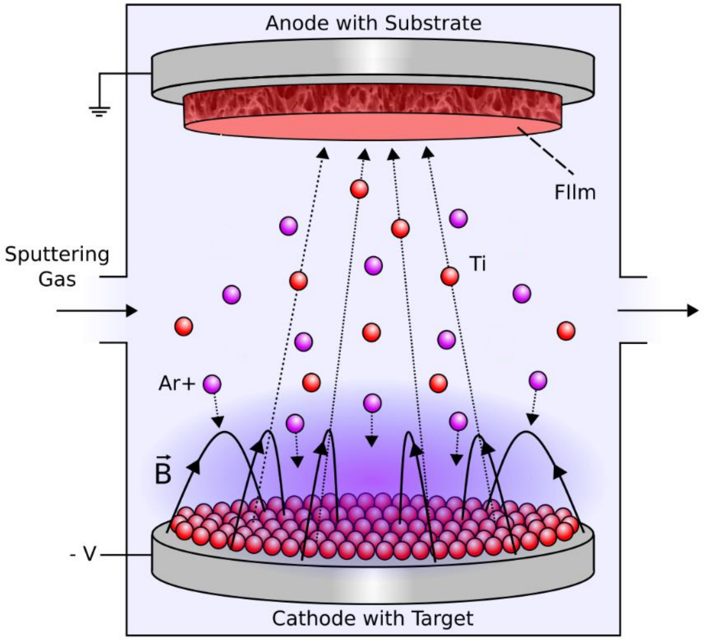
@ NanoLab

- High voltage + magnetic field
- **Uniform** deposition over large areas

DCMS

Direct Current

Magnetron Sputtering

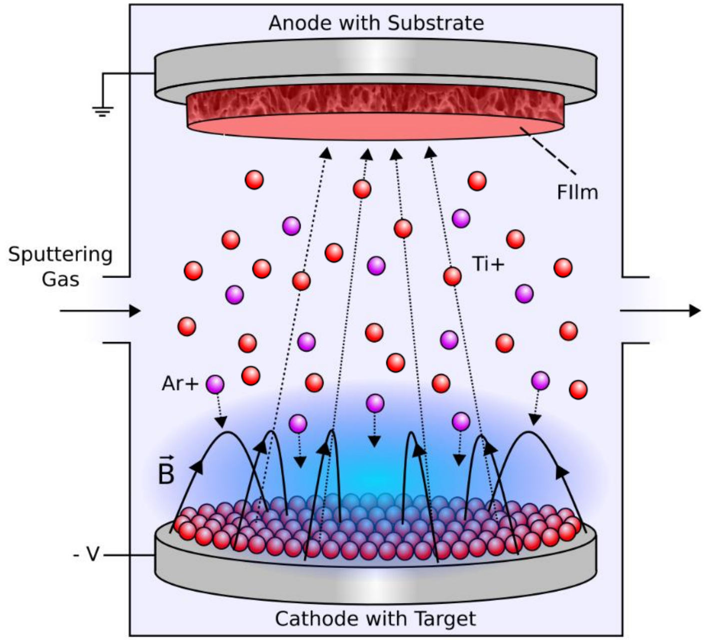


- **Well established**
- Mostly **neutral** species
- Higher deposition rate

HiPIMS

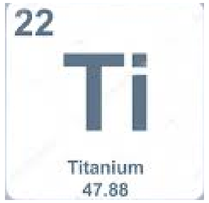
High Power Impulse

Magnetron Sputtering



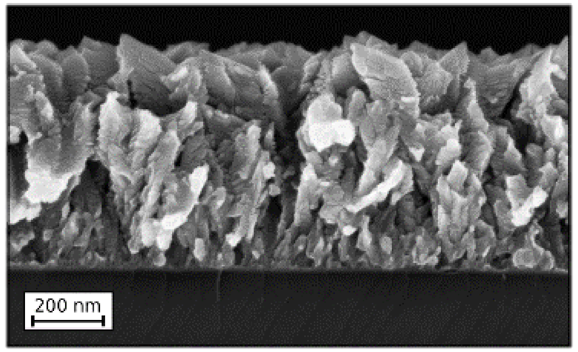
- **Ionization** fraction >50%
- Voltage bias (tunable sputtered ions energy)

Magnetron sputtering: films

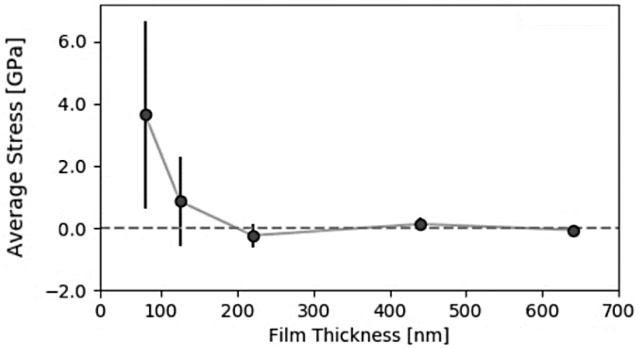


- Good physical and chemical properties
- **Established** for targetry

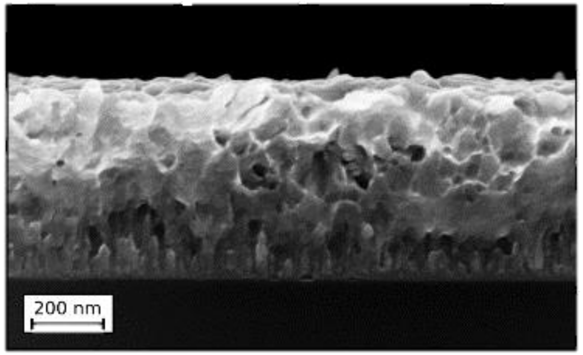
DCMS



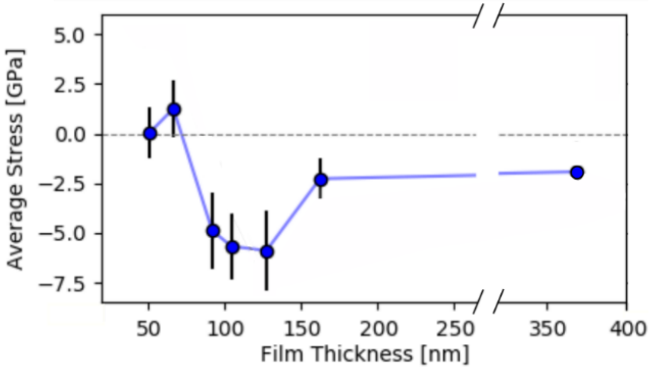
- **Columnar** growth
- Tensile stress state



HiPIMS



- **Compact** morphology
- Compressive stress state



D. Dellasega et al., Applied Surface Science 556 (2021)

Hybrid layers of DCMS and HiPIMS

Parametric study

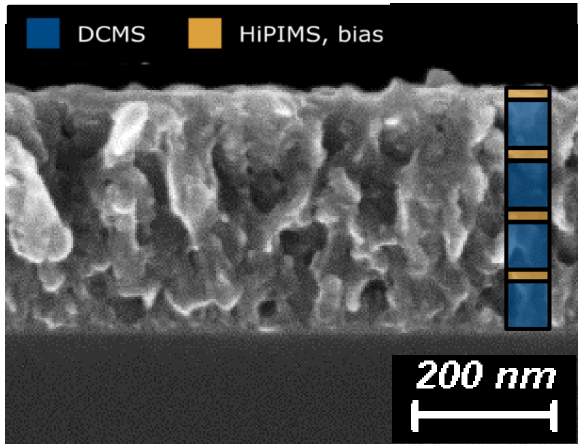
- % DCMS and HiPIMS
- Number of hybrid layers
- Voltage bias

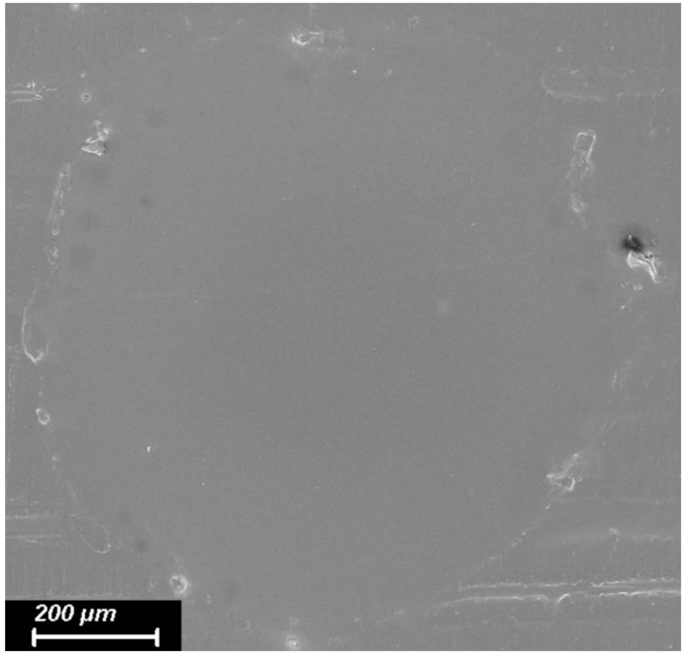
Magnetron sputtering: freestanding films

- 80% DCMS and 20% HiPIMS
- 4 hybrid layers
- 250 V bias

⇩

- $200\ nm\ \div 2\ \mu m$ thickness range
- Near-bulk density (80% or greater)
- **<5%** thickness uncertainty
- Low stress state
- **80-90%** intact freestanding films





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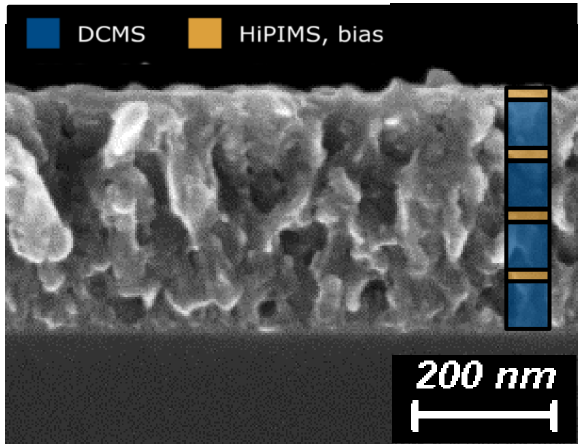

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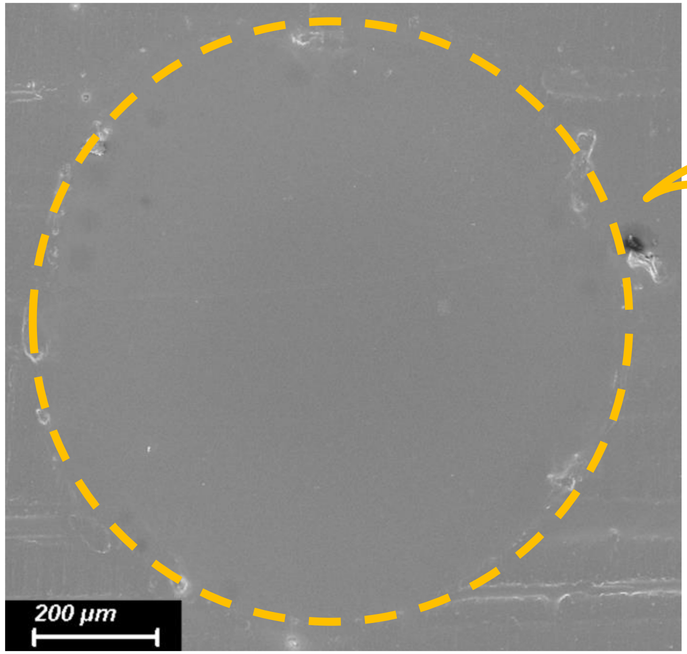
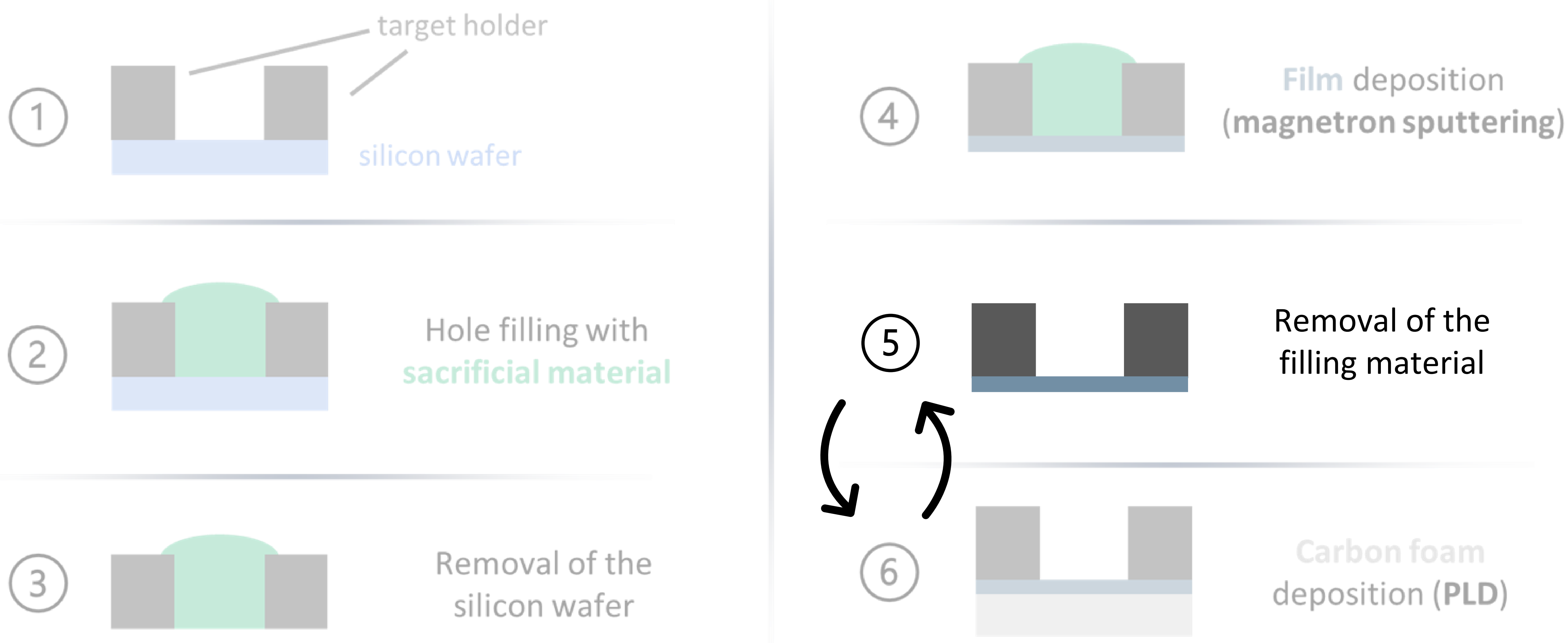


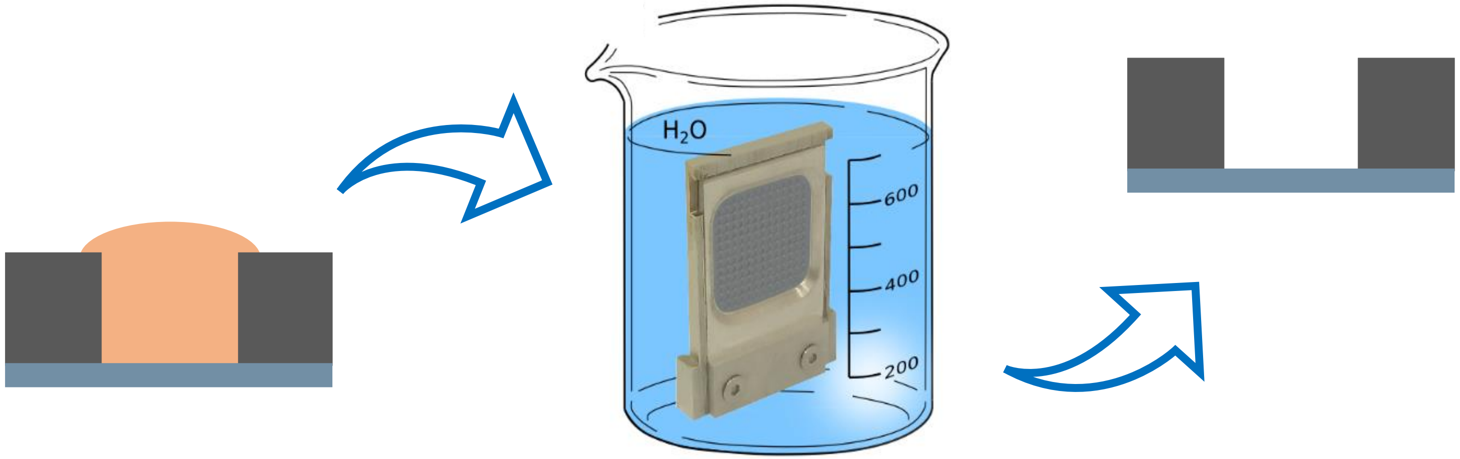
Hybrid layers of DCMS and HiPIMS

The hole shape can be **barely** seen

Removal of the filling material



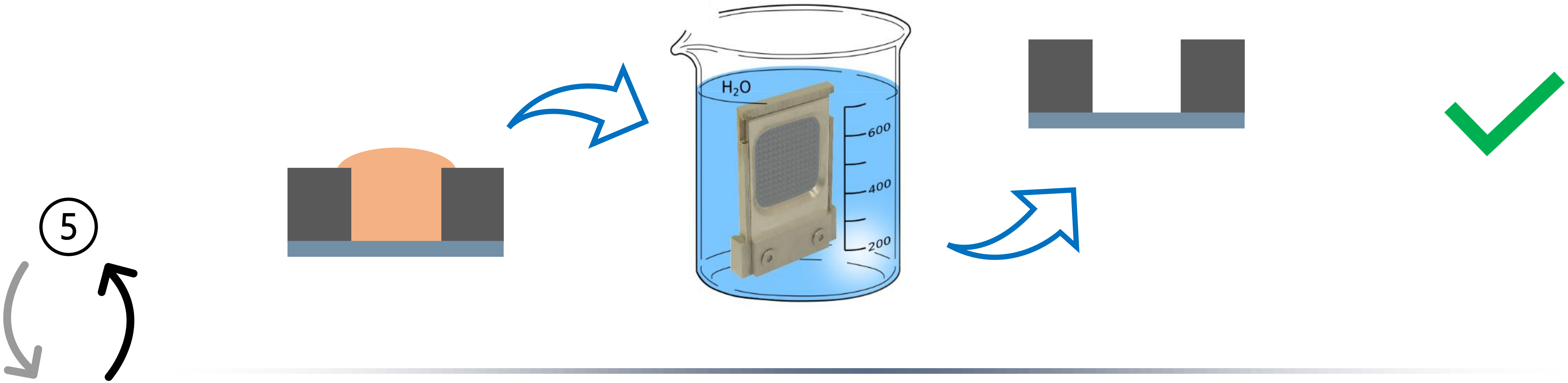
Removal of the filling material (caramel)

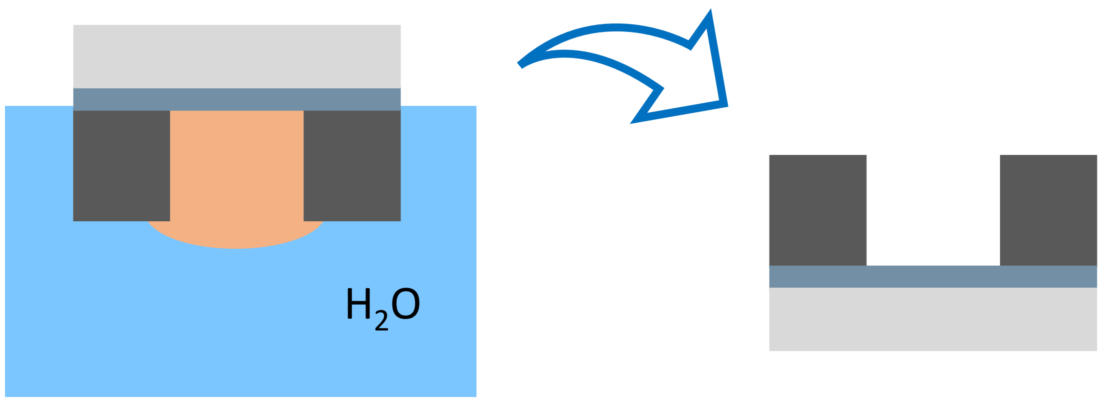


5

6

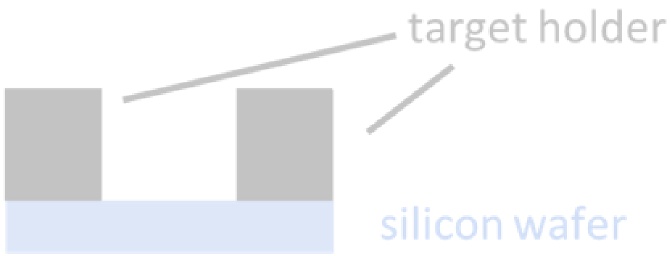
Removal of the filling material (caramel)

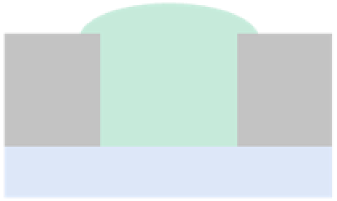




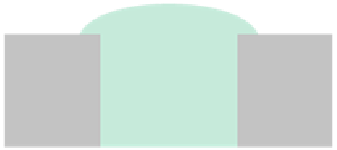
- More support during foam deposition
- No foam-water contact
- More defects in the foam (**dielectric**)

Near-critical carbon foam deposition

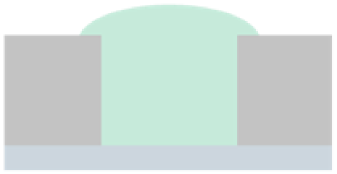
① 

② 

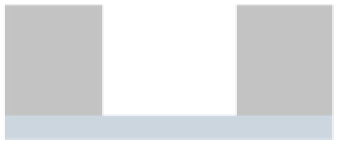
Hole filling with **sacrificial material**

③ 

Removal of the silicon wafer

④ 

Film deposition (**magnetron sputtering**)

⑤ 

Removal of the filling material

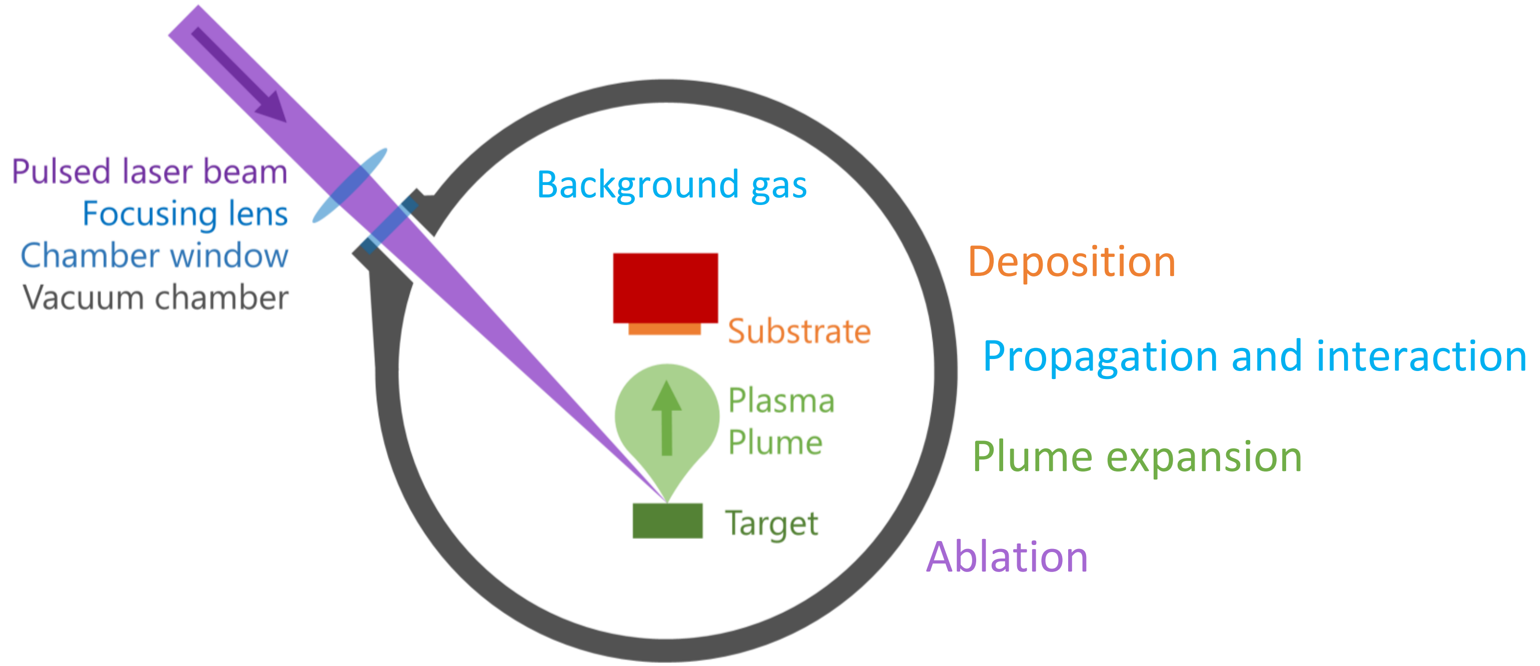
⑥ 

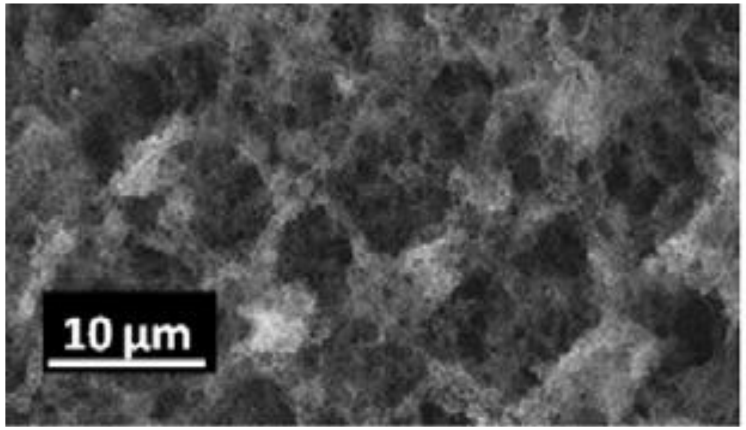
Carbon foam deposition (**PLD**)

Pulsed Laser Deposition (PLD)

A. V. Rode et al., Applied Physics A 70.2 (2000)

A. Zani et al., Carbon 56 (2013)





ns-PLD

- Well established
- Few ns pulses
- 100s mJ per pulse
- Up to 10 Hz

⇔

fs-PLD

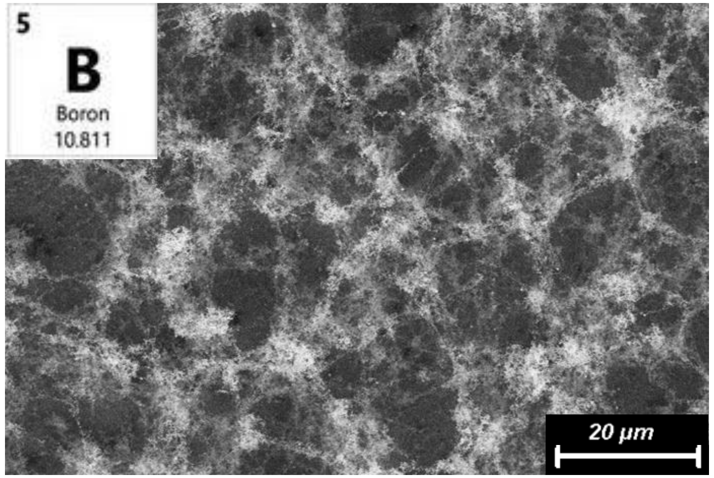
- Nonstandard technique
- <100 fs pulses
- Few mJ per pulse
- kHz or higher

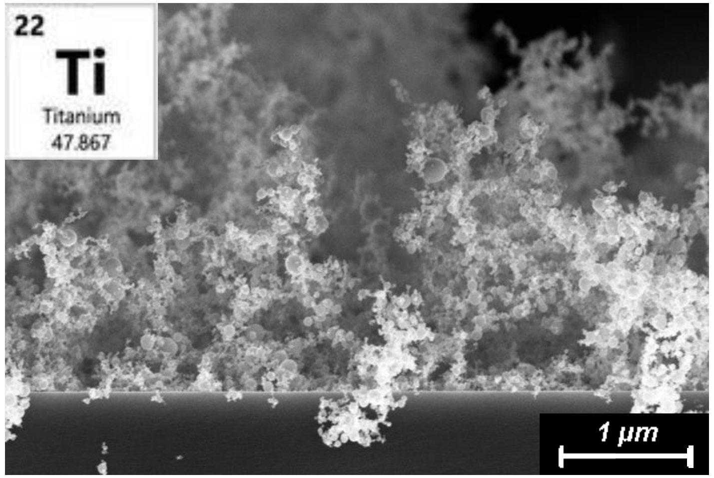
Parameters

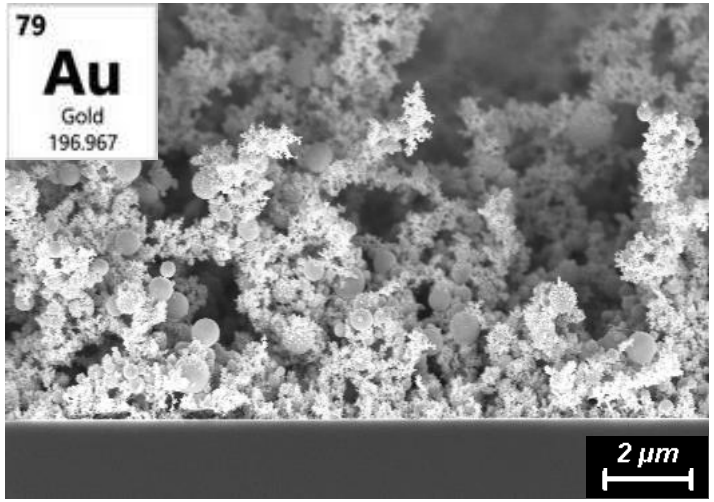
- Pulse energy and fluence
- Background gas pressure
- Pulse duration (**ablation regime**)

fs-PLD: nanofoam of different elements

Freedom in **element choice** for the nanofoam material







fs-PLD

- Nonstandard technique
- <100 fs pulses
- Few mJ per pulse
- kHz or higher

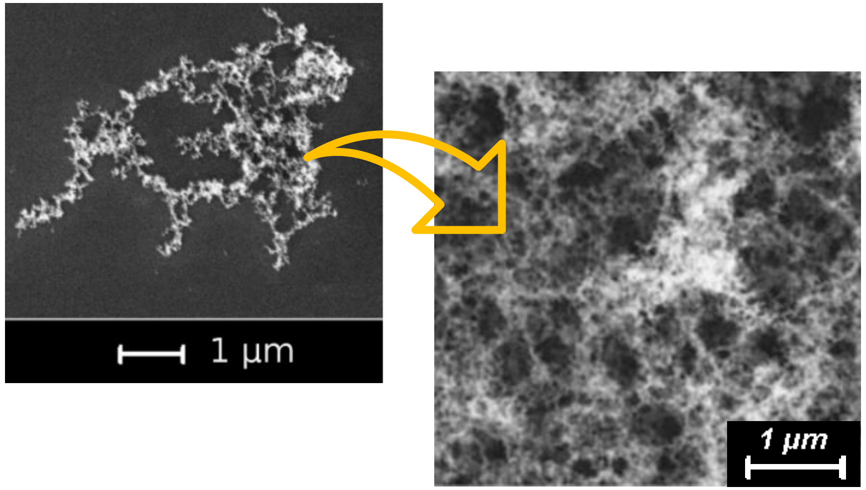
Parameters

- Pulse energy and fluence
- Background gas pressure
- Pulse duration (**ablation regime**)
- **Choice of the element**

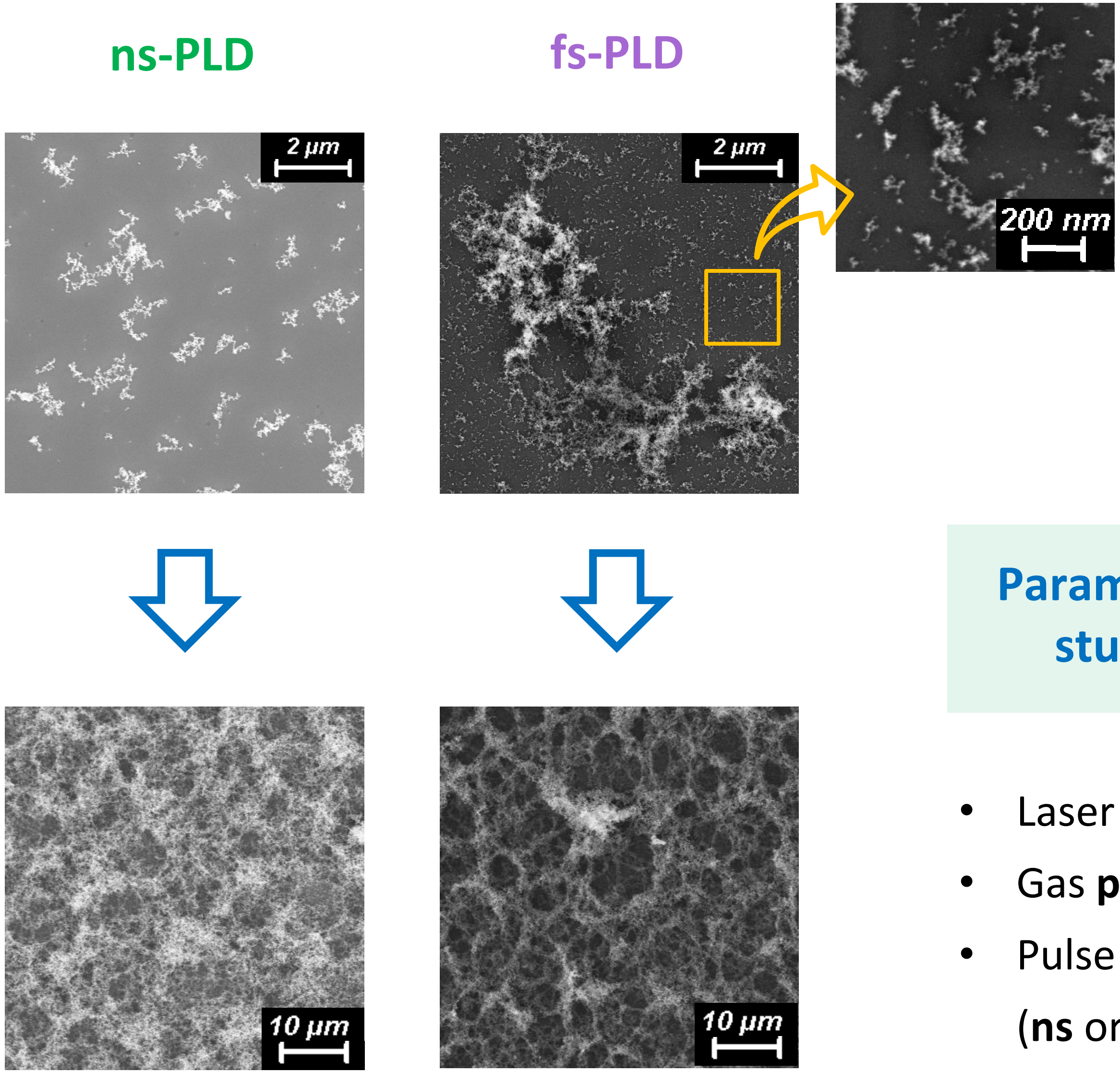
Near-critical carbon foams

Snowfall-like
aggregation model

- Nanoparticles
- Fractal aggregates
- Carbon foam



A. Maffini et al., Physical Review Materials 3.8 (2019)



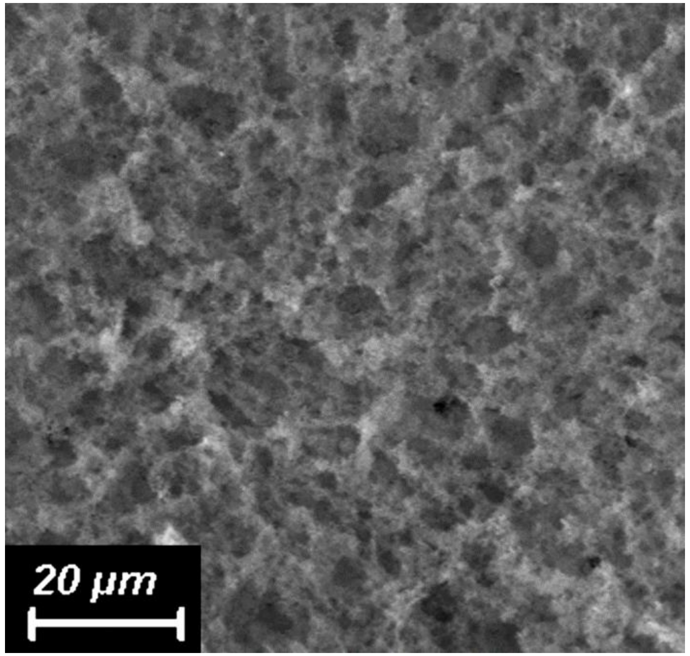
Parametric study

- Laser **fluence**
- Gas **pressure**
- Pulse duration (**ns** or **fs**)

Coupling with the freestanding substrate

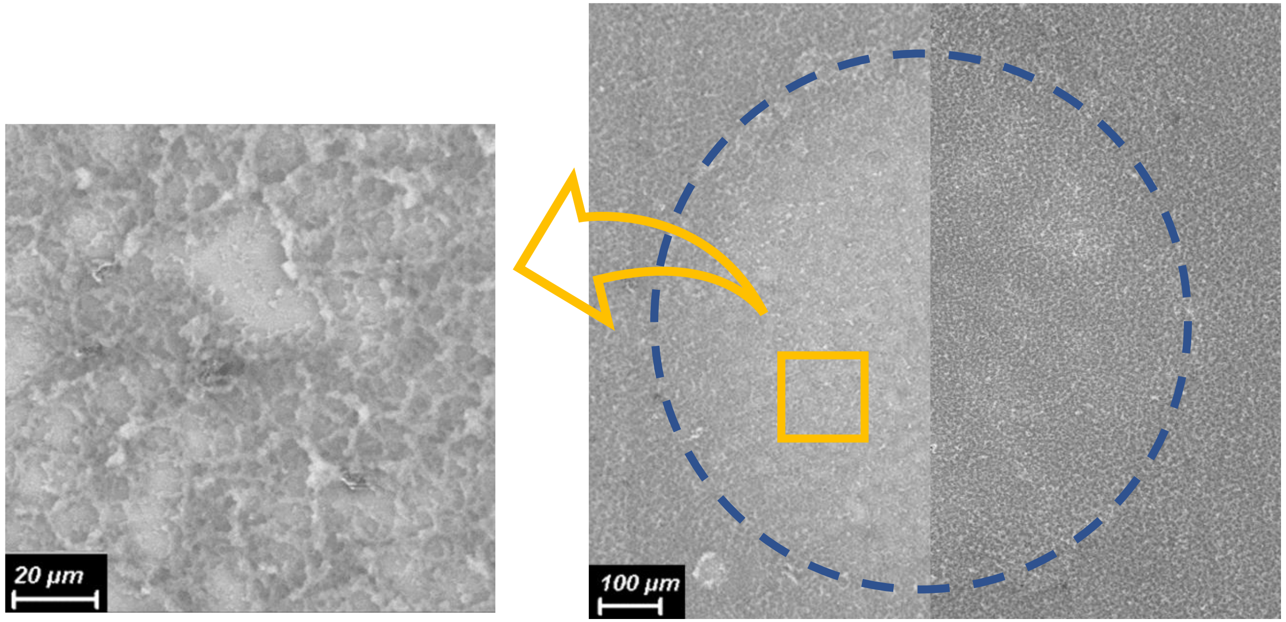
- Near-critical density
- Foam uniformity
- µm thickness
- Good substrate adhesion

- **fs-PLD**
- 2.6 mJ, 360 mJ/cm^2
- 250 Pa (Argon)



Freestanding substrate thickness

200 nm | **400 nm** and up



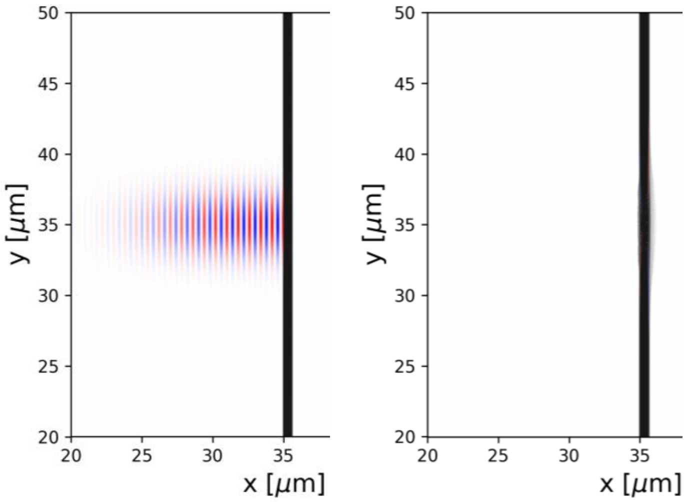
Hyp: Freestanding film membrane vibrations

2D Particle In Cell (PIC) simulations

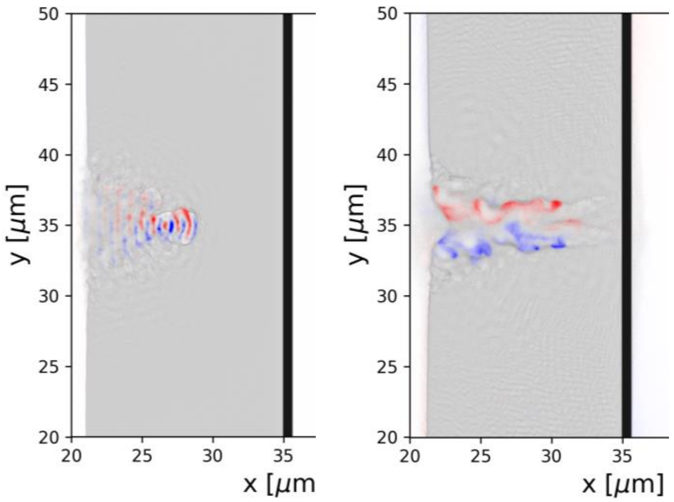
- **Experimental DLT** parameters
- 2D and **homogeneous foam**
- Two laser intensity regimes:

  a_0 = 5 and **a_0 = 50** (~ 10^{19} and 10^{21} W/cm^2 respectively)
- **Substrate thickness** parametric scan

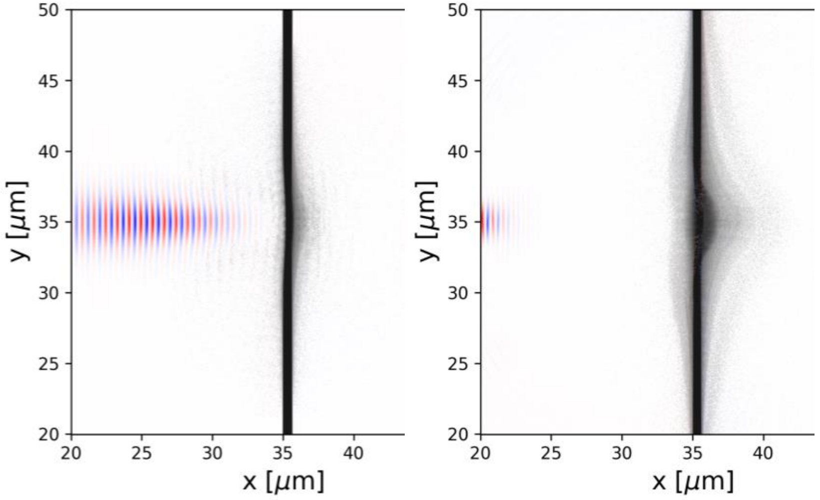
SLT, $a_0 = 5$



DLT, $a_0 = 5$

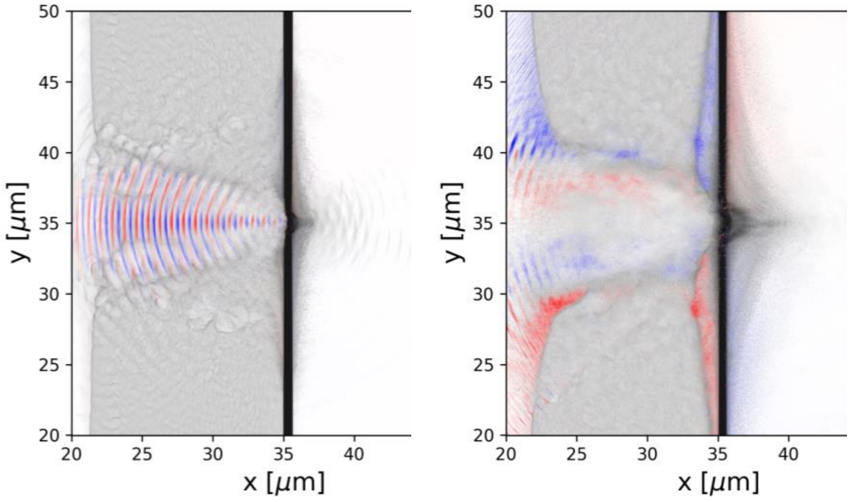


SLT, $a_0 = 50$



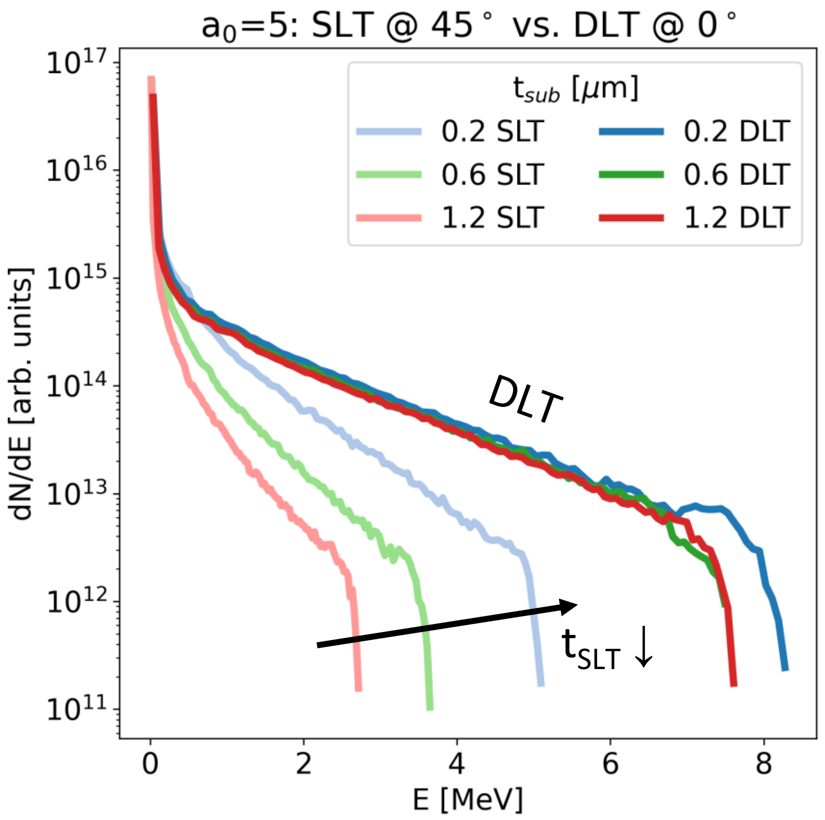
$$\left(t_{sub} \; = \; 600 \; nm \right)$$

DLT, $a_0 = 50$

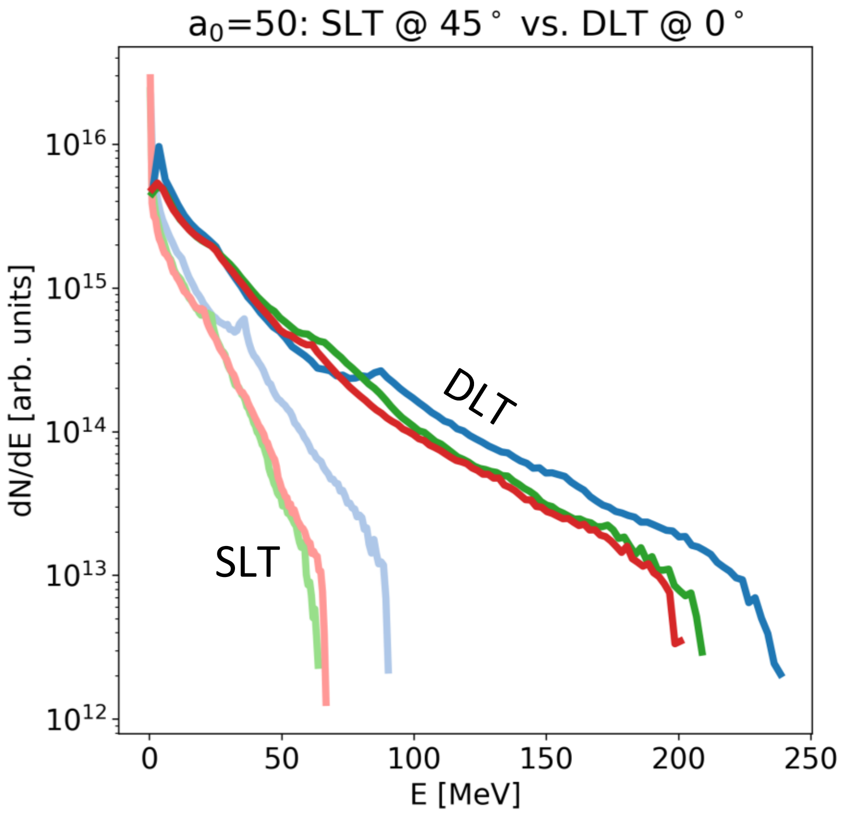


2D PIC simulations: proton spectra

$a_0 = 5$



$a_0 = 50$



Significant enhancement in proton energy and number

Weak dependence on **substrate thickness** for DLT

Freestanding film interesting as **SLT** for lower intensities

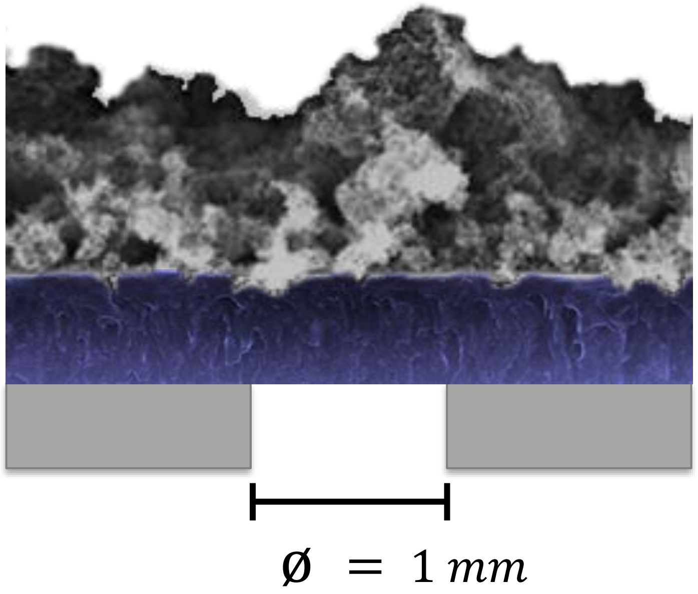
Conclusions and perspectives

Effective **production of near-critical DLT** directly on target holders

Experimental test in particle acceleration campaigns

both **SLT** and **DLT**

Perform **more realistic simulations**



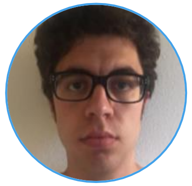
- ~ **10 µm**
- Near-critical density
- Good substrate adhesion

- $\mathbf{400\ nm \div 2\ \mu m}$
- Low stress state
- Near-bulk density
- Uniform thickness

Extend the available parameter range and **optimize** the design

Acknowledgments


M. Passoni


D. Vavassori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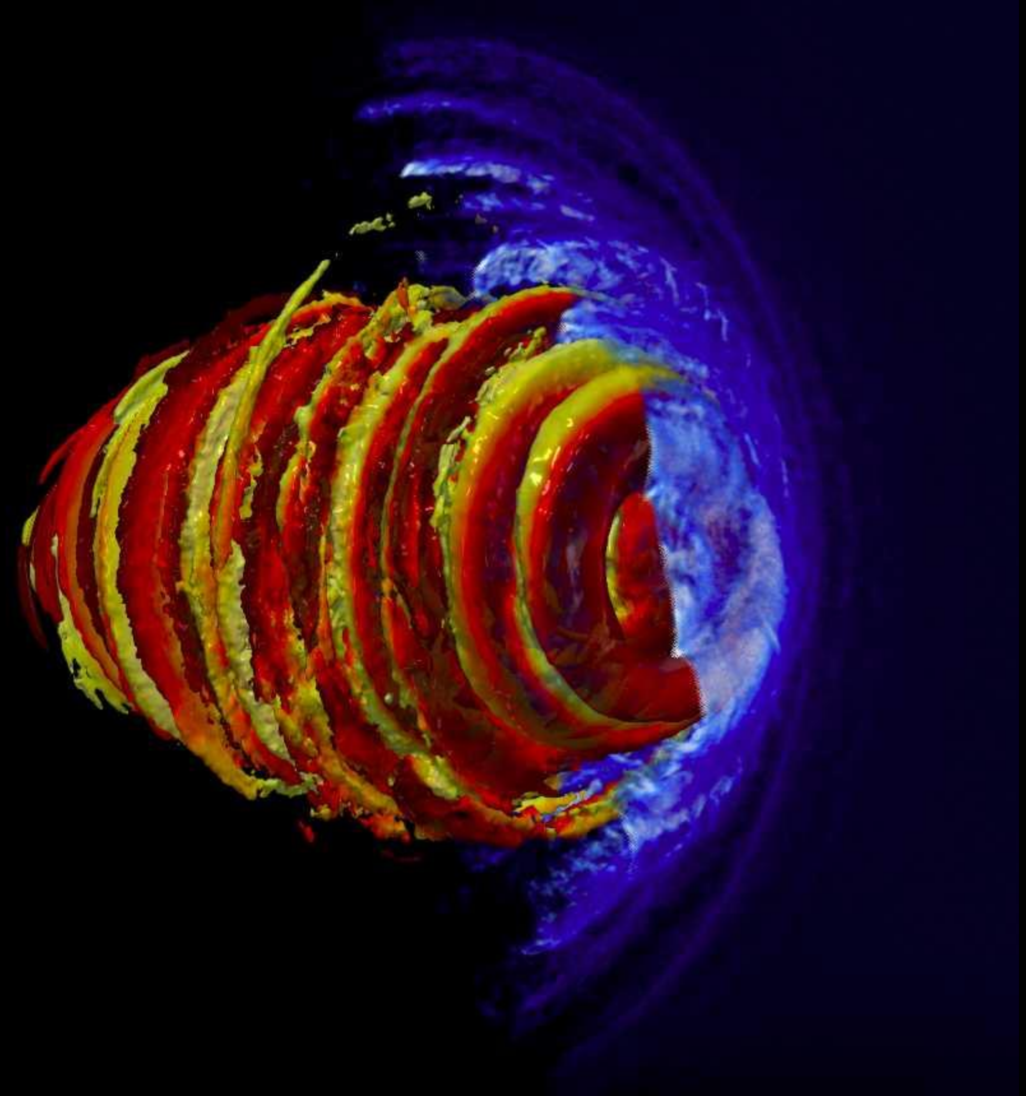

Thank you for your attention!