

Experimental investigations of laser-driven ion acceleration and fusion reaction enhanced by Plasmonic Nanostructured Targets

Imene Benabdelghani,

Márk Aladi, Péter Rácz, Gergő Hegedűs, Ádám Inger,
László P. Csernai, Tamás Sándor Biró, Norbert Kroó, and

Miklós Ákos Kedves

(Naplif collaboration)

Károly Osvay, Parvin Varmazyar, Tibor Gilinger
(University of Szeged, NLTL)

Targets: Attila Bonyár, Nóra Tarpatáki (BME)
Zsuzsanna Márton (ELI-ALPS)

Aim of the Experiments

Study laser-matter and plasma interactions: Utilize nanostructured targets to enhance energy absorption, examine plasmonic effects, and investigate efficient ion acceleration.

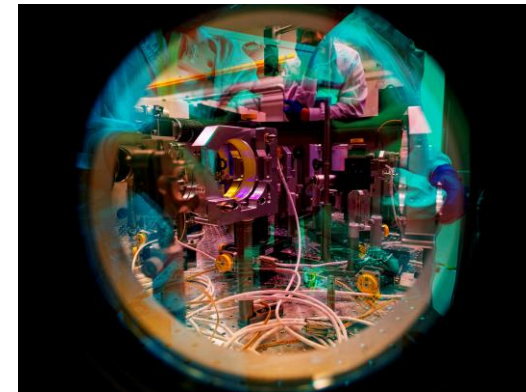
Explore Fusion Reactions:

Use accelerated ions for $p-^{11}\text{B}$ and D-D fusion

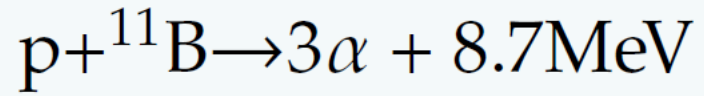
Detect fusion products (α -particles, neutrons)

Optimize Target Design:

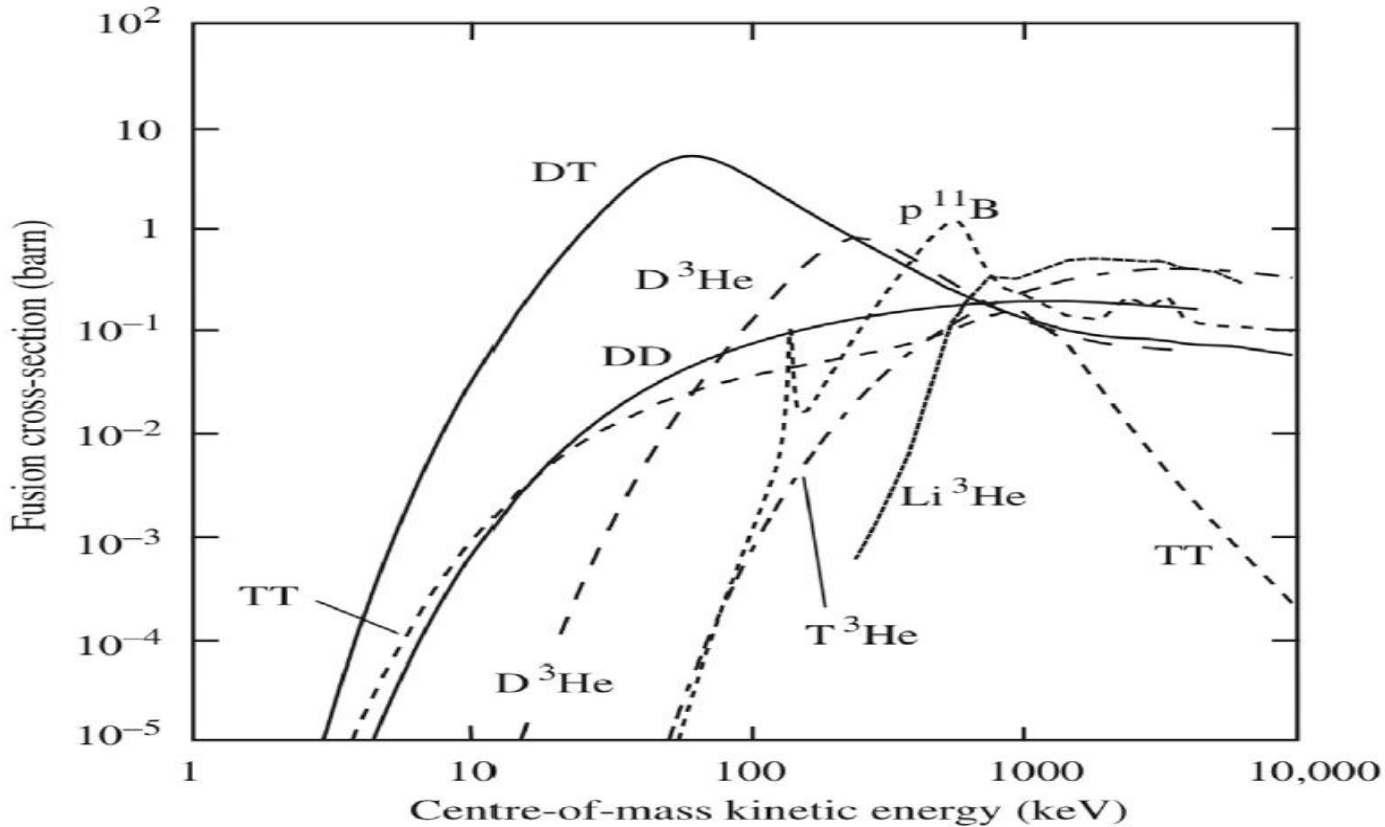
Develop efficient targets for compact fusion (@ ≤ 100 mJ laser energy range)



Proton-Boron nuclear reaction



Aneutronic fusion is a promising alternative in fusion research. pB fusion can serve as a source of alpha particles.



Requires a higher plasma ignition temperature

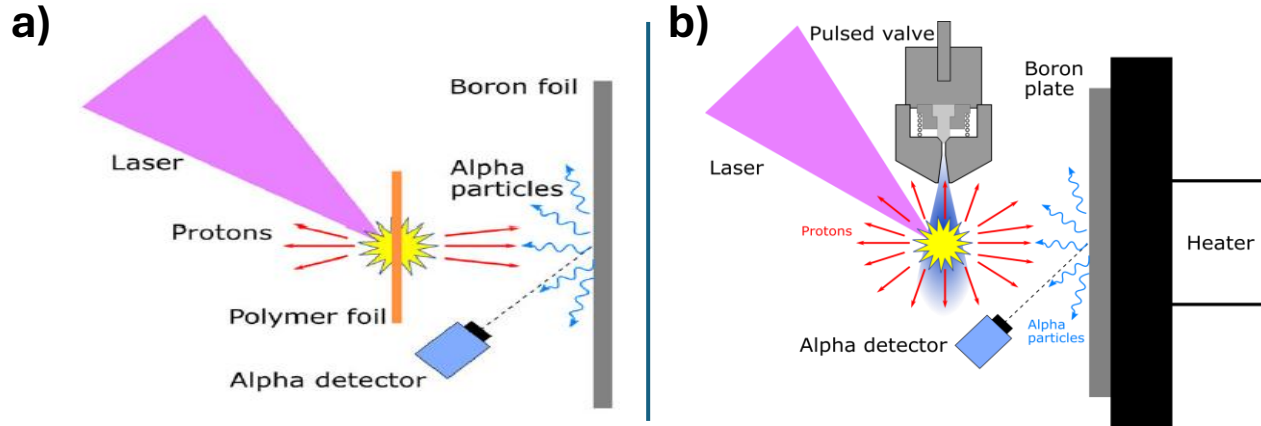
Advanced fusion reaction:

- High cross section (~ 1.2 barn), clean reaction
- Produces 3 alpha particles with high energy
- Two nuclear resonances for p energy $E_{k,p}$: 675 keV (main) and 160 keV (secondary).

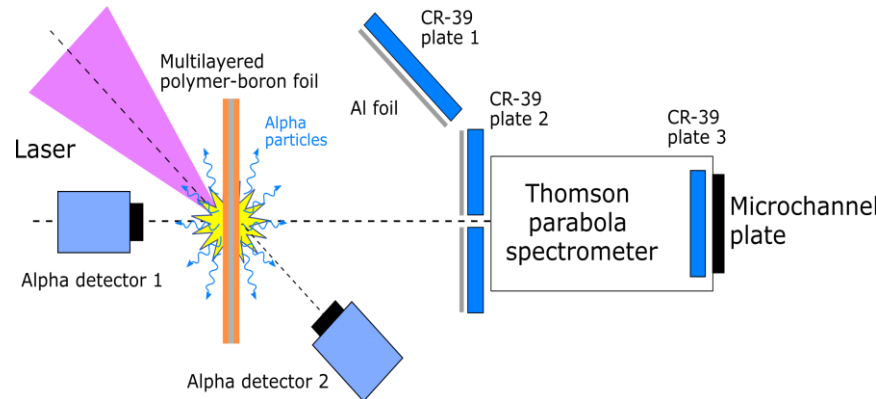
J. Ongena. EPJ Web Conf. 189, 00015 (2018)

Laser-Driven pB Fusion: Concept and Reaction Scheme

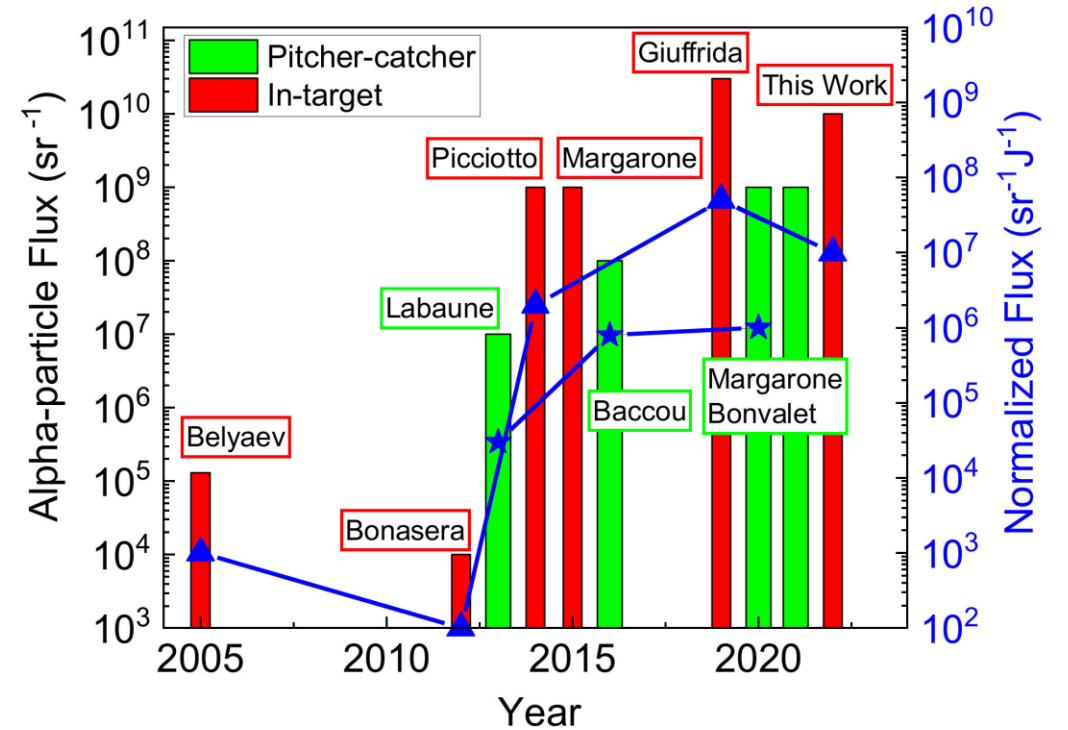
Pitcher-catcher



In-target



Since 2005, laser-driven $p-^{11}\text{B}$ fusion has shown steadily increasing yields, reaching $\sim 10^{10}$ particles/sr/shot.



Different target regimes were tested (colors on the sketch)

D. Margarone et al. Appl. Sci. 12, 1444 (2022)

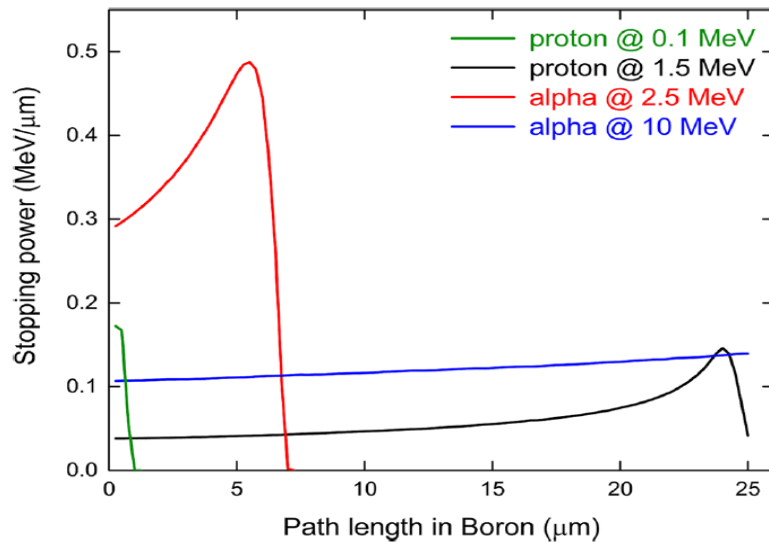
Numerical estimation of α -particle yield in fs Laser-Driven pB Fusion

Pitcher: Cryogenic hydrogen-cluster jet (H_2 clusters, ~ 14 nm cluster size, $\sim 10^{21}$ atoms/cm³ average atom density) accelerated by fs laser.

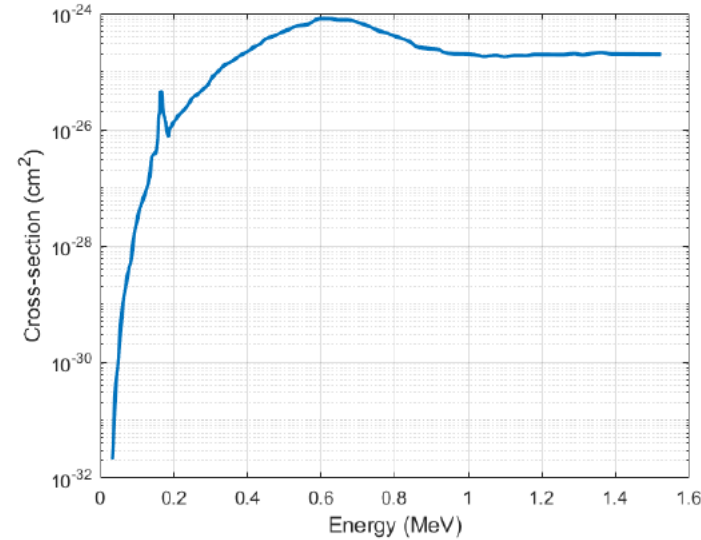
Catcher: 25 μm thick boron foil positioned ~ 25 mm from jet

M. Aladi et al., Eur. Phys. J. Spec. Top. (2025)

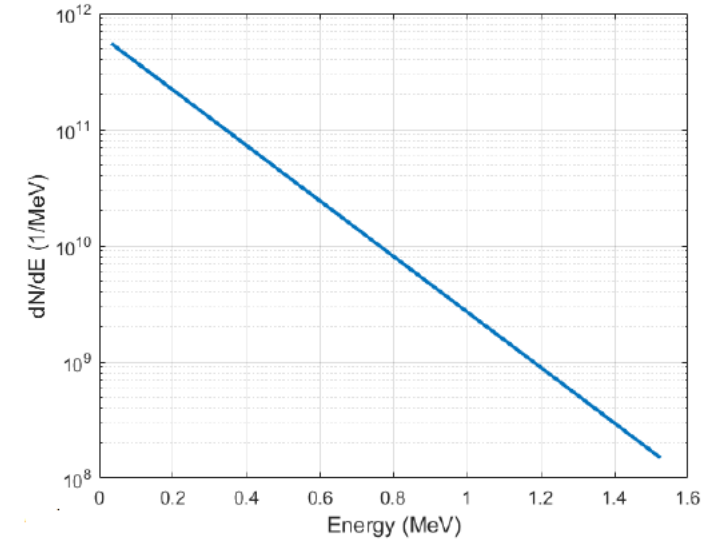
SRIM/TRIM Stopping-Power Simulation



p-B fusion cross-section (lab frame)



Exponential proton spectrum

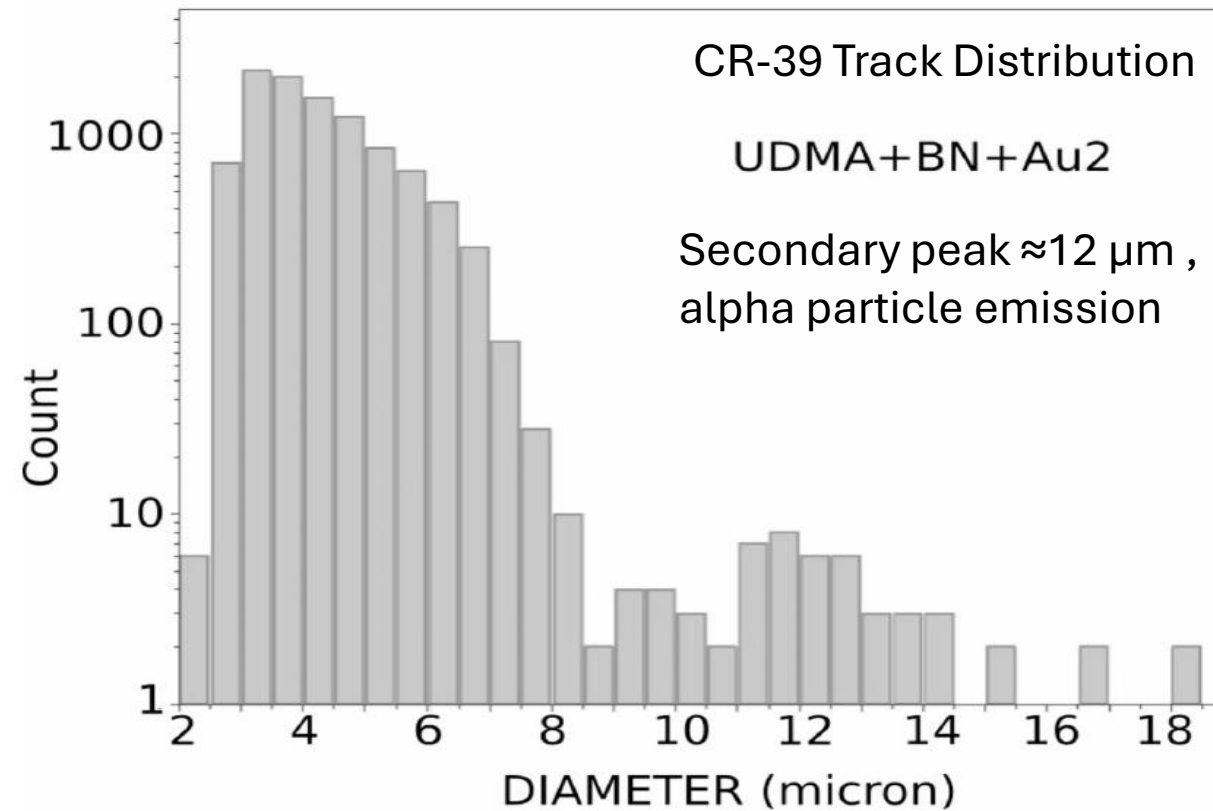


Proton energy distribution $E_{\text{cut off}} \approx 1.5$ MeV, spectral slope $\lambda = 5.5$ MeV⁻¹

Estimated yield: $N_{\alpha} = 3N_{\text{reaction}} = \sim 10^7$ α /shot using stated parameters

Indication of p + 11B reaction in Laser Induced Nanofusion experiment

Copolymer Base	Gold Nanorods	BN Nanoparticles	Laser Energy	Pulse Duration	Spot Size (radius)	Peak Intensity
UDMA-TEGDMA (3:1)	0.182% (85 x 25 nm)	2.5% content	25 mJ	12–360 fs	~3 μm	Up to $8 \times 10^{18} \text{ W/cm}^2$

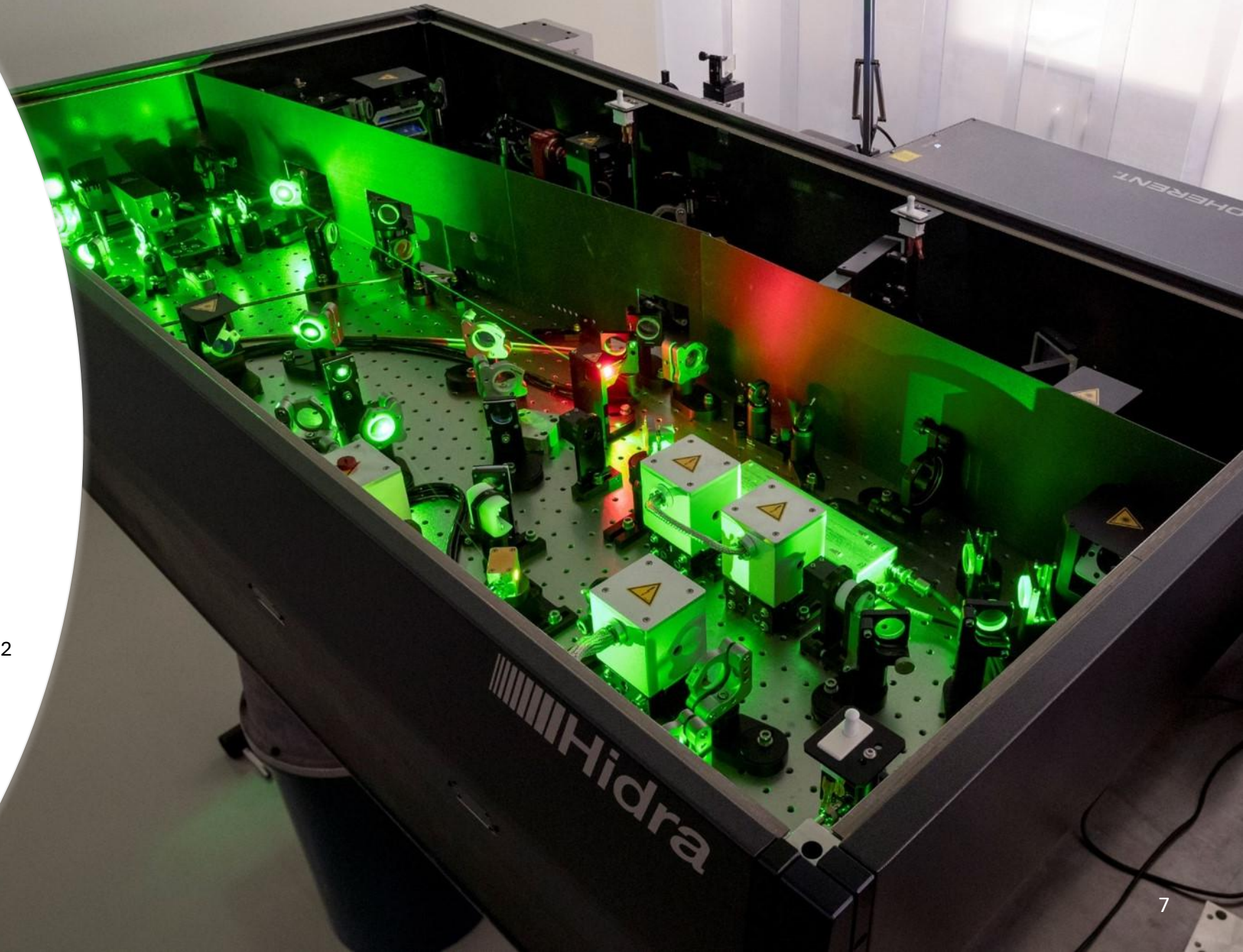


N. Kroó et al., Scientific Reports 14, 30087 (2024)

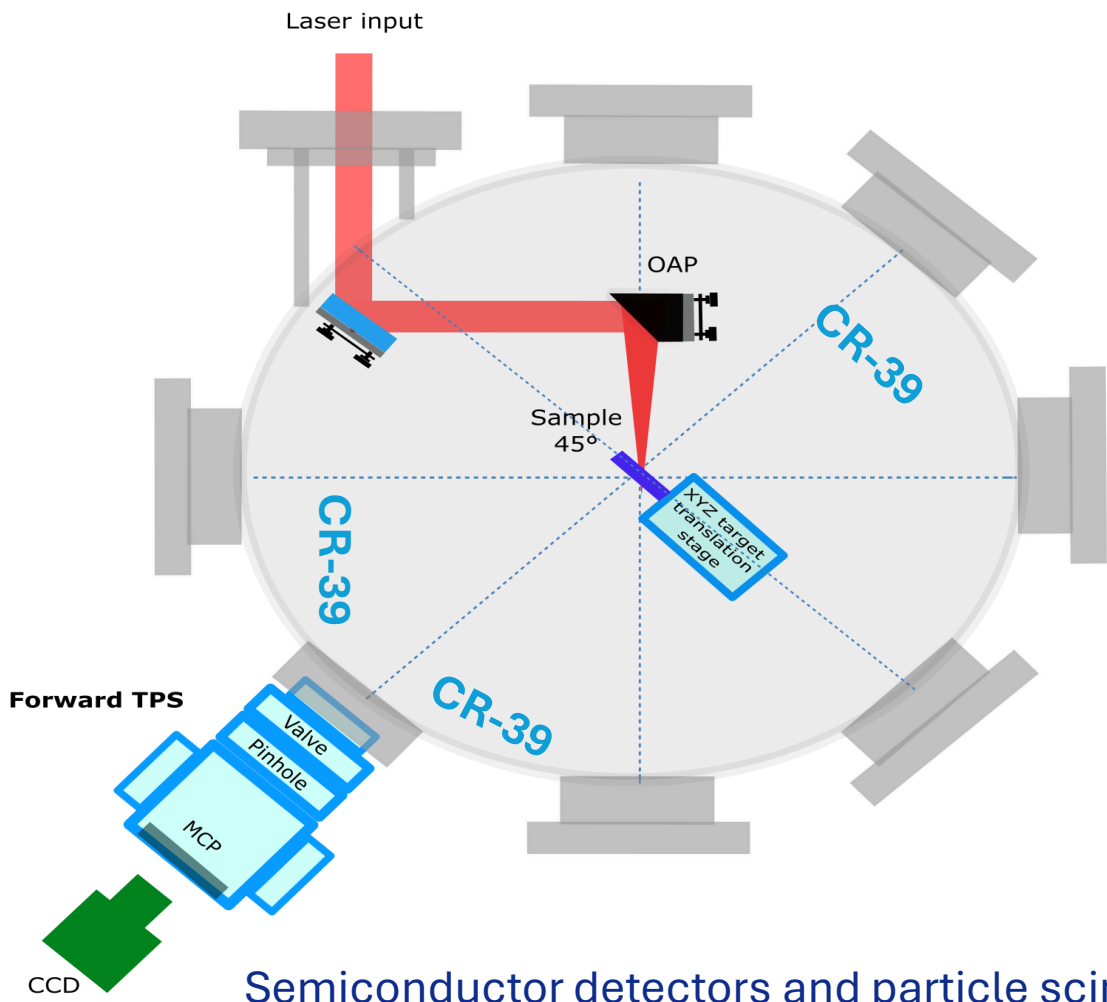
Measurements at the Wigner RCP

Applied Laser System: Femtosecond
Ti: Sapphire CPA

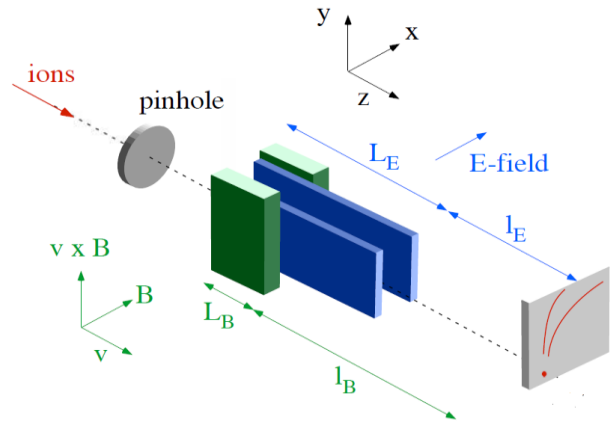
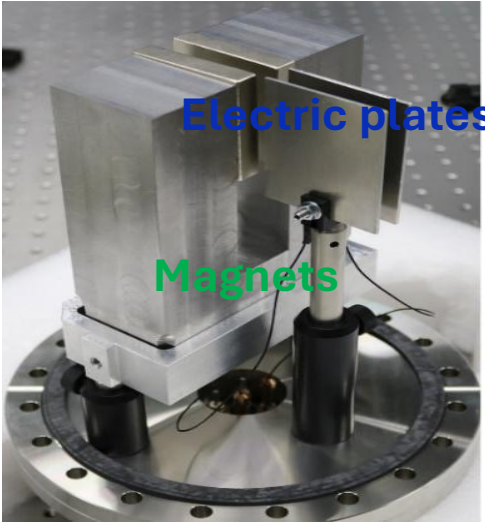
- Max. Laser Pulse Energy: 30 mJ
- Minimum pulse length used: 40 fs
- Central wavelength: 800 nm
- Repetition rate: 10 Hz
- Beam diameter ($1/e^2$): 15 mm
- Focused laser intensity: $>10^{17}$ W/cm²



Measurements at the Wigner RCP: Experimental setup



Ion Diagnostics: Thomson parabola spectrometer (TPS)



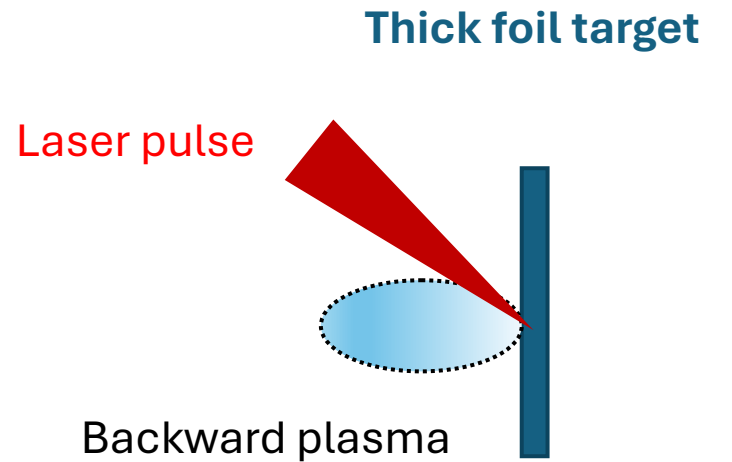
L. Willingale, PhD diss. (2007)

Ion detectors: CR-39 plates

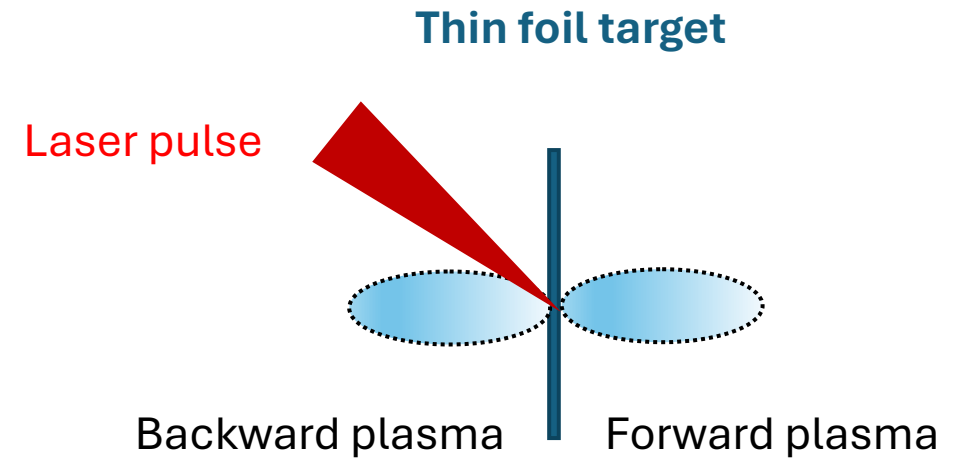


Semiconductor detectors and particle scintillators are planned for future implementation

Difference in particle jet directions based on the target thickness



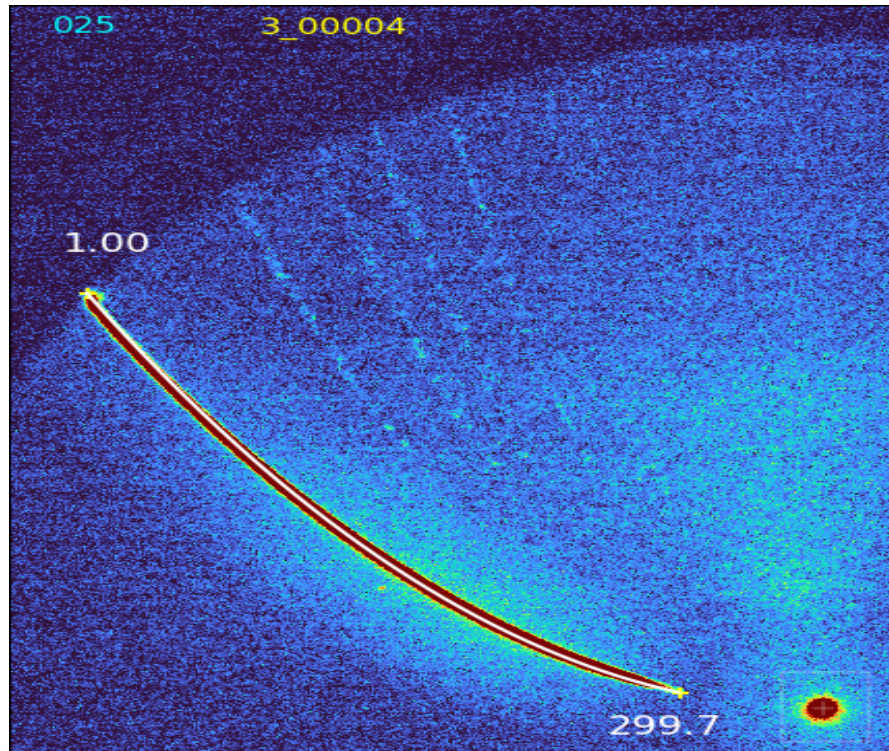
Particle jets are emitted in the
BWD direction



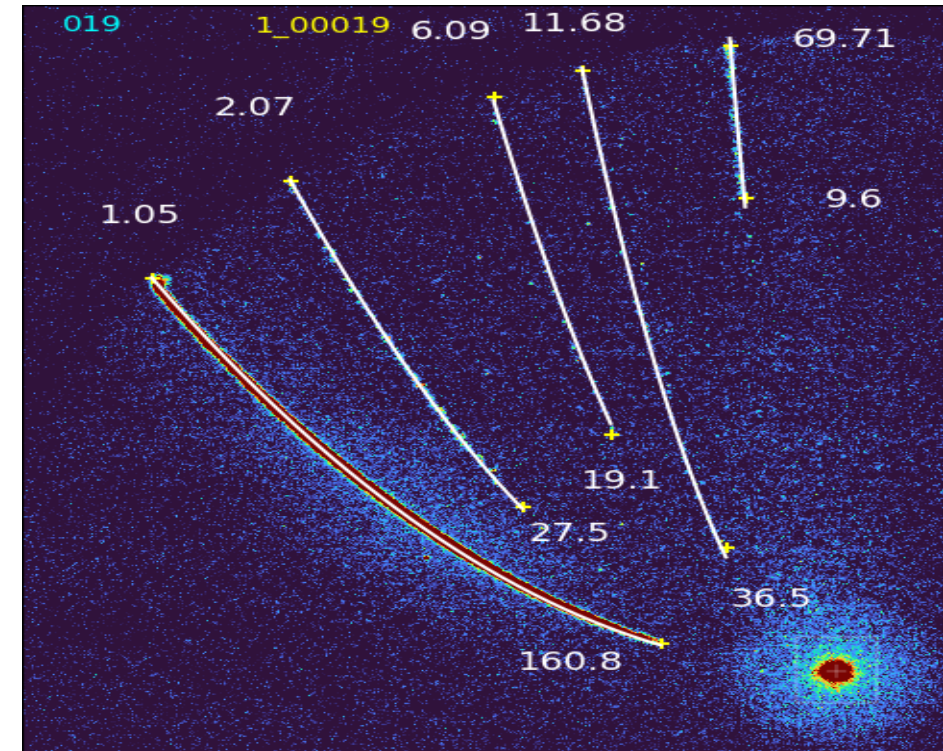
Particle jets are emitted in both
FWD and BWD directions

TP Spectra from Test Measurements at Wigner RCP

Thin Aluminum foil target_25 mJ

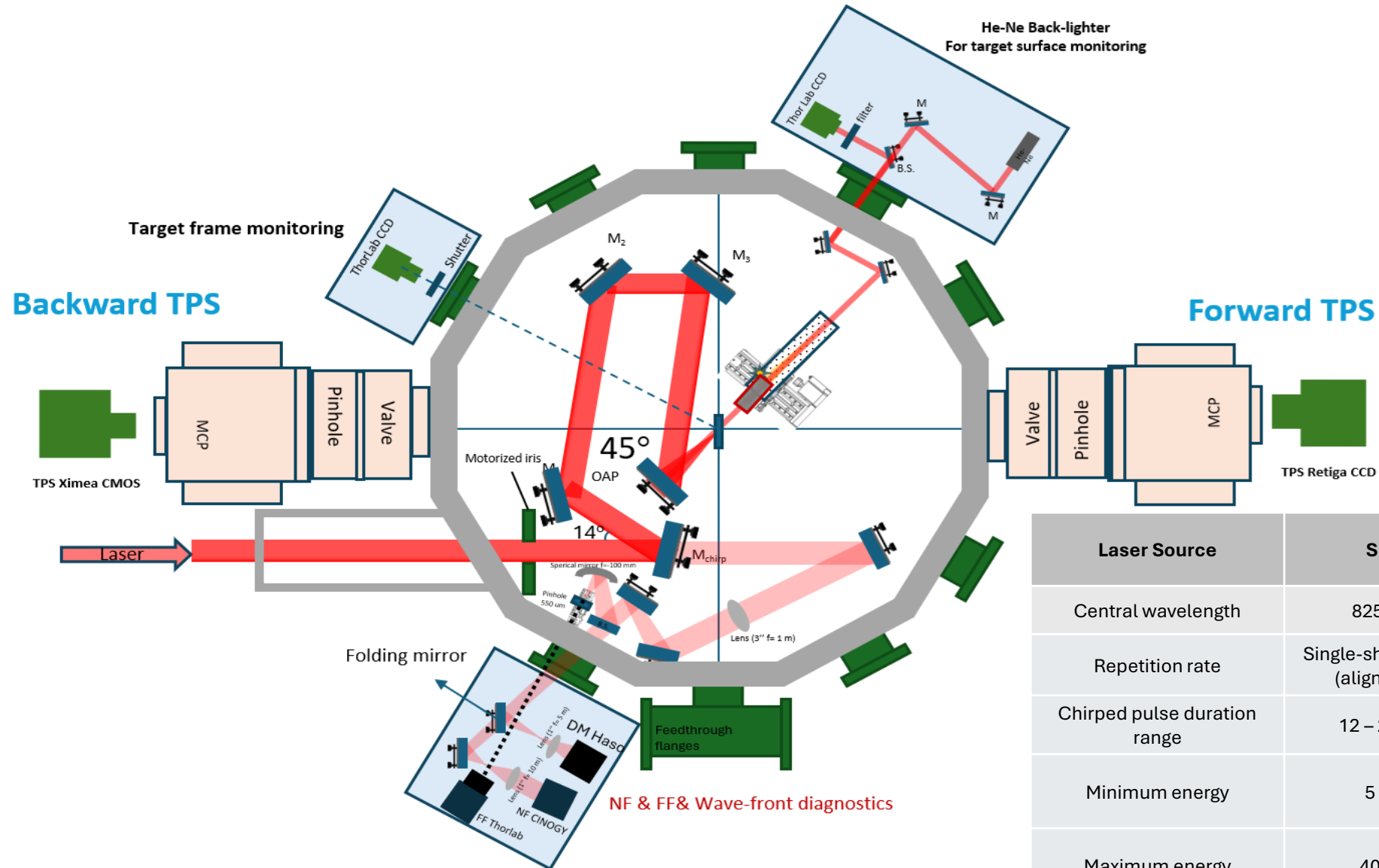


Thin Polymer foil target_25 mJ



- Protons reach up to **300 keV (Al foil)** and **160.8 keV (polymer foil)** → promising acceleration efficiency.

Measurements at Eli-ALPS: Experimental setup

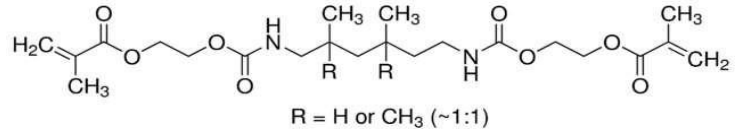


Laser Source	SEA	S3 (SYLOS3)
Central wavelength	825 nm	825 nm
Repetition rate	Single-shots, 10 Hz (alignment)	1 kHz
Chirped pulse duration range	12 – 250 fs	8– 250 fs
Minimum energy	5 mJ	20 mJ
Maximum energy	40 mJ	120 mJ

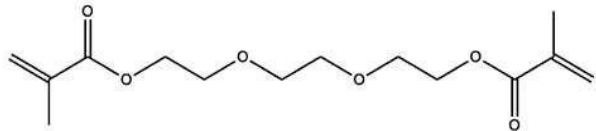
Target Types Used in the Experiments

UDMA: TEGDMA mixture (3:1)

UDMA (Urethane Dimethacrylate), $C_{23}H_{38}N_2O_8$



TEGDMA (Triethylene Glycol Dimethacrylate), $C_{14}H_{22}O_6$



Nanocomposite: UDMA:TEGDMA + resonant Au nanorods

Size of Au nanorods: 85 nm x 25 nm,

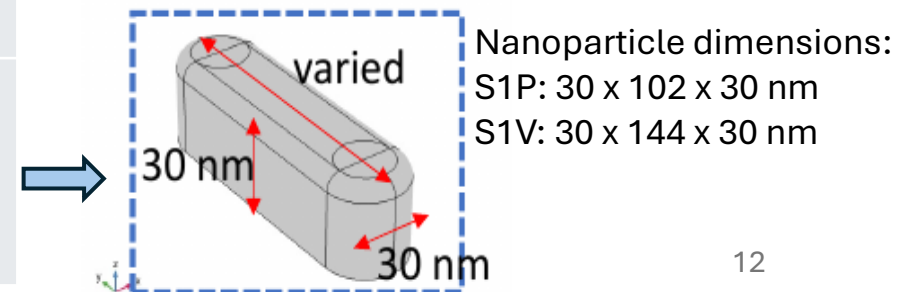
Plasmonic resonance to 795 nm

UDMA: MMA-D : Deuterated Sample (Methyl methacrylate): $C_5D_8O_2$

Target type	Composition	Coating	Sample Thickness	Substrate
UDMA-TEGDMA	Au0, Au2_RE	-	5 μ m	-
			120 μ m	Glass
UDMA-TEGDMA + BN	Au0, Au2_RE	-	5 μ m	-
			120 μ m	Glass
UDMA-MMA (Deuterated)	Au0, Au2_RE	-	5 μ m	-
			120 Mm	Glass
Oriented Au nanoparticle structures on Quartz	S1P	PMMA	PMMA: 170 nm Au Nanorods: 30 nm Boron: 50 nm	Quartz
	S1V	-		
	S1P_B	PMMA_Boron		
	S1V_B	Boron		

Au0: Without gold nanorods

Au2_RE: With resonant Au nanorods



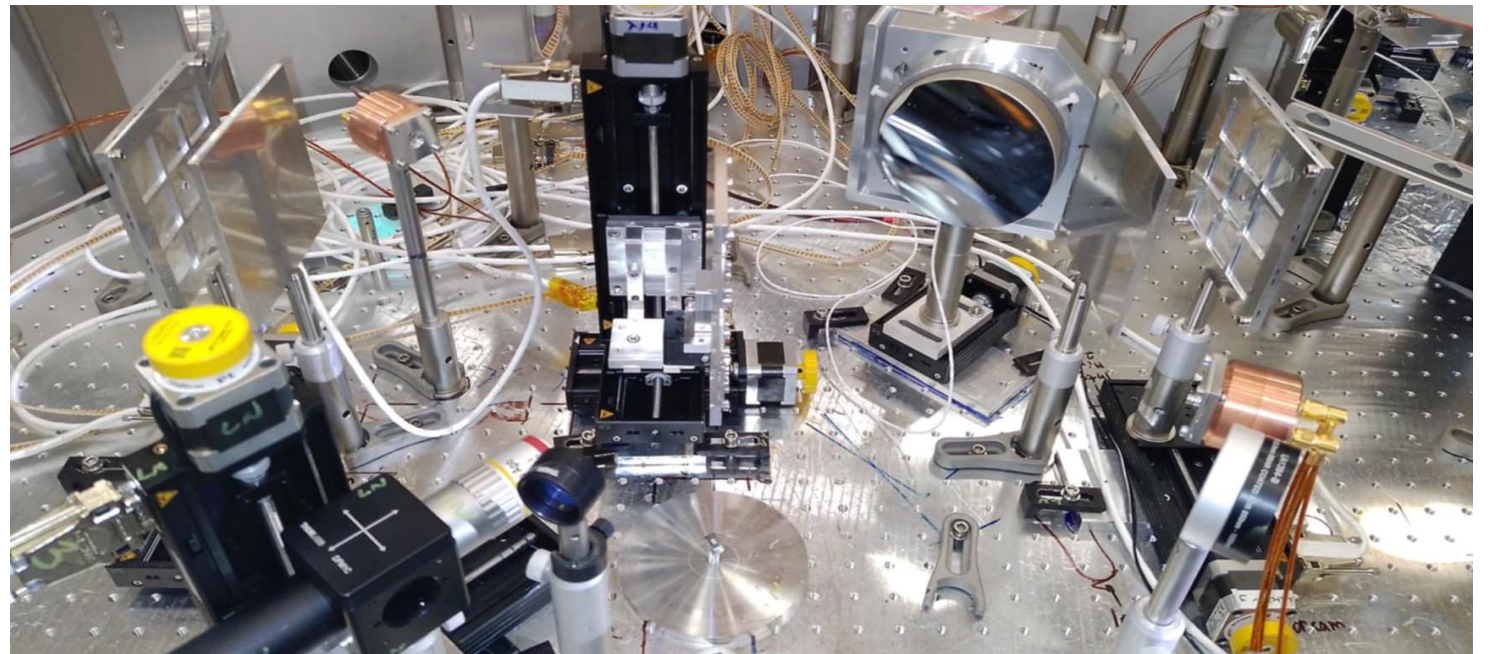
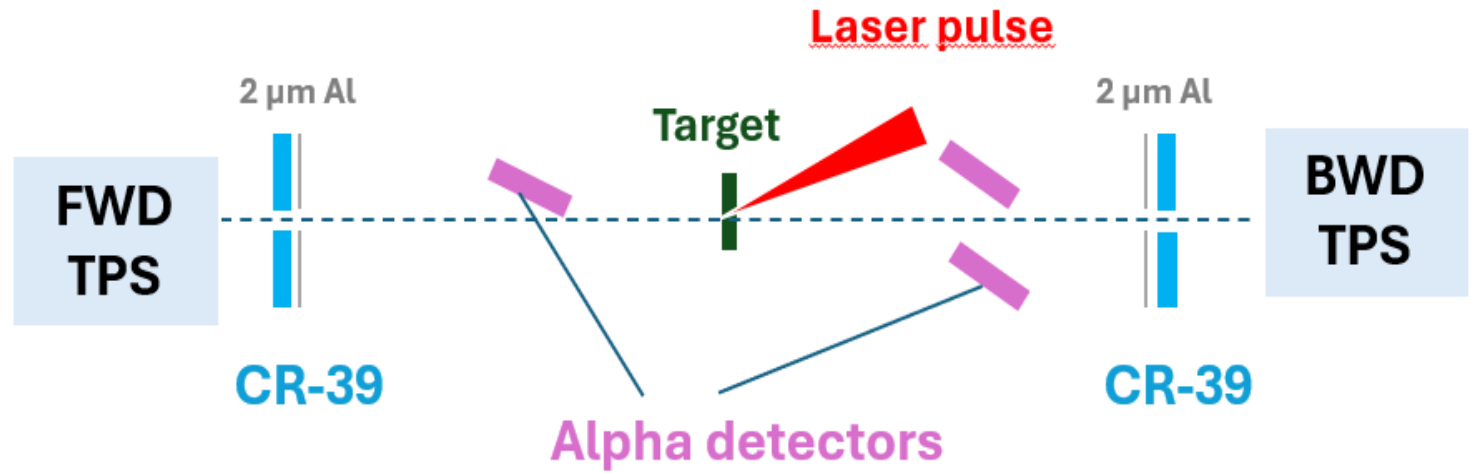
Detector Parameters and Configurations

Covered by 2 μm Al foil to block light and provide EM shielding, along with robust shielding of the entire detector (including the amplifier).

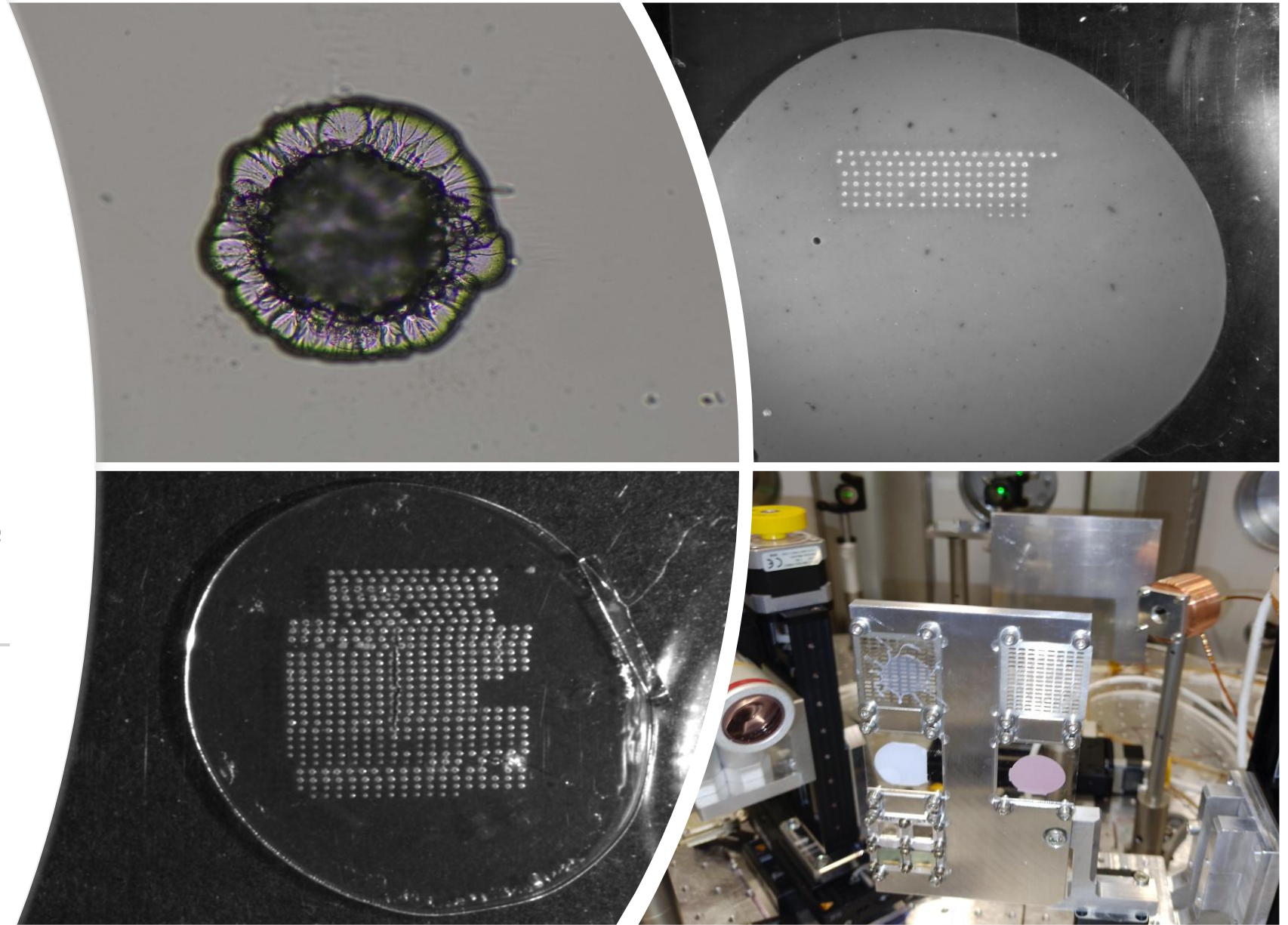
Detector	FDS_A (amplified)	FDS_B (bias only)	AXUV (bias only)
Sensor Material	Si		
Active Area [mm^2]	0.8	576.5	
Applied Bias [V]	10		
Rise Time	1 ns	50 μs	
Capacitance	6 pF	≈ 2.2 nF	
Dark Current [nA]	0.3	≈ 10	
Peak Responsivity [A/W]	0.44	≈ 0.45	

CR-39 & photodiodes arrangement inside vacuum chamber

- BWD and FWD Photodiode detectors at $\sim 25^\circ$ facing the target
- CR-39 detectors (FWD & BWD):
 - 9-piece array with 5 mm central hole
- Covered by $2\ \mu\text{m}$ Al foils (blocks low-energy ions)

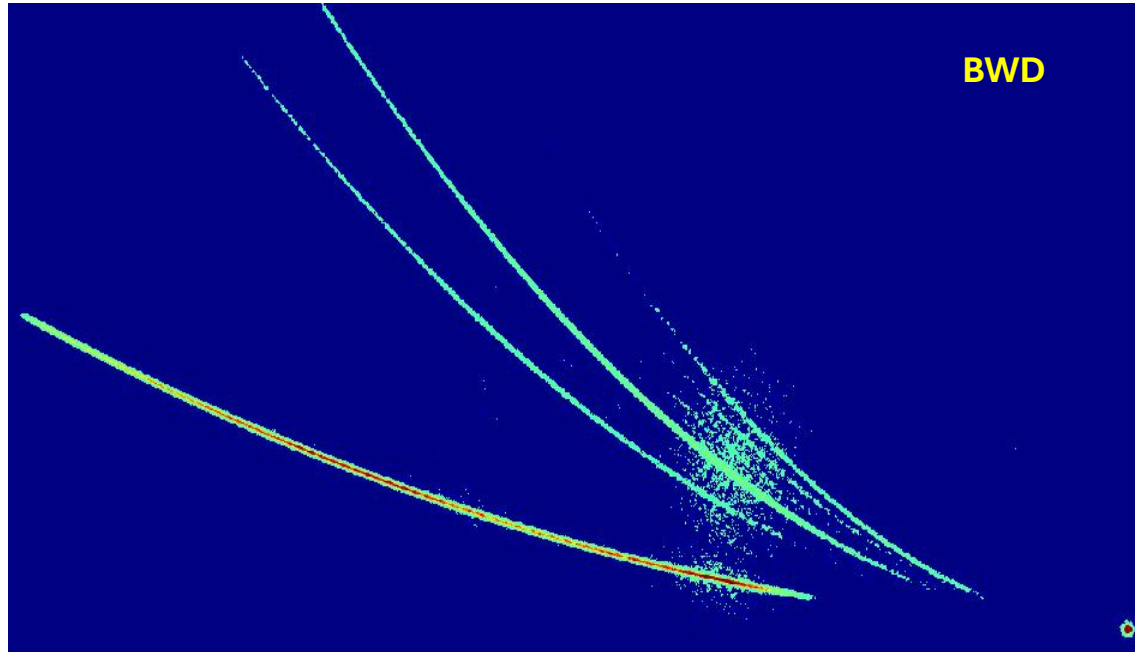


Pictures of the target mounted in the holder and the crater created by the laser shot with microscope image

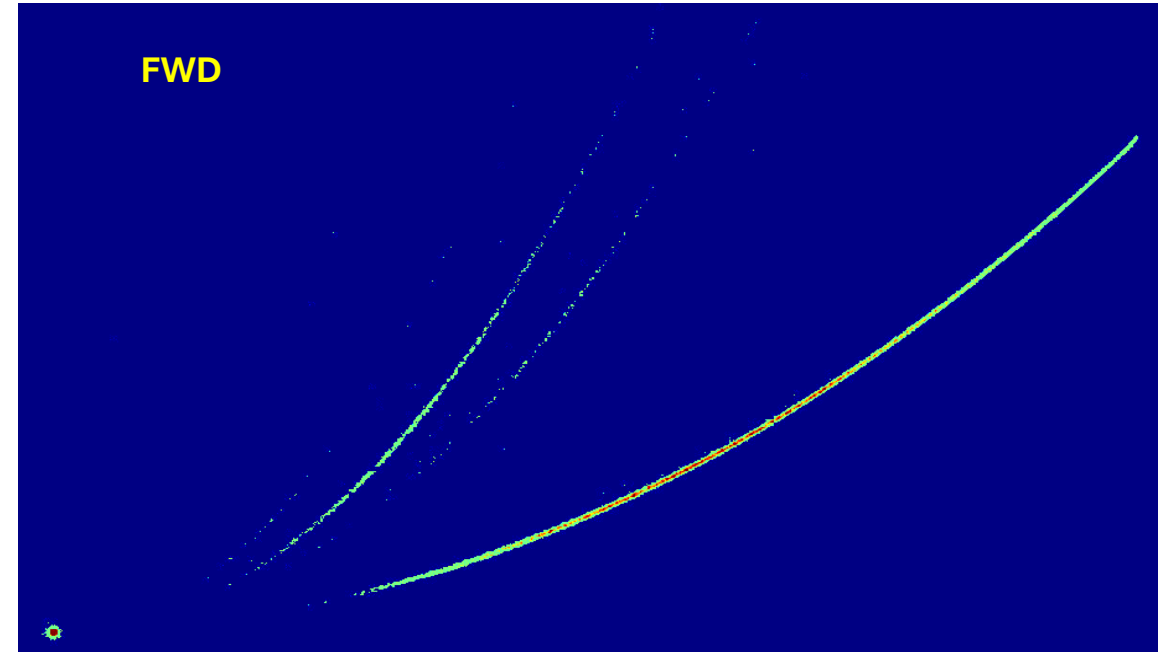


Sample TP Spectra from Different Targets_BWD&FWD direction

UDMA-Au2_RE_120 μ m_-800GDD
192.5 fs_133 shot_bwd_(03.06.2025)

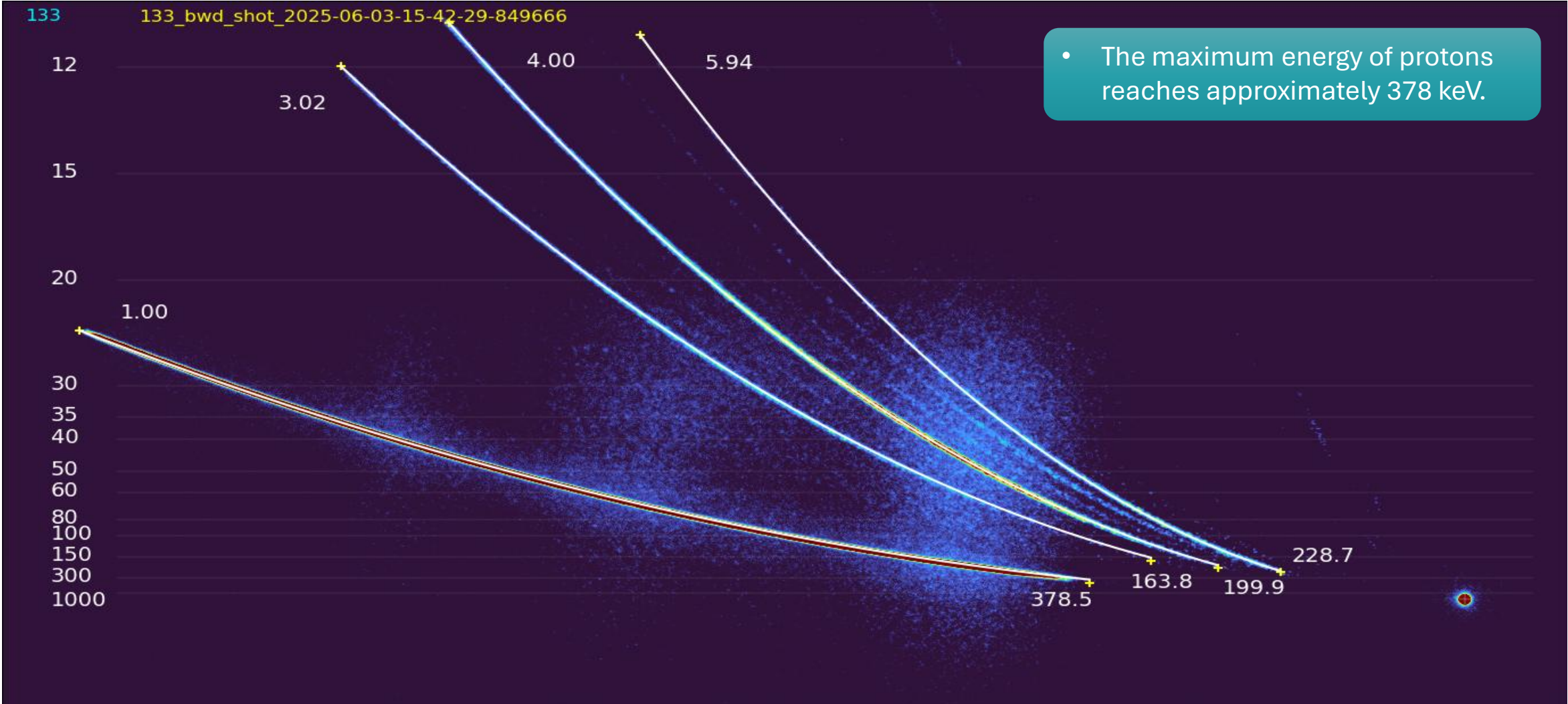


UDMA-Au2_RE_5 μ m_-500GDD
120.5 fs_104 shot_fwd_(30.05.2025)



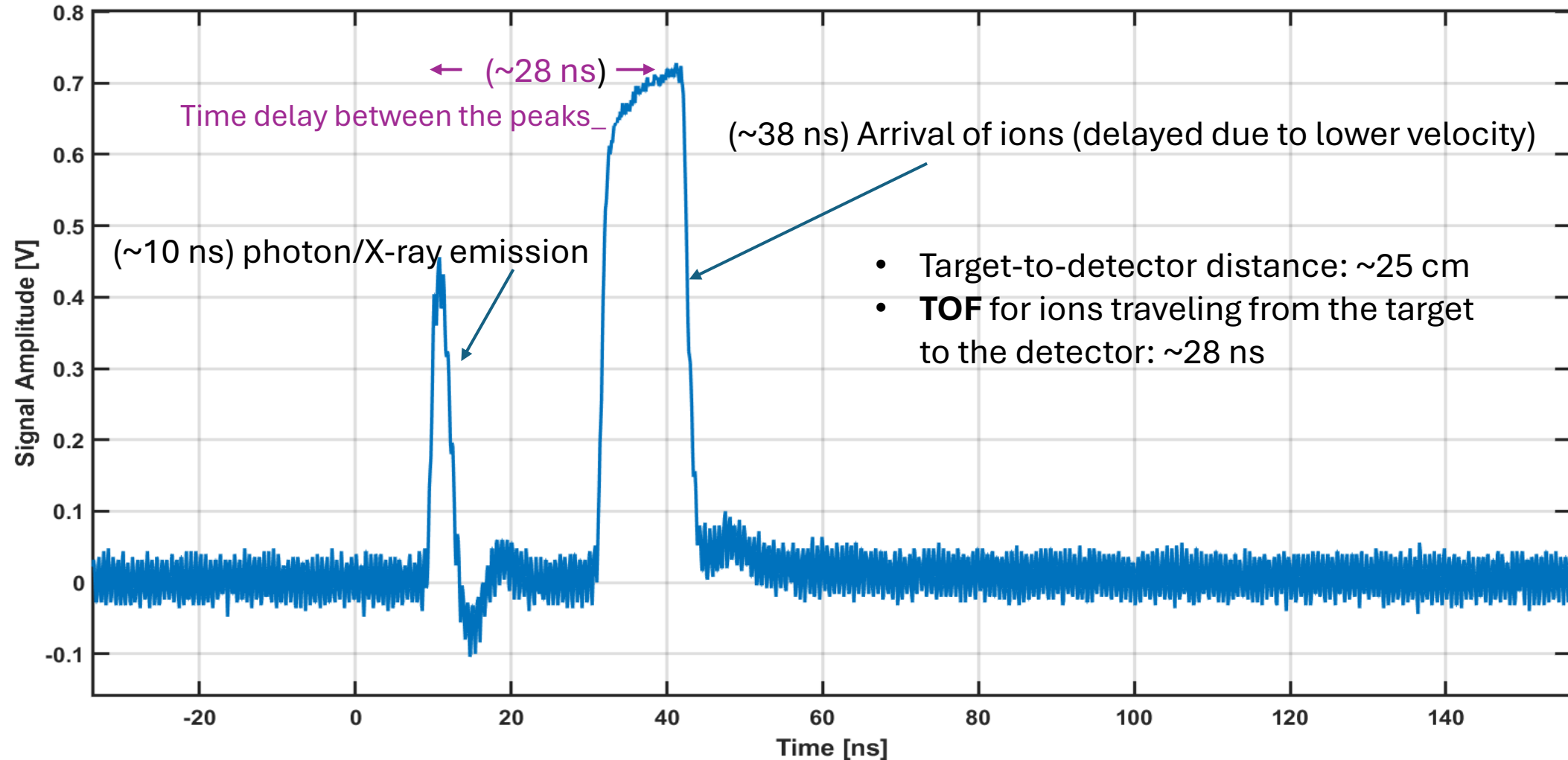
BWD TP Spectrum: Parabola Image with Calculated Parameters

UDMA-Au2_RE_120μm_-800 GDD_192.5 fs_133 shot_bwd_(03.06.2025)



Sample photodiode output signal_covered by 2 μ m Al foil

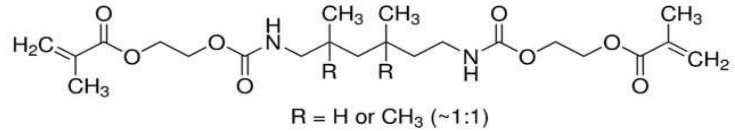
UDMA-Au2_RE_120 μ m_Chirp/GDD Setting: -800 fs²_192.5 fs_133 shot_bwd_(03.06.2025)



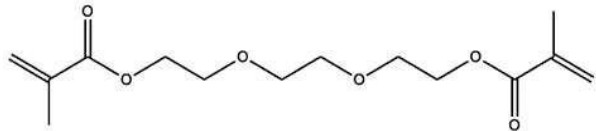
Target Types Used in the Experiments

UDMA: TEGDMA mixture (3:1)

UDMA (Urethane Dimethacrylate), $C_{23}H_{38}N_2O_8$



TEGDMA (Triethylene Glycol Dimethacrylate), $C_{14}H_{22}O_6$



Nanocomposite: UDMA:TEGDMA + resonant Au nanorods

Size of Au nanorods: 85 nm x 25 nm,

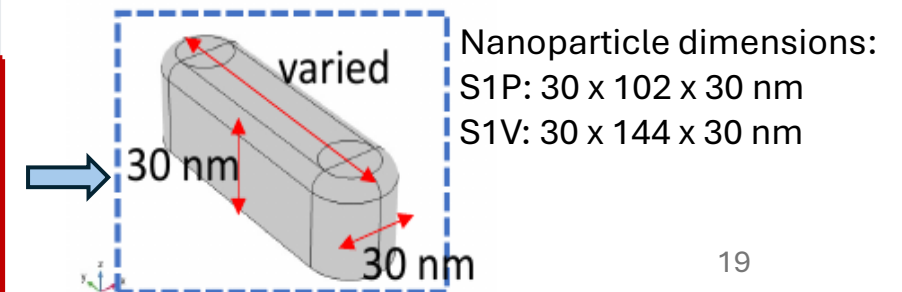
Plasmonic resonance to 795 nm

UDMA: MMA-D : Deuterated Sample (Methyl methacrylate): $C_5D_8O_2$

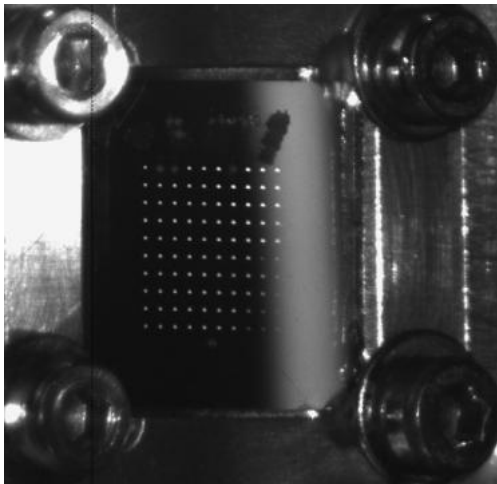
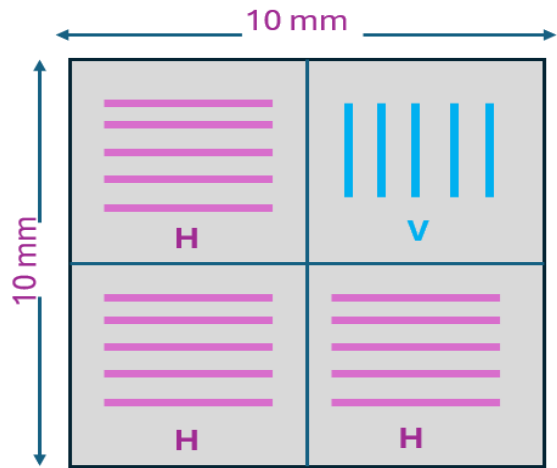
Target type	Composition	Coating	Sample Thickness	Substrate
UDMA-TEGDMA	Au0, Au2_RE	-	5 μ m	-
			120 μ m	Glass
UDMA-TEGDMA + BN	Au0, Au2_RE	-	5 μ m	-
			120 μ m	Glass
UDMA-MMA (Deuterated)	Au0, Au2_RE	-	5 μ m	-
			120 Mm	Glass
Oriented Au nanoparticle structures on Quartz	S1P	PMMA	PMMA: 170 nm Au Nanorods: 30 nm Boron: 50 nm	Quartz
	S1V	-		
	S1P_B	PMMA_Boron		
	S1V_B	Boron		

Au0: No gold nanorods

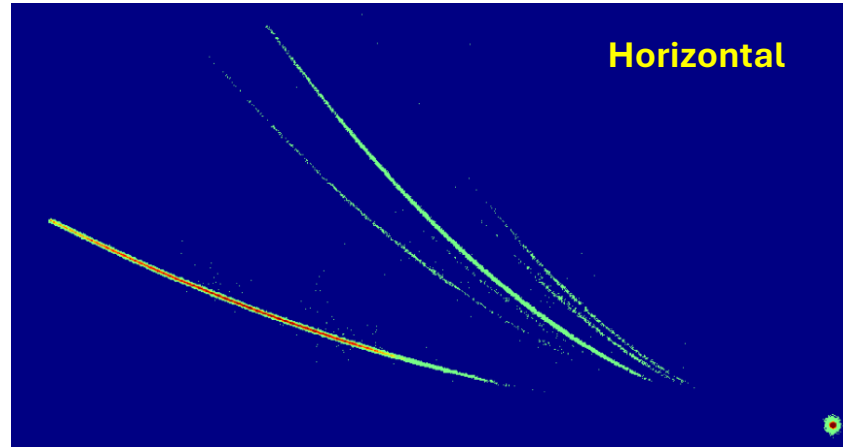
Au2_RE: With resonant Au nanorods



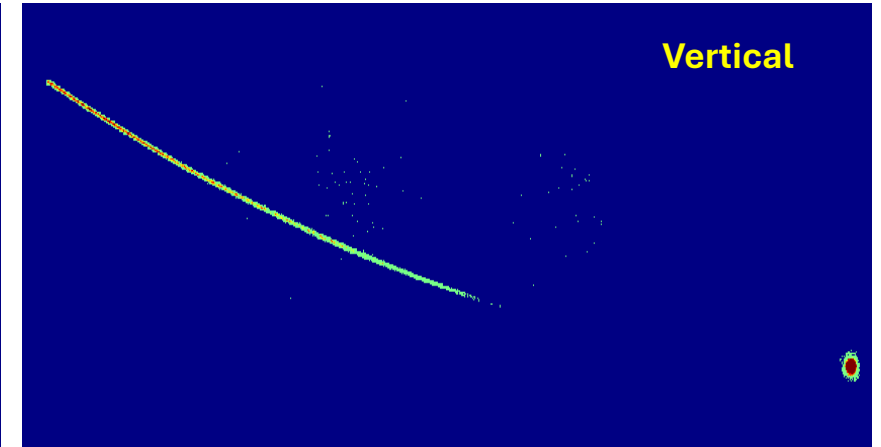
BWD TP Spectrum: Oriented Au nano.rod structures on Quartz Substrate



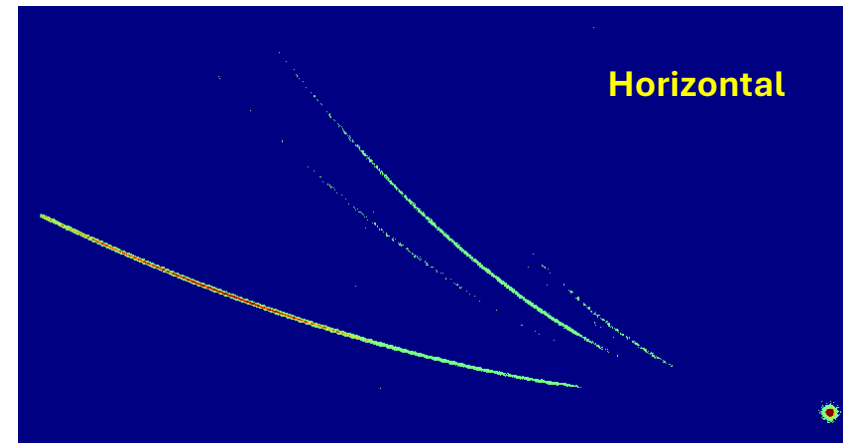
S1V_B_Orient.n.rods +50 nm B_
-500 GDD_120.5 fs_180shot_bwd_(06.06.2025)



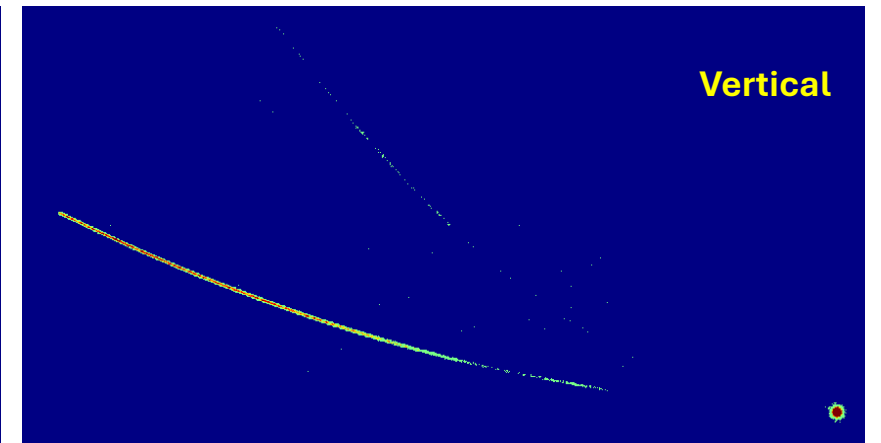
S1V_B_Orient.n.rods +50 nm B_
-500 GDD_120.5 fs_189shot_bwd_(06.06.2025)



S1P_Orient.n.rods+170 nm PMMA_
-500 GDD_120.5 fs_350 shot_bwd_(06.06.2025)



S1P_Orient.n.rods+170 nm PMMA_
-500 GDD_120.5 fs_363 shot_bwd_(06.06.2025)



Conclusion:

- Resonant nanoplasmonic targets, including thin foils and oriented nanorod arrays, were successfully irradiated with high-intensity fs lasers to study FWD and BWD ion beam generation
- Reliable techniques ensured precise sample positioning at the laser focal plane.
- Our TOF detector was implemented for the first time, enabling direct detection of laser-accelerated ion signals.
- Preliminary results were obtained using the SEA laser. And for the first time, high-intensity measurements (over 100 mJ, and 10^{19} W/cm²) were performed with the SYLOS3 laser; data evaluation is ongoing, and further measurements are planned.
- The analysis and discussion are still ongoing, and we hope to get some conclusive results.

Thank You For Your Attention