Advancing Resolution in LWFA-Driven X-ray Probing of Laser–Nanostructure Interactions

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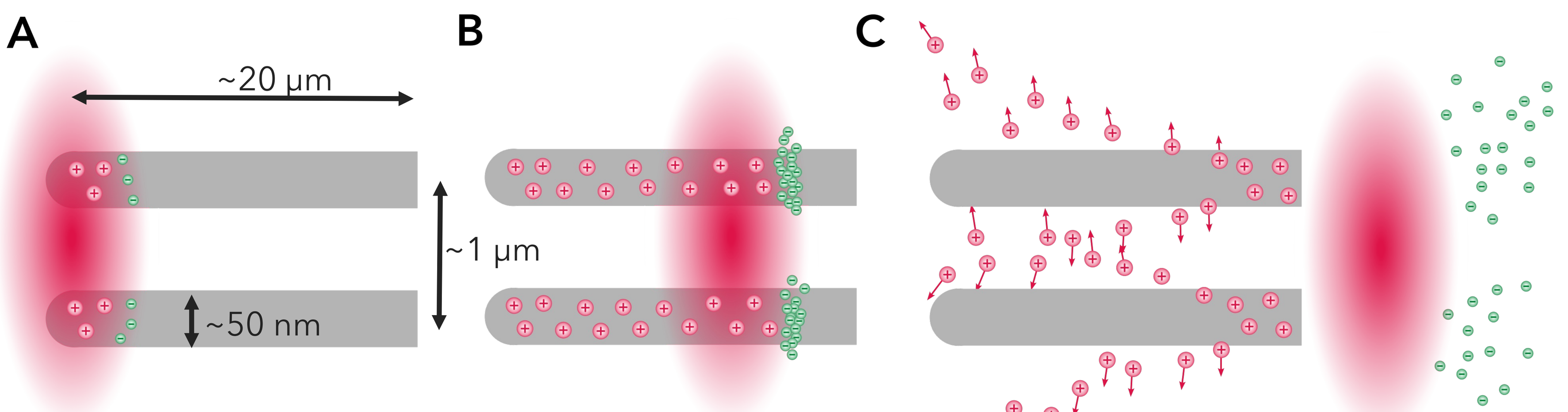
Nuclear fusion represents one of the most promising and at the same time challenging pathways toward a sustainable and reliable industrial-scale energy production. A novel inertial fusion concept (by Marvel Fusion) proposes the use of nanostructured targets [1] in the form of arrays of thin rods that are irradiated by high-intensity laser pulses. The resulting interaction leads to the generation of high energy electrons, ions and radiation, potentially enabling heating and compression of mixed solid fusion fuels [2]. Experimental validation of this approach is crucial, but the underlying dynamics unfold on femtosecond time scales and nanometer length scales, posing significant diagnostic challenges.

In the framework of the VANLIFE collaboration, this work investigates the feasibility of probing nanostructured targets during the laser-target interaction using laser-driven plasma-wakefield accelerators for X-ray generation, delivering ultrashort and high-brightness pulses via either Betatron radiation or inverse Compton scattering. We want to explore possibilities to use these radiation sources to probe the interaction at such nano targets and gain a better understanding of diagnostic challenges in probing rapidly expanding, high-density laser-plasma interactions.

MARVEL FUSION'S NANO ACCELERATOR CONCEPT [1]

A. Relativistic, ultra-short laser pulse propagates along the rod axis. The ponderomotive force of the light field expels electrons.
B. As the pulse progresses, all electrons are stripped from the rods and the (heavy) ions roughly remain in their original structure.
C. Eventually, the remaining ions Coulomb-explode radially to MeV energies.



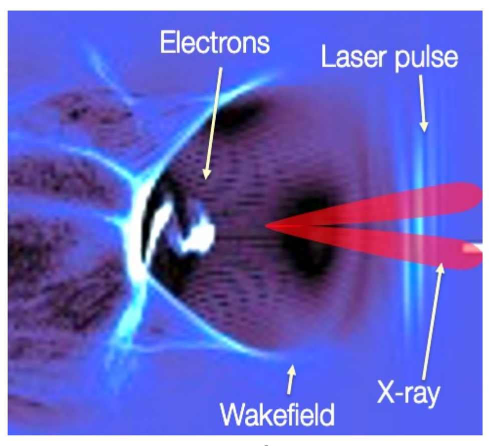
Our goal: Image the electron expulsion process with X-rays!

X-RAY GENERATION

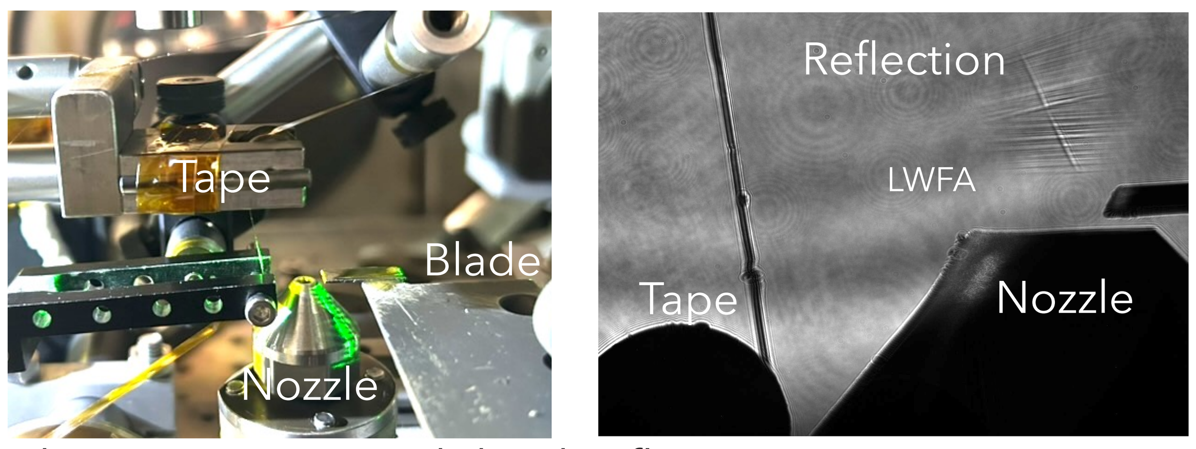
- **Betatron**
  - High photon numbers, broad spectrum
  - Source few µm but difficult to control
- **Thomson (inverse Compton) Scattering**
  - Spectrum governed by energy, bandwidth, divergence of electrons
  - Hard to obtain soft X-rays

X-RAY DETECTION

- **"Proxitronic" indirect CCD**
  - Scintillator: harder X-rays visible
  - Eff. pixel size too large (60µm)
- **Princeton Instruments direct CCD**
  - Efficiency drops around 15 keV
  - Small pixel size of 13.5 µm



Betatron radiation



Thomson setup with backreflecting tape

RESOLUTION LIMITING FACTORS FOR 10 KEV

PIXEL SIZE

$$s_{pixel} \approx 13.5\,\mu\text{m}$$

SOURCE SIZE BLURR

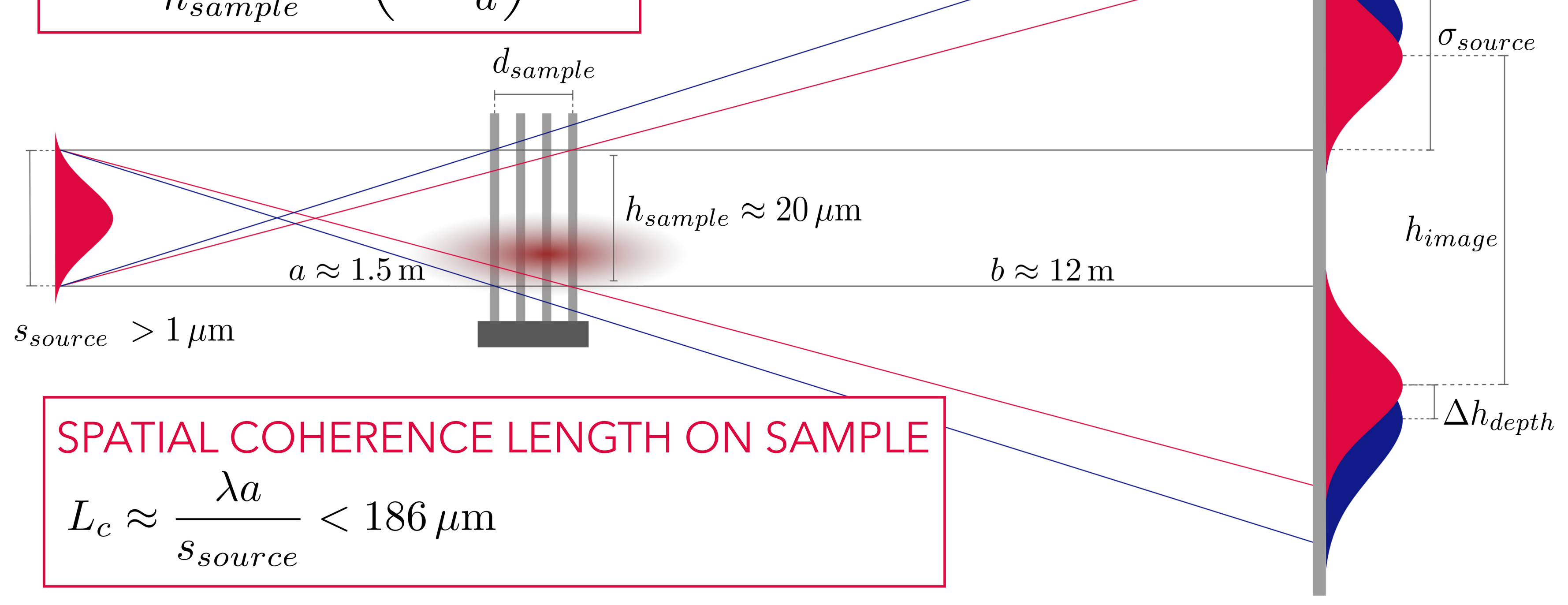
$$\sigma_{source} = \frac{b}{a} s_{source} > 9\,\mu\text{m}$$

DIFFRACTION SMEARING

$$F = \frac{h_{sample}^2}{\lambda b} \approx 0.27$$

MAGNIFICATION

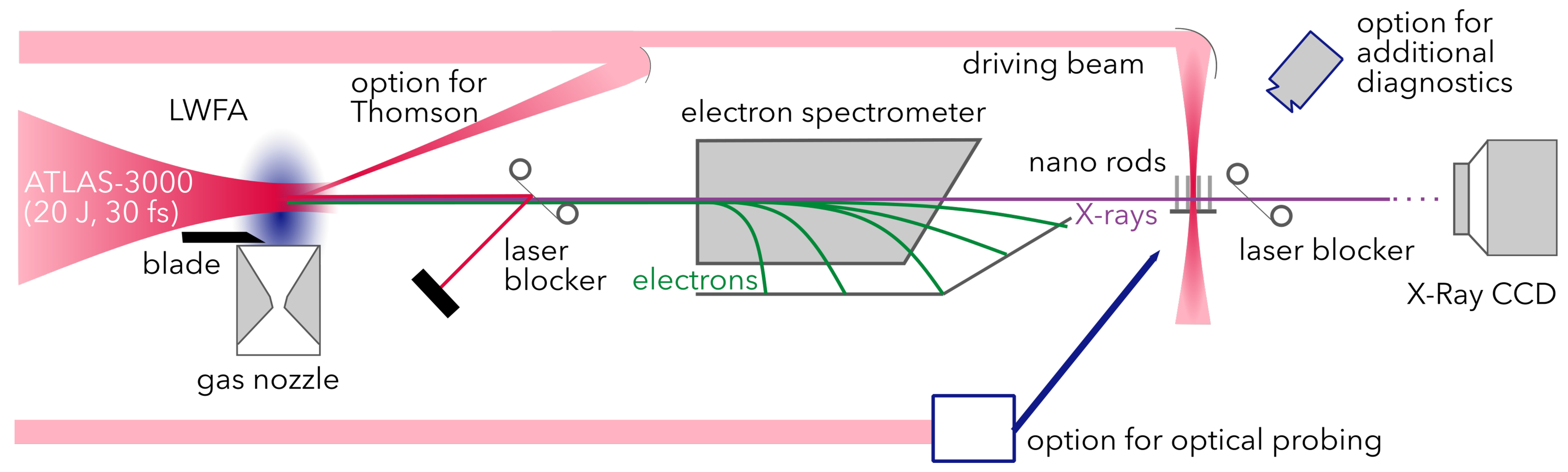
$$M = \frac{h_{image}}{h_{sample}} = \left(1 + \frac{b}{a}\right) \approx 9$$



SPATIAL COHERENCE LENGTH ON SAMPLE

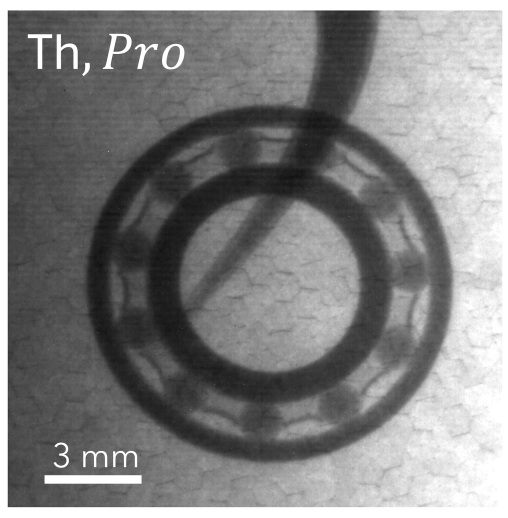
$$L_c \approx \frac{\lambda a}{s_{source}} < 186\,\mu\text{m}$$

ELECTRON ACCELERATION AND X-RAY GENERATION SETUP

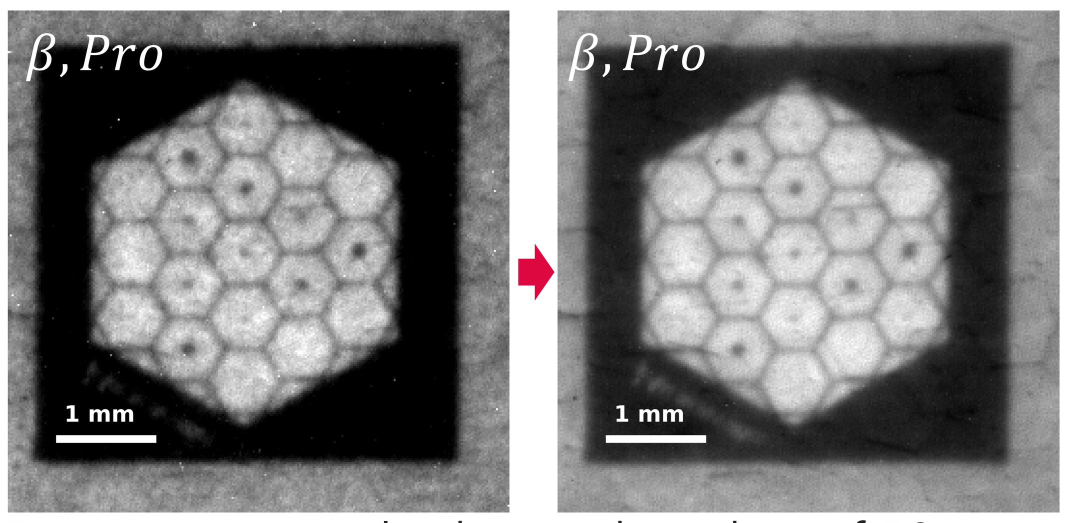


EARLY EXPERIMENTAL X-RAY IMAGES

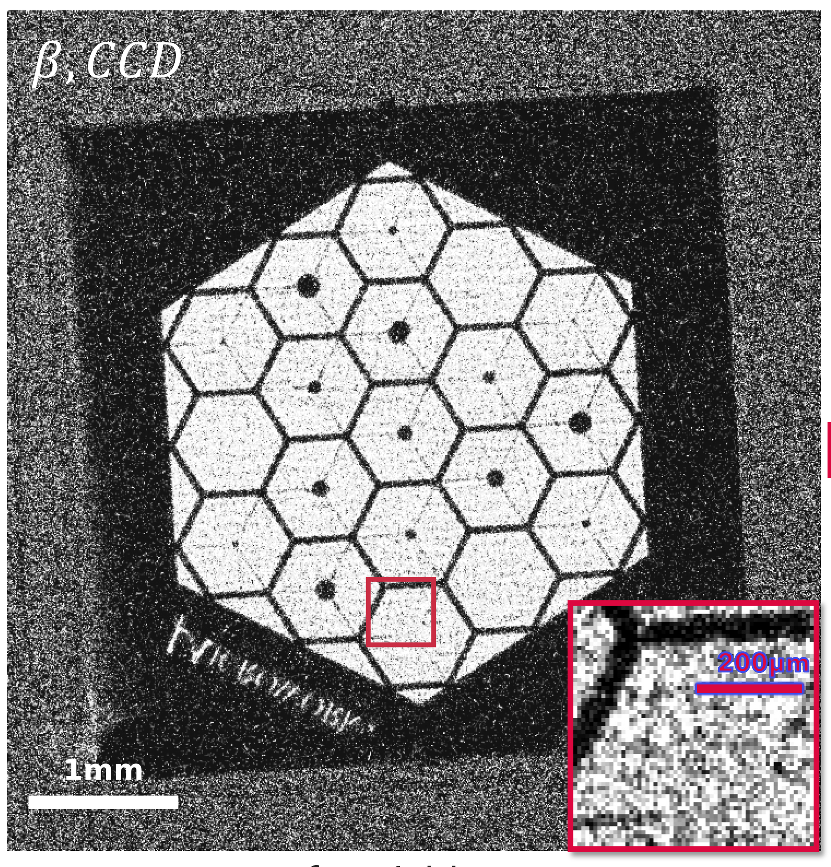
Th = Thomson, β = Betatron
Pro = Proxitronic, CCD = PI CCD



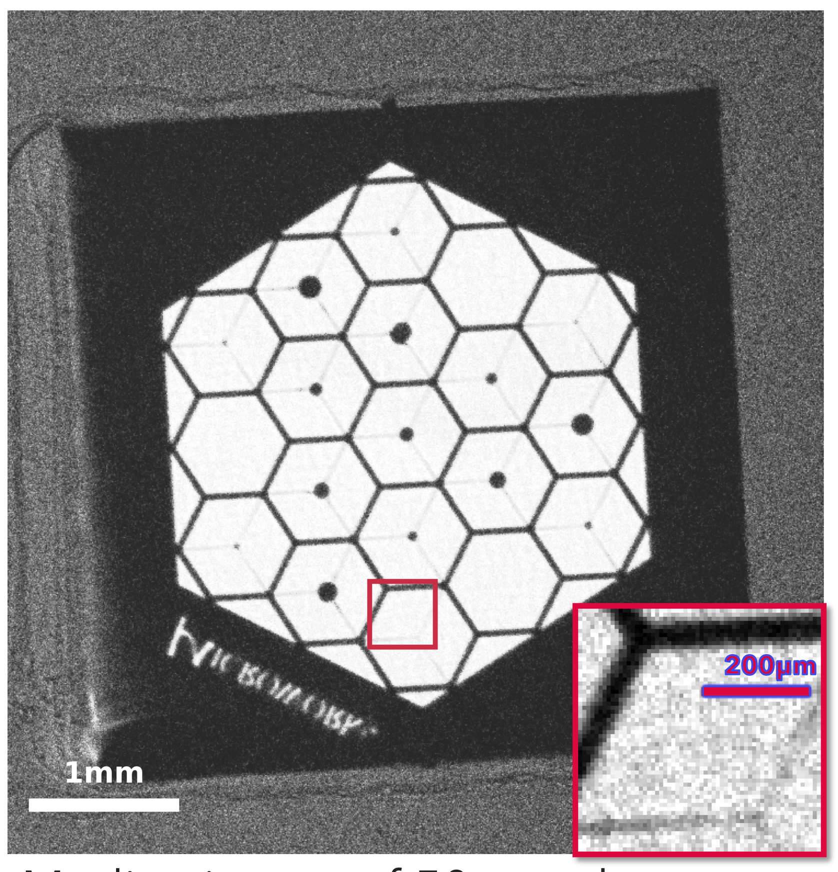
Ball bearing (20 median)



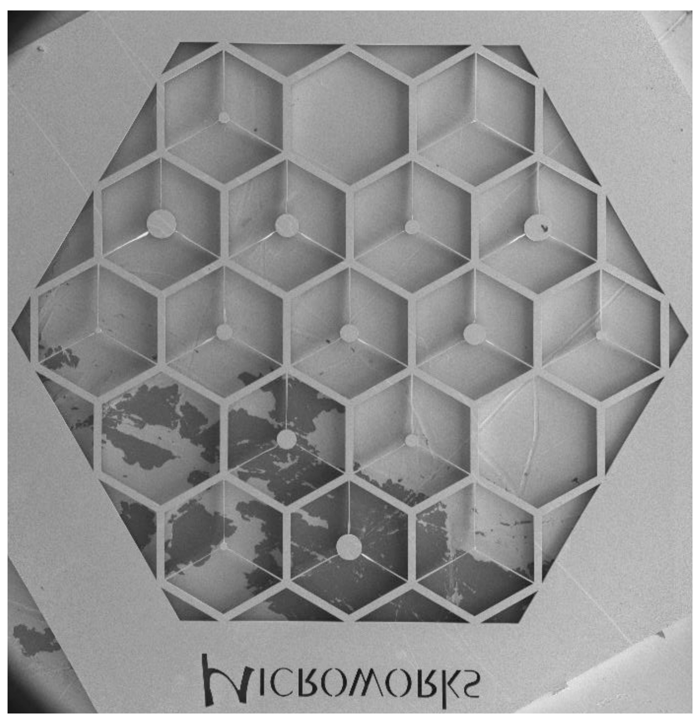
Beam stops, single shot and median of 50



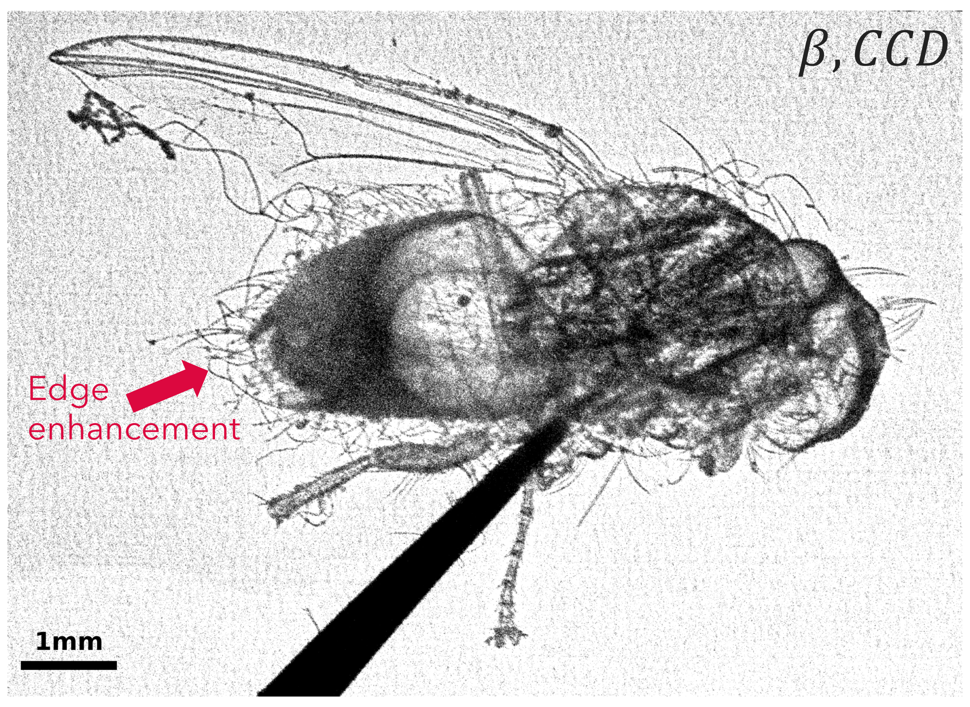
Raw image of gold beam stops



Median image of 50 raw shots.



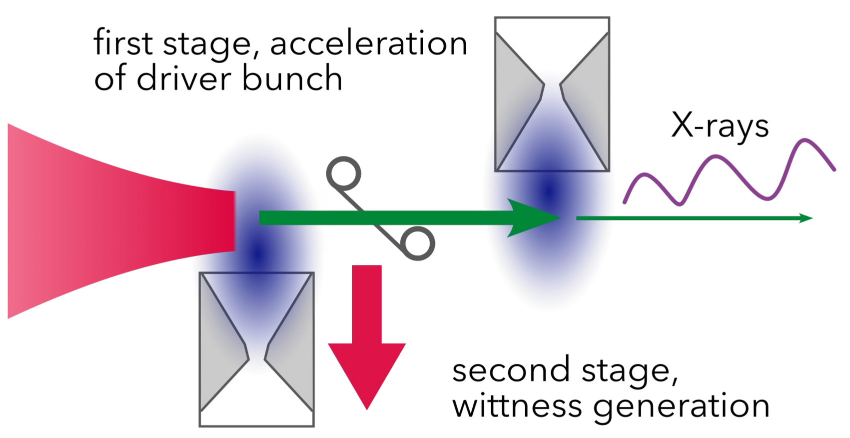
Electron microscopy image [3]



House fly (median filter of 19 shots)

OUTLOOK AND IDEAS

- Challenge 1: Images from first beam times: High energy hits → hard X-rays present in signal. Electron acceleration should be tuned towards lower energies to increase Betatron yield for <20 keV.
  - Idea 1a: Optimize electron spectrum by systematically tuning density and using short nozzles or late injections via wire injectors.
  - Idea 1b: Explore detector options – scintillator-based but still small pixel
- Challenge 2: If the detector is put further away from the samples, the system will eventually become source-size limited.
  - Idea 2a: Systematically measure effective (Betatron) source sizes and photon numbers
  - Idea 2b: Exploration of smaller source sizes via additional PWFA with the witness bunch of potentially smaller diameter.
- Idea 3: Potentially explore optical/UV/xUV auxiliary probing techniques



iFAST INFN VANLIFE

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REFERENCES
[1] H. Ruhl and G. Korn, arXiv:2212.1294 (2022)
[2] H. Ruhl, et al., J. Appl. Phys. 137, 215904 (2025)
[3] Image from Microworks GmbH, Technical documentation for "sub7029 Beamstop", Hermann-von-Helmholtz-Platz 6, 76344, Eggenstein-Leopoldshafen

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