Progress toward a short-pulse laser-driven x-pinch on the Titan laser

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2/11/26

Funding and Collaborators

- University of Michigan
  - P. T. Campbell, V. Contreras, I. Huegel, K. V. Kelso, S. R. Klein, T. Nutting, I. G. Rhind, J. P. Schell, M. Springstead, R. D. McBride, C. C. Kuranz
- General Atomics
  - M. J.-E. Manuel

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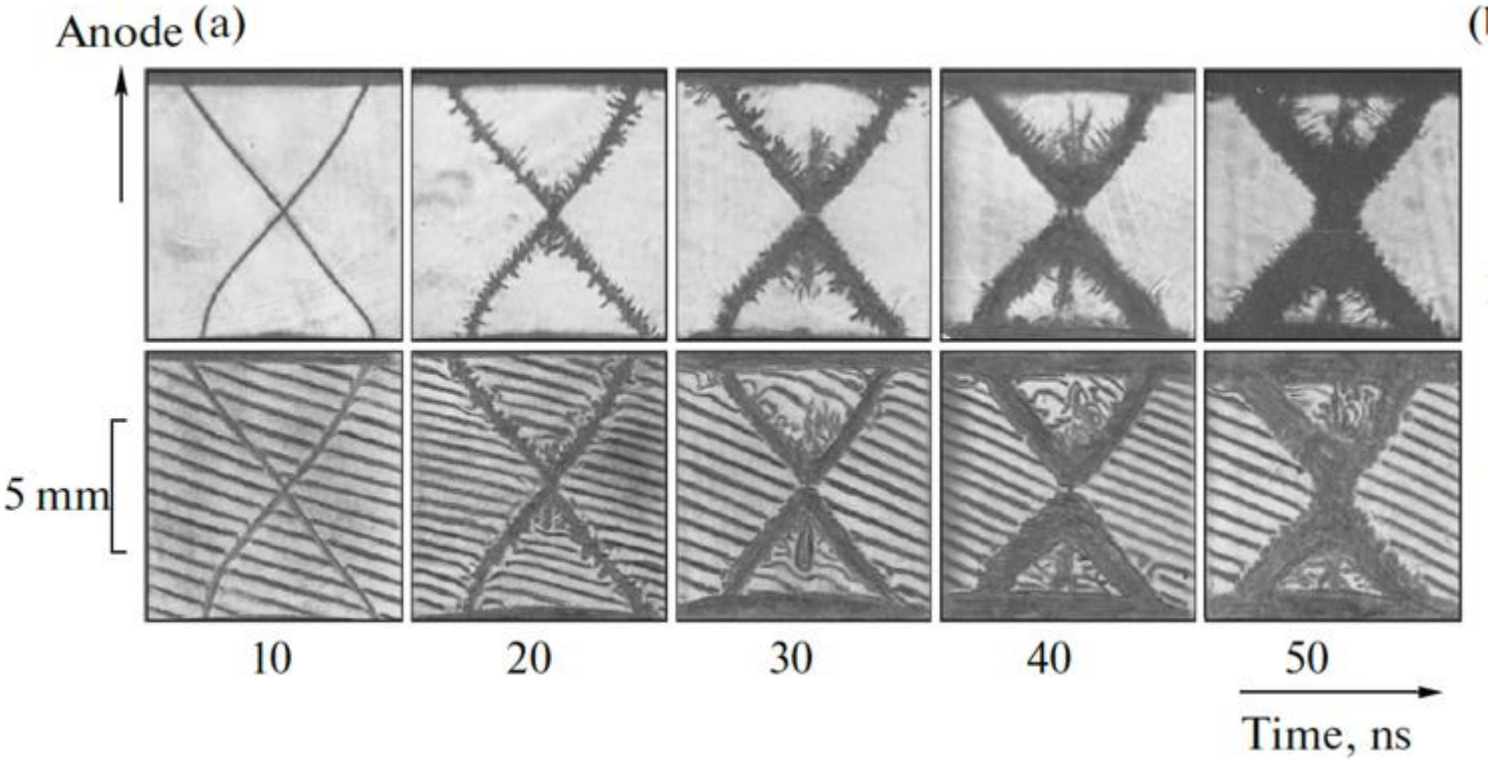
Why laser-driven x-pinches?

- X-pinch dynamics and interesting use cases
- Experiment setup on Titan and target details
- Preliminary data analysis from the Titan experiments

Goal: Use the currents from a short pulse laser-solid interaction to drive a magnetic pressure-driven pinch

- X-pinches are sources for high resolution radiography and other advanced x-ray diagnostics

- X-pinches are also unique ways to study extreme plasma conditions (>solid density at ~1 keV)
  - Magnetic and thermal pressures >100 Mbar



Pikuz et al. Plasma Physics Reports, 2015, Vol. 41, No. 4.; J. Read et al. Rev. Sci. Instrum. 95, 023508 (2024); M. P. Valdivia et al. Plasma Phys. Control. Fusion 64 (2022) 035011; D. B. Sinars PRL 109, 155002 (2012)

The pulsed power have demonstrated x-pinches as a source for several advanced x-ray diagnostics

Review of Scientific Instruments ARTICLE pubs.aip.org/aip/rsi

Point projection radiography of electromagnetically accelerated flyer plates with an external X-pinch driver

Cite as: Rev. Sci. Instrum. 95, 023508 (2024); doi: 10.1063/5.0185351
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J. Read,[1,a)] G. Burdiak,[1] S. N. Bland,[2] L. S. Caballero Bendixsen,[1] L. Paxton-Fear,[1] N. Niasse,[1] C. Dobranszki,[1] and N. Hawker[1]

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Typical x-pinch

< 10 micron source size

< 50 ps duration

The pulsed power have demonstrated x-pinches as a source for several advanced x-ray diagnostics

Review of Scientific Instruments ARTICLE pubs.aip.org/aip/rsi

PHYSICS OF PLASMAS **19**, 056302 (2012)

Time and space resolved measurement of the electron temperature, mass density and ionization state in the ablation plasma between two exploding Al wires[a)]

P. F. Knapp,[1,b),c)] S. A. Pikuz,[1] T. A. Shelkovenko,[1] D. A. Hammer,[1] and S. B. Hansen[2]
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(Received 7 December 2011; accepted 25 January 2012; published online 19 March 2012)

We have determined the properties of plasma around and between two exploding wires using high-resolution x-ray absorption spectroscopy. Plasma densities and temperatures ranging from $\gtrsim 0.1\ g/cm^3$ and a few eV to less than $0.01\ g/cm^3$ and 30 eV have been measured in experiments at Cornell University with two 40 μm aluminum (Al) wires spaced 1 mm apart driven by ~150 kA peak current pulses with 100 ns rise time. The wire plasma was backlit by the 1.4–1.6 keV continuum radiation produced by a Mo wire X-pinch. The spectrometer employed two spherically bent quartz crystals

The pulsed power have demonstrated x-pinches as a source for several advanced x-ray diagnostics

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Plasma Physics and Controlled Fusion
Plasma Phys. Control. Fusion **64** (2022) 035011 (14pp)
https://doi.org/10.1088/1361-6587/ac4b95

Wire, hybrid, and laser-cut X-pinches as Talbot–Lau backlighters for electron density diagnostics

M P Valdivia[1,2,*], G W Collins IV[1,3], F Conti[1] and F N Beg[1]

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[2] Department of Physics and Astronomy, Johns Hopkins University, Baltimore, MD 21218, United States of America
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The pulsed power have demonstrated x-pinches as a source for several advanced x-ray diagnostics

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Plasma Phys. Control. Fusion **64** (2022) 035011 (14pp) https://doi.org/10.1088/1361-6587/ac4b95

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REVIEW OF SCIENTIFIC INSTRUMENTS **86**, 033507 (2015)

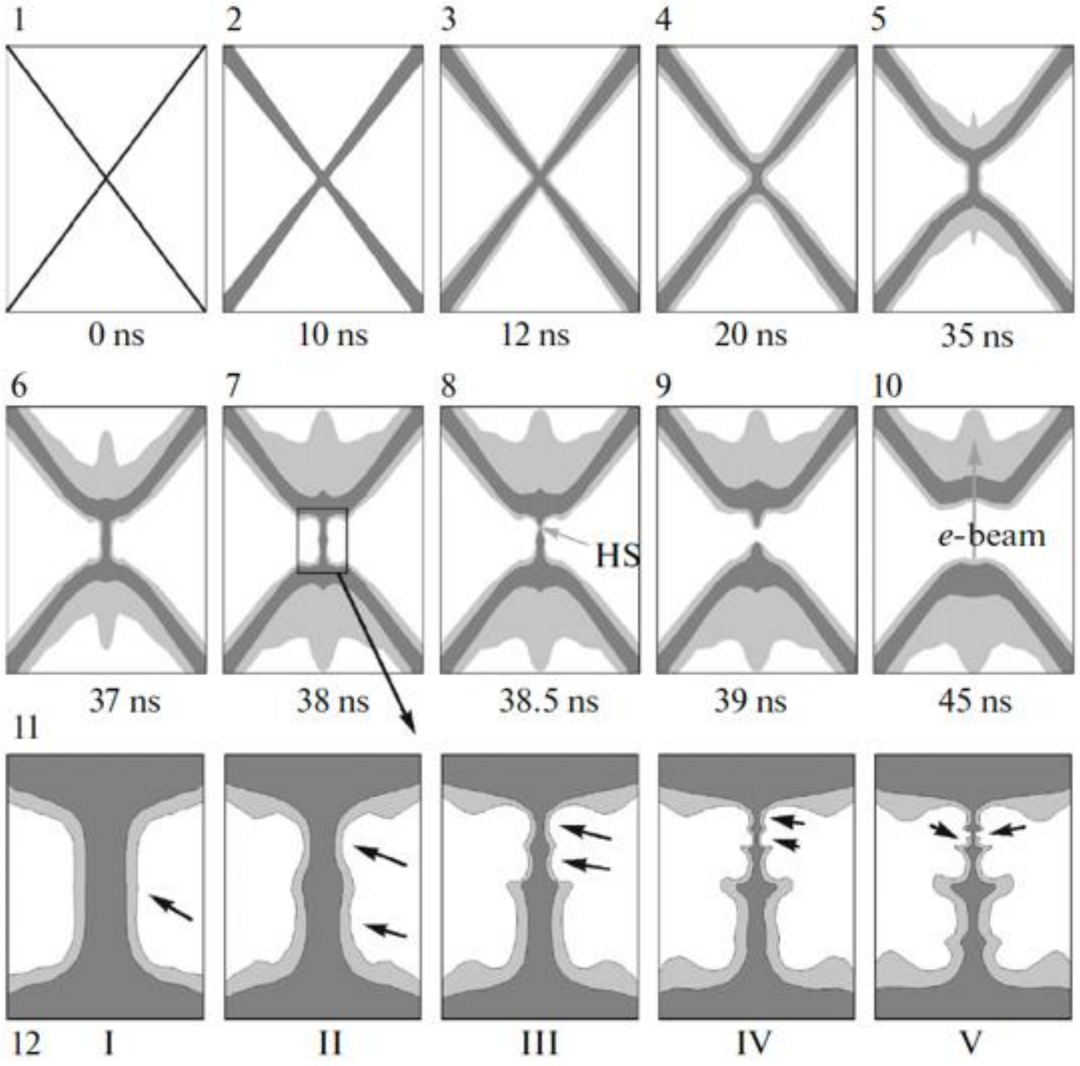
Characteristics of a molybdenum X-pinch X-ray source as a probe source for X-ray diffraction studies

F. Zucchini,[1] S. N. Bland,[2] C. Chauvin,[1] P. Combes,[1] D. Sol,[1] A. Loyen,[1] B. Roques,[1] and J. Grunenwald[1]
[1]*CEA, DAM, GRAMAT, F-46500 Gramat, France*
[2]*Blackett Laboratory, Imperial College, London SW7 2BW, United Kingdom*

(Received 31 October 2014; accepted 8 March 2015; published online 23 March 2015)

X-ray emission from a molybdenum X-pinch has been investigated as a potential probe for the high pressure states made in dynamic compression experiments. Studies were performed on a novel 300 kA, 400 ns generator which coupled the load directly to a low inductance capacitor and switch combination. The X-pinch load consisted of 4 crossed molybdenum wires of 13 μm diameter, crossed

X-pinches are current-driven devices that concentrate the magnetic pressure at some crossing point in the conductor



Wire ablation and neck formation

Micropinching, hot spot formation, and diode e-beam

Detail of micropinch cascade

S. A. Pikuz Plasma Physics Reports, 2015, Vol. 41, No. 4, pp. 291–342; D. B. Sinars Rev. Sci. Instrum. 72, 2948–2956 (2001)

The “rules” of x-pinching

- dI/dt > 1 kA/ns at the leading edge of the current pulse
- Opening angle between 45 and 90 degrees
- > 100 kA peak current
    - There are a few examples of x-pinching below 100 kA

Pikuz et al. Plasma Physics Reports, 2015

Laser experiments could benefit from this capability, but it is not possible at most facilities

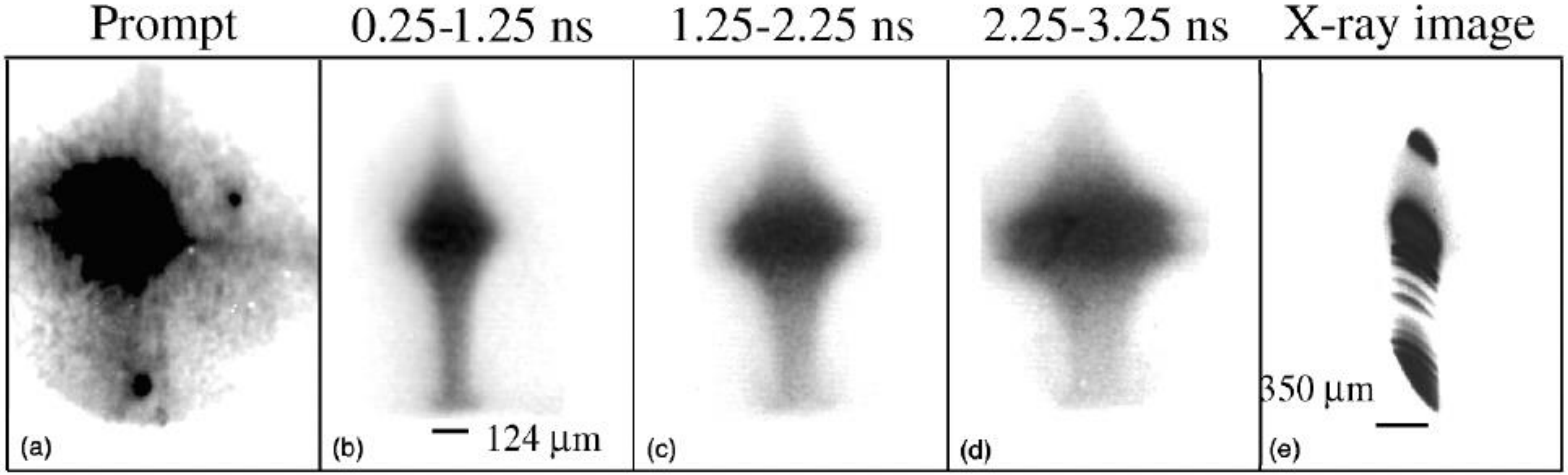
- Co-locating is a technical challenge
  - There are portable pulser techniques
- Damage concerns from debris and soot
- Jitter of ~ 1 ns in the arrival of peak current
- Existing technology does not scale well to high repetition rates

Table 1. Summary of system jitter and pre-fire rates. Values shown are averages over 50 shots.

System	1-σ jitter	Pre-fire rate
Primary trigger generator	300 ps	<0.01%
Trigger Marxes	2.5 ns	<0.1%
Marxes	9.8 ns	<0.001%
Laser triggered gas	5.4 ns	<0.1%
Water switches	<3 ns	<0.0001%
Load current	2.7 ns	<0.1%

M. E. Savage et al. 2011 IEEE Pulsed Power Conference; J. Strucka et al. Matter Radiat. Extremes 7, 016901 (2022); J. Read et al. Rev. Sci. Instrum. 95, 023508 (2024)

The work of Beg et al. observed z-pinching in short-pulse laser driven wires

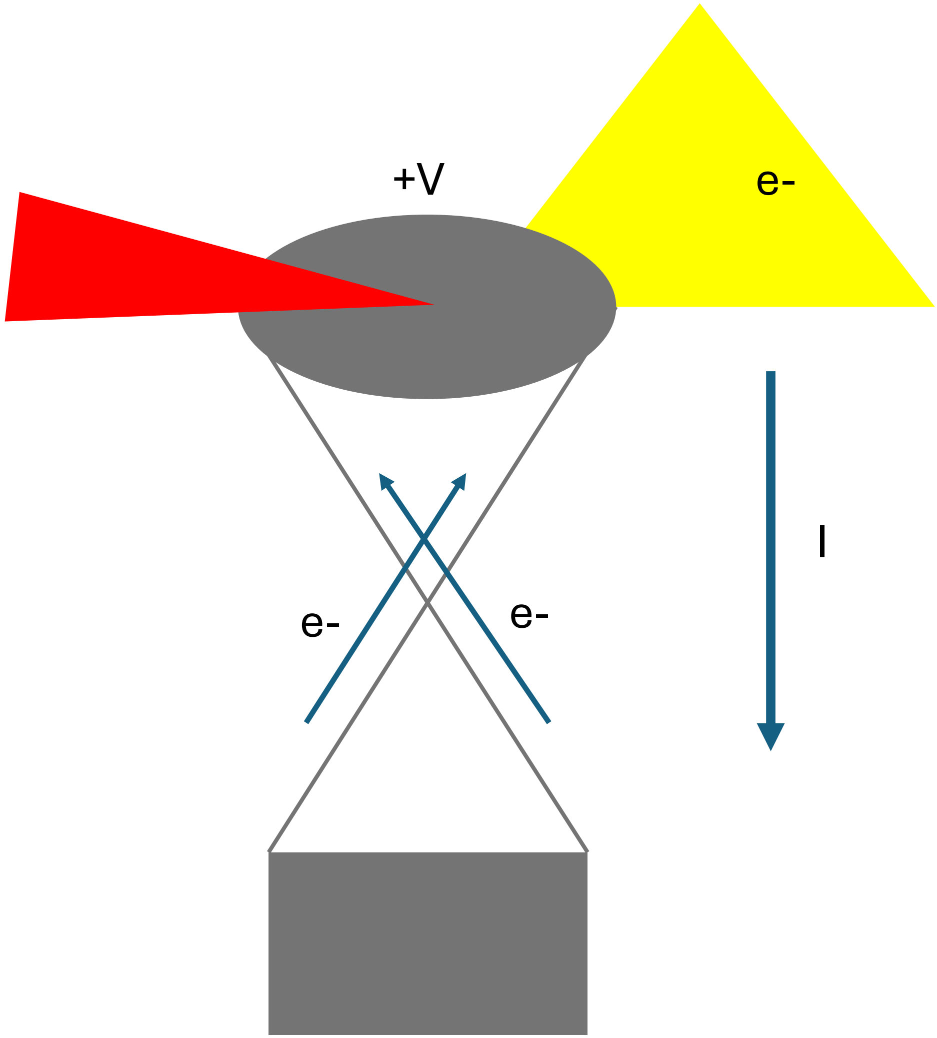


Vulcan laser: 70 J, 1 ps, ~5x10^{19} W/cm^2, Cu wires 20 µm in diameter

There are multiple efforts to utilize and understand laser-induced currents

F. Beg et al. Phys. Rev. Lett. **92**, 095001 (2004); J. Griff-McMahon et al. PHYSICAL REVIEW RESEARCH 6, 033312 (2024); H. Morita et al. PHYSICAL REVIEW E 103, 033201 (2021);
A. Chien et al. Phys. Plasmas 28, 052105 (2021); J. L. Peebles et al. Phys. Plasmas 27, 063109 (2020); L. Yang et al. Matter Radiat. Extremes 9, 047204 (2024);
G. J. Williams J. Appl. Phys. 127, 083302 (2020); M. Ehret et al. Phys. Plasmas 30, 013105 (2023)

The laser-driven x-pinch uses the currents induced from laser-solid interactions to drive large magnetic pressure



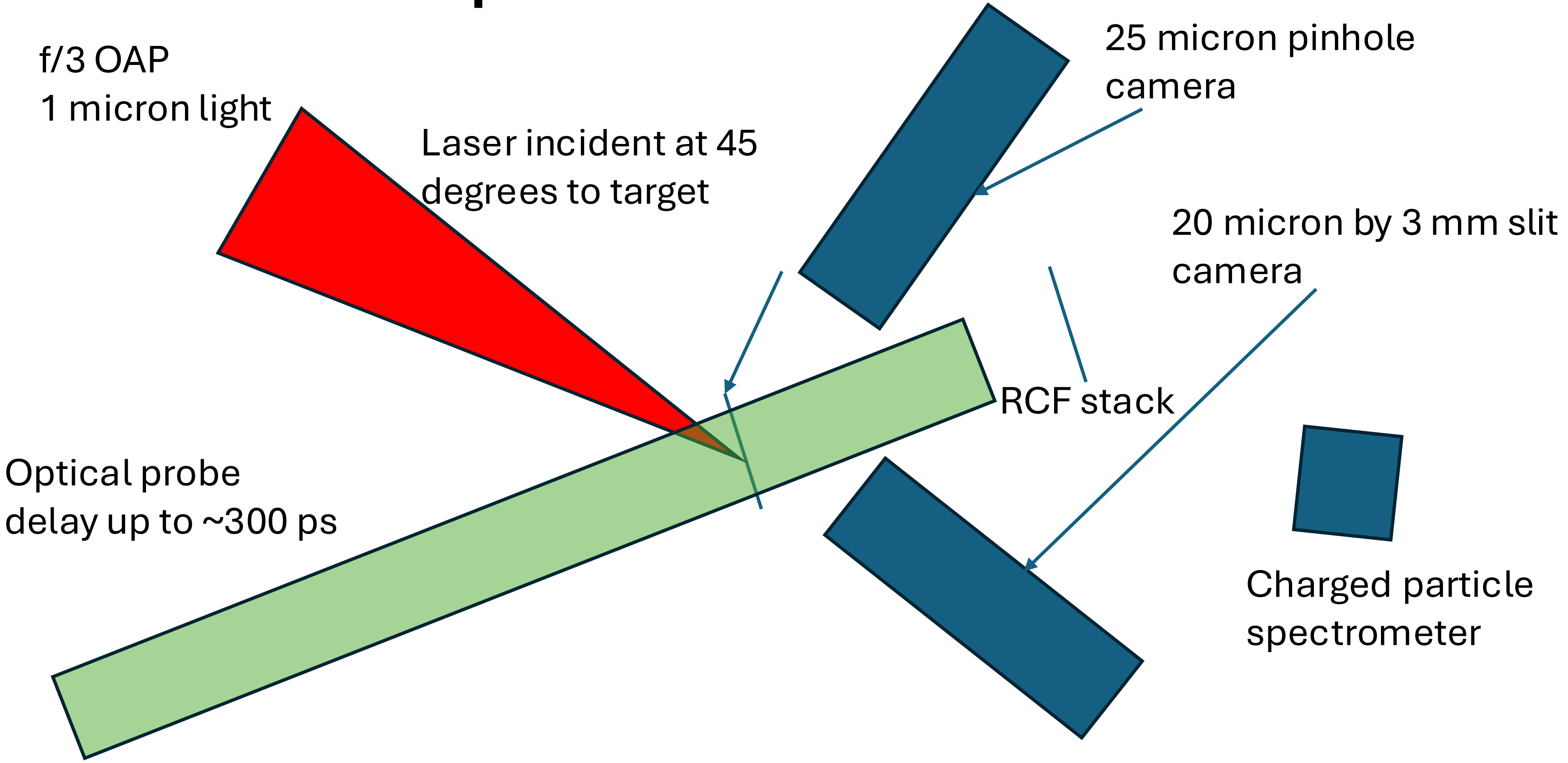
$P_{mag} \propto I^2/r^2$

B. K. Russell *et al*. PHYSICAL REVIEW RESEARCH 7, 013294 (2025); L. Gao *et al*. Appl. Phys. Lett. 127, 094101 (2025); M. Ehret *et al*. Phys. Plasmas 30, 013105 (2023); F. N. Beg et al. Appl. Phys. Lett. 84, 2766–2768 (2004)

A recent LaserNetUS experiment at the Titan laser explored laser-driven x-pinches

Titan Laser at LLNL:
~120 J in ~1 ps
~1x10^{20} W/cm^2

Optical probe:
10s mJ in ~ 1ps
2w



The targets used two different manufacturing techniques, which provided varying surface roughness

About 13 micron wires

~20 micron wide cross over region

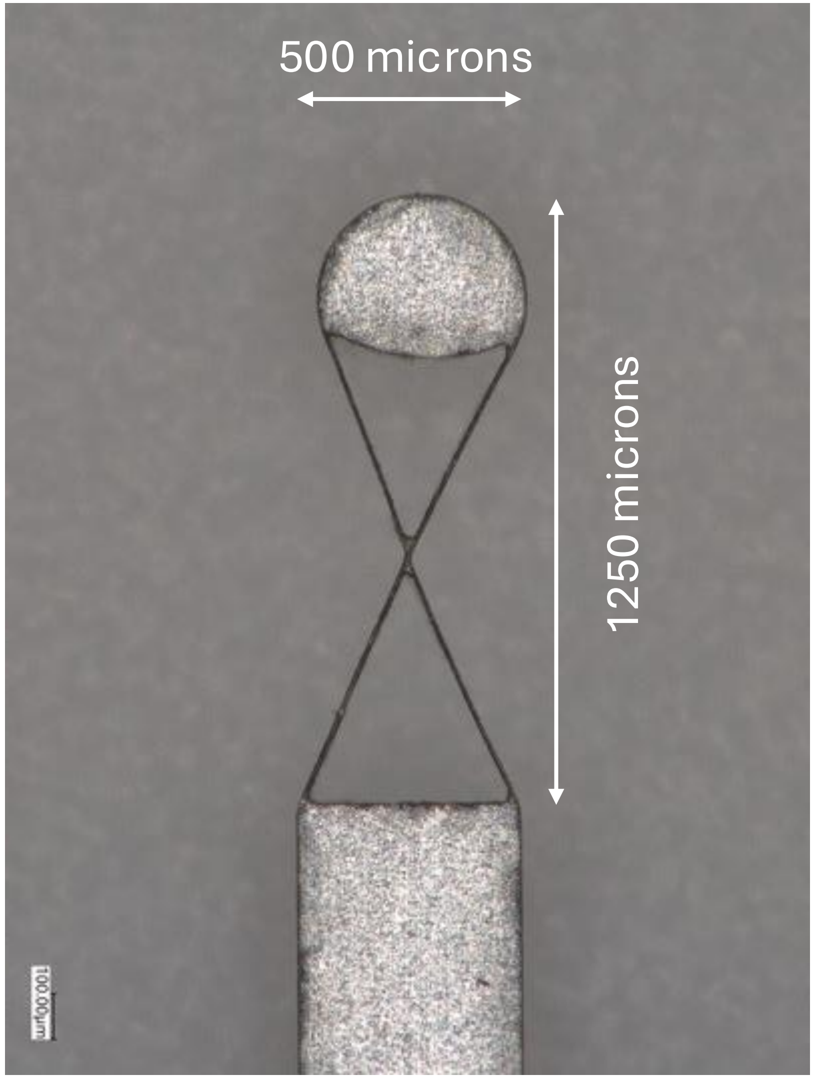
~80 micron tall cross over region

~$90/part

Potomac photonics

Thanks to MiTRF for Target support

Al laser-cut targets



Cu electroformed targets

About 7-18 micron wires

~15-26 micron wide cross over region

~30-50 micron tall cross over region

About $1500 for tooling and ~$1/part

Gilder grids

Recent experiments on Titan use similar diagnostics to pulsed power experiments to observe x-pinches

- A 10s mJ short pulse (~1 ps) probe beam provides shadowgraphy measurements
- An Electron-Proton-Positron Spectrometer collects the accelerated particles
- X-ray pinhole cameras observes time-integrated emission images
- A radiochromic film stack images the protons emitted normal to the rear surface of the target

Thanks to Hui Chen and Jackson Williams for use of the EPPS

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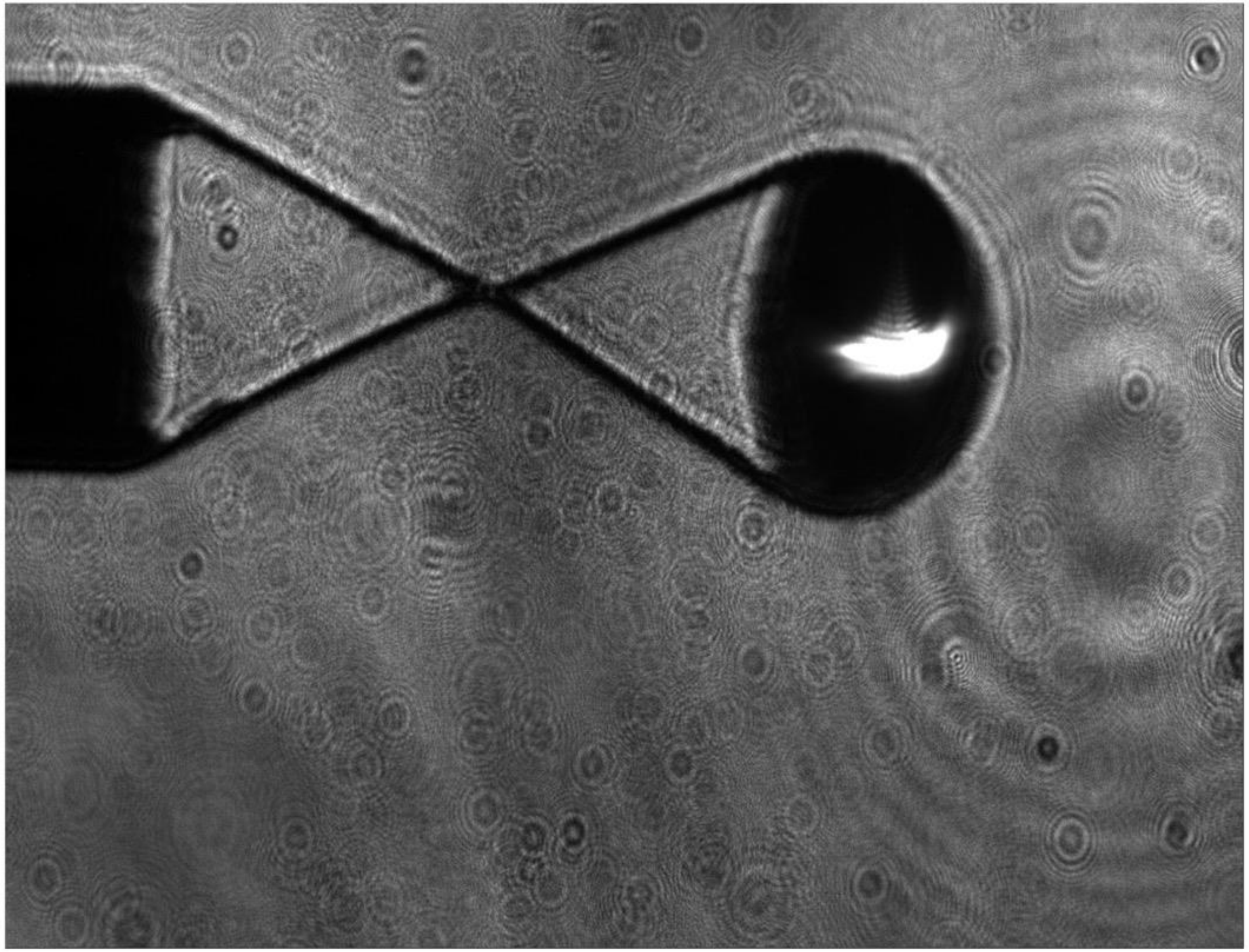
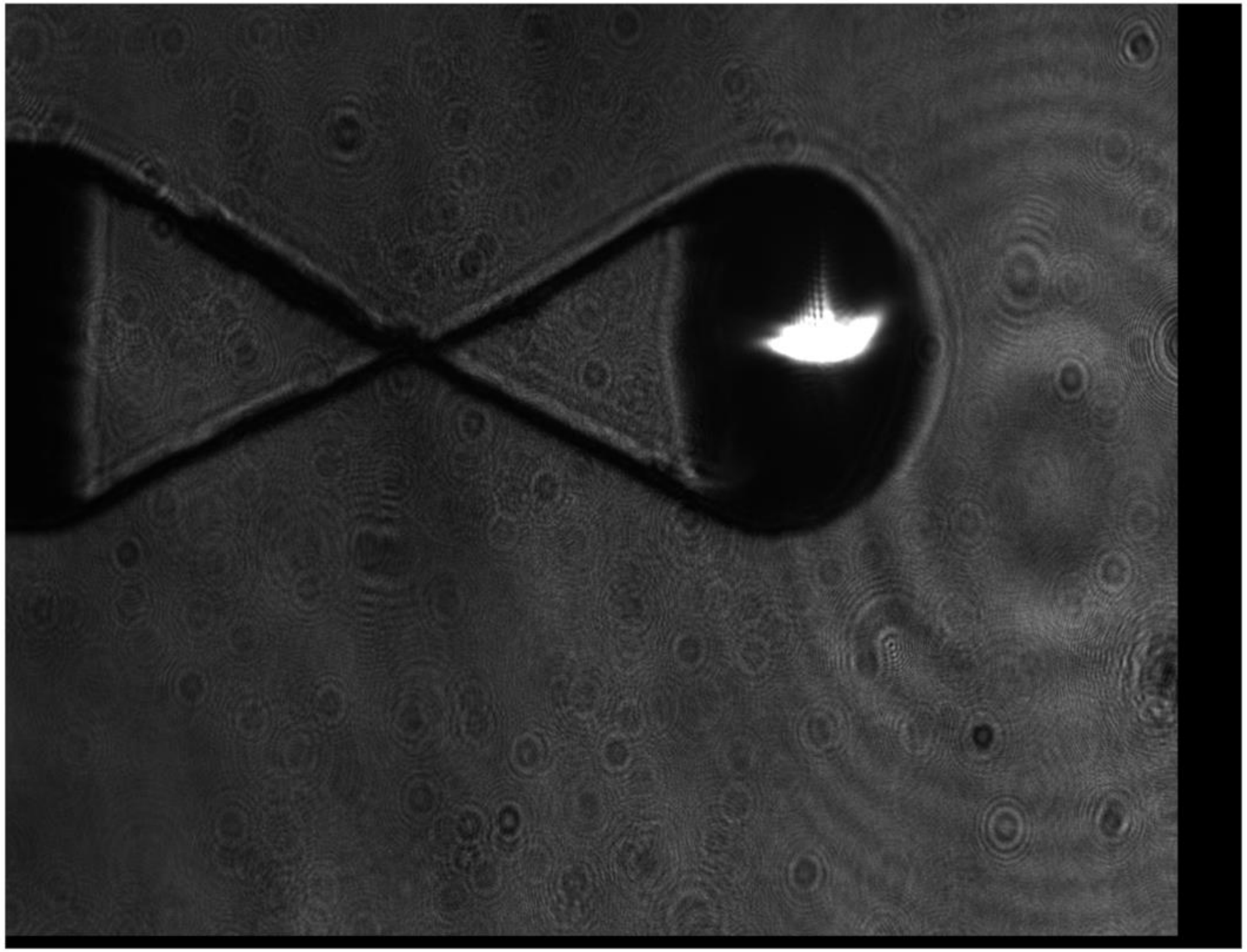
Optical probe data shows rapid onset of instability in the Al x-pinch targets

Al x-pinch 0 ps



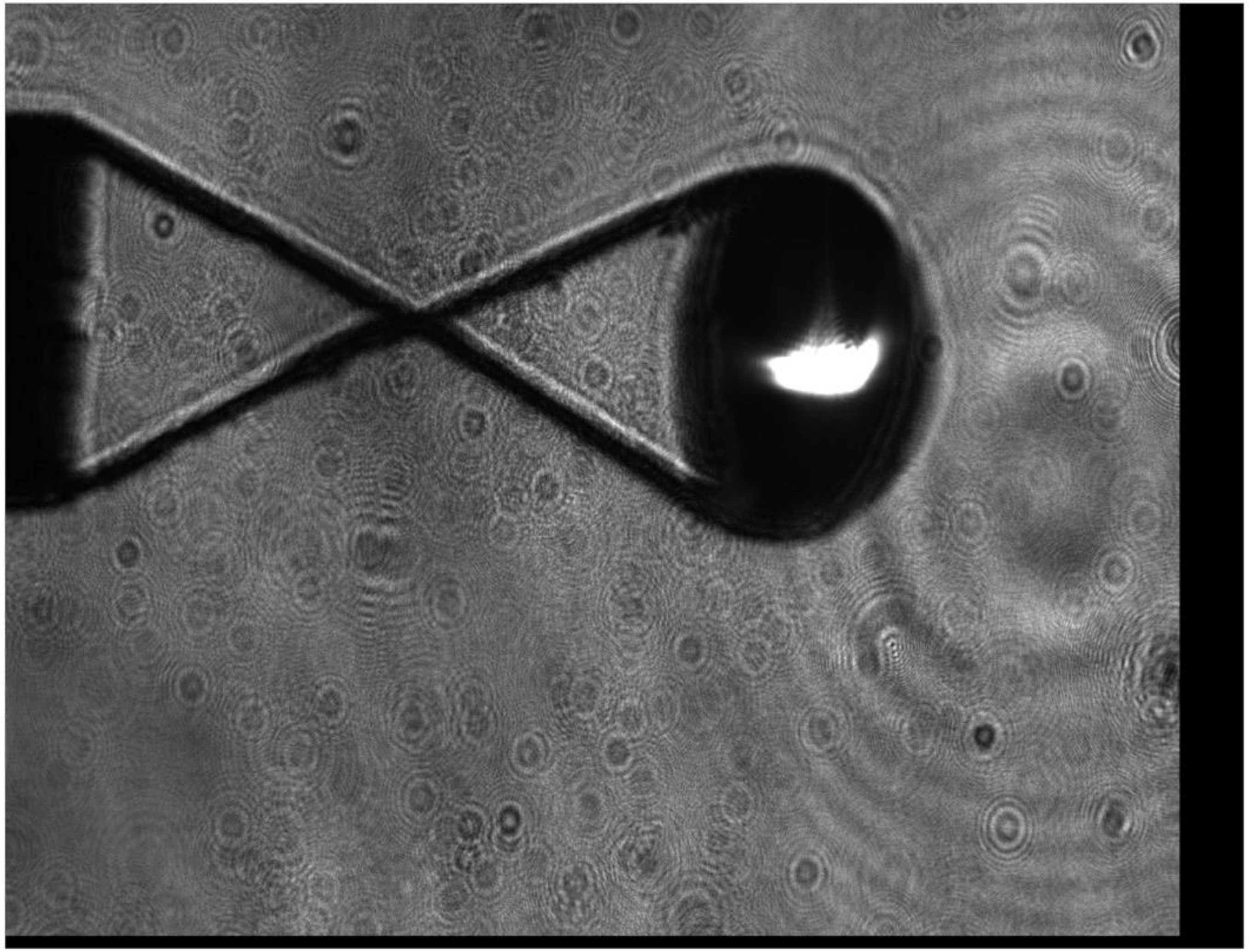
Optical probe data shows rapid onset of instability in the Al x-pinch targets

Al x-pinch 5 ps



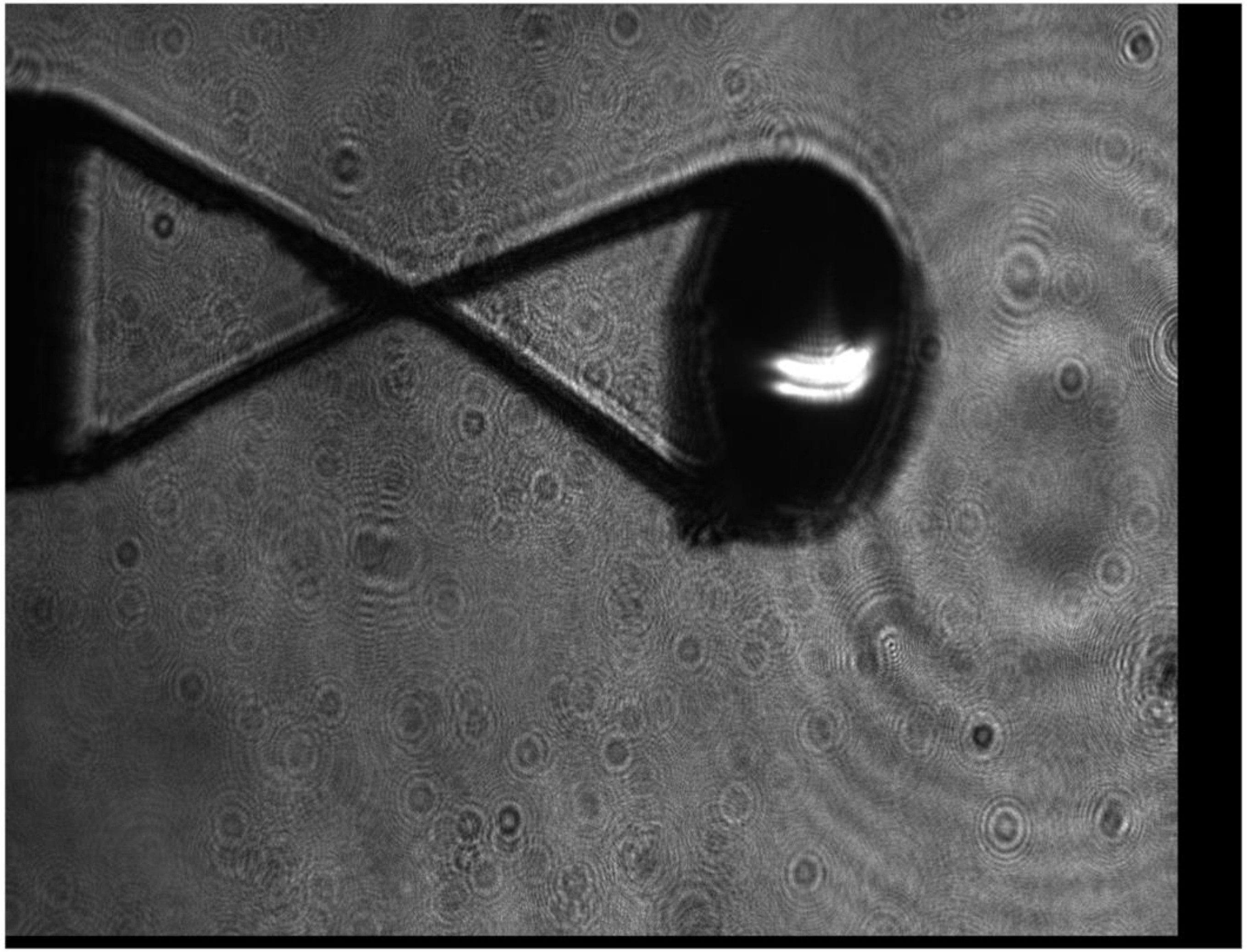
Optical probe data shows rapid onset of instability in the Al x-pinch targets

Al x-pinch 20 ps



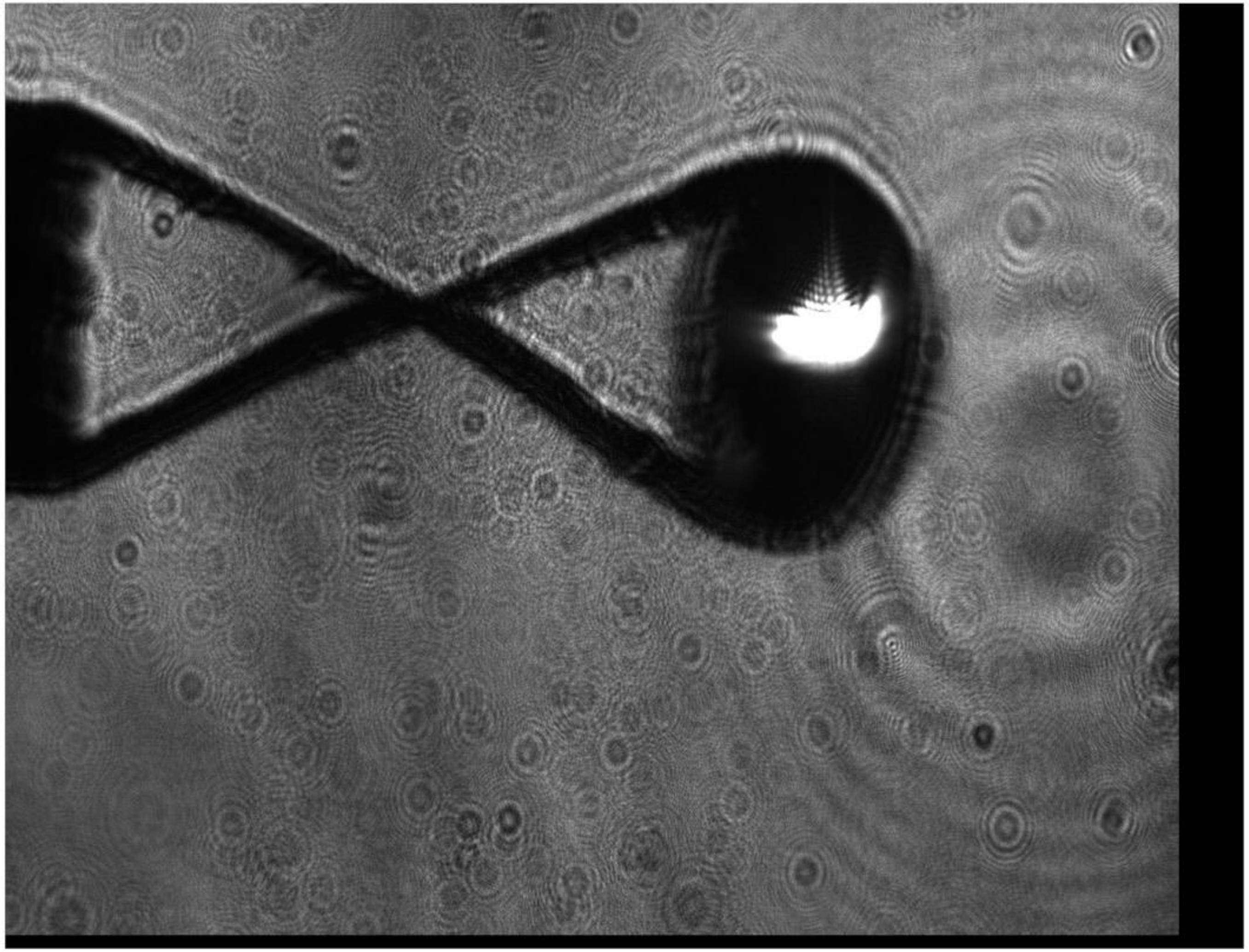
Optical probe data shows rapid onset of instability in the Al x-pinch targets

Al x-pinch 40 ps



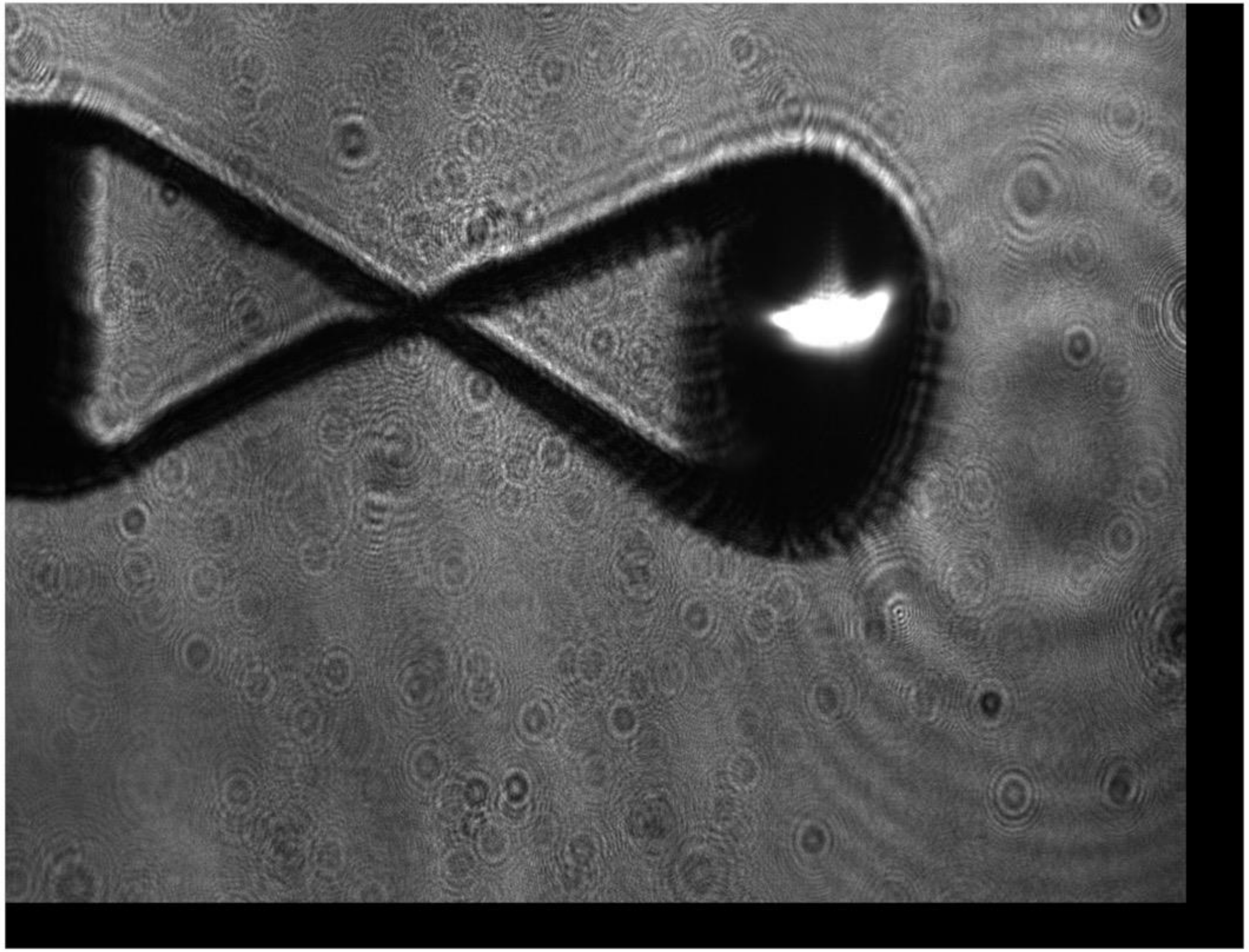
Optical probe data shows rapid onset of instability in the Al x-pinch targets

Al x-pinch 60 ps



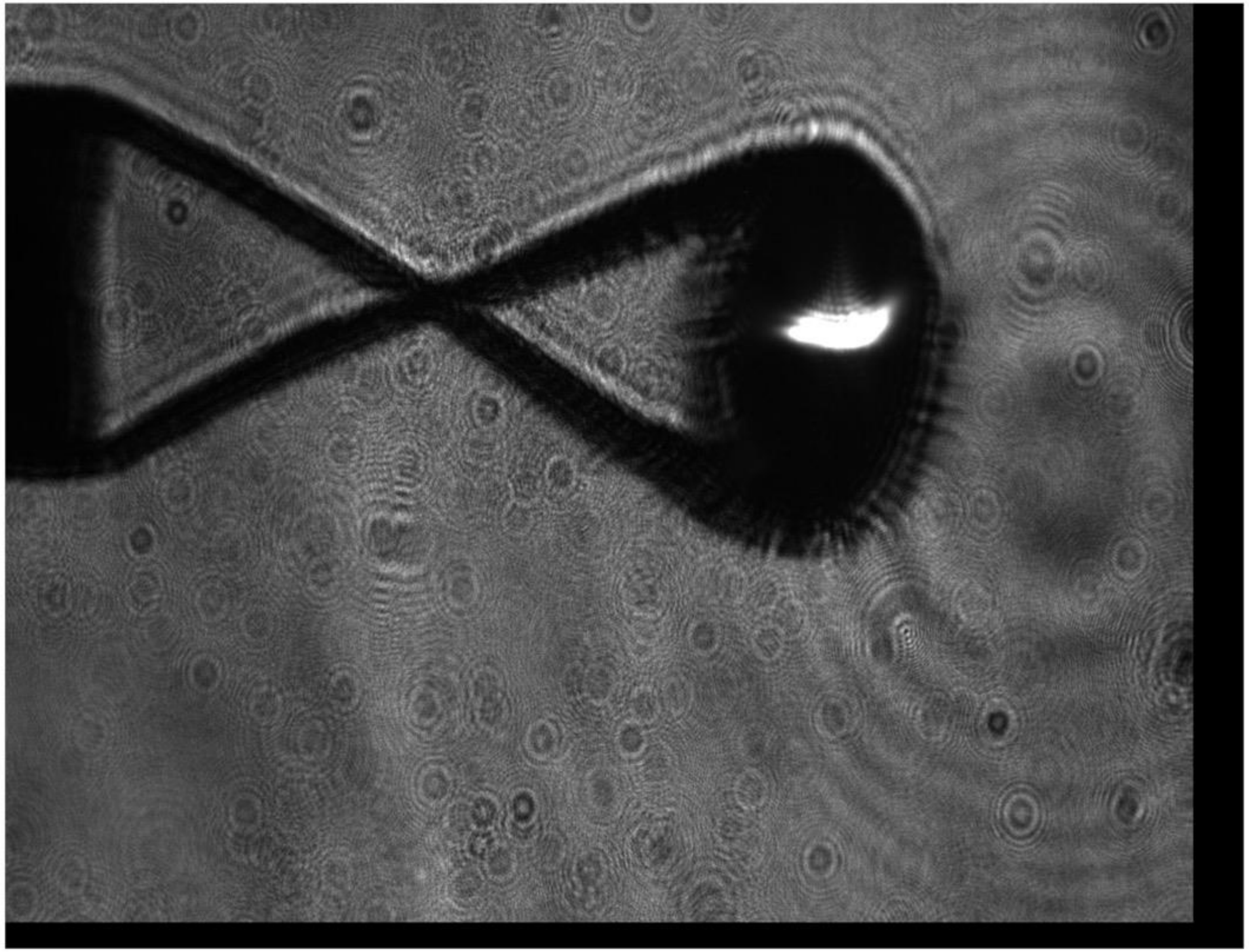
Optical probe data shows rapid onset of instability in the Al x-pinch targets

Al x-pinch 80 ps



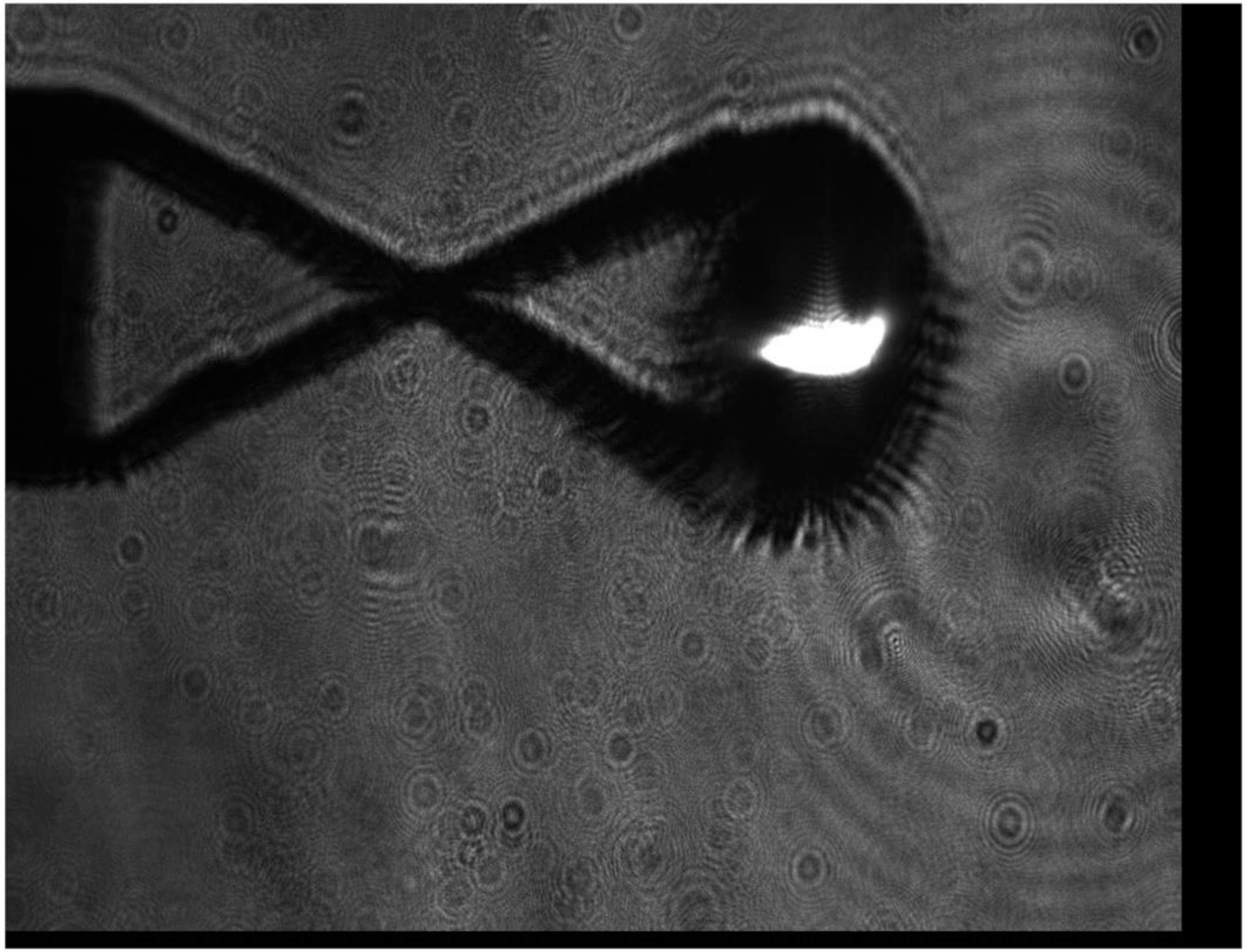
Optical probe data shows rapid onset of instability in the Al x-pinch targets

Al x-pinch 100 ps



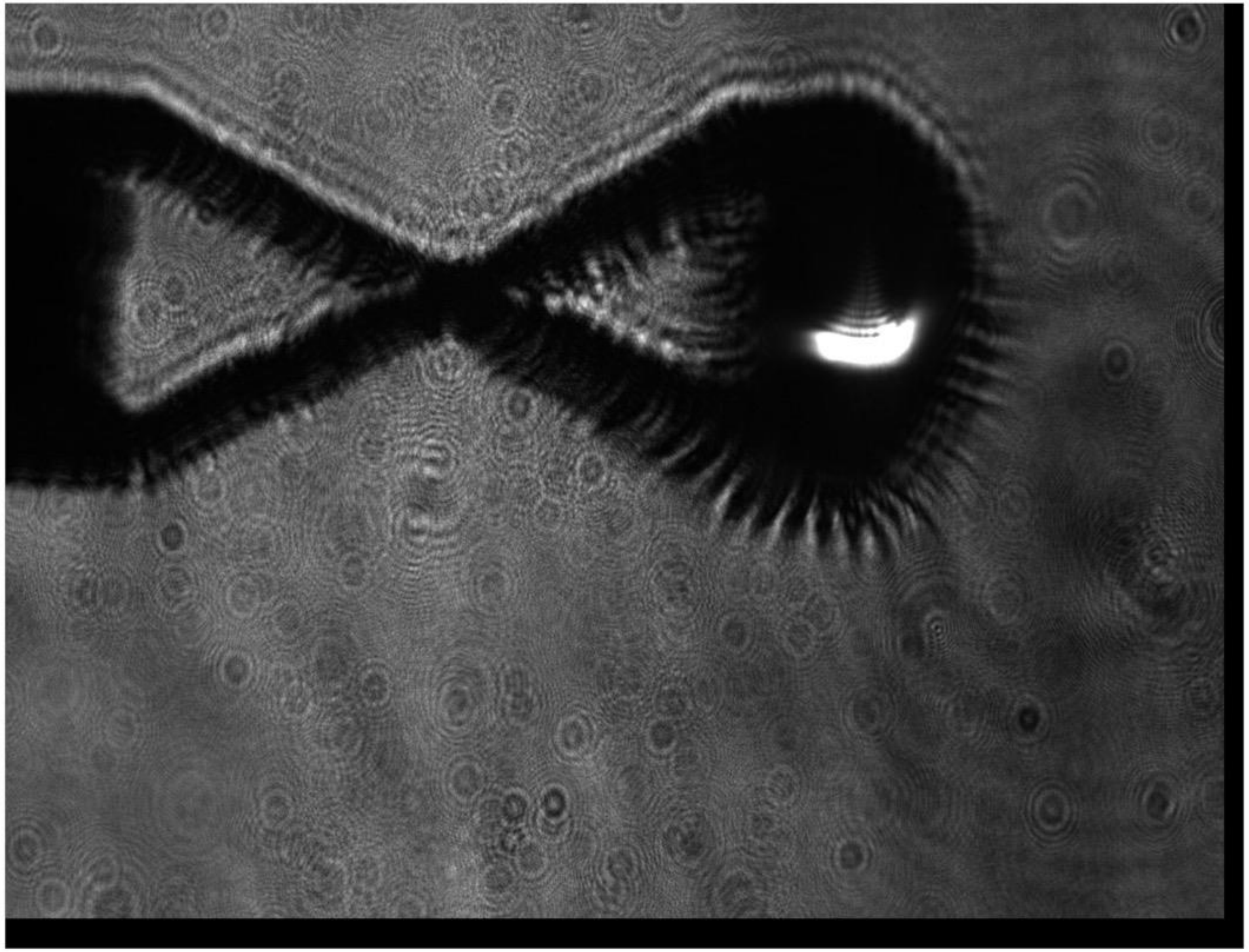
Optical probe data shows rapid onset of instability in the Al x-pinch targets

Al x-pinch 140 ps



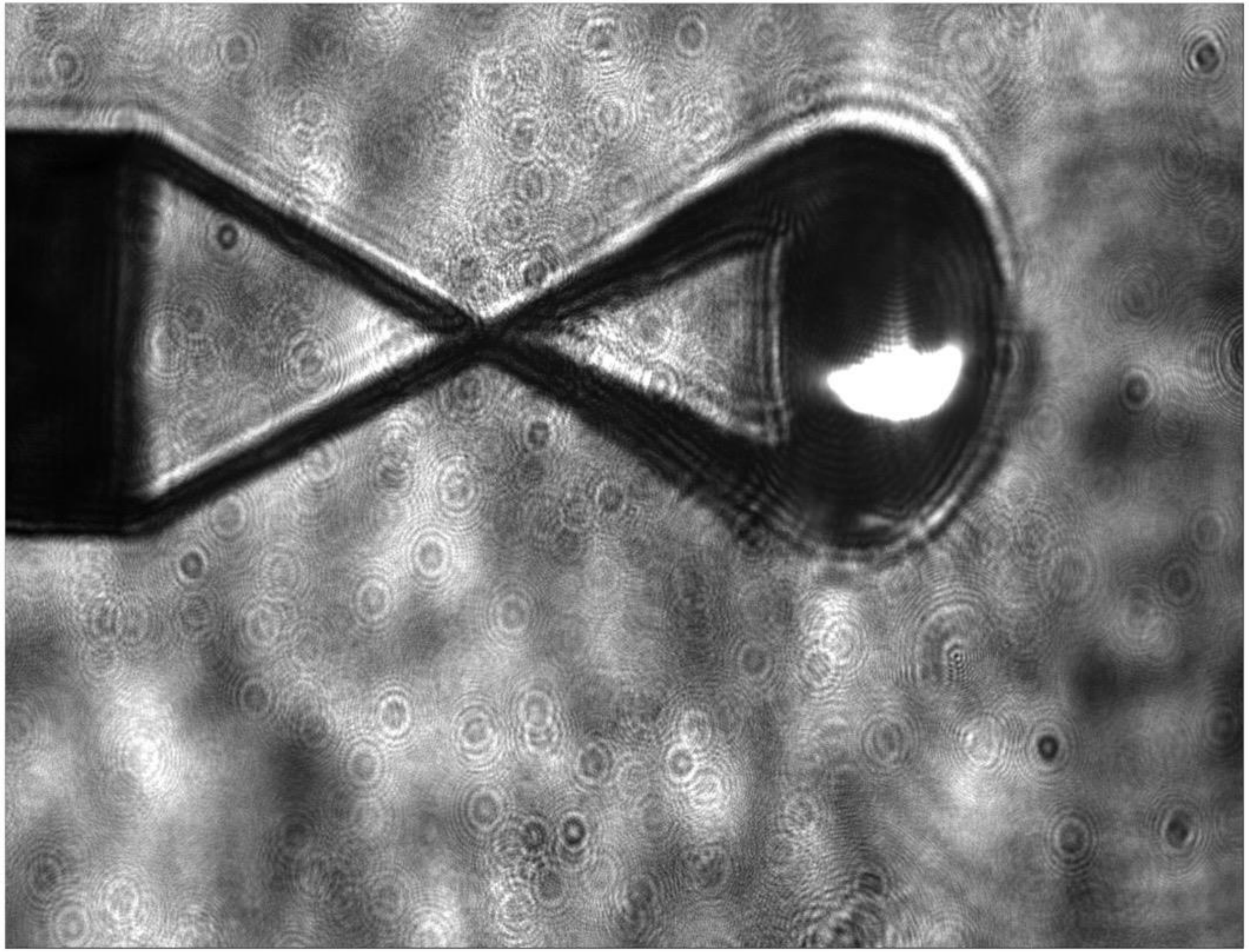
Optical probe data shows rapid onset of instability in the Al x-pinch targets

Al x-pinch 240 ps



The thin Cu targets seem to have slower instability growth compared to the Al targets

10 μm Cu x-pinch 150 ps



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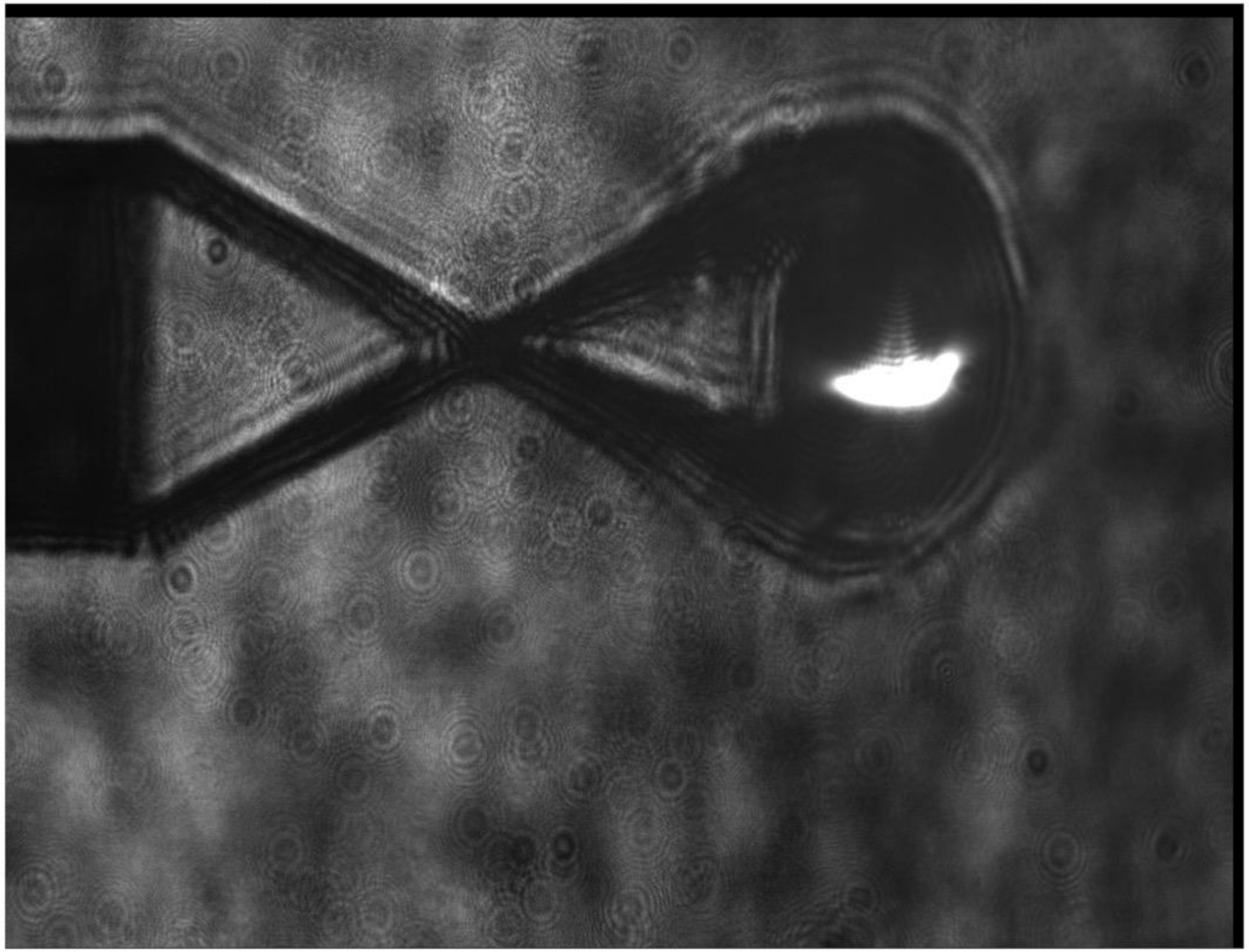
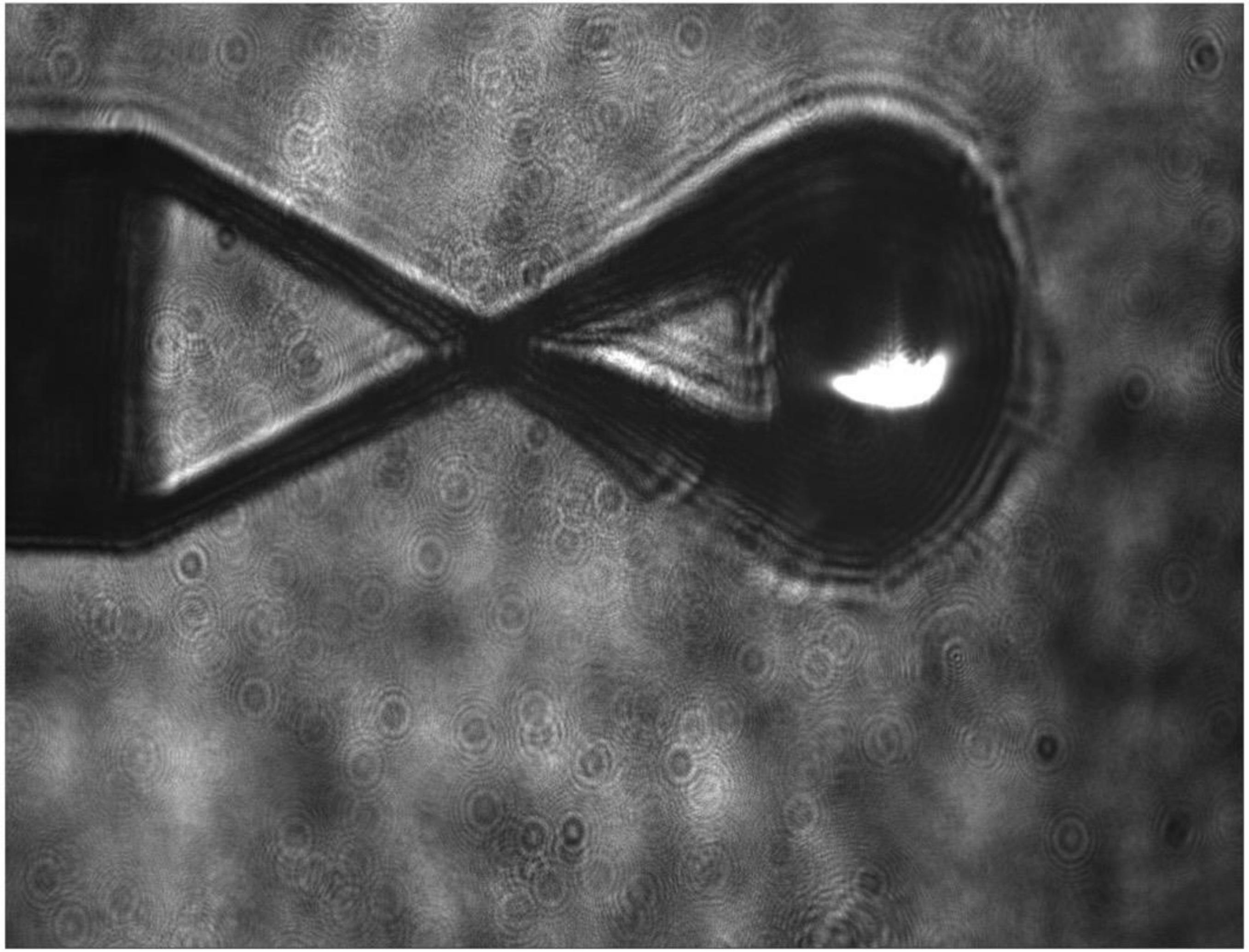
10 μm Cu x-pinch 220 ps



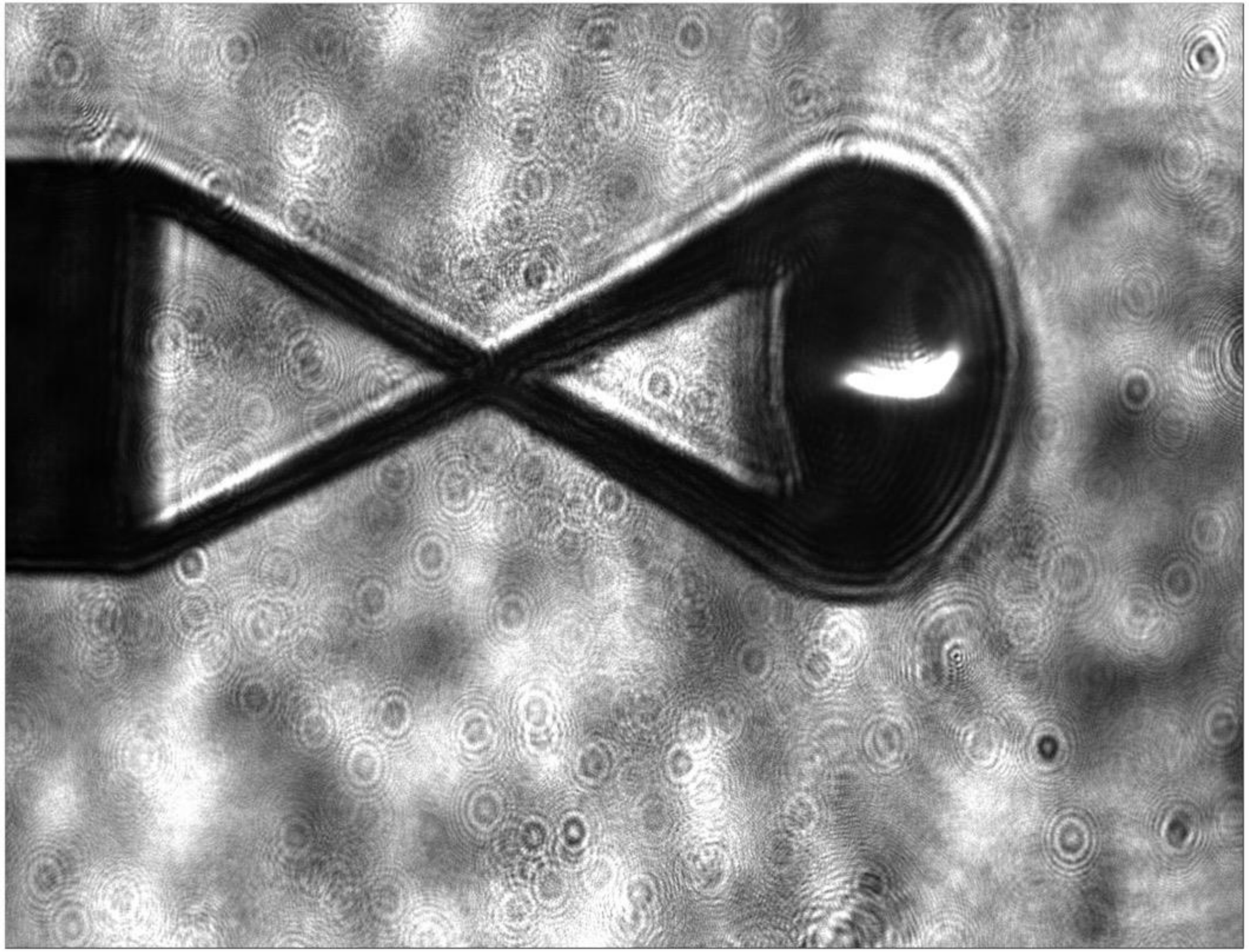
The thin Cu targets seem to have slower instability growth compared to the Al targets

10 μm Cu x-pinch 310 ps



The thick Cu targets also show a slower onset of instability growth

20 μm Cu x-pinch 80 ps



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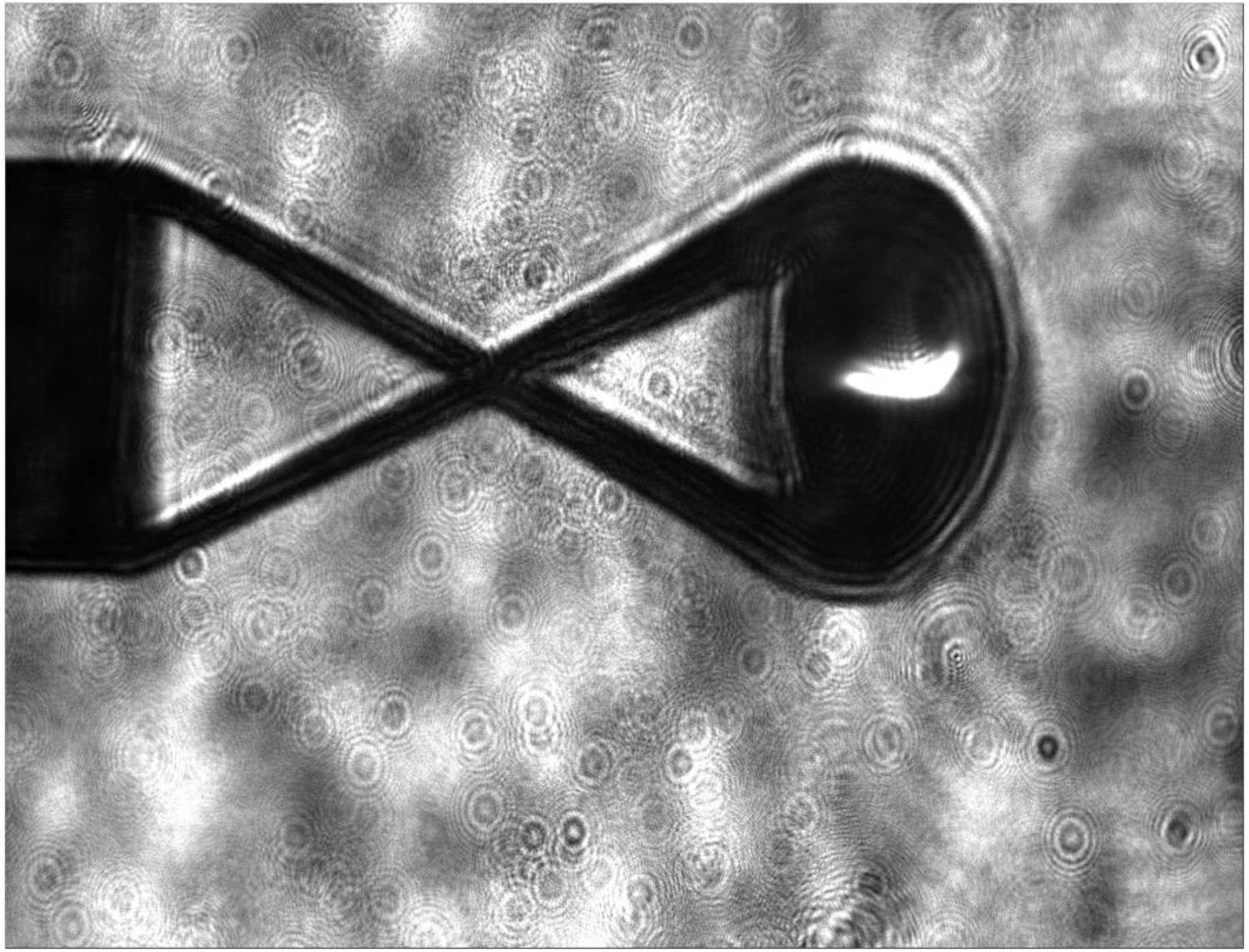
20 μm Cu x-pinch 80 ps



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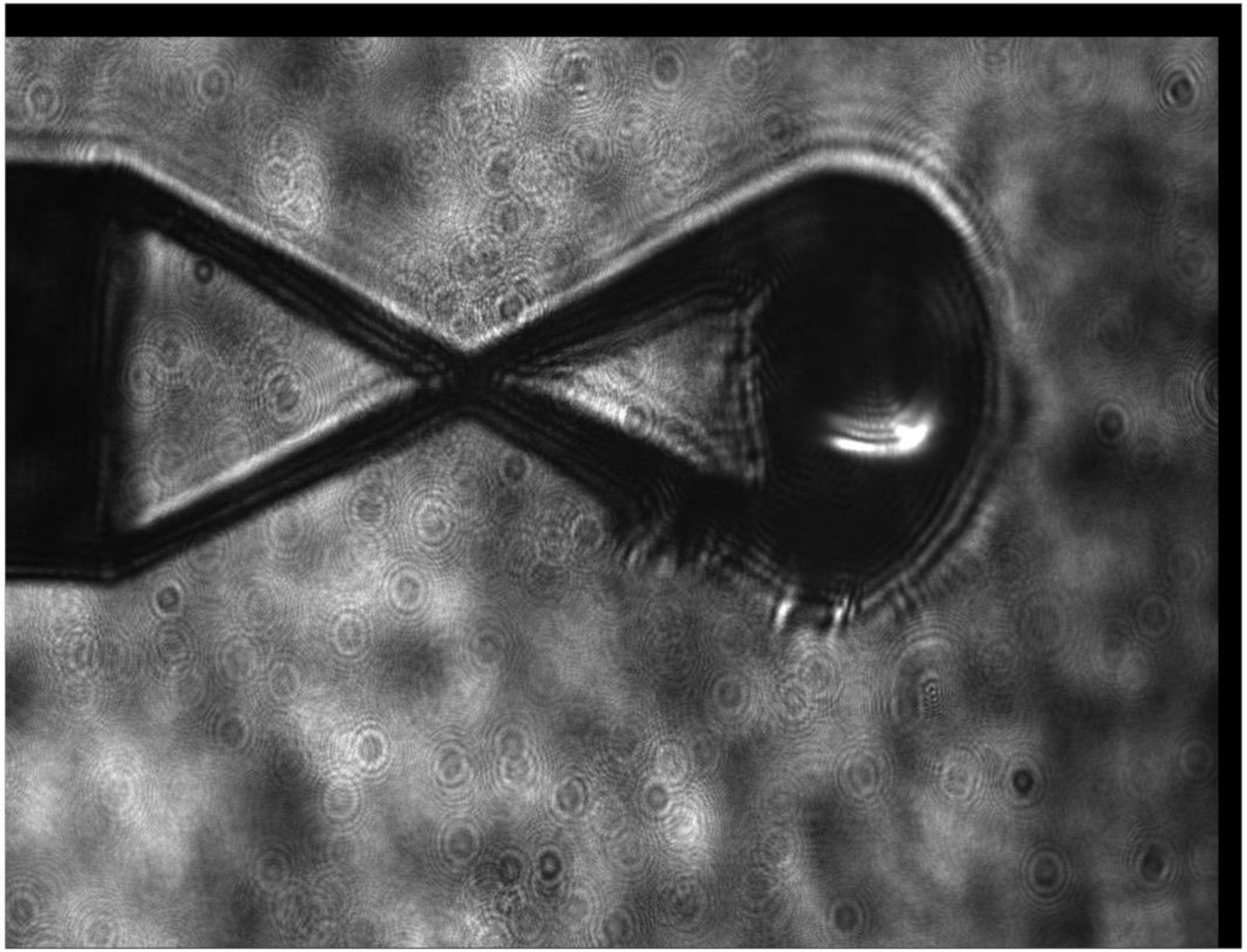
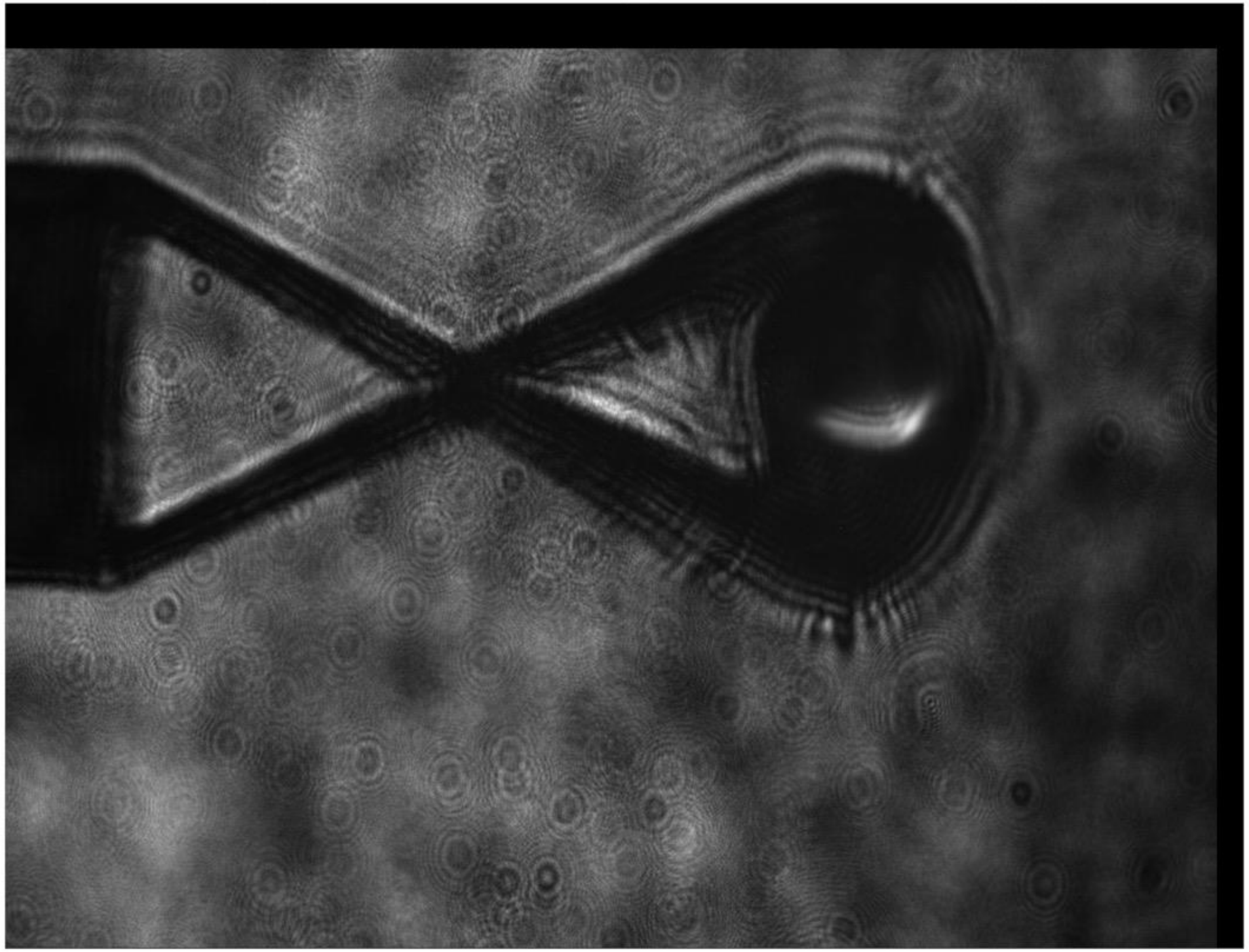
20 μm Cu x-pinch 150 ps



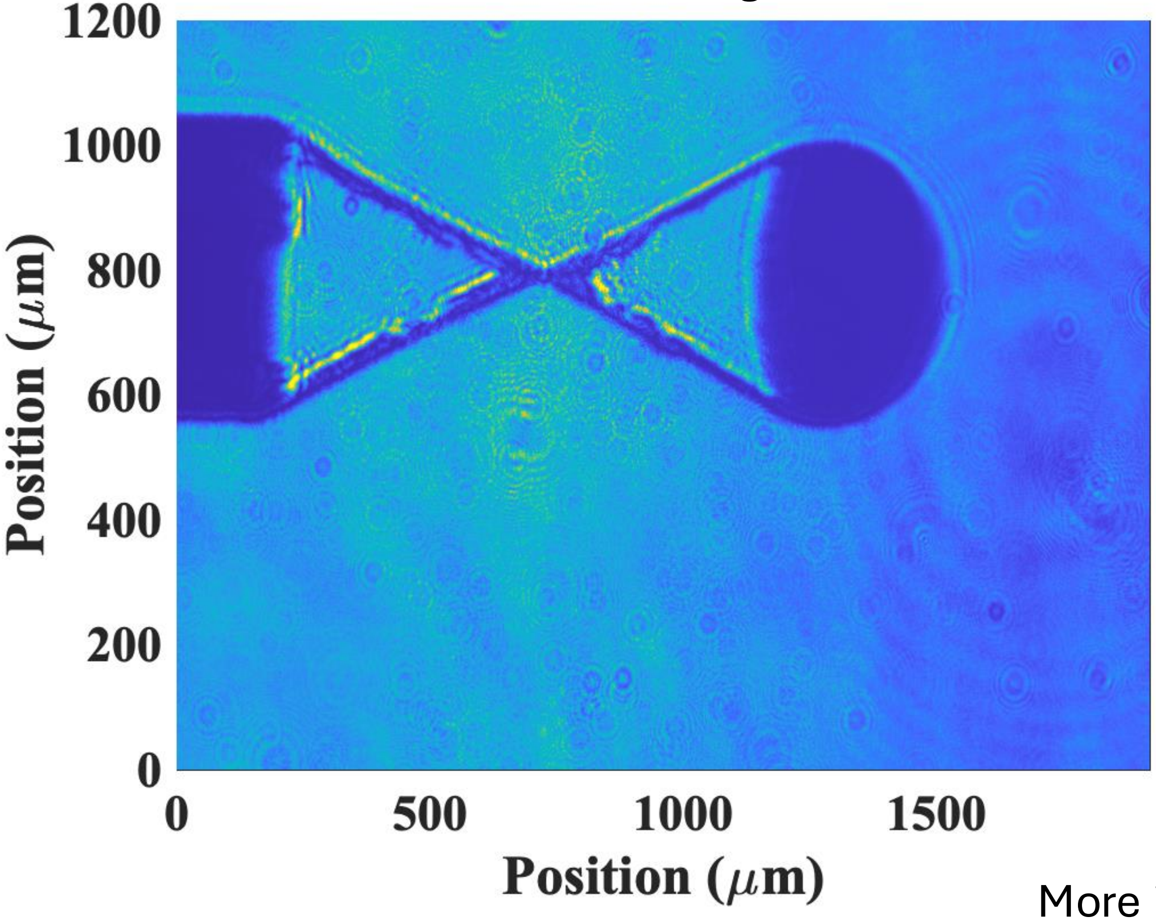
The thick Cu targets also show a slower onset of instability growth

20 μm Cu x-pinch 220 ps



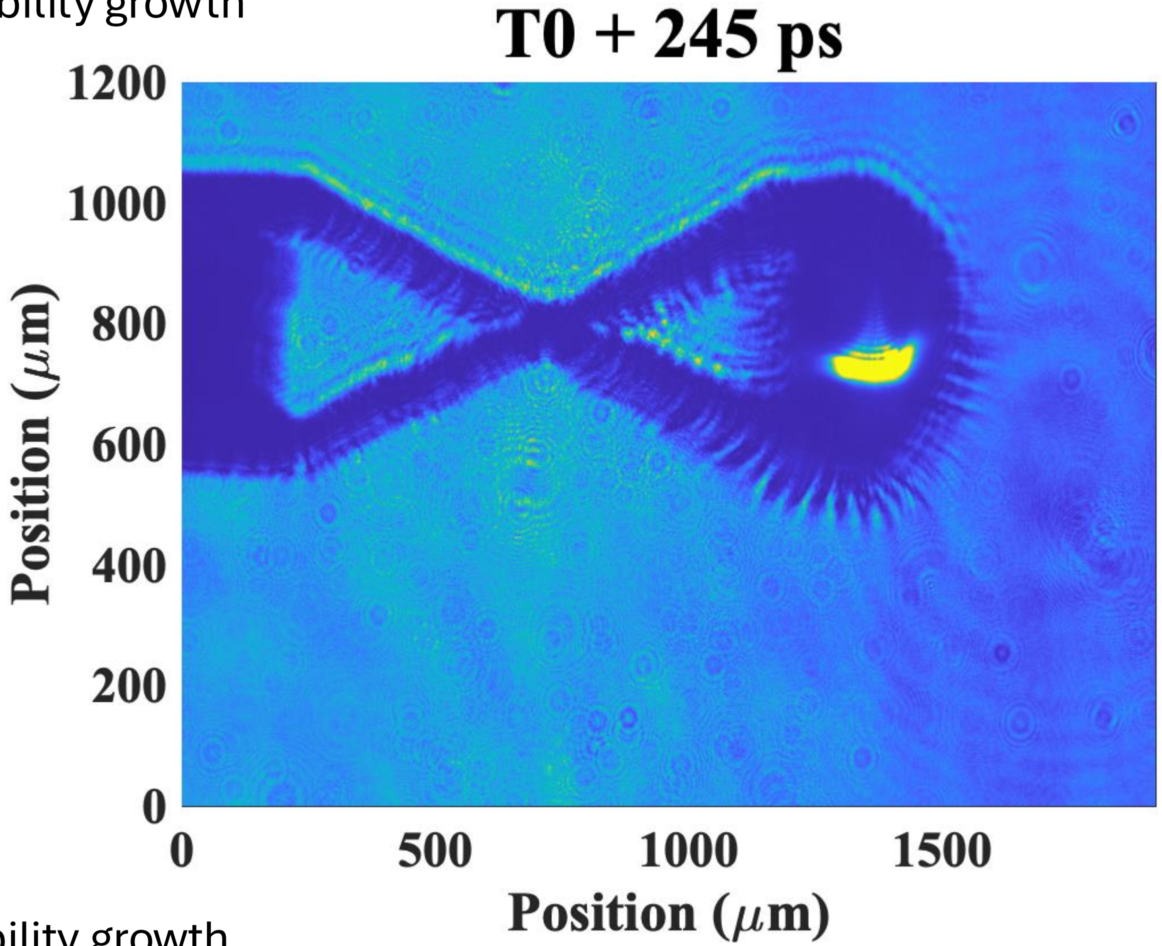
The wire expansion shows several asymmetries during the experiment

Pre-shot image



Less instability growth

More instability growth

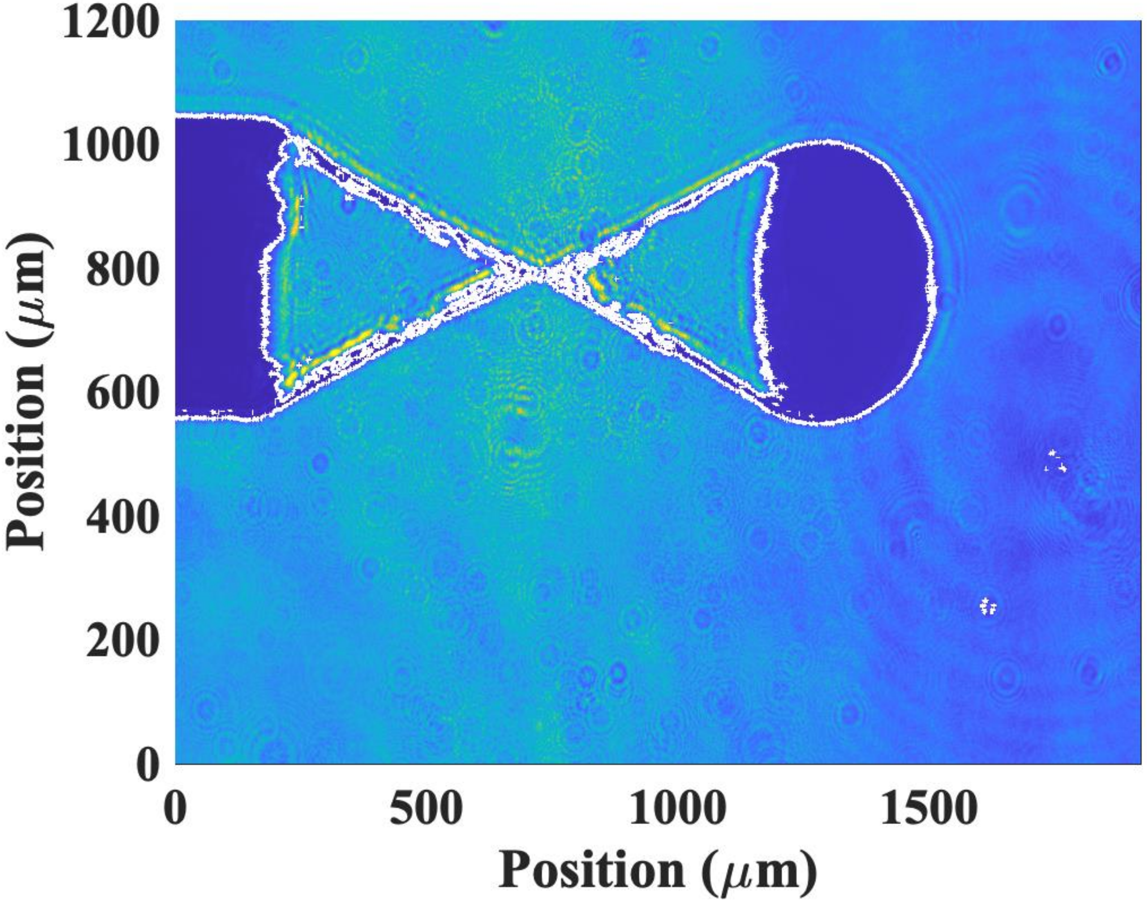


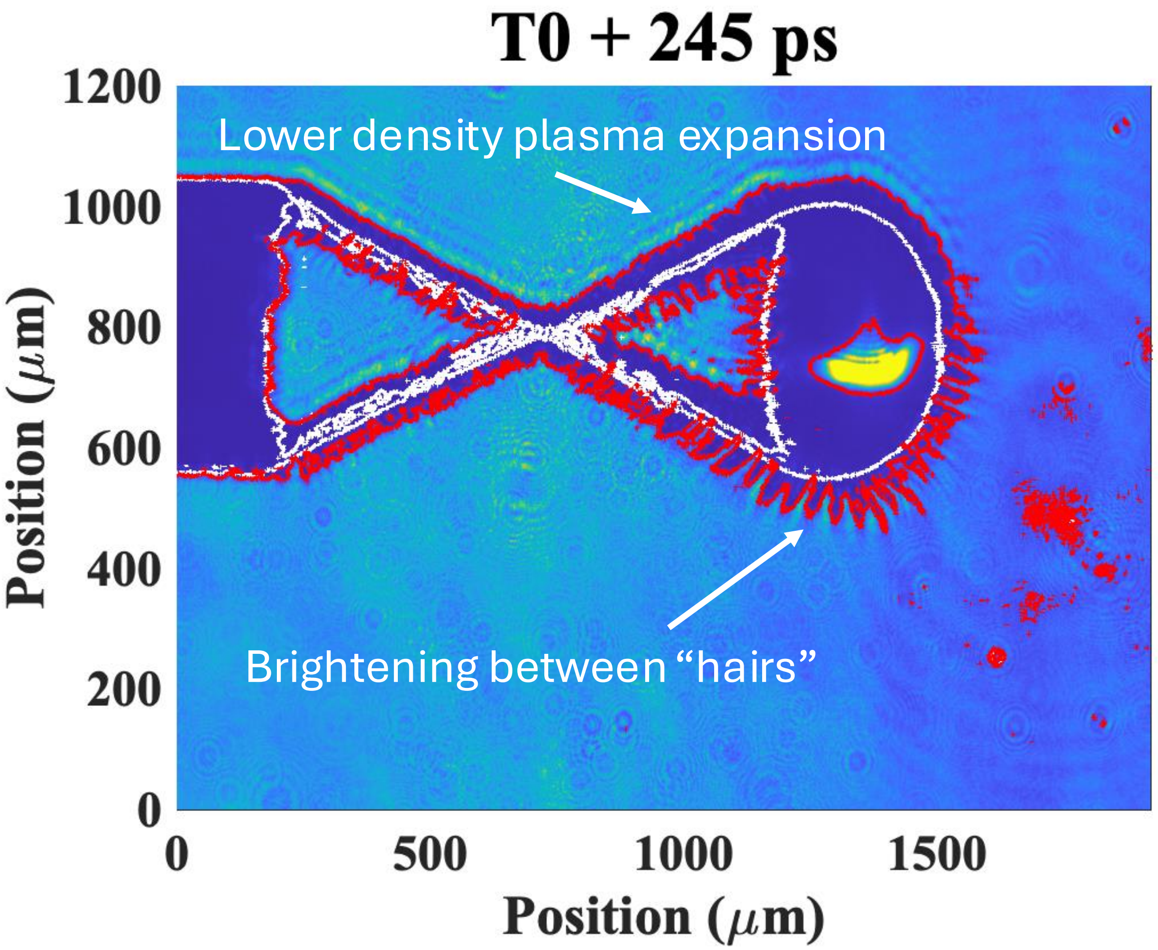
Less wire expansion

More wire expansion

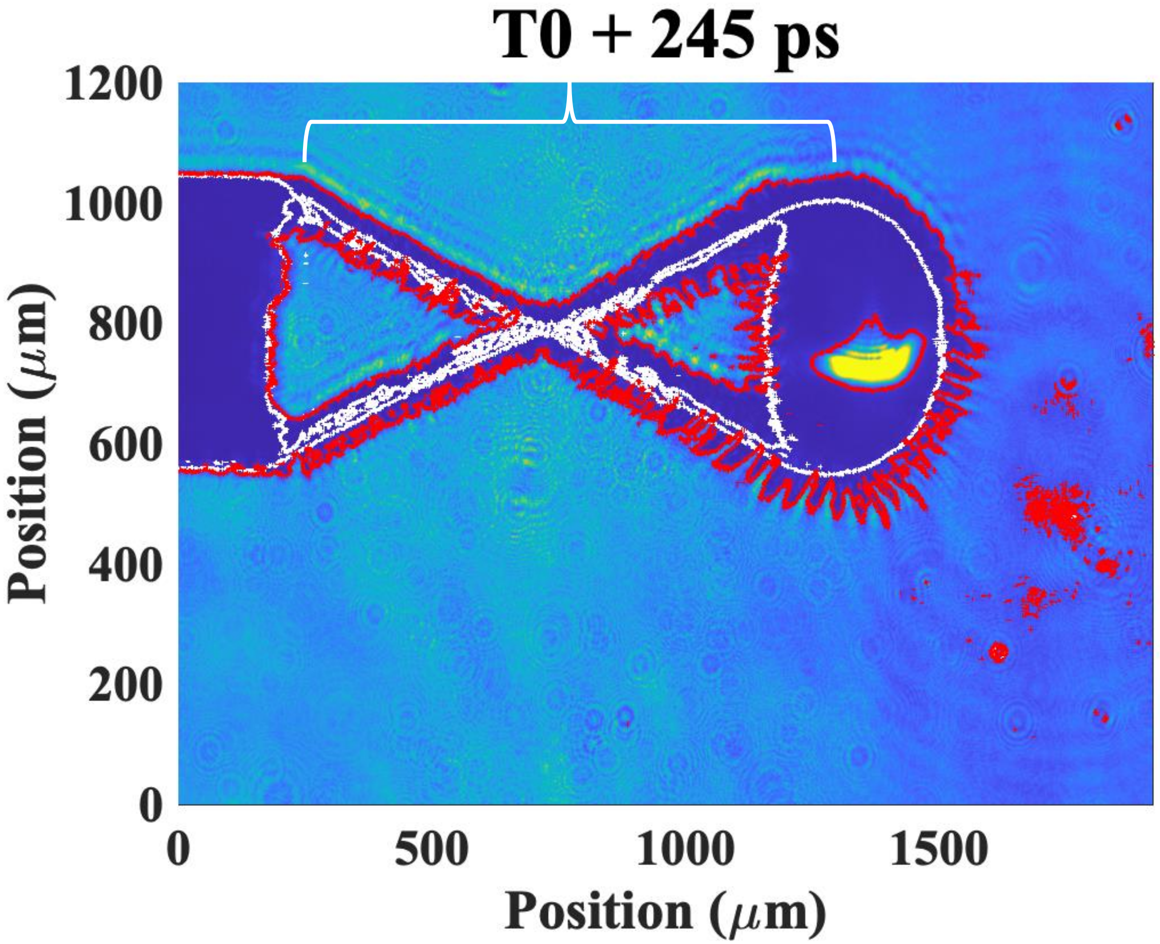
Contours at 10% of the maximum signal show that the instability grows into the original wire location

Pre-shot image





The asymmetry in the instability growth provides an opportunity to measure the wire expansion velocity



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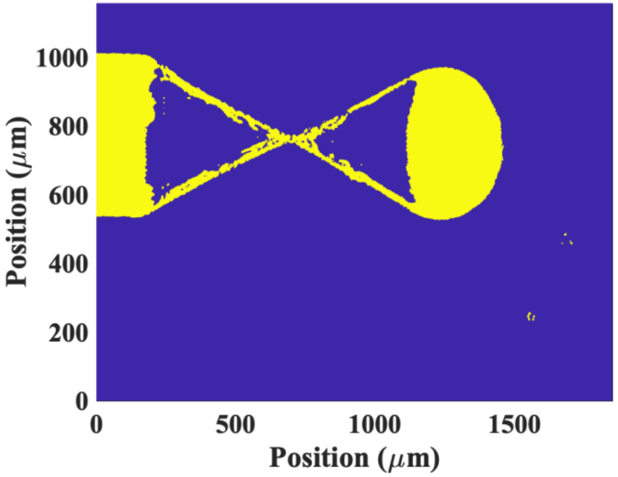
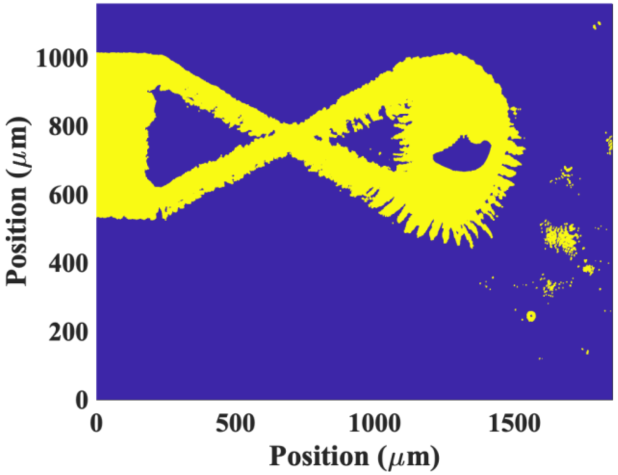
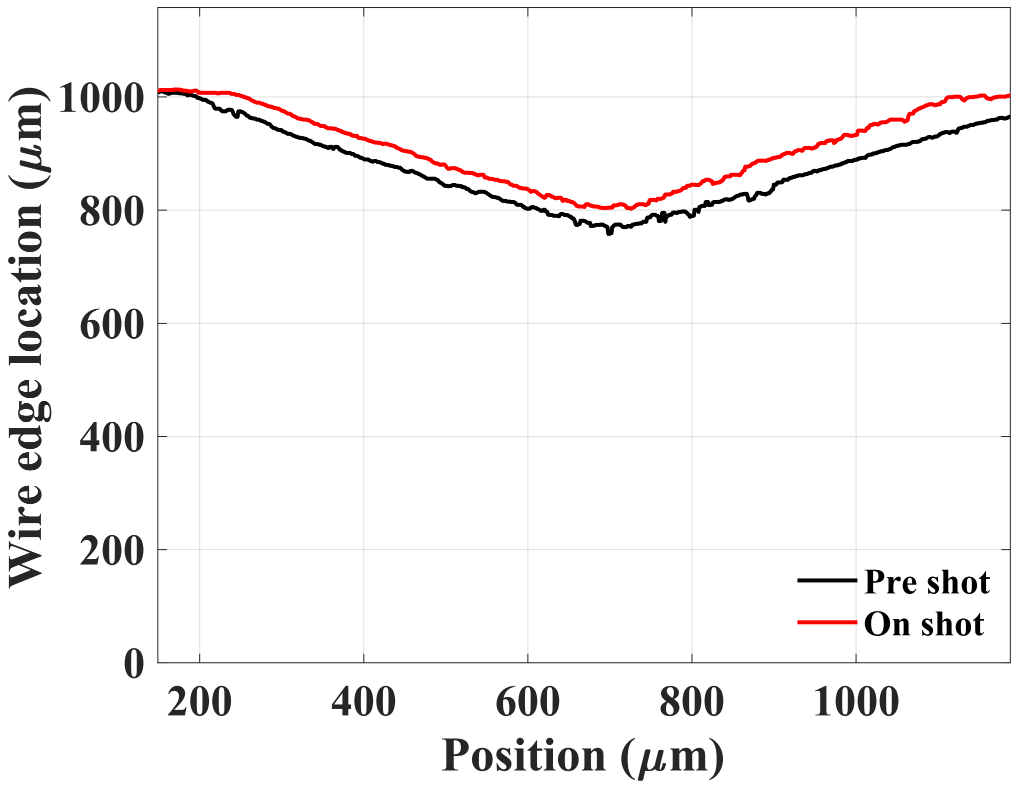
Box threshold

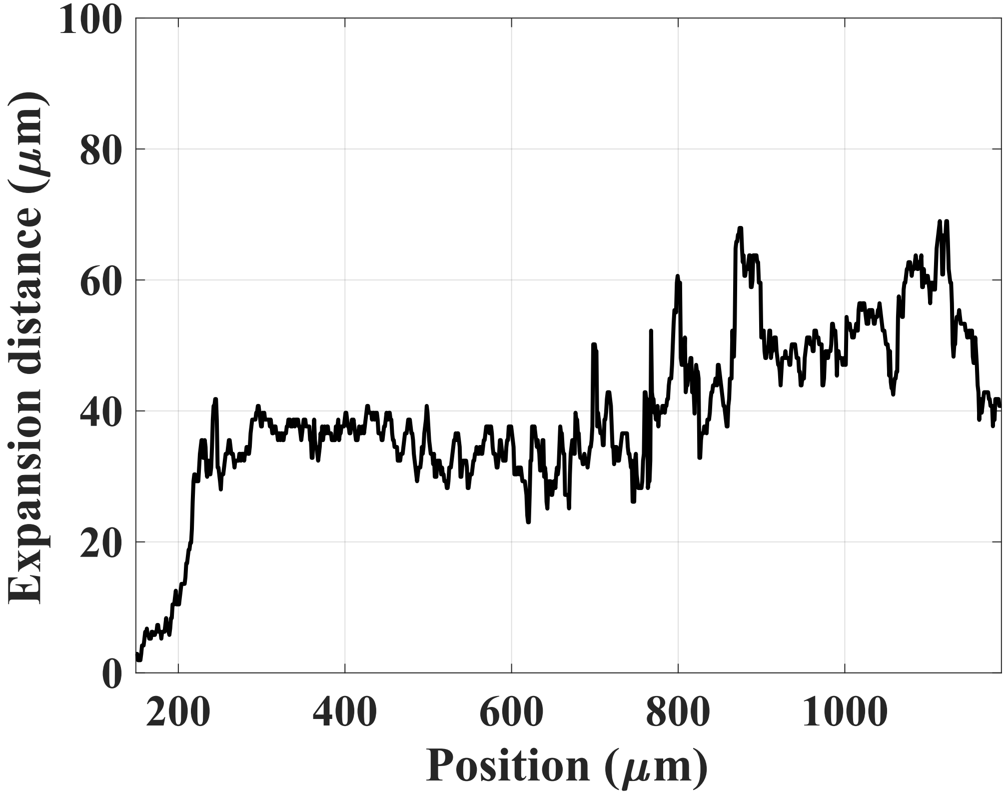




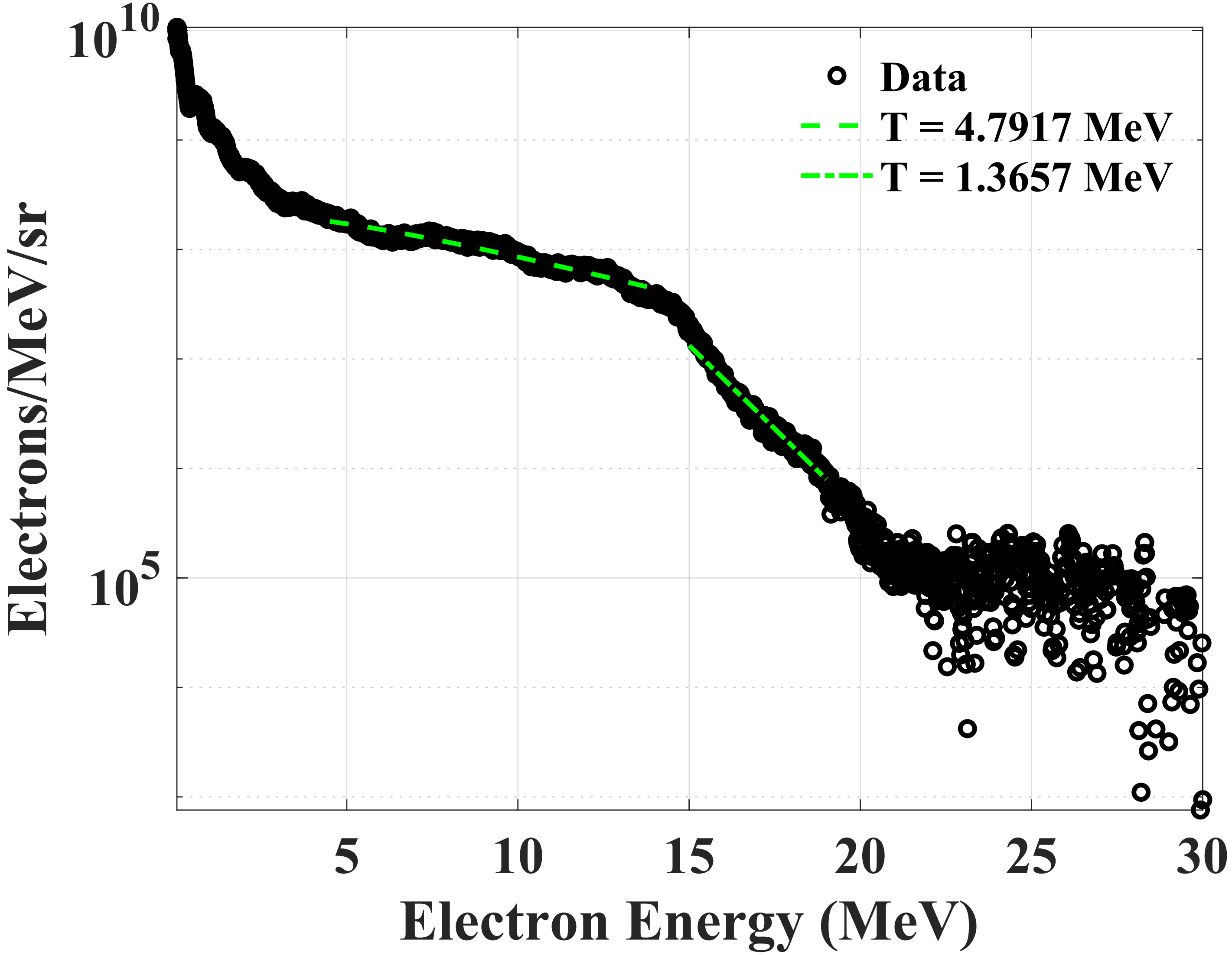
The difference between the edges of the segmented images provides the wire core expansion

Probe delay: 240 ps





Electron spectra generally show a two-temperature distribution

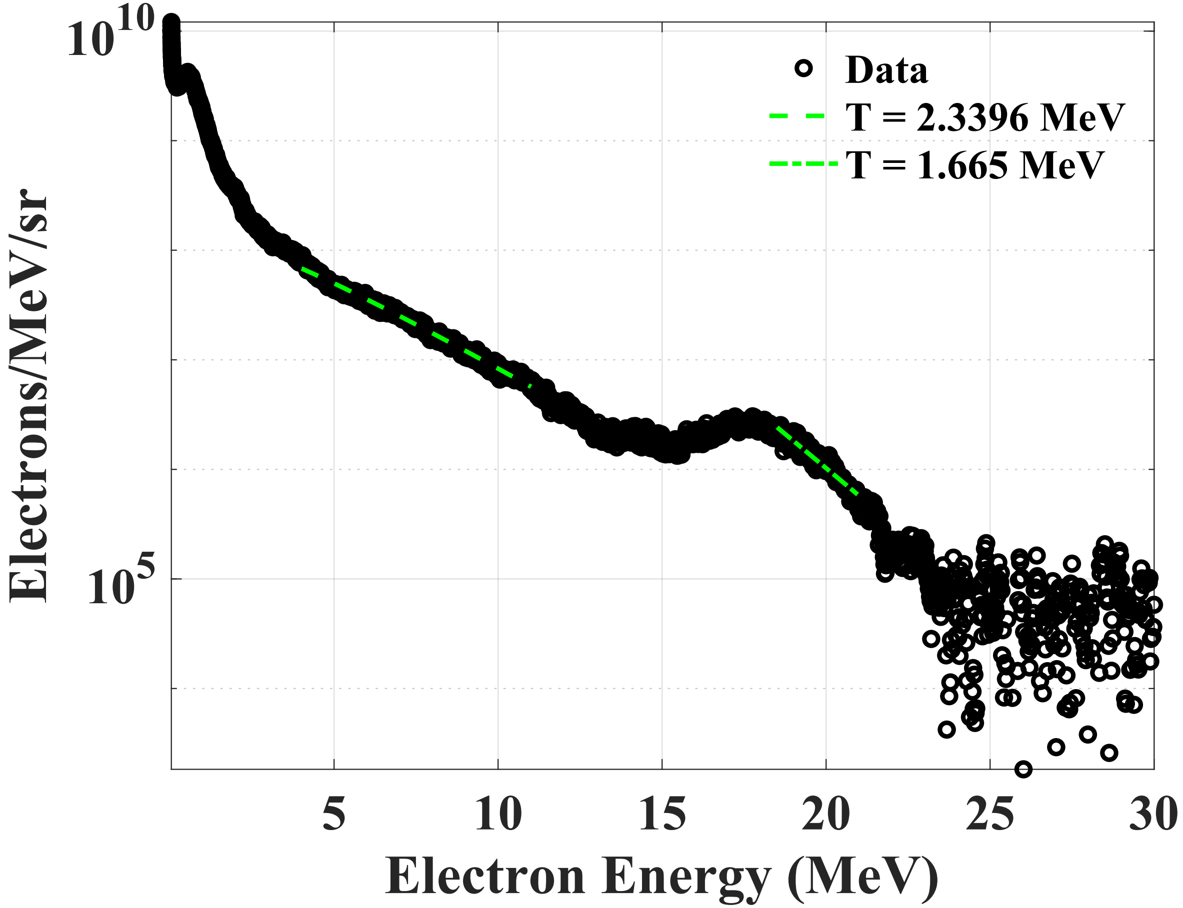


Al x-pinch

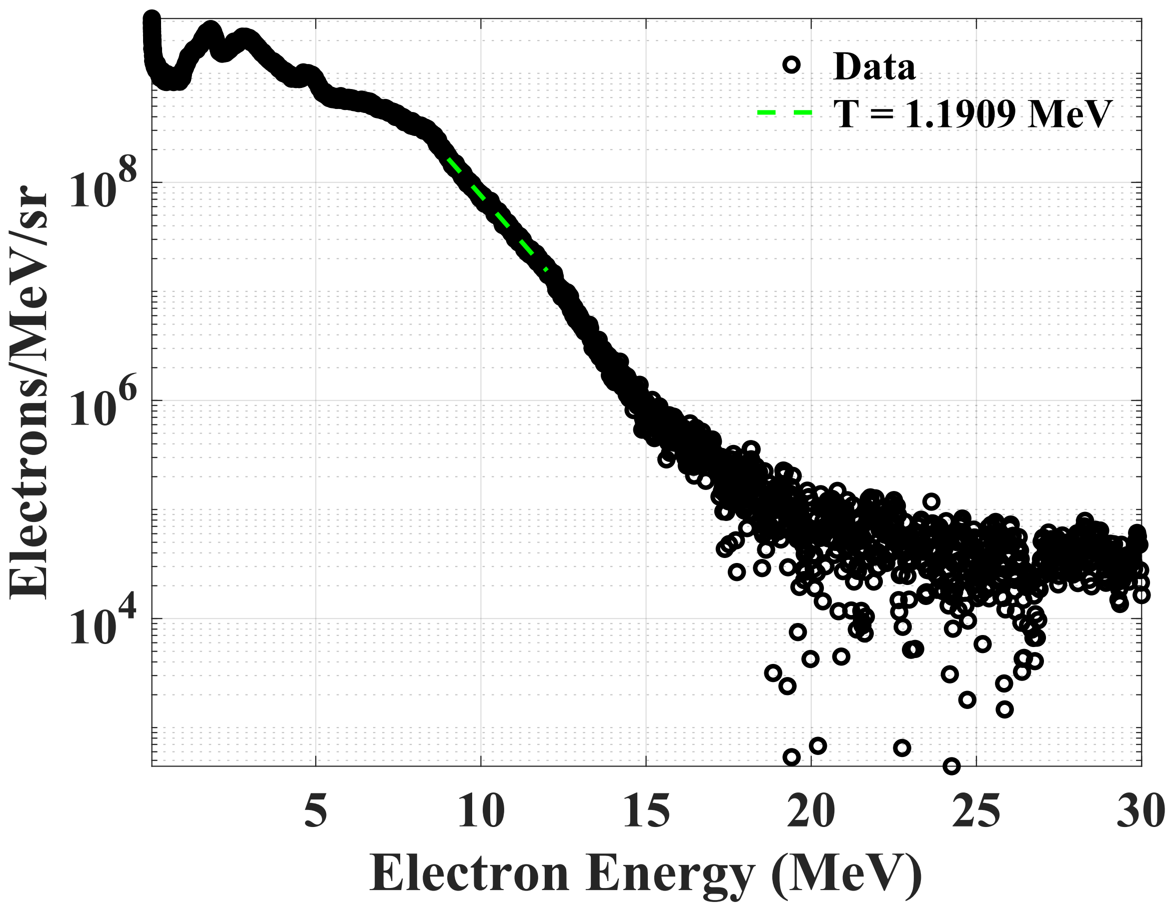
124.7 J on shot

Comparison between an x-pinch target and a flat foil with similar laser energy show differences

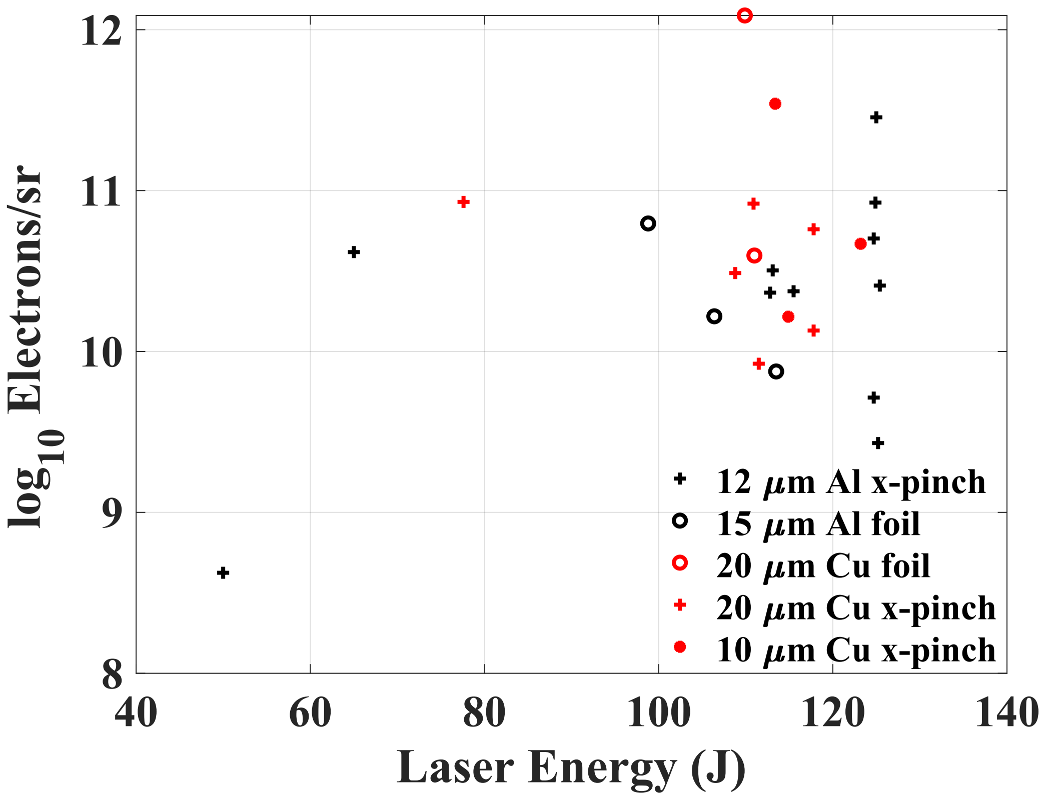
12.5 micron thick Al x-pinch 112.8 J

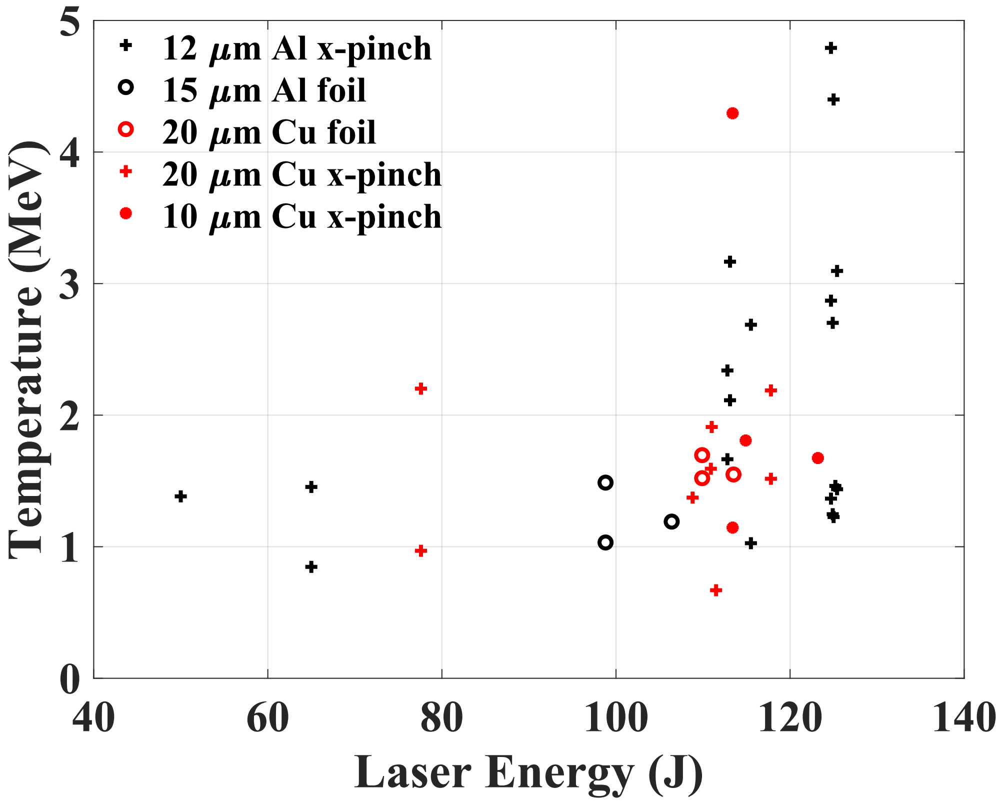


15 micron Al foil 106.4 J



Comparisons of the electron spectra with the input laser energy show different behavior at higher laser energy





Summary

- Recent experiments at the Titan laser explored laser-induced currents in “x” structured targets
- This could lead to X-pinch sources for advanced diagnostics at high repetition rate
- There is also the potential for studies of extreme conditions (~1 keV and >solid density) at high repetition rate
- There are promising results from the experiments and decisions about material and manufacturing choice are important in future work