Low-Density Plasma Focussing of High Repetition Rate Ion Sources

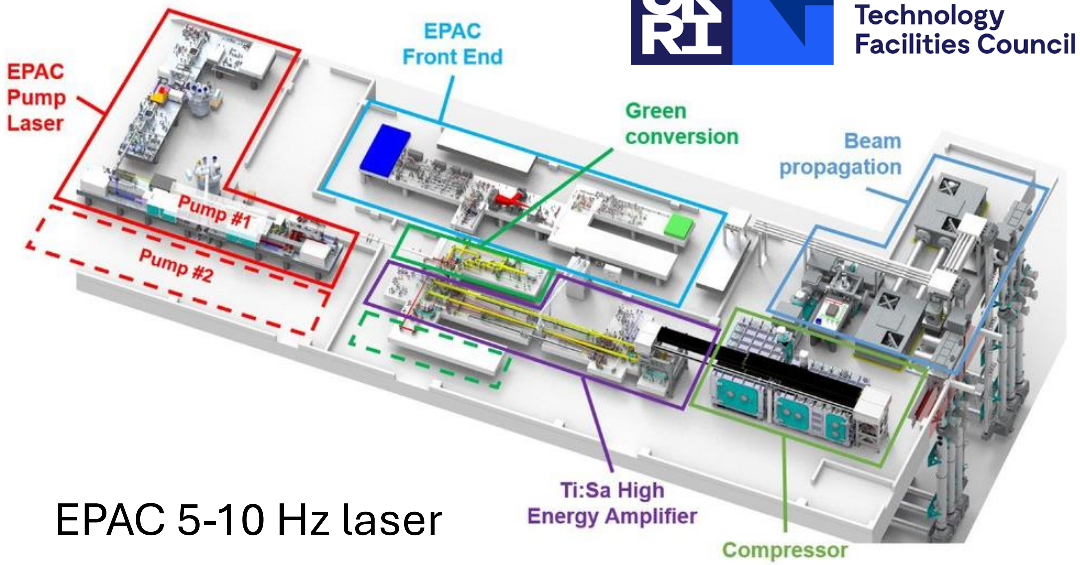
Jimmy Weeks – Advanced Accelerator Concepts
(they/them)

Work Group 2
27/08/2026

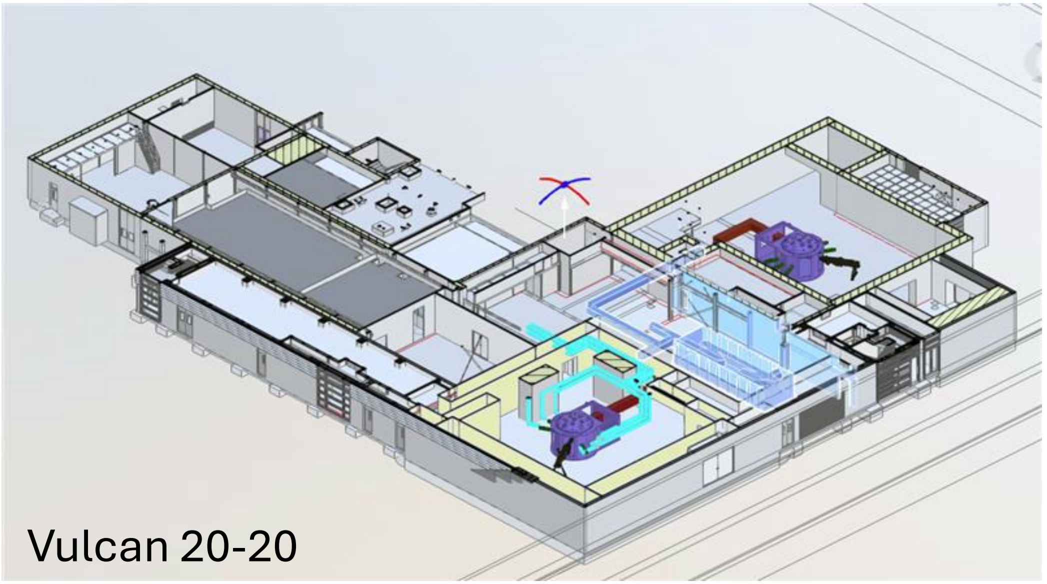
1: Introduction

- Modern high-power laser science is pushing us in two directions
  - Applications!
    - ***Multi-Hz sources***
  - Ultra high-intensities!!
    - Order of 10^{23} W/cm^2
- In this talk, we will focus on the multi-Hz sources
  - Where do they stand currently?
  - What is holding them back?
  - How do we get past that?

Science and Technology Facilities Council



EPAC 5-10 Hz laser



Vulcan 20-20

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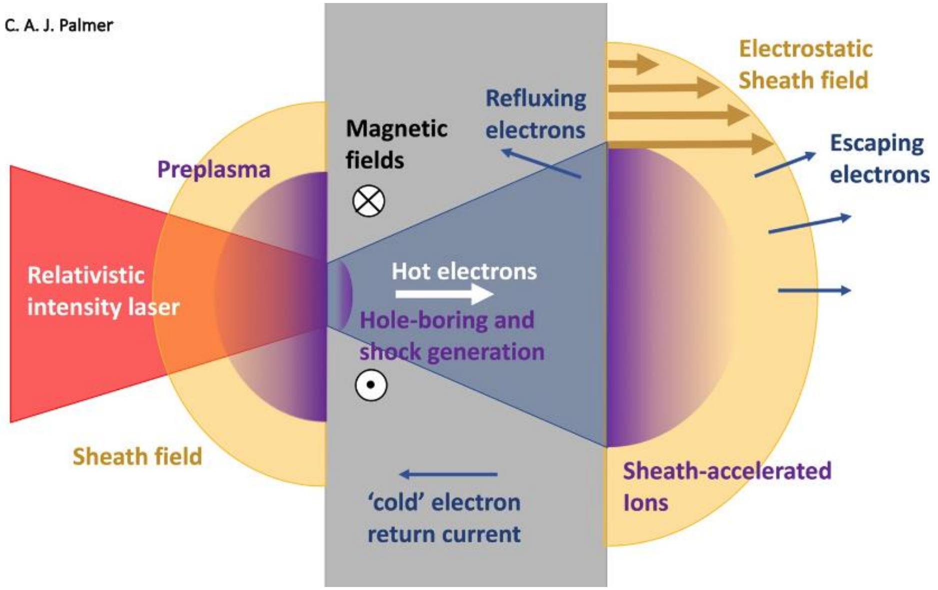
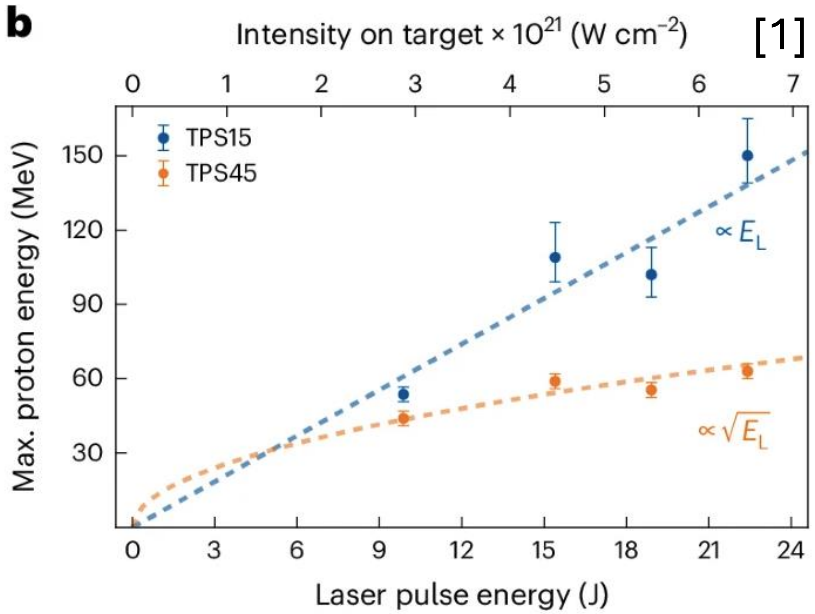
2: Laser-Driven Ion Sources

- Relativistic laser interactions with solid density targets accelerates protons
  - Sheath fields ~ TV/m along target normal (TNSA)
- These proton beams have:
  - Short pulse durations (ps)
  - High currents (100 A)
  - High energies
- The current maximum energy published is 150 MeV [1]





[1] Ziegler, T *et al* (2024). Laser-driven high-energy proton beams from cascaded acceleration regimes. *Nature Physics* doi:https://doi.org/10.1038/s41567-024-02505-0.

3: Why Are We Not Using Them

- **Repetition rate compatibility**
- Shot-to-shot stability and reproducibility
- Cut off energies and
  energy spectrum spread
- **Beam divergence and emittance**
- **Target fabrication**
- **Debris and damage to optics**
- Laser contrast requirements
- Diagnostics and real-time feedback

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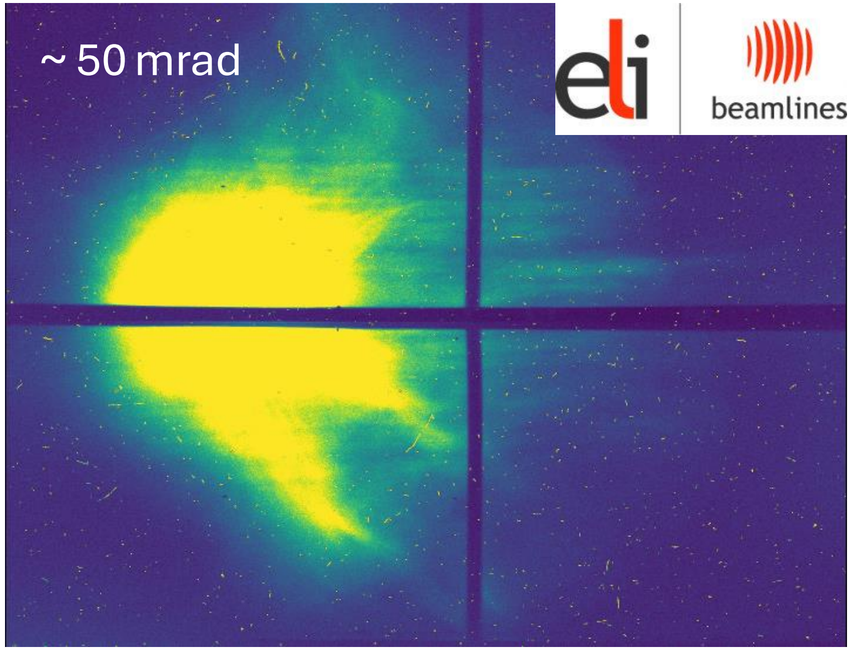
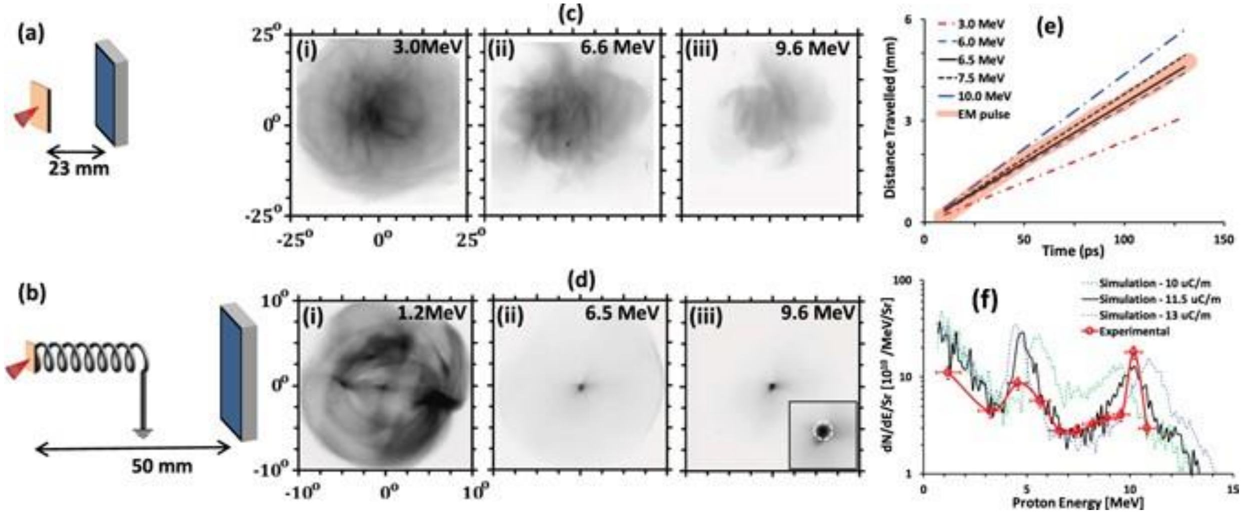
4: Beam Divergence

- TNSA beams have an inherently large divergence (10s – 100s mrad)
- For high flux applications or beam capturing this presents an issue
- Sophisticated targetry such as coils can be used reduced this divergence
    - Currently incompatible with high repetition rates





[2]

[2] Ahmed, H. *et al*. (2017). *Scientific Reports*, 7(1). doi:https://doi.org/10.1038/s41598-017-06985-4.

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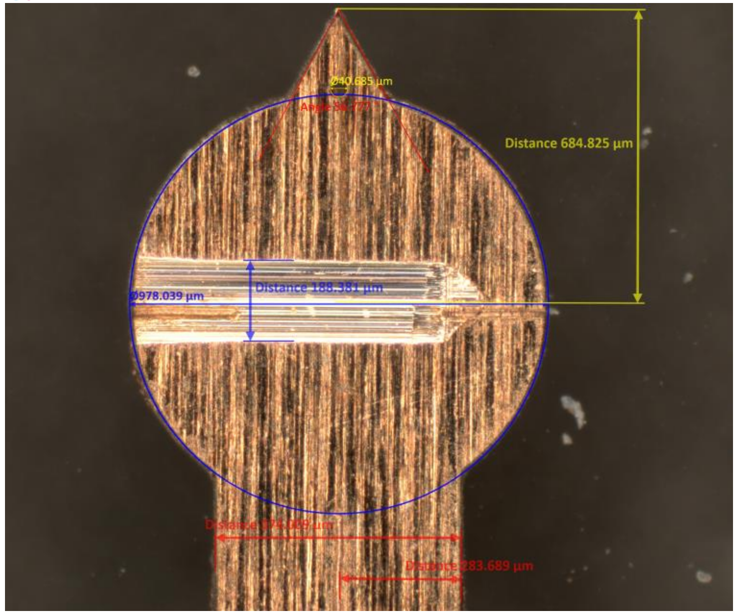
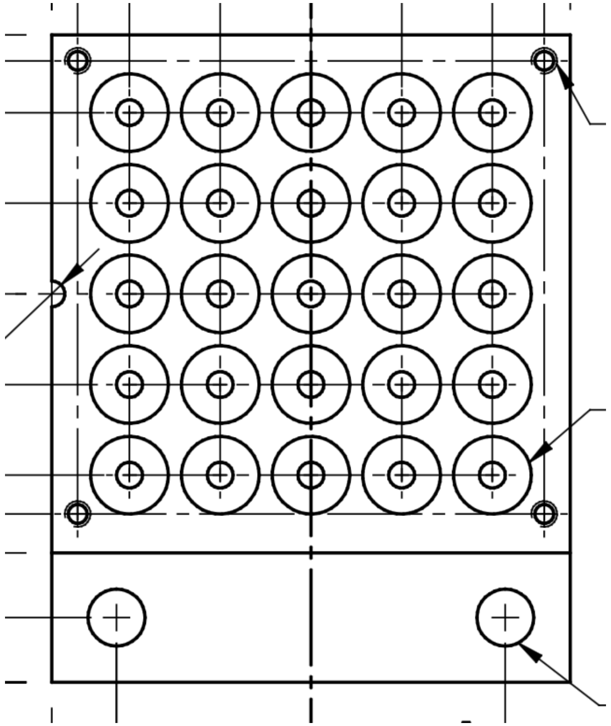
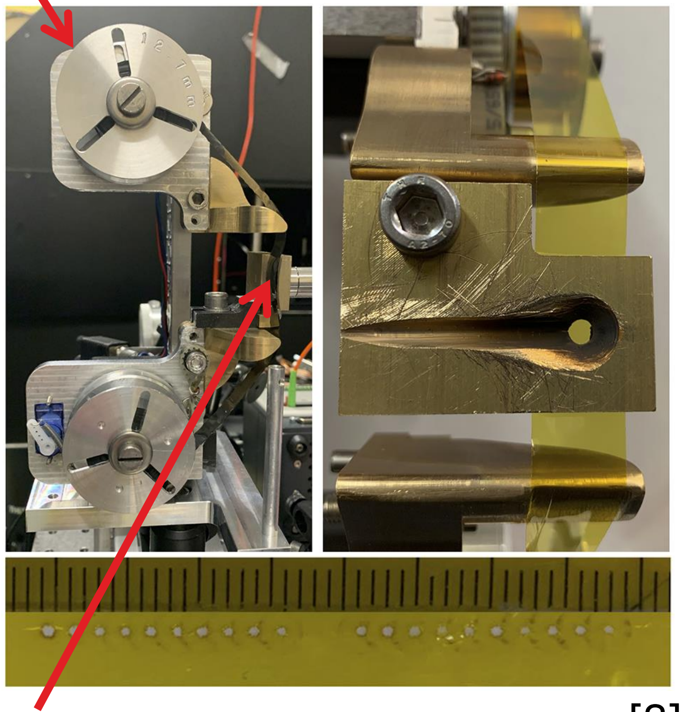
5: The Push for High-Repetition-Rates

- There is a need for targetry that can fully exploit these new facilities i.e. EPAC
- Targets such as tape-drives have been demonstrated to operate at 5 Hz [3]







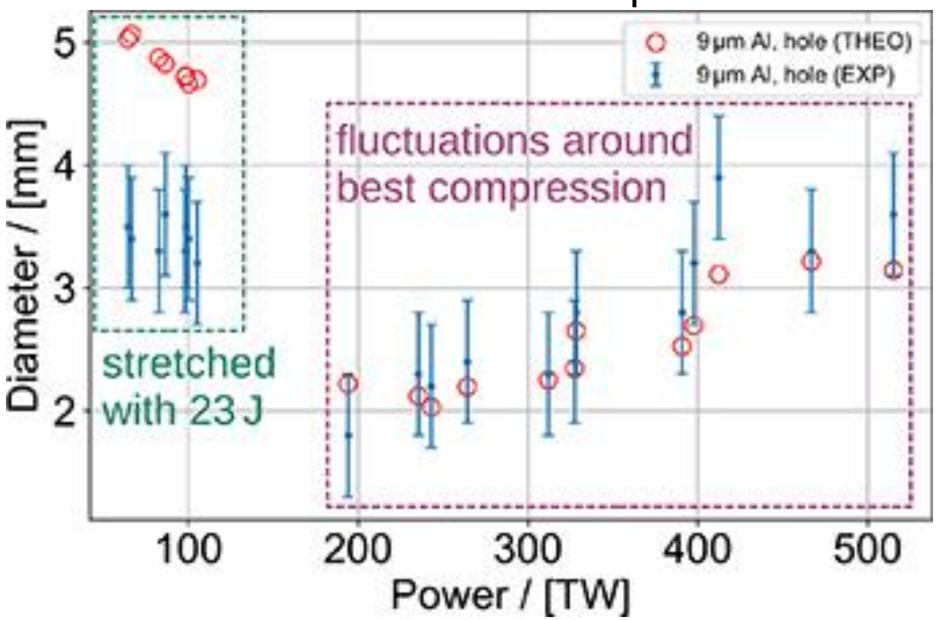
[3]

[3] Xu, N. *et al.* (2023) *High Power Laser Science and Engineering*, 11, p. e23. doi:10.1017/hpl.2023.27.

6: The Debris Problem

- The interaction produces debris that is sent into the chamber
- This debris coats the chamber, burns onto optics and poses a risk for the vacuum system

Hole size vs laser power



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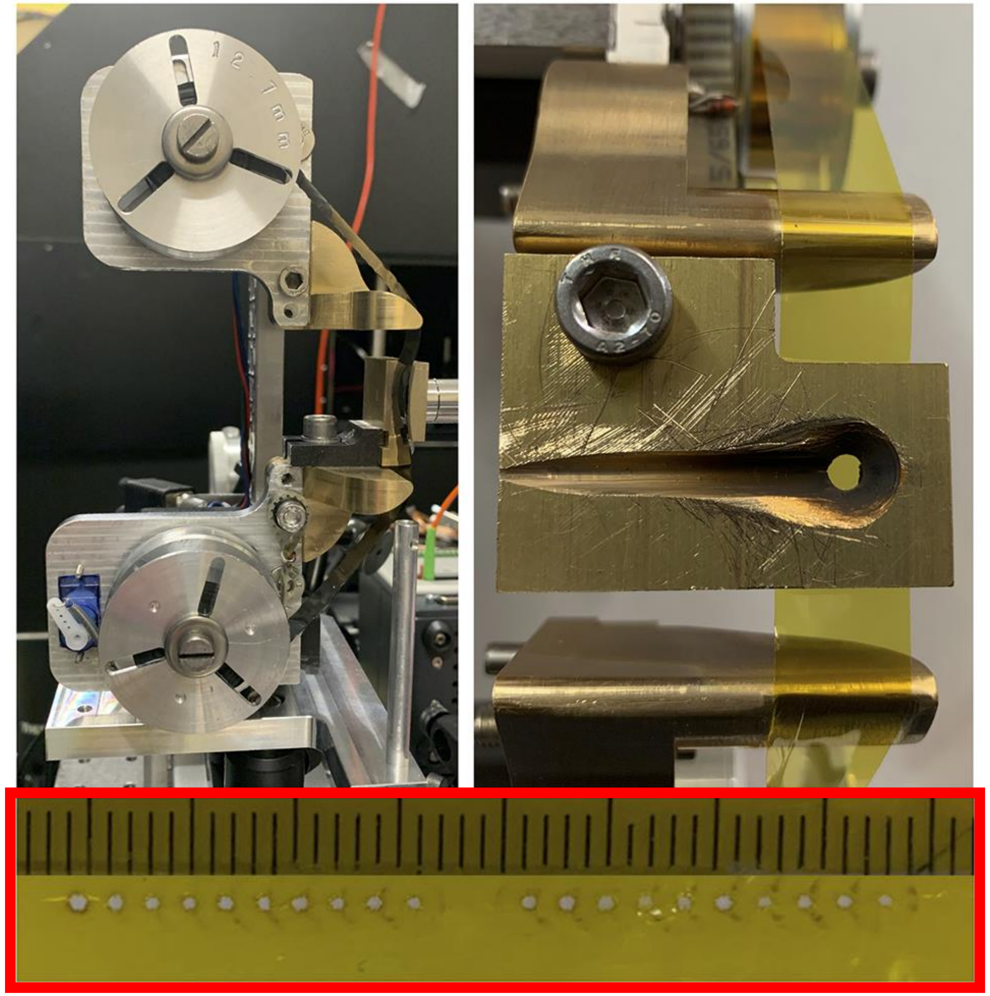

[3]

[4] Ehret, M *et al* (2024) *Plasma Physics and Controlled Fusion*, 66(4), p.045003. doi:https://doi.org/10.1088/1361-6587/ad2690.

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6: The Debris Problem

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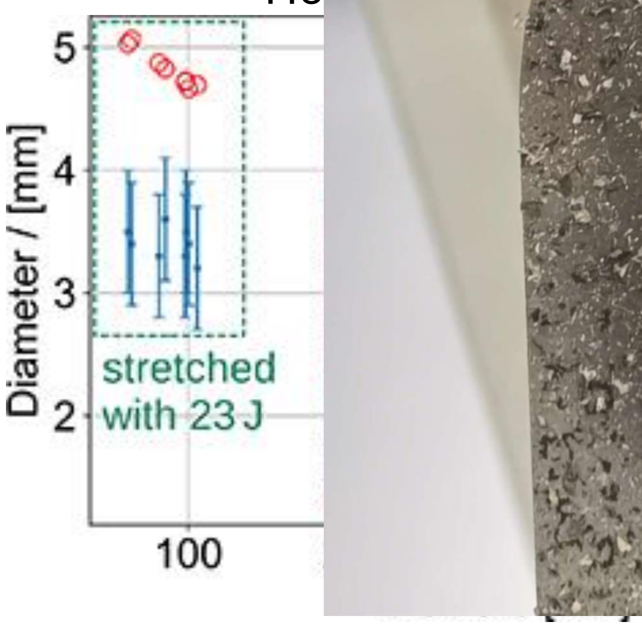
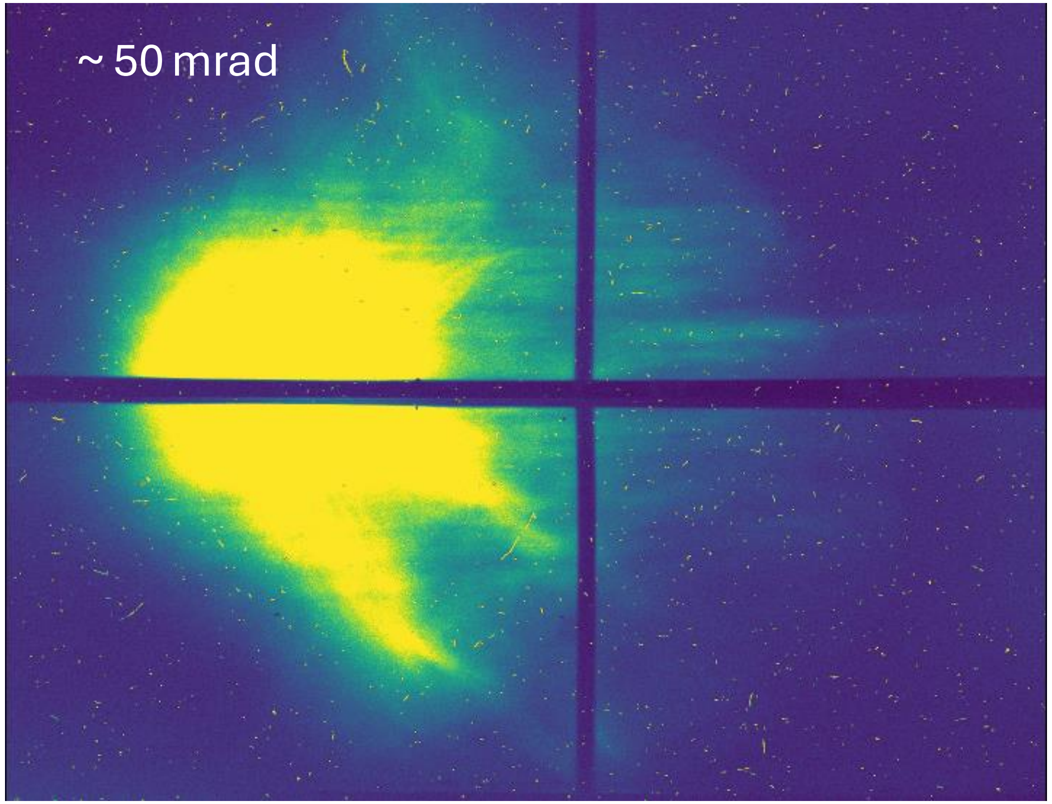
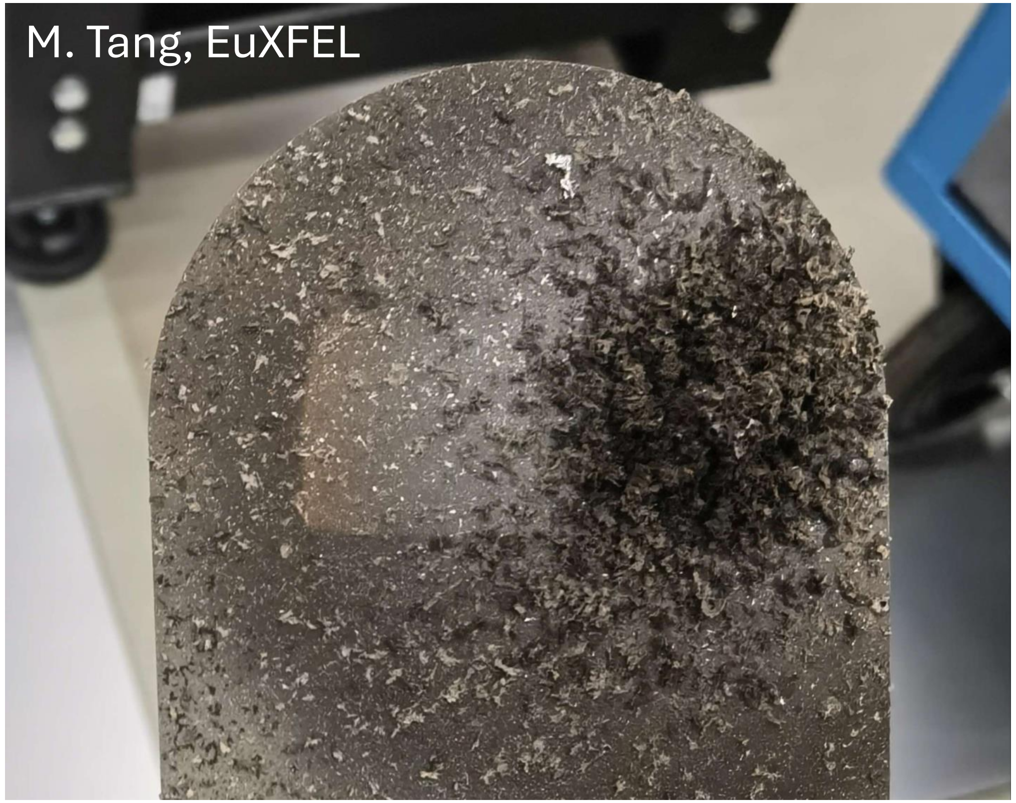


[3]

[4] Ehret, M *et al* (2024) *Plasma Physics and Controlled Fusion*, 66(4), p.045003. doi:https://doi.org/10.1088/1361-6587/ad2690.

7: Solving Both





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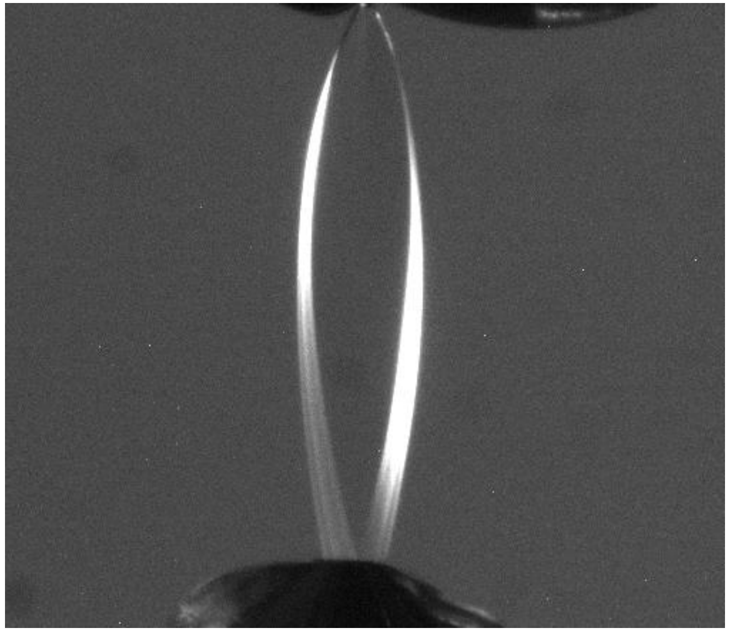
8: The Liquid - Sheet

- The liquid-sheet is varying thickness target created by converging the flow of water [5]
- Liquid-sheets formed from a colliding micro channel design have been demonstrated in the kHz regime [6]
- They are both low-debris and stable, with position fluctuations of < 5 µm [7]



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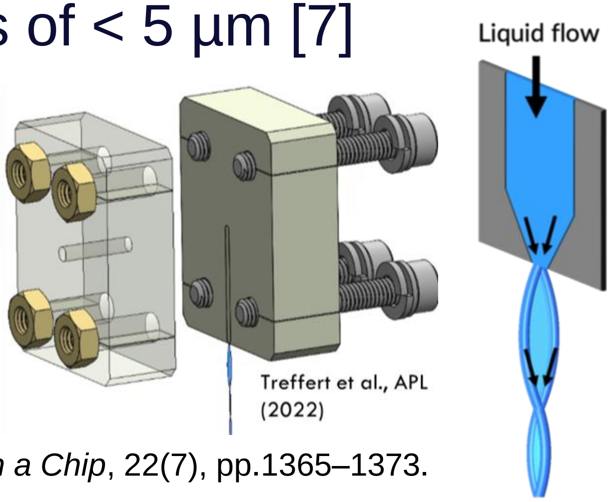

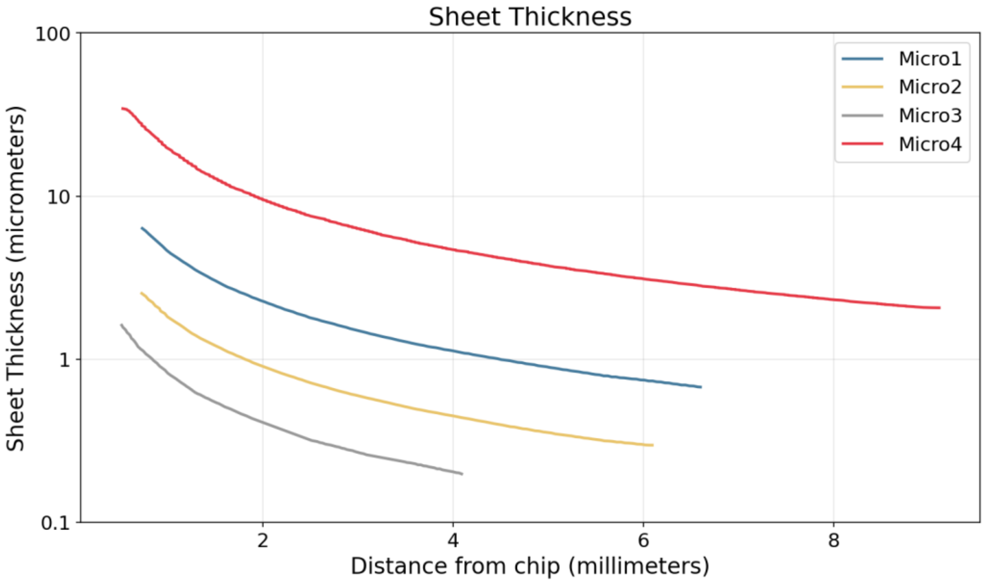

[5] Crissman, C.J *et al*. (2022) *Lab on a Chip*, 22(7), pp.1365–1373. doi.:10.1039/d1lc00757b.
[6] Morrison, J.T *et al,* 2018. *New Journal of Physics*, 20: doi:10.1088/1367-2630
[7] Treffert, F. *et al*. (2022), Physics of Plasmas, doi:10.1063/5.0097857.

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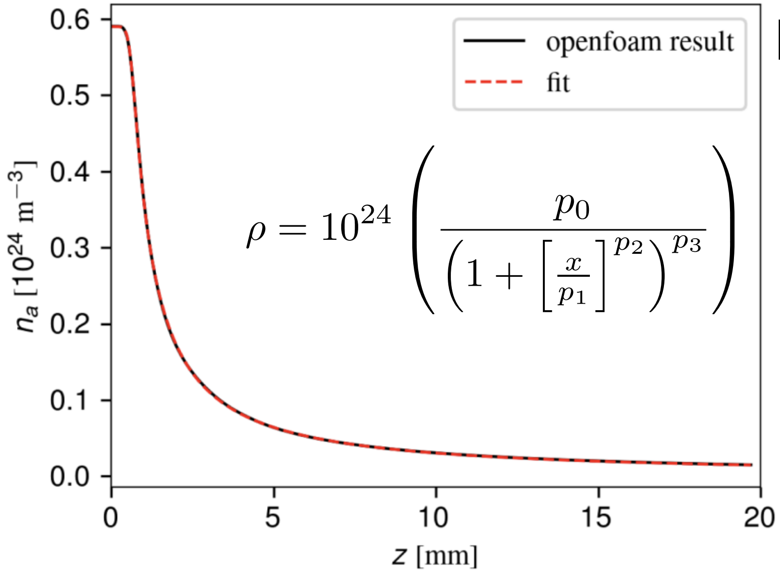
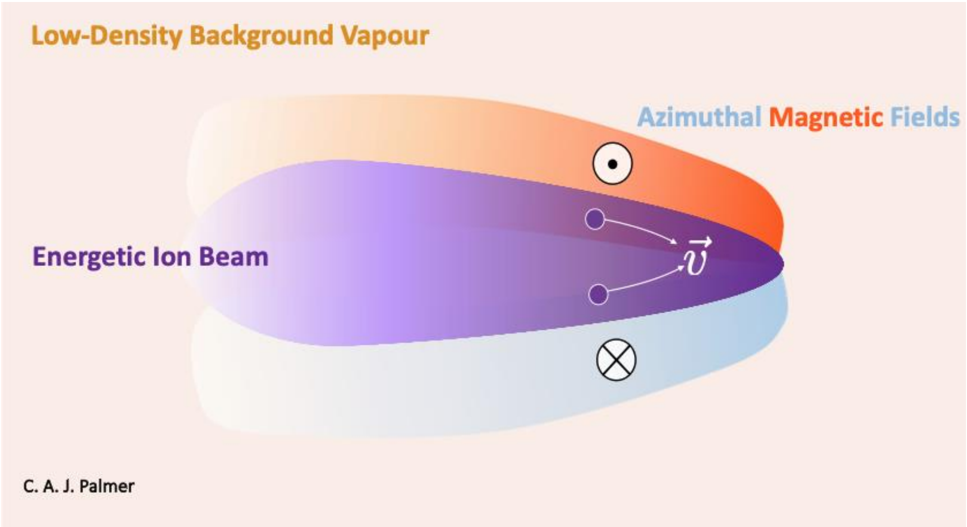
9: Proton Focusing in Low-Density Plasma

- The liquid-sheet produces a vapour due to surface evaporation
- Particles accelerated into this vapour ionise it to form a plasma
- This plasma supports the generation of beam currents
  - Two stream instability strips electrons from the beam
  - These currents give rise to magnetic fields which act to focus the protons



[8]



[8] Streeter, J. V. M, *et al* (2025) *Nature Communications*, 16(1). doi:https://doi.org/10.1038/s41467-025-56248-4.

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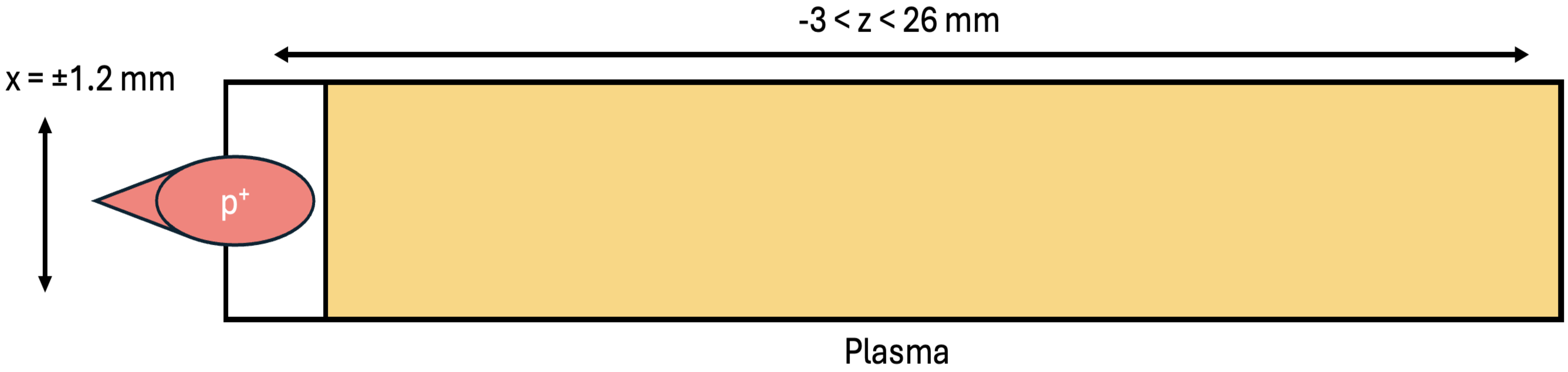
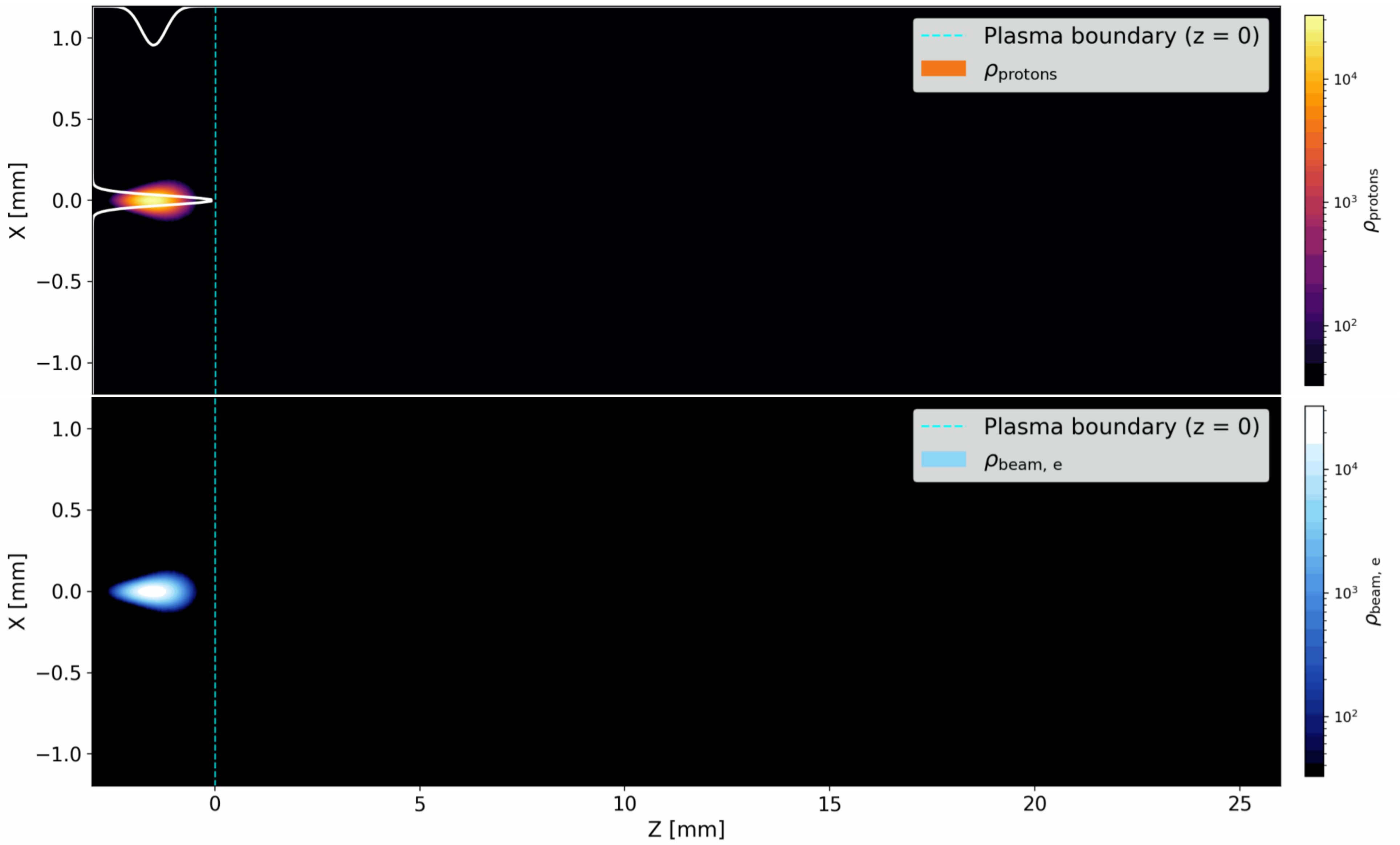
10: Exploring this Effect in WarpX



- Simulate a proton beam (w/ co-propagating electrons) into a plasma
  - The beam has some time to expand in vacuum
  - The plasma has a sharp boundary with the vacuum, and a constant density throughout the simulation

11: What Do We See?



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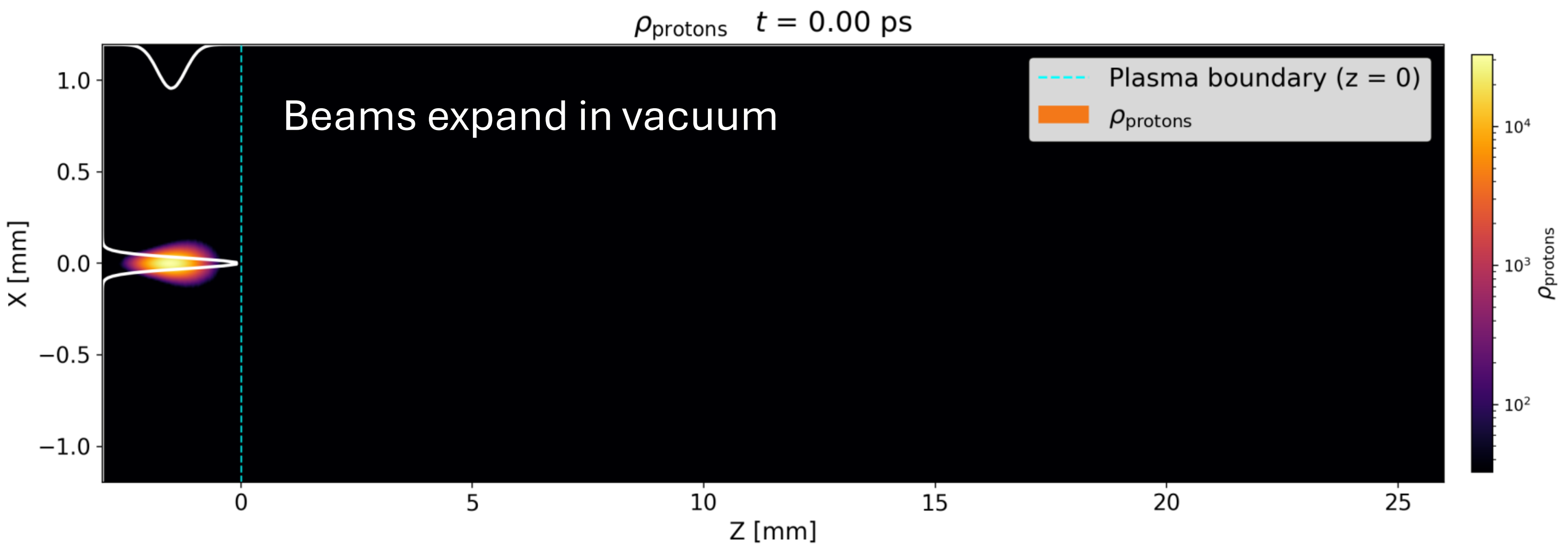
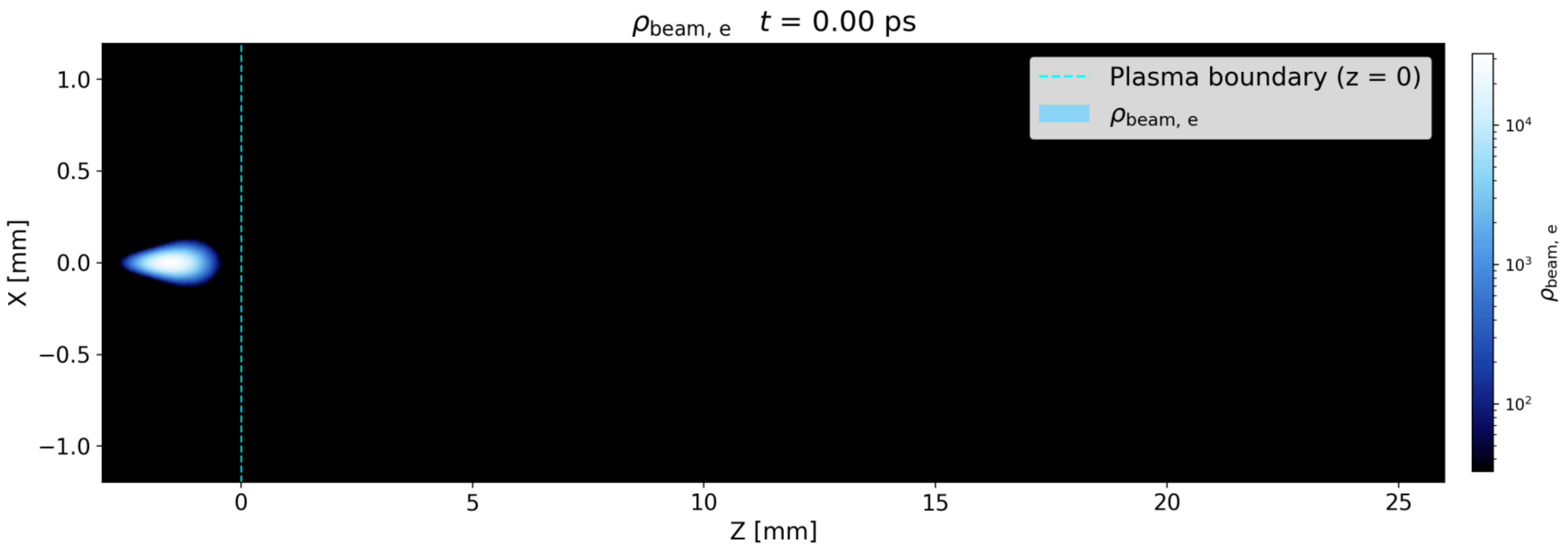
11.1: Simulation Output - Stills





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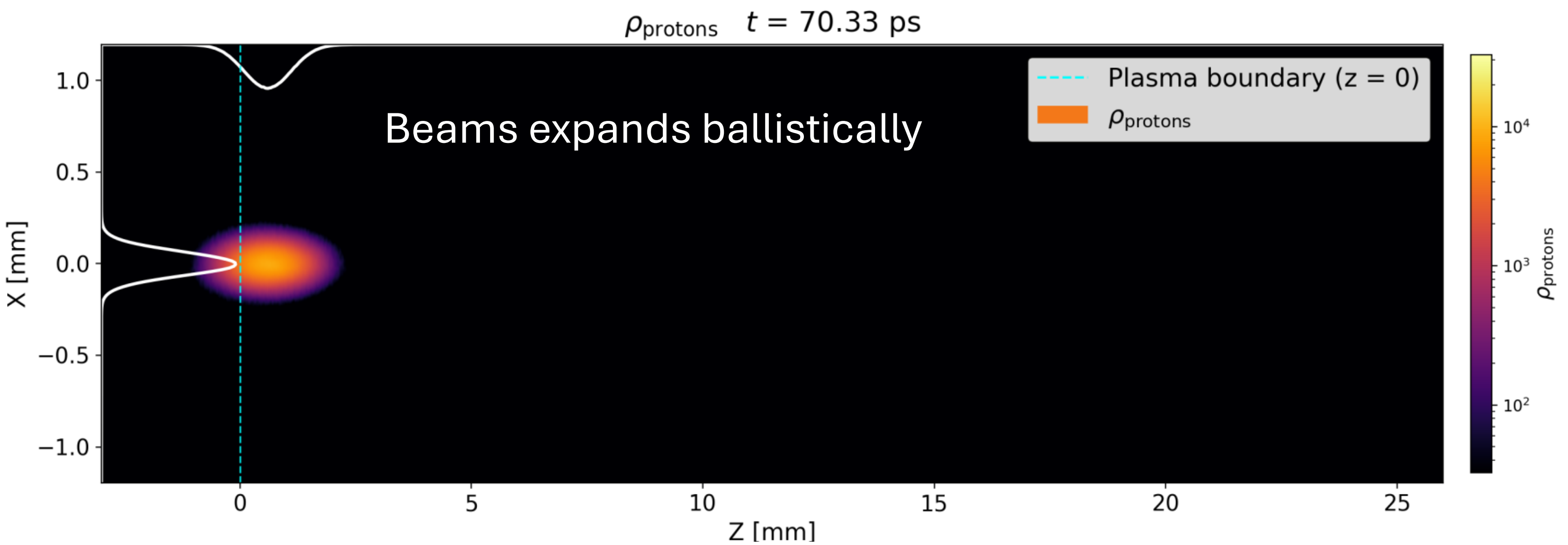
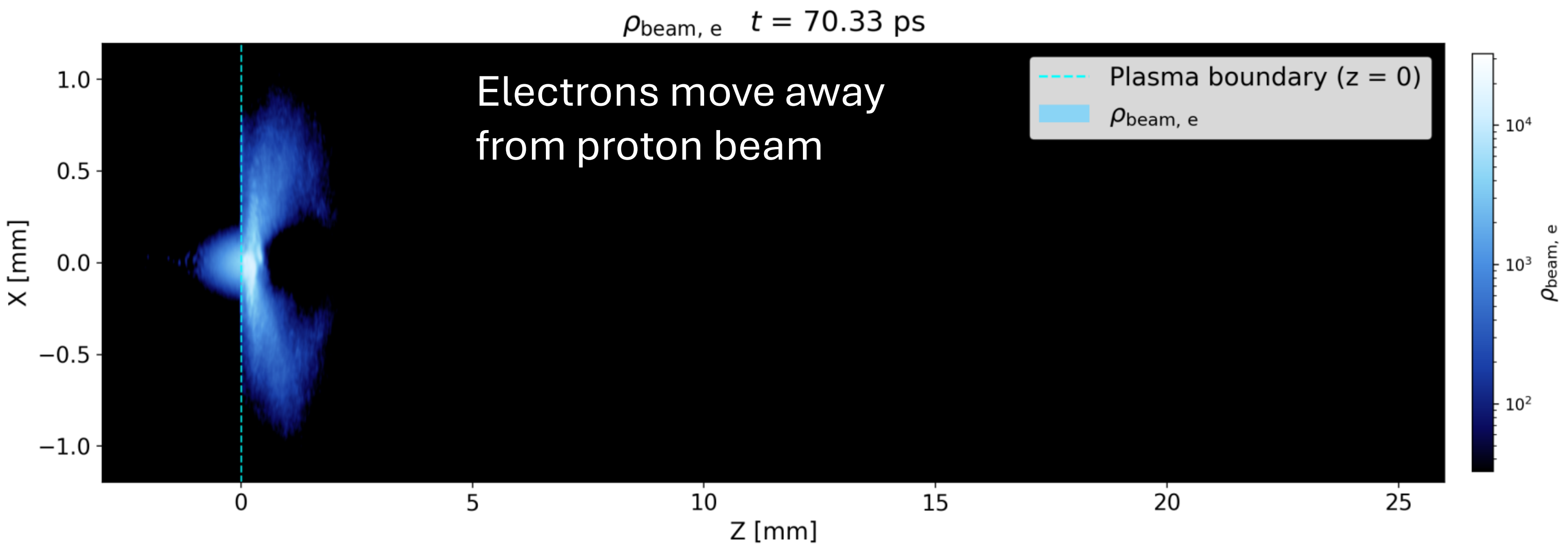
11.2: Simulation Output - Stills





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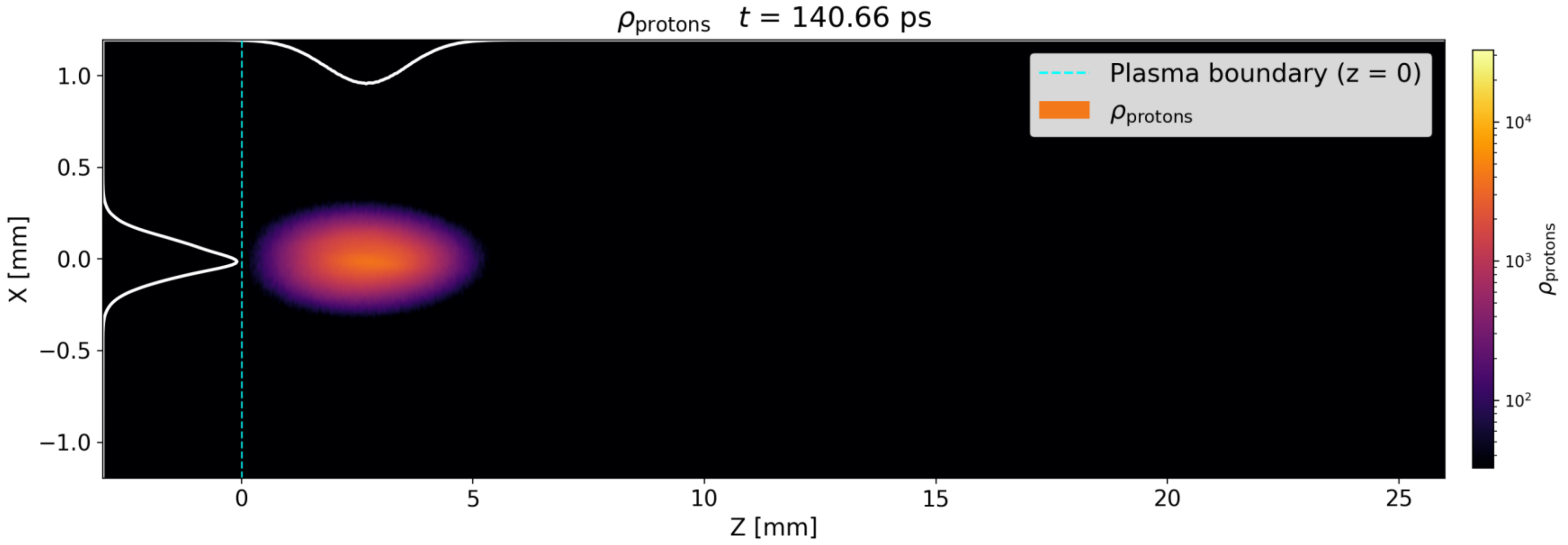
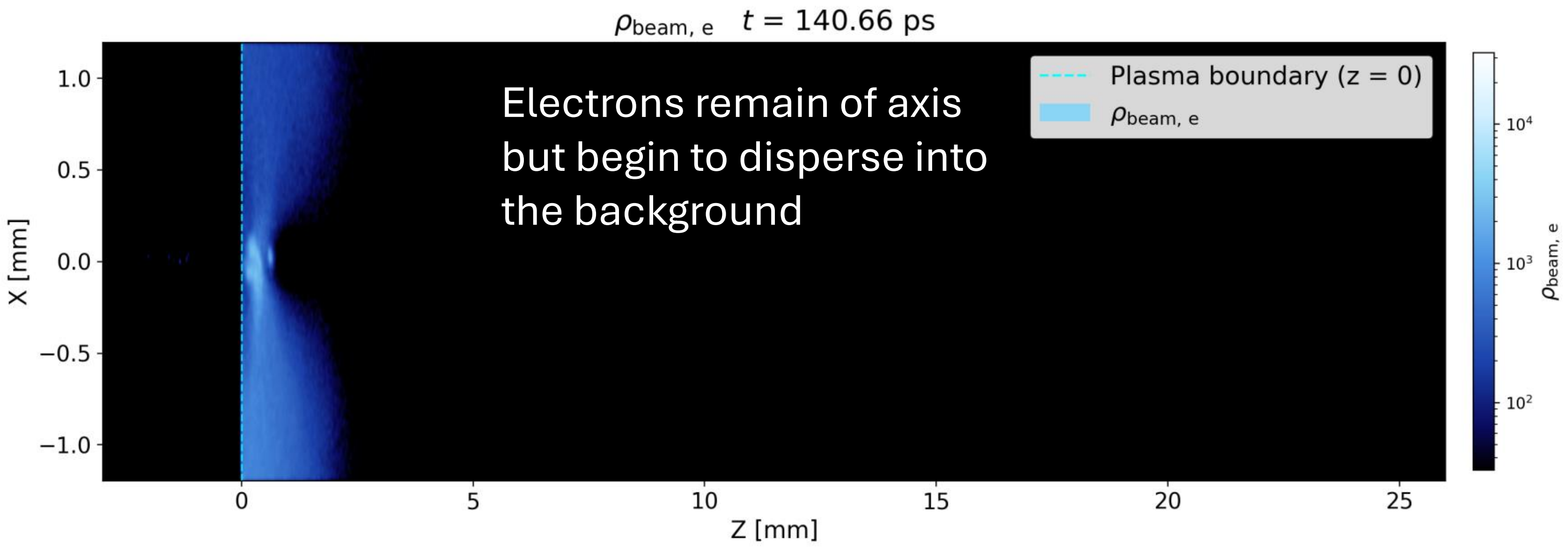
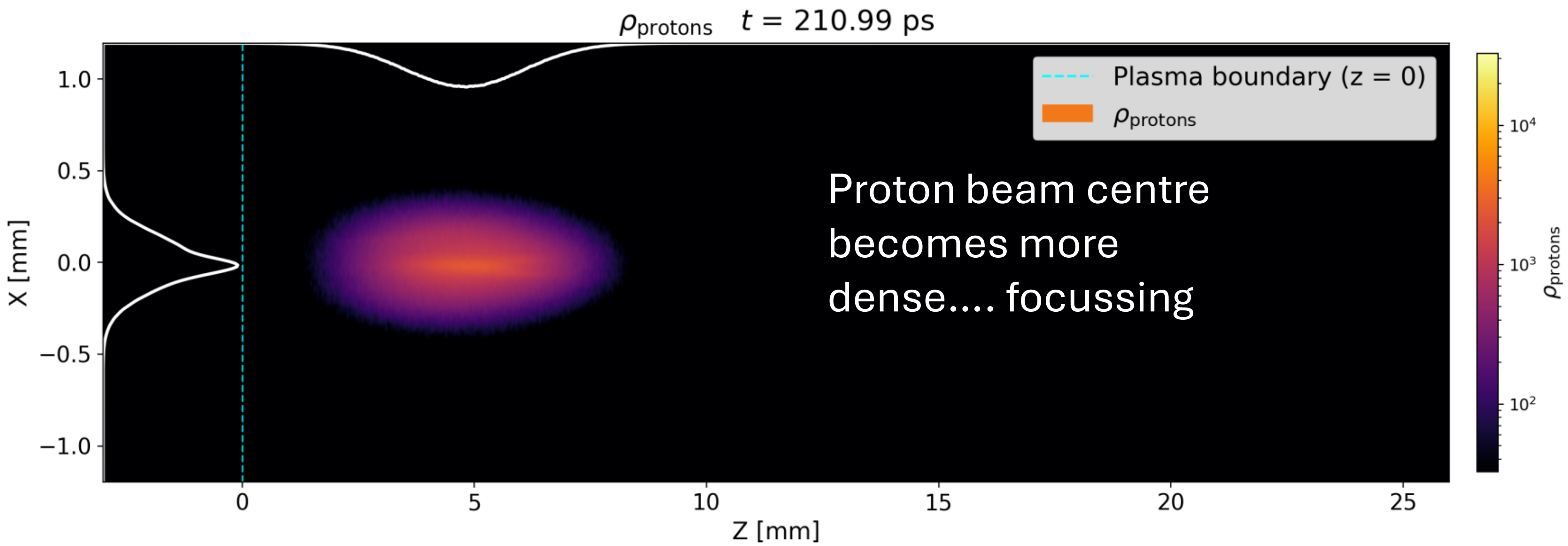
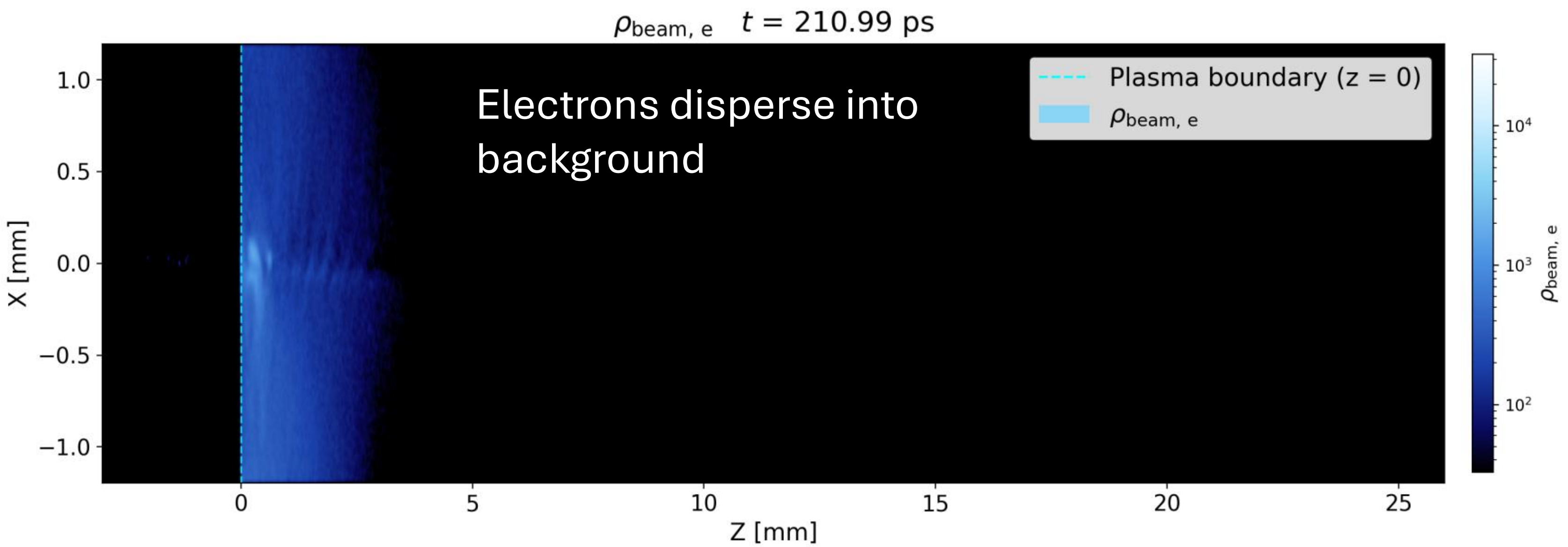
11.3: Simulation Output - Stills





11.4: Simulation Output - Stills





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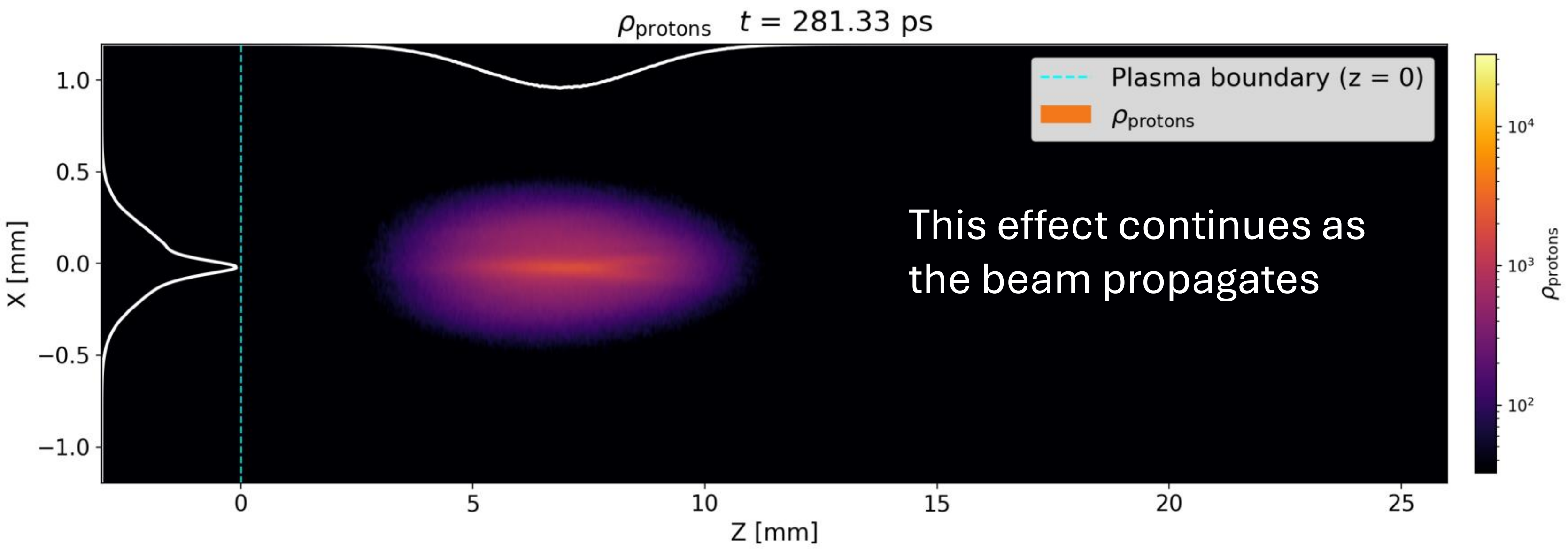
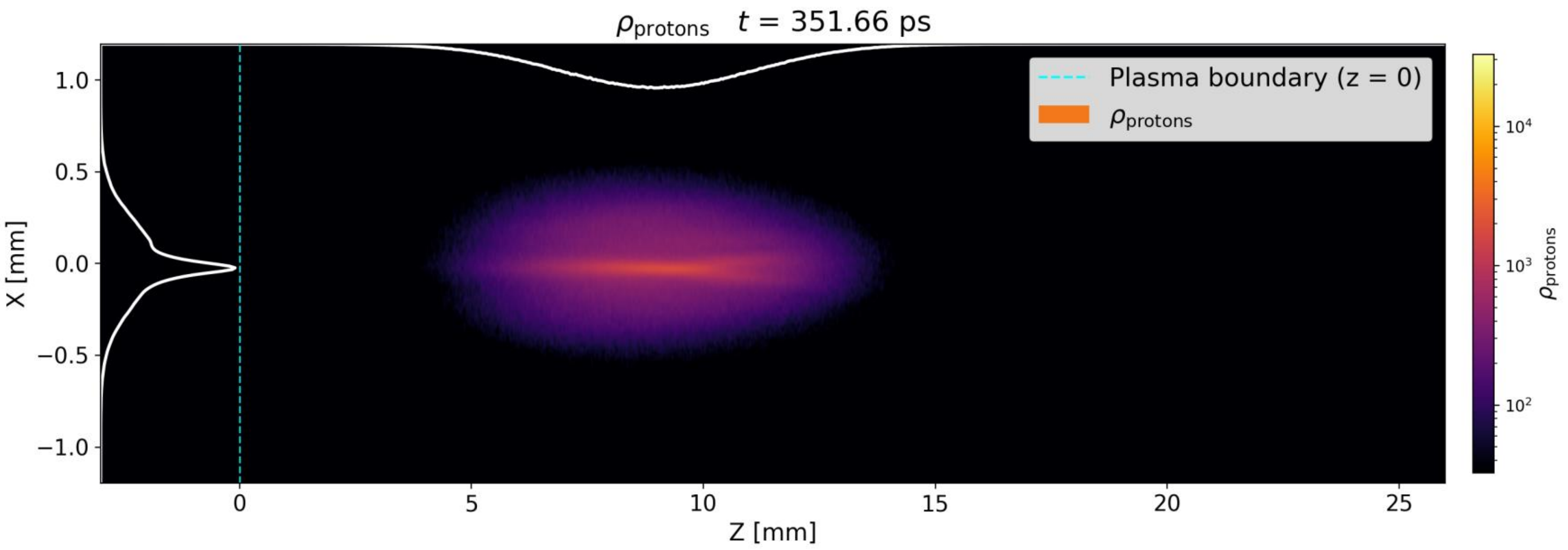
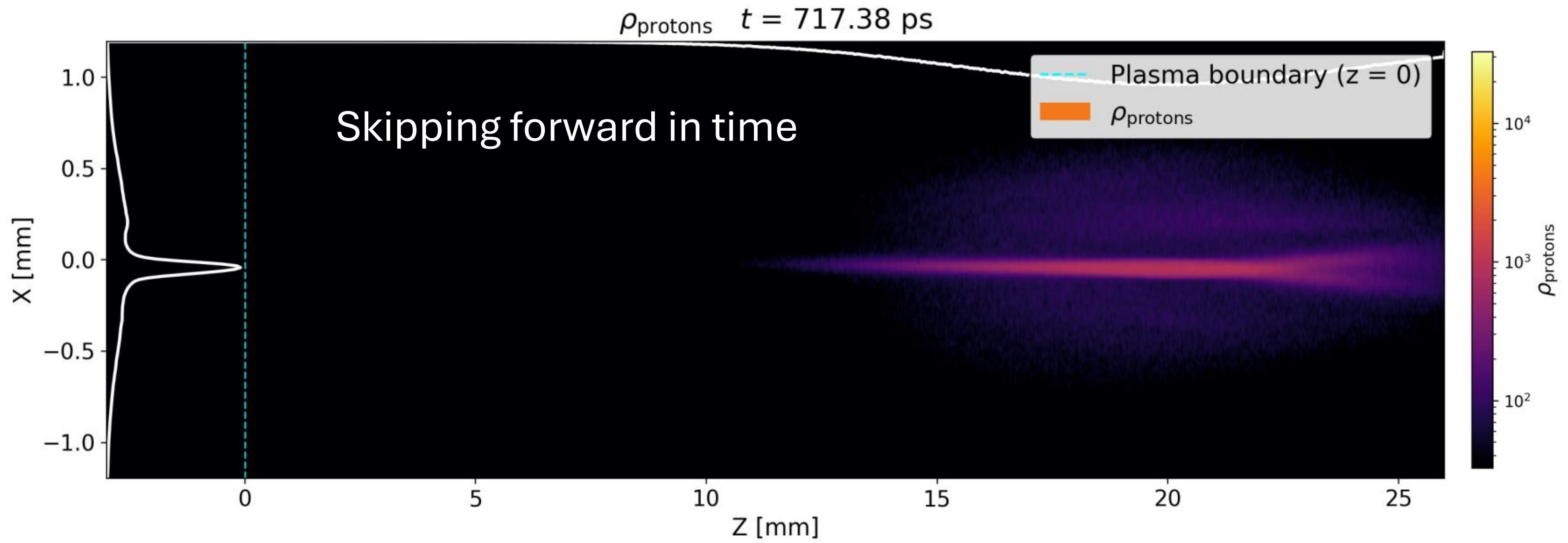
11.5: Simulation Output - Stills

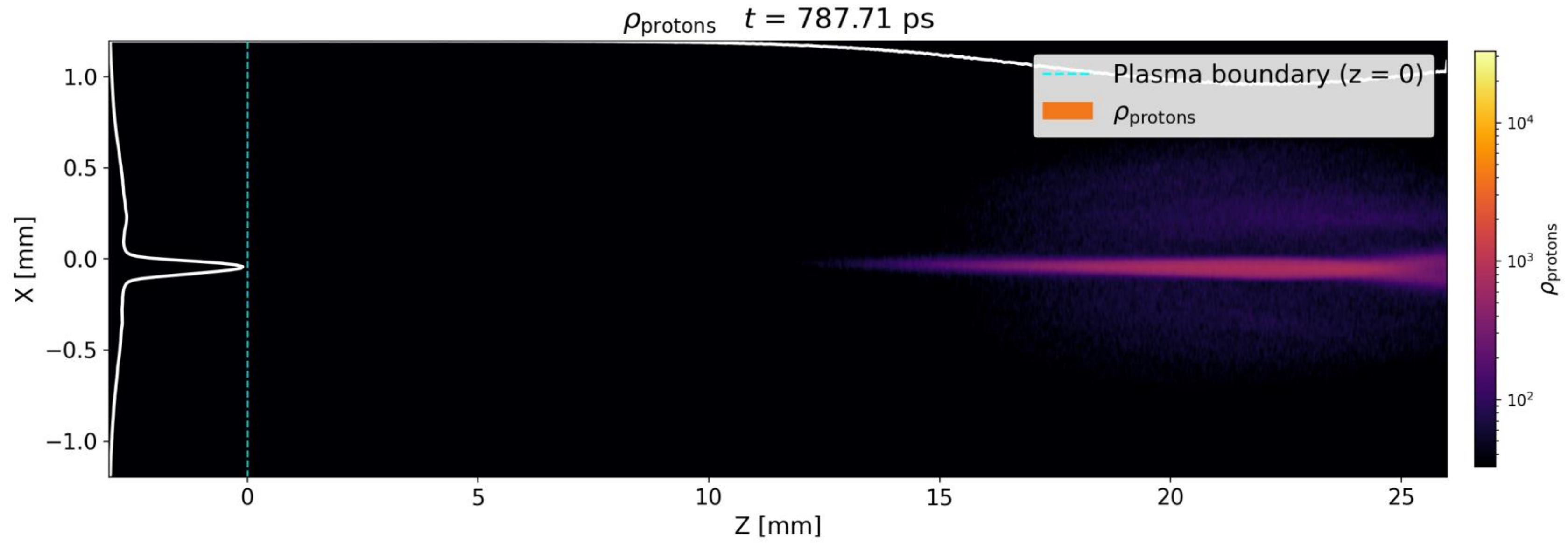


This effect continues as the beam propagates



11.6: Simulation Output - Stills





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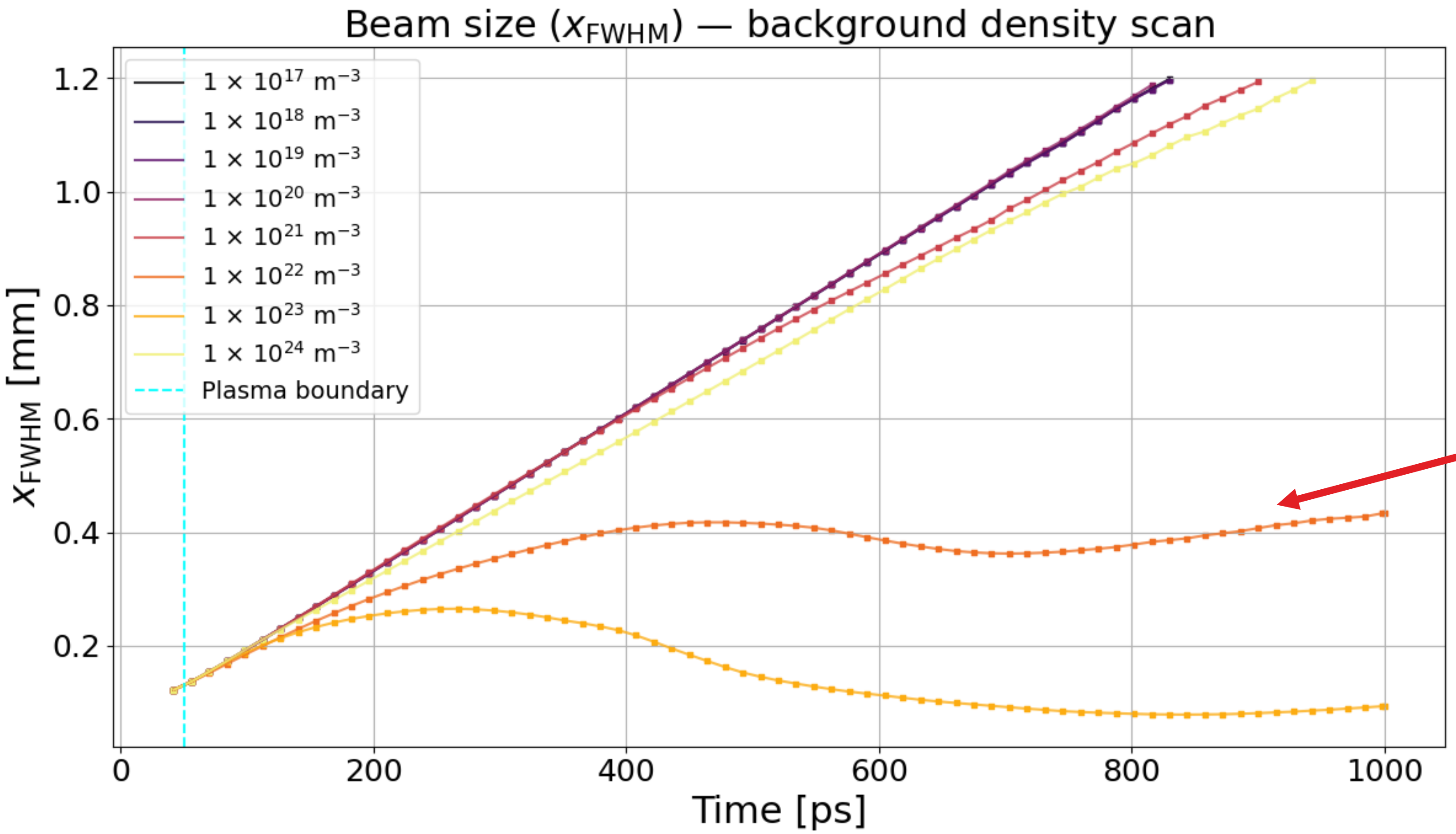
12: Background Plasma Density

- Scanning through the electron density of the background plasma

- 50 nC beam, 20 mrad initial divergence



Bouncing effect caused by some beam leaving the box

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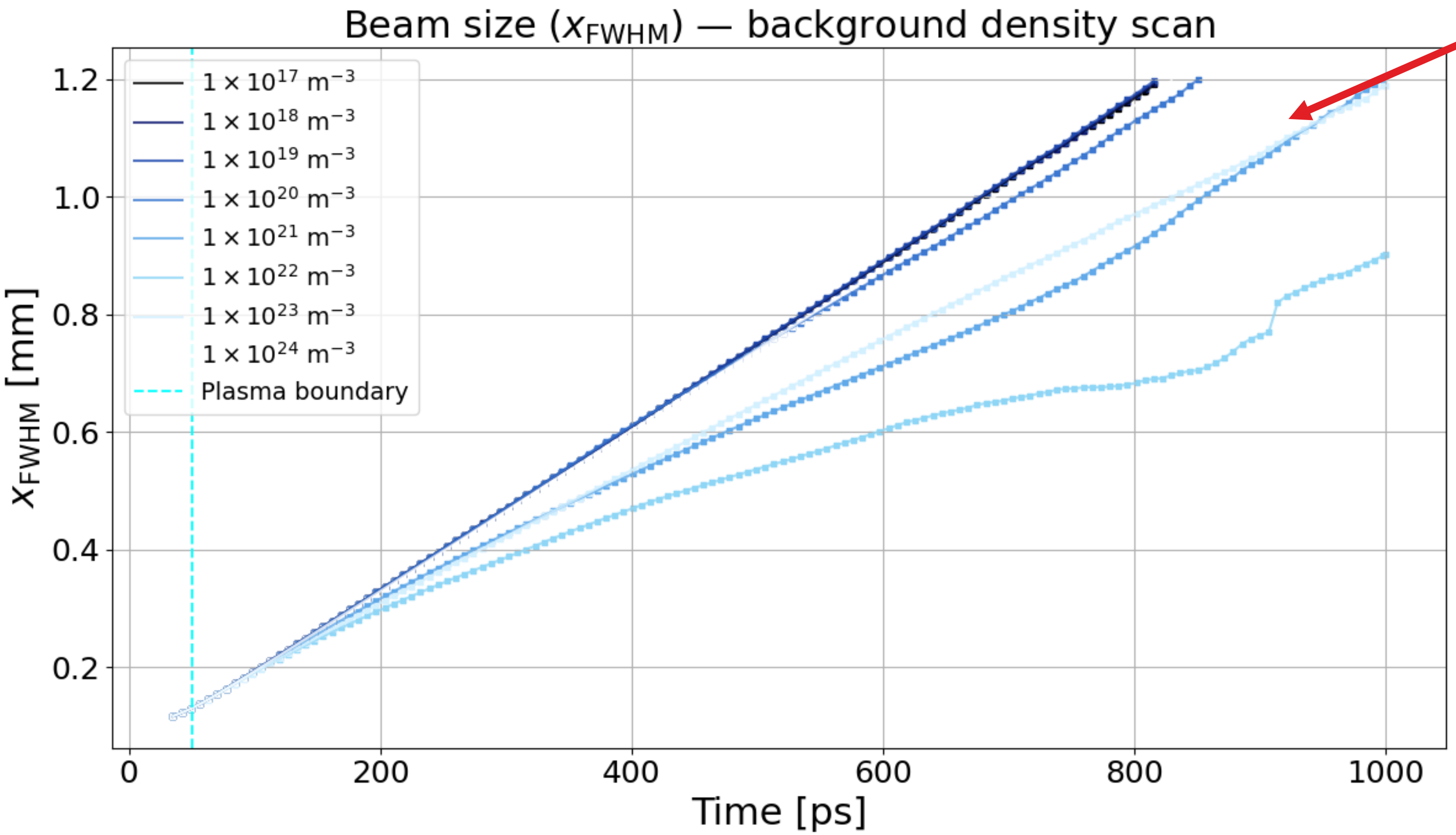
13: Background Plasma Density

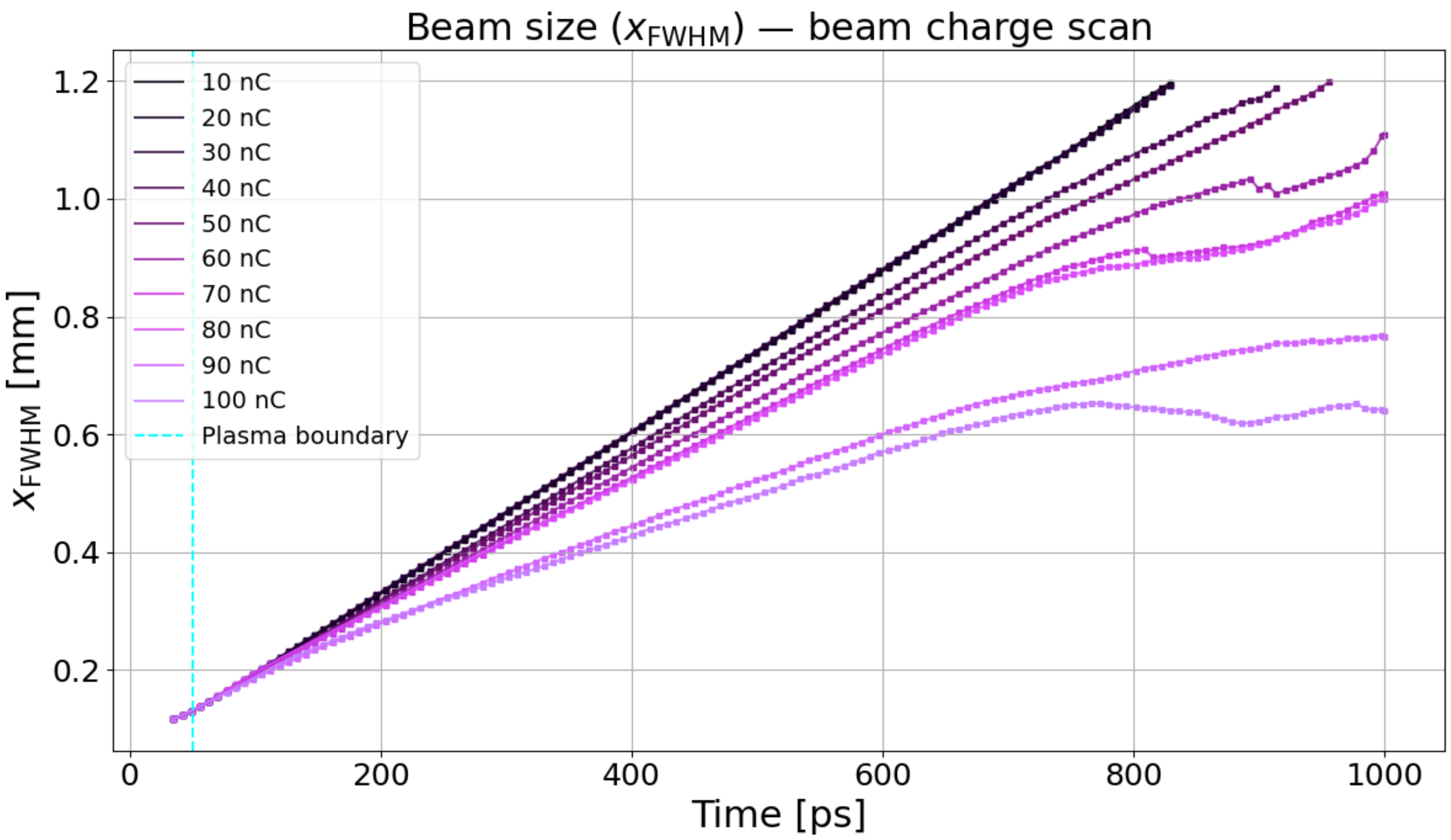
- Scanning through the electron density of the background plasma
- 10 nC beam, 20 mrad initial divergence



Background electrons move in reducing focussing

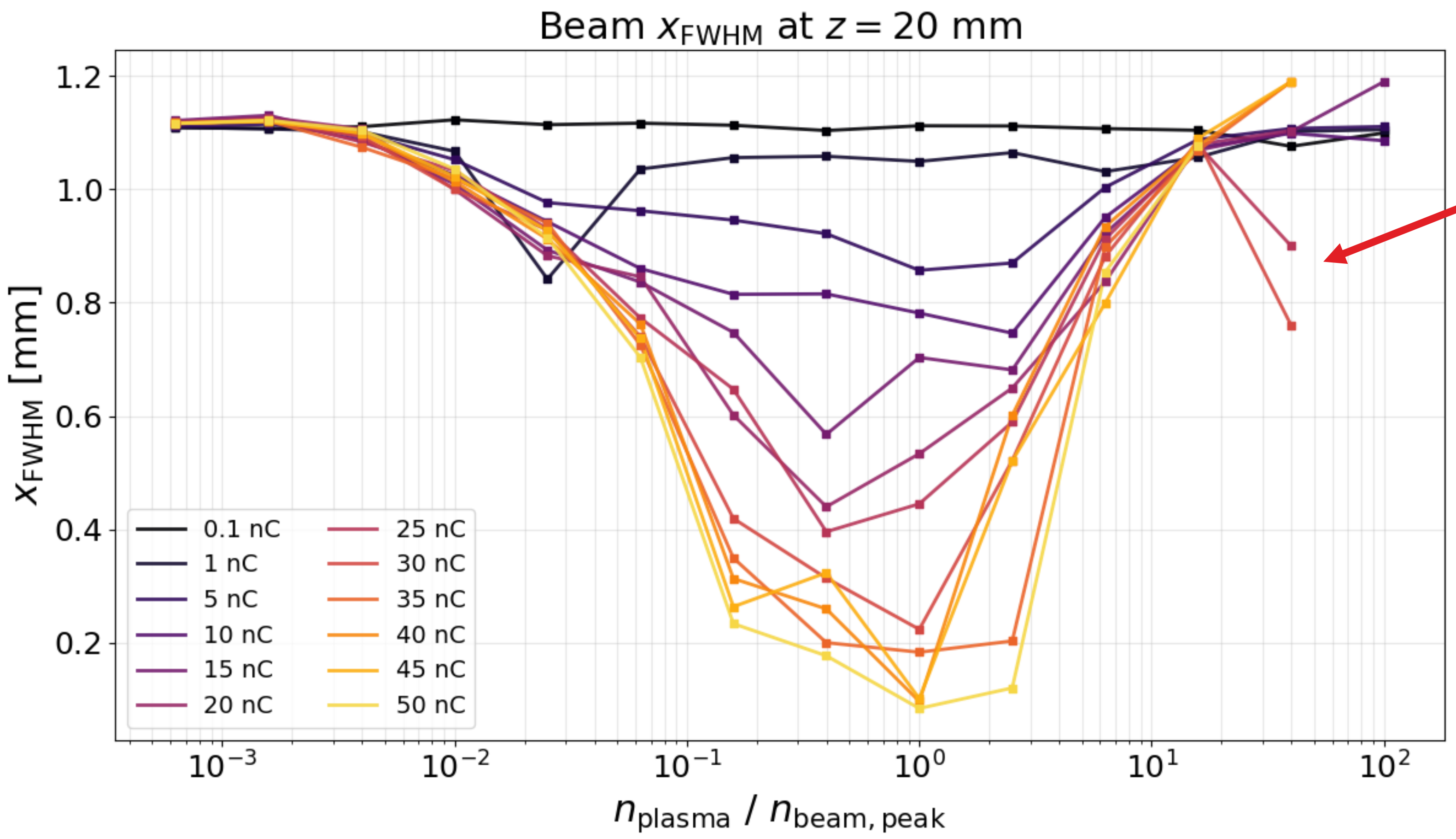
14: Beam Charge

- The beam has an initialised charge ($q_p = - q_e$)
    - Changing this in action changes the *beam density*



15: Beam Charge and Background Density

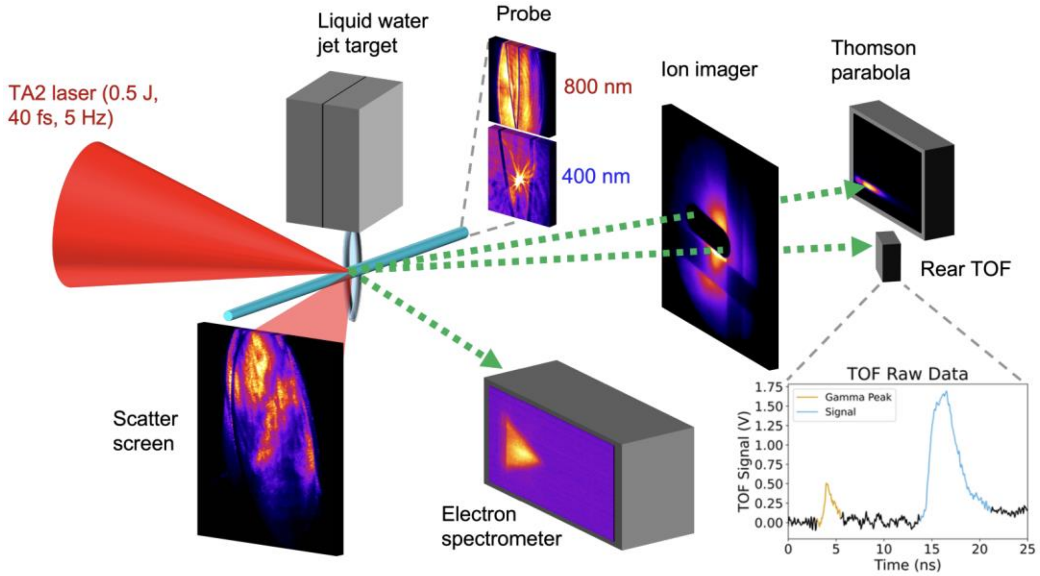
- Beam size at 20 mm propagation
- Higher charges show larger reductions around a ratio of 1

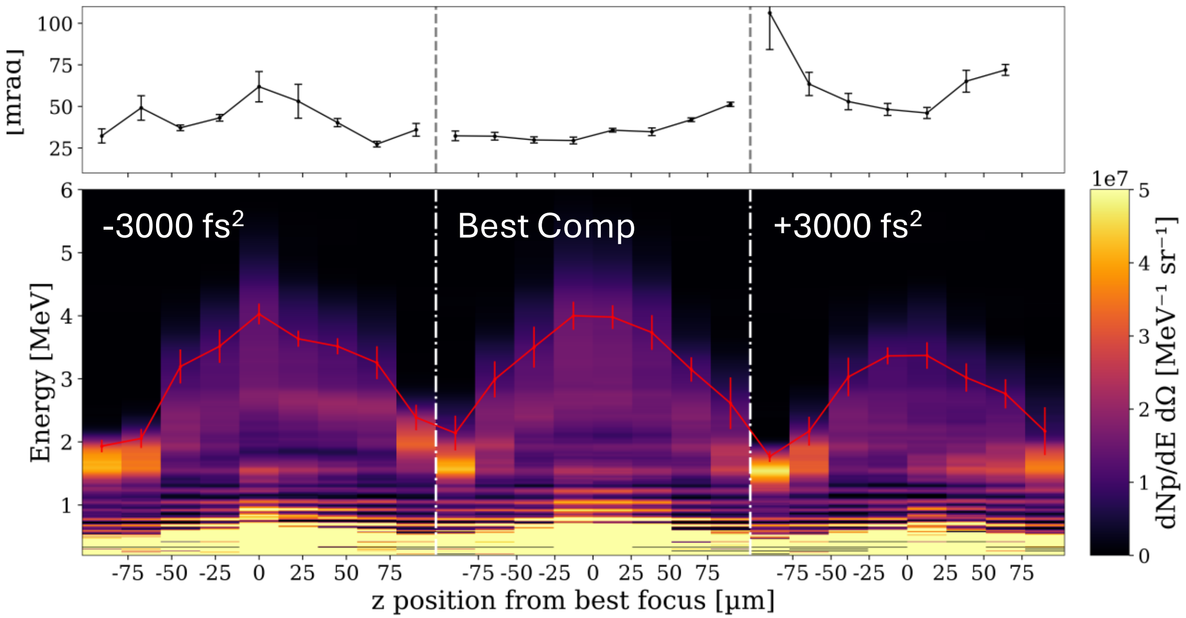


Beam filamenting into smaller bunches that are being focussed

16: Achieving This On Campaign

- Come and see my poster!!! (the red one)





Low-Divergence High-Repetition-Rate Ion Sources from Liquid Sheet Target

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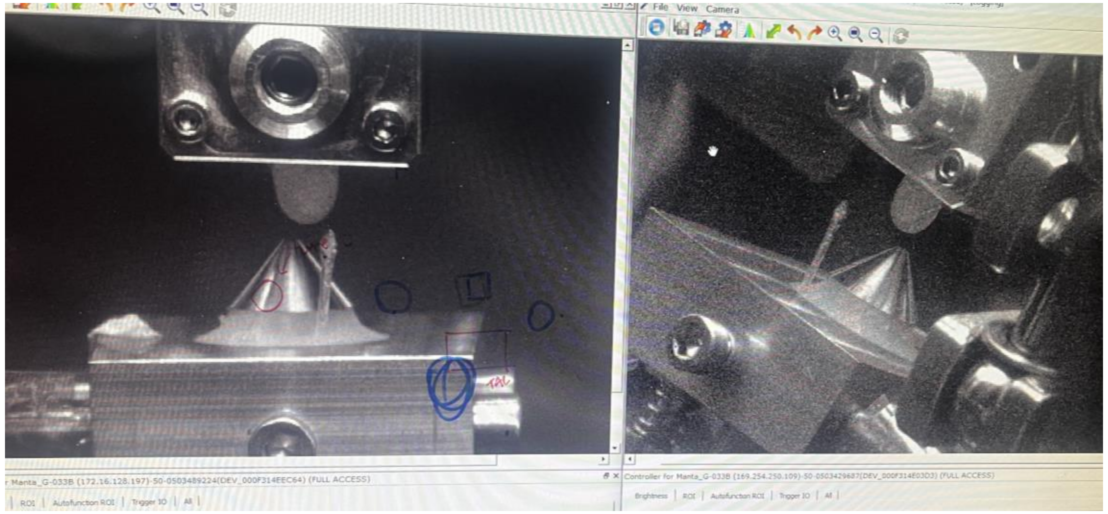
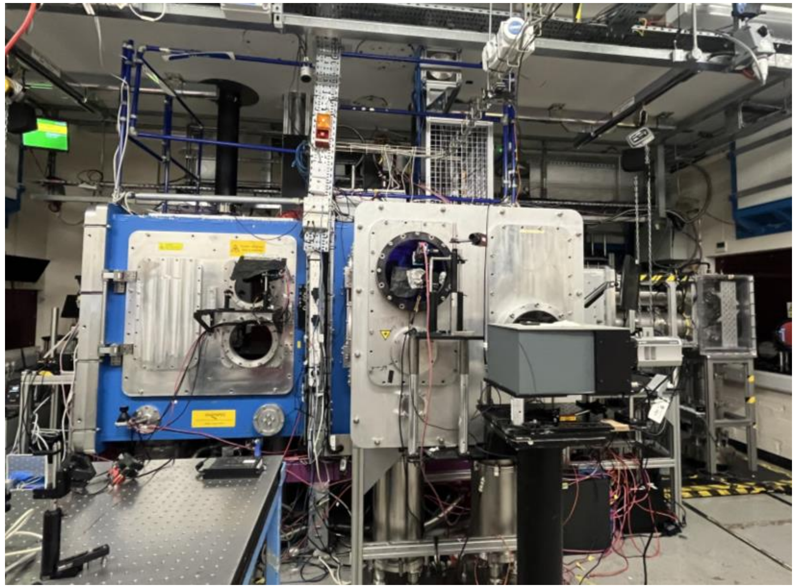
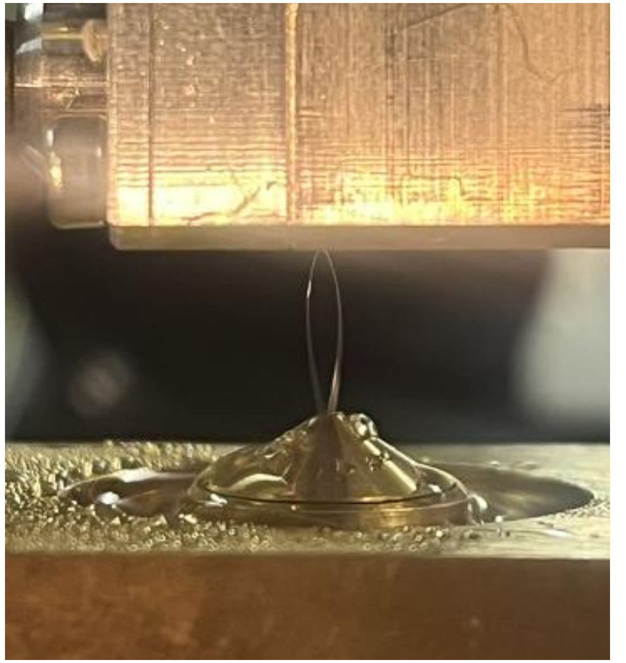
What Next?

- Expand on experimental data sets with a campaign at ***BELLA next week***
- Characterise the vapour profile of the liquid-sheet to inform simulations at the CLF
- Investigate the fields using LWFA electrons and the liquid-sheet in Gemini at the CLF
- Debug the use of the sheet







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With thanks too:

QUB: **D. Molloy**, M. J. V. Streeter, B. Loughran, J. P. Kennedy, C. J. R. Fitzpatrick, C. I. Prestwood, P. Parson, C. J. A. Palmer

SLAC: G. Griffin, G. Gain, M. Gauthier, S. H. Glenzer

CLF: S. Astrbury, N. Bourgeois, H. Ahmad, S. J. D. Dann, J. S. Green, D. Symes

LLNL: F. Treffert

UMich: A. G. R. Thomas

ICL: N. P. Dover

ELI-Beamlines: L. Giuffrida