AE133: High-intensity laser interactions with near-critical density plasmas

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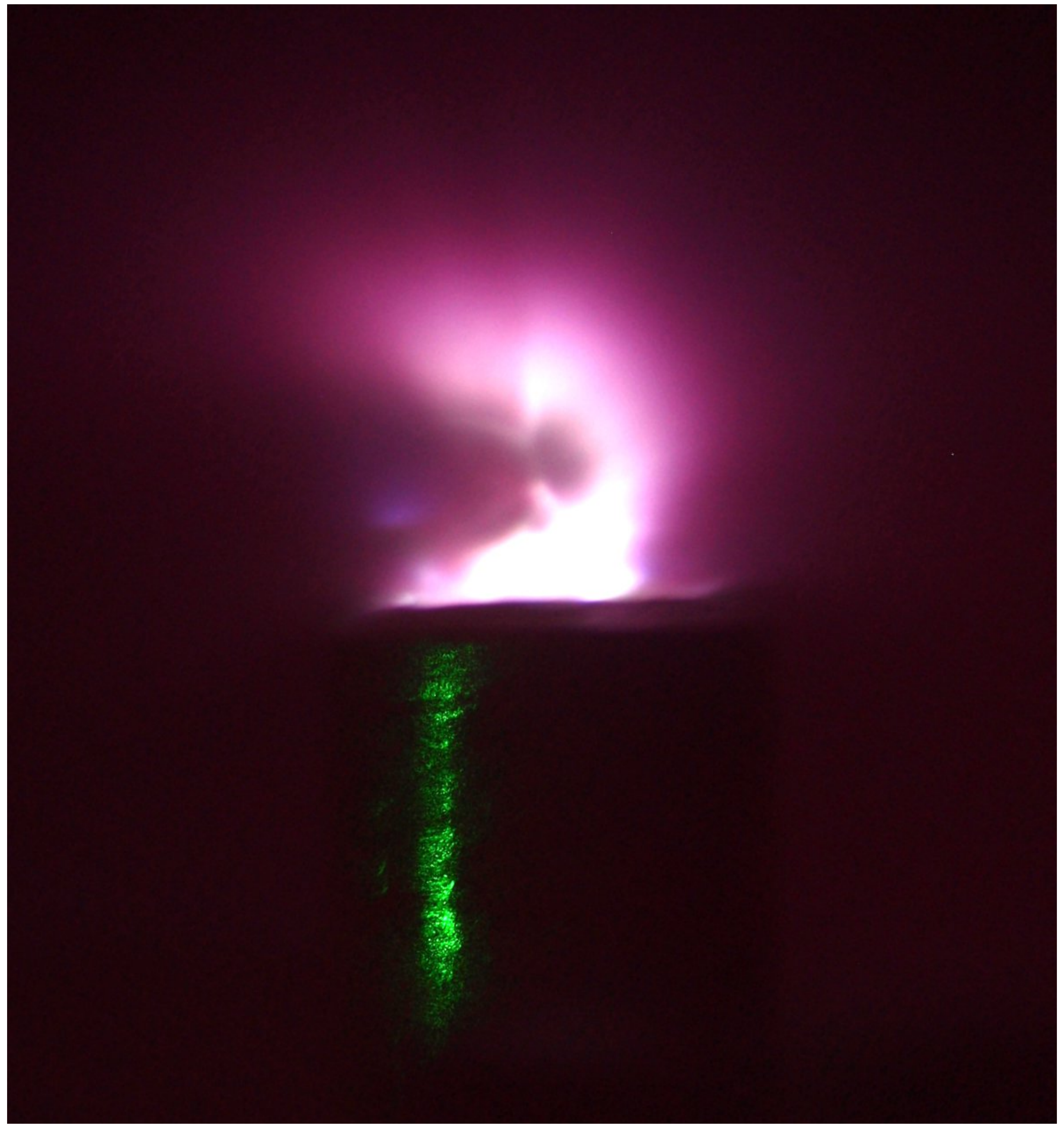
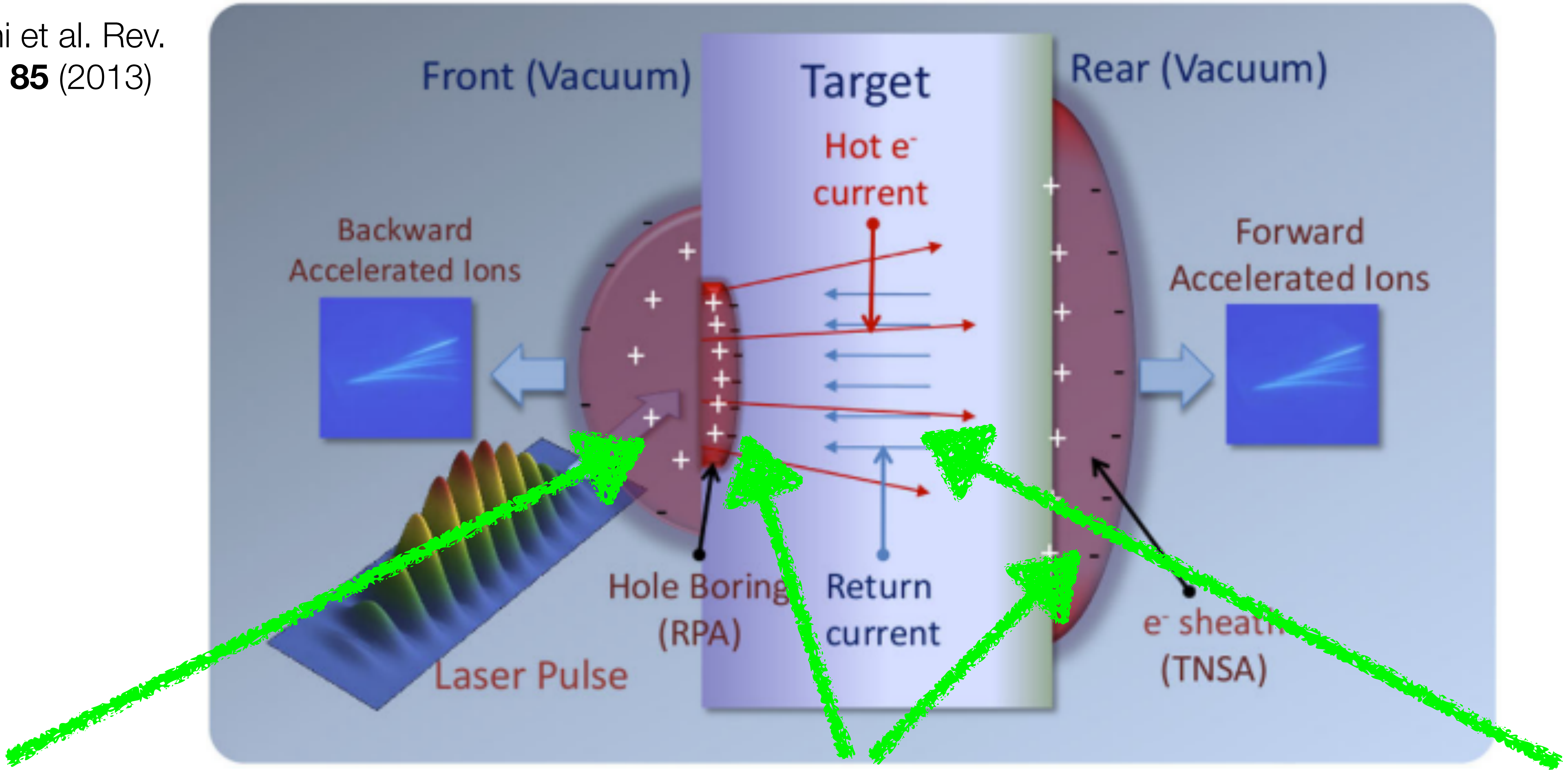
ATF User Meeting,
30th April 2025



Funding: STFC ST/V001639/1 (Received)

Physics of laser driven ion sources difficult to diagnose directly

From Macchi et al. Rev. Mod. Phys. **85** (2013)



Laser propagation in underdense plasma

Acceleration of ions at critical density surface and plasma boundary

Propagation of “fast” electrons in the target

Ion sources undergo multiple nonlinear and dynamic processes, near-impossible to see experimentally

Diagnosing laser driven ion sources - a new approach?

Nearly all laser driven ion source experiments performed in the near-IR

	Time	*Length*	*Density*
Typical dynamical scales	~10 fs	~1 μm	>~10^{21} cm^{-3}
Can we diagnose it?	Too quick ☹️	Too short ☹️	Too dense ☹️

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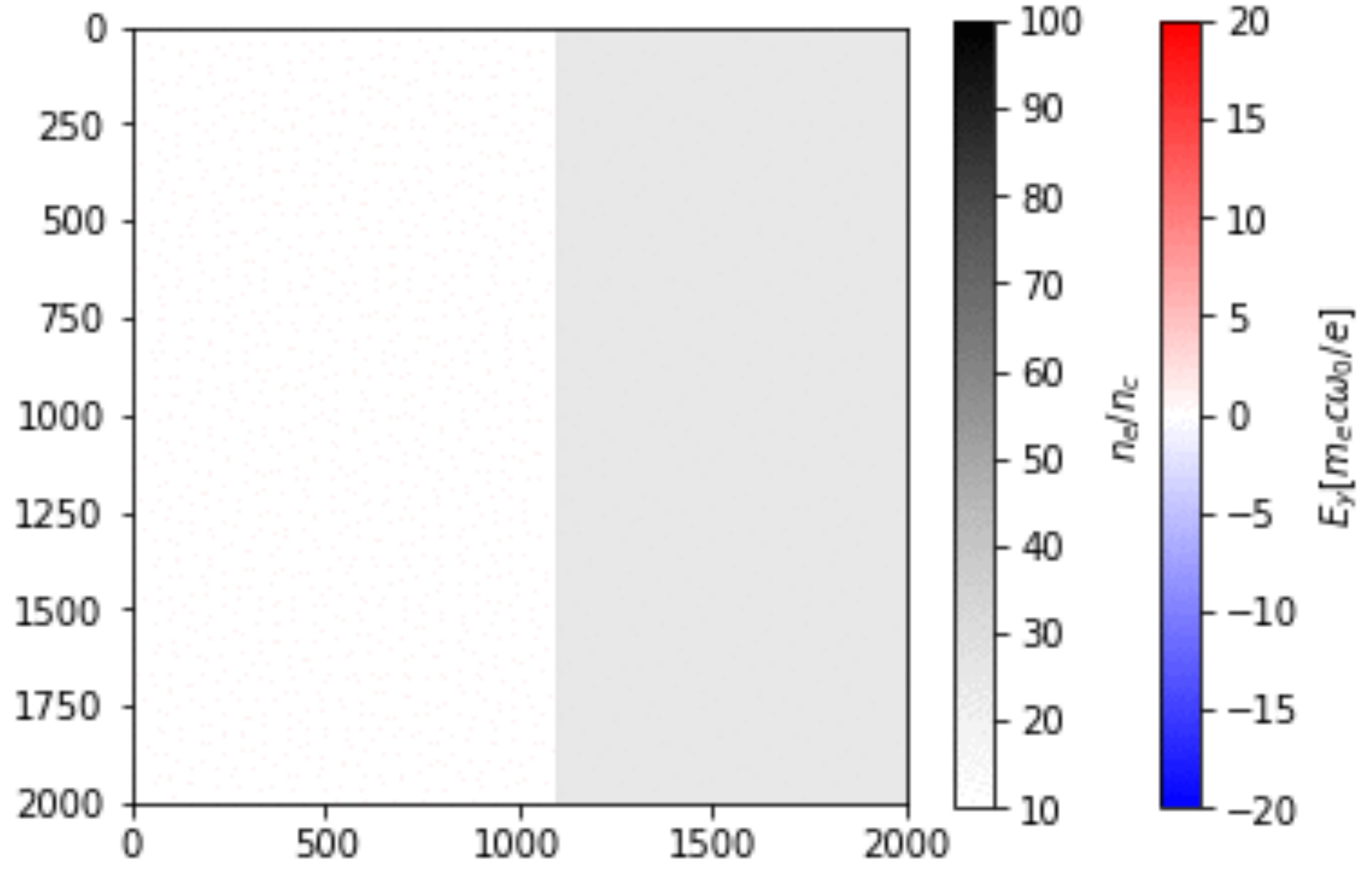

Rely on simulations, many assumptions

- Reduced dimensionality
- Uncertainty over experimental parameters
- Can only verify by looking at outputs e.g. ion beam

Exploiting dimensional scaling of collisionless laser-plasmas

Collisionless laser plasmas can be defined using reference frequency*:

	Time	*Length*	*Density*	
	$\tilde{x} = \boxed{\frac{\omega_L}{c}} x$	$\tilde{t} = \boxed{\omega_L t}$	$\tilde{n} = \frac{1}{n_c} n \propto \frac{1}{\boxed{\omega_L^2}} n$	
near-IR	~10 fs	~1 μm	>~10[21] cm[-3]	☹️

*if e.g. ionisation/QED not important

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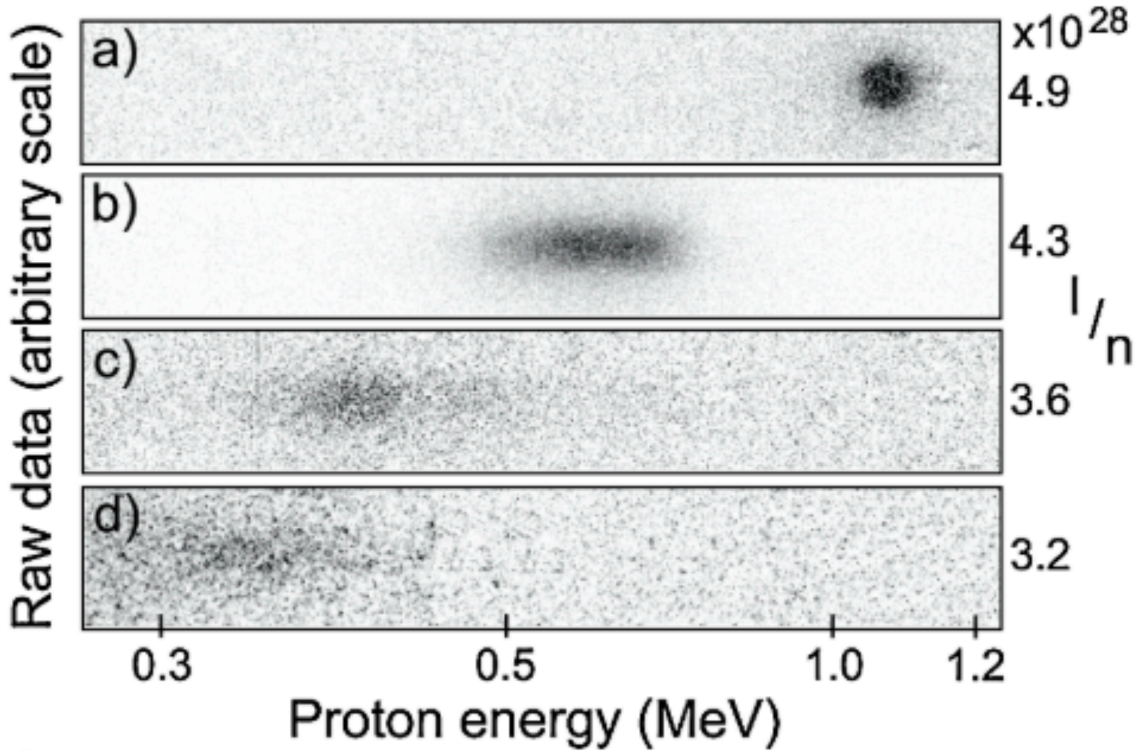
near-IR	~10 fs	~1 μm	>~10^{21} cm^{-3}	☹
longwave-IR	~100 fs	~10 μm	>~10^{19} cm^{-3}	😃
	Resolvable	Resolvable	Ideal for optical probing	

*if e.g. ionisation/QED not important

Earlier experimental results at the ATF

Ion beam generation using the ATF LWIR drive



Palmer+, Phys. Rev. Lett. 106, 014801 (2011)

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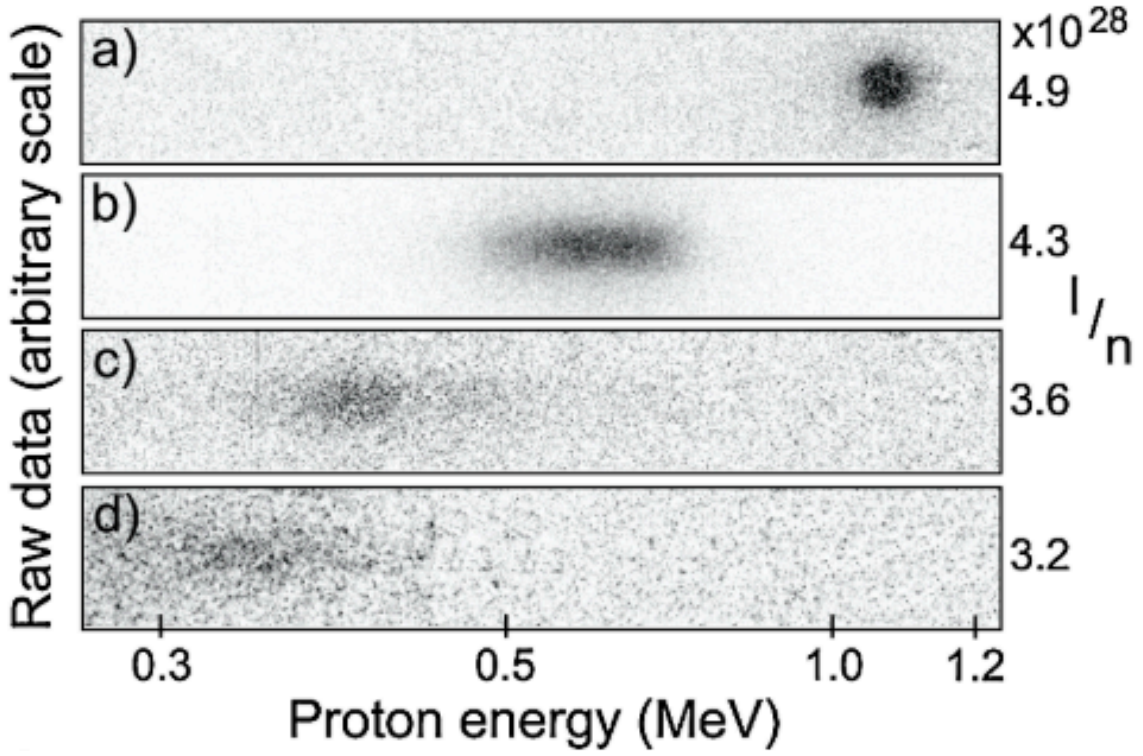

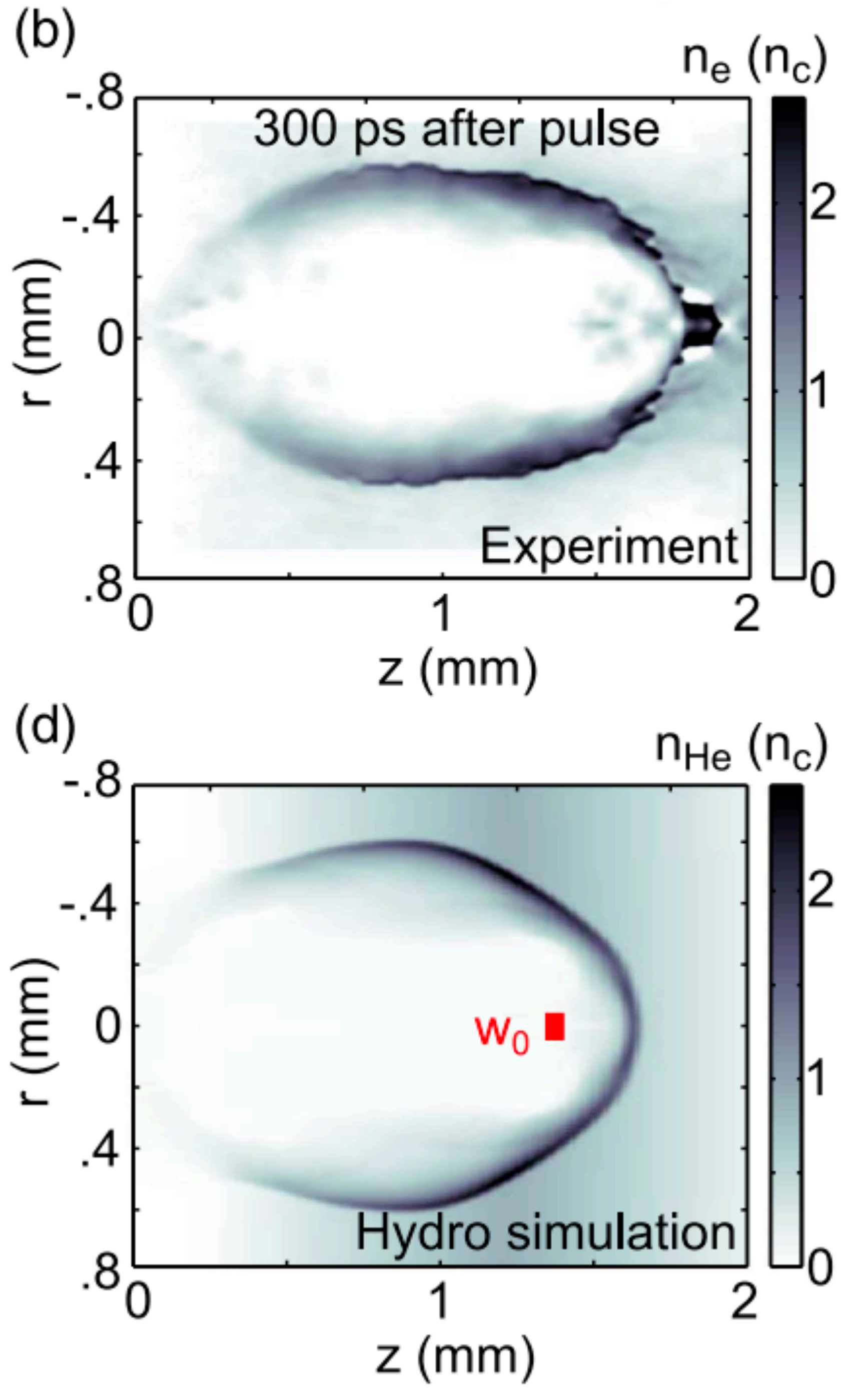

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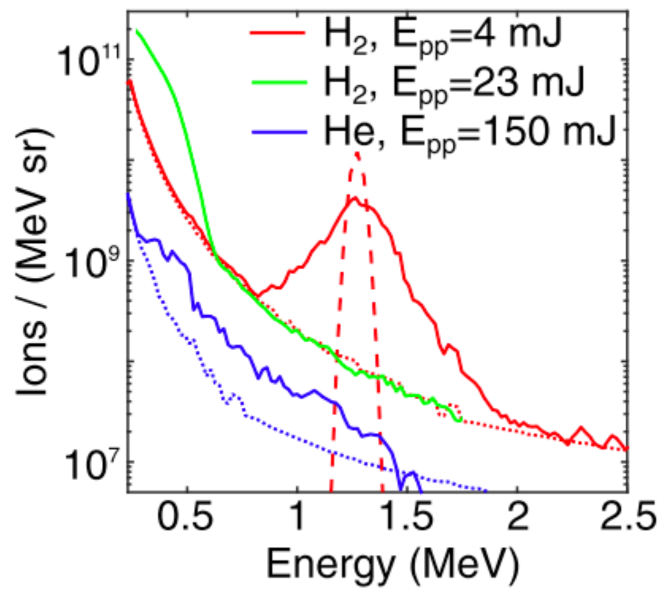

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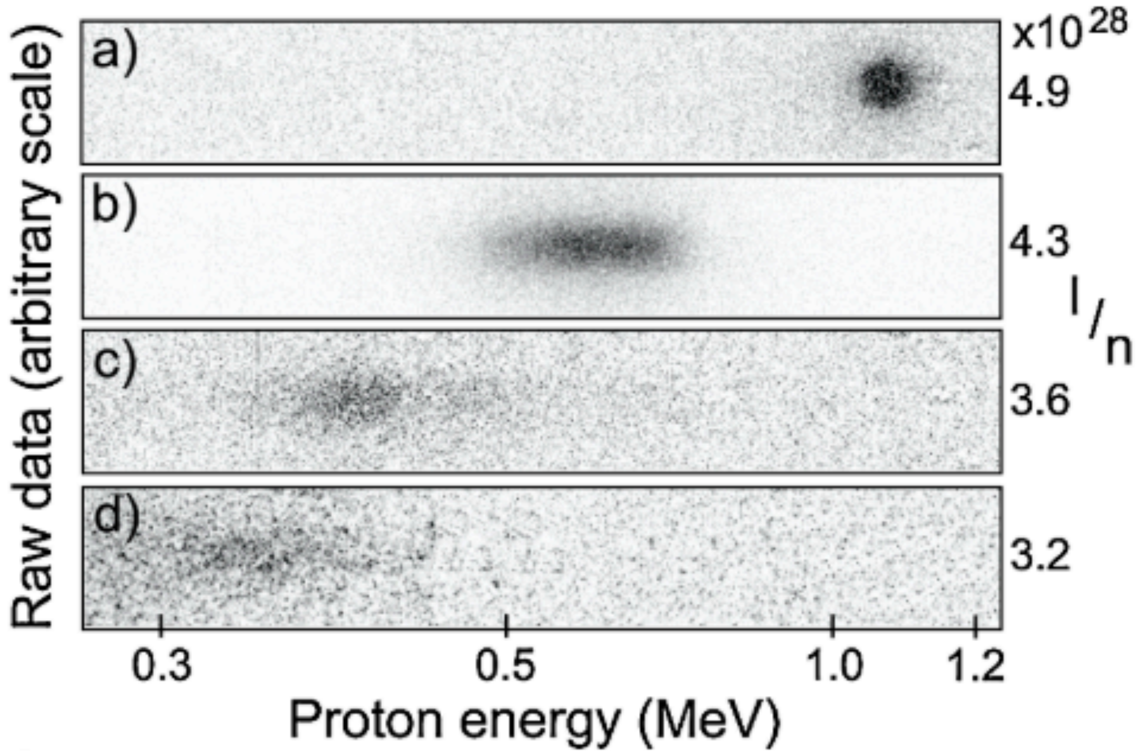

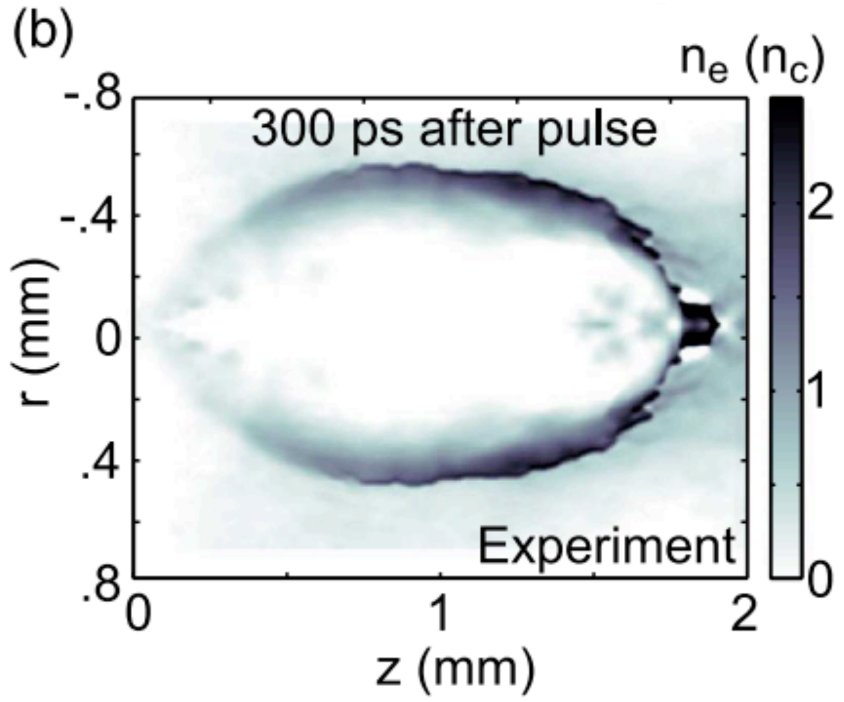

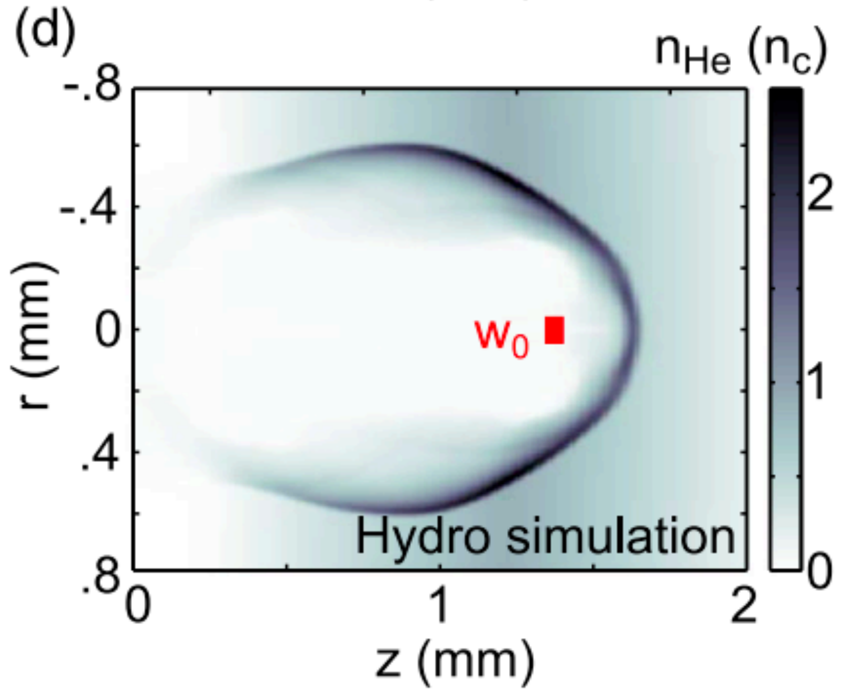

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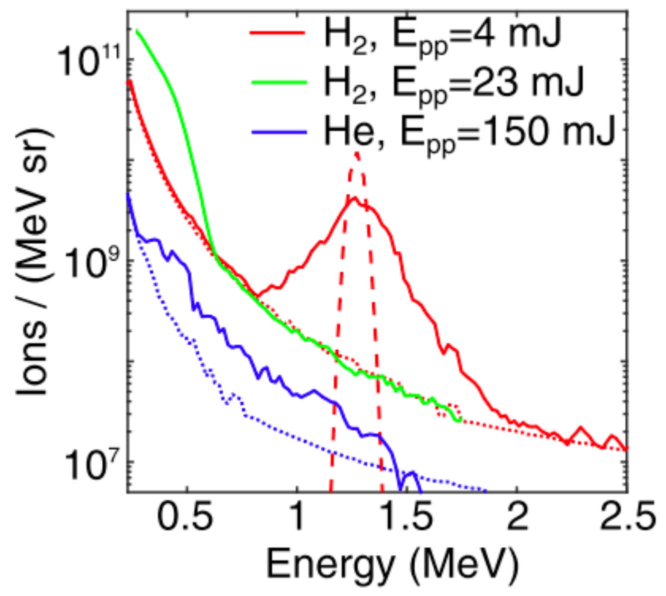
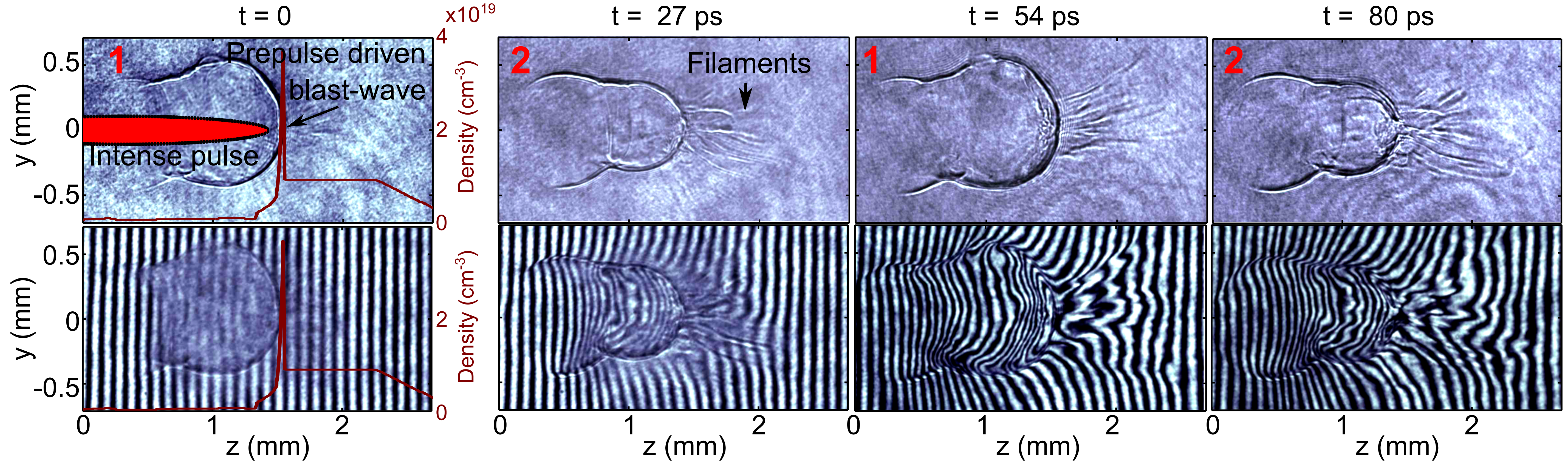
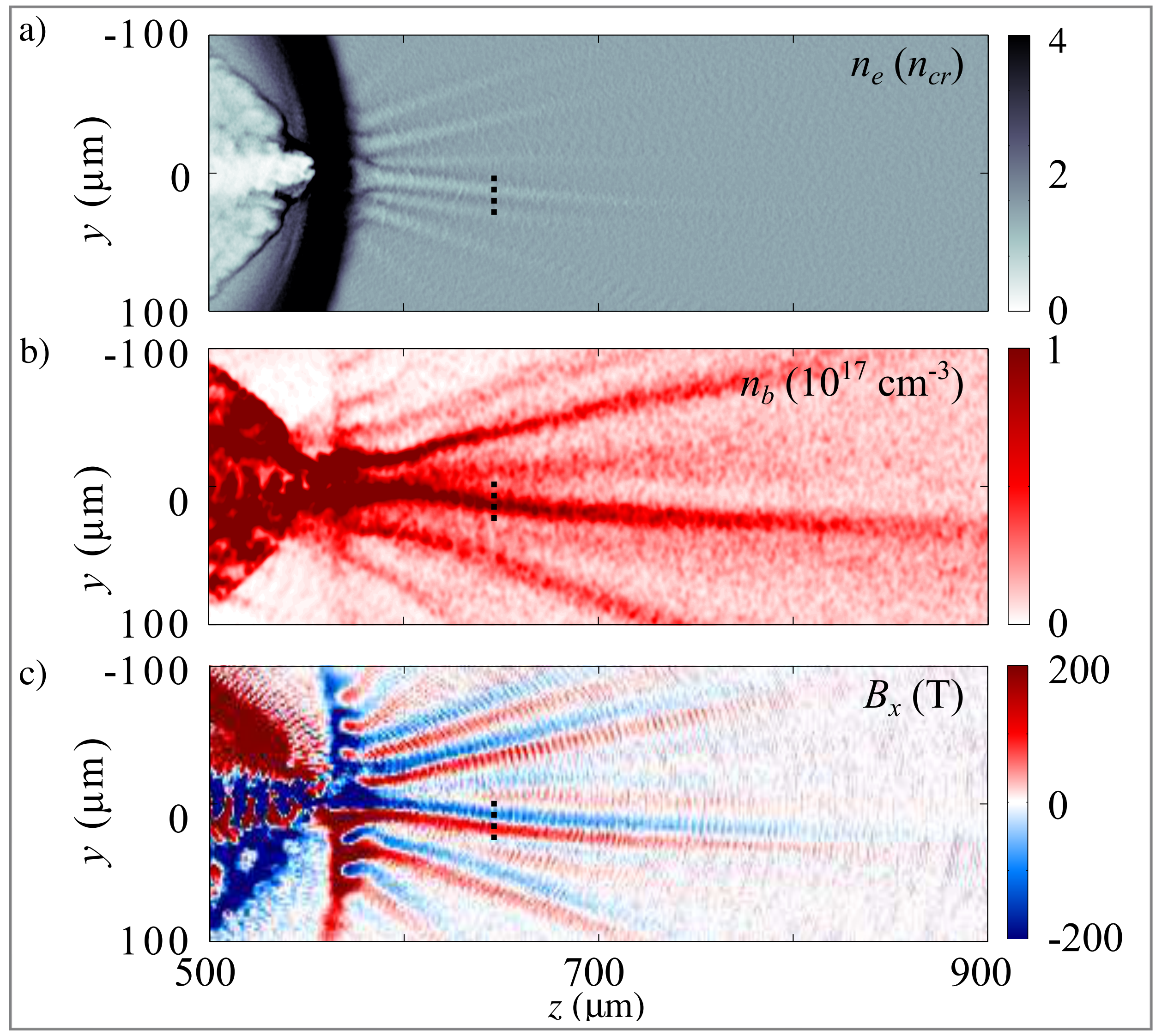


Fast electron filamentation in overcritical density plasma





Dover+, Phys. Rev. Lett. 134, 025102 (2025)

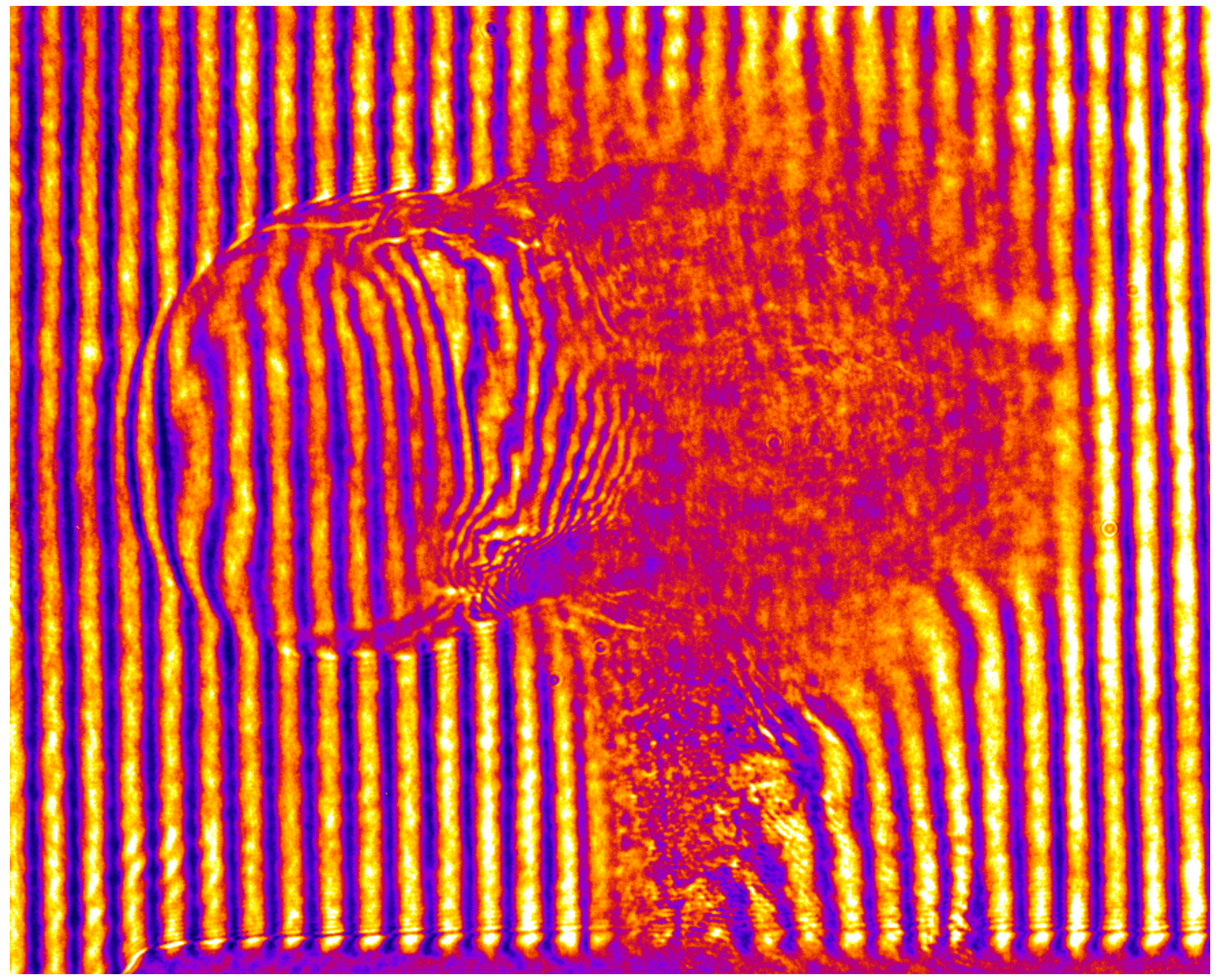
Previous measurements were limited because growth phase was not resolvable with old YAG probe. **TiS will enable time-resolved characterisation of filamentation.**

A unique facility at the ATF for investigating ion source physics

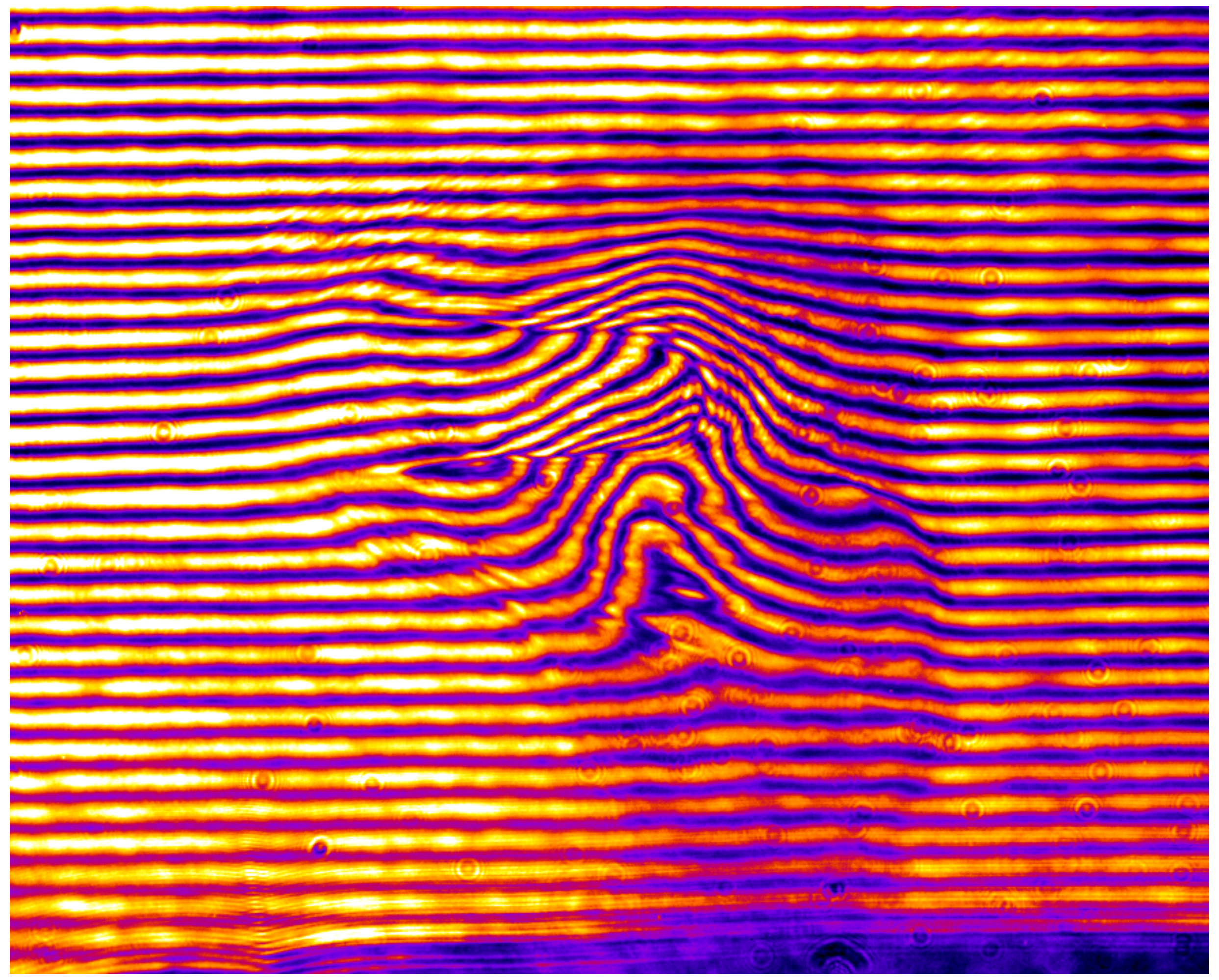
Utilising the ATF's NIR and MWIR laser facilities, we have a unique and exciting platform for investigating ion source physics dynamics

- CO_2 laser - 2 ps, 9.3 μm wavelength drive laser for ion acceleration @ 10^{19} cm^{-3}
- TiS laser - <100 fs, 800 nm wavelength laser ideal for optical probing such densities

Enables *direct dynamic observation* of fundamental scale-independent processes driving all laser driven ion sources



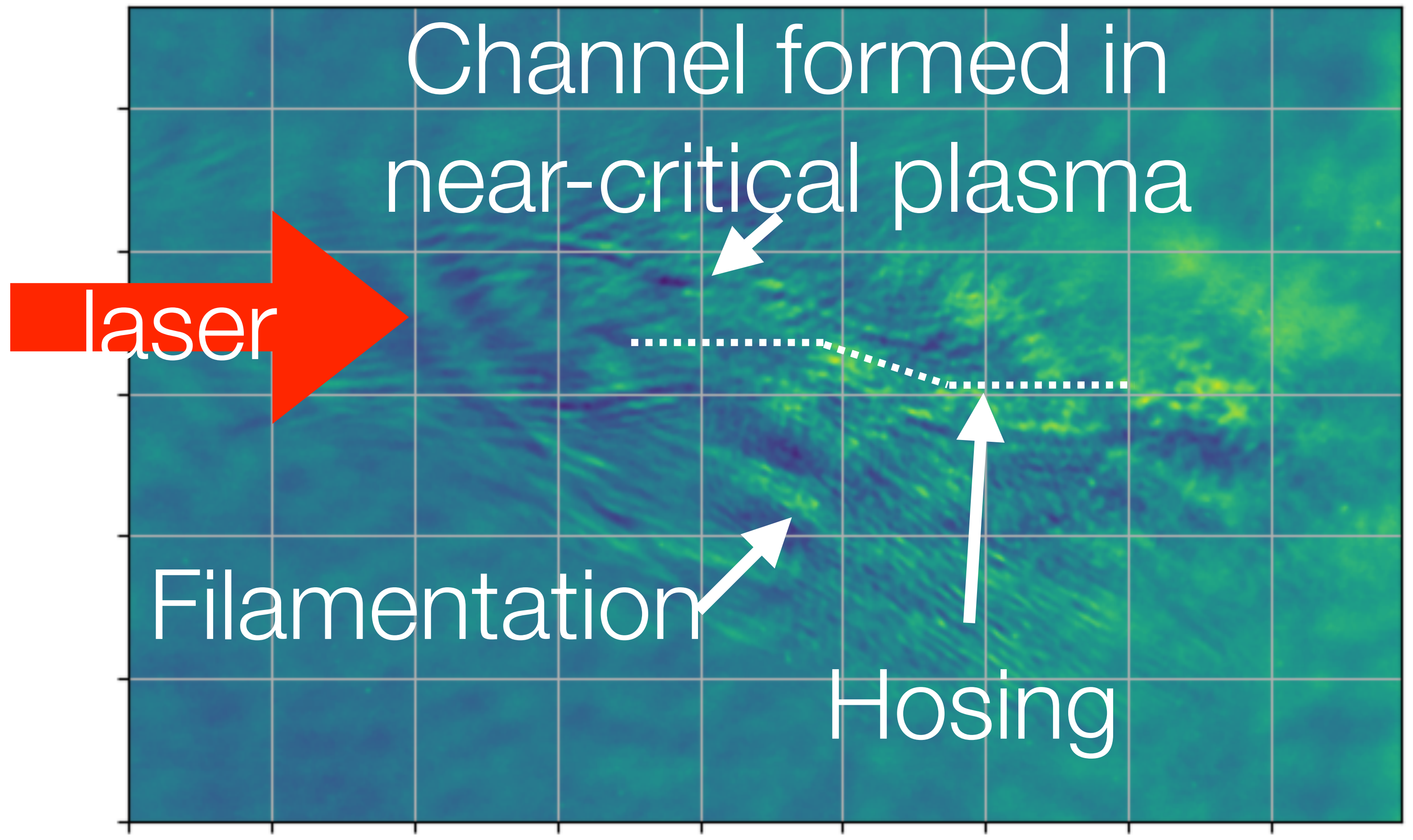
Previously: blur due to ionisation and plasma dynamics when temporal overlap between drive and probe

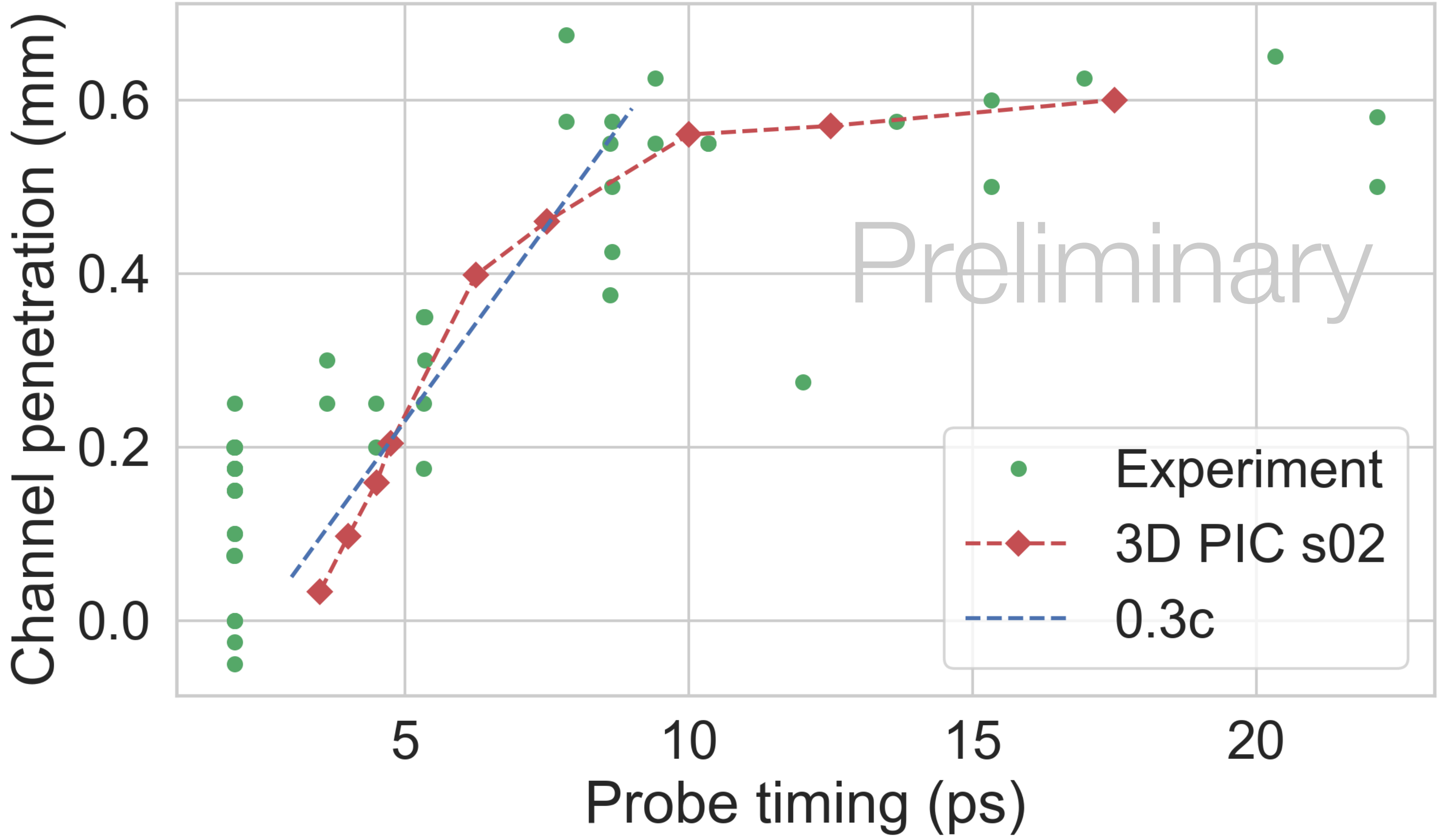


Now: clean images when overlapping drive and probe, allowing measurements of evolving overdense LPI

Preliminary results: Channeling in near critical density plasmas & sheath acceleration in gas jets

N.P. Dover+ *in preparation* (2025)





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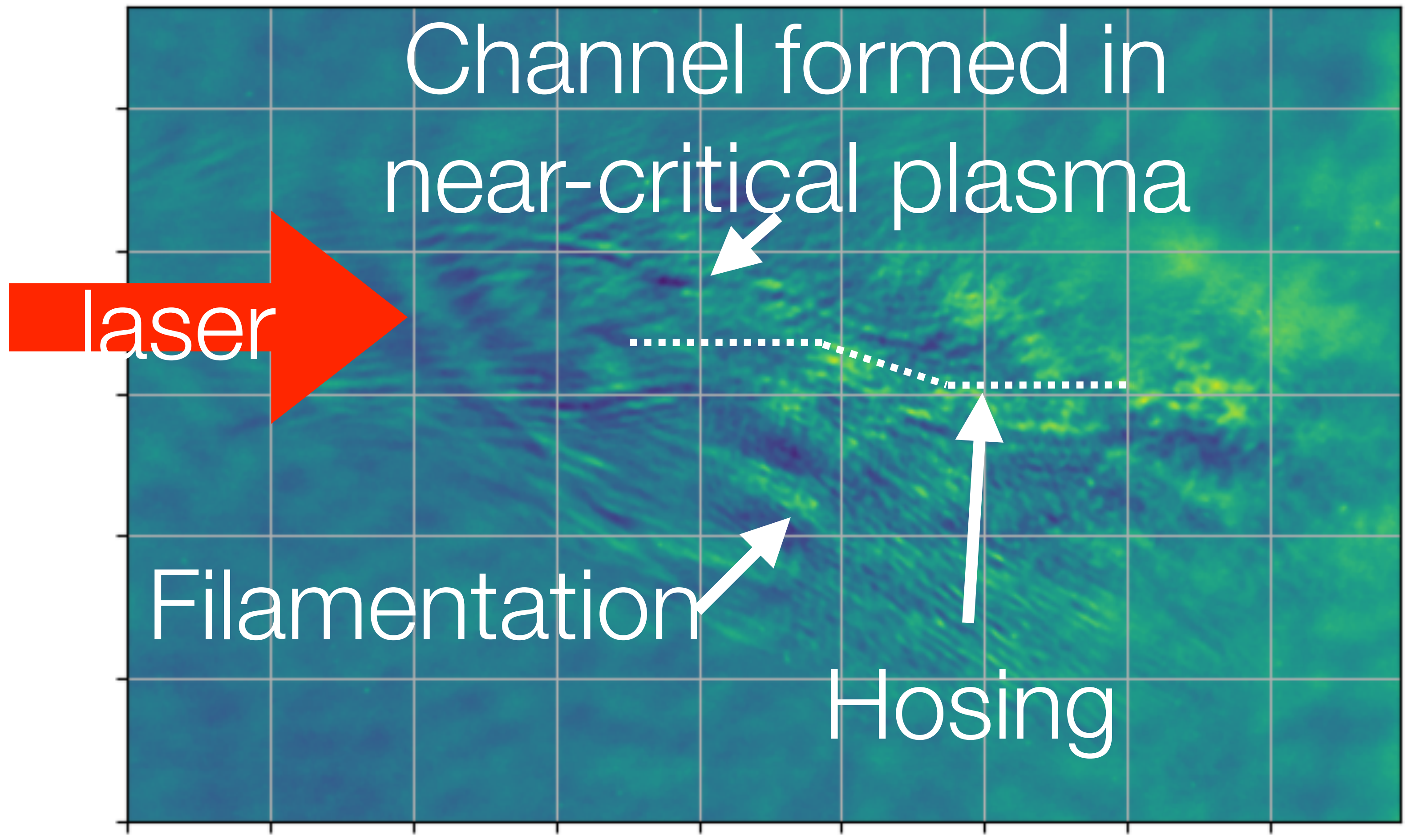
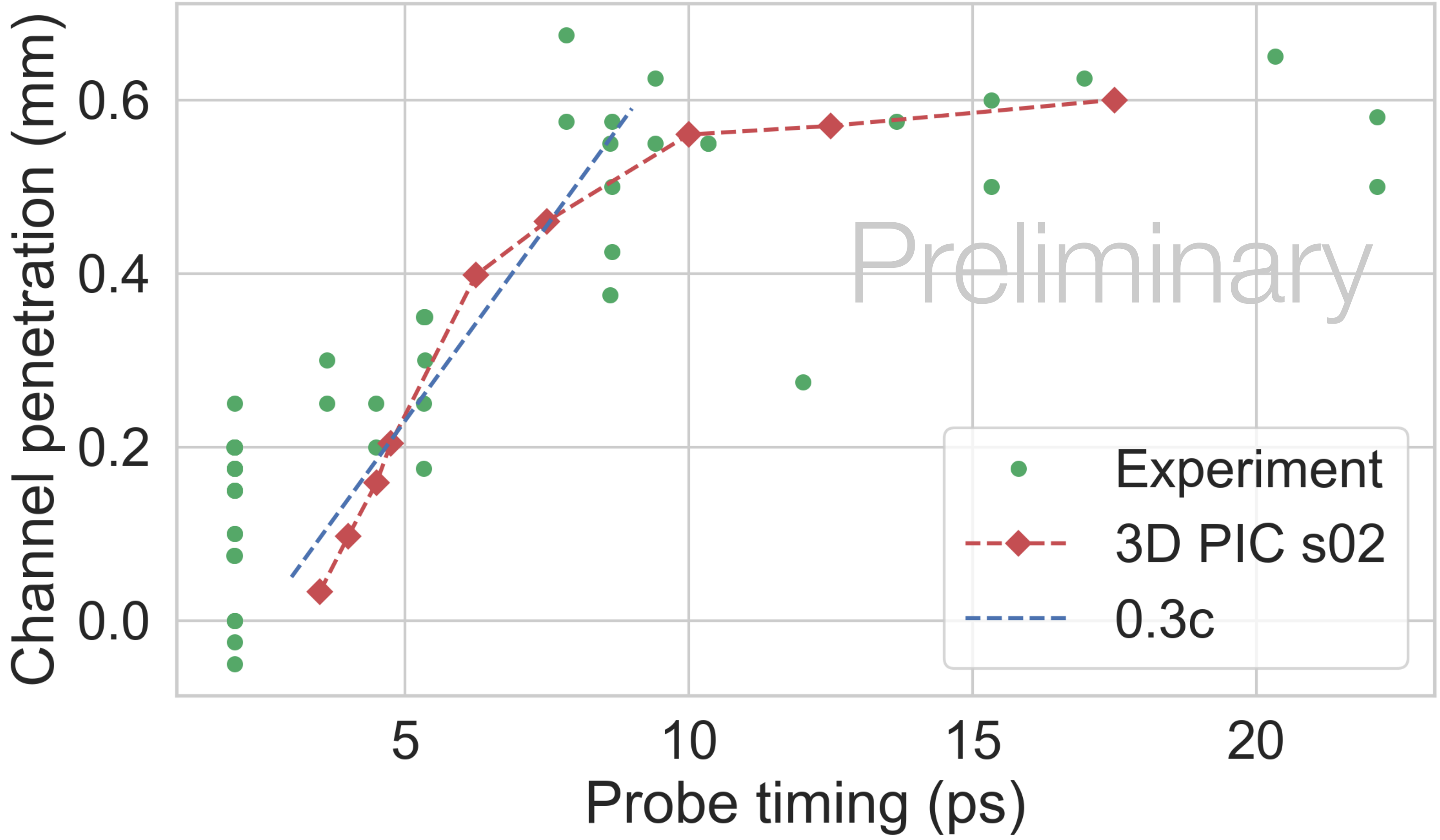
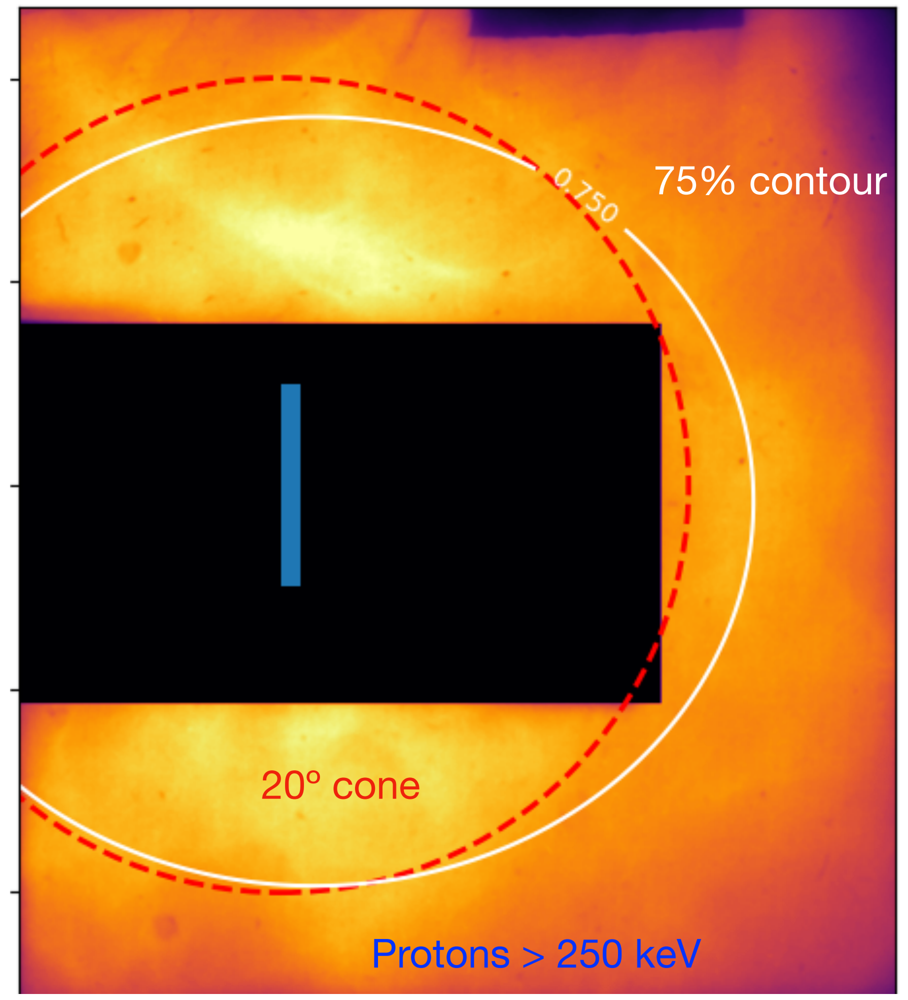
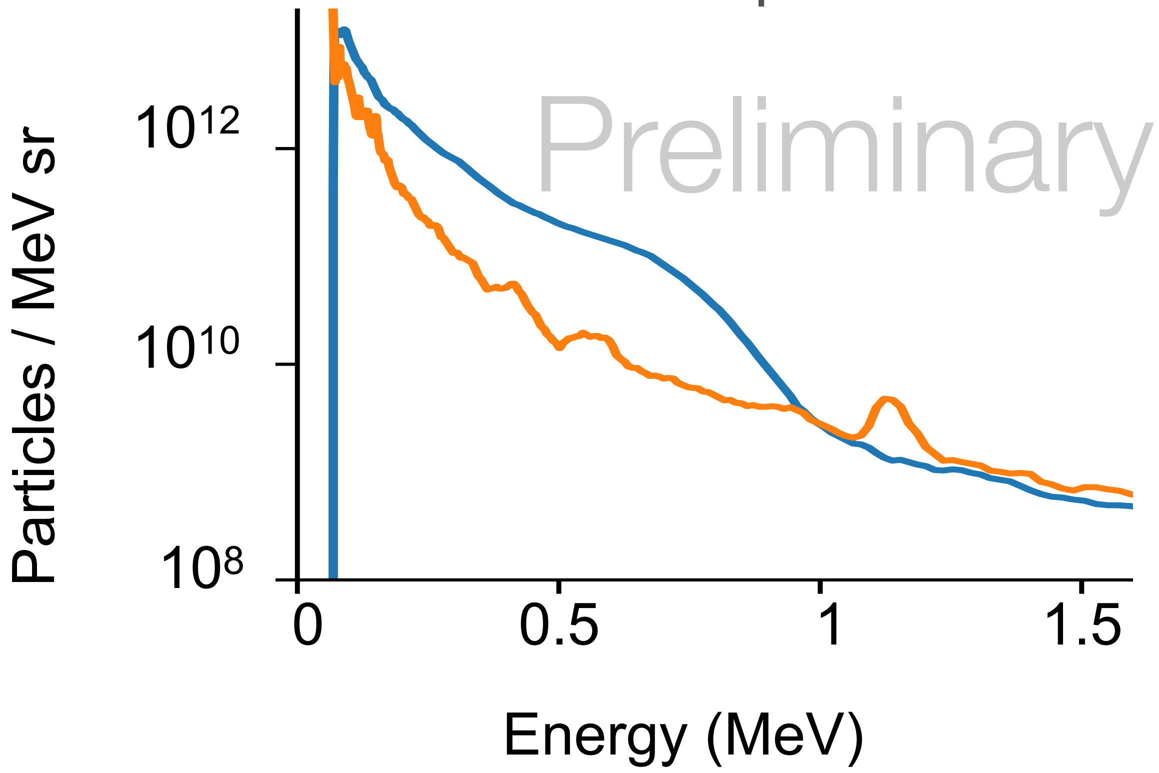




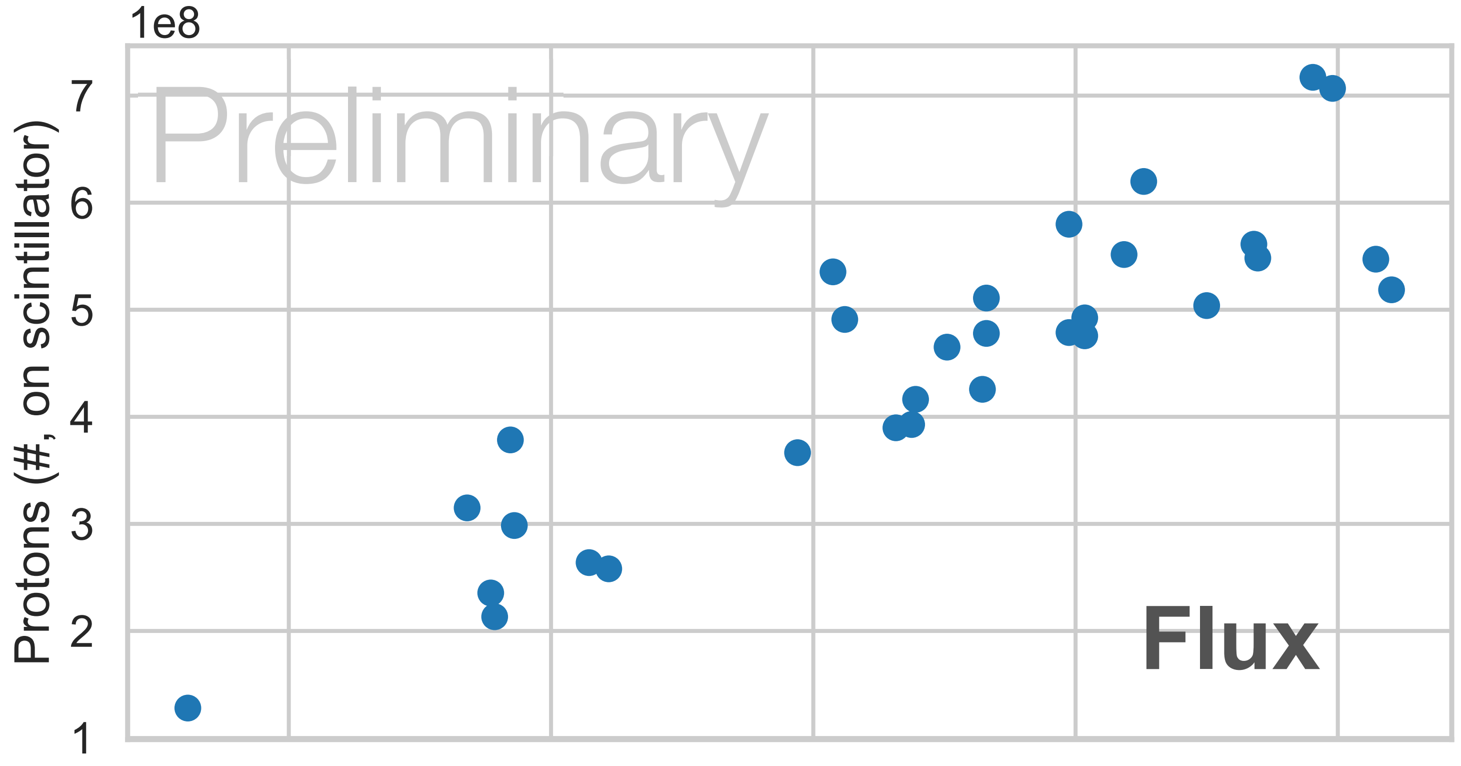
Proton beam spatial profile

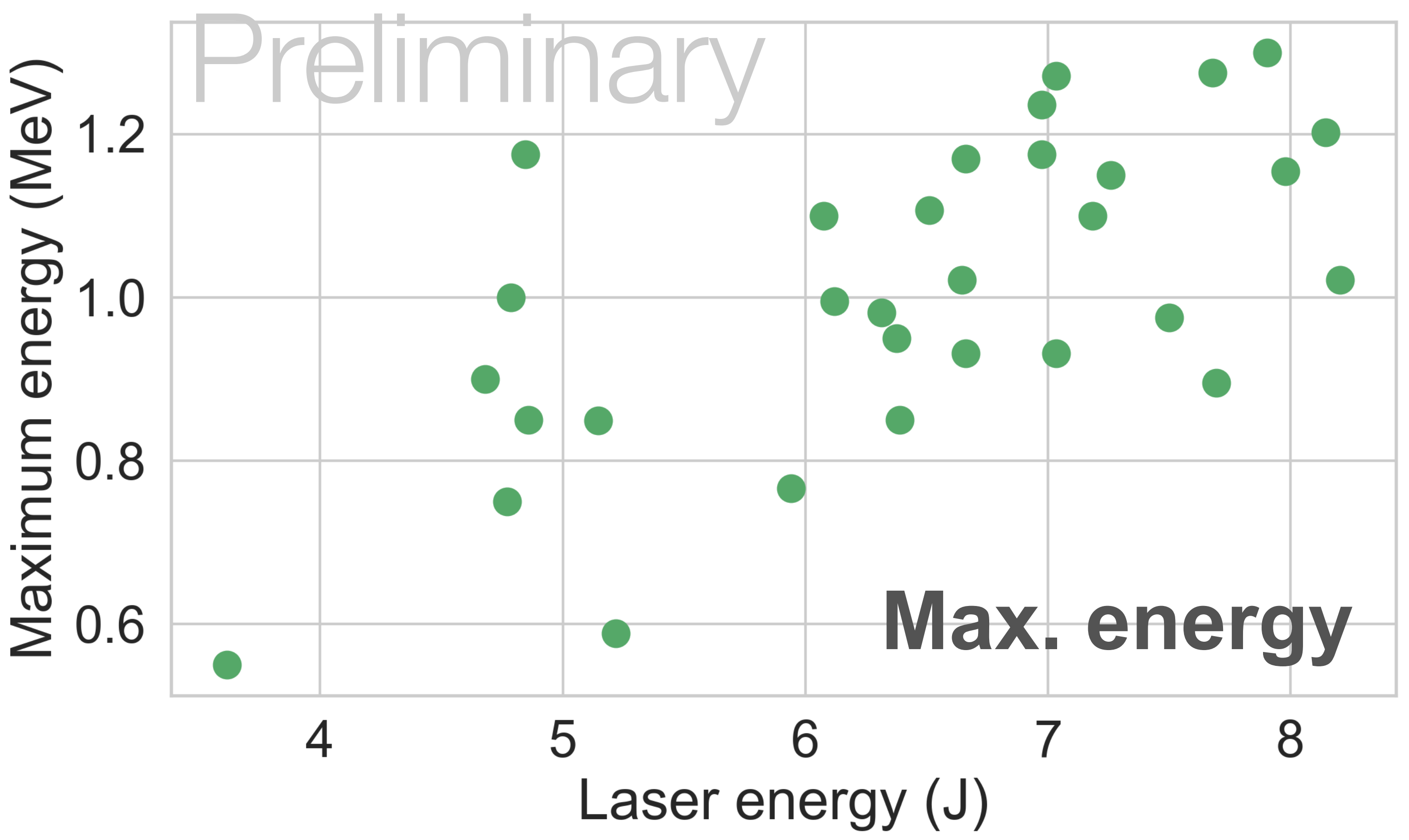


Proton spectra



Beams are:
- Divergent (>30° FWHM)
- Quasi-thermal
- Relatively low energy (max ~1 MeV)
- Strongly correlated to laser energy





Preliminary results: Channeling in near critical density plasmas & sheath acceleration in gas jets

IMPERIAL

John Adams Institute for Accelerator Science

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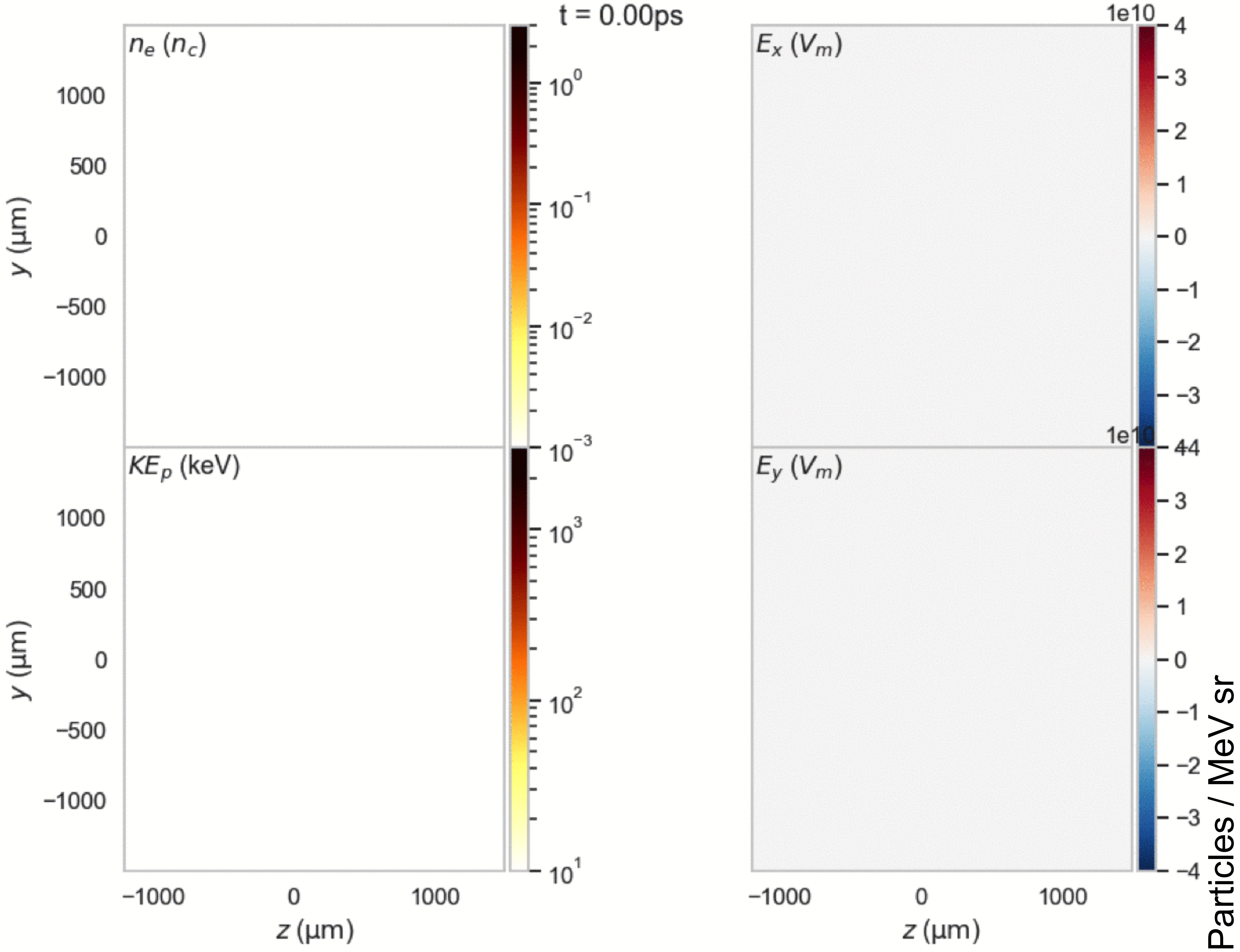

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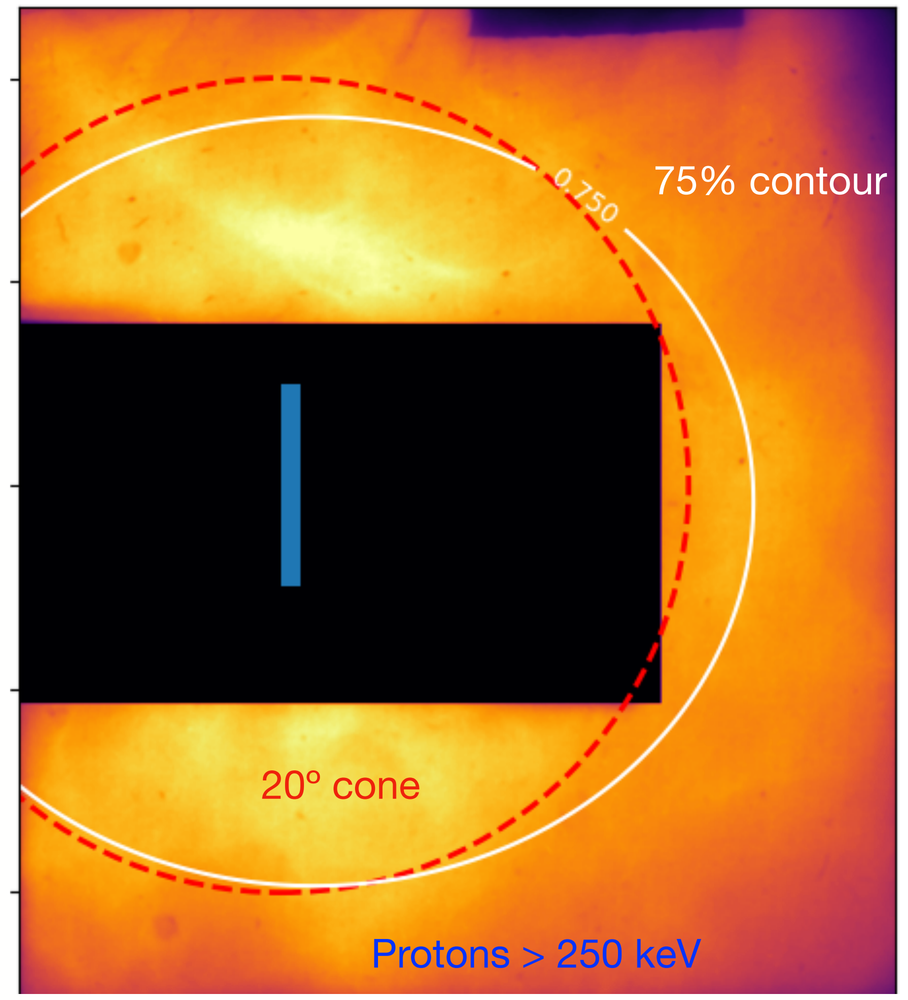

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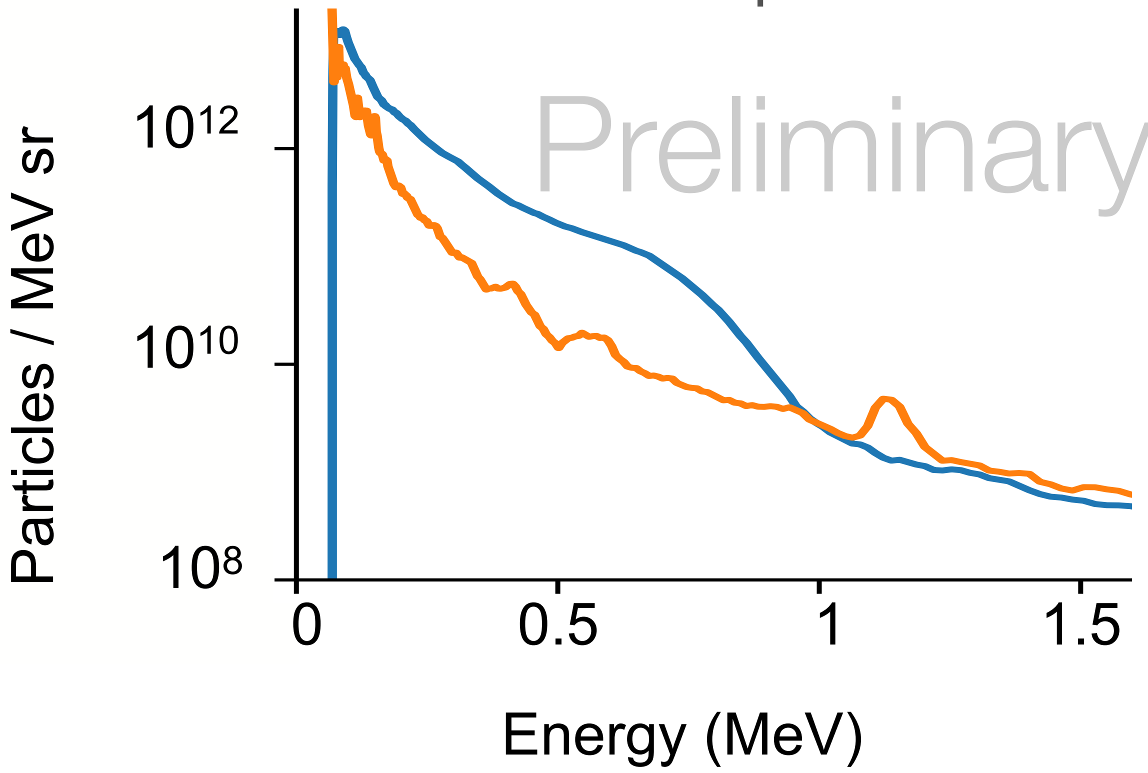

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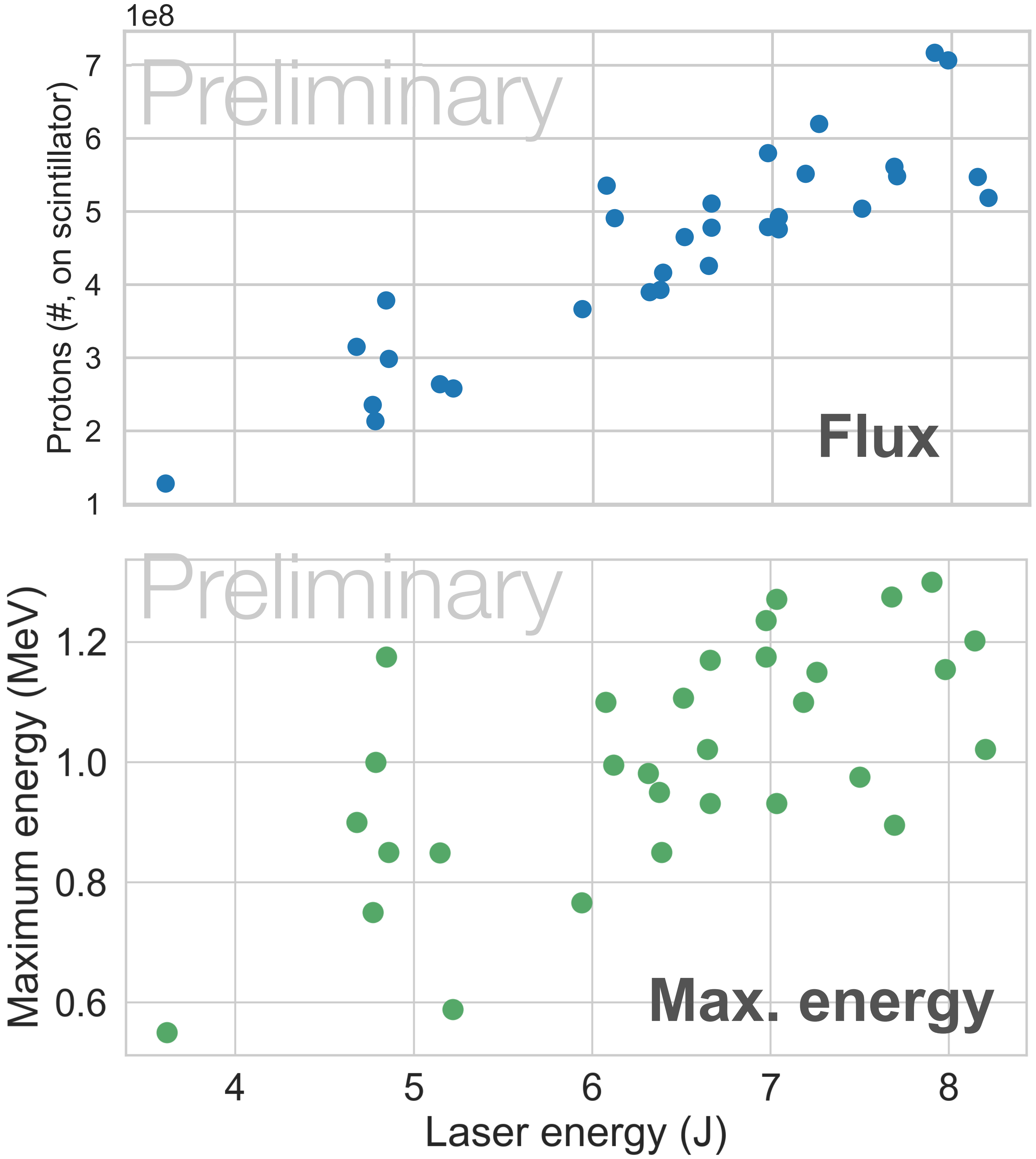
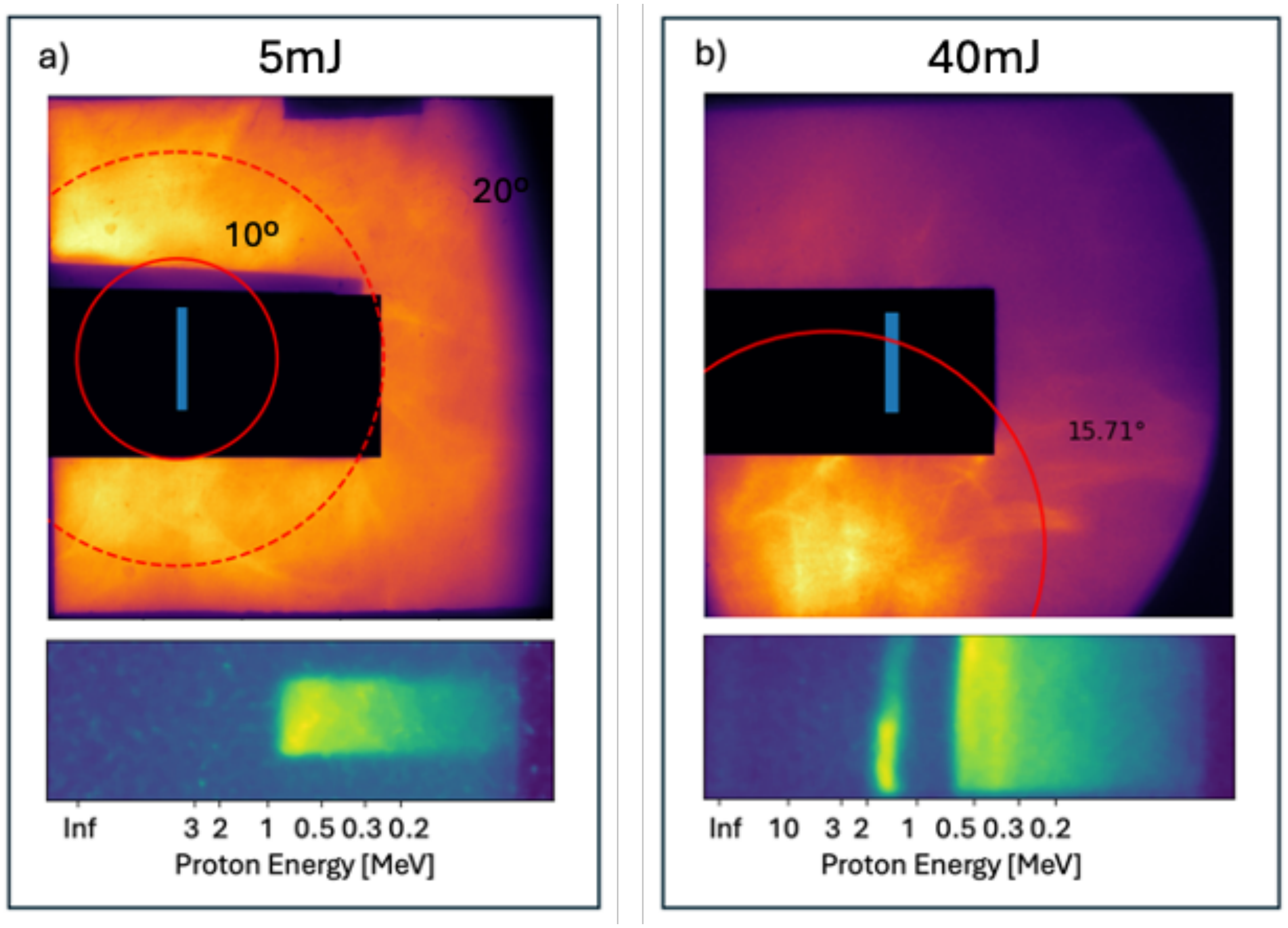


Preliminary results: Steering of shock accelerated proton beams

G. Casati+ *in preparation* (2025)



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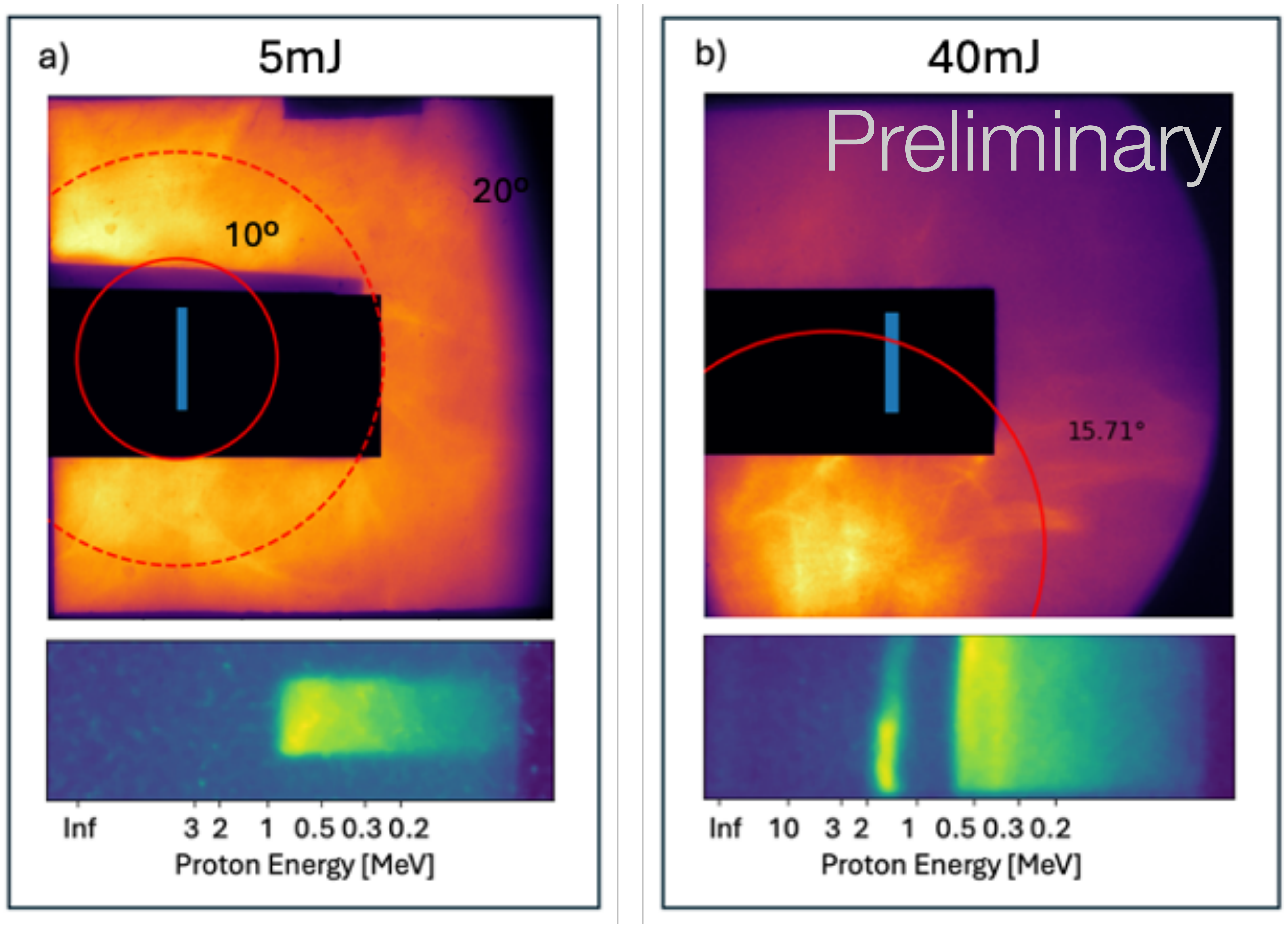

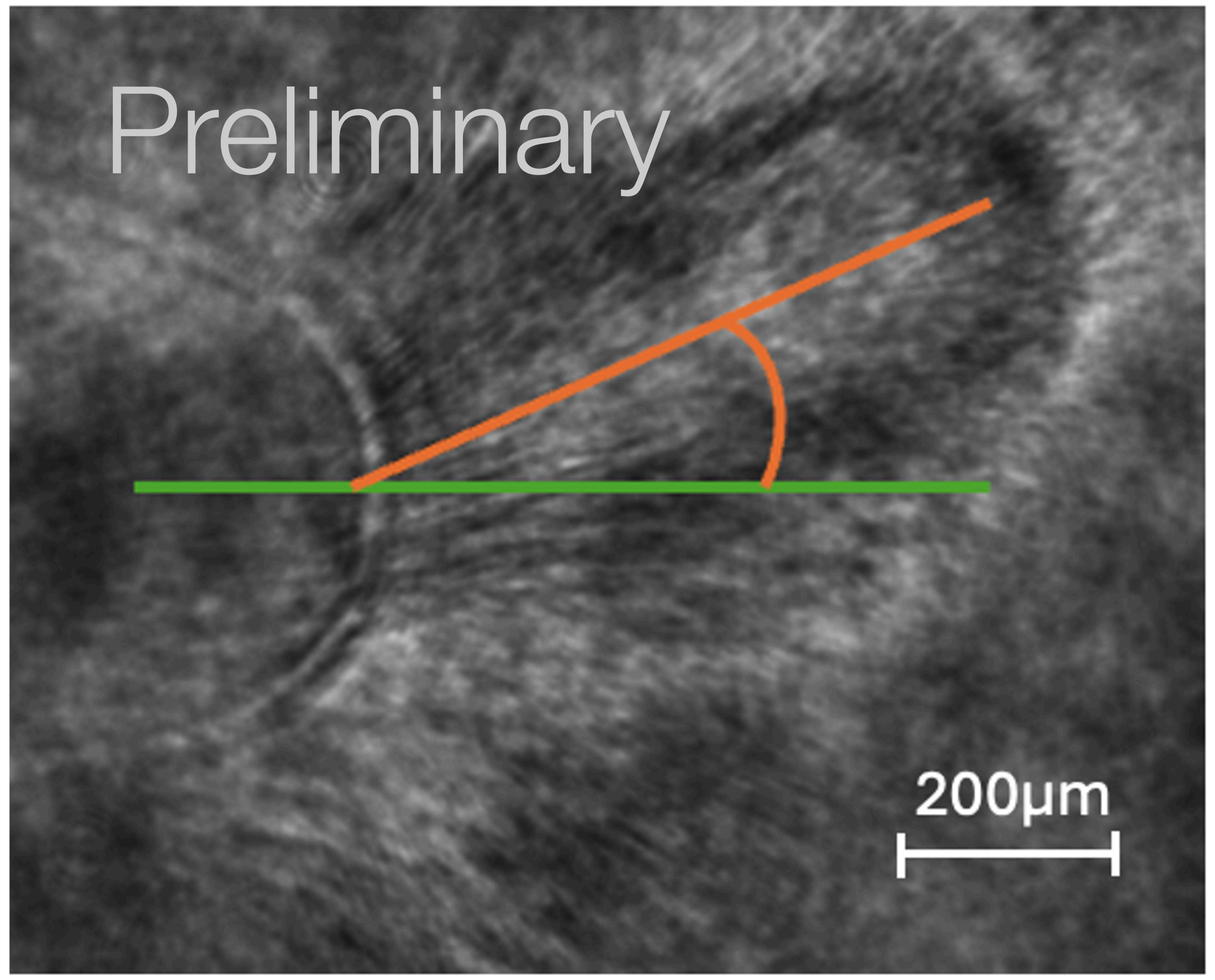

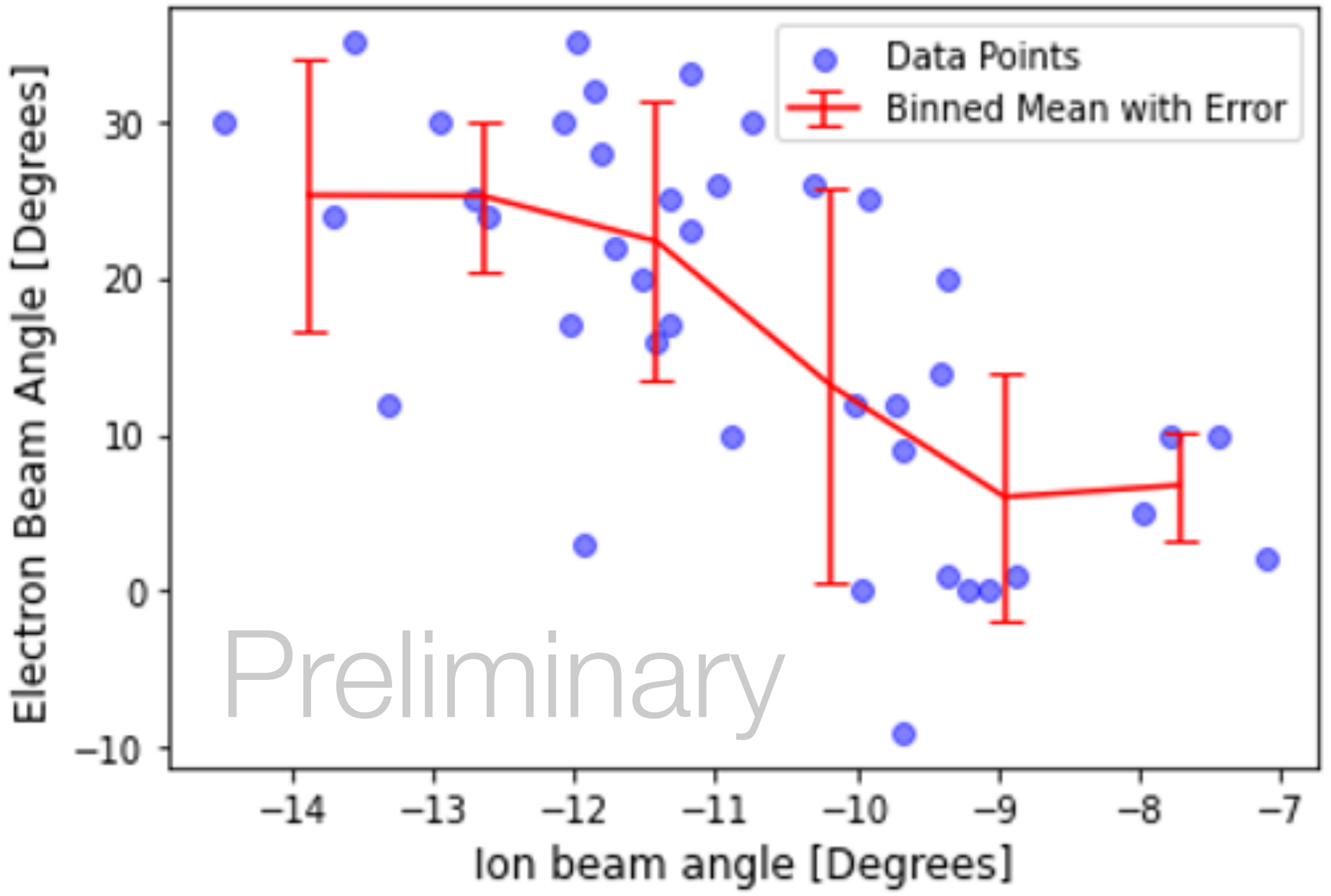

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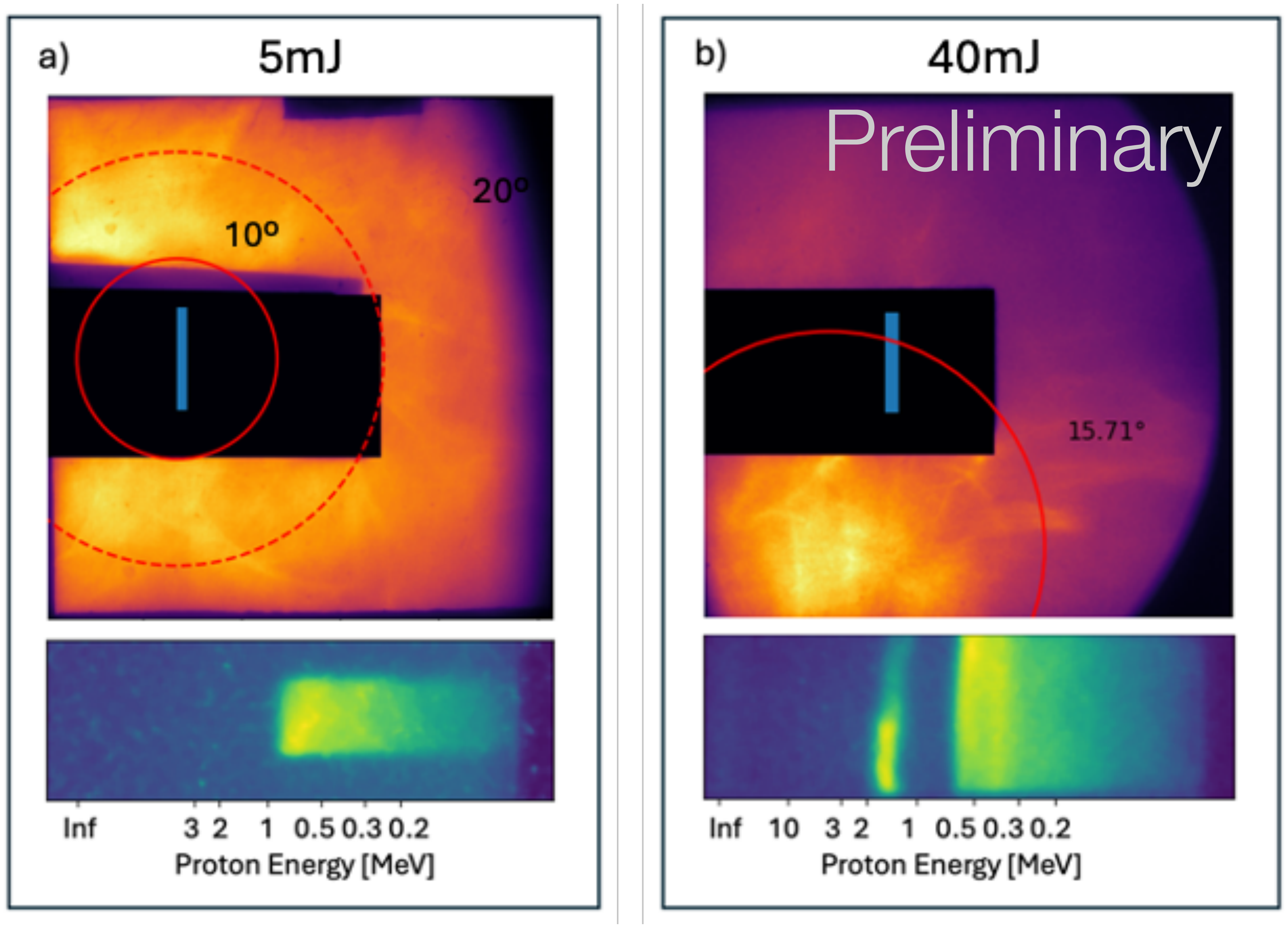

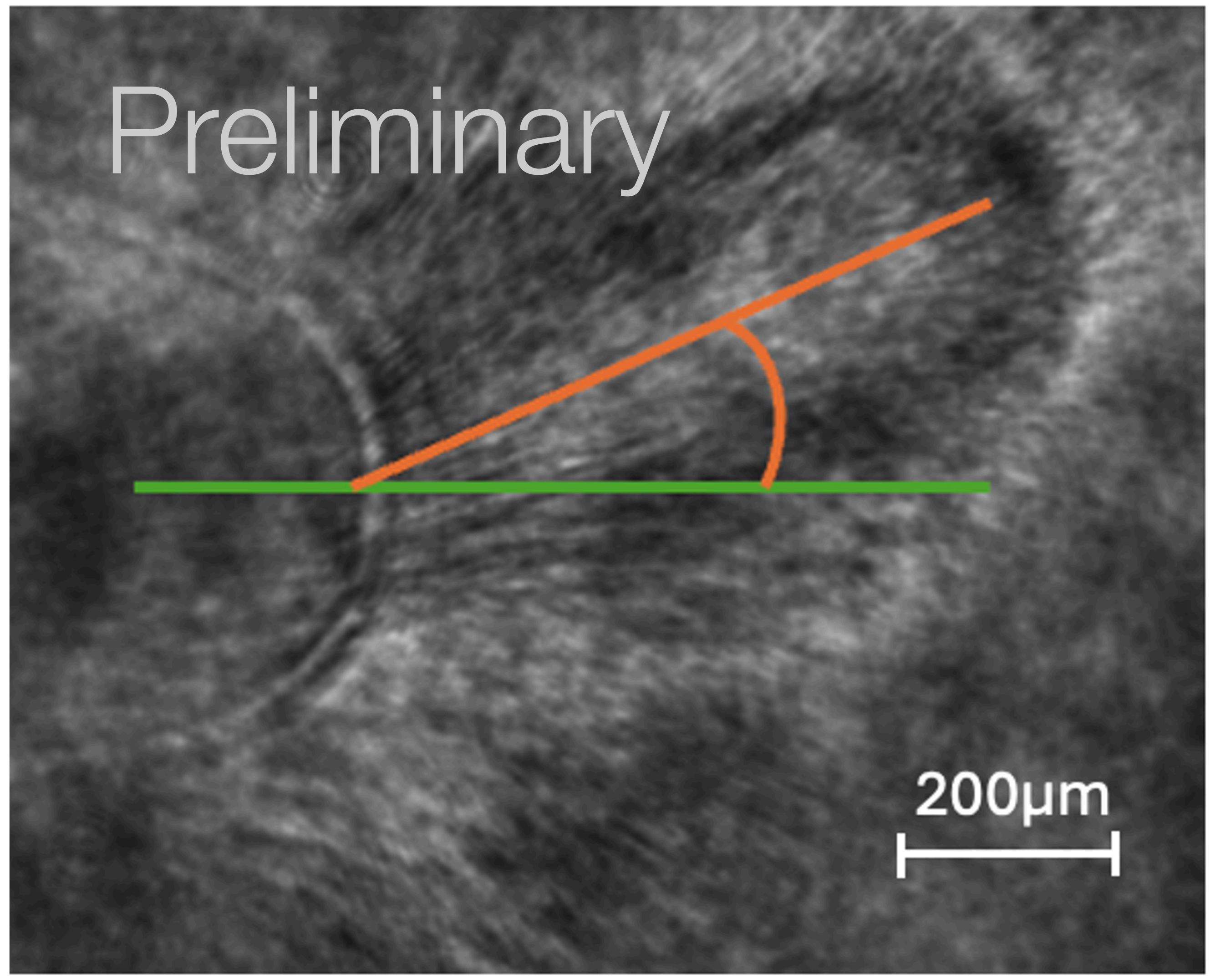

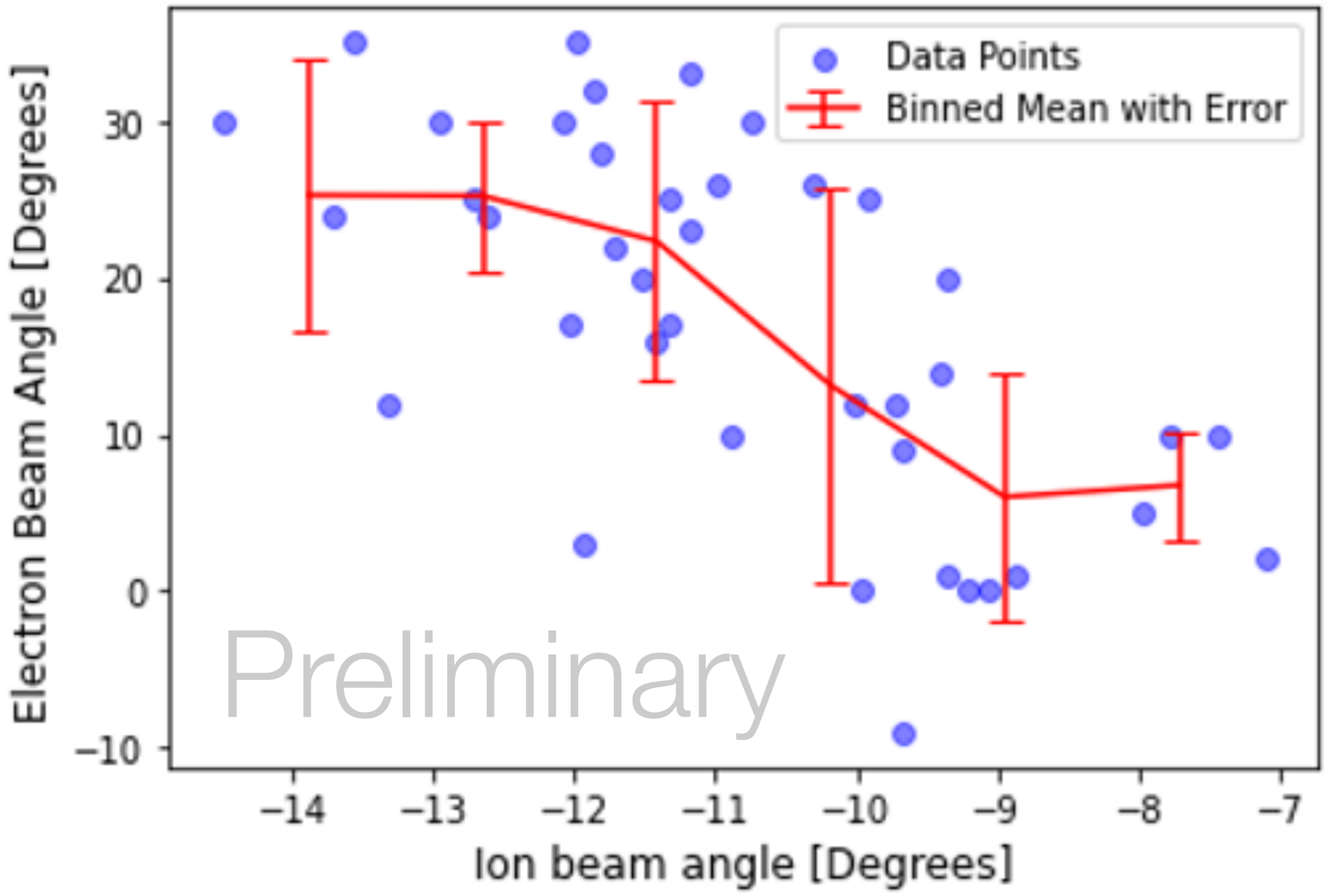

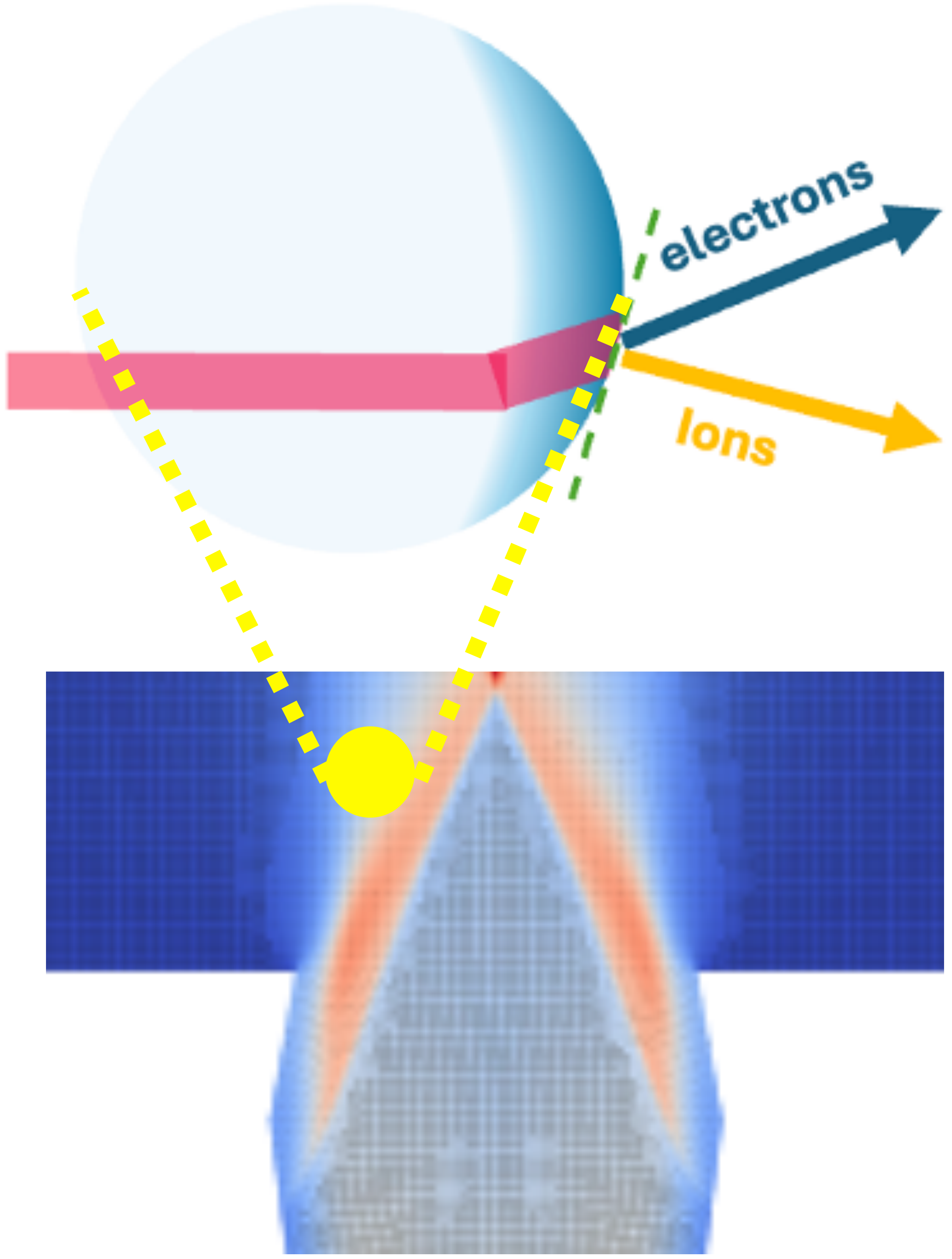

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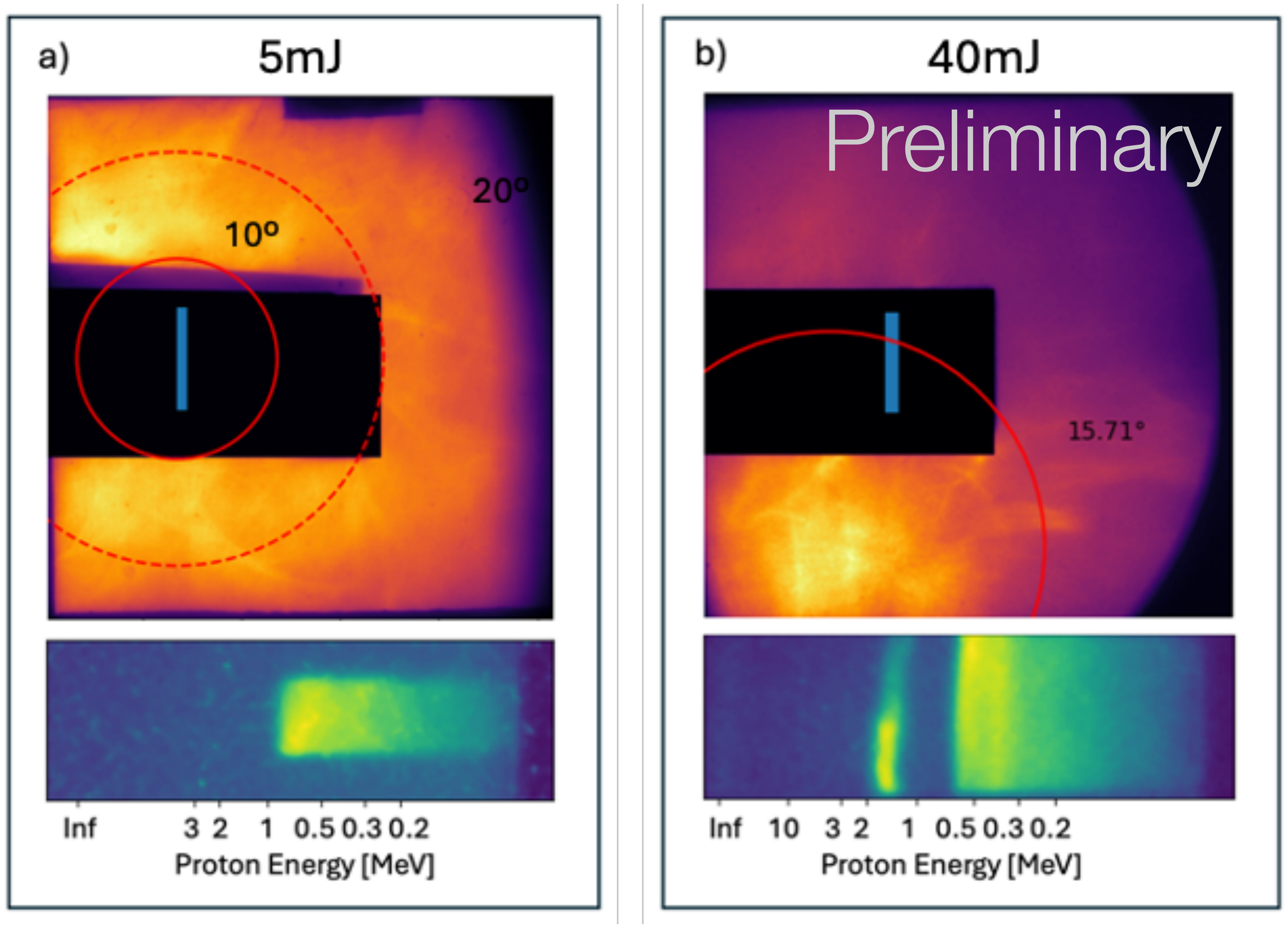
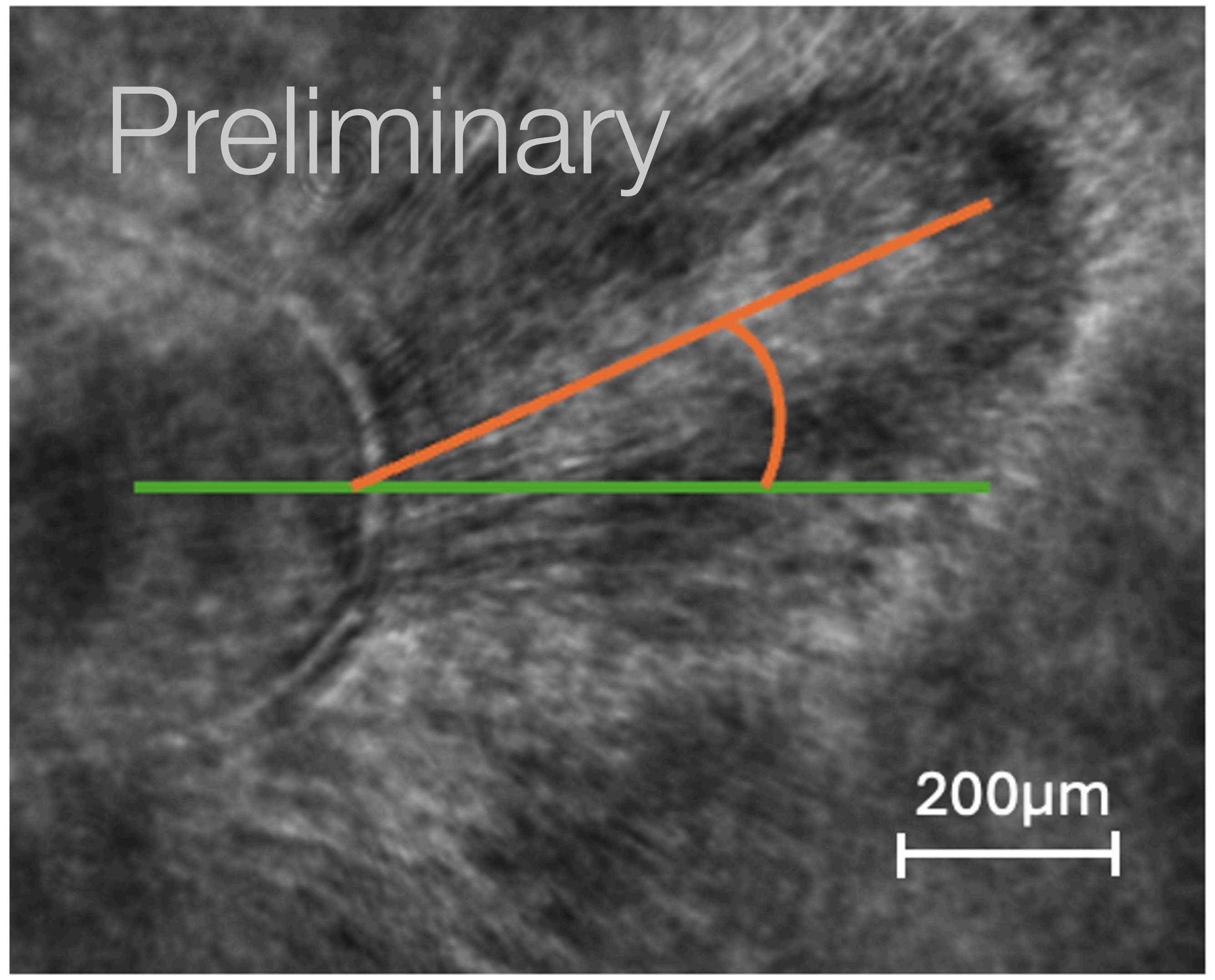
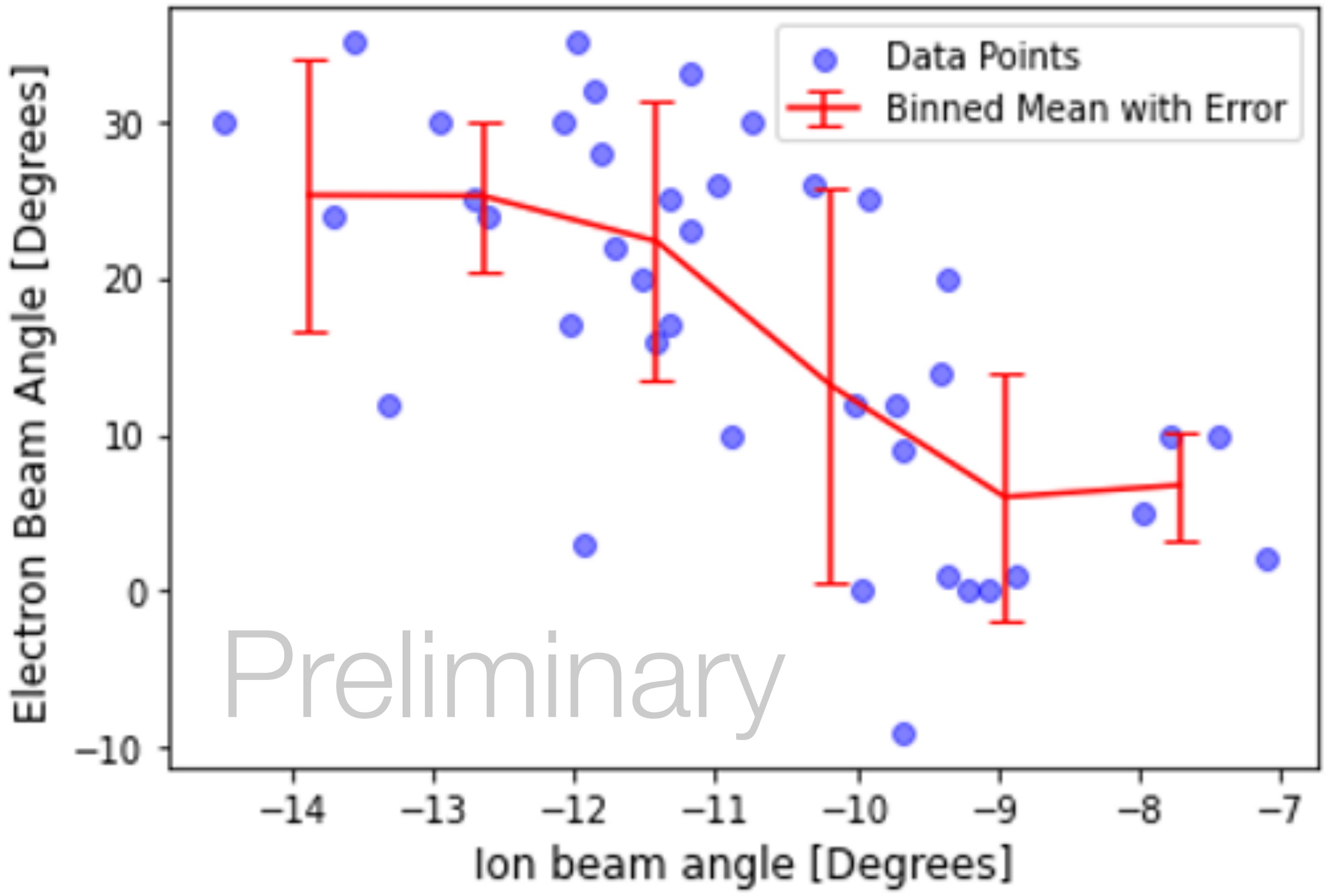
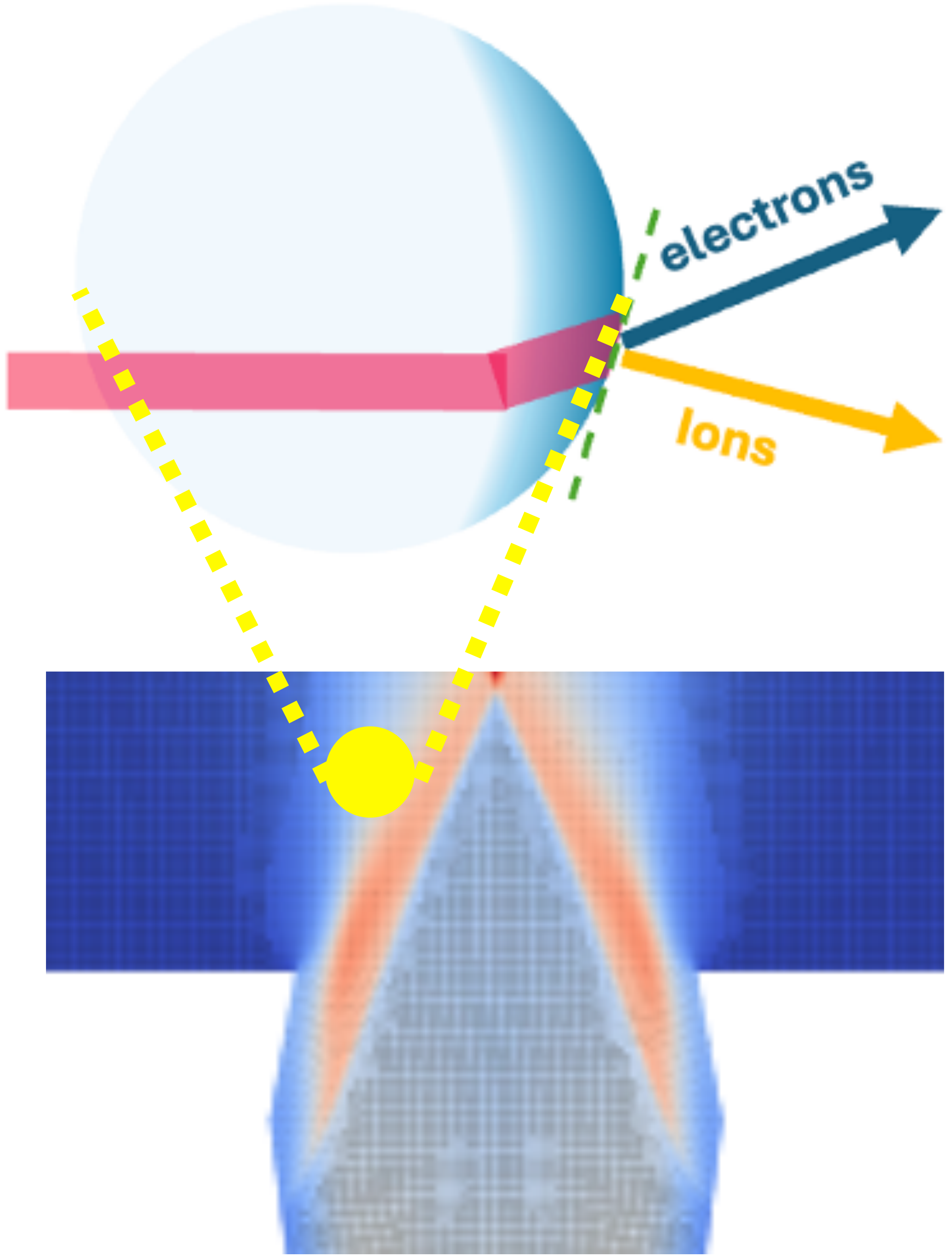




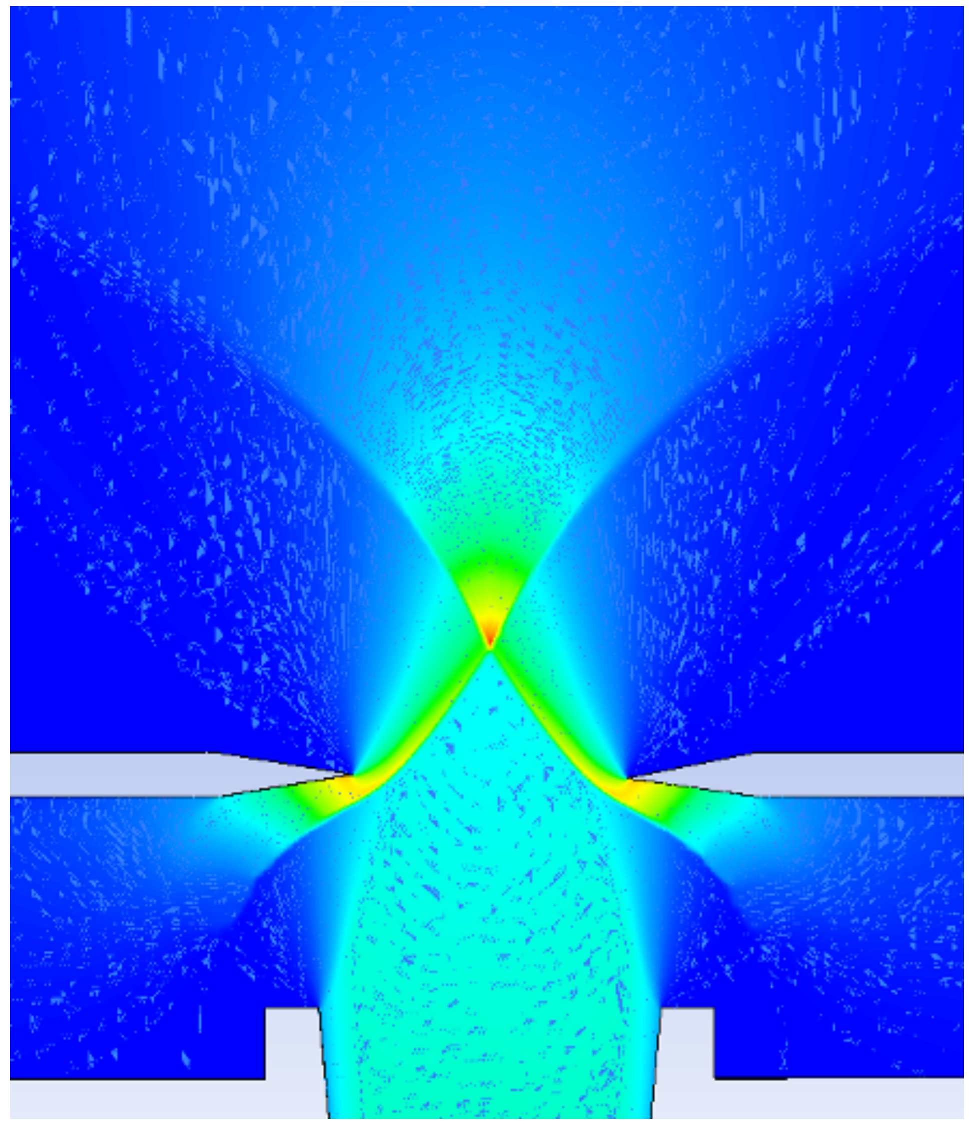


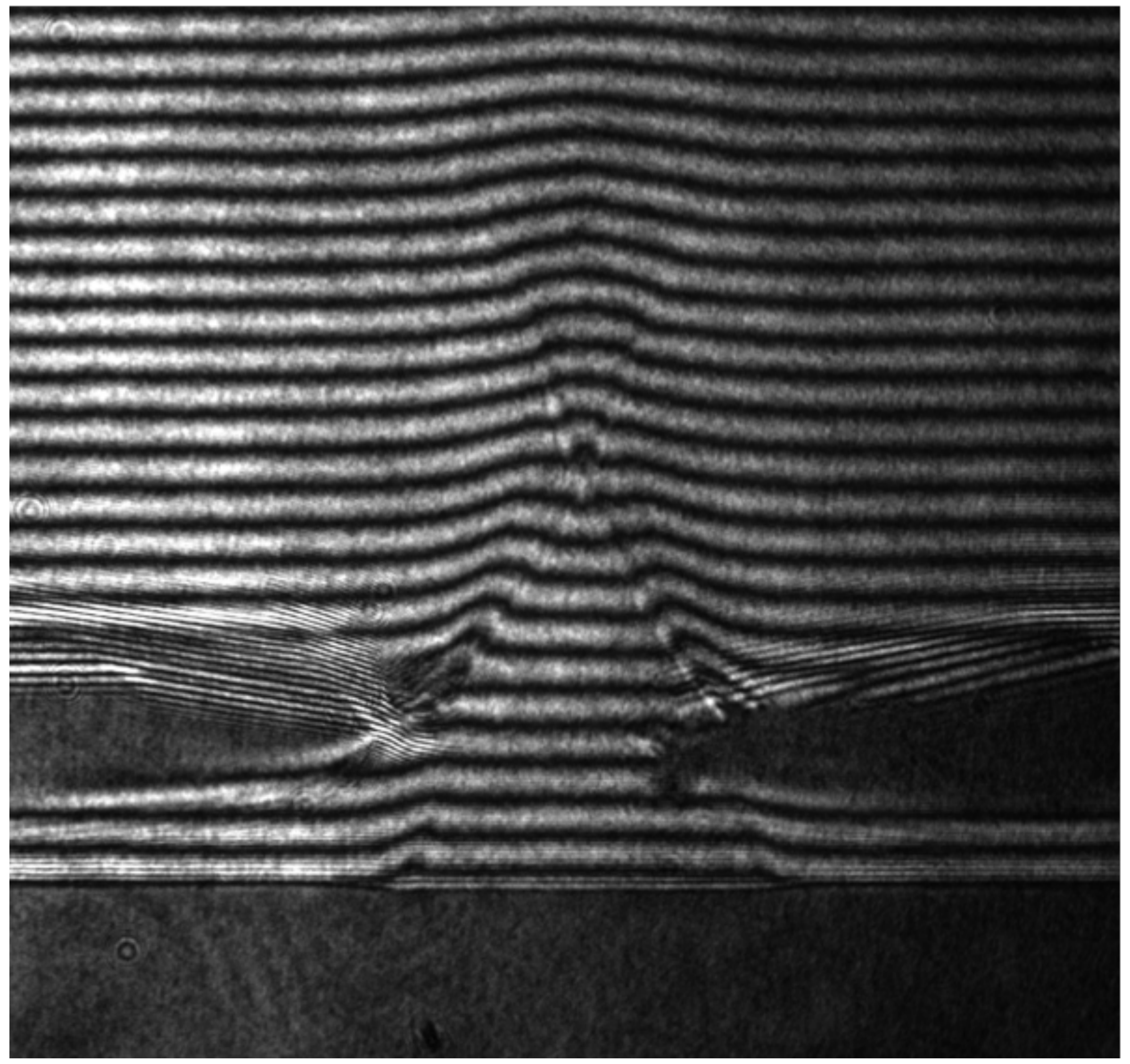


Poor stability of density profile hindered efforts to image ion acceleration at front surface

Experimental plans for the next year

New gas targetry

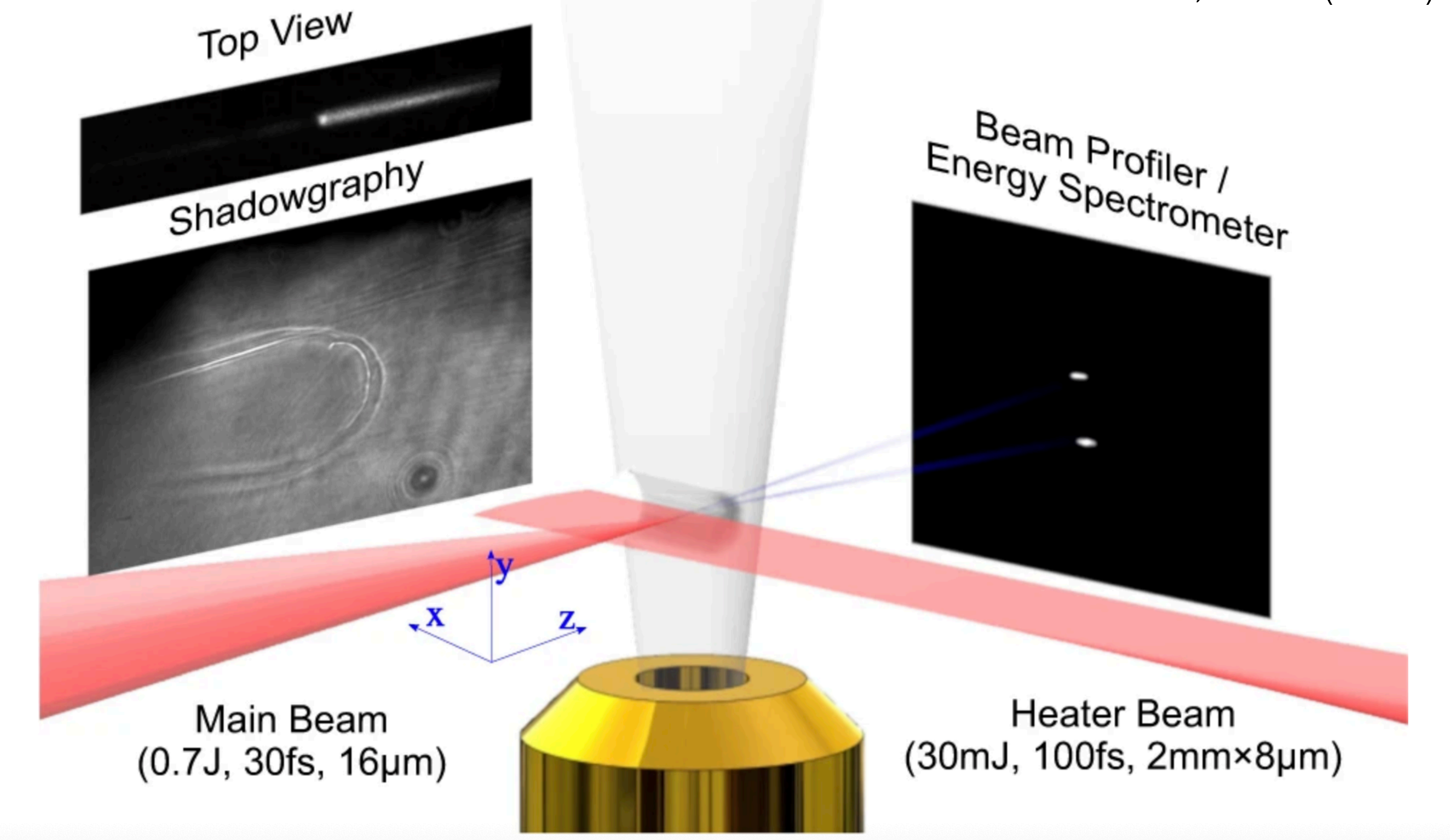




Shock convergence by opposing razor blades

Gas shaping using transverse beam

Taken from Seemann et al. Nature Communications 14, 3296 (2023)



Use YAG beam as heater, TiS as probe, CO_2 as drive

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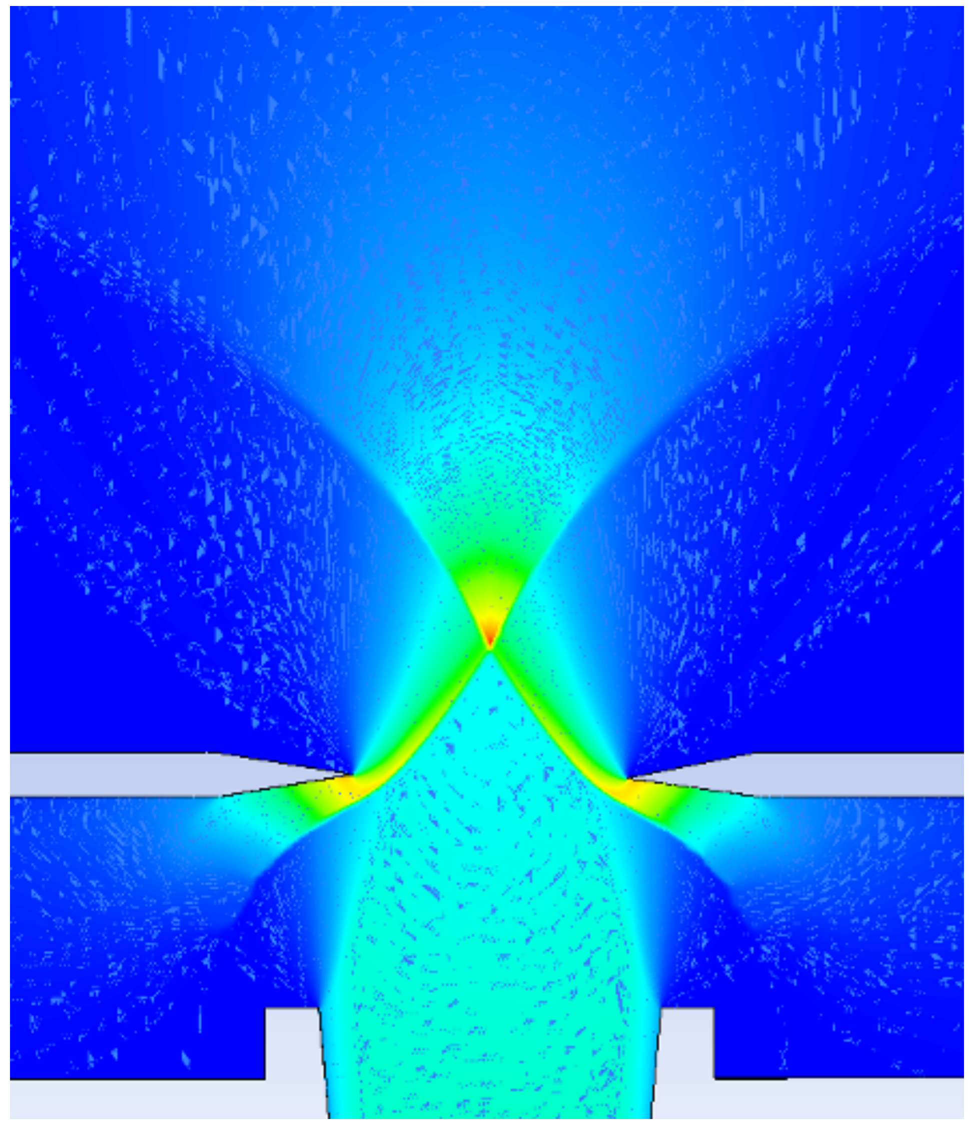

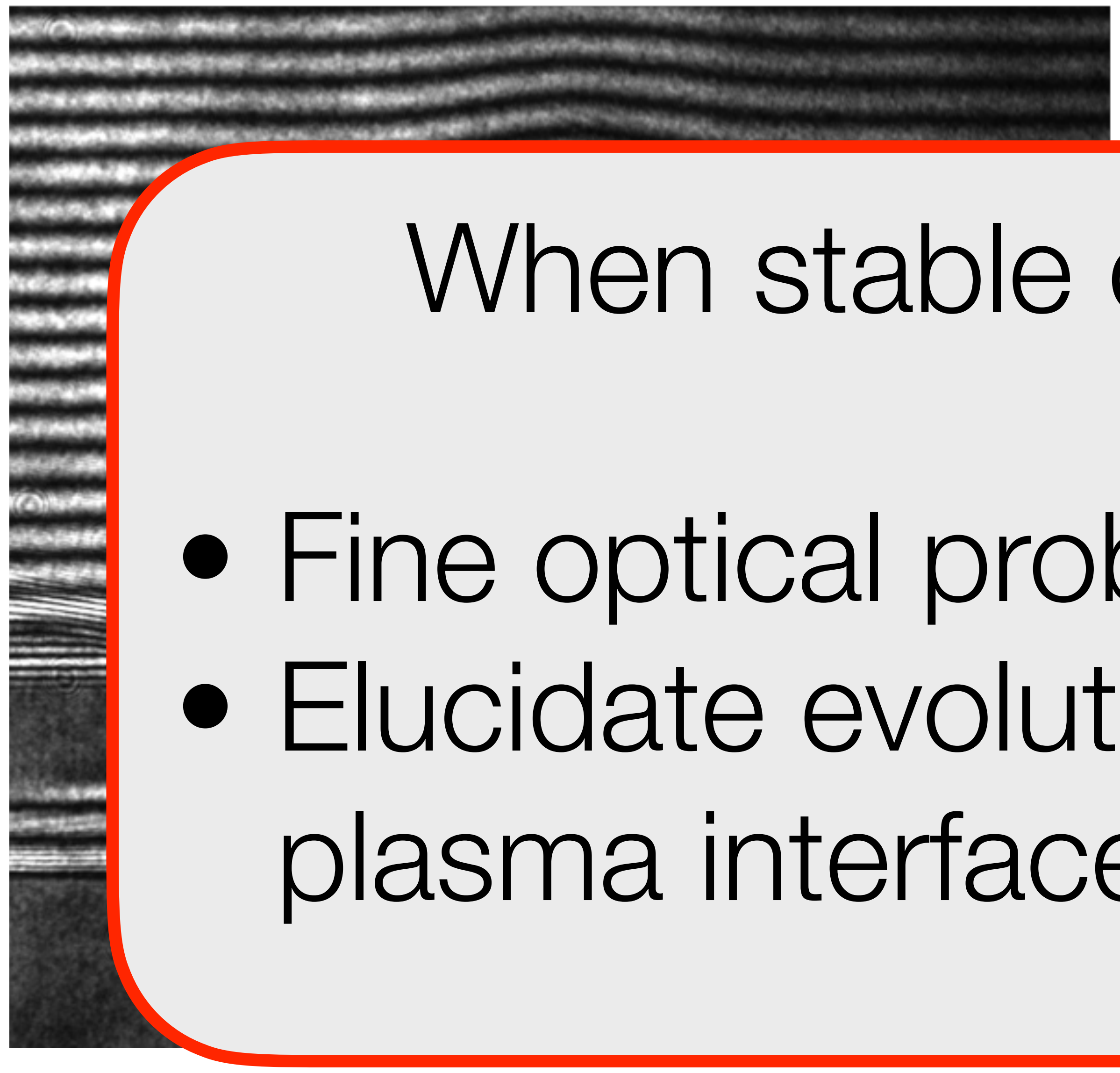

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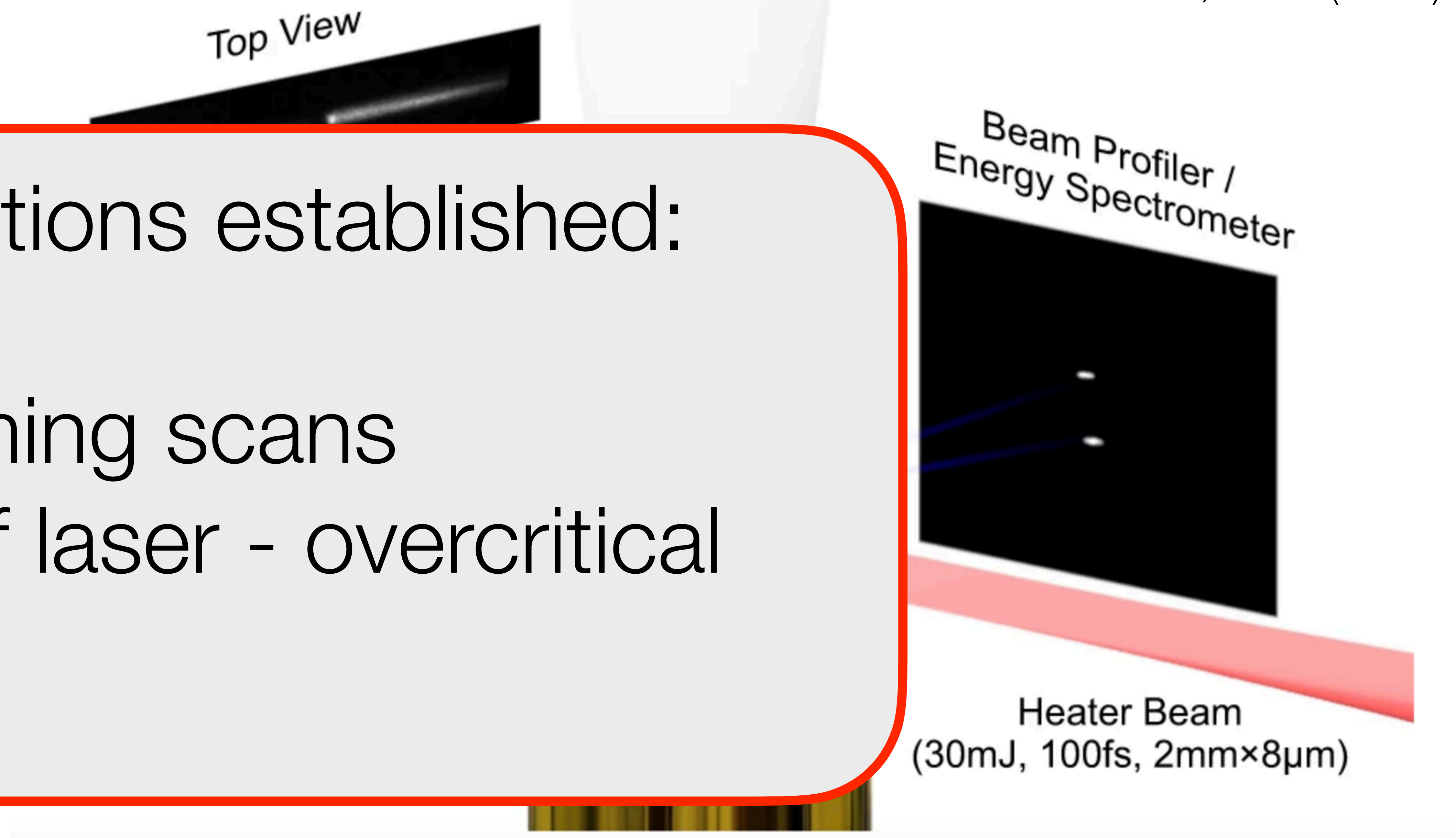


Use YAG beam as heater, TiS as probe, CO_2 as drive

When stable conditions established:

- Fine optical probe timing scans
- Elucidate evolution of laser - overcritical plasma interface

Products from the work to date (including AE100)

- **Conference talks from last 12 months:**
  - IOP Plasma Meeting 2025 (G. Casati)
  - High Power Laser Christmas Meeting 2024 (G. Casati)
  - Channeling 2024 (G. Casati)
  - HEDS 2024 (N.P. Dover - invited)
- **Papers in preparation:**
  - N.P. Dover et al. (ICL) - "Sub-luminal intense laser propagation in near-critical density plasma"
  - G. Casati et al. (ICL) - "Steering of shock accelerated proton beams"
  - O. Ettlinger et al. (ICL) - "Experimental demonstration of shock-driven proton acceleration scaling at near-critical densities"
- **Peer reviewed journal articles related to AE133 forerunner ATF experiments**
  - N.P. Dover et al. - " Observation of laser-generated fast electron Weibel filaments" PRL 134, 025102 (2025)
  - Y-H. Chen et al. - "Proton acceleration in an overdense hydrogen plasma by intense CO2 laser pulses with nonlinear propagation effects in the underdense preplasma" - Phys. Plasmas 30, 053106 (2023)
  - N.P. Dover et al.- "Optical shaping of gas targets for laser-plasma ion sources " JPP 82, 415820101 (2016)
  - O. Tresca et al.- "Spectral modification of shock accelerated ions using a hydrodynamically shaped gas target" - PRL 115, 094802 (2015)
  - C.A.J. Palmer et al. - "Manipulation of laser-generated energetic proton spectra in near critical density plasma", JPP 81, 365810103 (2015)
  - C.A.J. Palmer et al. - "Monoenergetic Proton Beams Accelerated by a Radiation Pressure Driven Shock", PRL 106, 014801 (2011)
  - Z. Najmudin et al.- "Observation of impurity free monoenergetic proton beams from the interaction of a CO_2 laser with a gaseous target", Phys. Plasmas 18, 056705 (2011)

Electron Beam Requirements

Parameter	Units	Typical Values	Comments	Requested Values
Beam Energy	MeV	50-65	*Full range is ~15-75 MeV with highest beam quality at nominal values*	
Bunch Charge	nC	0.1-2.0	*Bunch length & emittance vary with charge*	
Compression	fs	Down to 100 fs (up to 1 kA peak current)	*A magnetic bunch compressor available to compress bunch down to ~100 fs. Beam quality is variable depending on charge and amount of compression required.* *NOTE: Further compression options are being developed to provide bunch lengths down to the ~10 fs level*	
Transverse size at IP (σ)	μm	30 – 100 (dependent on IP position)	*It is possible to achieve transverse sizes below 10 um with special permanent magnet optics.*	
Normalized Emittance	μm	1 (at 0.3 nC)	*Variable with bunch charge*	
Rep. Rate (Hz)	Hz	1.5	*3 Hz also available if needed*	
Trains mode	---	Single bunch	*Multi-bunch mode available. Trains of 24 or 48 ns spaced bunches.*	

Electron beam not required

CO_2 Laser Requirements

Configuration	Parameter	Units	Typical Values	Comments	Requested Values
CO_2 Regen. Amplifier	Wavelength	μm	9.2	*Wavelength determined by mixed isotope gain media*	
	Peak Power	GW	~3		
	Pulse Mode	---	Single		
	Pulse Length	ps	2		
	Pulse Energy	mJ	6		
	Repetition Rate	Hz	1.5	*3 Hz also available if needed*	
CO_2 CPA Beam	Wavelength	mm	9.2	*Wavelength determined by mixed isotope gain media*	
Note that delivery of full power pulses to the Experimental Hall is presently limited to Beamline #1 only.	Peak Power	TW	2-3	*Up to 5 TW operation will be available in a limited number of shots upon the user's request*	2-3 TW
	Pulse Mode	---	Single		
	Pulse Length	ps	2	*3-year development effort to achieve <500fs at >10 TW and deliver to users is in progress*	2 ps
	Pulse Energy	J	~5	*10J will be available in a limited number of shots upon the user's request*	5 J
	Strehl Ratio	---	~0.5	*Recommended conservative estimate subject to verification*	Highest possible
	Repetition Rate	Hz	0.01	*Burst operation at up to 0.05 Hz for a limited period is possible upon user's request. This regime should be avoided to extend the lifetime of the HV spark gaps in the amplifiers's PFN*	0.01
	Polarization		Linear	*Adjustable linear polarization along with circular polarization can be provided upon request*	LP/CP

Other Experimental Laser Requirements

Ti:Sapphire Laser System	**Units**	**Stage I Values**	**Stage II Values**	**Comments**	**Requested Values**
Central Wavelength	nm	800	800	*Stage I parameters are presently available and setup to deliver Stage II should be available summer 2025*	√
FWHM Bandwidth	nm	20	13		√
Compressed FWHM Pulse Width	fs	<50	<75	*Transport of compressed pulses will initially include a very limited number of experimental interaction points.*	*≤75*
Chirped FWHM Pulse Width	ps	≥50	≥50		*N/A*
Chirped Energy	mJ	10	200		*N/A*
Compressed Energy	mJ	7	~20	*20 mJ is presently operational with work underway this year to achieve our 100 mJ goal*	*20*
Energy to Experiments	mJ	>4.9	>80		*4.9*
Power to Experiments	GW	>100	>1000		*100*

Nd:YAG Laser System	**Units**	**Typical Values**	**Comments**	**Requested Values**
Wavelength	nm	1064	*Single pulse*	√
Energy	mJ	100		*100*
Pulse Width	ps	14		*14*
Wavelength	nm	532	*Frequency doubled*	*N/A*
Energy	mJ	0.5		*N/A*
Pulse Width	ps	10		*N/A*

Special Equipment Requirements and Hazards

- Electron Beam N/A
- CO_2 Laser
  - Please note any specialty laser configurations required here:
- Ti:Sapphire and Nd:YAG Lasers
  - Please note any specialty non-CO_2 laser configurations required here:
    - YAG amplifier for highest possible energies
- Hazards & Special Installation Requirements
    - New magnet installation for particle spectrometer - 0.6T (already ordered)
    - HV for time-of-flight diamond detector

Experimental Time Request

CY2025 Time Request

Capability	Setup Hours	Running Hours
Electron Beam Only		
Laser* Only (in Laser Areas)	40	80
Laser* + Electron Beam		

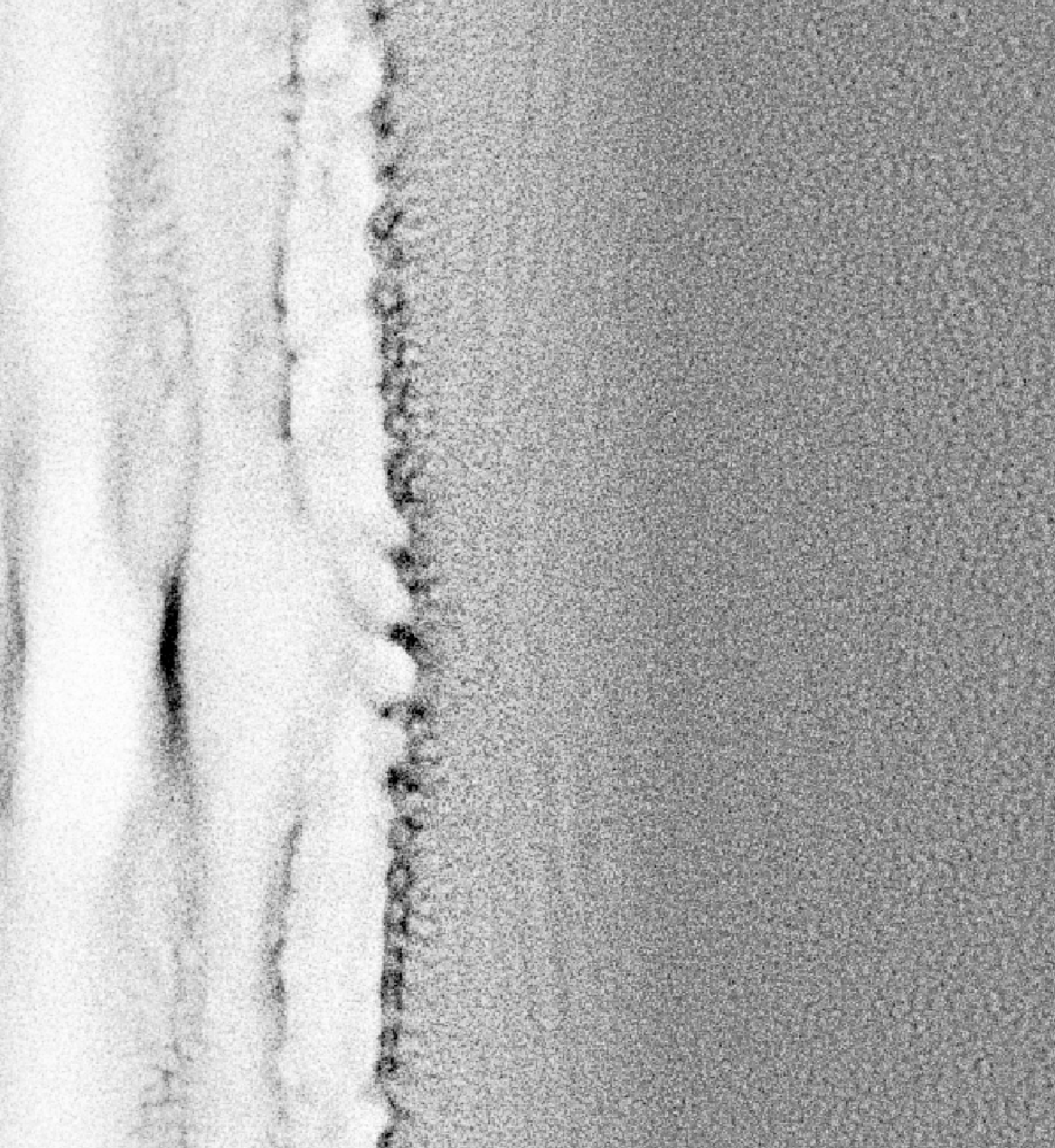
Total Time Request for the Experiment remaining duration

Capability	Setup Hours	Running Hours
Electron Beam Only		
Laser* Only (in Laser Areas)	120	360
Laser* + Electron Beam		

* Laser = Near-IR or LWIR (CO_2) Laser

Summary - AE133

- Aim to investigate underlying physics of the ion acceleration process:
  - Laser propagation dynamics in underdense plasmas
  - Acceleration physics at the critical surface
  - Particle beam propagation in plasmas
- Next step is to stabilise density profile in interaction:
  - Improve gas targetry
  - Investigate transverse blast wave shaping as an alternative to using prepulse



Experimental Layout