High-intensity laser interactions with near-critical density plasmas: NP-315758

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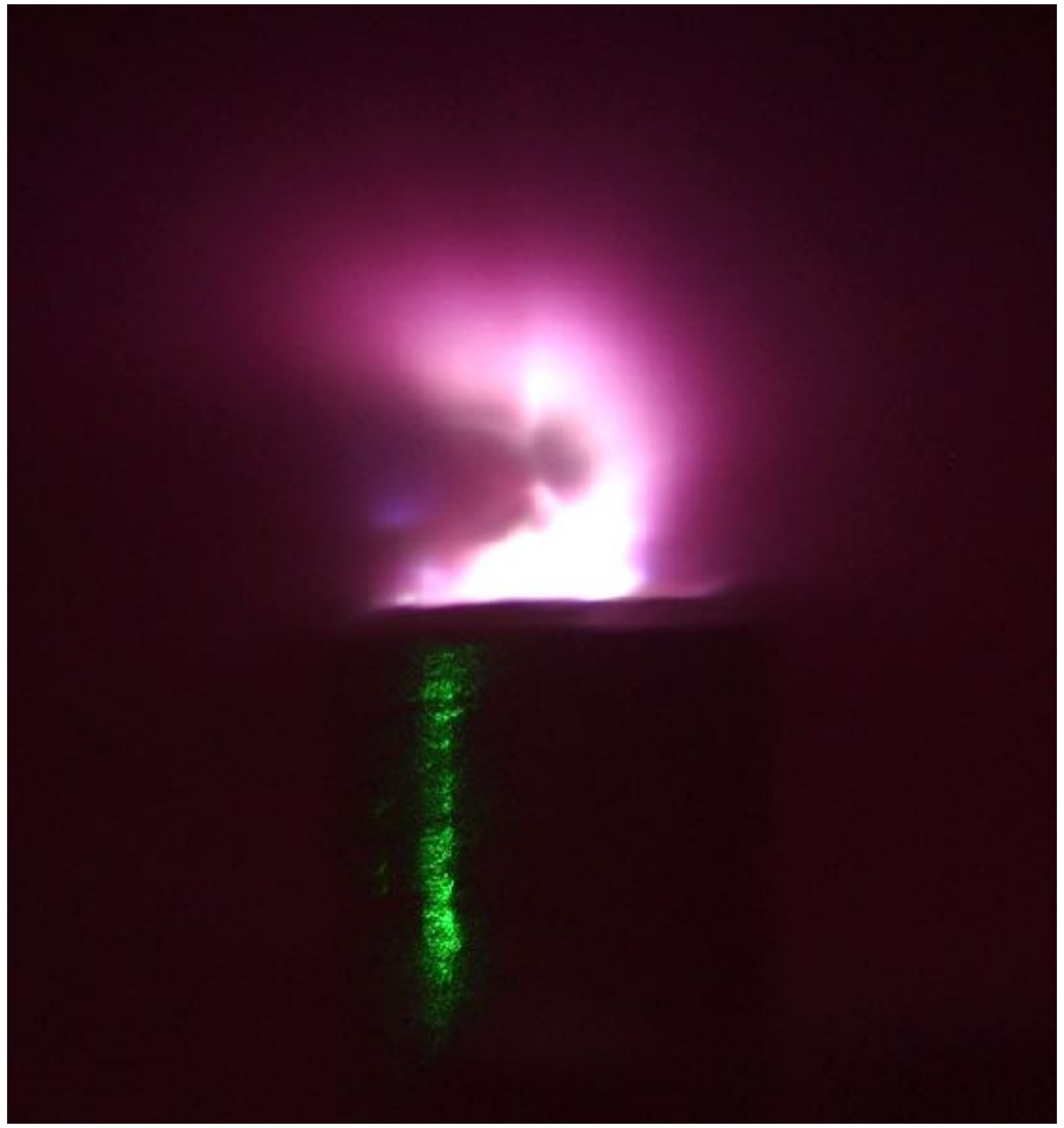

ATF User Meeting,
27th March 2024

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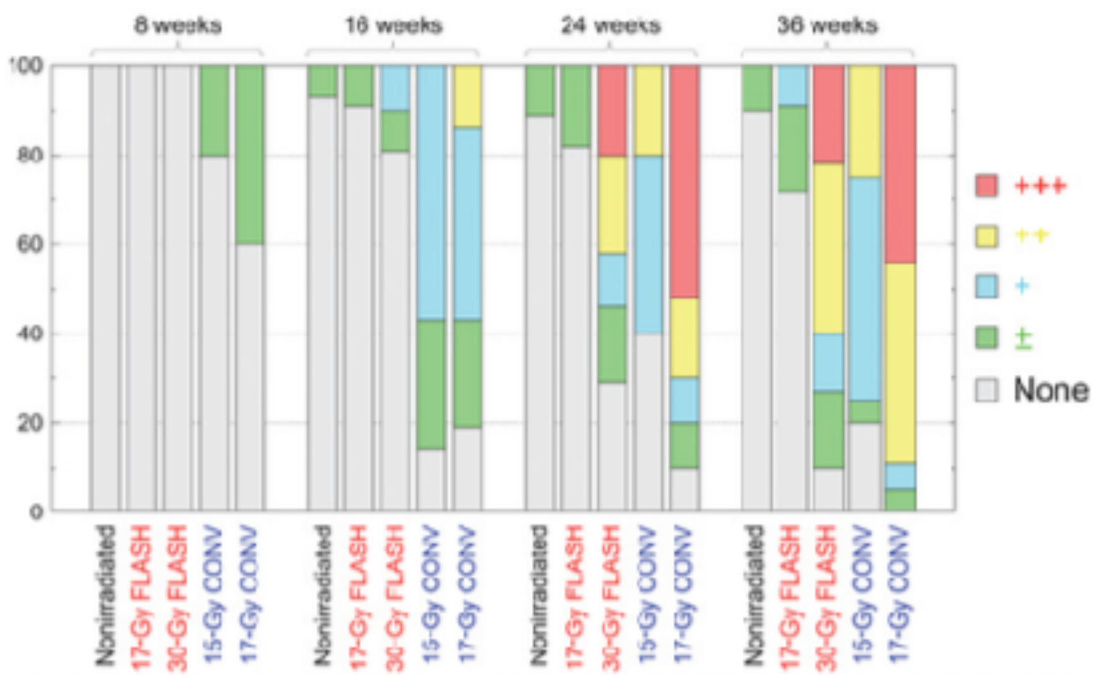
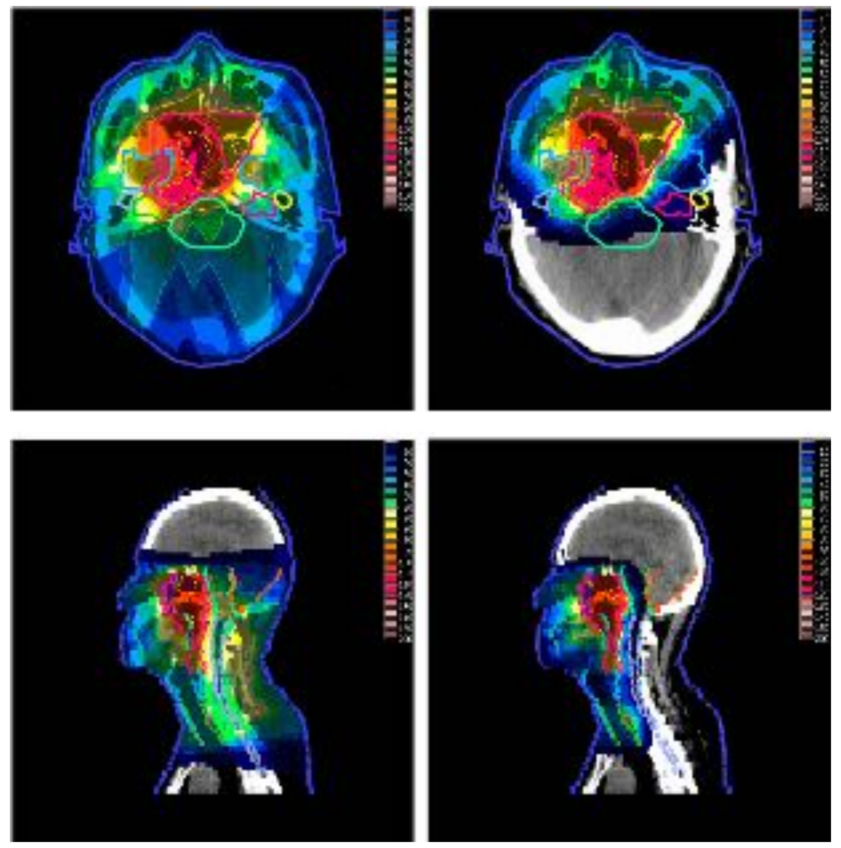
Motivation for laser-driven ion sources

Why laser driven ion sources?

Favaudon et al., Sci. Transl. Med. 6, 245 (2014)





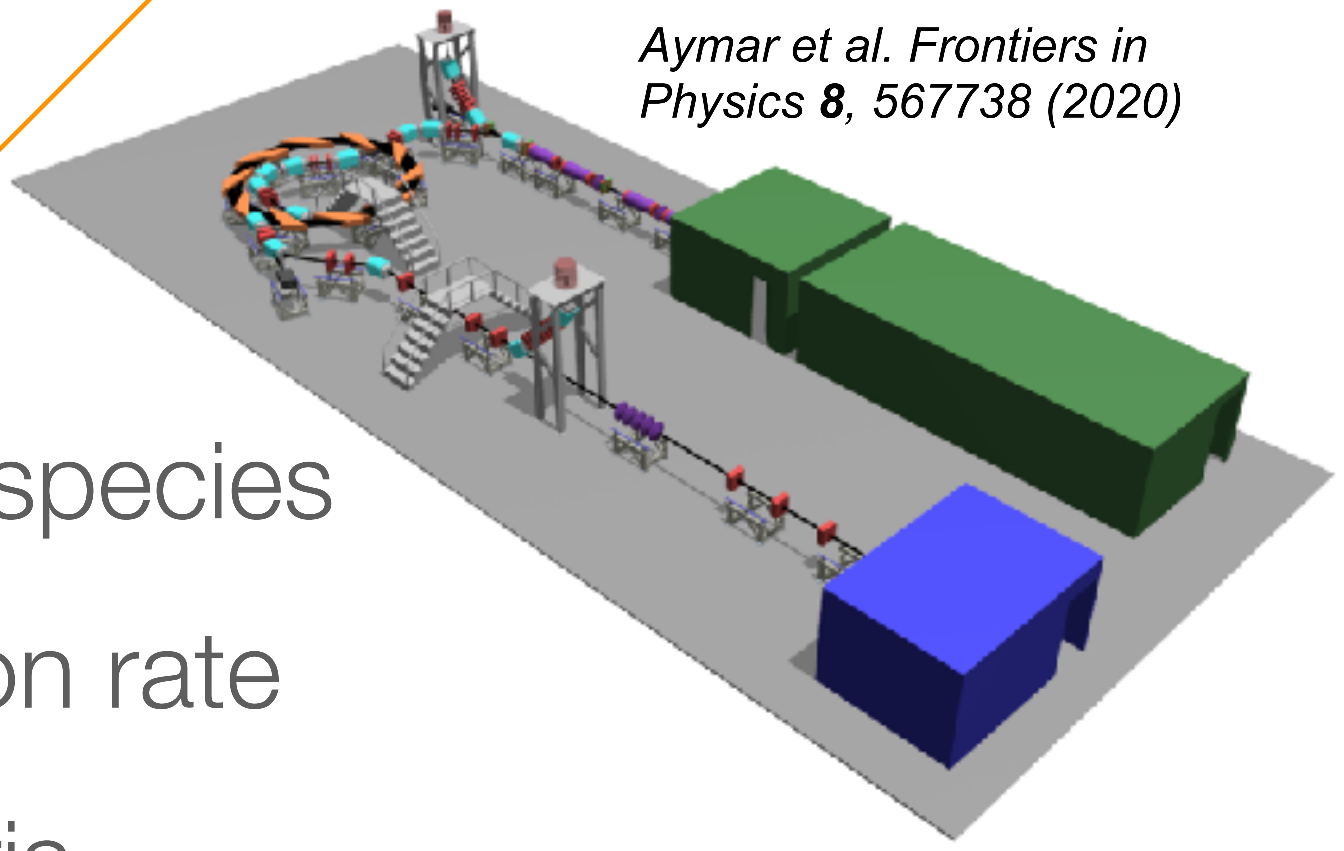
*Z. Taheri-Kadkhoda et al. Radiation Oncology **3** (2008)*

Laser driven ion sources increasingly attractive due to high source energy and short bunch length

For example, these sources are well suited for high dose rate radiobiology - e.g. FLASH

Important characteristics of laser driven source for applications

- High energy
- High flux
- Different ion species
- High repetition rate
- Minimal debris

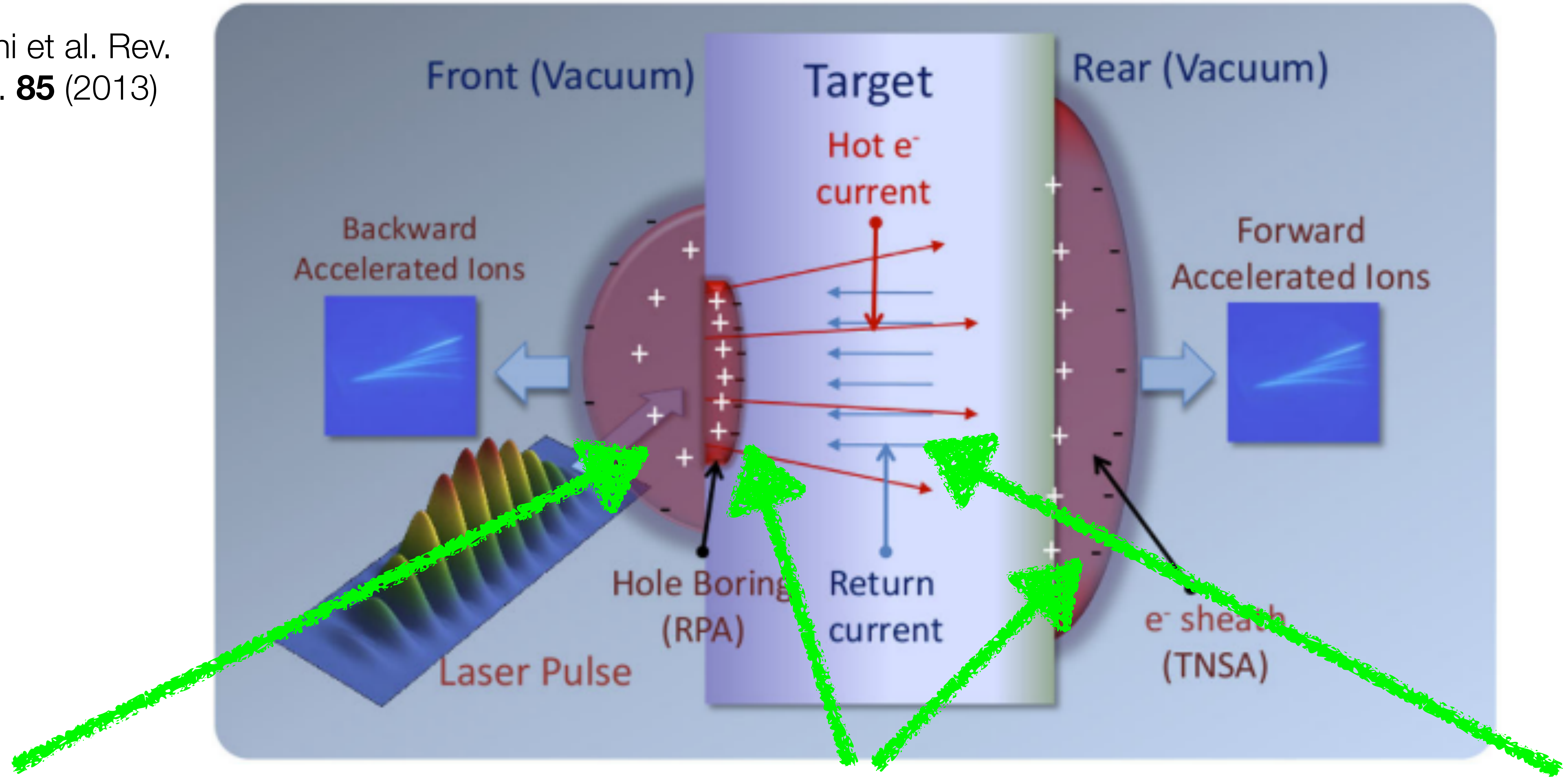


*Aymar et al. Frontiers in Physics **8**, 567738 (2020)*

Gaseous targets are a great choice, if high energy, high flux ions can be produced…

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

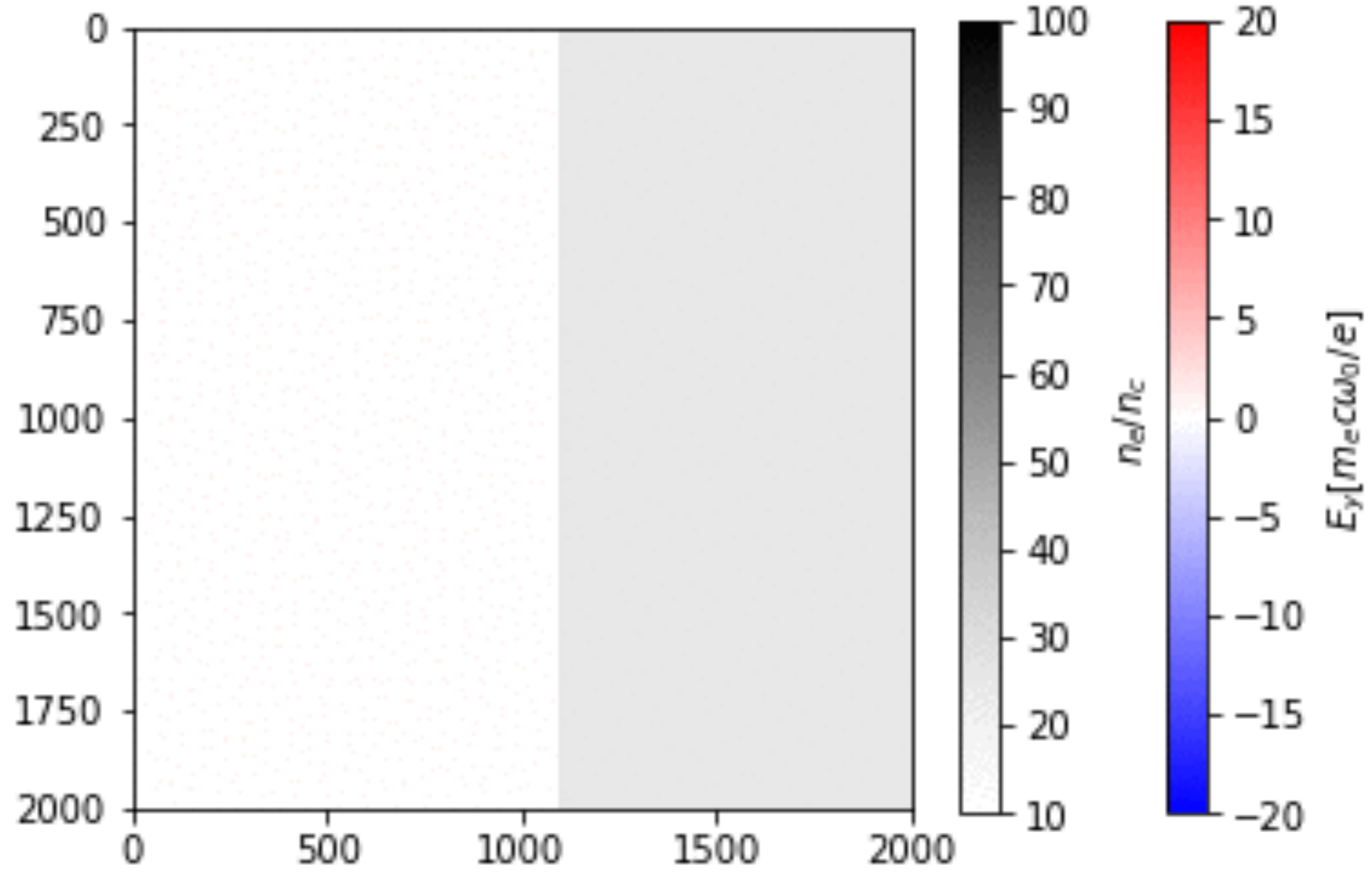
Propagation of “fast” electrons in the target

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 🙁



Rely on simulations, many assumptions

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

Exploiting dimensional scaling of collisionless laser-plasmas

Collisionless laser plasmas can be defined using reference frequency*:

	Time	*Length*	*Density*	
	$\tilde{t} = \omega_L t$	$\tilde{x} = \frac{\omega_L}{c} x$	$\tilde{n} = \frac{1}{n_c} n \propto \frac{1}{\omega_L^2} n$	
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	

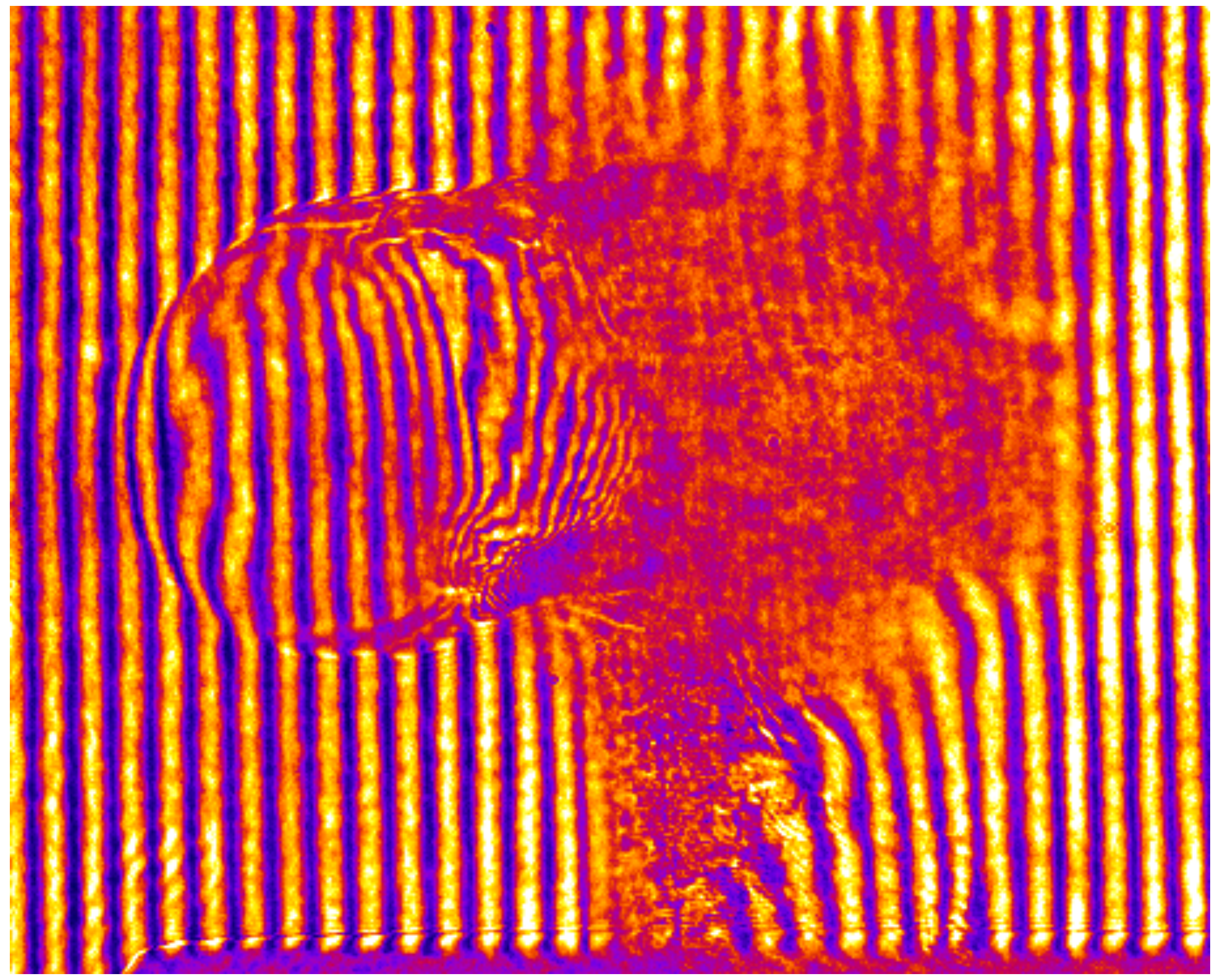
*if e.g. ionisation/QED not important

A unique facility at the ATF for investigating ion source physics

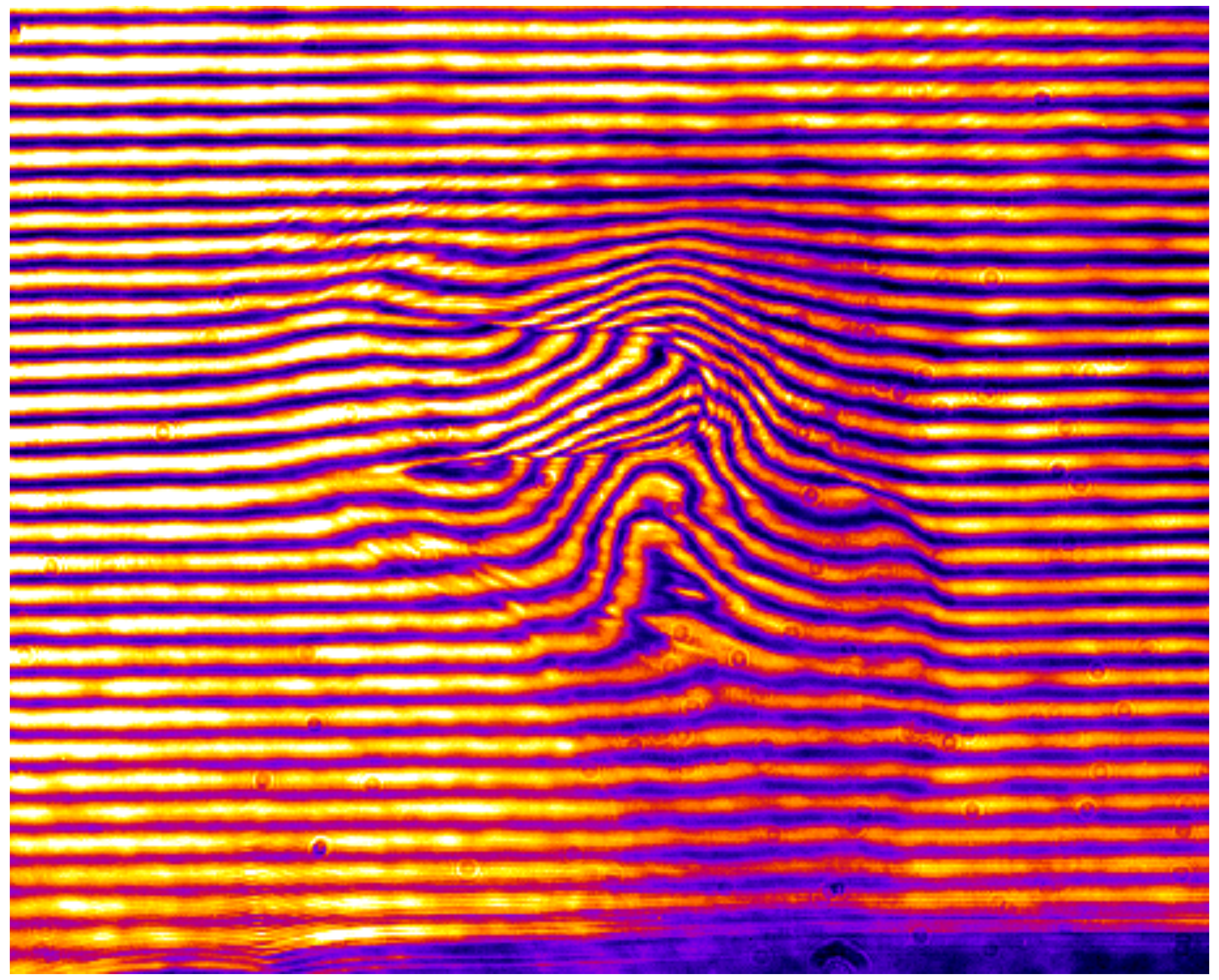
Utilising the ATF's NIR and MWIR laser facilities, we have a unique and exciting platform for investigating ion source physics dynamics

- CO_2 laser - 2 ps, 9.2 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

Proposed Objectives

We plan to exploit this setup to investigate three regimes of importance to ion acceleration:

1. Laser propagation in underdense plasmas preceding the critical surface

2. The dynamics of ion acceleration by shock structures

3. Particle beam propagation through plasmas

Proposed Investigation

We plan to exploit this setup to investigate three regimes of importance to ion acceleration:

1. **Laser propagation in underdense plasmas preceding the critical surface**

2. The dynamics of ion acceleration by shock structures

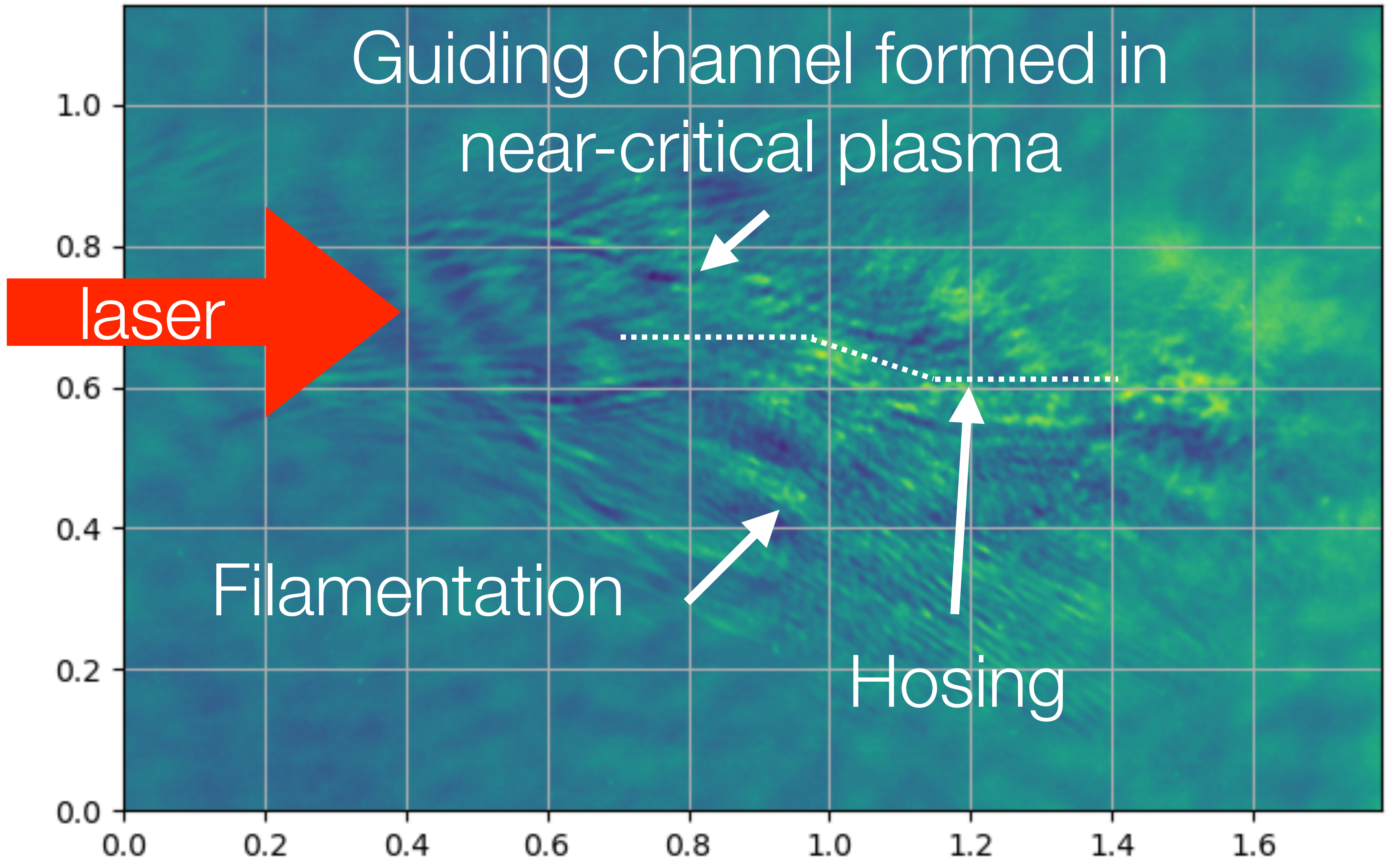
3. Particle beam propagation through plasmas

Laser propagation in underdense plasmas

To fully understand the acceleration process laser conditions at the critical surface must be fully understood

A number of effects can occur as a laser propagates an underdense plasma:

- relativistic self-focussing and dispersion
- laser hosing
- filamentation



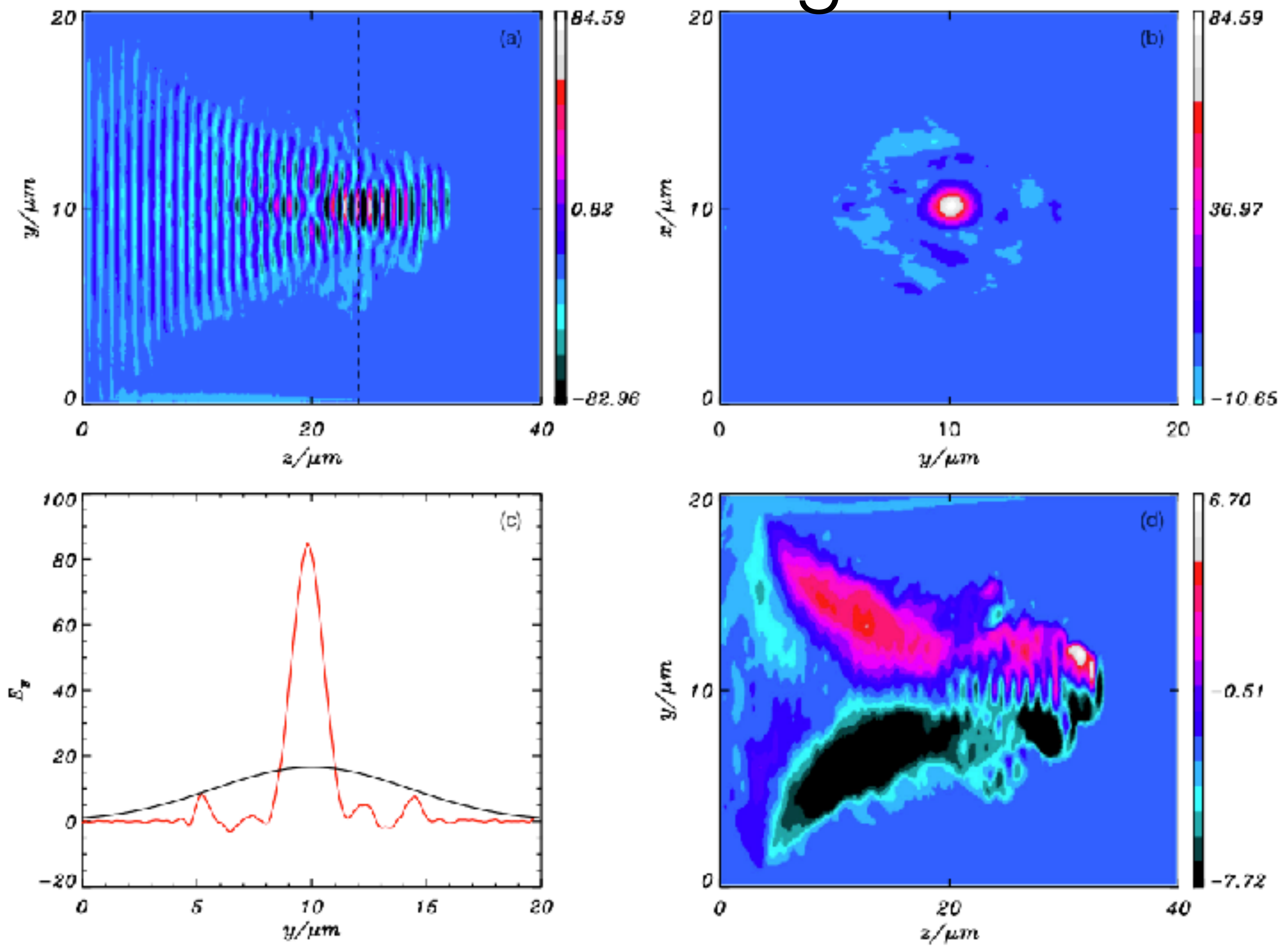
Preliminary data taken during AE100

Laser propagation in underdense plasmas

These processes affect laser conditions at critical density surface

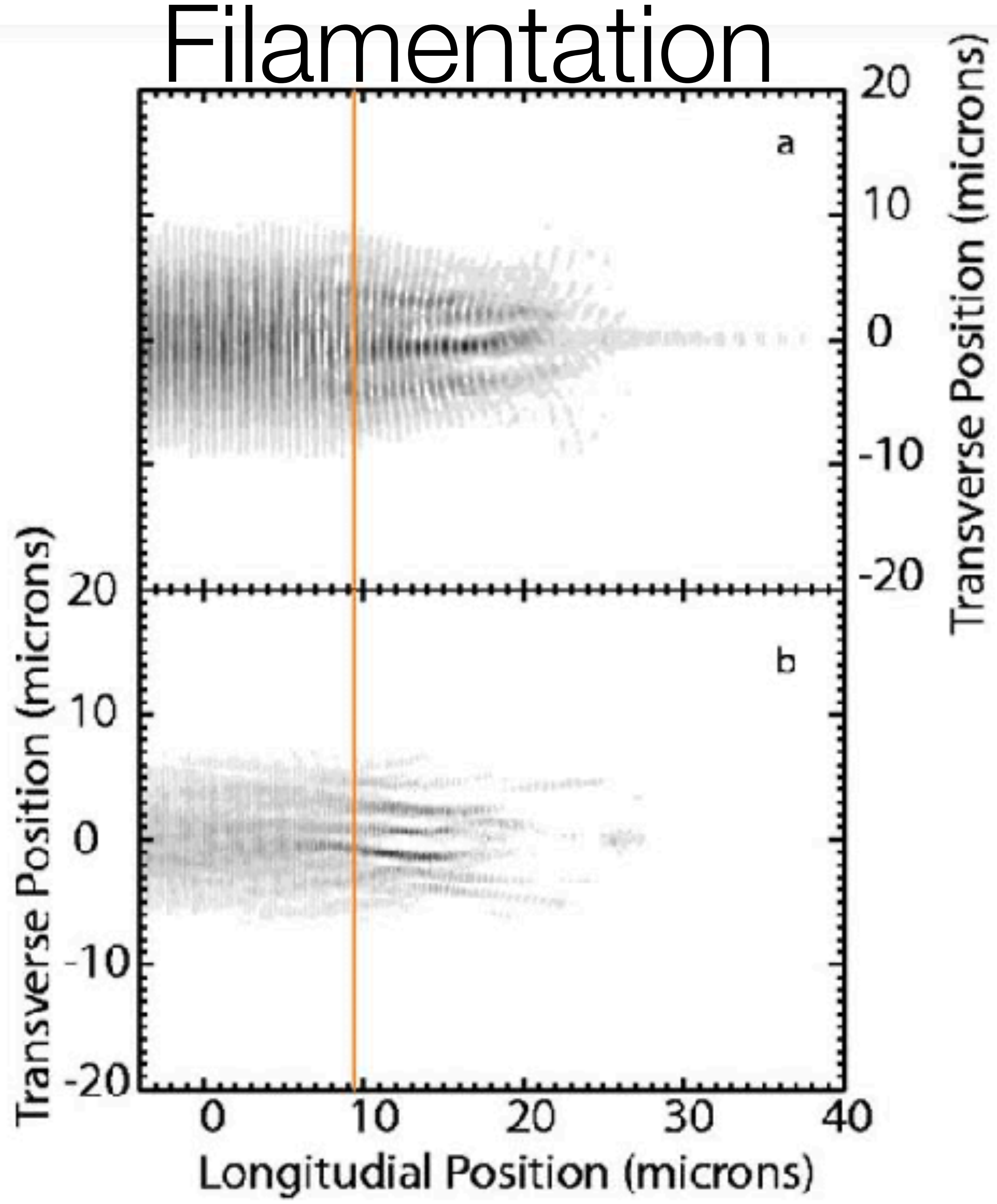
- ➡ uncertainty in laser energy, focal spot size and shape
- ➡ Can enhance or degrade acceleration performance

Self focusing



From Jiang et al. PRL **107** (2011)

Filamentation



From Brady et al. Phys. Plasmas **19** (2012)

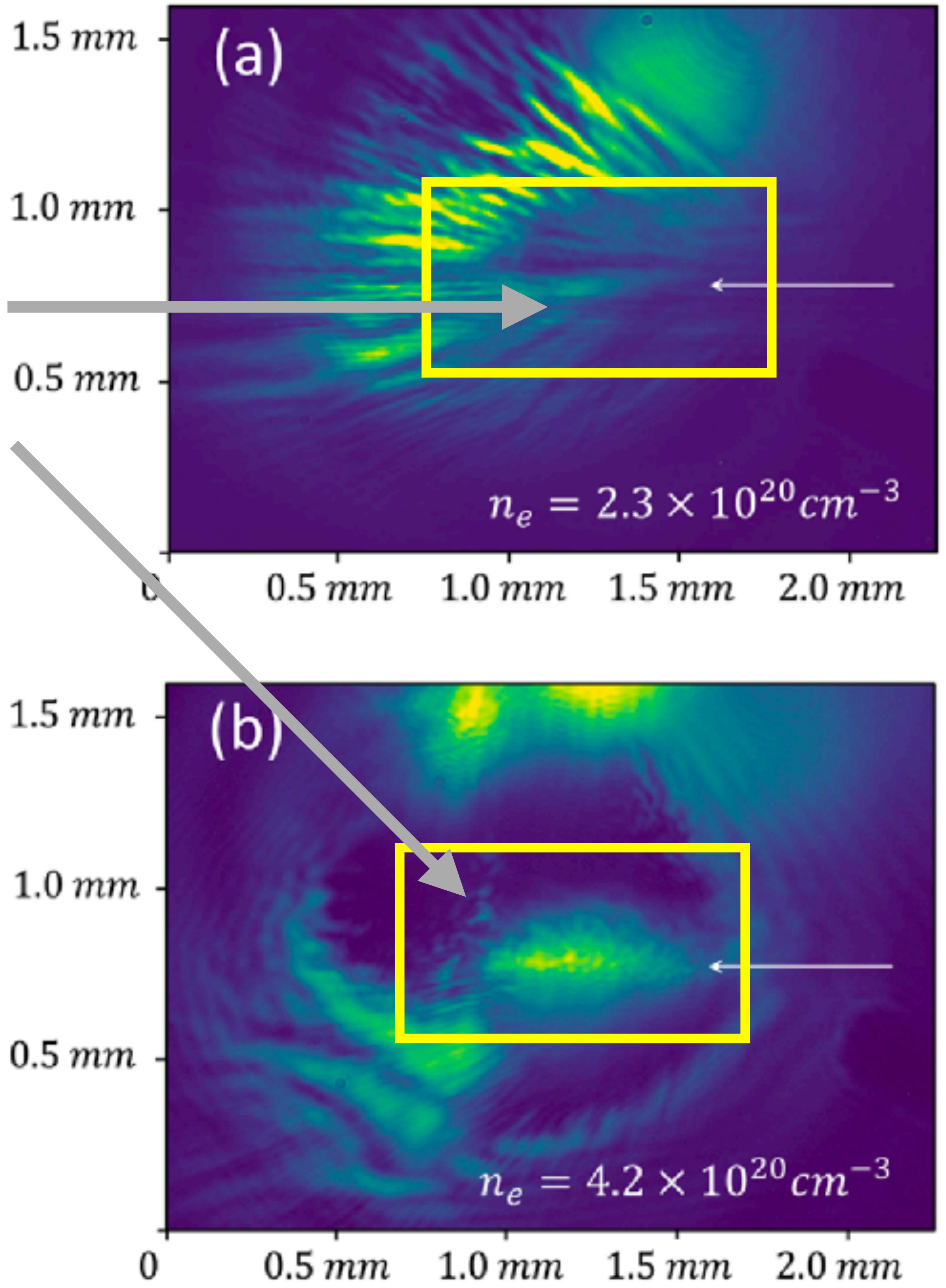
Experimental investigation of these concepts

We will use the unique setup to investigate these processes:

- ➡ Measure plasma dynamics and transmitted laser properties
- ➡ Vary density and density gradients
- ➡ Vary laser parameters

Example with near-IR drive: LPI completely obscured due to high densities

From Singh et al. Sci. Rep. **10** (2020)



We will directly image these phenomena at near-critical densities, not possible with near-IR drivers

Proposed Investigation

We plan to exploit this setup to investigate three regimes of importance to ion acceleration:

1. Laser propagation in underdense plasmas preceding the critical surface
2. **The dynamics of ion acceleration by shock structures**
3. Particle beam propagation through plasmas

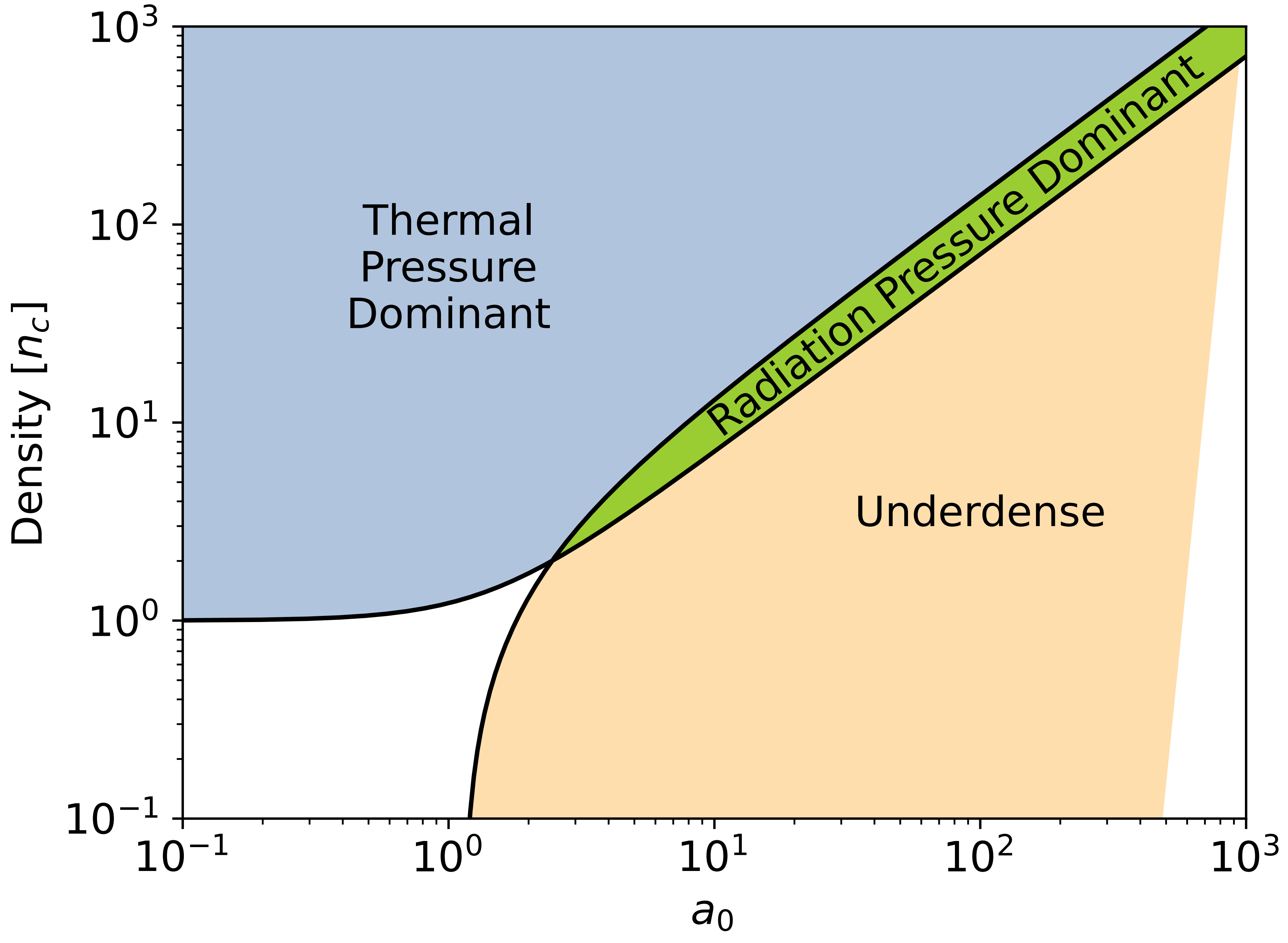
ATF acceleration conditions

CO_2 laser allows near-critical investigations, enabling the study of shock acceleration mechanisms

Changing the laser and target conditions enables transition of hole-boring (HB) and collisionless shock acceleration (CSA)

$$P_R = n_c m_e c^2 {a_0}^2$$

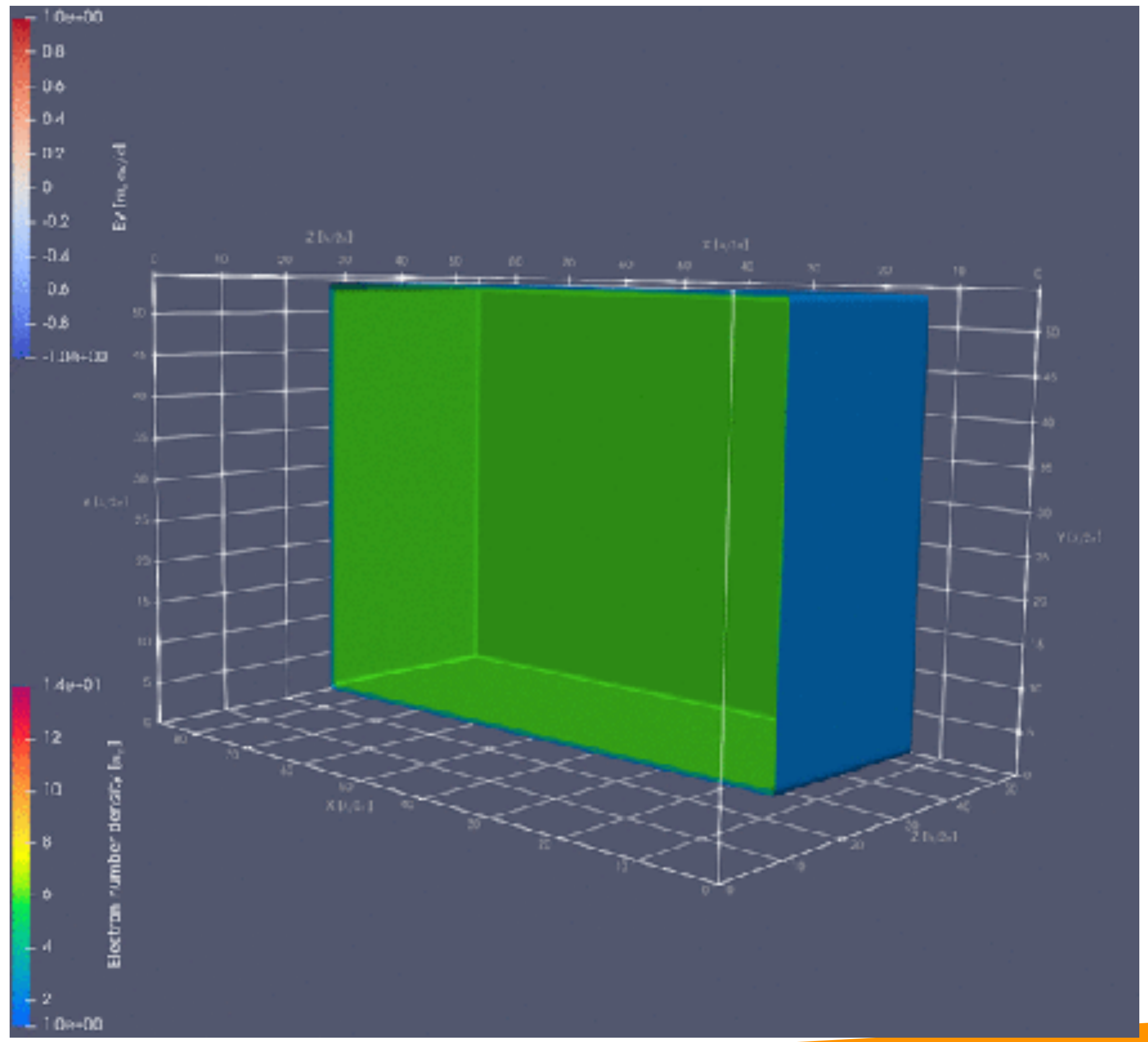
$$P_{Th} = n_e m_e c^2 \left[\sqrt{1 + \frac{{a_0}^2}{2}} - 1 \right]$$

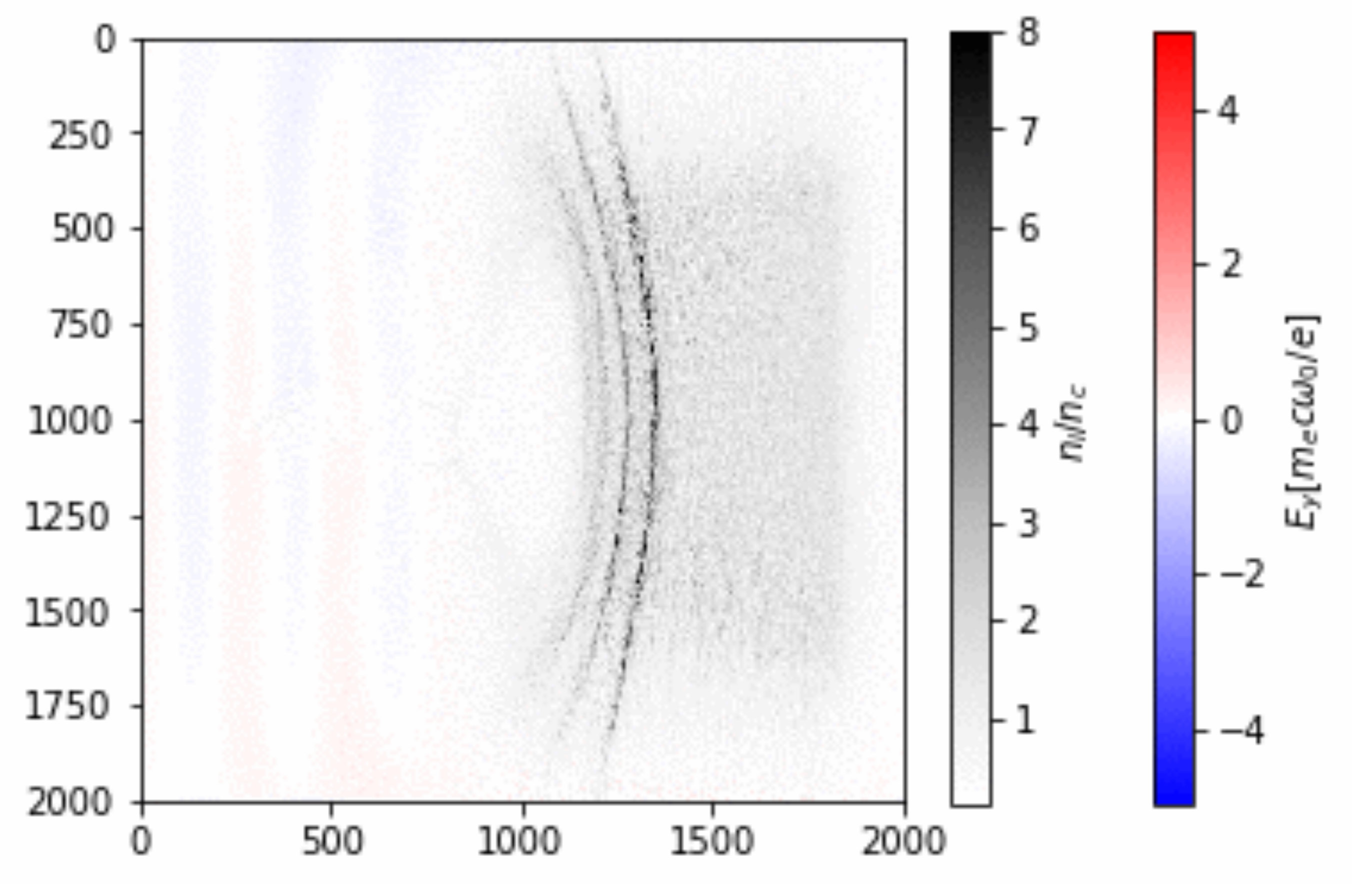


Proposed areas of study

A number of interesting areas of study:

- Continue work of AE100 and make first detailed optical studies of the ion acceleration phase





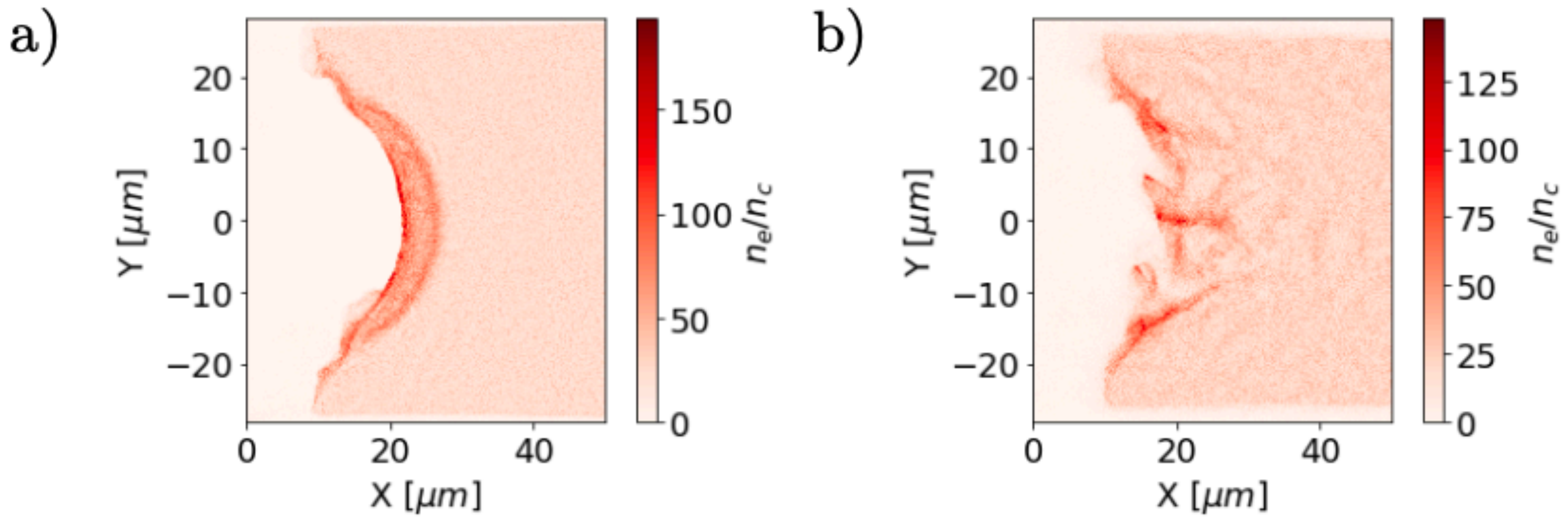
At T_e ~ 1 MeV, and 1e7 shock velocity, feature size is ~ μm scale. In 2 ps, shock moves ~20 μm

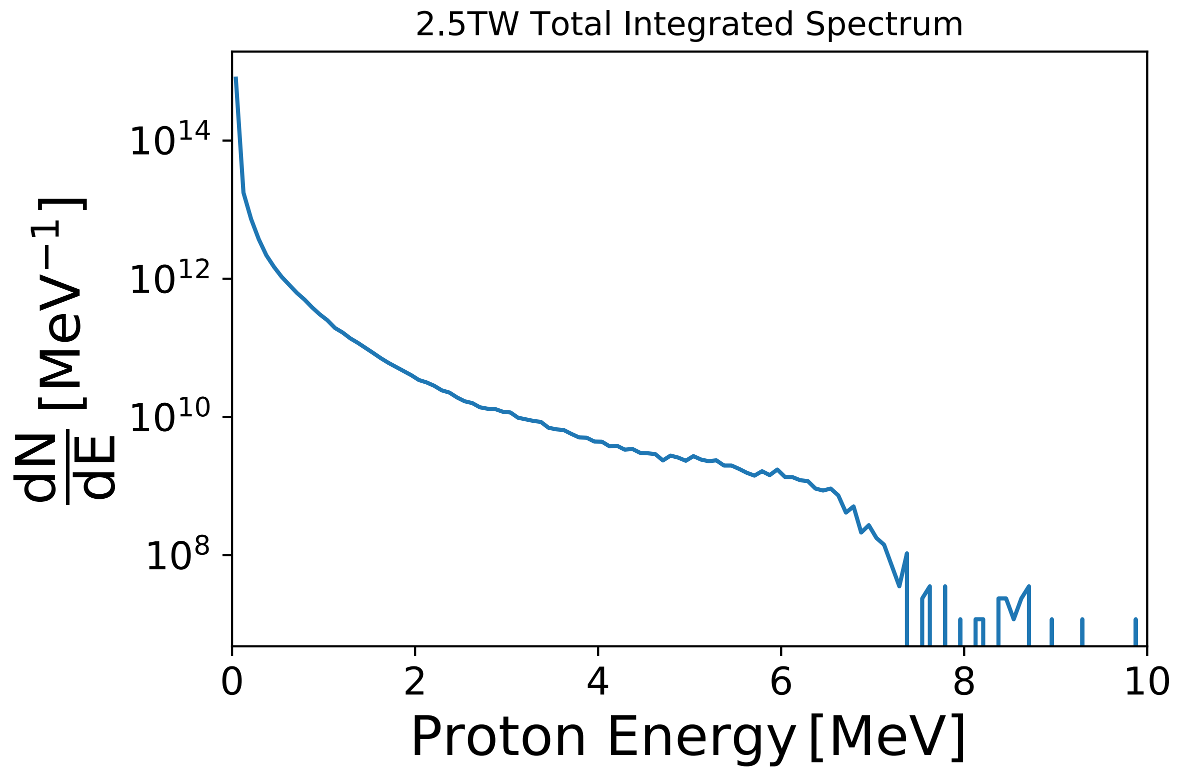
—> sub 100 fs probe needed

Proposed areas of study

A number of interesting areas of study:

- First detailed optical studies of the ion acceleration phase
- Interplay between CSA and HB and how to control this

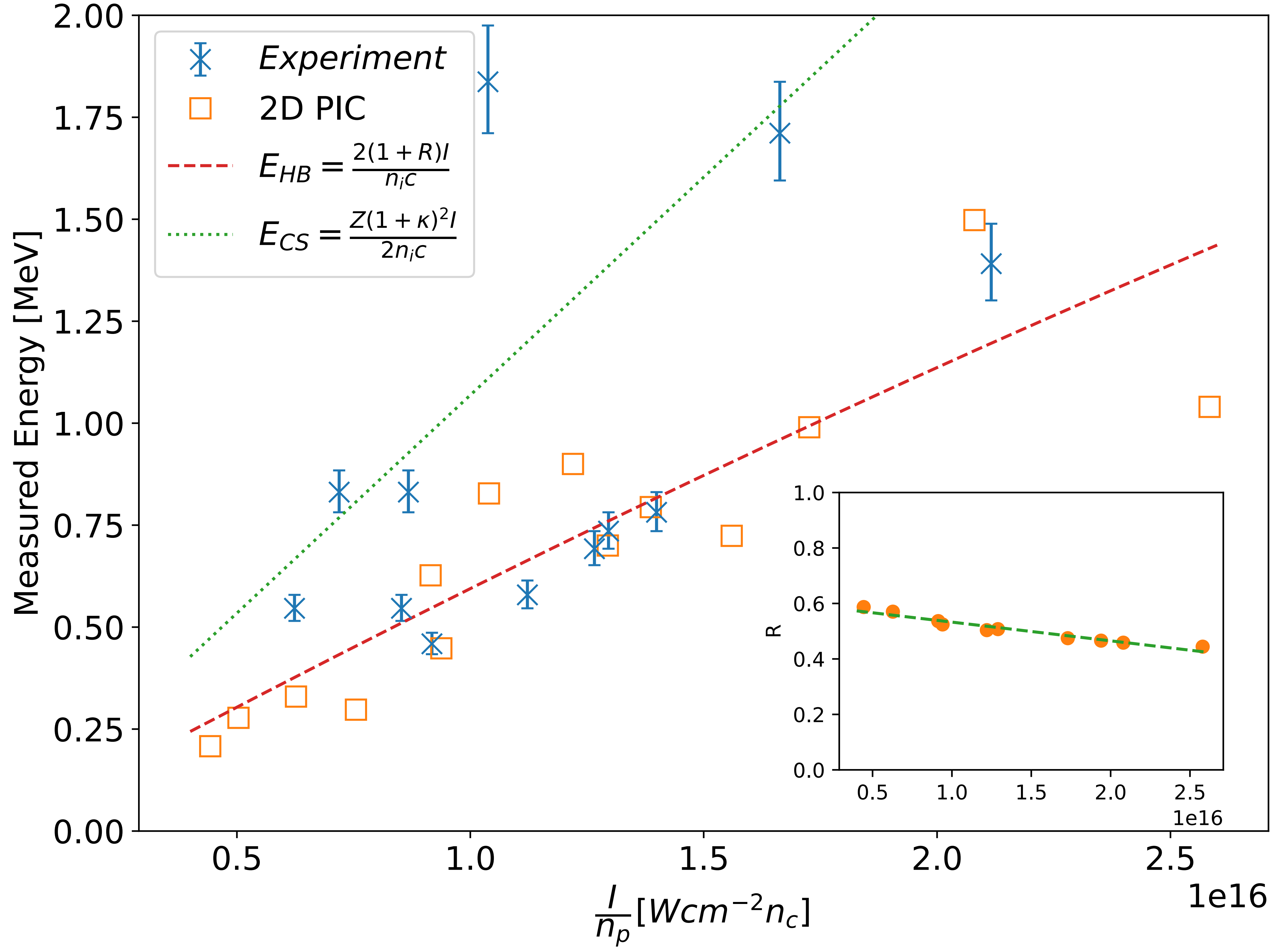




Proposed areas of study

A number of interesting areas of study:

- First detailed optical studies of the ion acceleration phase
- Interplay between CSA and HB and how to control this
- Improved ion acceleration performance at multi-TW level



Proposed Investigation

We plan to exploit this setup to investigate three regimes of importance to ion acceleration:

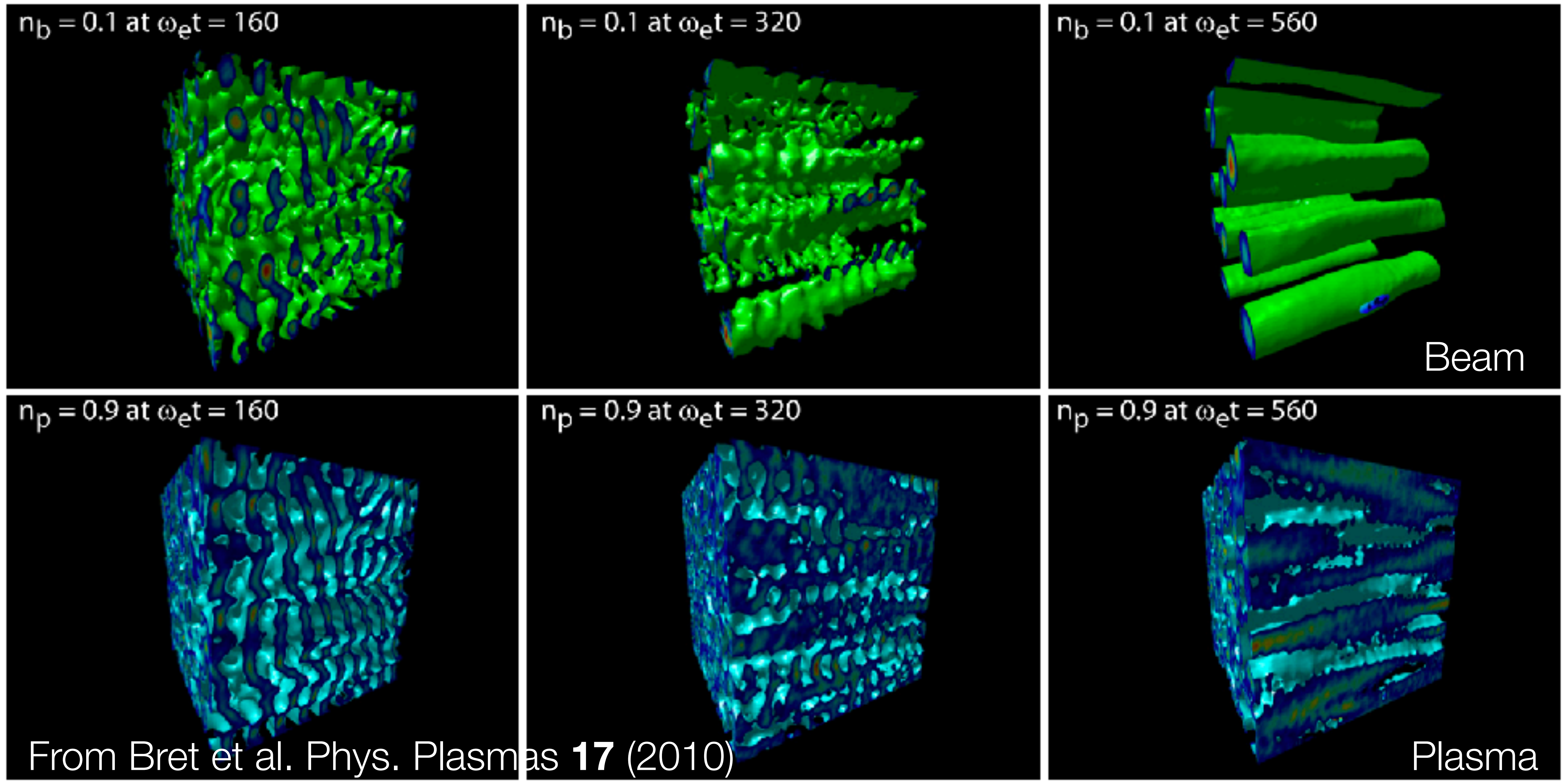
1. Laser propagation in underdense plasmas preceding the critical surface

2. The dynamics of ion acceleration by shock structures

3. **Particle beam propagation through plasmas**

Beam propagation through plasmas

- Energetic electrons are generated in LPI and propagate into upstream plasma
- Their current greatly exceeds Alfvén limit -> balanced by return current
- These counter propagating populations are subject to collisionless instabilities, such as the current filamentation instabilities



From Bret et al. Phys. Plasmas **17** (2010)

- Affects electron beam transport
- Can degrade ion generation
- Proposed mechanism for magnetic field generation in some astrophysical scenarios

John Adams Institute for Accelerator Science

Imperial College London

Beam propagation through plasmas

Studies with near-IR cannot measure this in dense plasmas directly, only through subsequent impact on particles

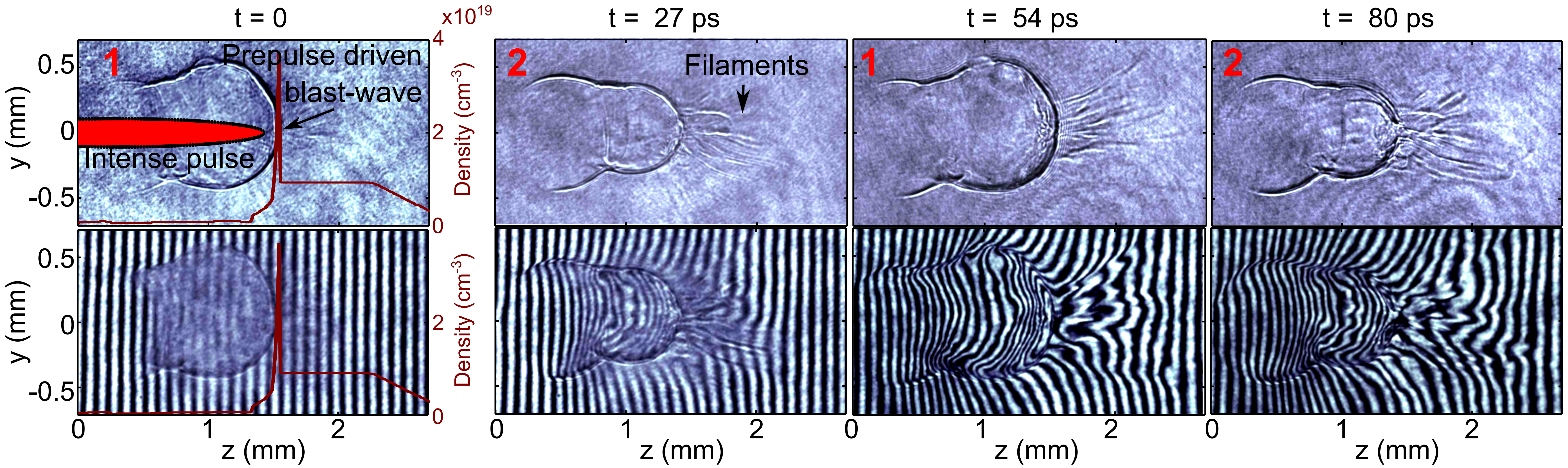
The ATF can study the same physics, but on a different scale:

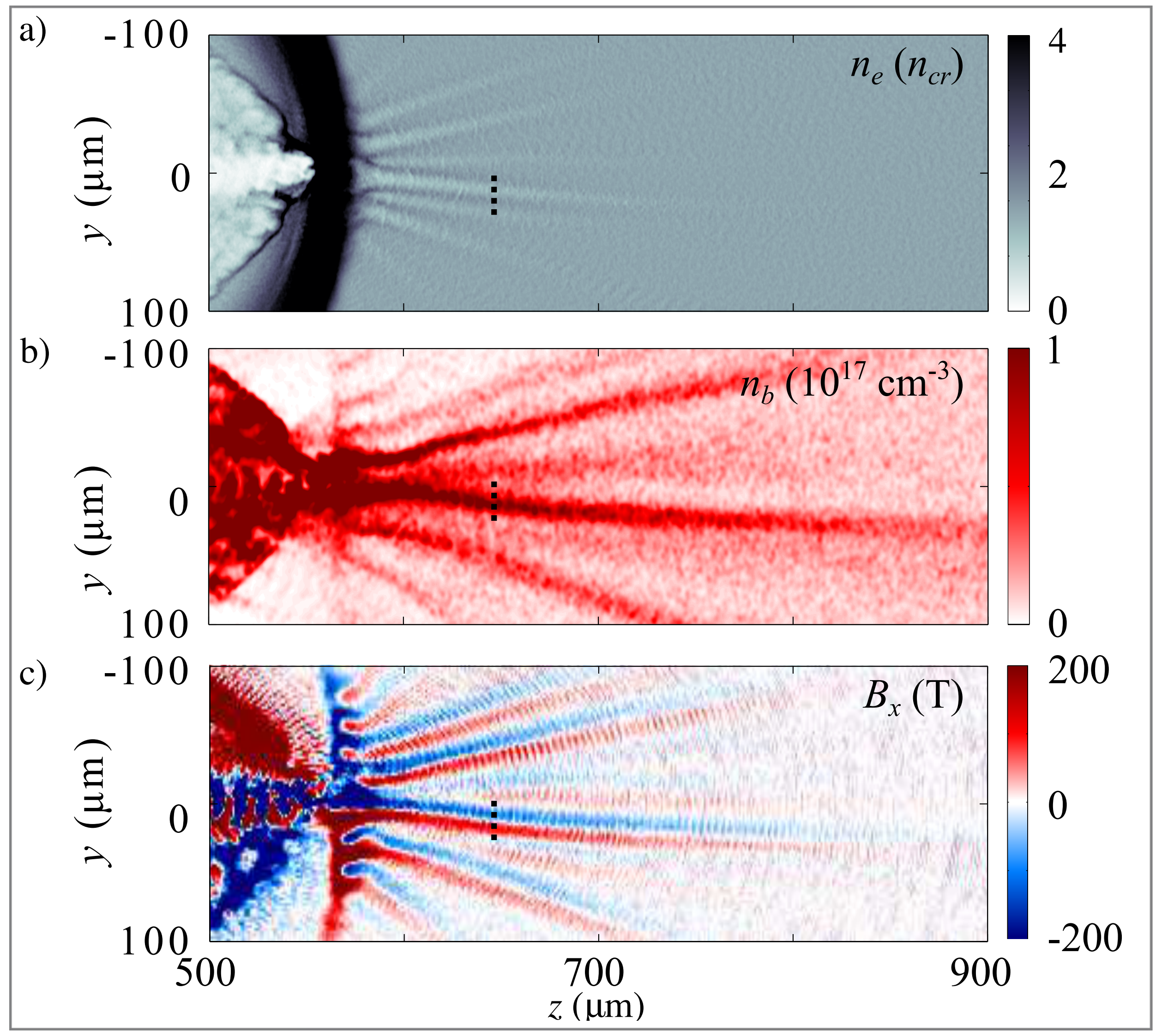
1) Density achievable by gas jets and ideal for optical probing
2) Filament 10x wider - resolvable using TiS
3) Instability driven over 10x longer time - time evolution can captured using TiS

	CO_2 laser@ BNL	Equivalent NIR
λ_L (μm)	9.2	0.8
a_0	3	3
τ_L (fs)	2000	200
n_e (cm^{-3})	1.3×10^{19}	1.7×10^{21}
γ_e	~3	~3
$\alpha=n_b/n_e$	~0.1	~0.1
λ_{Fil}~$2\pi c/\omega_p$ (μm)	~10	~1
τ_f (fs)	~10	~1
e-folds	~200	200

Beam propagation through plasmas

Previously observed the *endpoint* of current filamentation instability, measuring filamentary density structures after the end of LPI



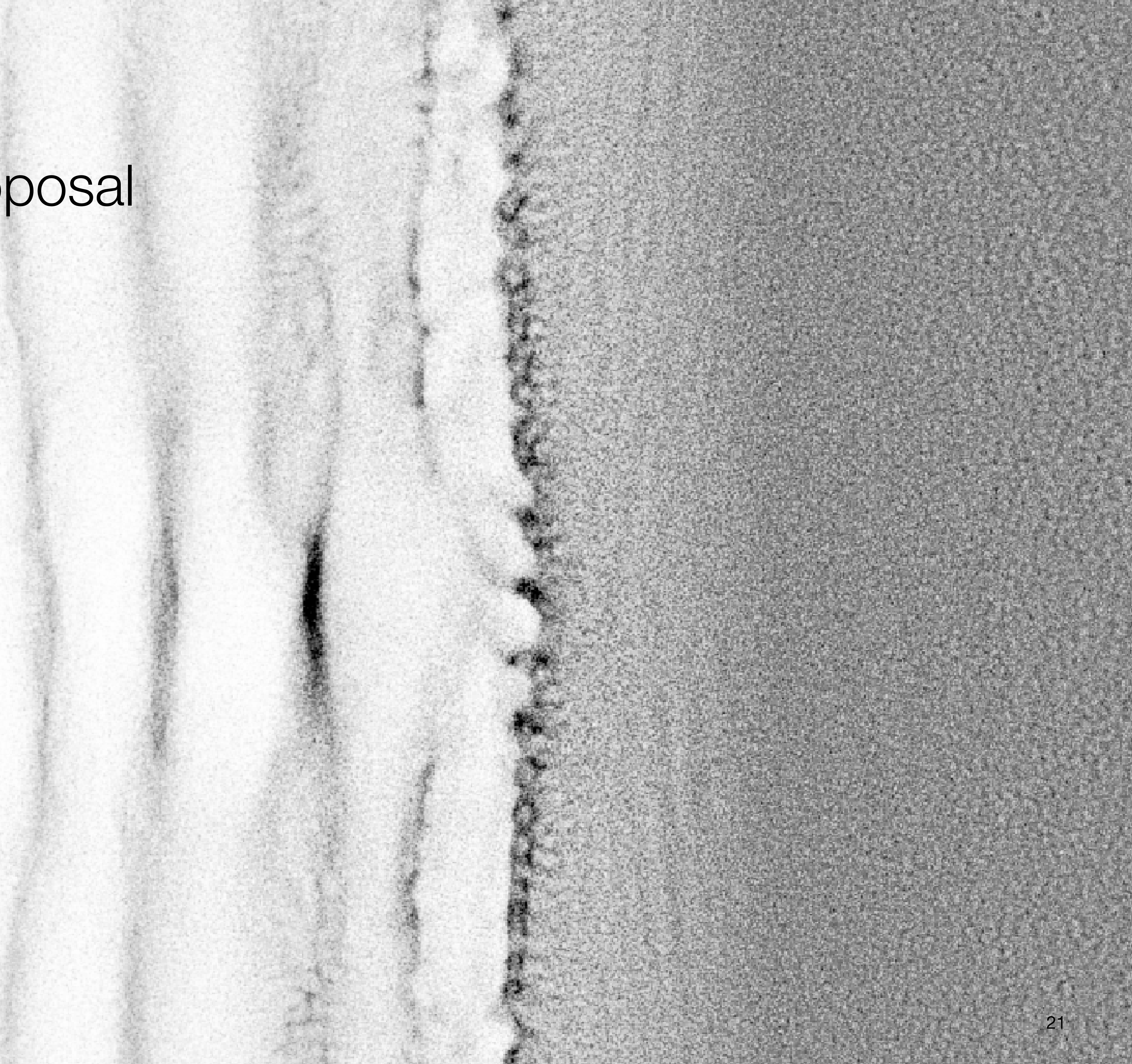


Previous measurements were limited because growth phase was not resolvable with old YAG probe. **Ti:S will enable time-resolved characterisation of filamentation.**

N. Dover, in preparation

Summary - NP-315758 Proposal

- Proposal builds on experience of AE66 and AE100 experiments, exploiting improved laser capabilities
- Objective is to investigate each stage of the ion acceleration process:
  - Laser propagation dynamics in underdense plasmas
  - Acceleration physics at the critical surface
  - Particle beam propagation in plasmas



Thank you for listening.
Questions?

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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

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CO_2 Laser Requirements

Configuration	Parameter	Units	Typical Values	Comments	Requested Values
CO_2 Regenerative Amplifier Beam	Wavelength	mm	9.2	*Wavelength determined by mixed isotope gain media*	
	Peak Power	GW	~3		
	Pulse Mode	---	Single		
	Pulse Length	ps	2		
	Pulse Energy	mJ	6		
	M^2	---	~1.5		
	Repetition Rate	Hz	1.5	*3 Hz also available if needed*	
	Polarization	---	Linear	*Circular polarization available at slightly reduced power*	
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	Peak Power	TW	5	*~5 TW operation will become available shortly into this year's experimental run period. A 3-year development effort to achieve*	5TW
	Pulse Mode	---	Single		
	Pulse Length	ps	2		2ps
	Pulse Energy	J	~5	*Maximum pulse energies of >10 J will become available within the next year*	5
	M^2	---	~2		
	Repetition Rate	Hz	0.05		Highest available
	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 should be achieved by mid-2020, while Stage II parameters are planned for late-2020.*	*√*
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		
Chirped Energy	mJ	10	200		
Compressed Energy	mJ	7	100		*7*
Energy to Experiments	mJ	>4.9	>80		*4.9*
Power to Experiments	GW	>98	>1067		*99*

Nd:YAG Laser System	Units	Typical Values	Comments	Requested Values
Wavelength	nm	1064	*Single pulse*	
Energy	mJ	5		*5mJ+*
Pulse Width	ps	14		
Wavelength	nm	532	*Frequency doubled*	*X*
Energy	mJ	0.5		*X*
Pulse Width	ps	10		*X*

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

CY2024 Time Request

Capability	Setup Hours	Running Hours
Electron Beam Only		
Laser* Only (in FEL Room)	40	120
Laser* + Electron Beam		

Time Estimate for Full 3-year Experiment (including CY2024-26)

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

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

Experimental Layout