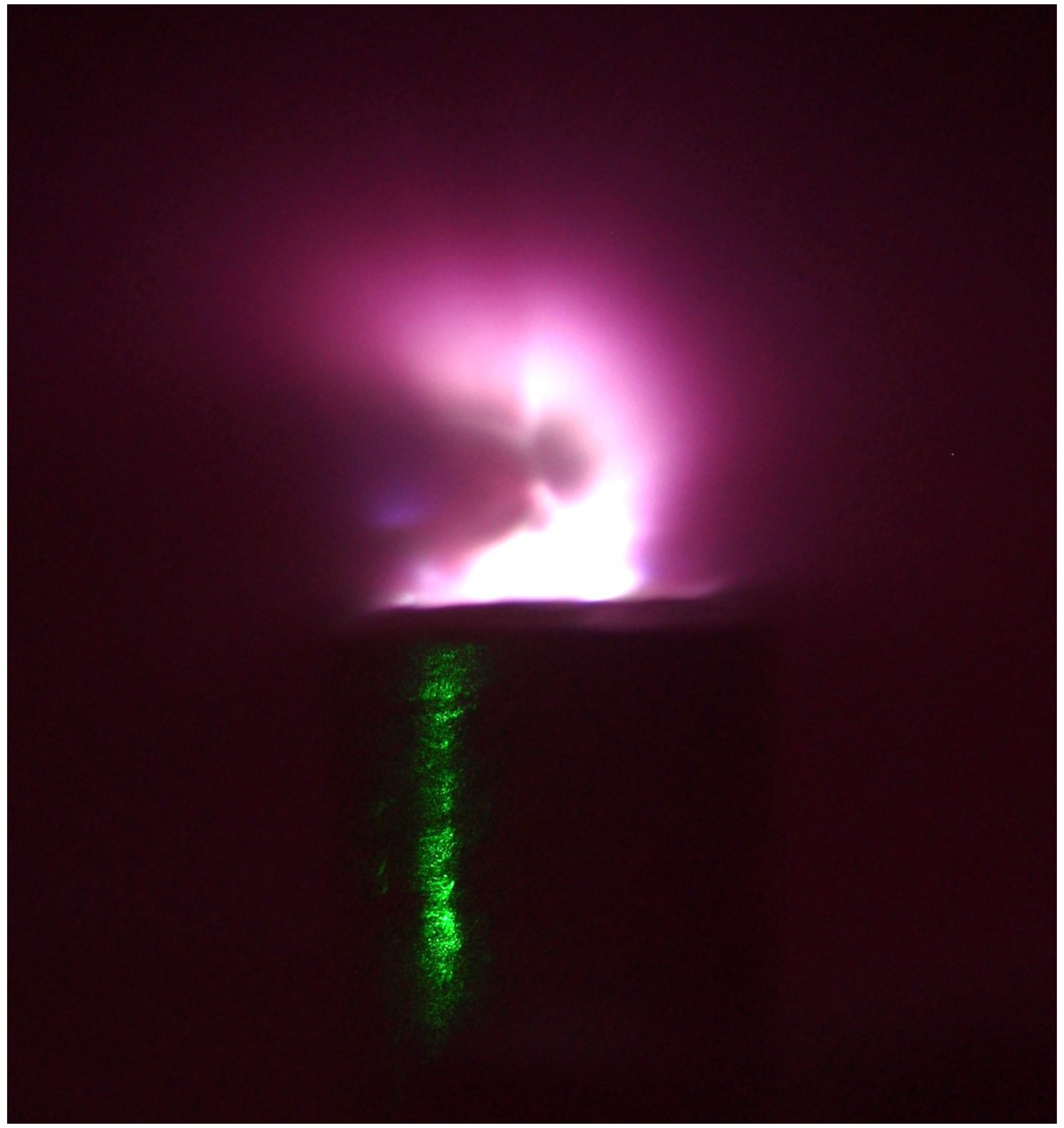
Ion Acceleration with the upgraded ATF laser - ID306044

Zulfikar Najmudin, Oliver Ettlinger, George Hicks
John Adams Institute for Accelerator Science, Imperial College London

Nick Dover
National Institutes for Quantum and Radiological Science and Technology, Kizugawa, Kyoto 619-0215, Japan

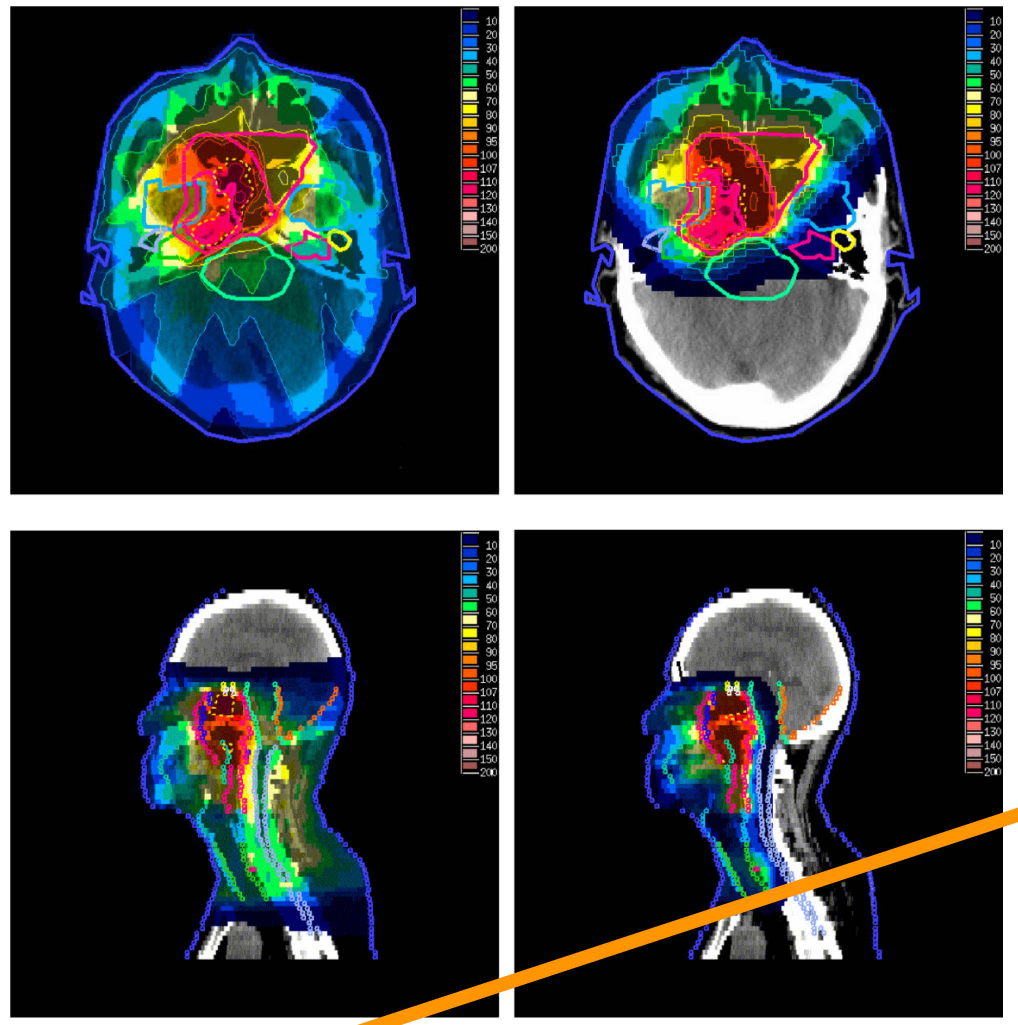
Charlotte Palmer
Department of Atomic and Laser Physics, University of Oxford, U.K.



ATF User Meeting 2019,
4th December 2019

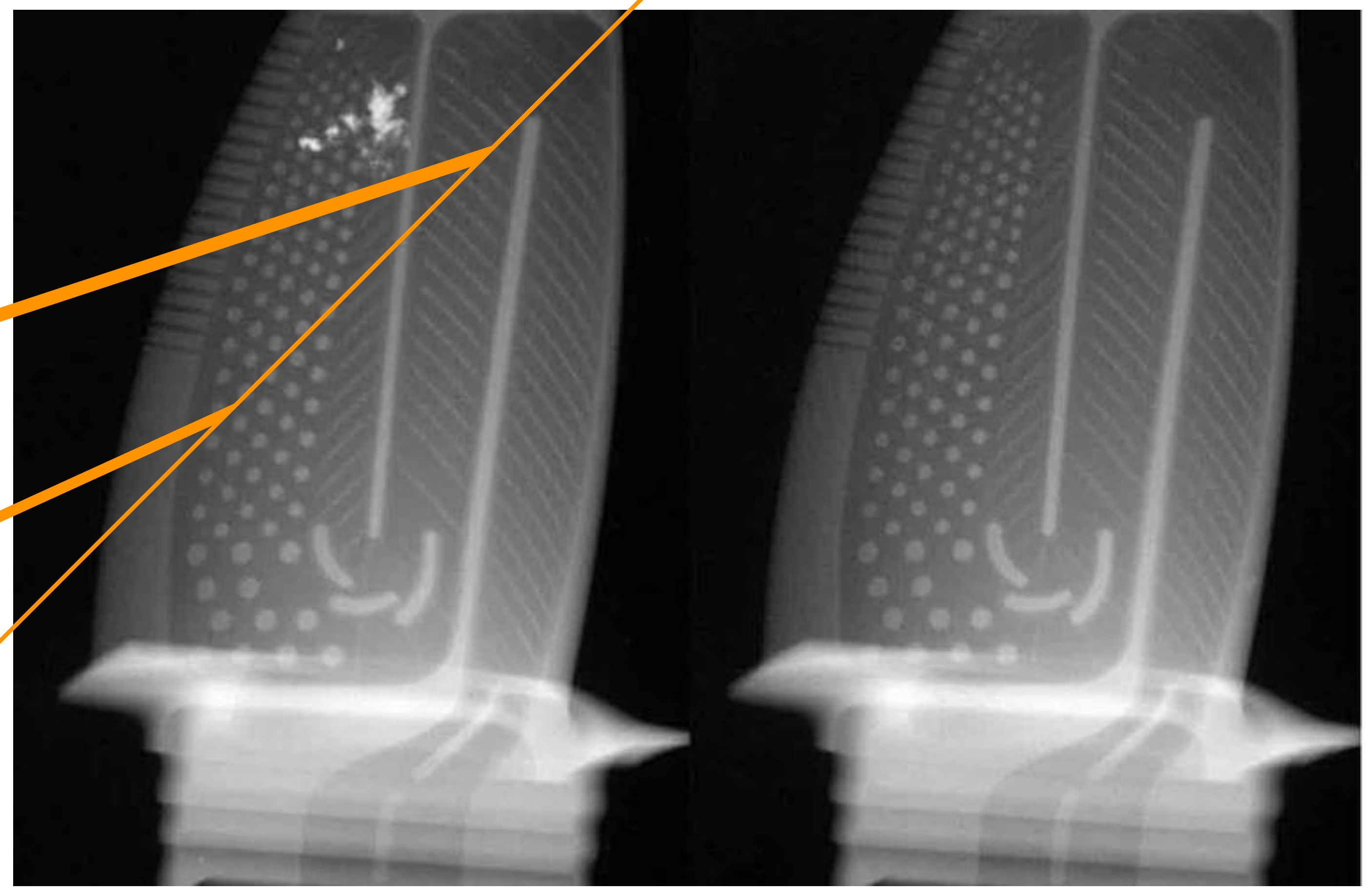
Some Motivation…

Protons/Carbon ions for particle therapy



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

Neutron production for industrial imaging



http://www.applus.com

- Also isochoric heating, proton radiography, medical isotope production, fast ignition, etc…

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The benefits of longer wavelengths?

Relativistic electron response scales favourably with laser wavelength

$$a_0 = \frac{eE_0}{m_e c} \cdot \frac{\lambda}{2\pi c}$$

Critical density of a plasma scales favourably with wavelength

$$n_c = \gamma \frac{\epsilon_0 m_e}{e^2} \cdot \frac{4\pi^2 c^2}{\lambda^2}$$

Other target requirements become relaxed - scale length

Easier to realise advanced acceleration schemes?

$$L_{opt} \sim \sqrt{\frac{I_L}{n_i^2}} \approx 1\mu m$$

Proposed Investigation

Four areas of primary interest:

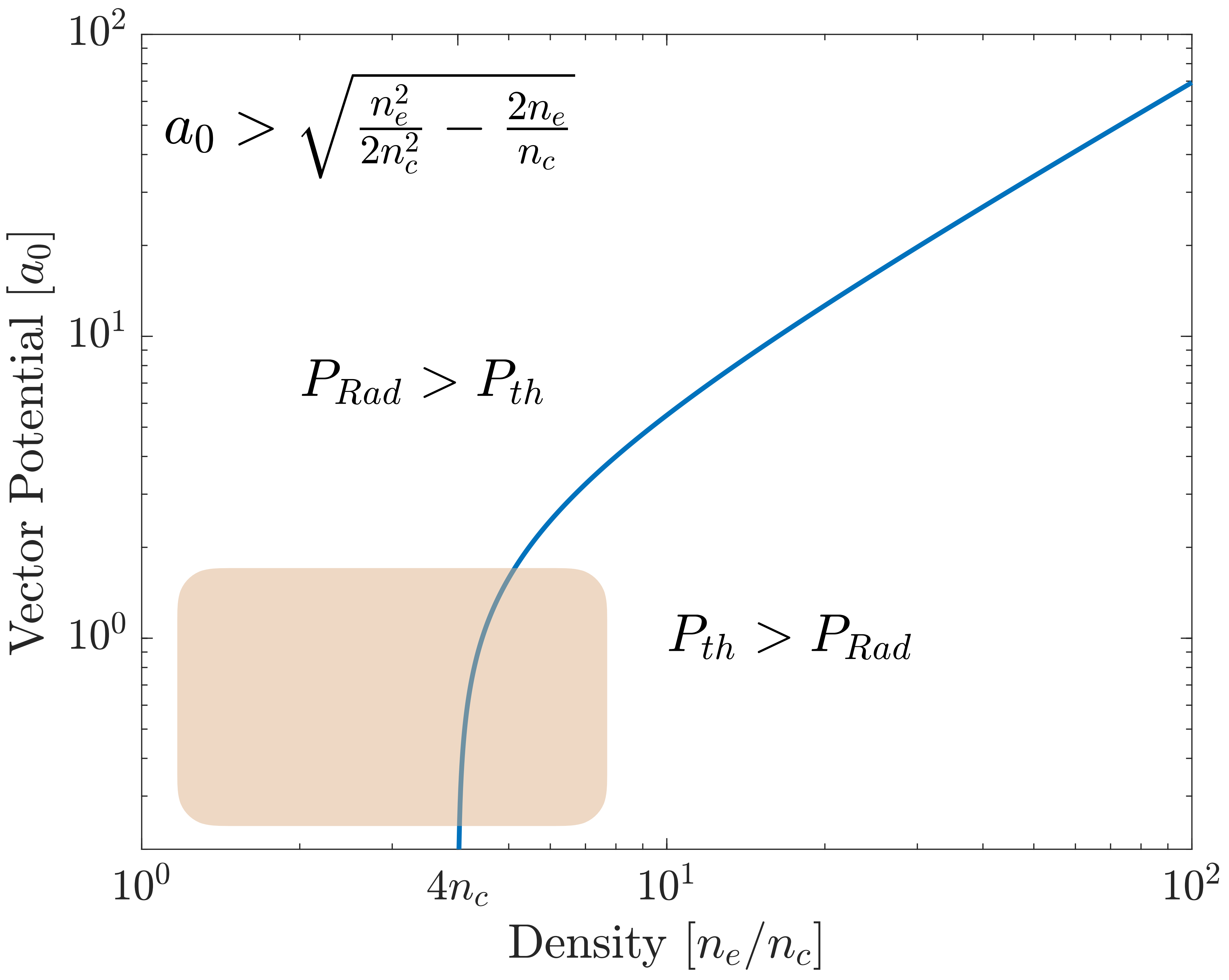
1. Polarisation control to optimise shock based acceleration
2. Scaling of HB-RPA to higher intensities
   i) pulse length effects
   ii) ion species
3. Fundamentals of collisionless shocks
4. Optical Imaging of shocks

Study polarisation effects

Balance between radiation pressure of laser and thermal plasma pressure determine ion acceleration regime and achievable performance - maximum ion energy, energy spread…

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

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

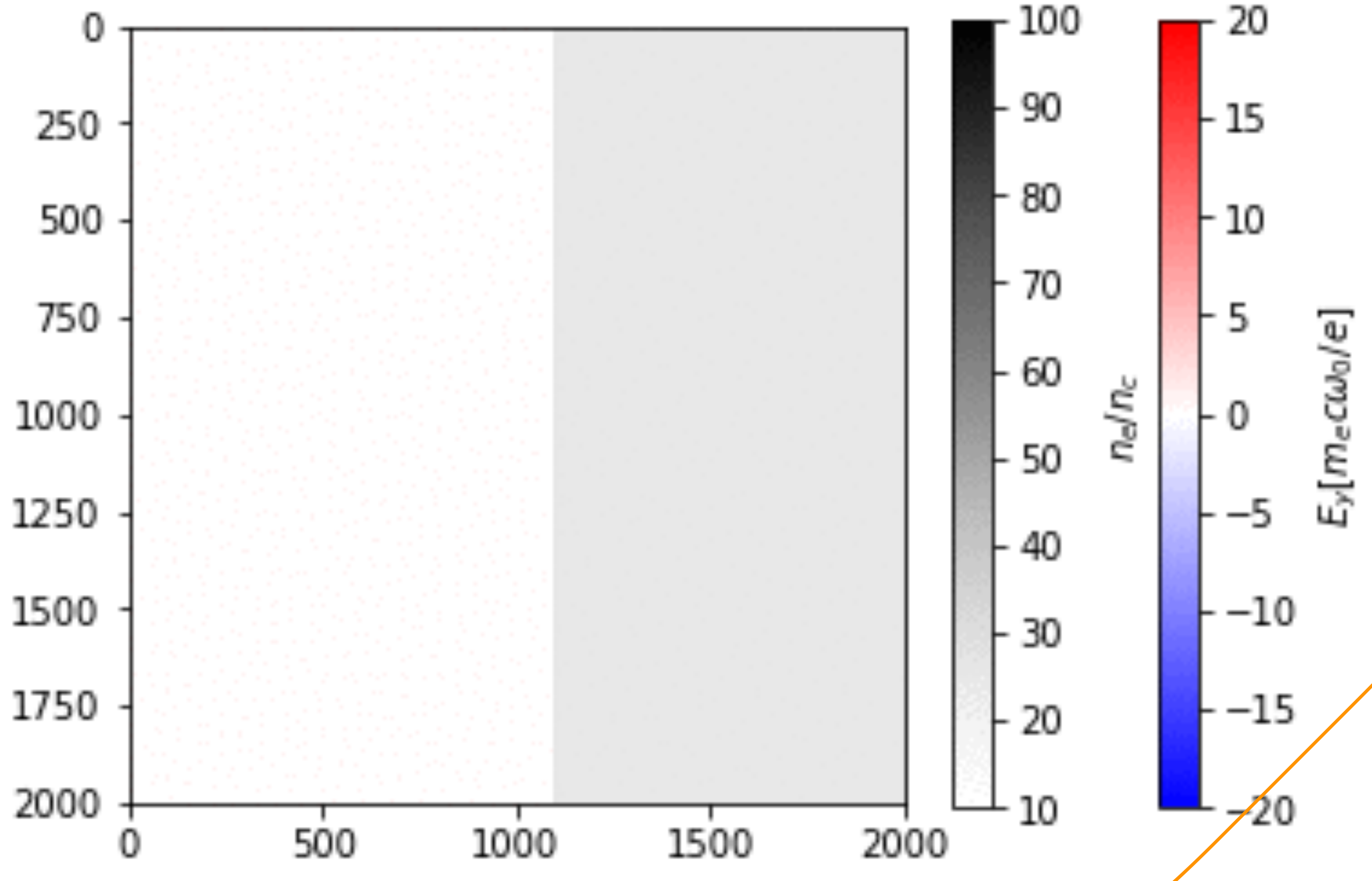


Study polarisation effects

Circular polarisation - Suppressed electron heating in the laser field

$$P_R \gg P_{Th}$$

Hole-boring dominant



Benefits of circular polarisation:

- Faster HB shock velocities and so higher proton energies - ~3MeV so far for linear polarisation
- lower energy spreads due to lower background temperature - few % best case so far

Study polarisation effects

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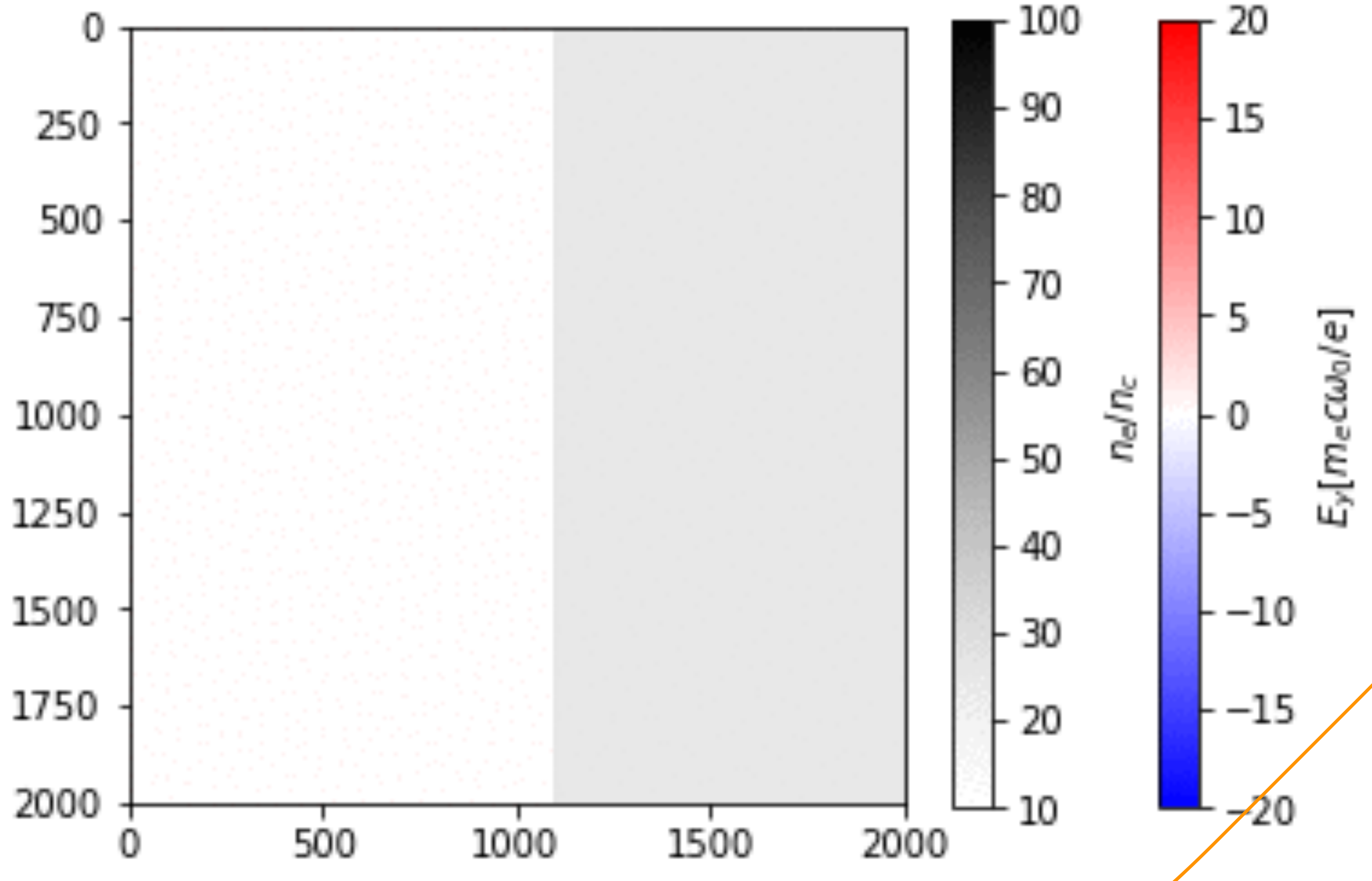
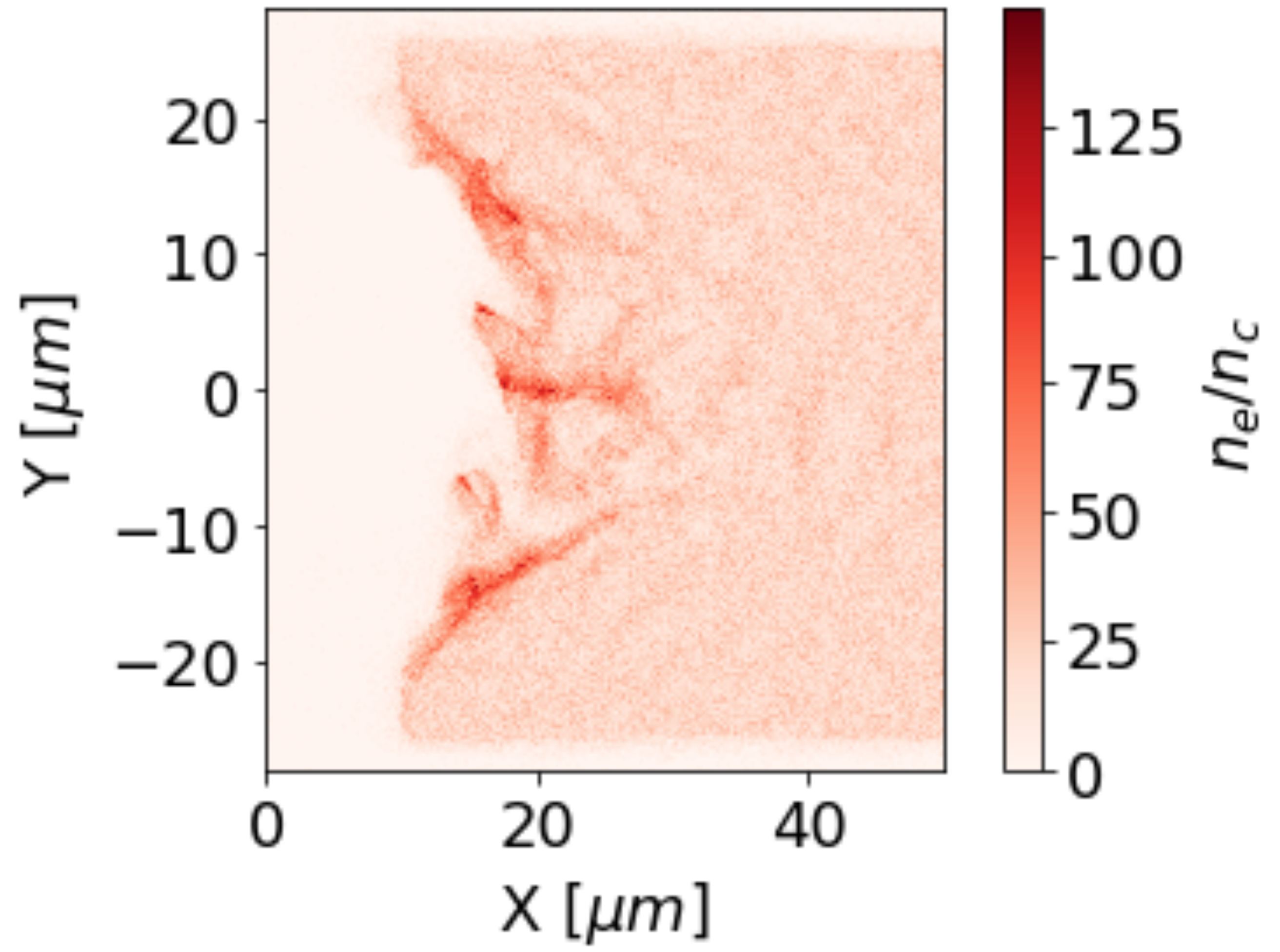
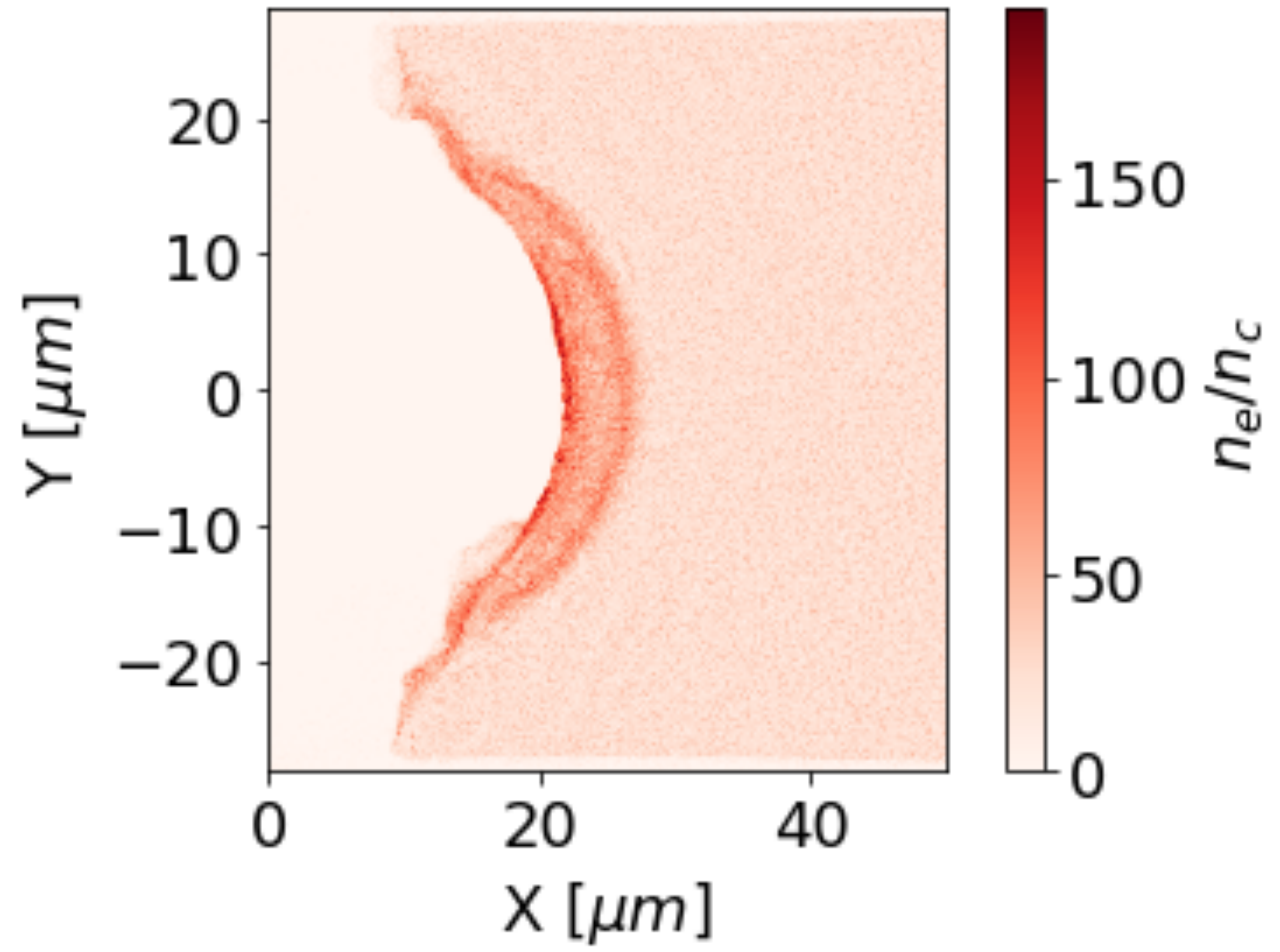


Linear



Circular



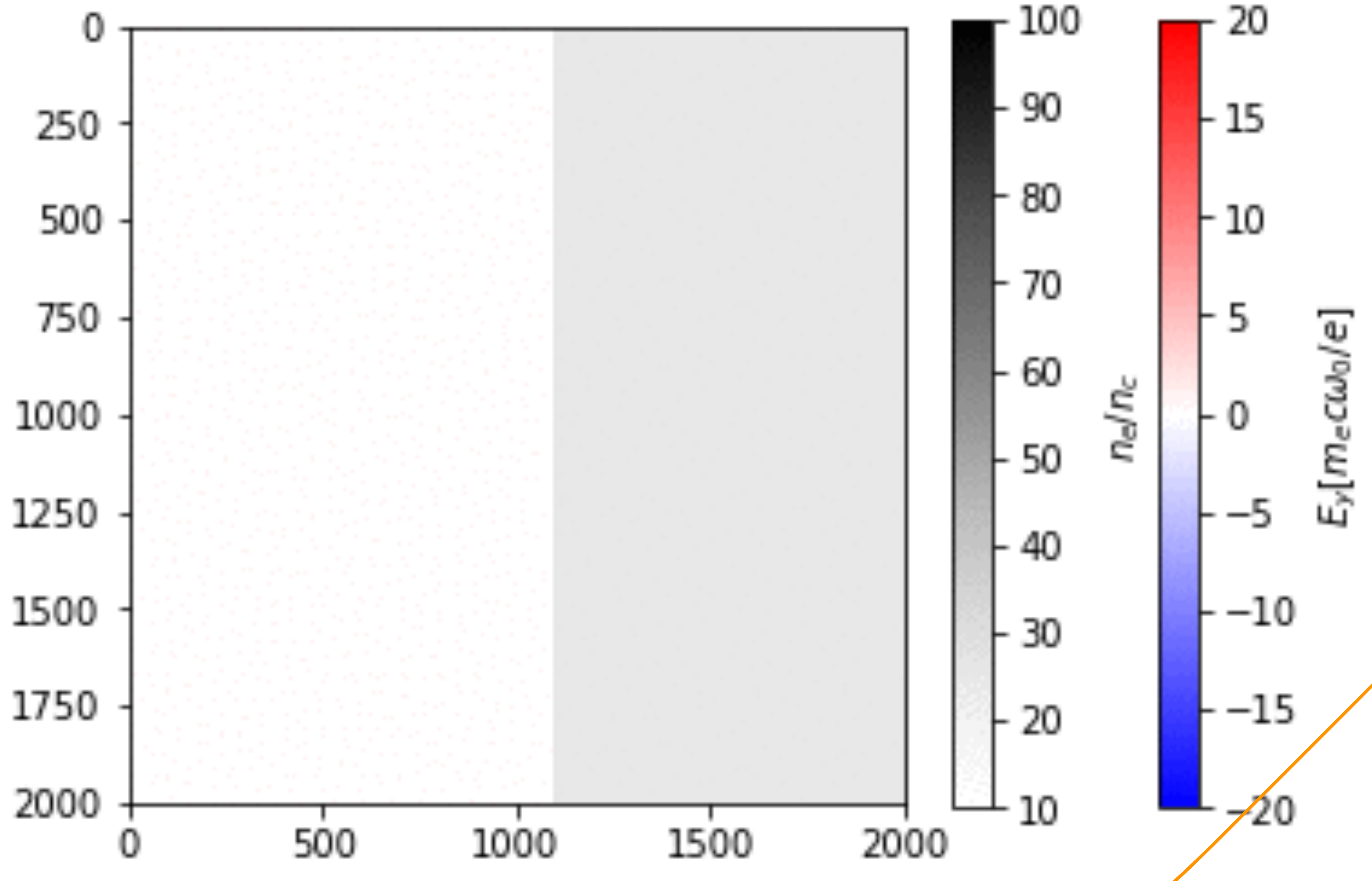
Improved shock conditions - better acceleration

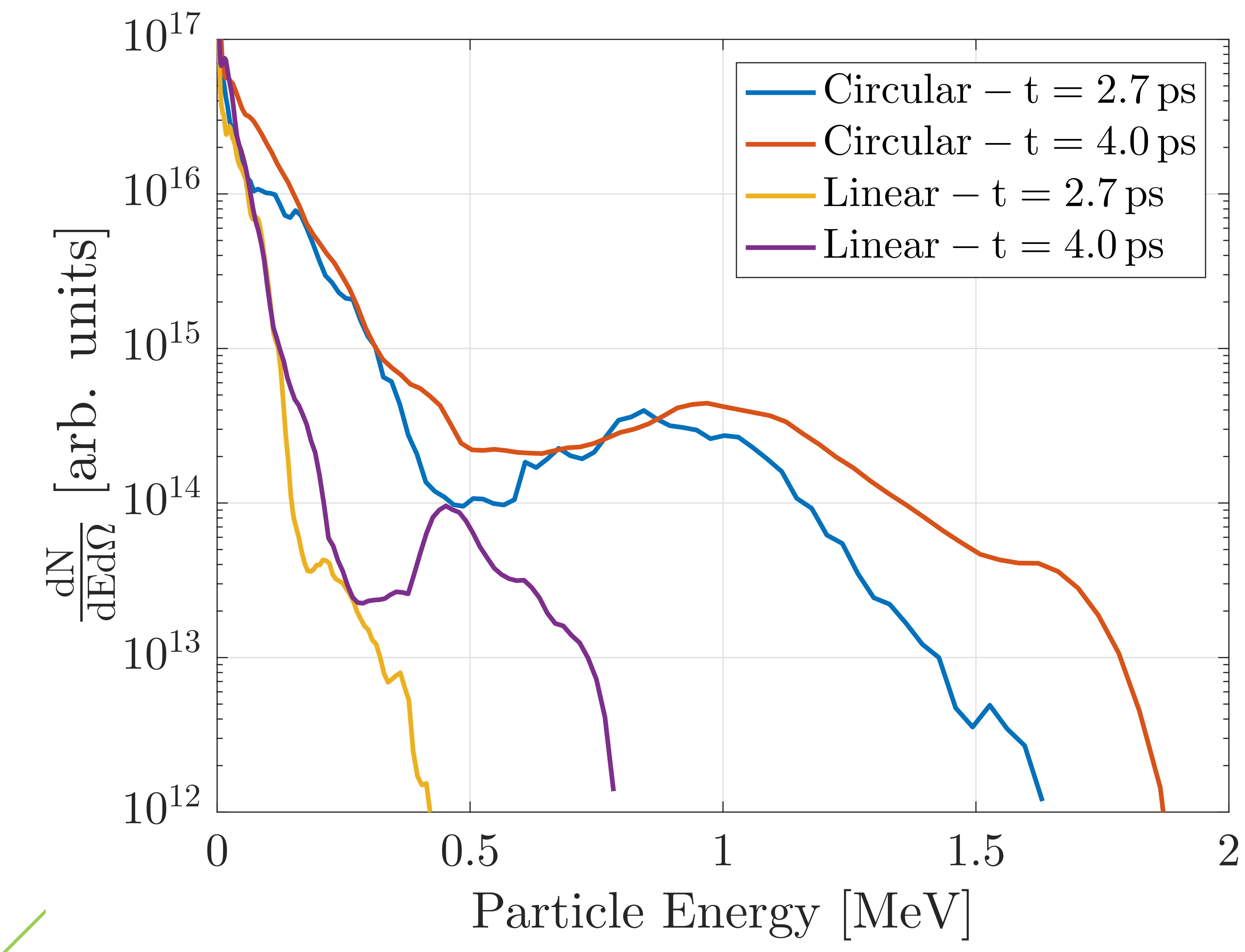
Study polarisation effects

Circular polarisation - Suppressed electron heating in the laser field

$$P_R \gg P_{Th}$$

Hole-boring dominant



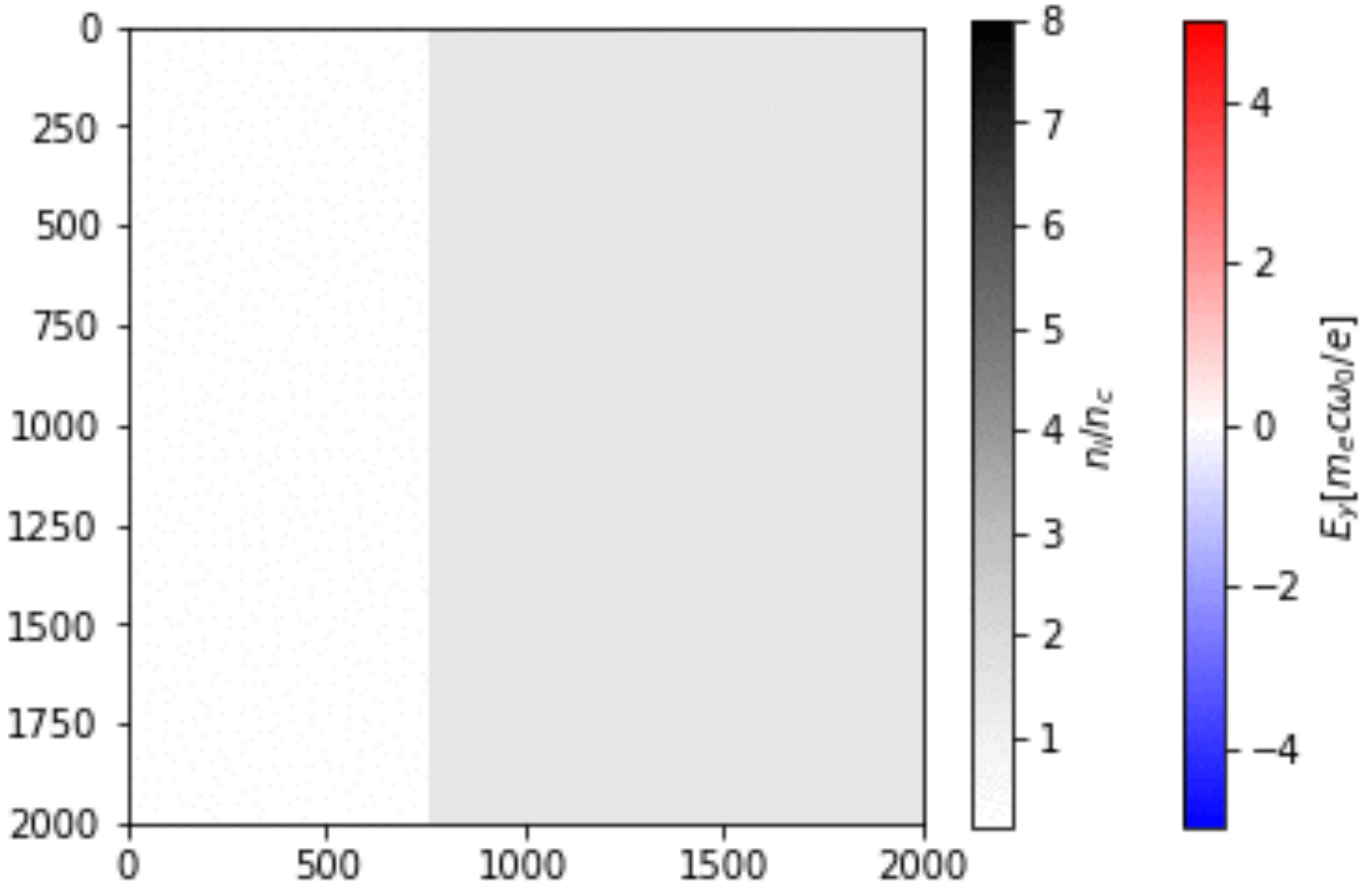


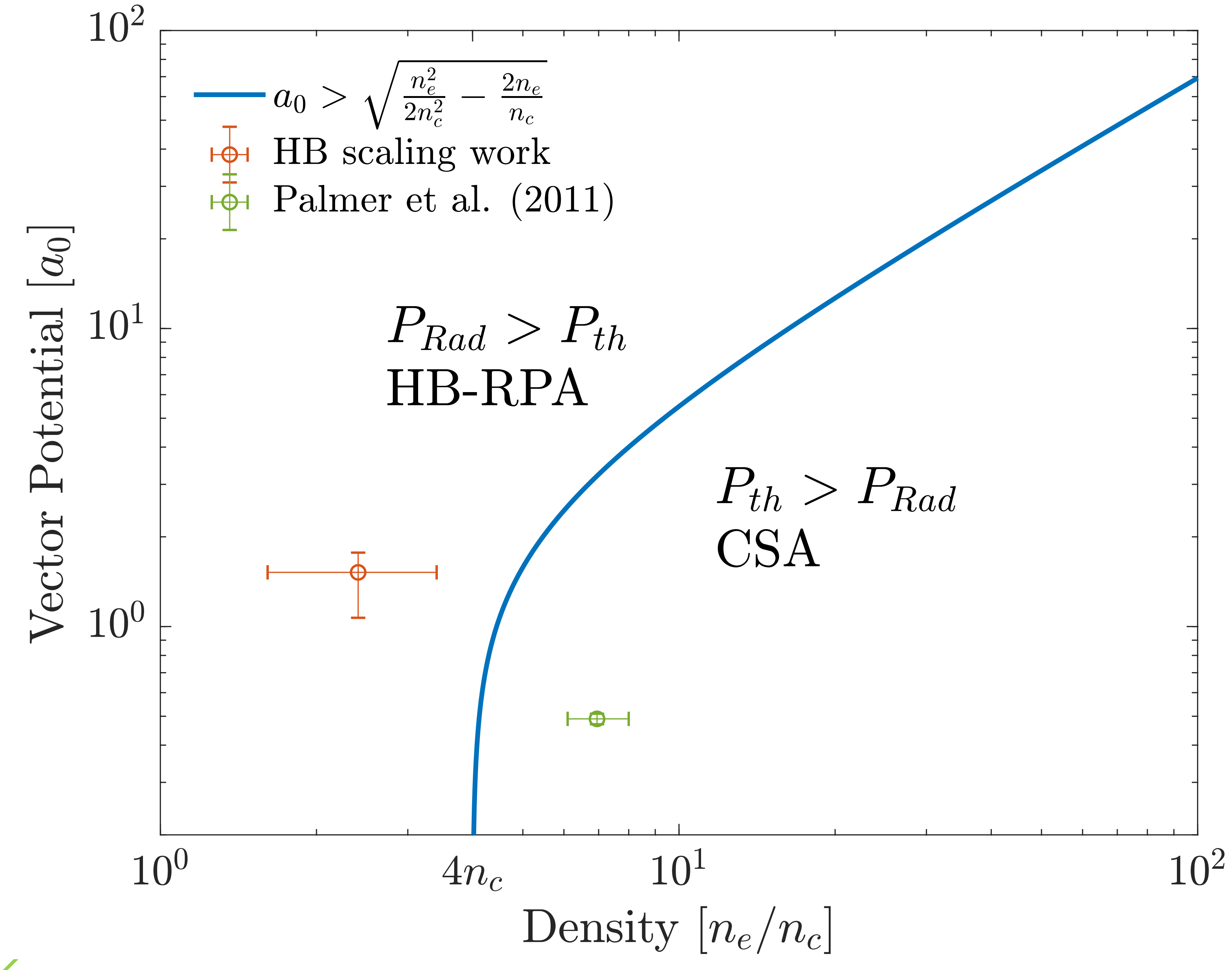
Improved proton energies for circular polarisation - 2x increase in certain conditions

Study polarisation effects

Linear polarisation - collisionless shock acceleration of ions

$$P_{Th} \gg P_R$$





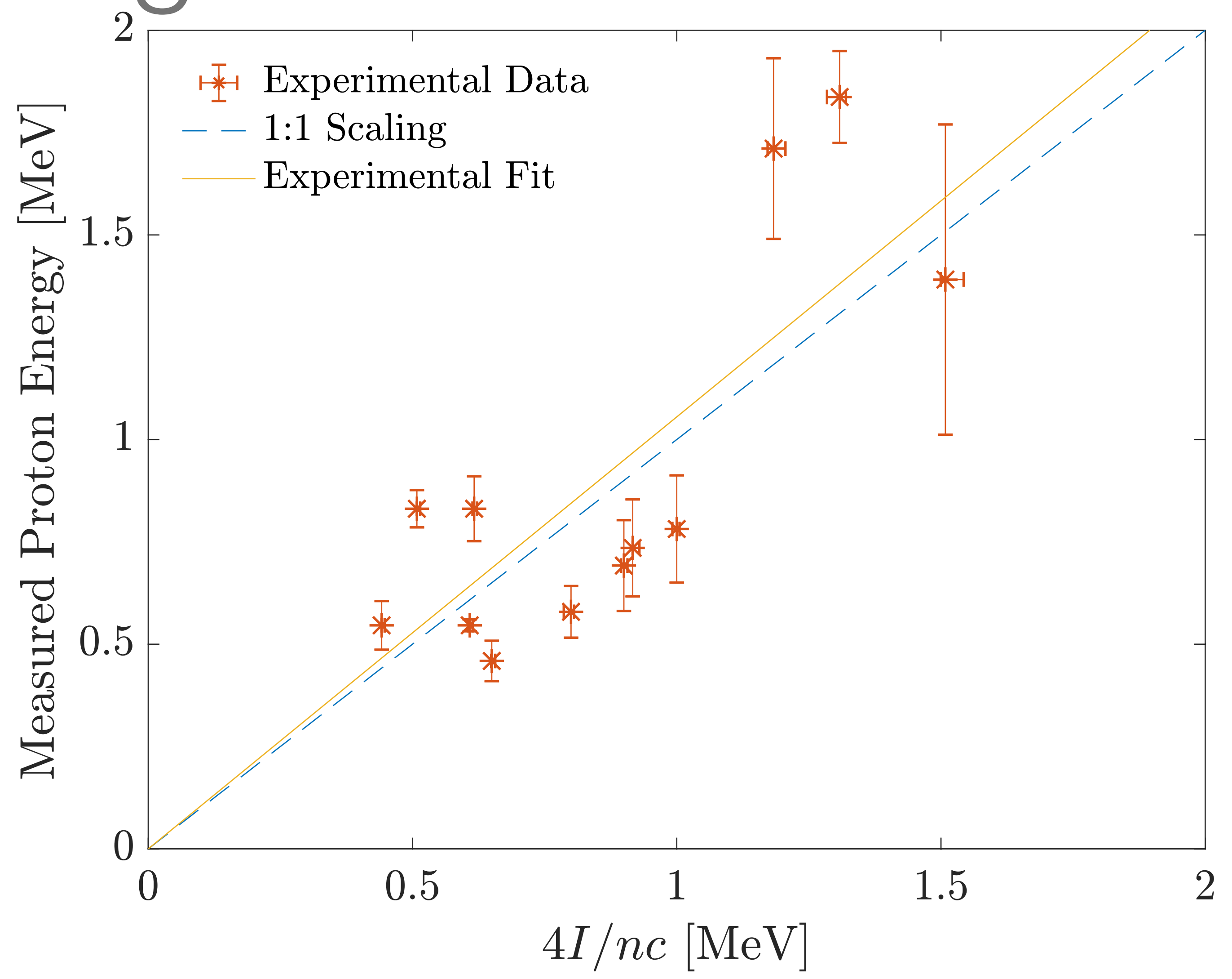
Still important work to understand CSA and the transition with HB regime - ATF uniquely positioned to study this

HB-RPA at higher intensities

Shock based acceleration schemes shown to scale with laser intensity - verified experimentally for $a_0 \sim 1$

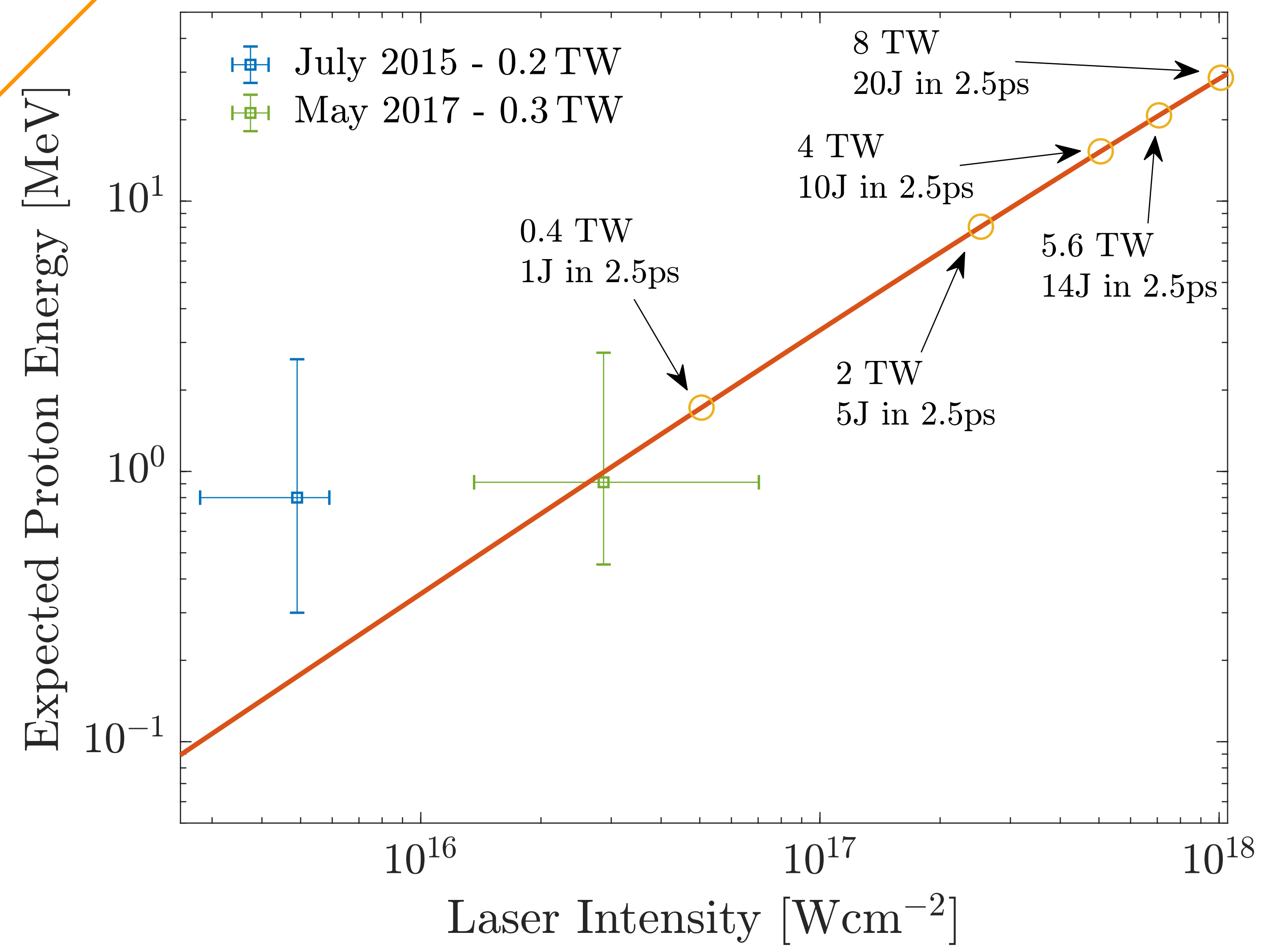
$$E_i = \frac{4I_L}{\gamma n_i c}$$

Previous work verifying HB scaling



*In preparation

Projected up to 10MeV and beyond



Increased Laser Powers

Shock based acceleration schemes shown to scale with laser intensity - verified experimentally for $a_0 \sim 1$

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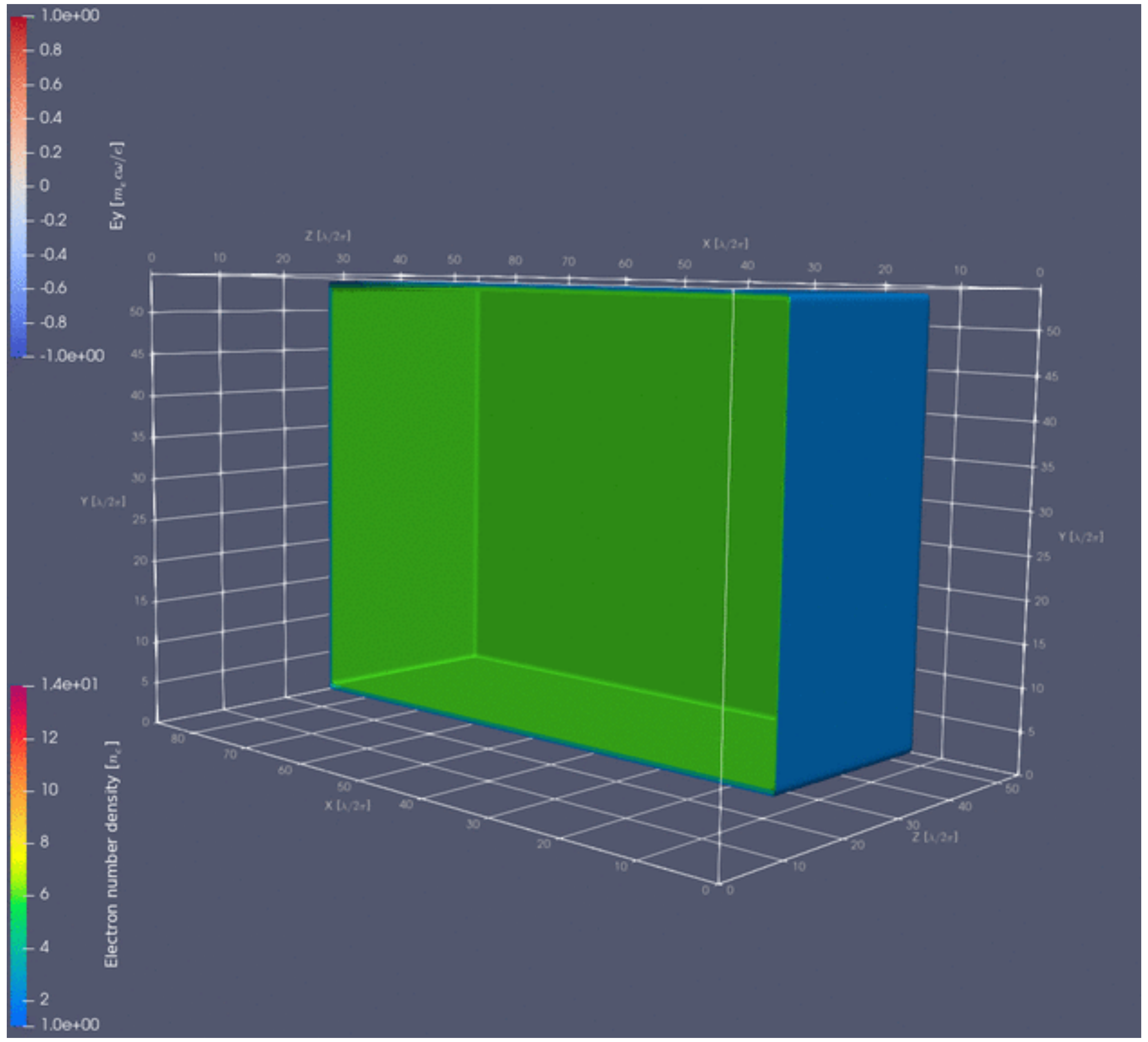
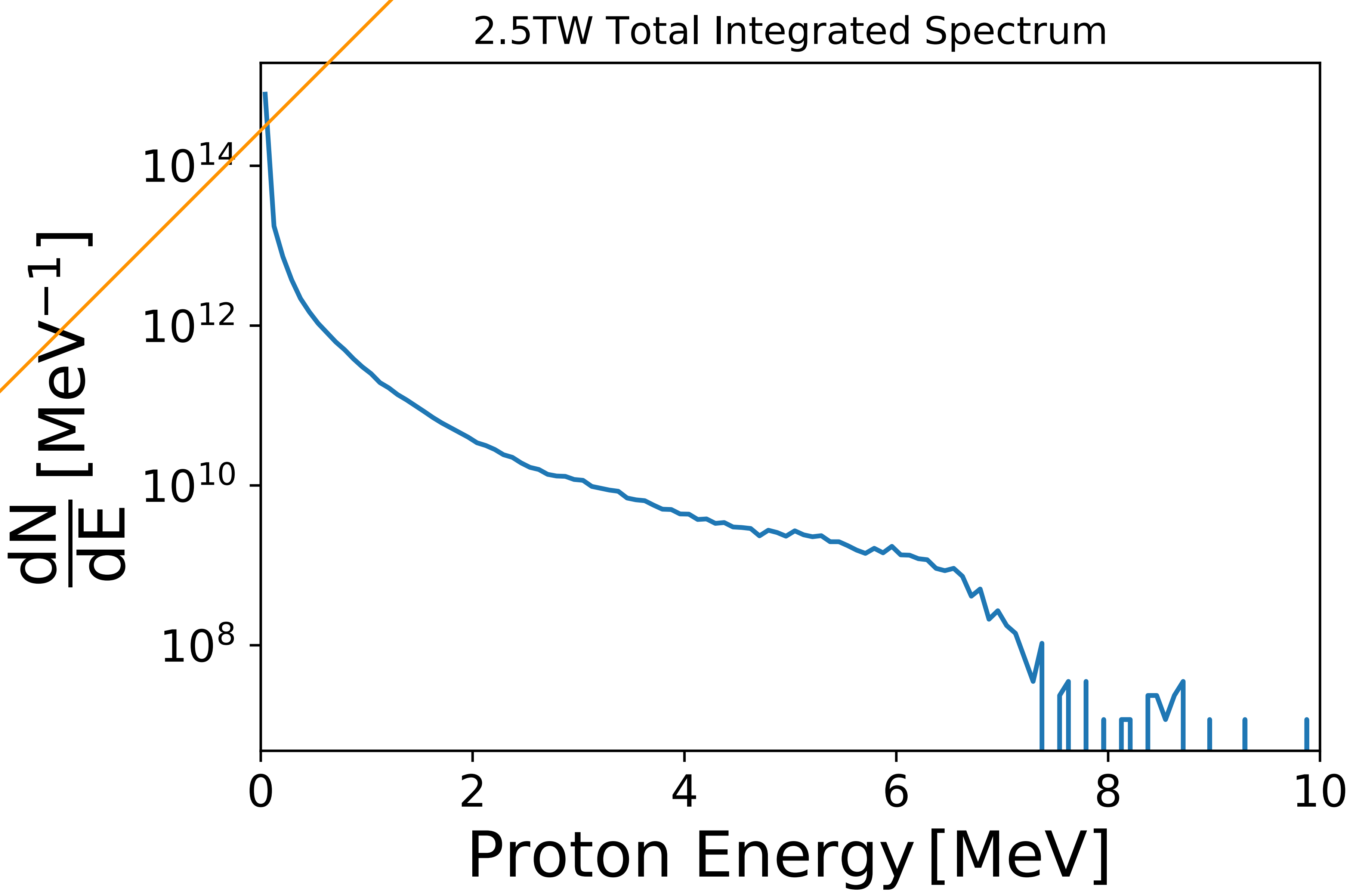


2.5TW Integrated Spectrum



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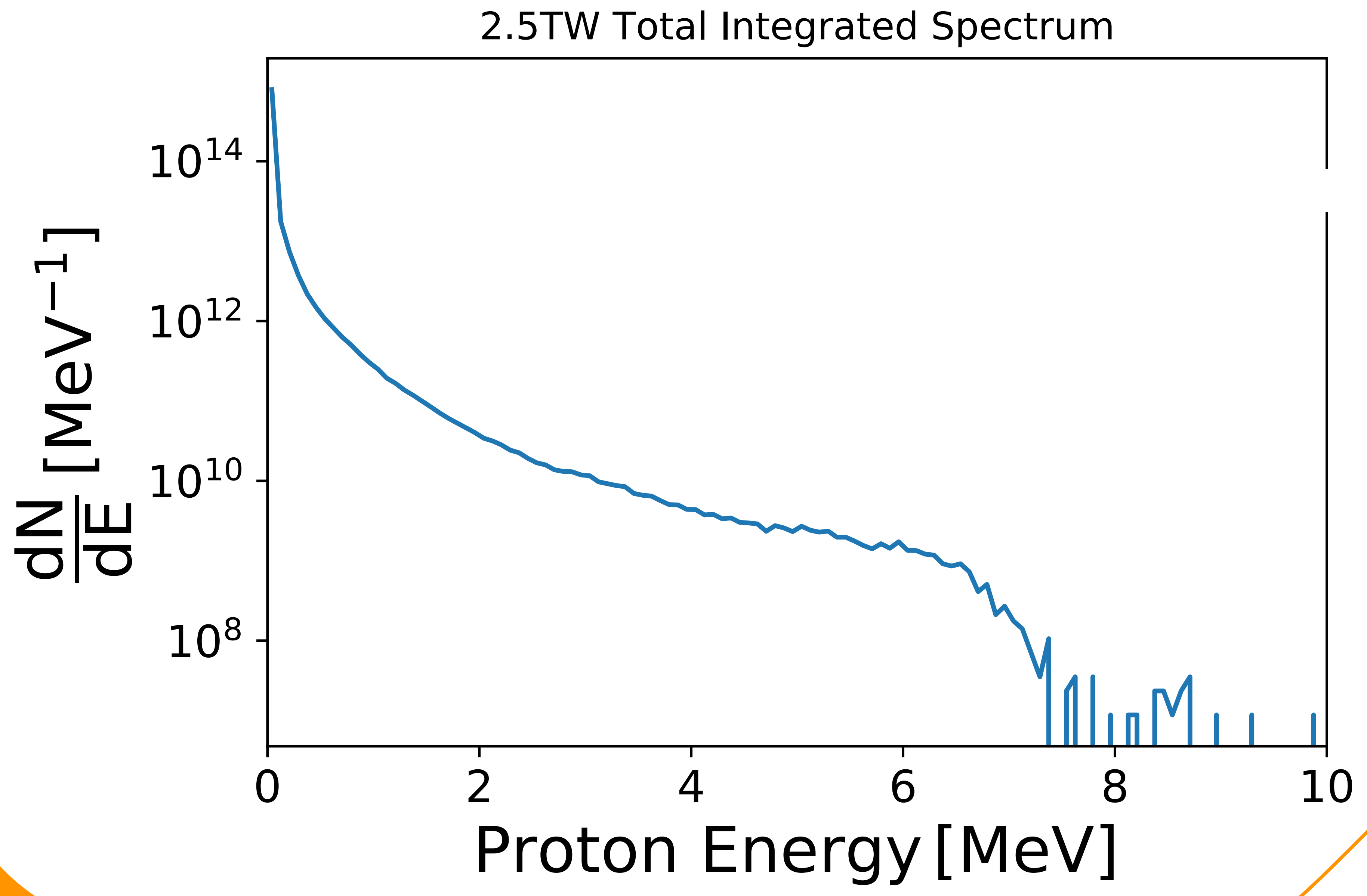
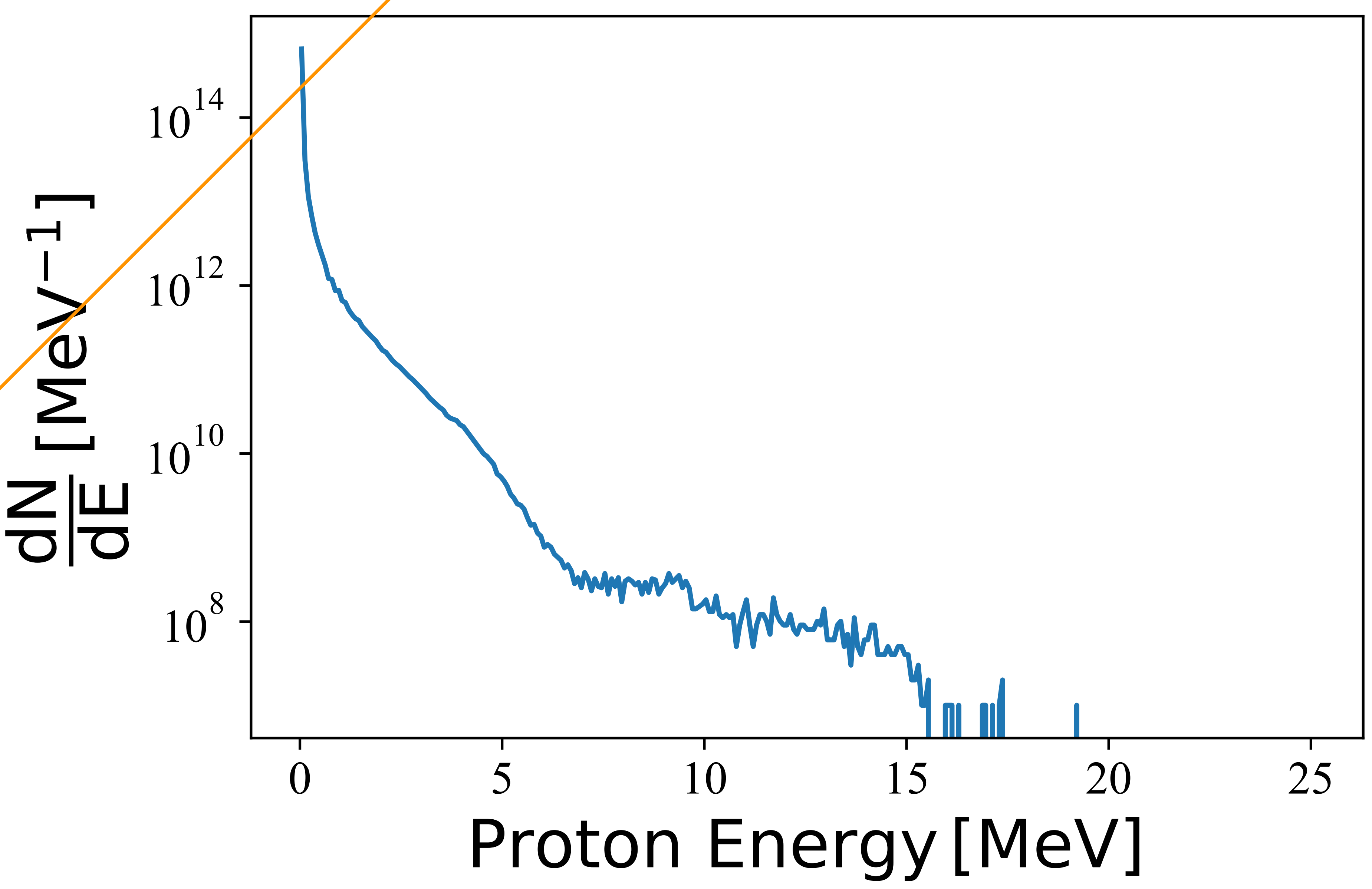
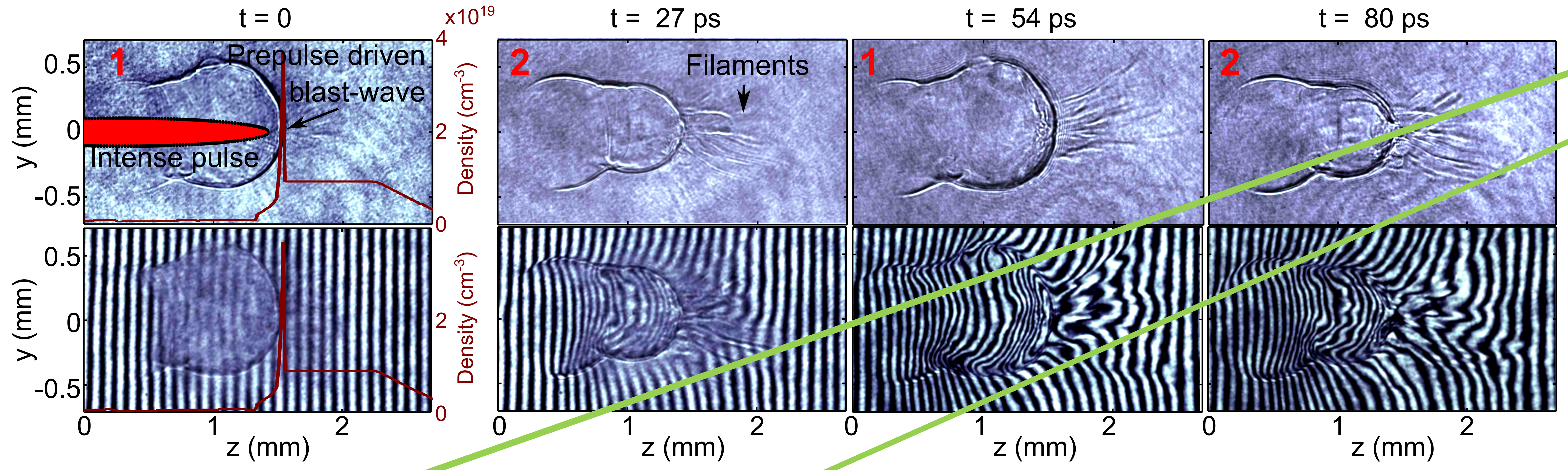


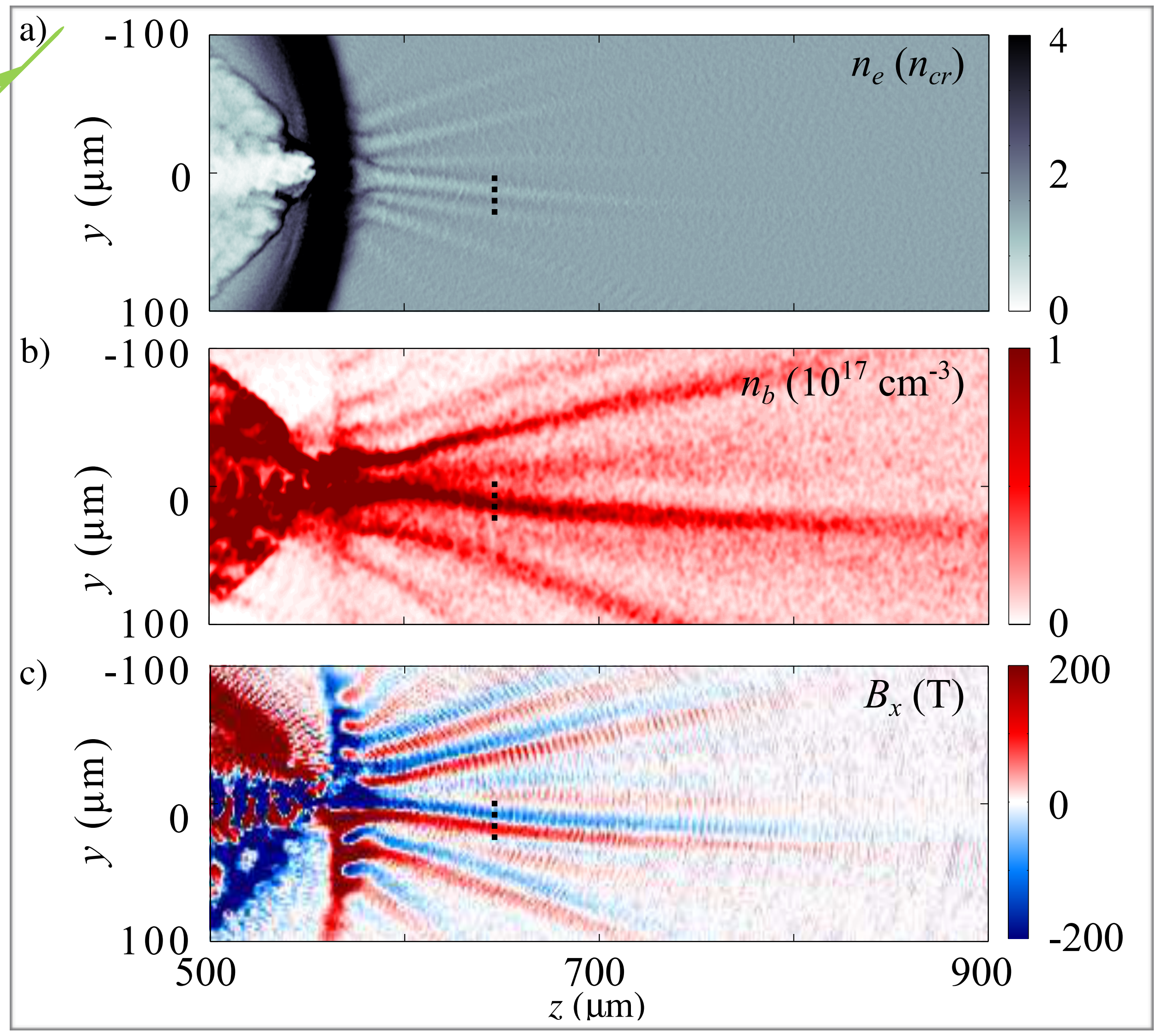
5TW Integrated Spectrum



Other fundamental studies

Interesting outcome from previous experiments - electron filamentation instability





*Courtesy N. Dover. In preparation

Higher laser powers offer study of electron heating and the instability over wider range of parameter space

Observation of shocks

All of these studies require a short pulse probe beam for imaging these interactions, present and future

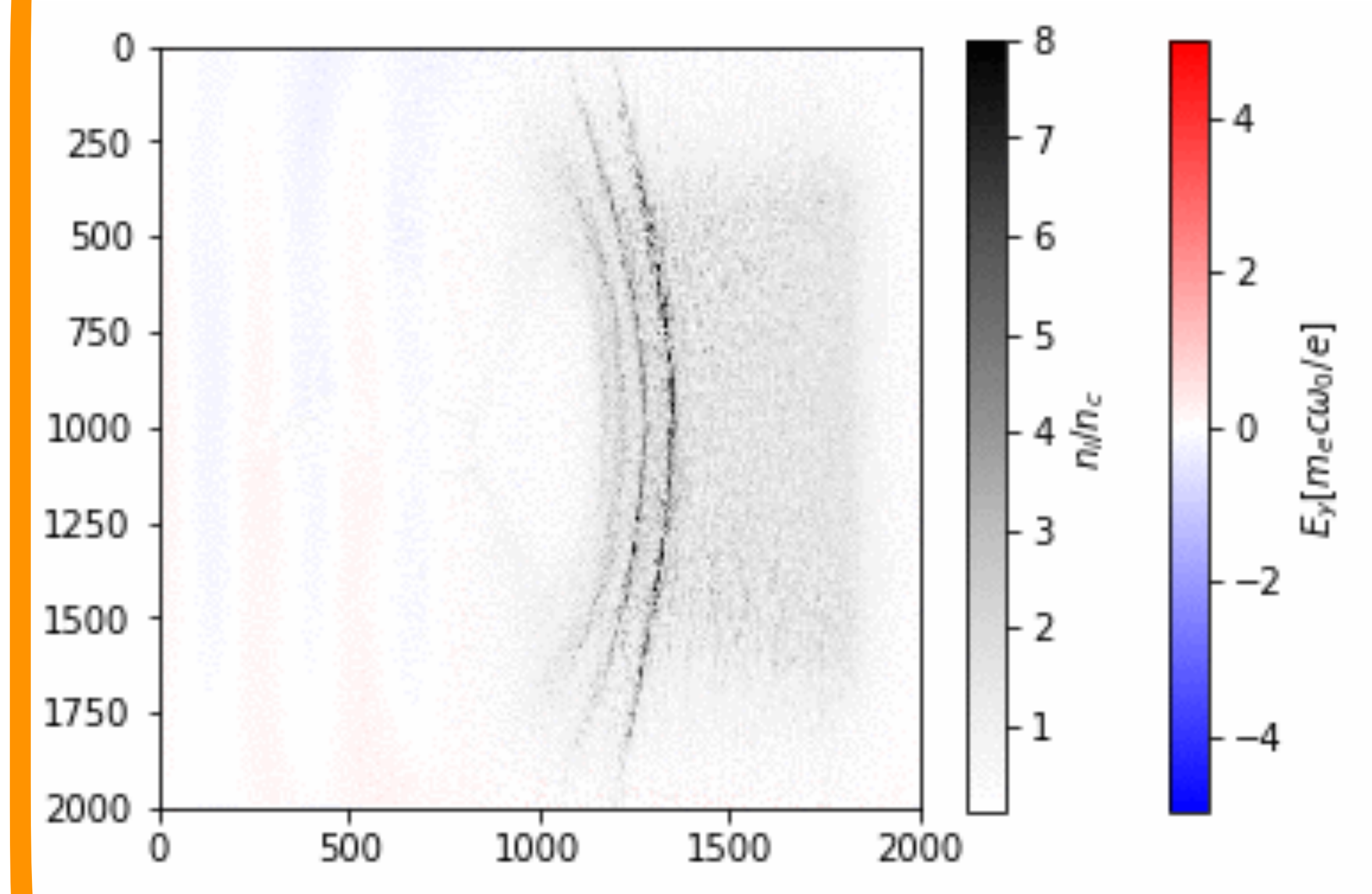
One of the main attractions of CO_2 interactions is the ability to probe due to the critical density scaling

$$n_c = \gamma \frac{\epsilon_0 m_e}{e^2} \cdot \frac{4\pi^2 c^2}{\lambda^2}$$

Everything previously integrated over entire interaction, limiting effectiveness - conditions have to be inferred in other ways

Observation of shocks

All of these studies require a short pulse probe beam for imaging these interactions, present and future



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

—> sub 100fs probe needed

ATF conditions uniquely suited to imaging these accelerating shock structures

- HB still never optically probed

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	μm	9.2		*(used for blast wave studies)*
CO_2 CPA Beam	Wavelength	μm	9.2	*Wavelength determined by mixed isotope gain media*	√
	Peak Power	TW	2	*~5 TW operation is planned for FY21 (requires further in-vacuum transport upgrade). A 3-year development effort to achieve >10 TW in progress.*	*Experiments at both 5 TW and then at 10 TW*
	Pulse Mode	---	Single		√
	Pulse Length	ps	2		√ *(or longer)*
	Pulse Energy	J	~5	*Maximum pulse energies of >10 J will become available in FY20*	√ *(or more)*
	M^2	---	~2		√ *(or better)*
	Repetition Rate	Hz	0.05		√
	Polarization		Linear	*Adjustable linear polarization along with circular polarization will become available in FY20*	*LP and CP required*

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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*	*(as backup)*
Energy	mJ	5		
Pulse Width	ps	14		
Wavelength	nm	532	*Frequency doubled*	
Energy	mJ	0.5		
Pulse Width	ps	10		

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Special Equipment Requirements and Hazards

- Electron Beam N/A
- CO_2 Laser
  - Please note any specialty laser configurations required here:
    - Controllable pre-pulse required - already successfully implemented
    - Uncompressed CO_2 - bypass compressor?
- Ti:Sapphire and Nd:YAG Lasers
  - Please note any specialty non-CO_2 laser configurations required here:
    - Ti:sapphire required for probing at <100fs
- Hazards & Special Installation Requirements N/A

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Experimental Time Request

CY2020 Time Request

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

* Dependent on experiment using current location in FEL room

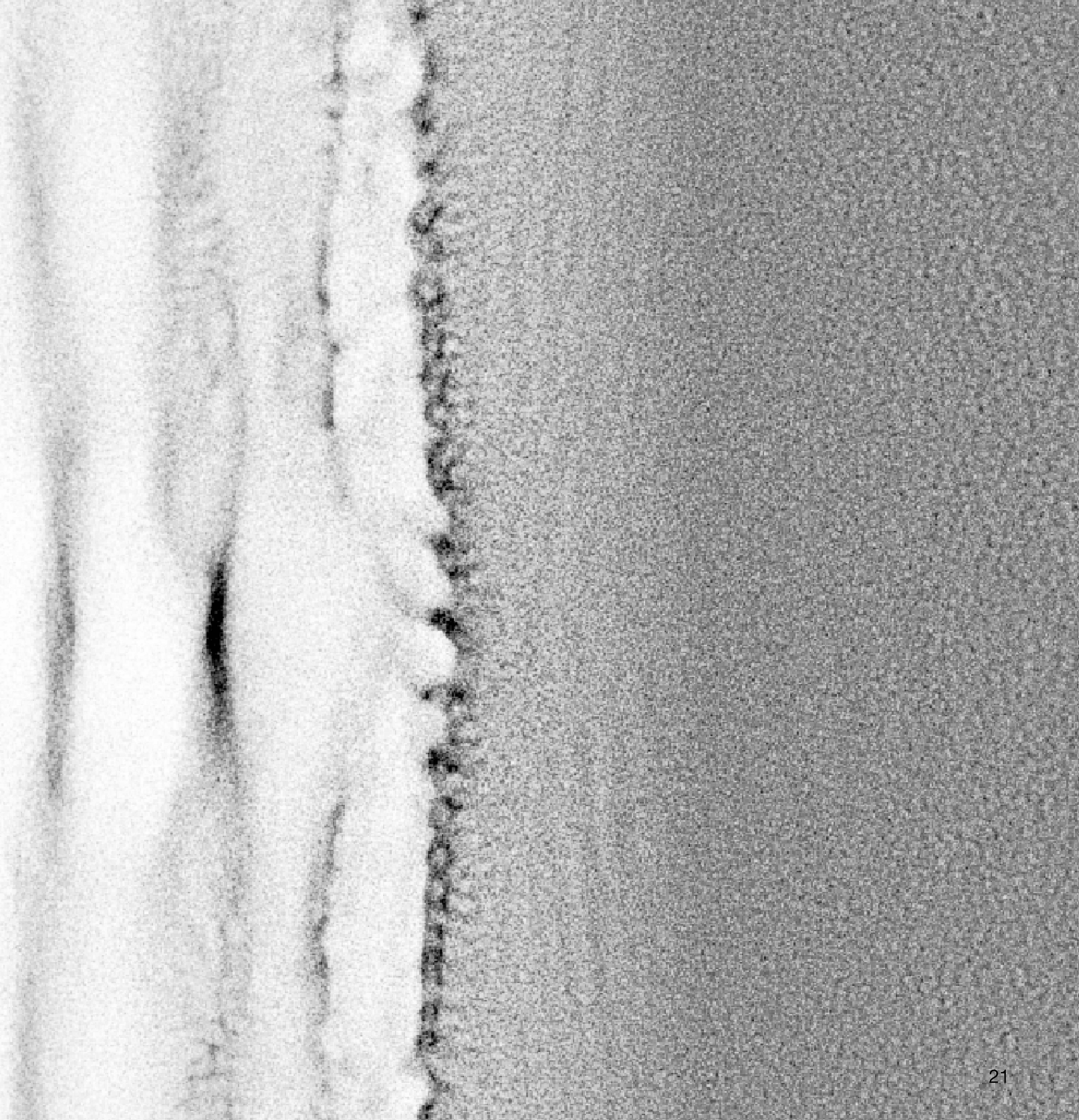
Time Estimate for Full 3-year Experiment (including CY2020)

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

Summary - ID306044 Proposal

- Proposal to continue on from work in AE66 experiment, with new, improved laser conditions
- Study the fundamentals of shock acceleration of ions in a higher intensity regime, for $a_0 > 1$, which the ATF is uniquely suited to do
- (Finally) optically probe these interactions for the first time



Thank you for listening.
Questions?