AE100 - The study of high-intensity laser pulse interactions with near-critical density plasmas

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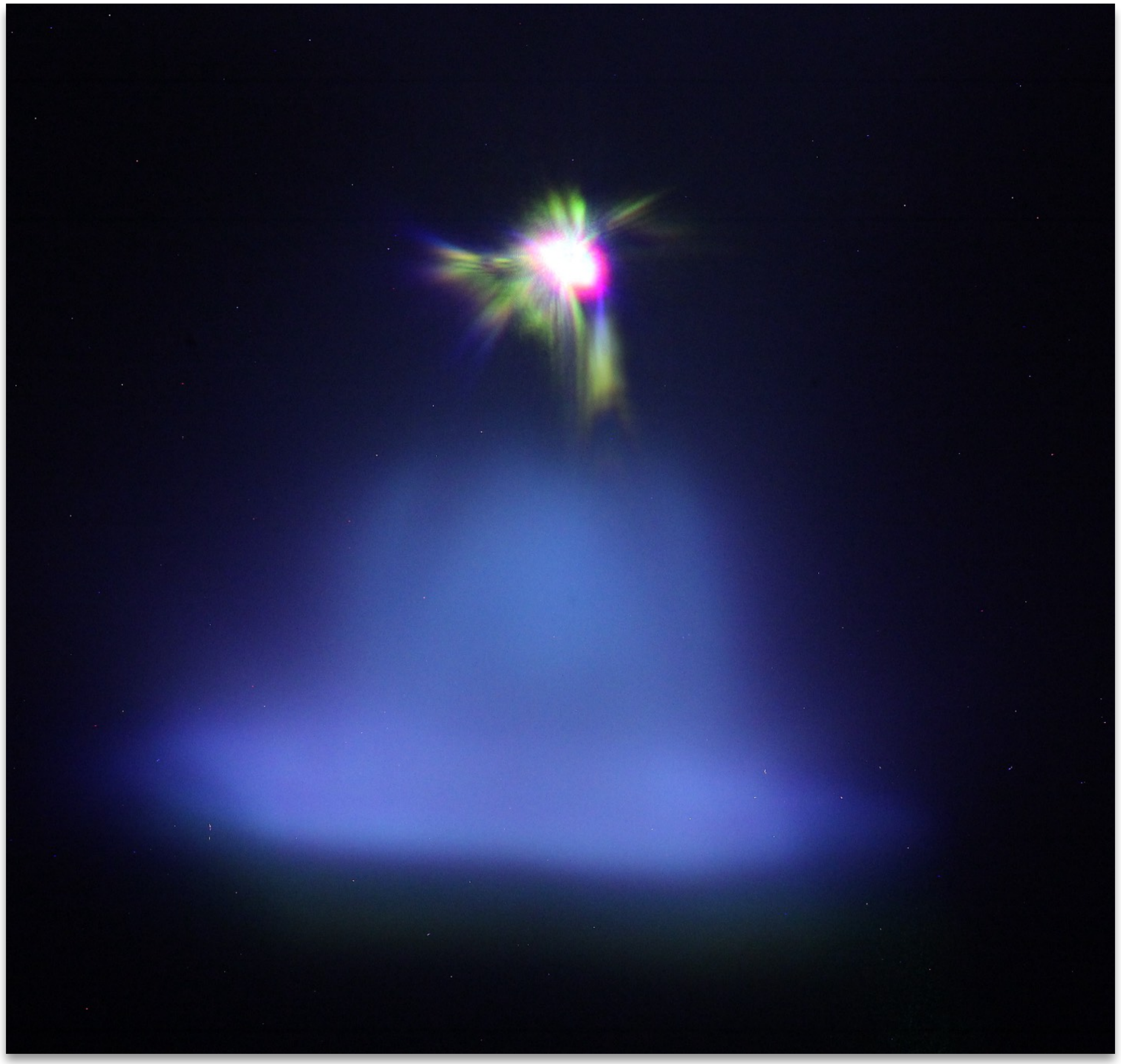
ATF User Meeting 2023,

1st March 2023

Active Funding: STFC ST/V001639/1

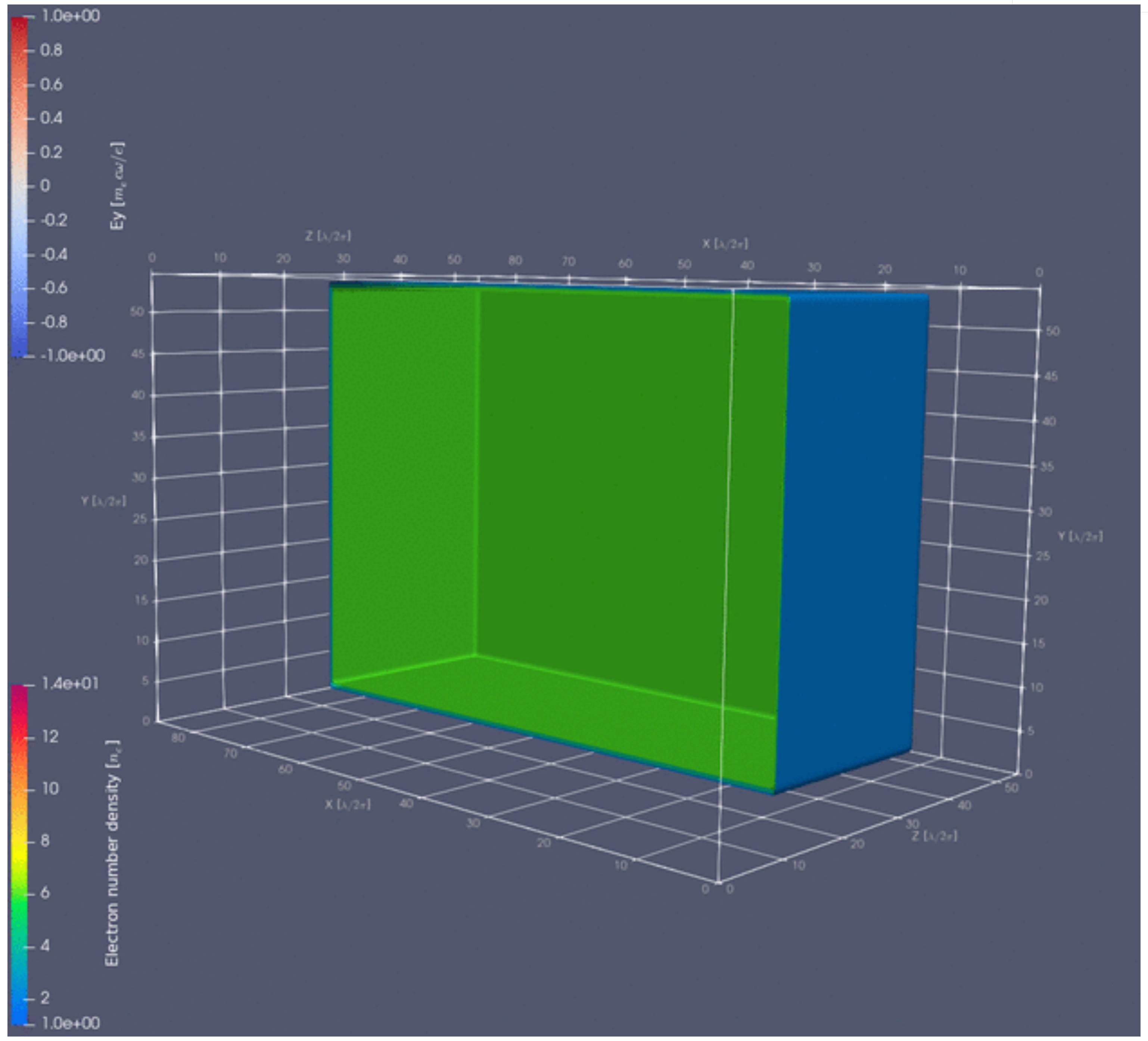
Recent Funding: EPSRC EP/N018680/1, EU Horizon 2020 No 894679

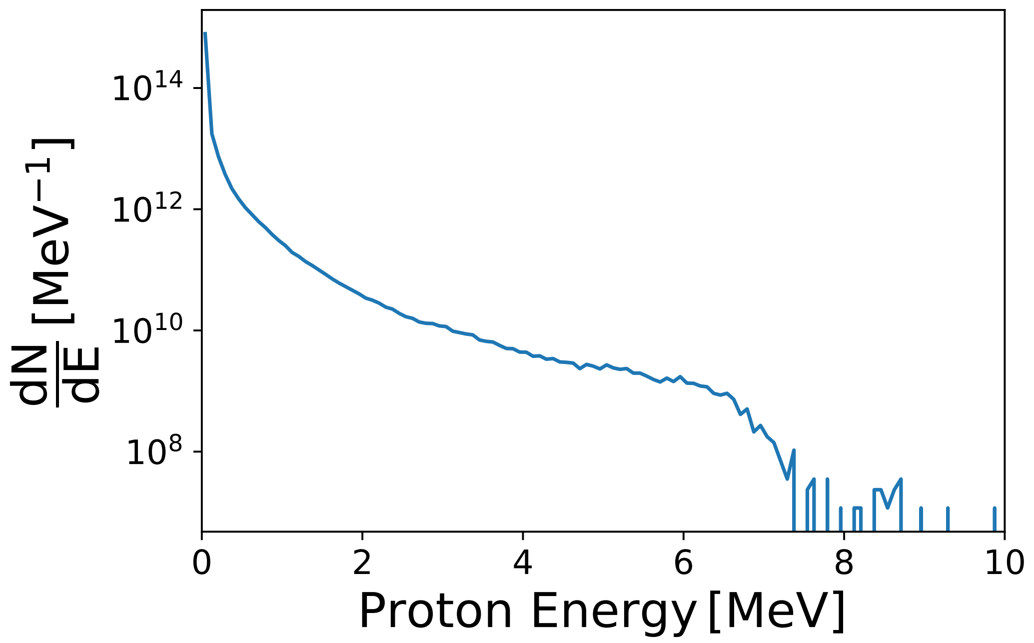


Experimental goals

Main proposal objectives for AE100

- Scaling of hole boring acceleration to higher intensities and shorter laser pulses
- Polarisation control of laser to critical density plasma coupling
- Direct observation of collisionless shocks
- Fundamentals of collisionless shocks and related laser-plasma interaction

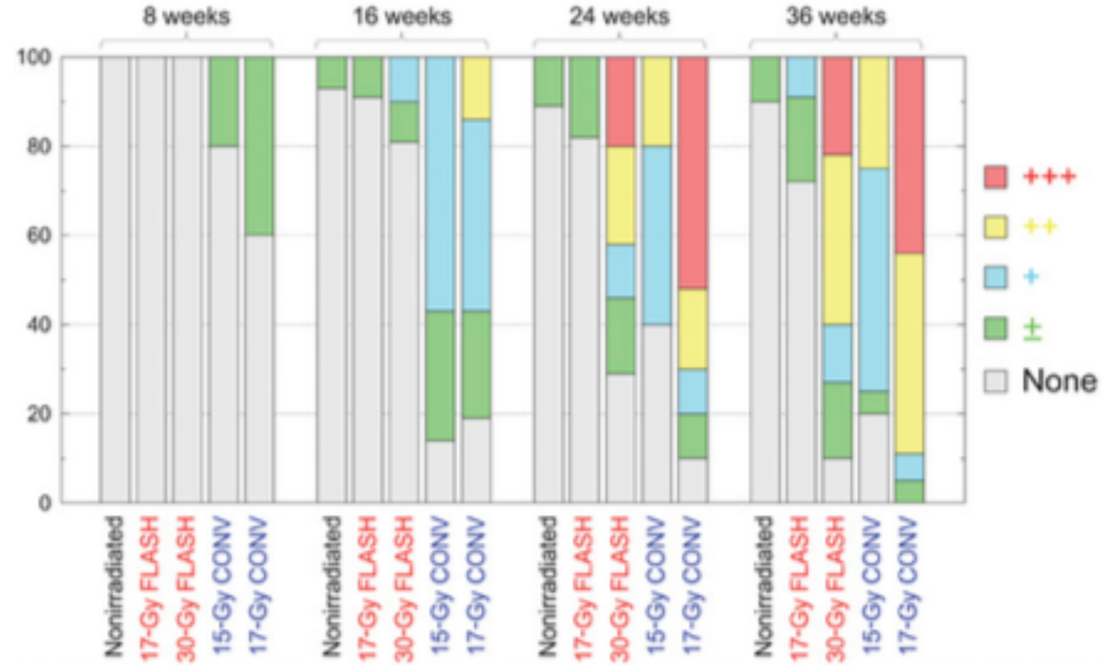


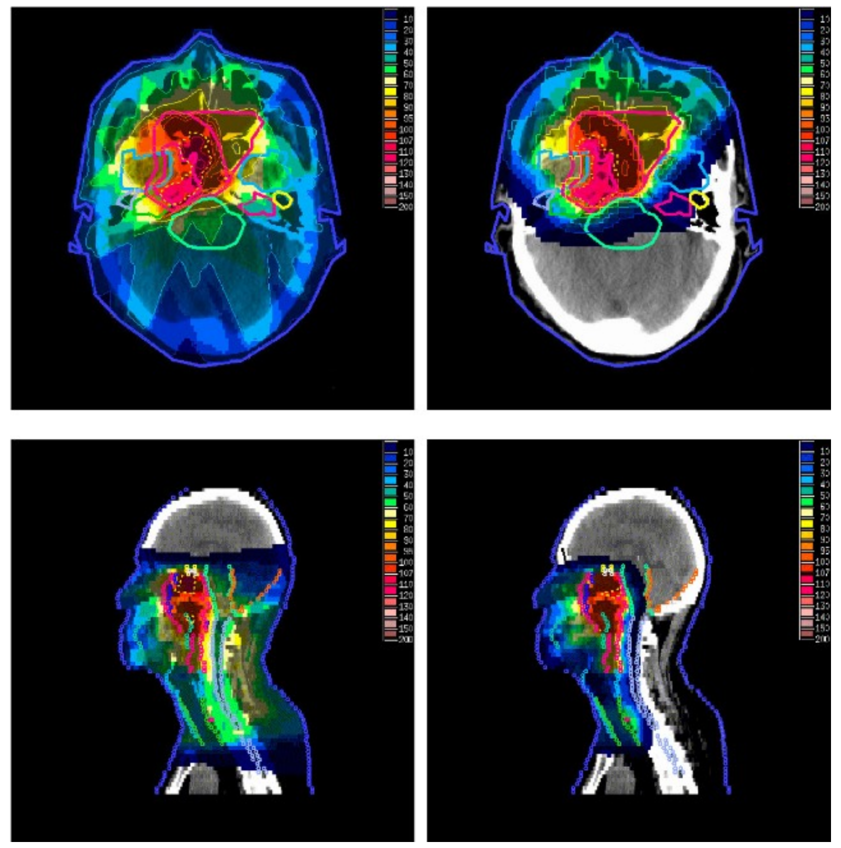


Experimental Overview (1)

Why laser driven ion sources?

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





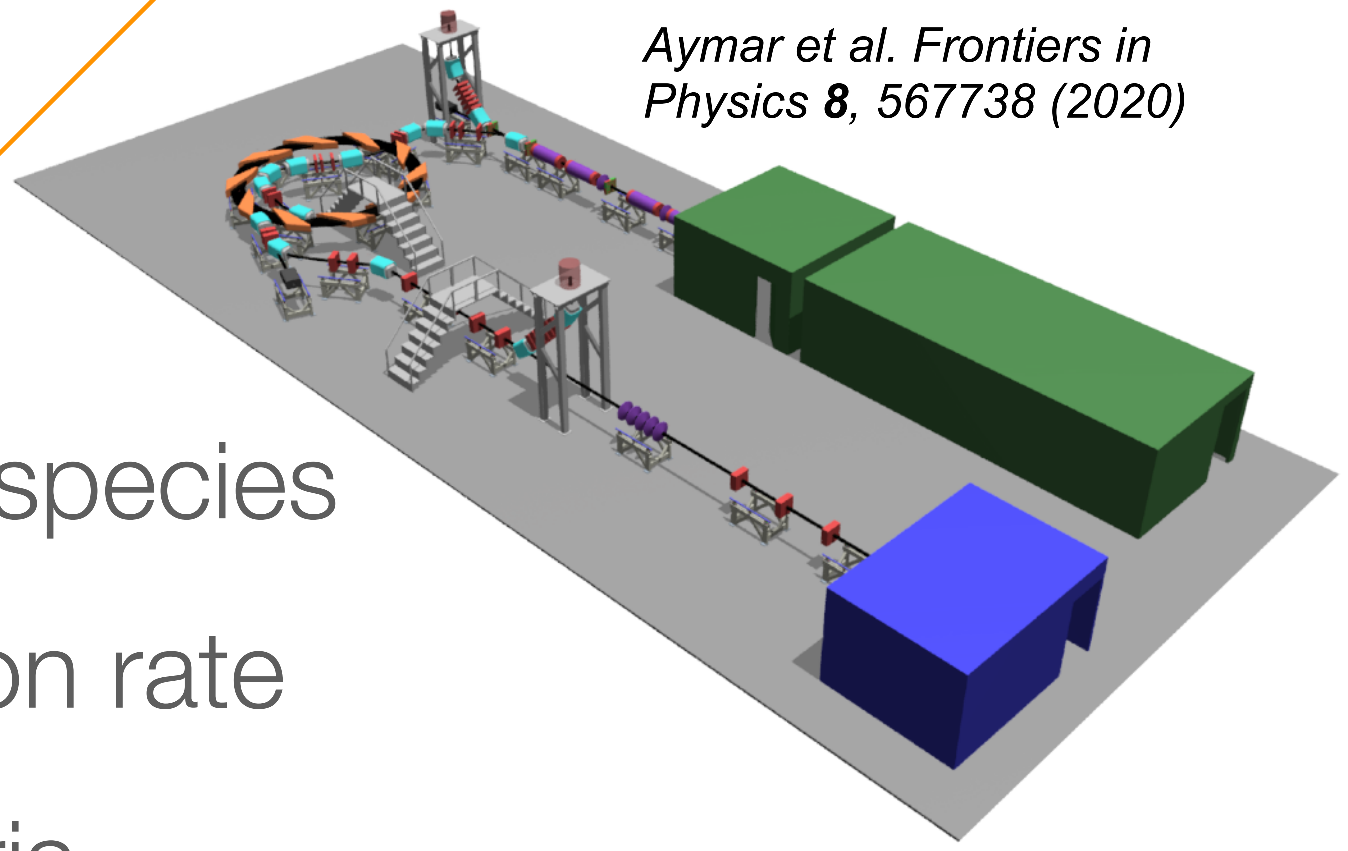
Z. Taheri-Kadkhoda et al. Radiation Oncology ***3*** *(2008)*

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…

Experimental Overview (2)

- In order to generate large static electric fields from EM fields, typically require:
  - Laser to be stopped by the plasma
  - Electrons need to gain significant energy to generate space charge

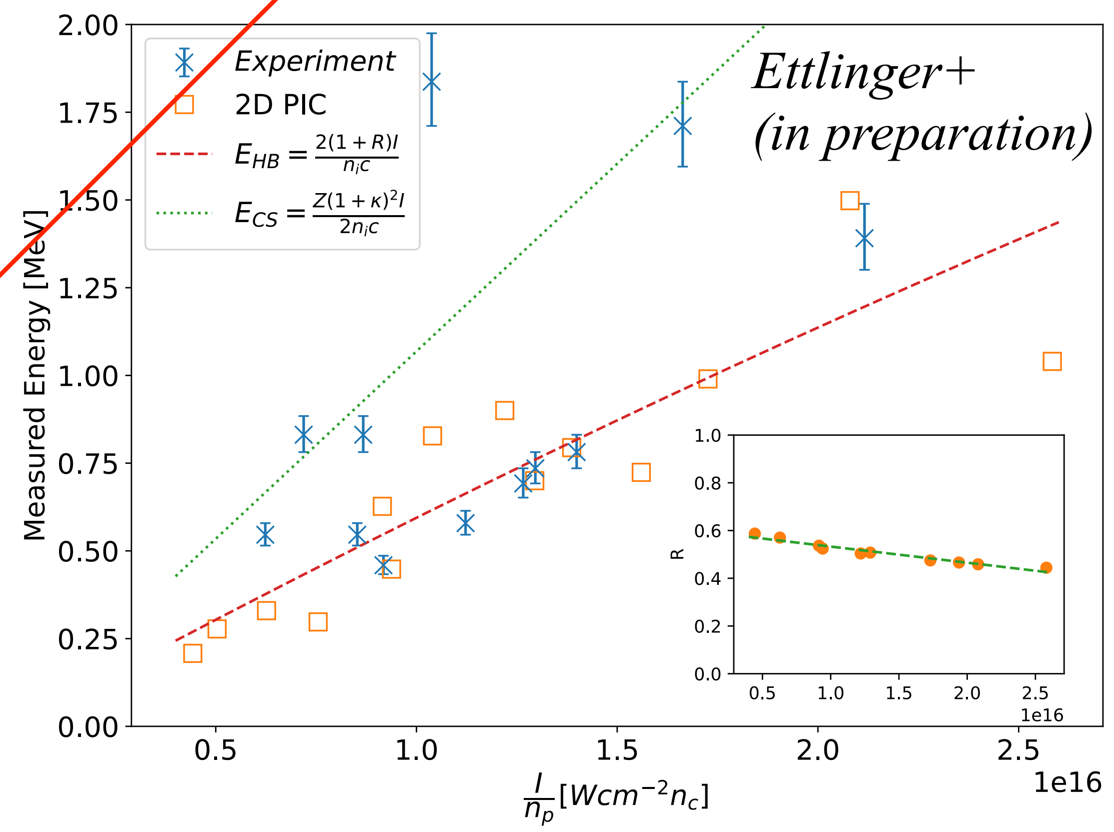
Critical density of a plasma scales favourably with wavelength

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

Relativistic electron response scales favourably with laser wavelength

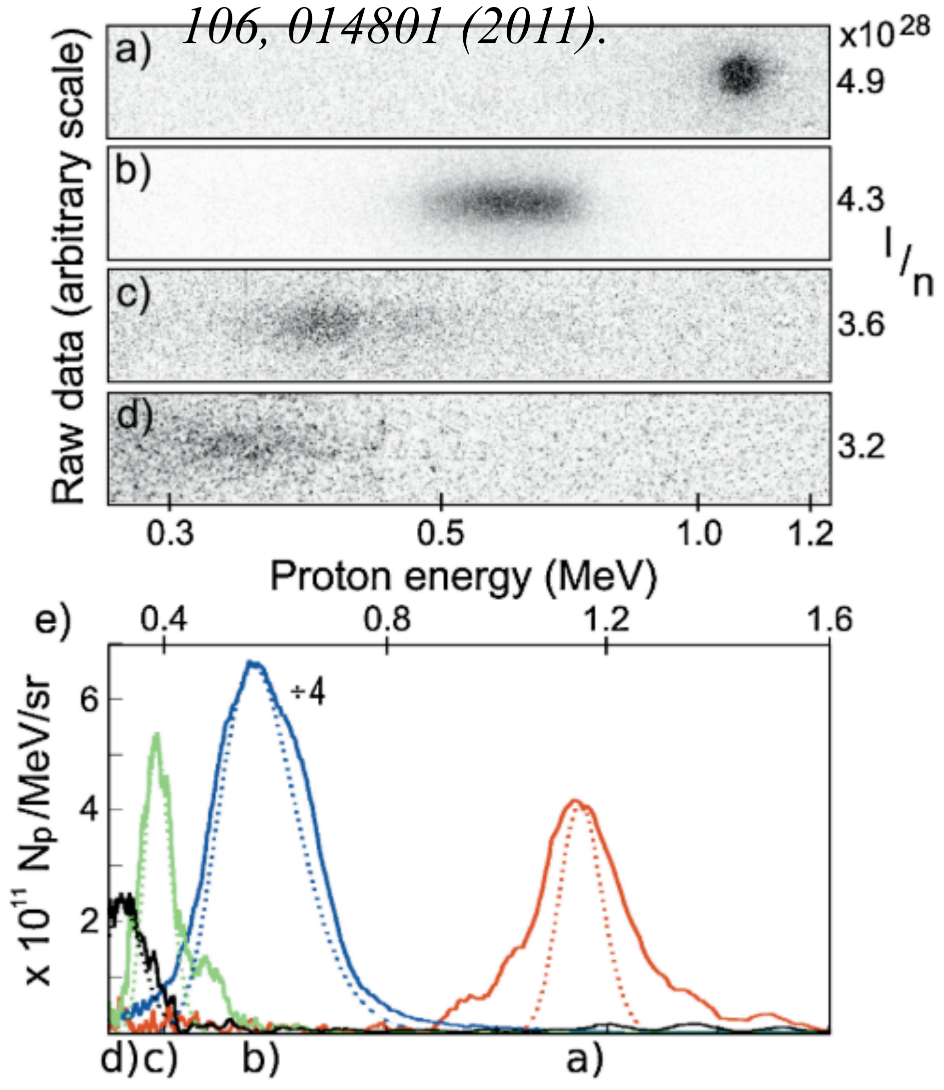
$$a_0 = \frac{eE_0}{m_e c} \cdot \frac{\lambda}{2\pi c}$$

The ATF's long wavelength high power CO_2 laser is ideal



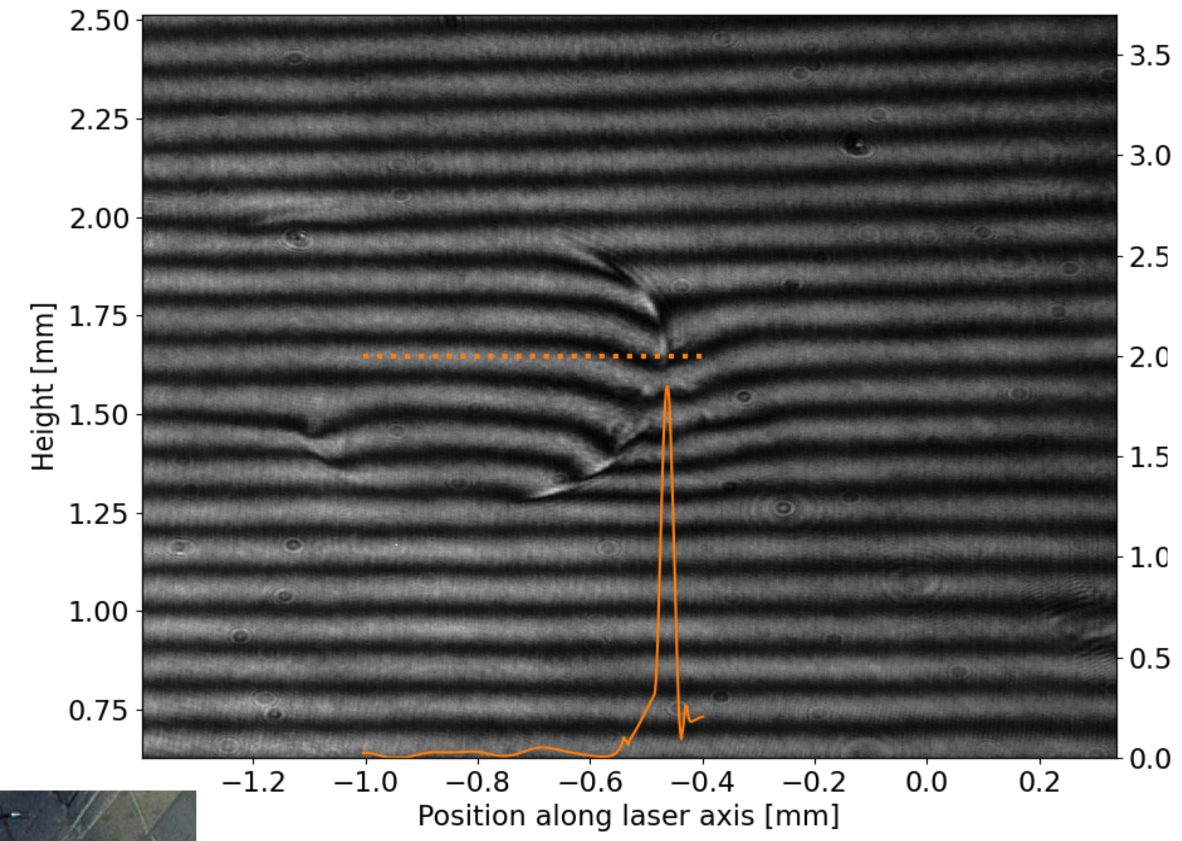
Ettlinger+ (in preparation)

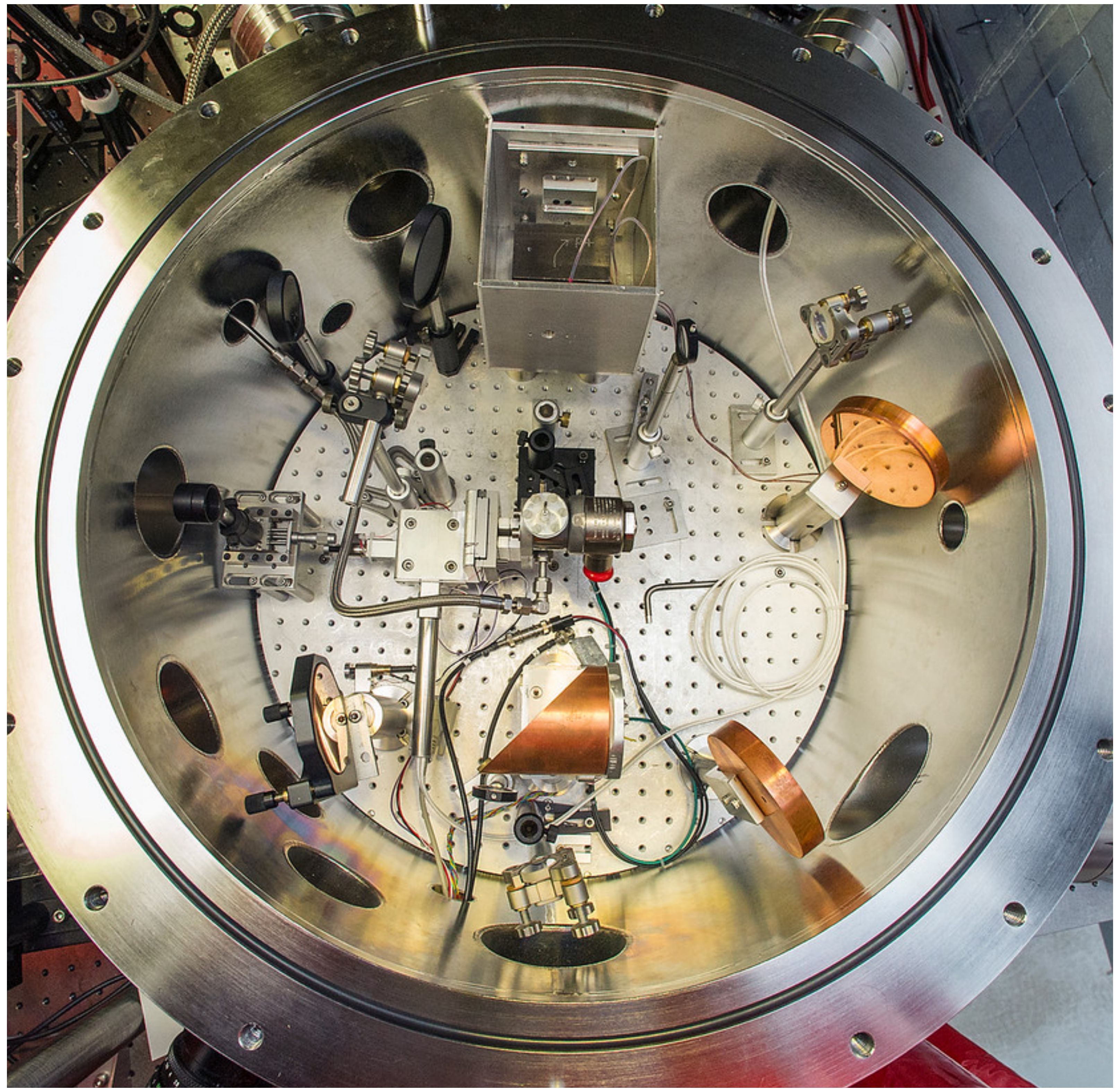
Palmer+, Phys. Rev. Lett. 106, 014801 (2011).

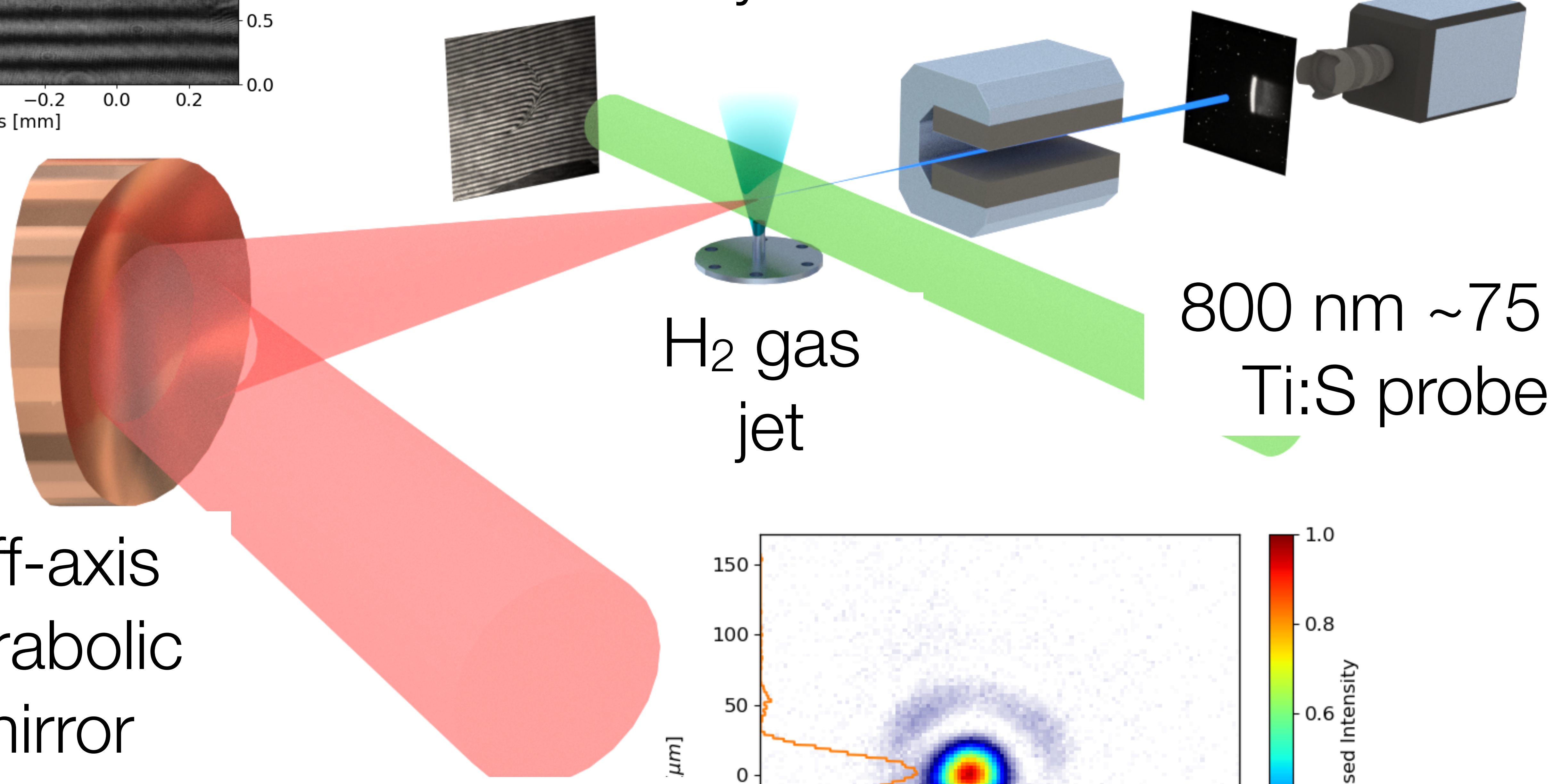


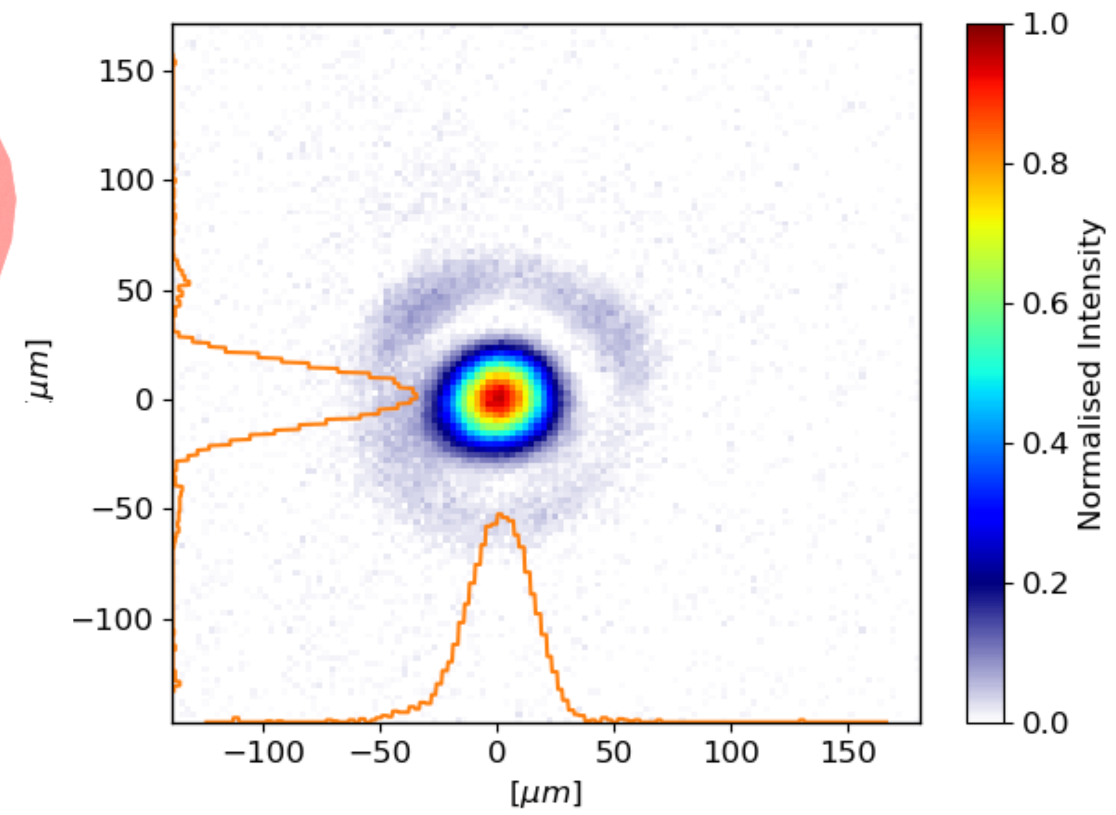
Experimental Overview (3)

mJ level laser pre-pulse to shape gas, optimising density profile - a “blast wave” - Tresca et al. PRL 115 (2015)







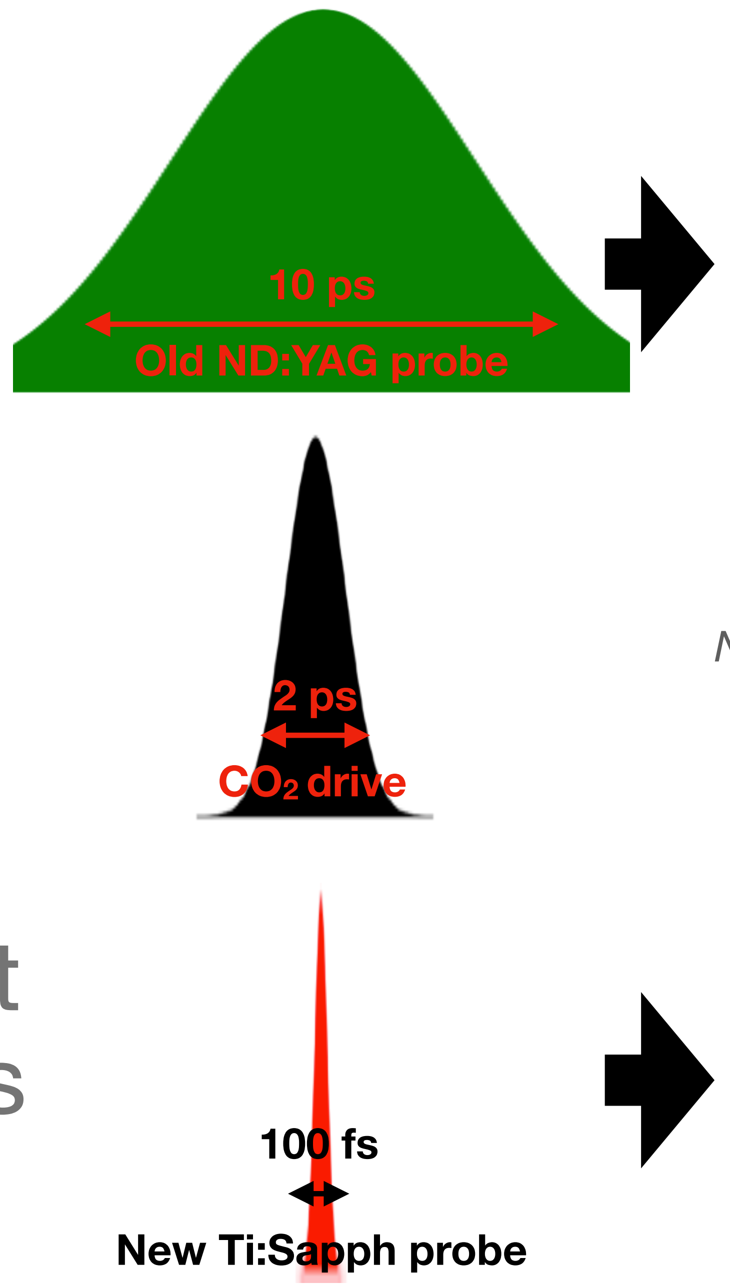


Summary of major results and preparations (1)

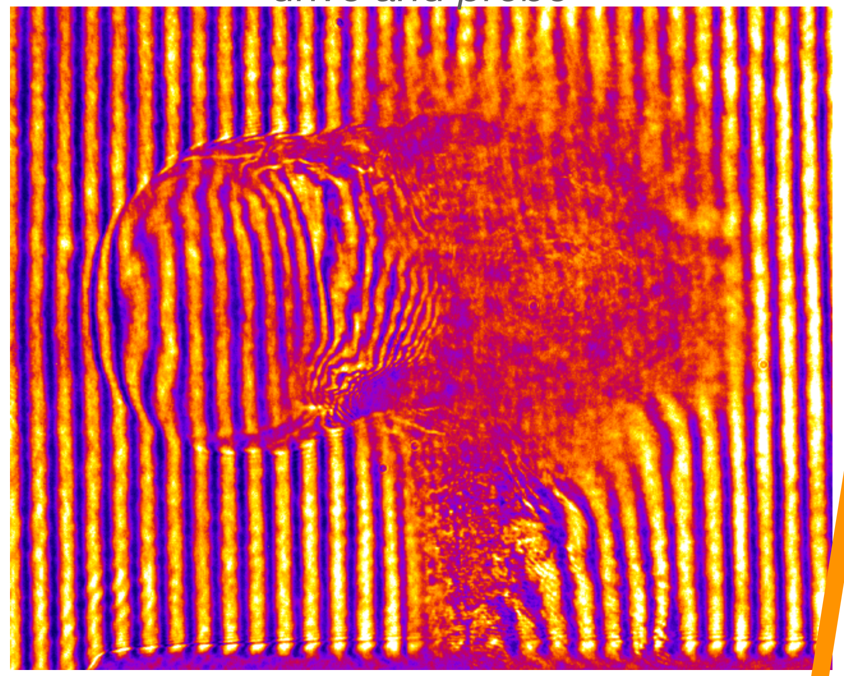
Achieved in the 2 week 2022 beamtime:

New femtosecond probe for measuring intrapulse dynamics

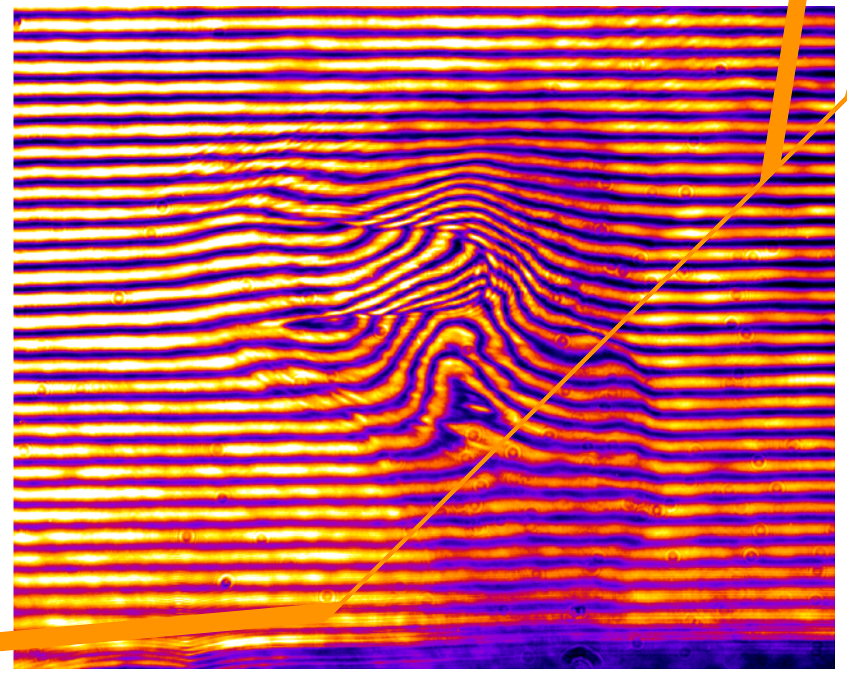
- Previously: 10 ps ND:YAG, results in significant image blur
- New in 2022: Implemented <100 fs Ti:Sapphire probe, allowing measurement of intrapulse dynamics



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

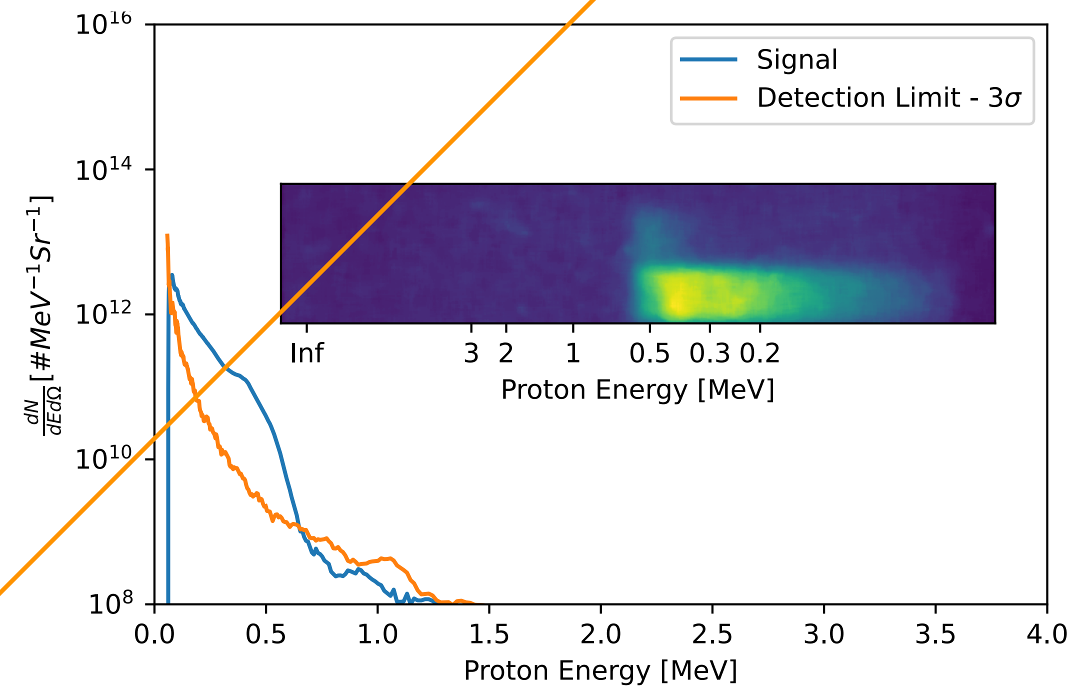


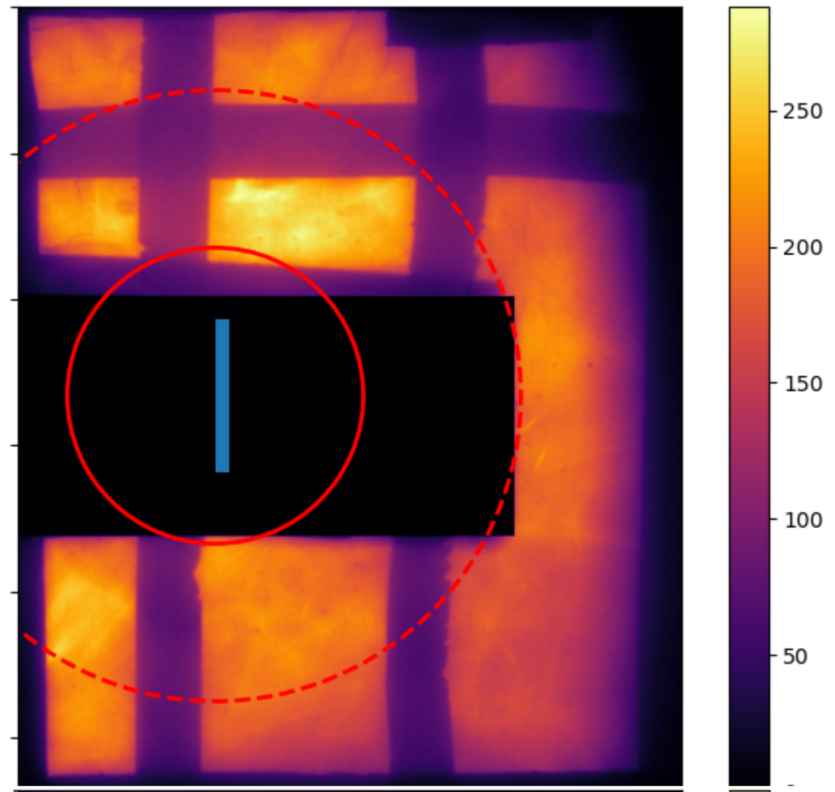
Now: clean images when overlapping drive and probe, allowing measurements of evolving overdense LPI



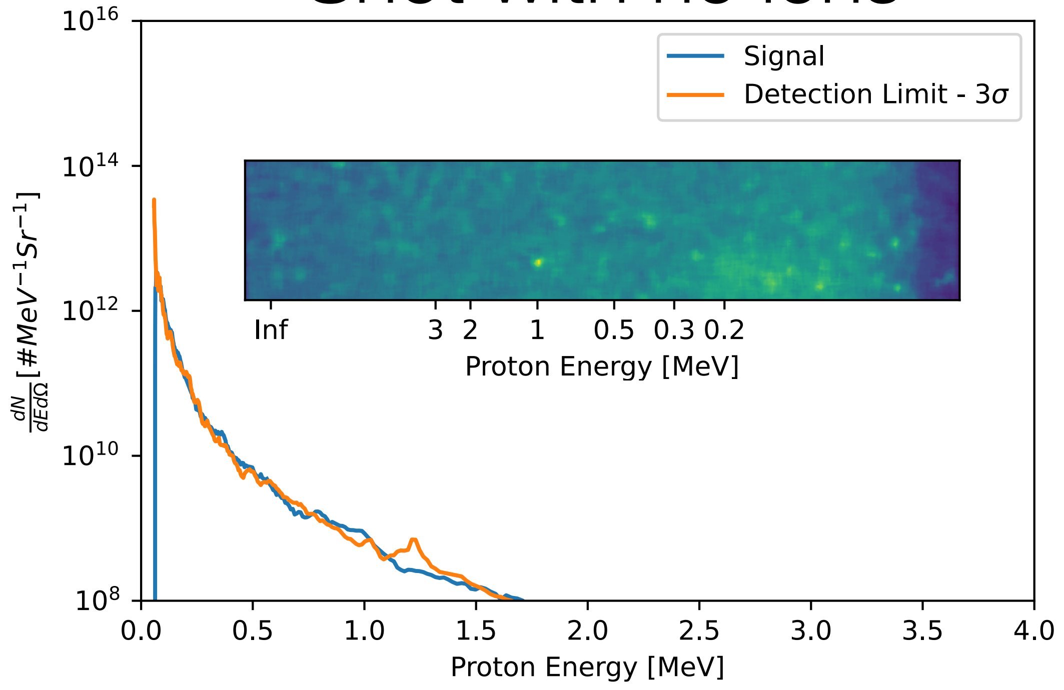
High repetition proton beam spatial profiler

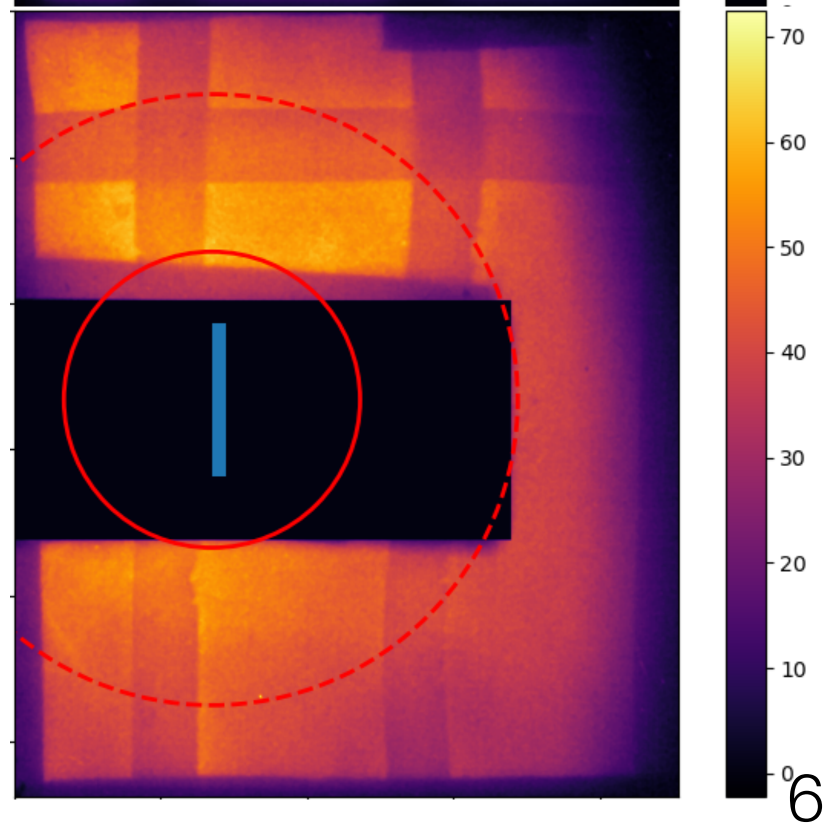
Shot with ions





Shot with no ions

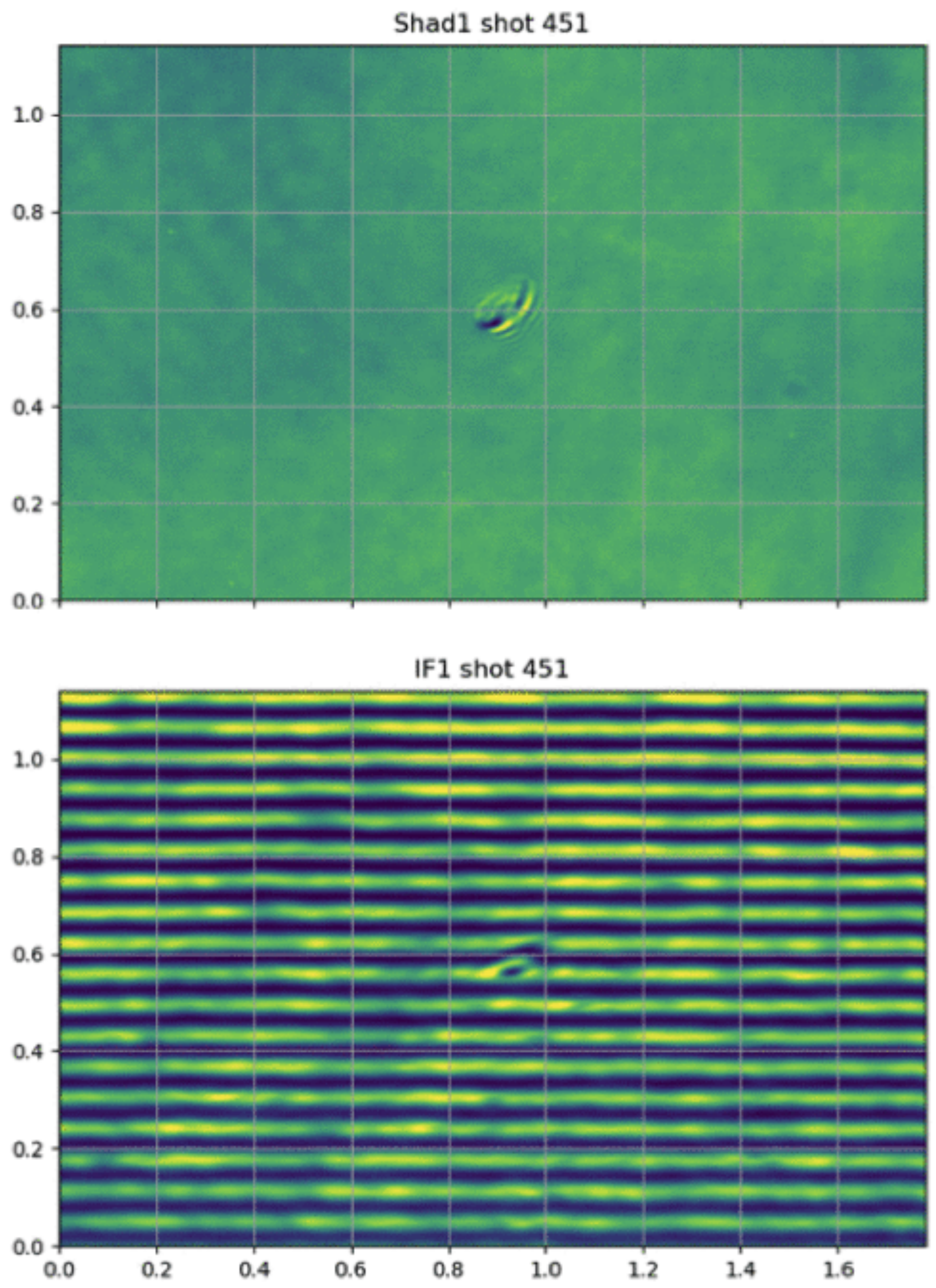




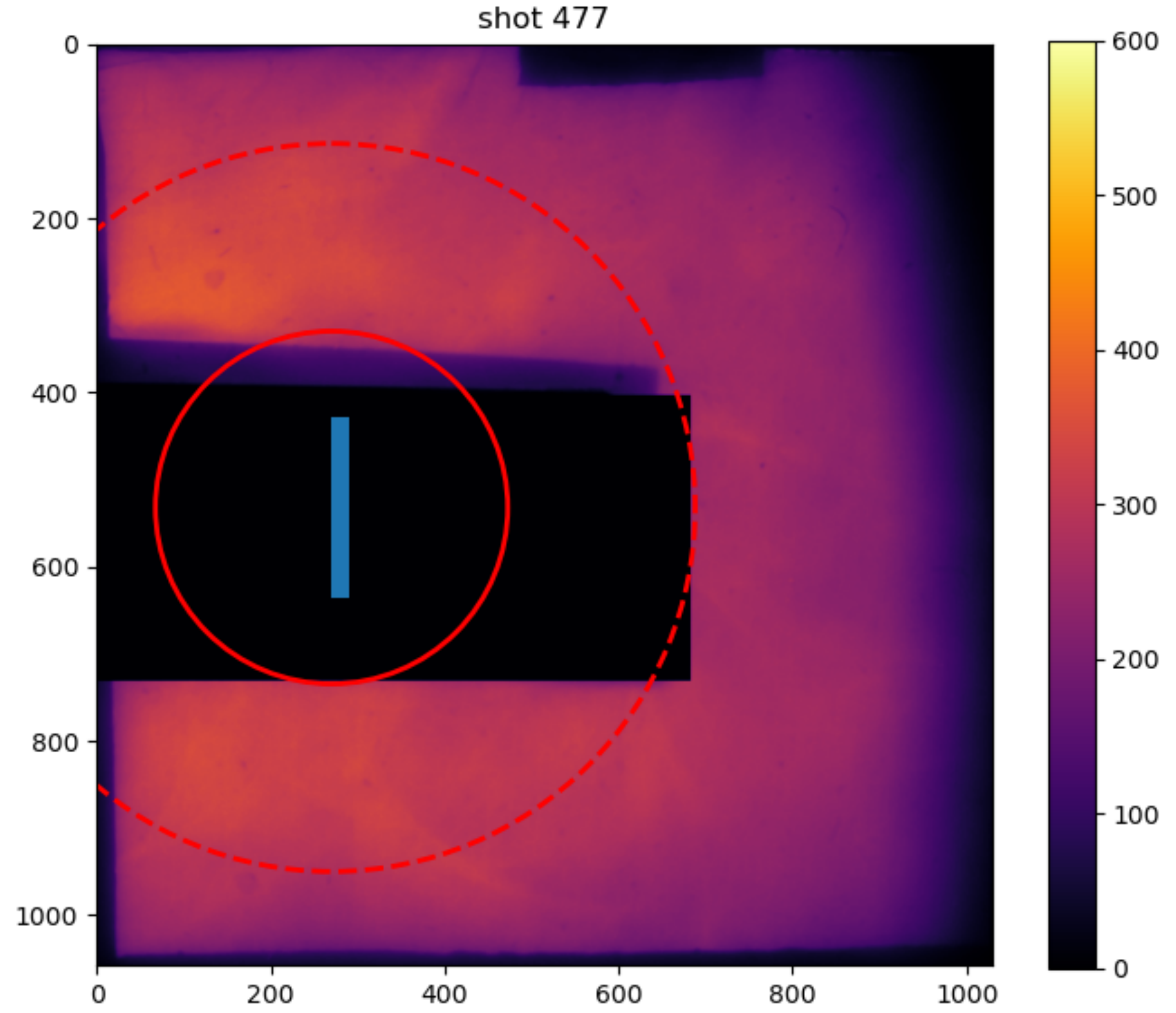
Summary of major results and preparations (2)

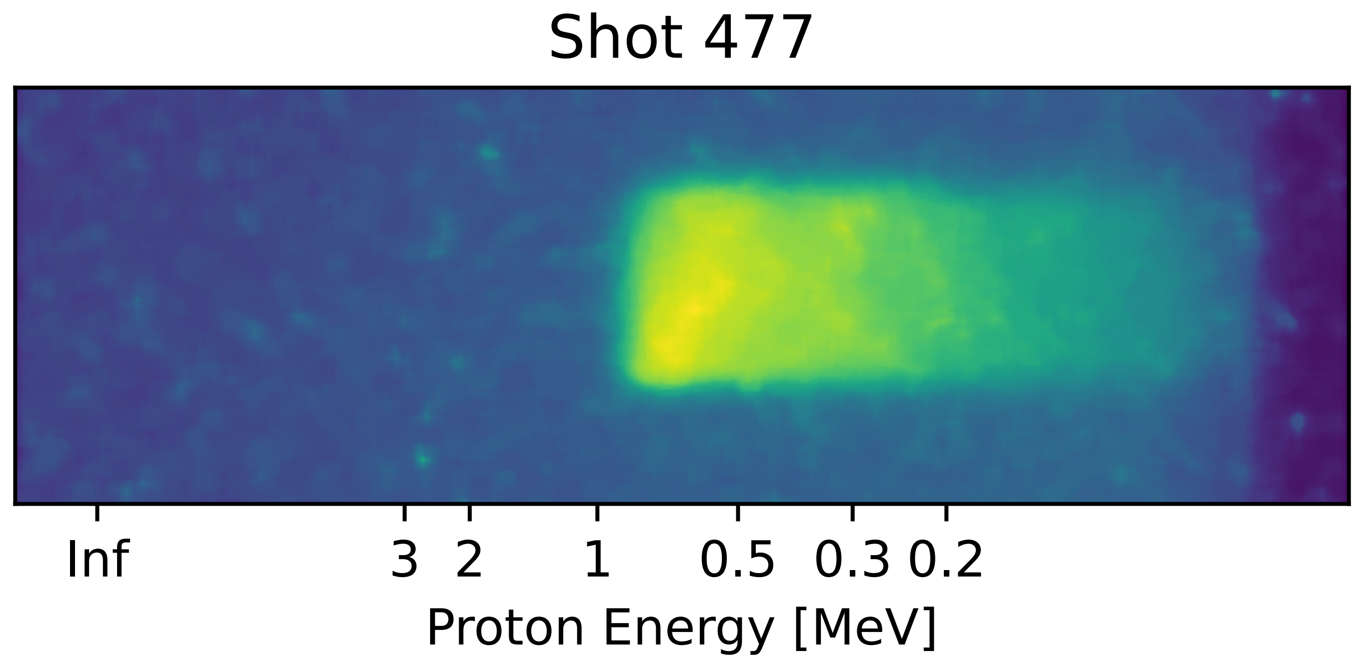
- Clear channeling of CO_2 pulse observed, coinciding with ion generation
  - Extremely stable ion generation, albeit low energy

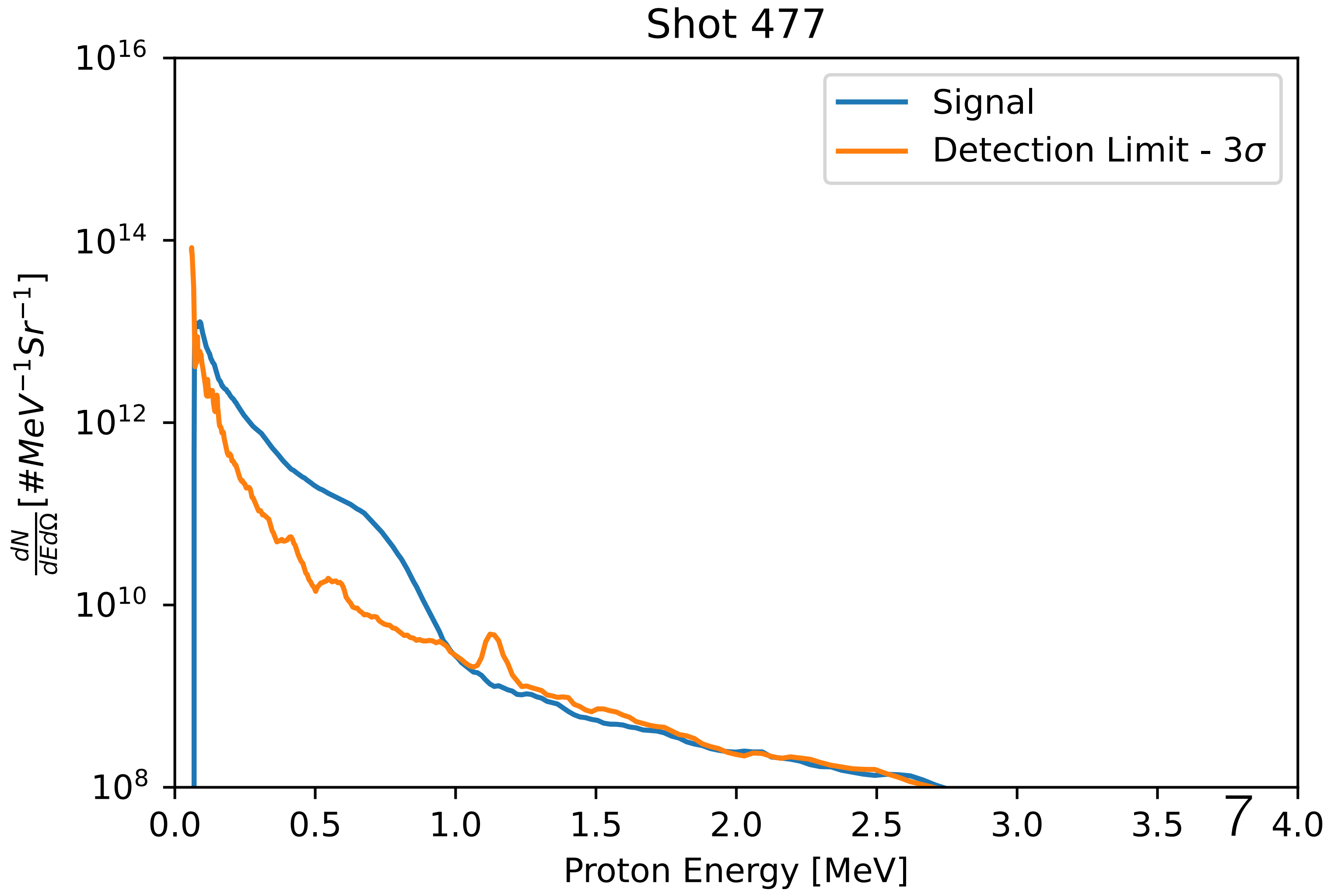
t=-61 ps



Typical ion beam parameters







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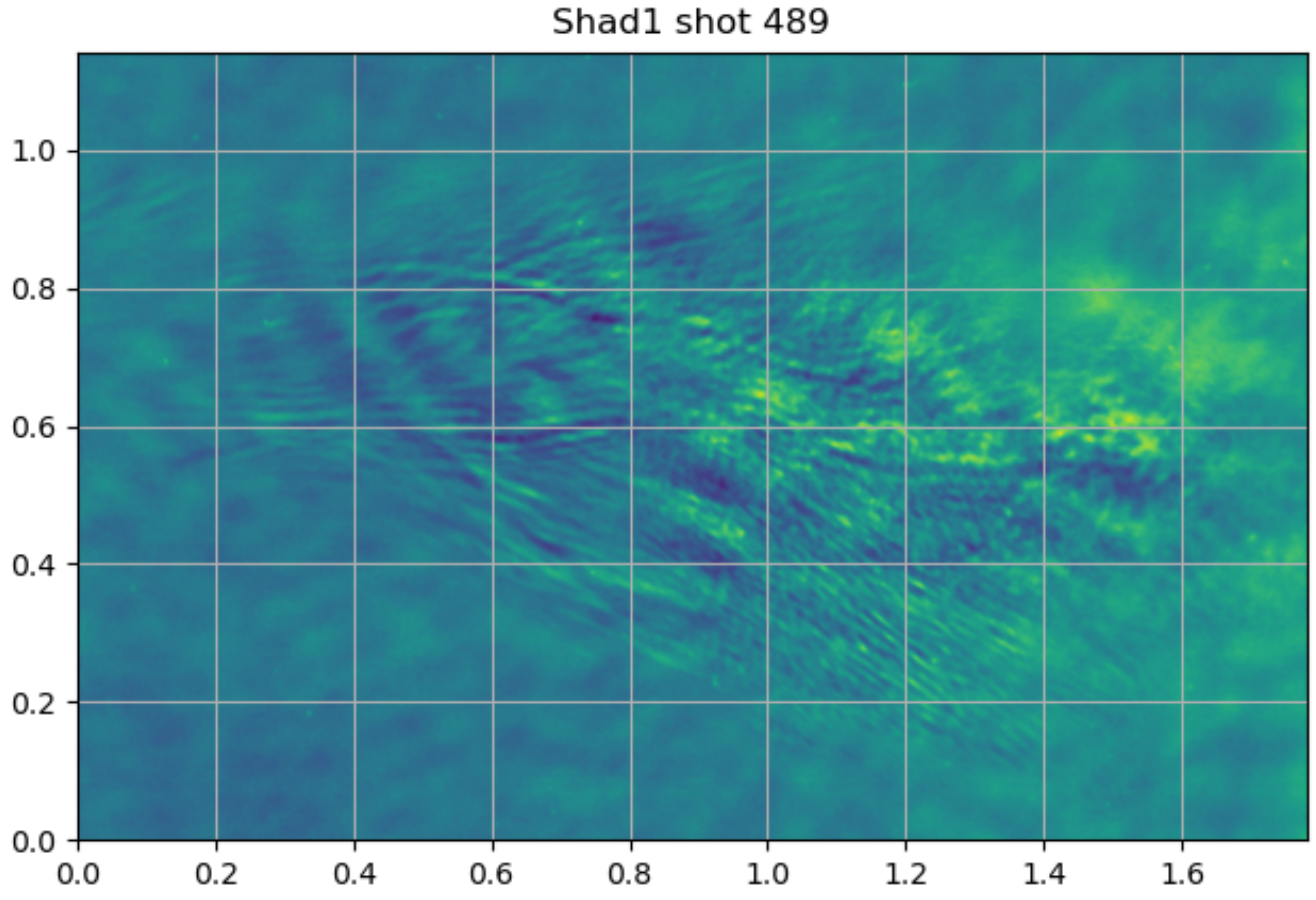

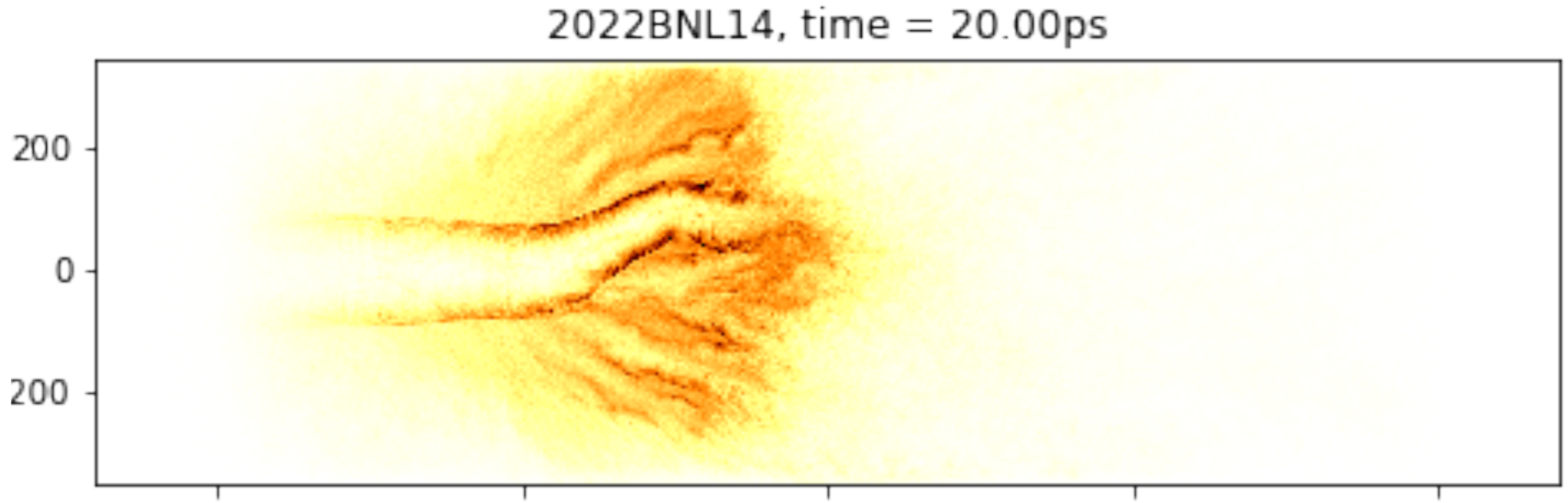

Good agreement with 2D PIC - more simulations ongoing

Experimental plans for next year

- In 2022, unable to generate hole-boring / shock acceleration
  - Blast wave from prepulse unsuitable for generating steep density gradient
  - Reason unclear - lower f-number due to down-collimation at plasma shutter?
  - For next run, we are developing different blast wave generation scheme, from e.g. secondary optical laser
- Vary laser polarisation to optimise ion generation
- Use newly implemented diagnostics for characterisation of shockwave acceleration

Summary of products delivered from work to date

- **Recent talks:**
    - AAC 2022 (Igor Pogorelsky)
- **Papers in preparation:**
    - Y-H. Chen et al. (NRL) - “Proton acceleration in an overdense hydrogen plasma by intense CO2 laser pulses with nonlinear propagation effects in the underdense preplasma“ - submitted to POP (2023)
    - O. Ettlinger et al. (ICL) - “Proton acceleration from a near-critical density plasma grating” - in preparation
    - O. Ettlinger et al. (ICL) - “Experimental demonstration of shock-driven proton acceleration scaling at near-critical densities” - in preparation
    - N. Dover et al. (ICL) - “ Observation of laser-generated fast electron Weibel filaments” - in preparation
- **Papers related to AE100 forerunner ATF experiments**
    - S. Passaladis et al. - “Hydrodynamic computational modelling and simulations of collisional shock waves in gas jet targets“ HPLSE 8, e7 (2020)
    - 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 (2015)
    - C.A.J. Palmer et al. - "Manipulation of laser-generated energetic proton spectra in near critical density plasma”, JPP 81 (2015)
    - C.A.J. Palmer et al. - “Monoenergetic Proton Beams Accelerated by a Radiation Pressure Driven Shock”, PRL 106 (2011)
    - Z. Najmudin et al.- “Observation of impurity free monoenergetic proton beams from the interaction of a CO(2) laser with a gaseous target”, POP 18 (2011)

John Adams Institute for Accelerator Science

Imperial College London

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 Beamline	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 >10 TW and deliver to*	*√ (5 TW)*
	Pulse Mode	---	Single		*√*
	Pulse Length	ps	2		*√ (or longer)*
	Pulse Energy	J	~5	*Maximum pulse energies of >10 J will become available within the next year*	*√*
	M^2	---	~2		*√*
	Repetition Rate	Hz	0.05		*√*
	Polarization		Linear	*Adjustable linear polarization along with circular polarization can be provided upon request*	*LP and CP required*

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	~20	*20 mJ is presently operational with work underway this year to achieve our 100 mJ goal*	
Energy to Experiments	mJ	>4.9	>80		*20*
Power to Experiments	GW	>98	>1067		

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		

Special Equipment Requirements and Hazards

- Electron Beam N/A
- CO_2 Laser
  - Please note any specialty laser configurations required here:
    - Controllable pre-pulse required - or better understanding of parasitic pulses
- Ti:Sapphire and Nd:YAG Lasers
  - Please note any specialty non-CO_2 laser configurations required here:
    - Continue using Ti:sapphire for probing
- Hazards & Special Installation Requirements
  - Possible new magnet for updated ion spectrometer
  - HV for time-of-flight ion diagnostic

Experimental Time Request

CY2023 Time Request

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

Time Estimate for the 3-year Experiment (including CY2023-25)

Capability	Setup Hours	Running Hours
Electron Beam Only		
Laser* Only (in FEL Room)	120	240
Laser* + Electron Beam		

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

Summary - AE100

- So far, 2-week beam times in Feb 2020 and Oct 2022
  - New Ti:S probing capability transformational for understanding LPI
  - Exciting results on real-time imaging of channeling and ion acceleration in near-critical density plasma
- Next run would aim to:
  - Address issue with reliable blast-wave generation for density scale length shaping
  - Make direct measurements of hole-boring front
  - Investigate LP/CP effects on ion acceleration