AE100 - Ion Acceleration at ATF

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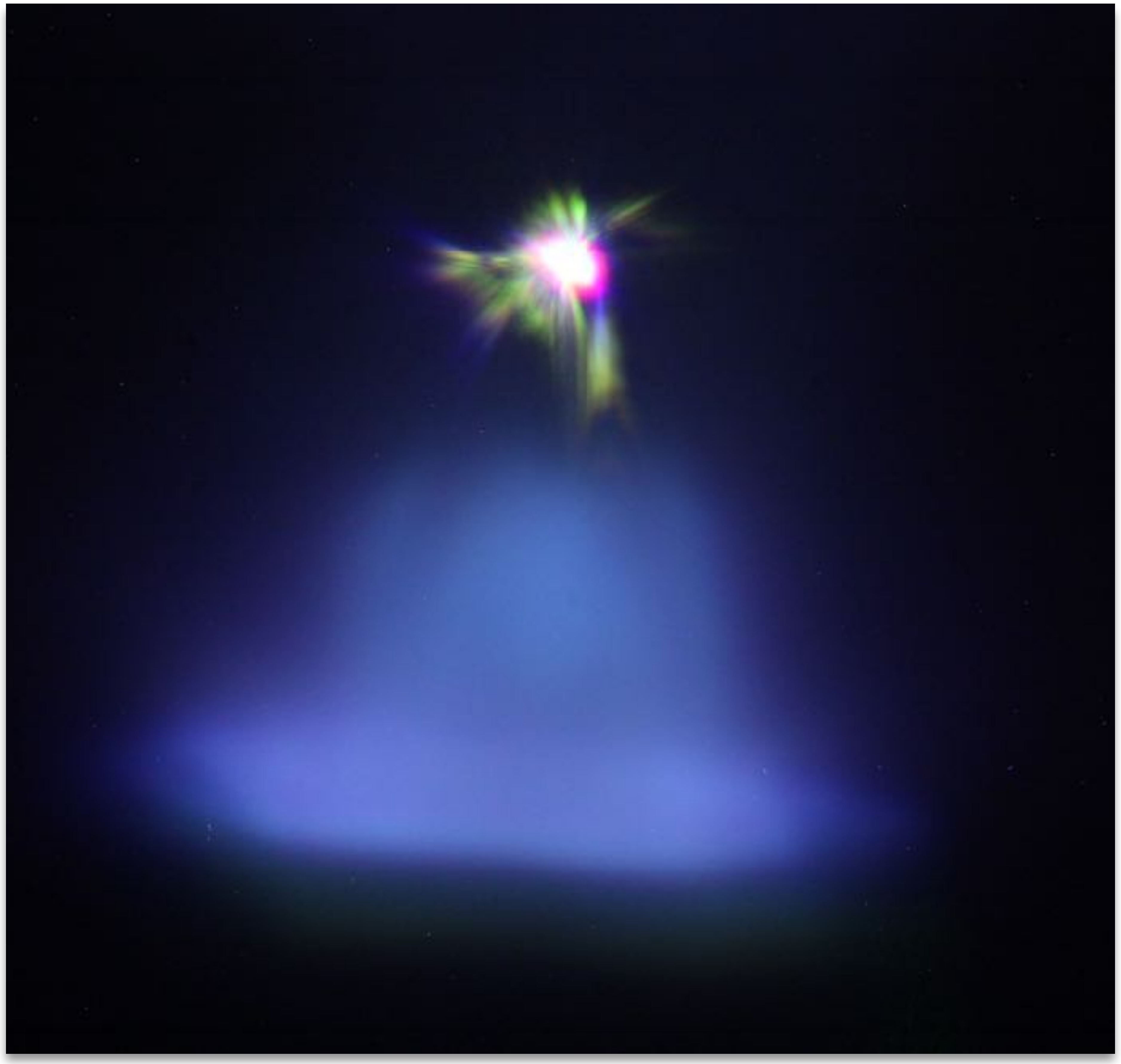
ATF User Meeting 2020,
9th December 2020



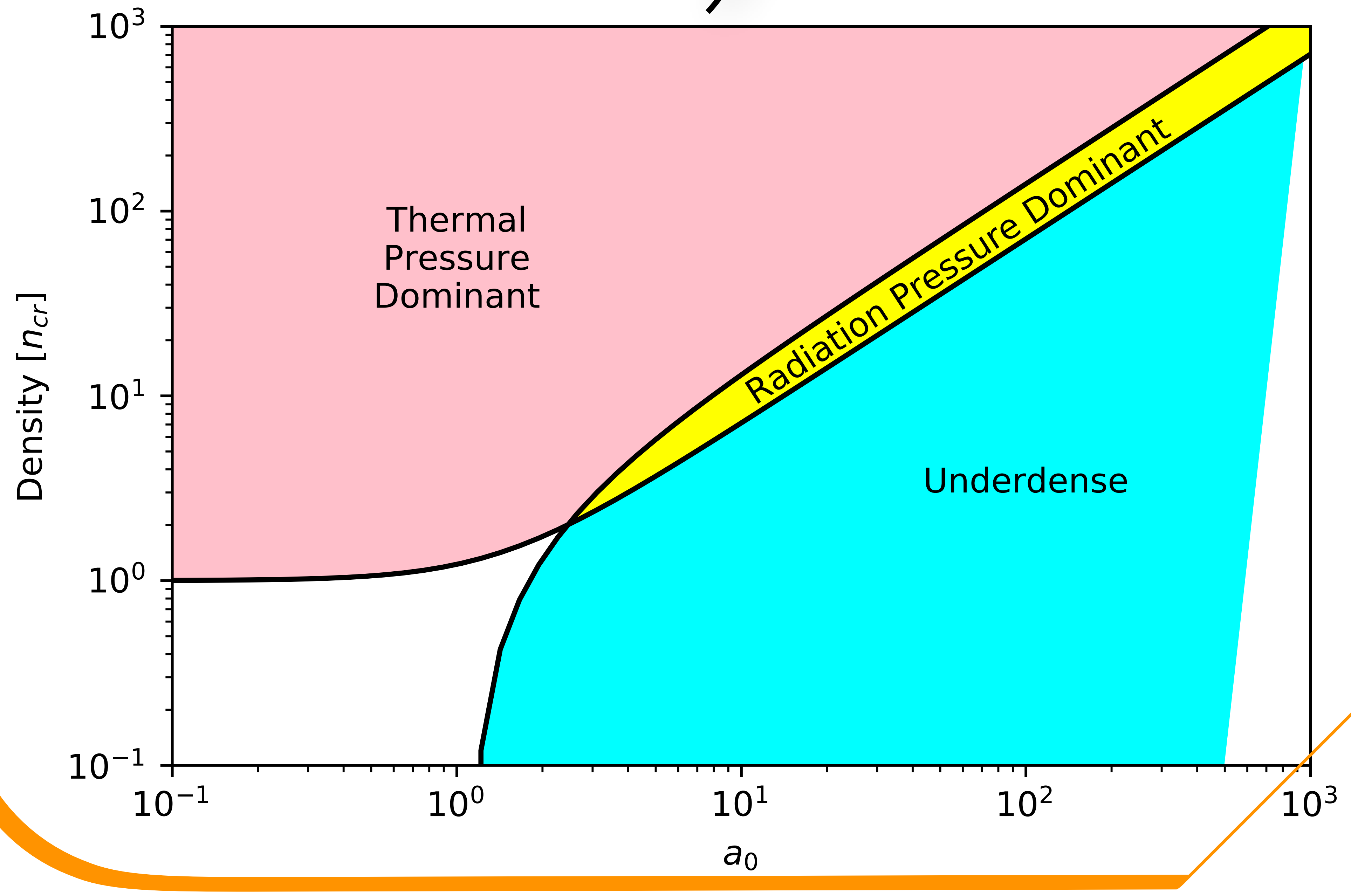
Shock Acceleration

v_f

$$P_R = (1+R)\left(\frac{I}{c}\right)$$

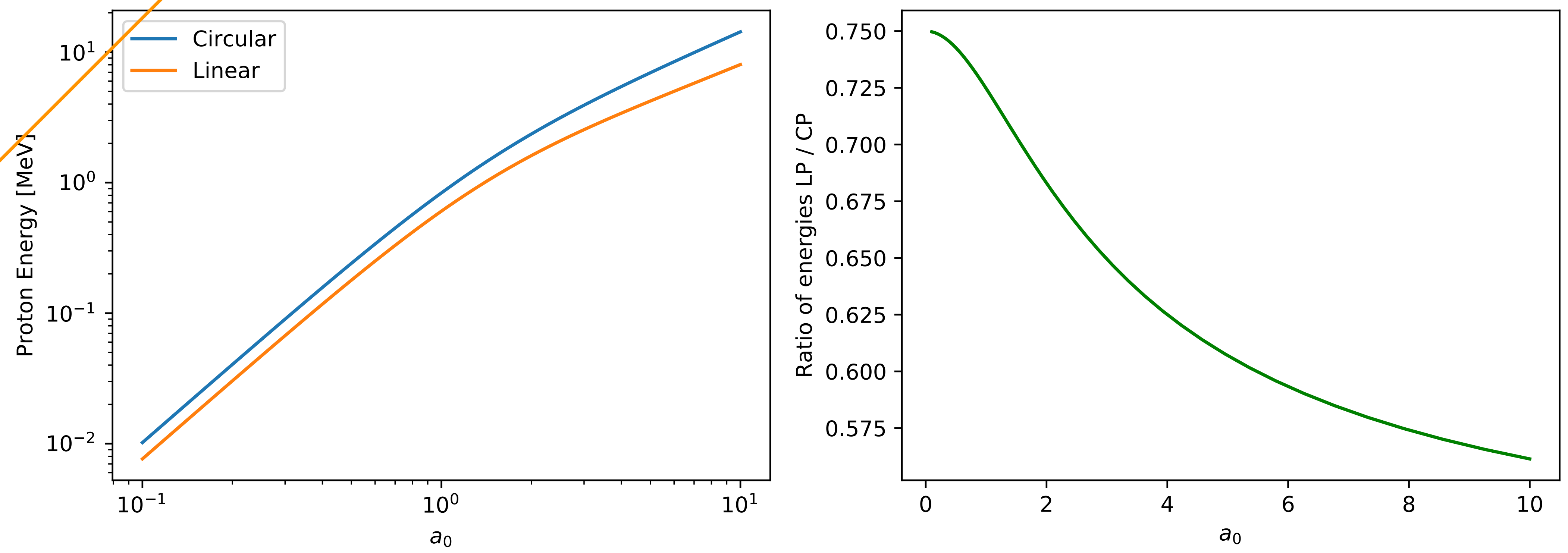
$$P_{\text{ram}} = n_0 m_i {v_f}^2$$

$$P_{\text{th}} = n_e k_B T_e$$

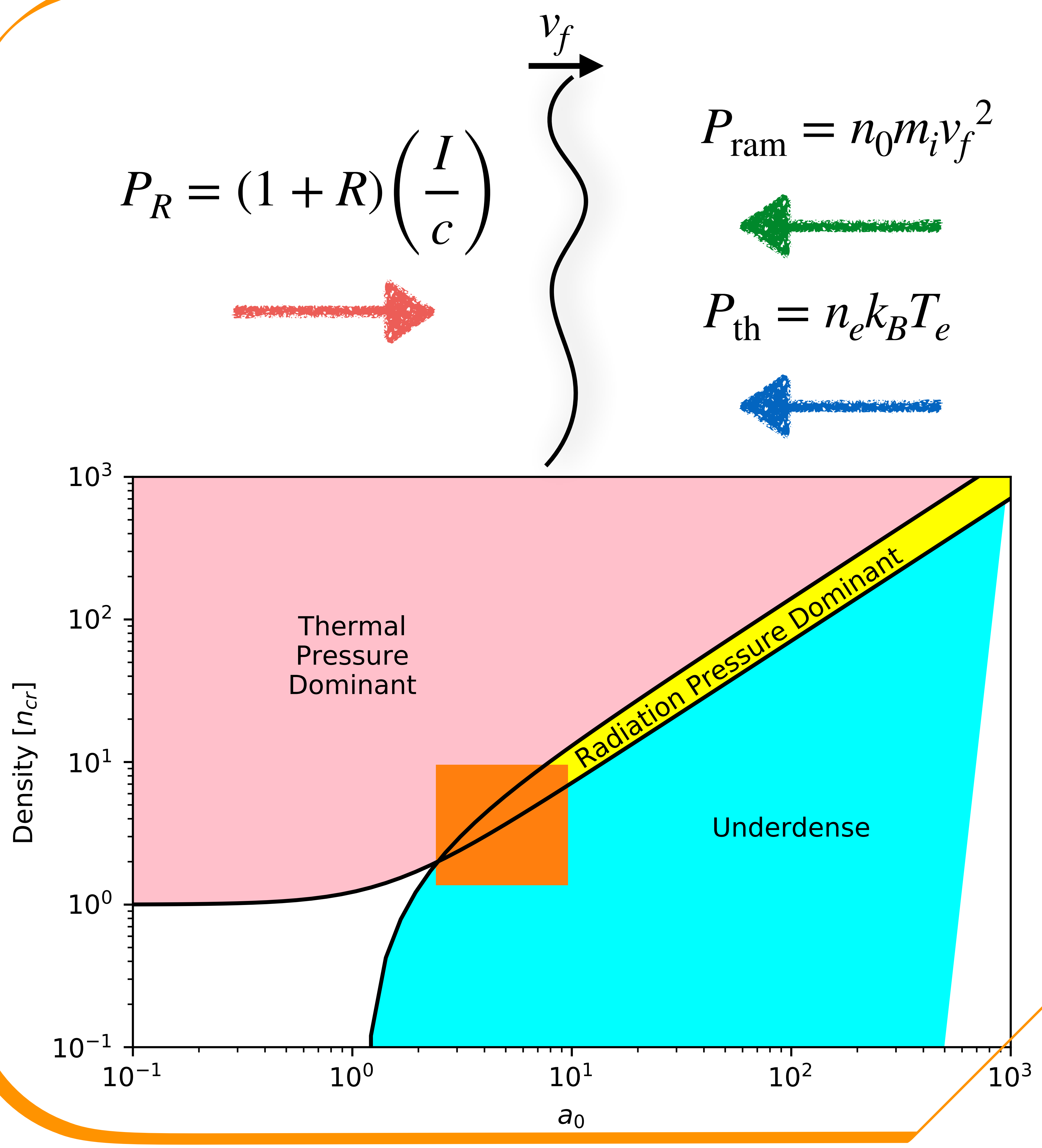


Modified HB to include thermal effects

$$\mathscr{E}_s = 2m_e c^2 \left[\left(\frac{n_{cr}}{n_0} a_0^2 \right) - \left(\sqrt{1 + a_0^2/2} - 1 \right) \right]$$



Shock Acceleration



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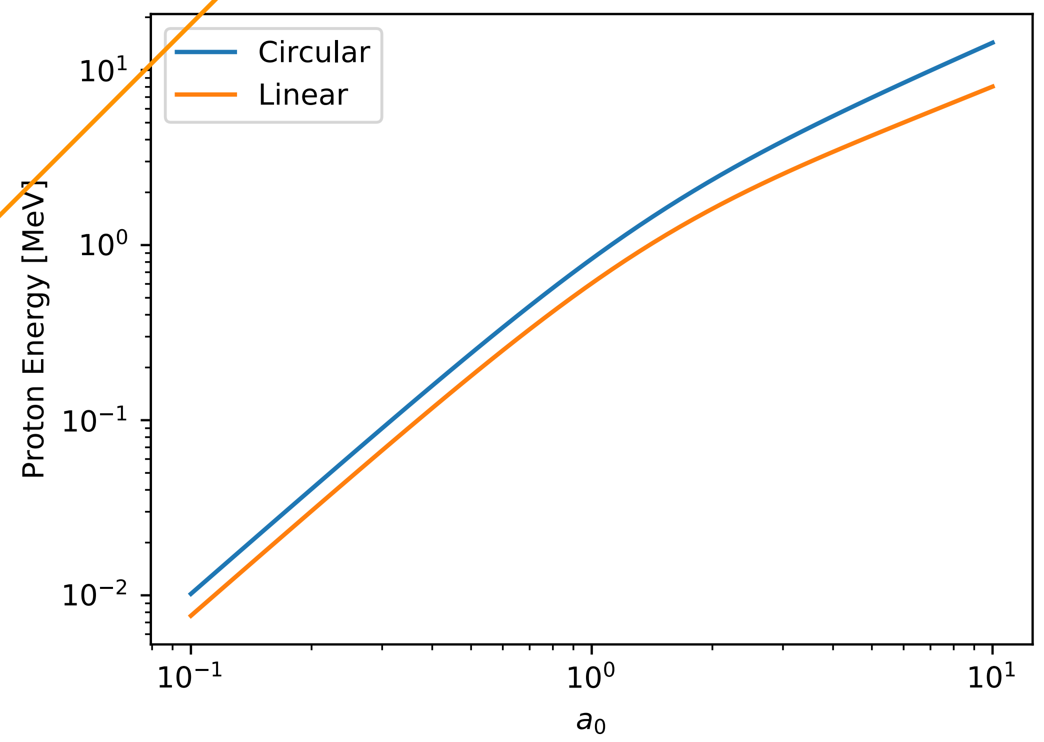

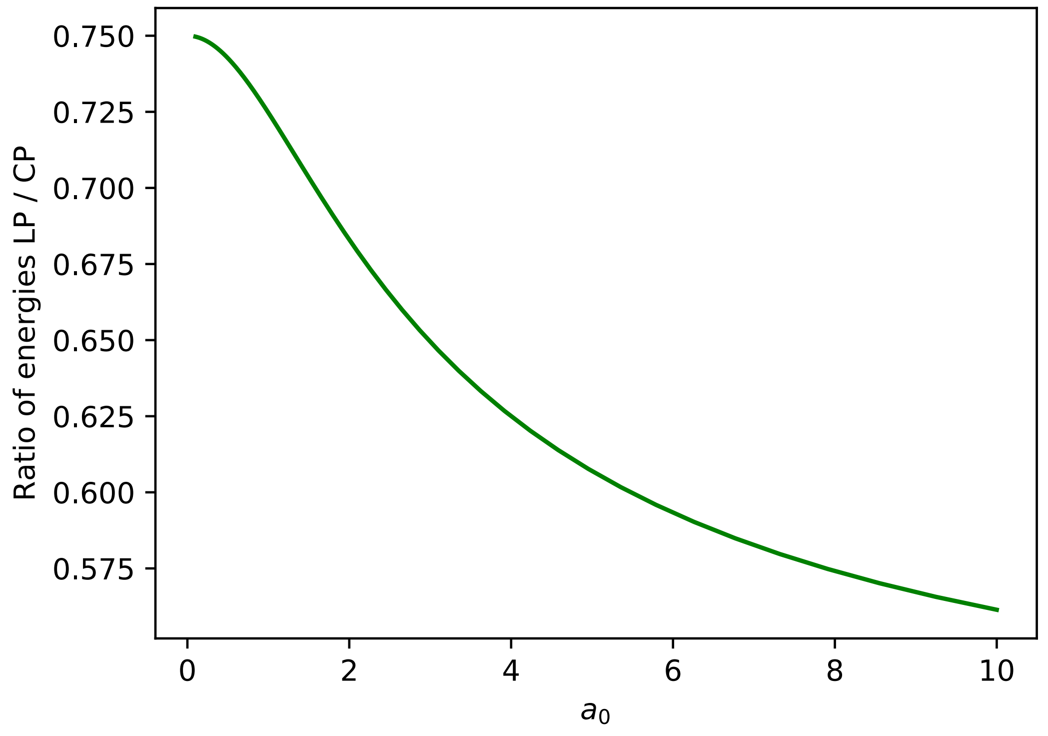

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MURI MIR
MID-INFRARED STRONG-FIELD INTERACTION

Imperial College London

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?

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

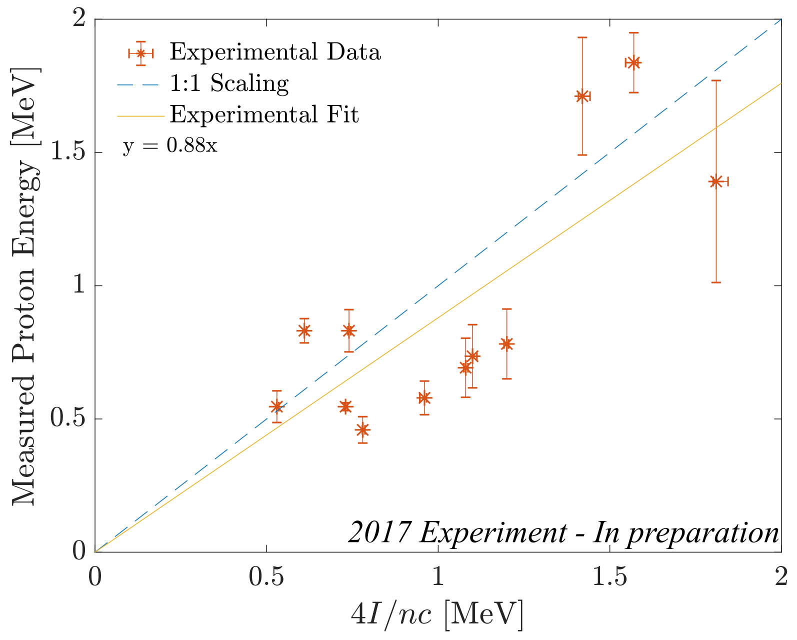
AE100 - A reminder

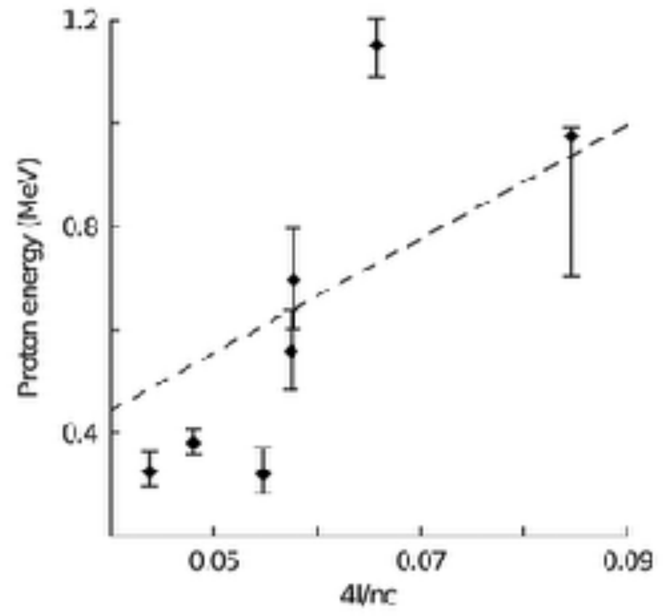
Objectives for early 2020:

- Study the fundamentals of shock acceleration of ions at higher intensities than previously, for $a_0 > 1$

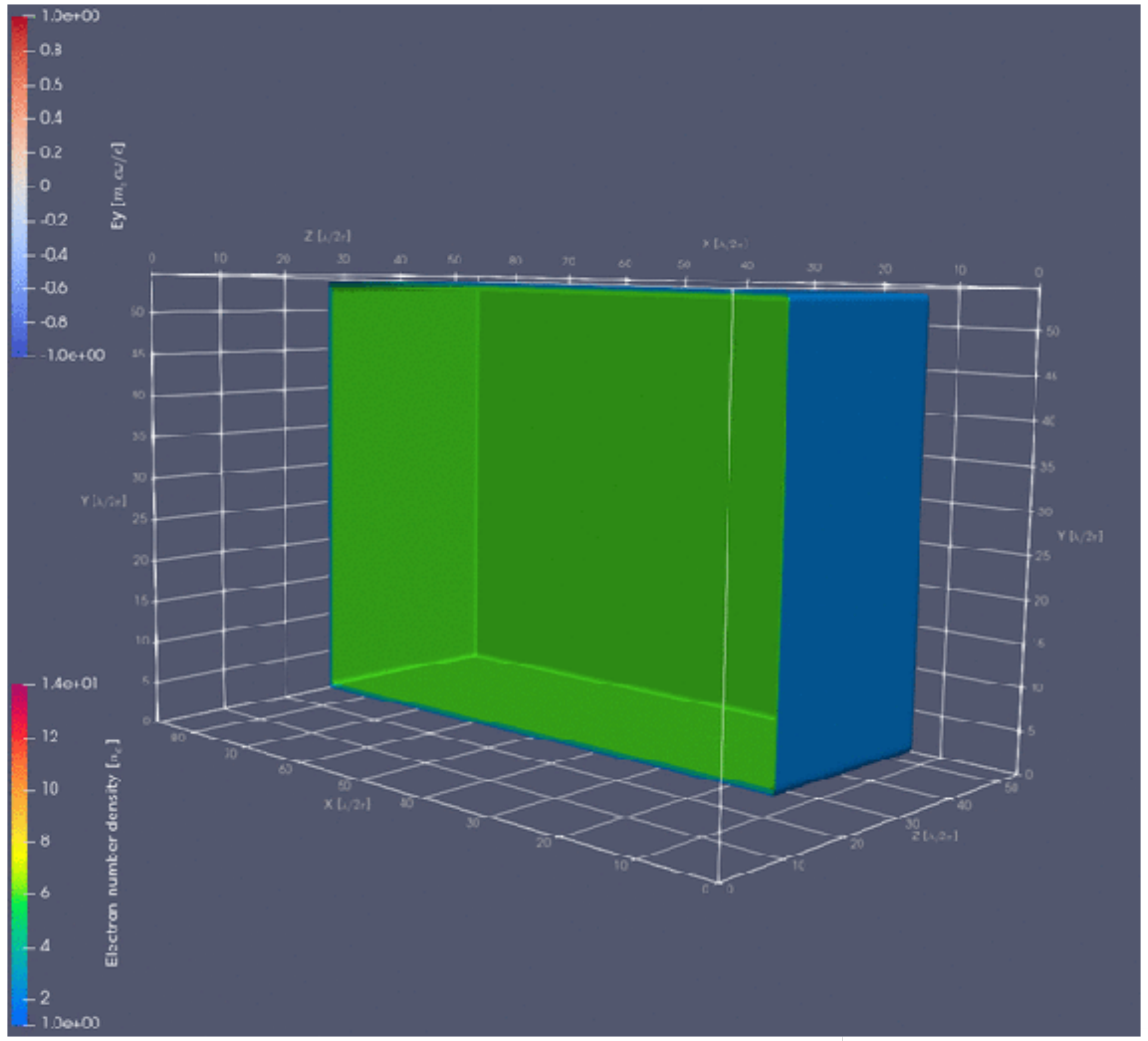
  ➡ Effect of polarisation, pulse length, etc.

- Optically probe these interactions for the first time



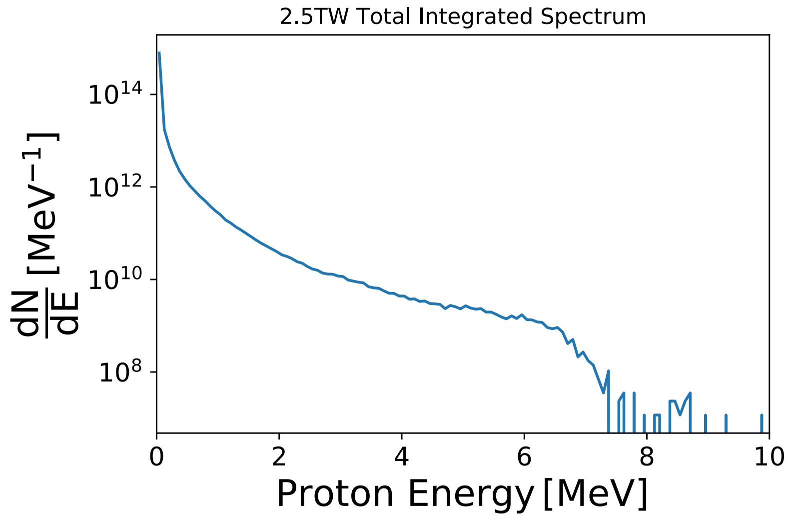


C. A. J. Palmer, N. P. Dover, I. Pogorelsky, M. Babzien, G. I. Dudnikova, M. Ispiryan, M. N. Polyanskiy, J. Schreiber, P. Shkolnikov, V. Yakimenko, Z. Najmudin, and M. Ispiryan, Phys. Rev. Lett. 106, 014801 (2011).

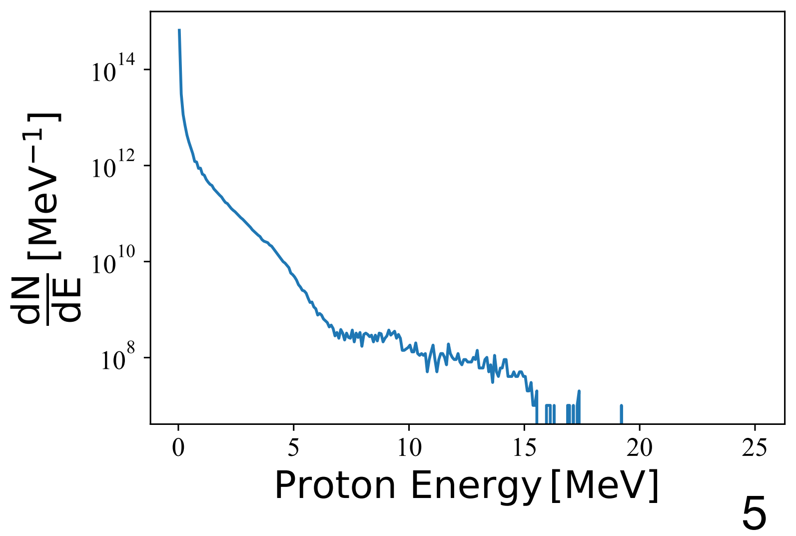


Smilei)

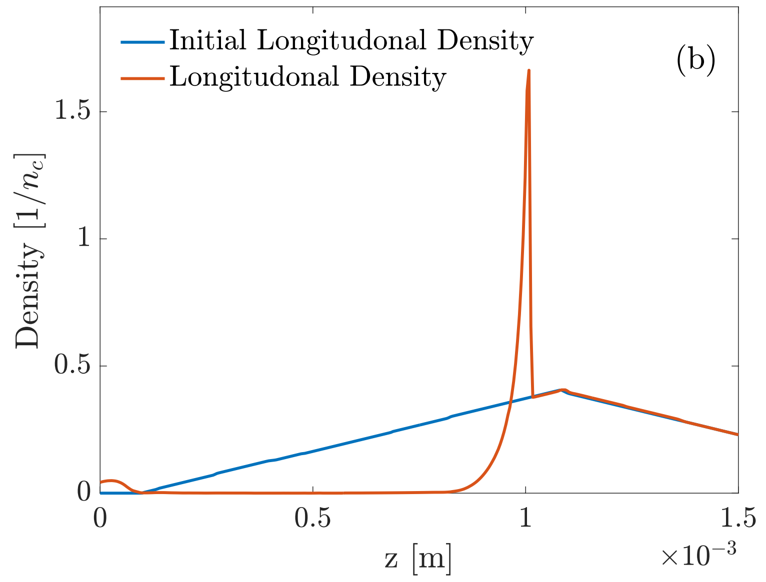
2.5TW Integrated Spectrum

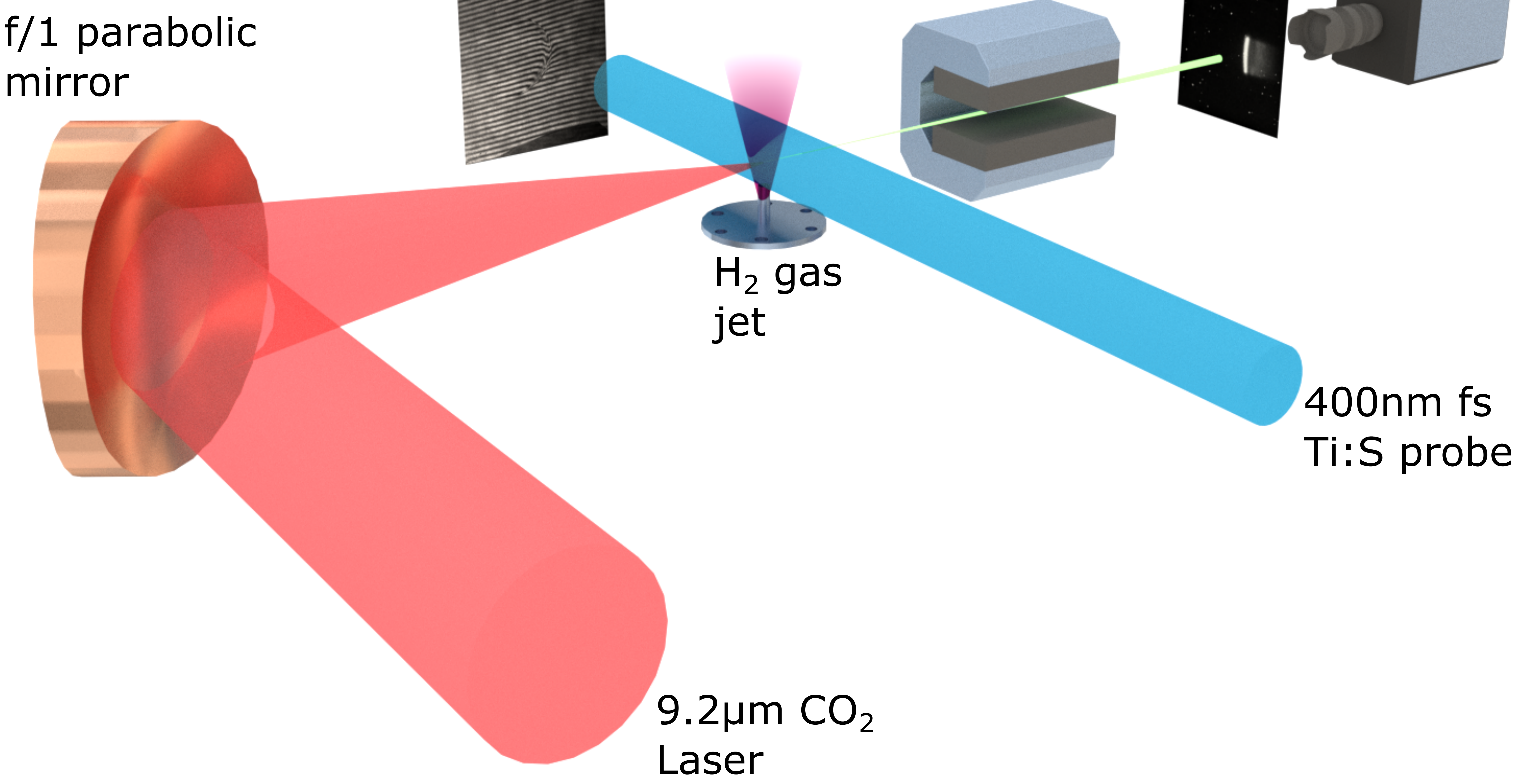


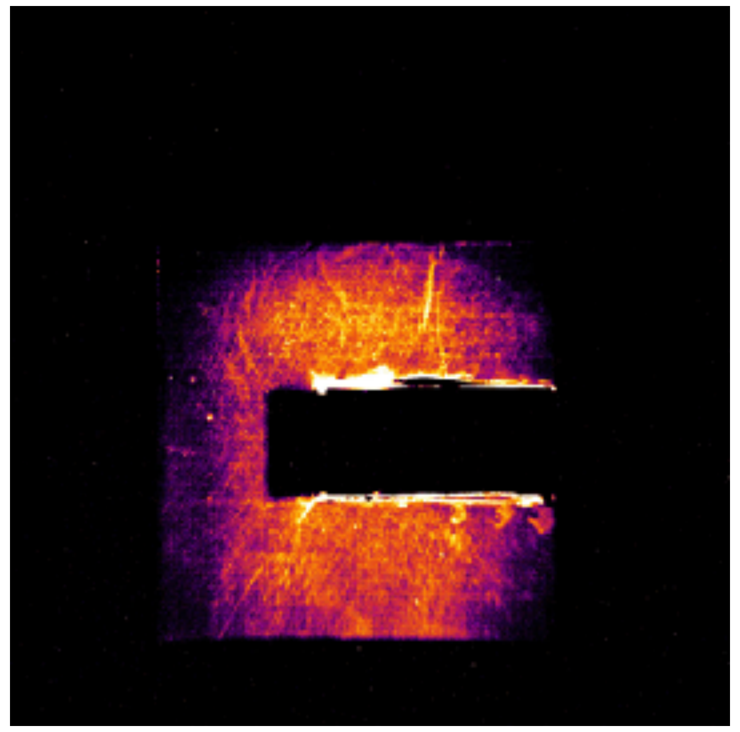
5TW Integrated Spectrum

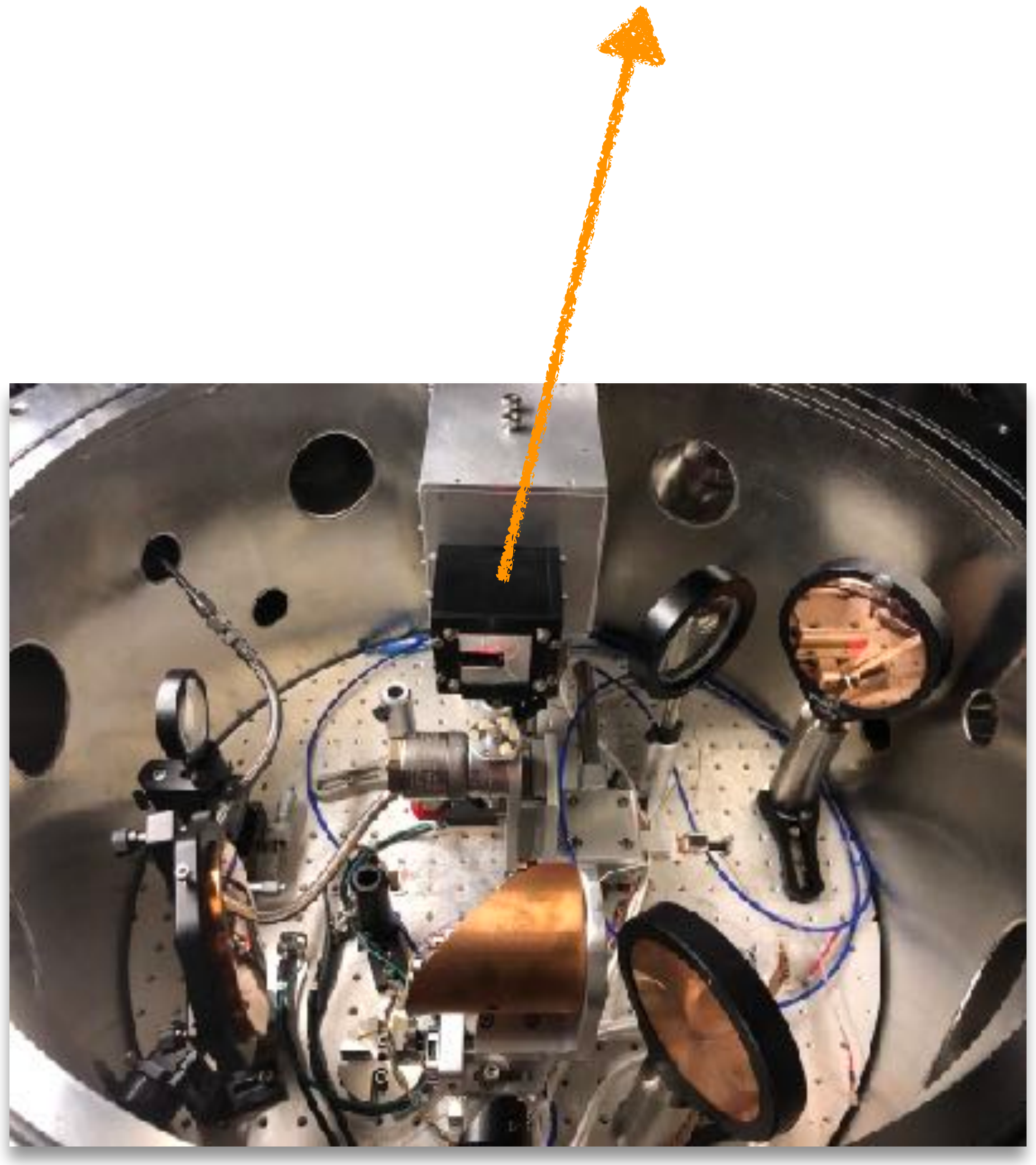


Experimental Layout







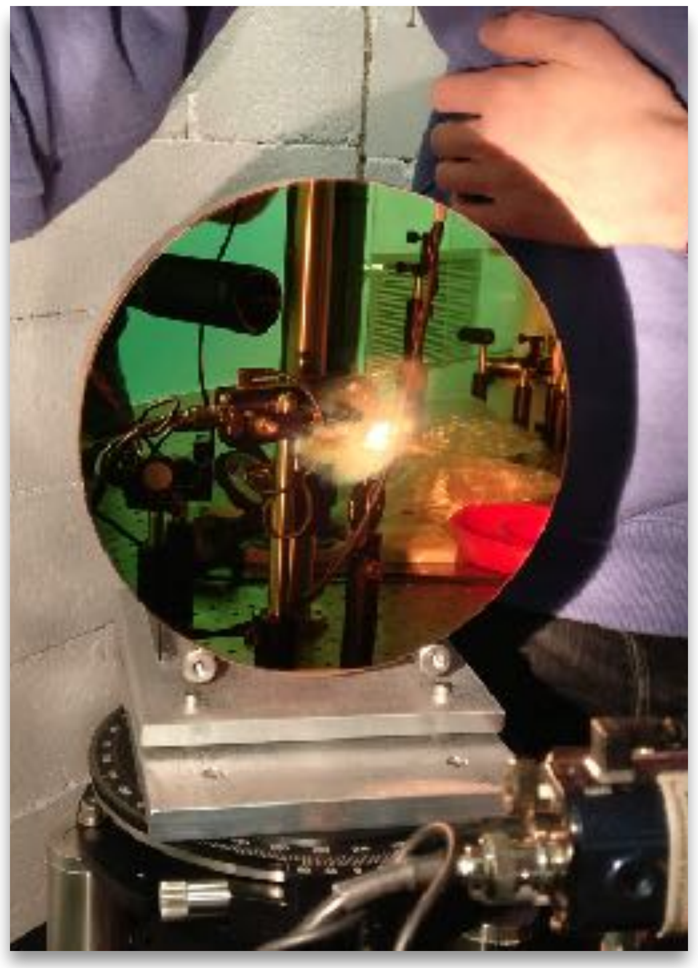


February 2020 - New Capabilities

New Capabilities:

<u>CO2:</u>

- Upgraded CO2 gives shorter pulses and higher peak powers - up to 5TW?
- Option for both linear and circular polarisation

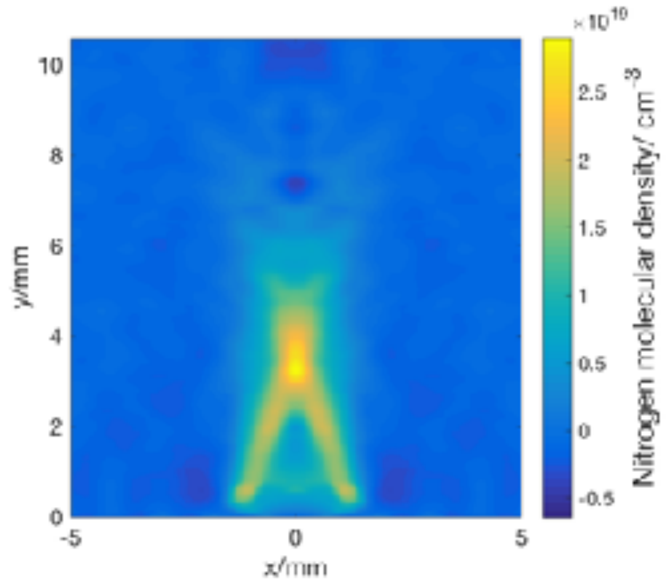


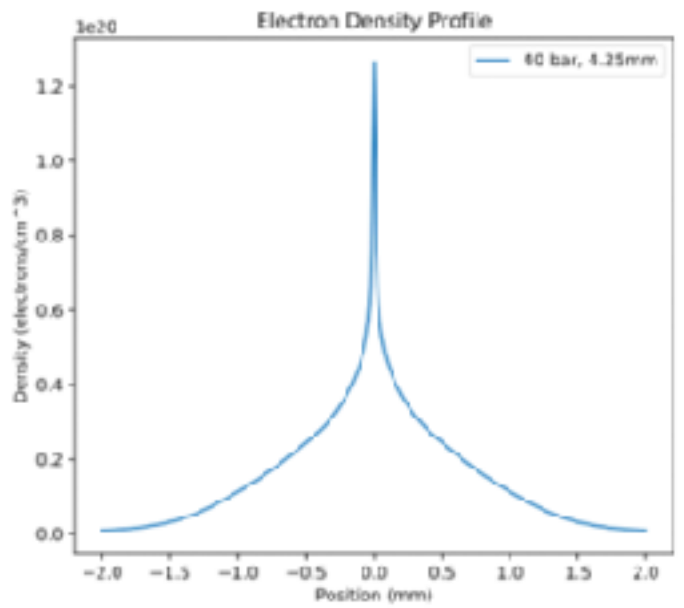
- Shorter focussing parabola (f/1), giving smaller focal spots and higher intensities than before (f/2.5)

$$\mathcal{E}_s = \frac{4I_L}{\gamma n_i c}$$

<u>Targets:</u>

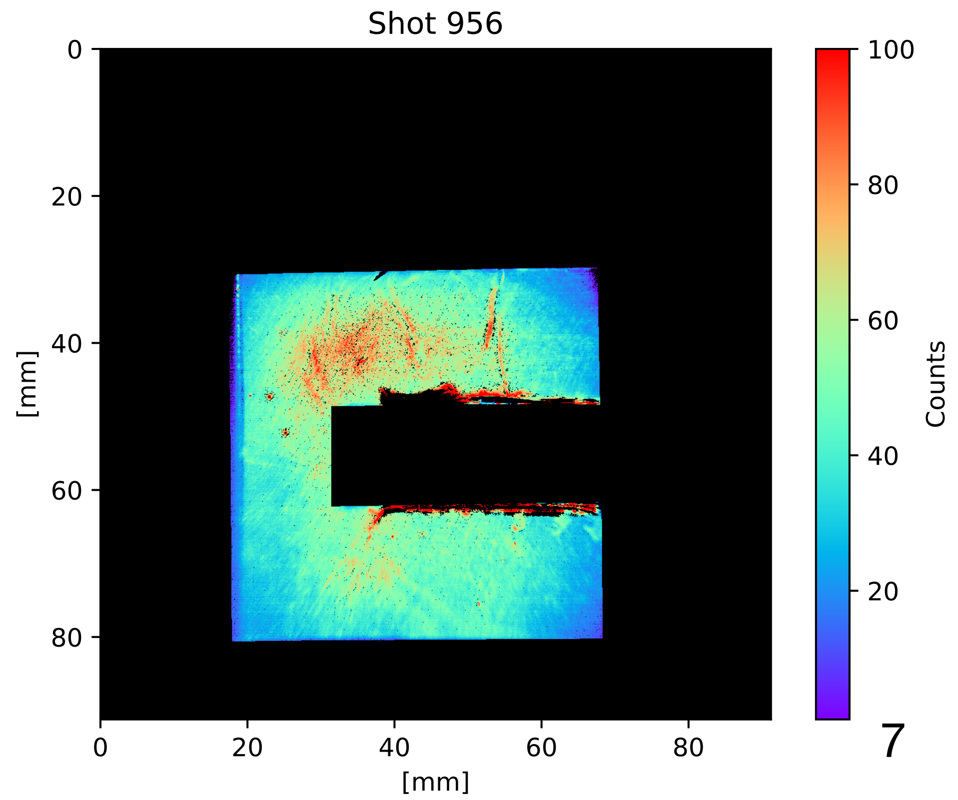
- New gas nozzle designs





<u>Diagnostics:</u>

- Proton beam profile

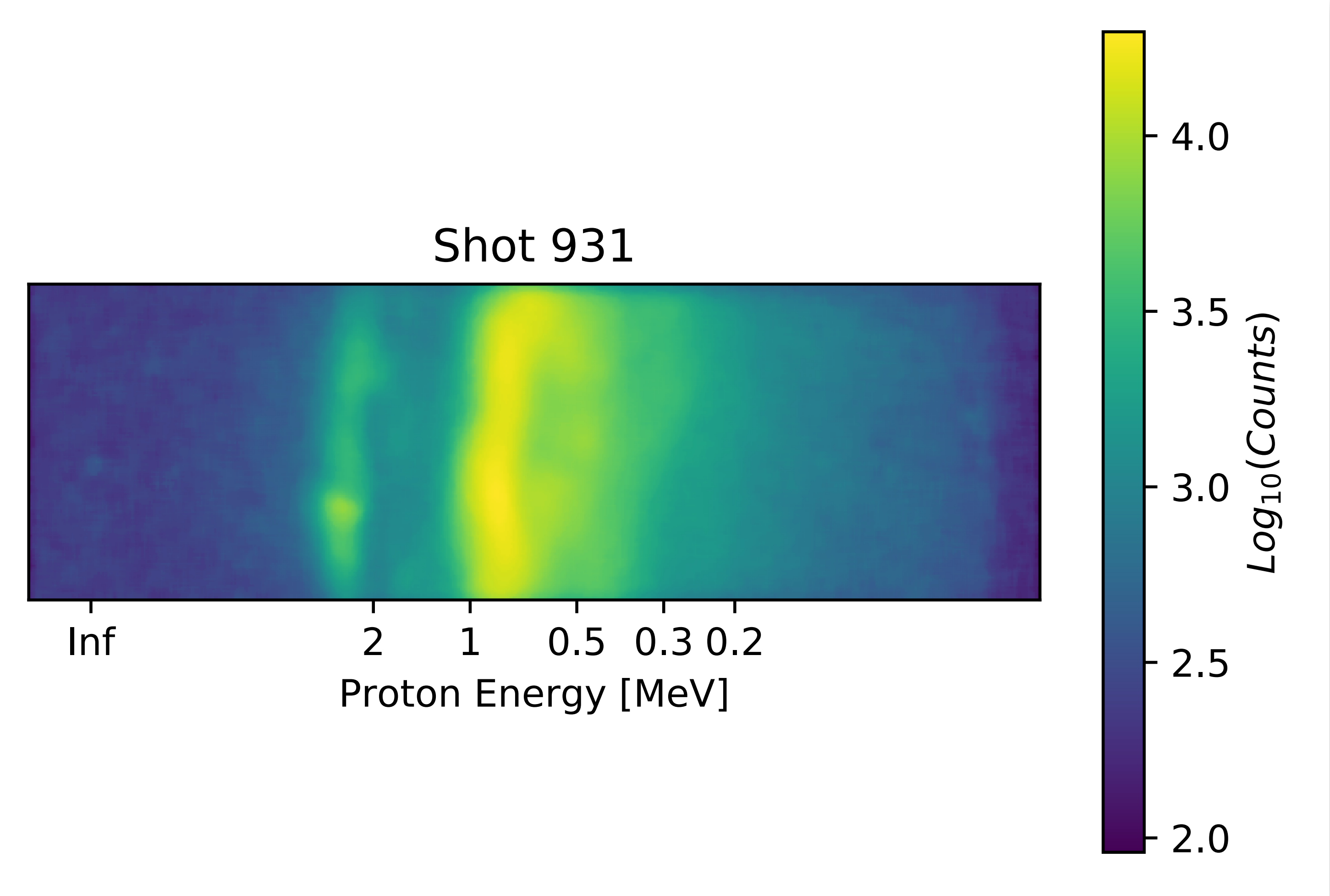


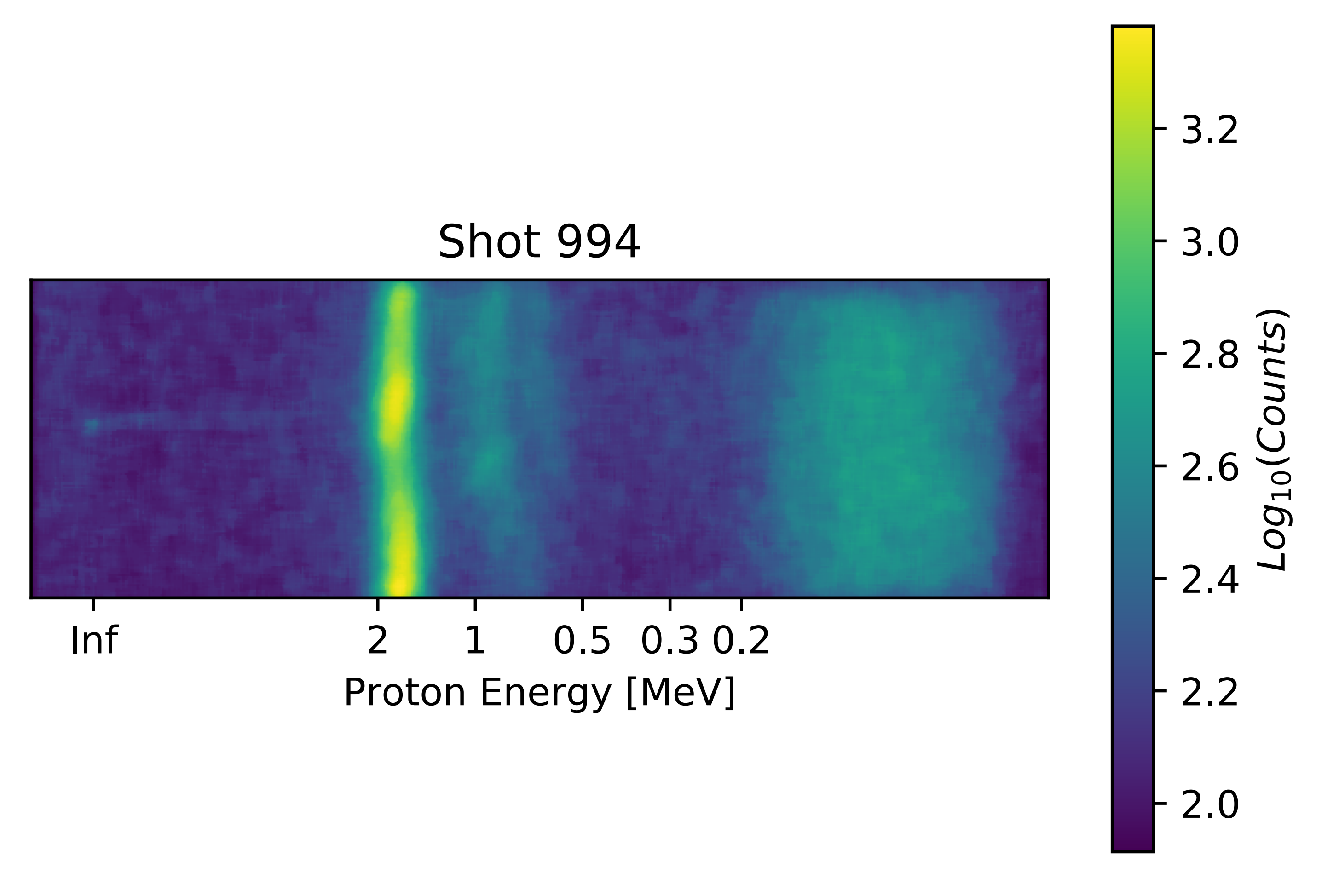
February 2020 - Preliminary Results

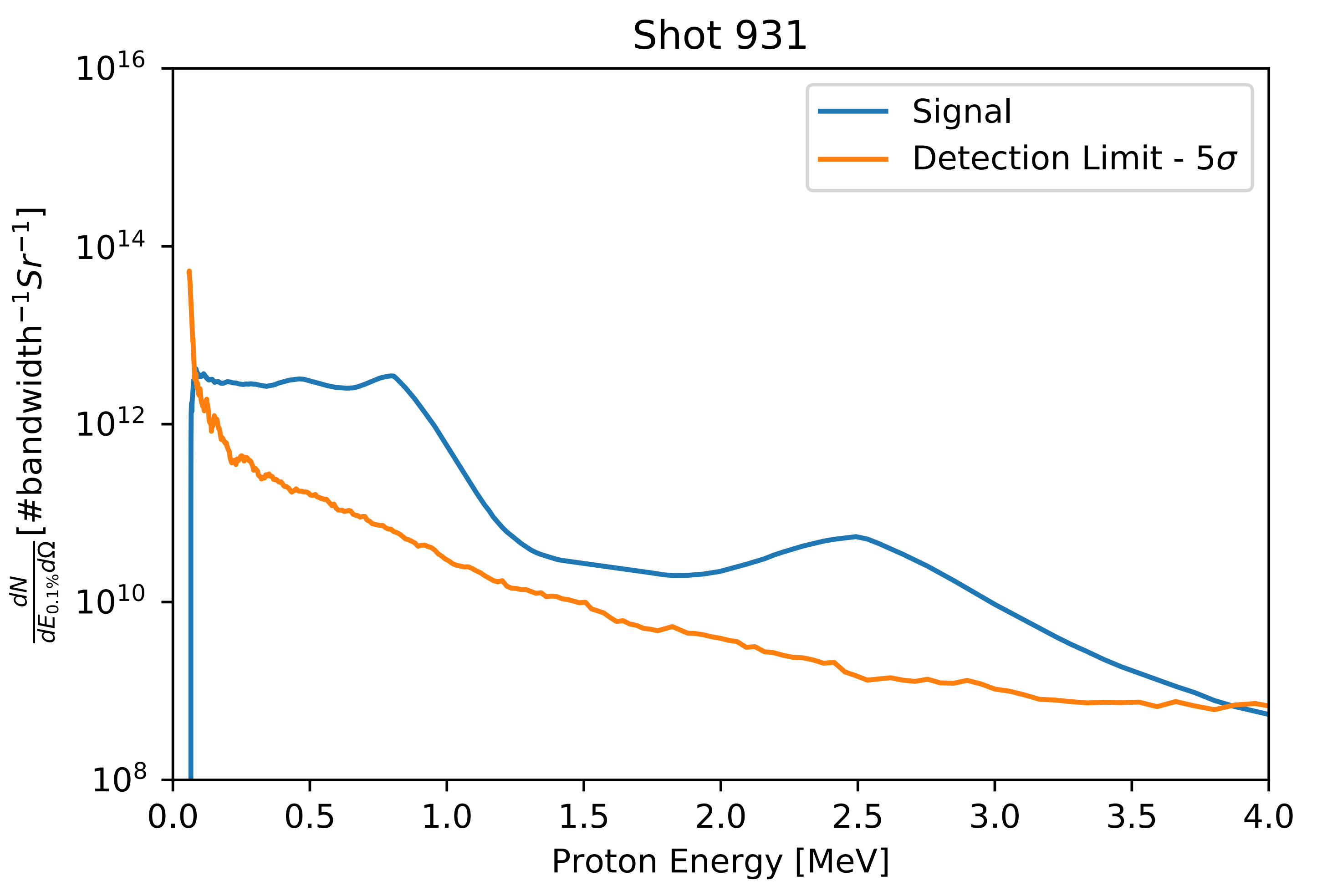
Over 1000 shots:

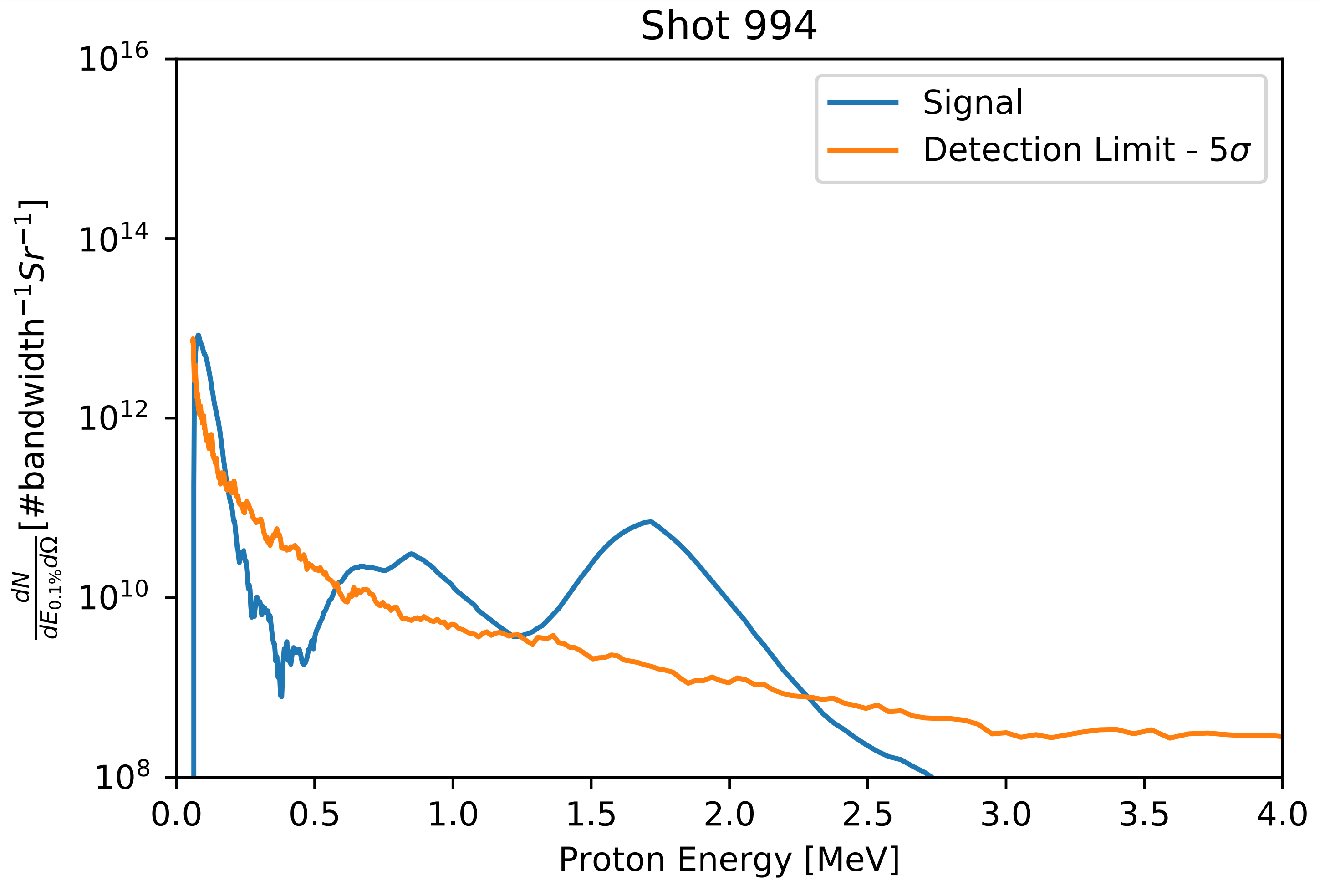
- both circular and linear polarisation

- now able to operate in regimes where proton beams possible 100% of the time.



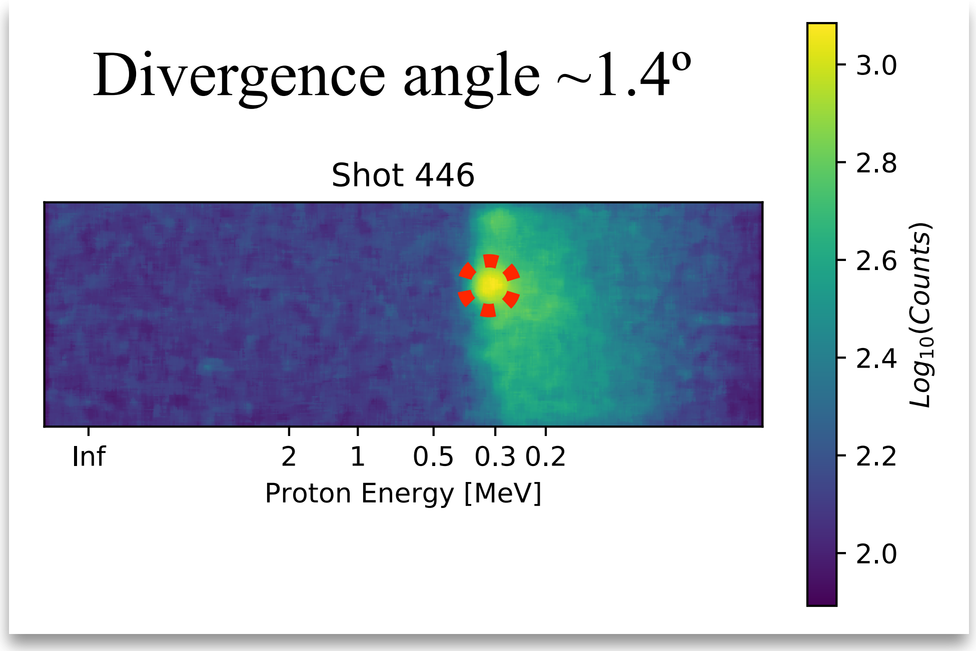


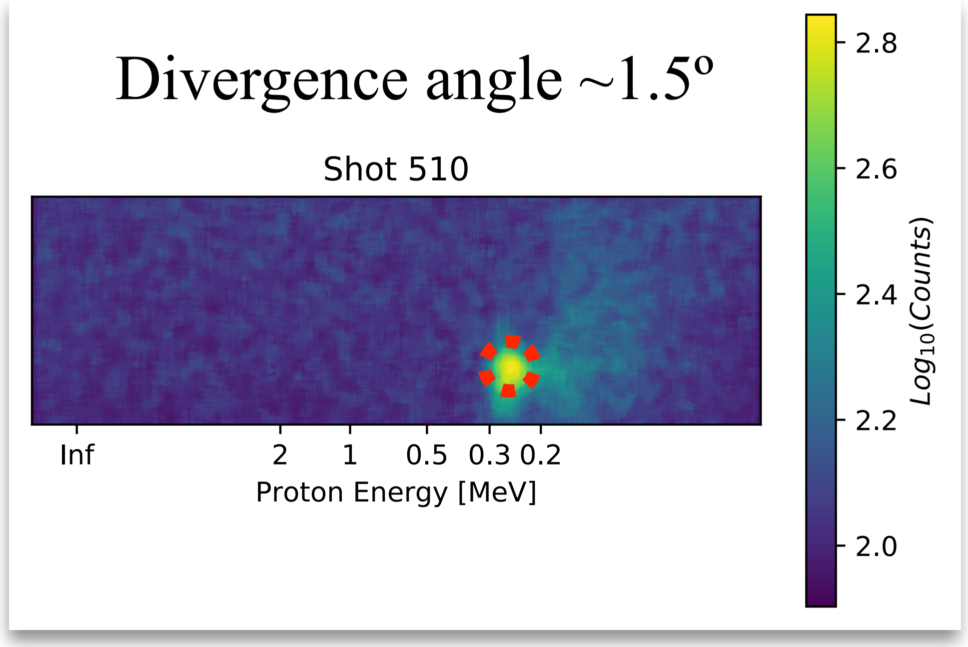


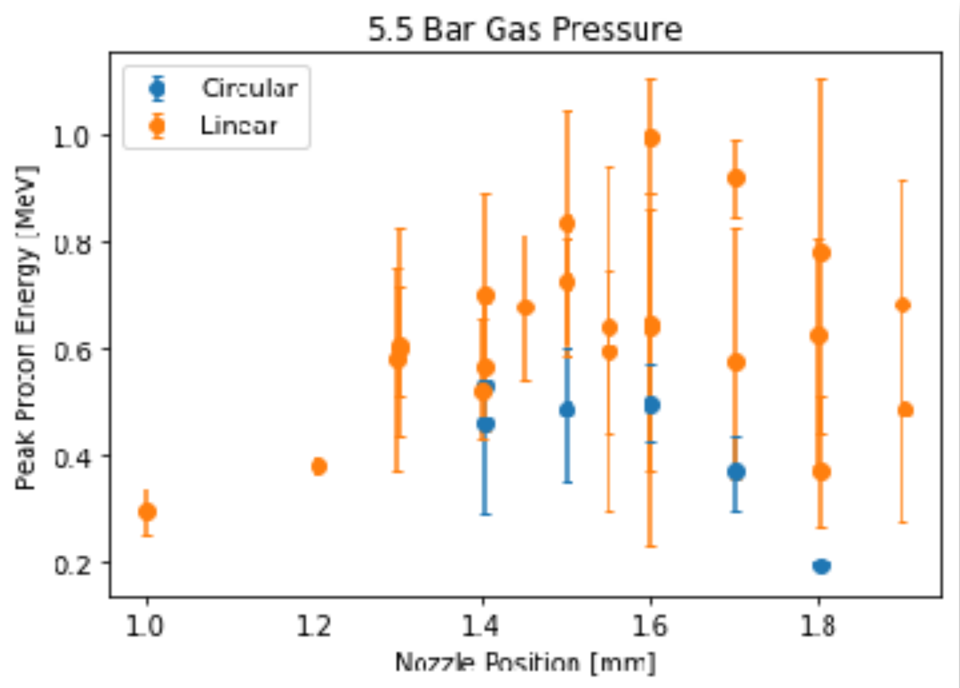


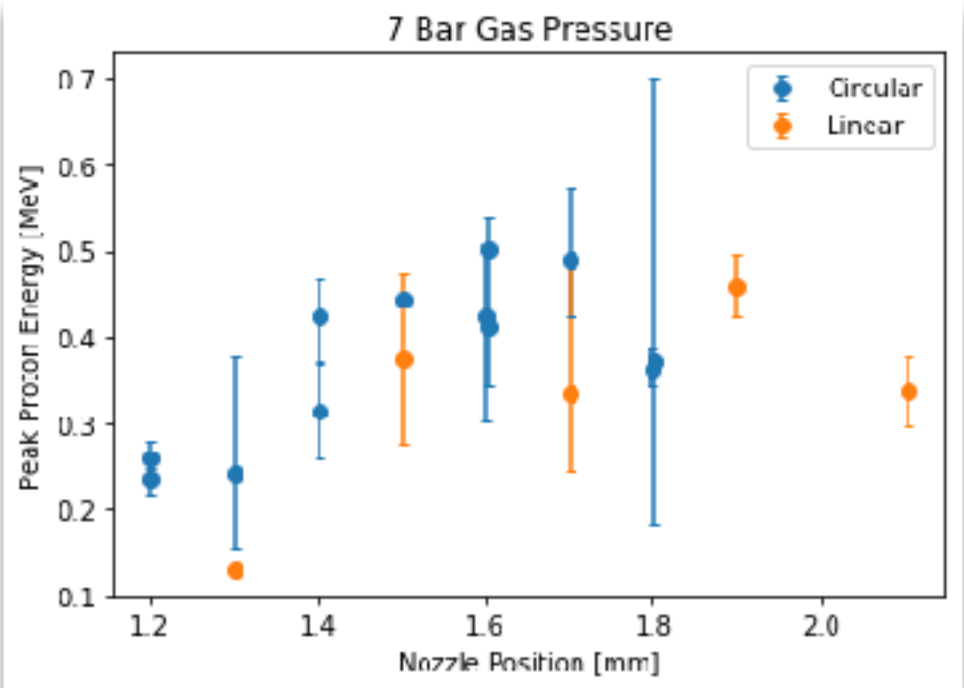
February 2020 - Preliminary Results

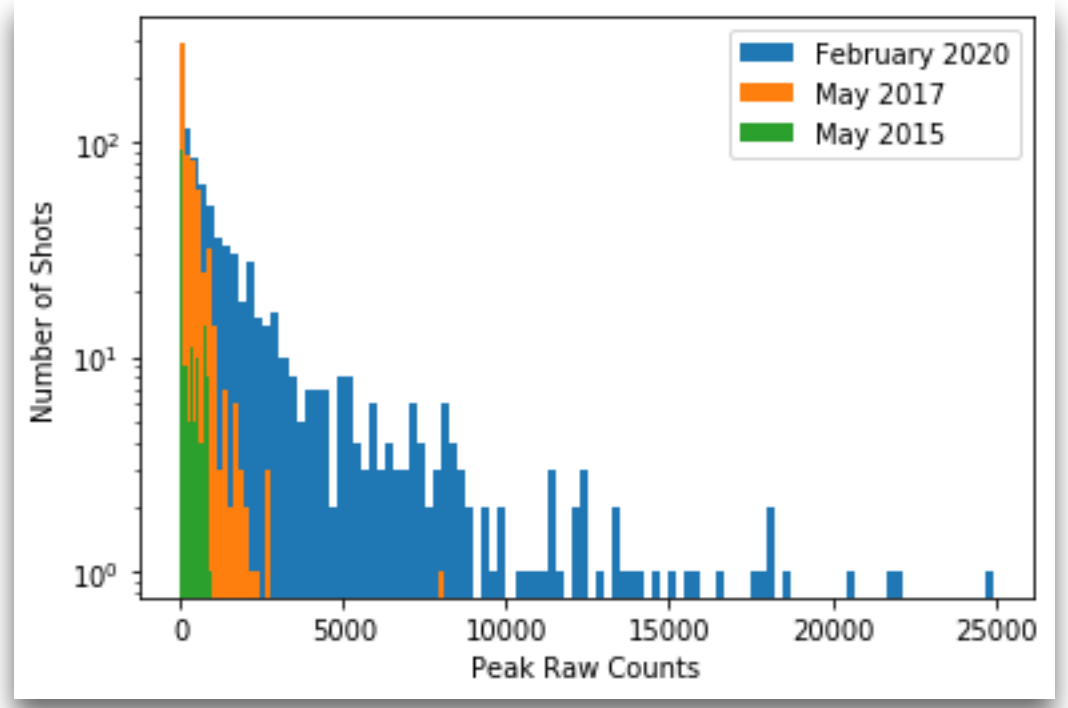
- Observed low divergence (lower energy) beams - possibly due to filamentation of the laser
- Circular versus linear polarisation investigated at different densities
  - Linear appear to be better for lower pressures (densities) and circular better at higher densities?
  - Circular relatively less sensitive to target density?
- Increased beam charge during experiment with ~3.7x increase in average detector counts on ion spectrometer compared to previous experiments





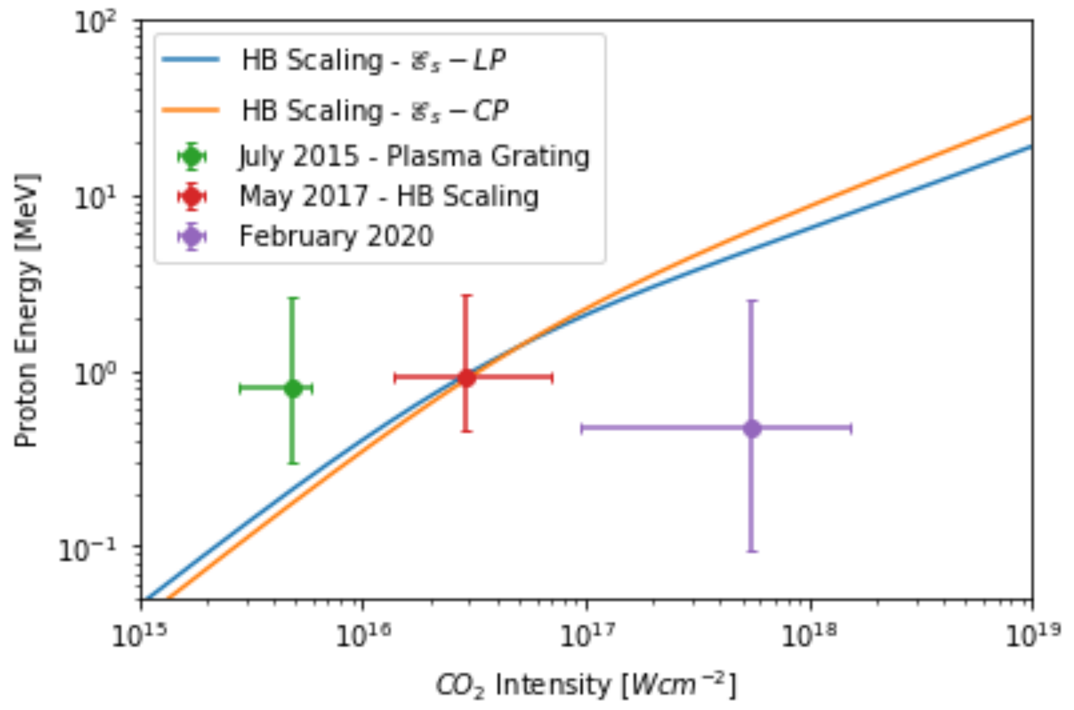




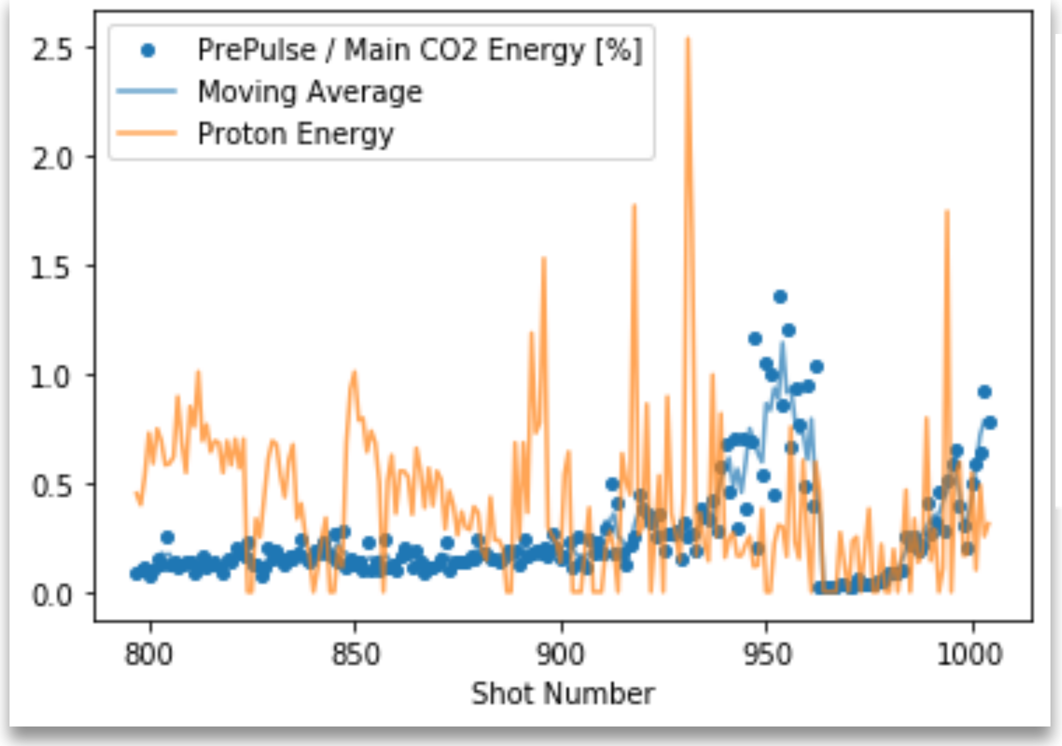


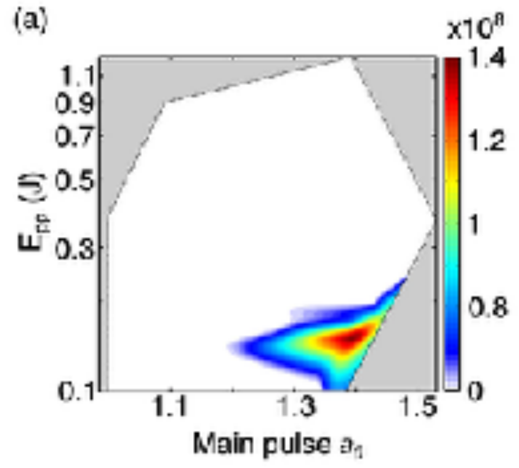
February 2020 - Challenges

- No obvious increase in maximum proton energy - still investigating why…



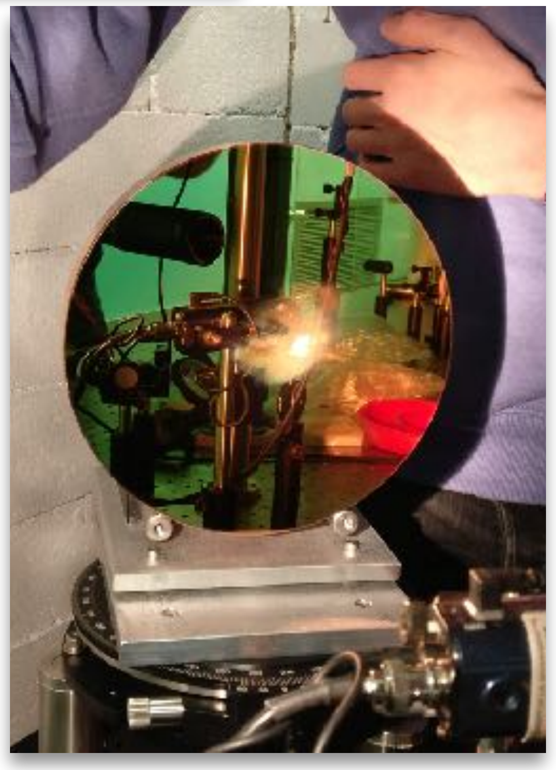
- Parasitic pre-pulse arising from leakage through regenerative amplifier germanium pulse switcher
  - pre-pulse time fixed by regen geometry (20ns)
  - energy depends on amplifier conditions
  - germanium gets damaged over time, leading to further variability





O. Tresca, N. P. Dover, N. Cook et al., Phys. Rev. Lett. 115, 094802 (2015).

- Phase change mirror showed signs of damage despite earlier tests



- Radiation alarm triggering…

COVID-19 Pandemic Impacts

- Please summarize any significant impacts from COVID-19 on your experiment and team during 2020

  - Unable to conduct radiation tests in April, as planned.

  - Unable to conduct further experiments in second half of year

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 2TW - 5TW if available*
	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*

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		

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
    - Uncompressed CO_2 - bypass compressor possible?
- Ti:Sapphire and Nd:YAG Lasers
  - Please note any specialty non-CO_2 laser configurations required here:
    - Ti:sapphire required for probing at <75fs
- Hazards & Special Installation Requirements
  - Updated shielding requirements, depending on outcome of radiation tests
  - Possible new magnet for updated ion spectrometer

Experimental Time Request

CY2021 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 due to radiation concerns

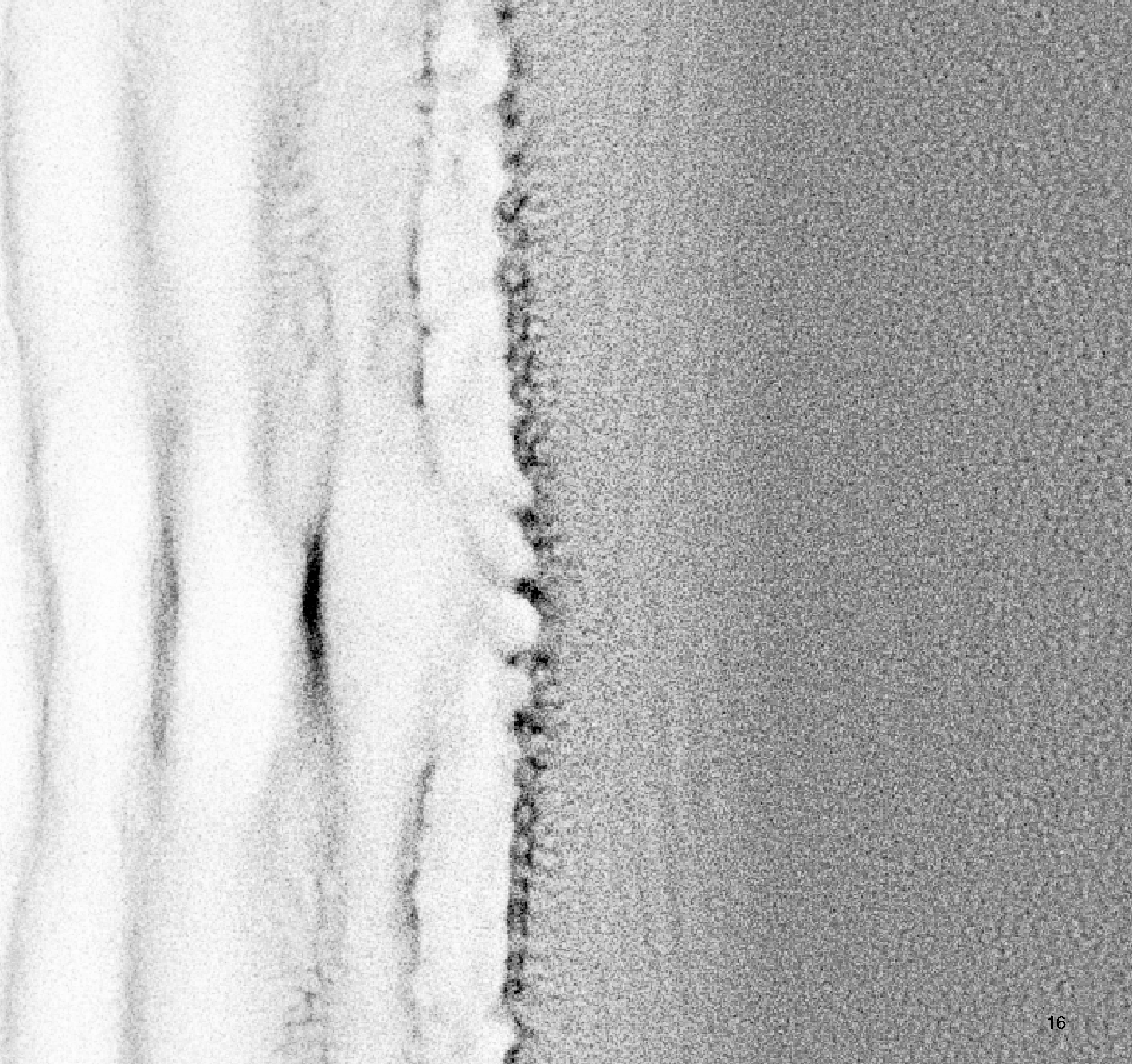
Time Estimate for Remaining Years of Experiment (including CY2021)

Capability	Setup Hours	Running Hours
Electron Beam Only		
Laser* Only (in FEL Room)	100	300
Laser* + Electron Beam		

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

Summary - AE100

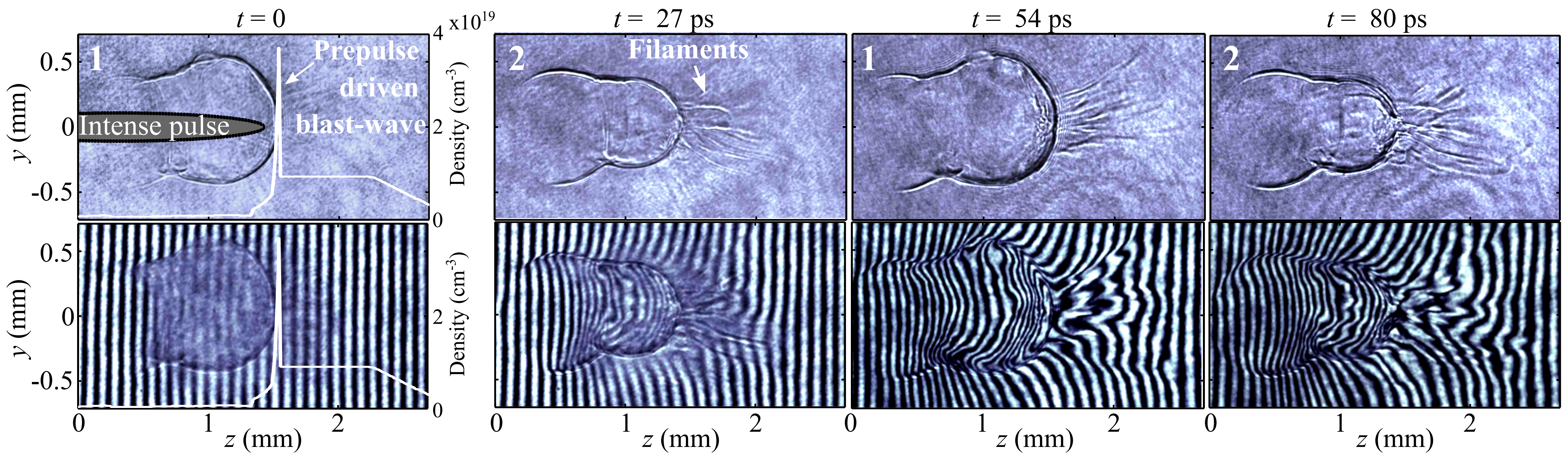
- Stable regime of acceleration observed with increased charge
- No increase in ion energies with shorter focussing
  - still to implement full prepulse control (time and energy)
  - need to remove parasitic pulses
- Circular polarisation does show increase in energies under certain parameters
  - limited parameter space explored
- A number of significant challenges still to be addressed



Thank you for listening.
Questions?

Driving Weibel-type filamentation by CO2 laser driven electrons

*Courtesy of Nick Dover



Relativistic laser plasma interaction with just-overdense targets results in energetic electrons with beam density just a little lower than target density

$$\alpha = \frac{n_b}{n_e} \approx 0.1$$

Weibel-type filamentation instabilities grow as

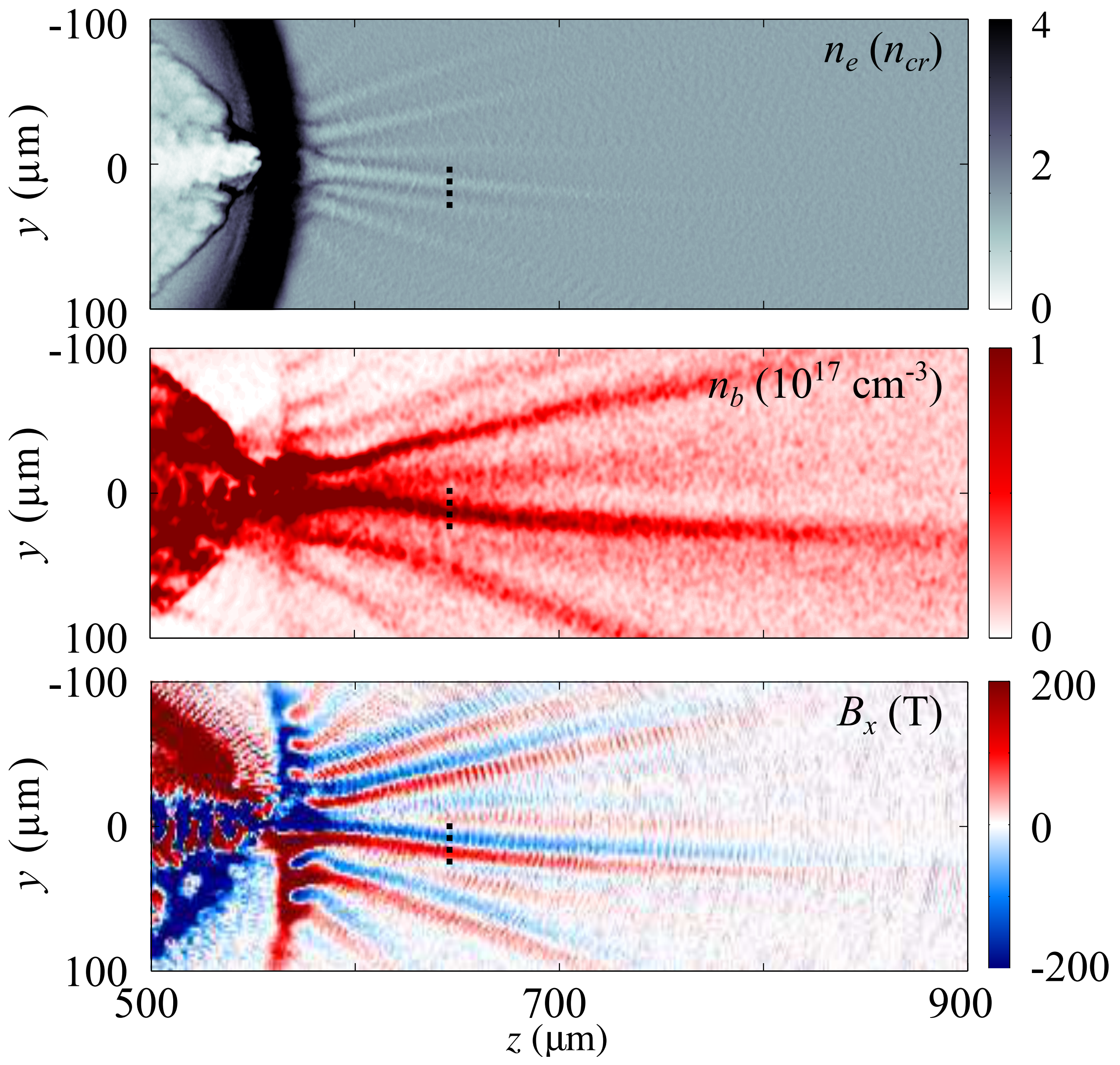
$$\delta \approx \omega_p \left(\frac{\alpha}{\gamma_b}\right)^{1/2} \beta_b$$

For $n_e \approx n_c$ and $a_0 \approx 1$, this is (very roughly)

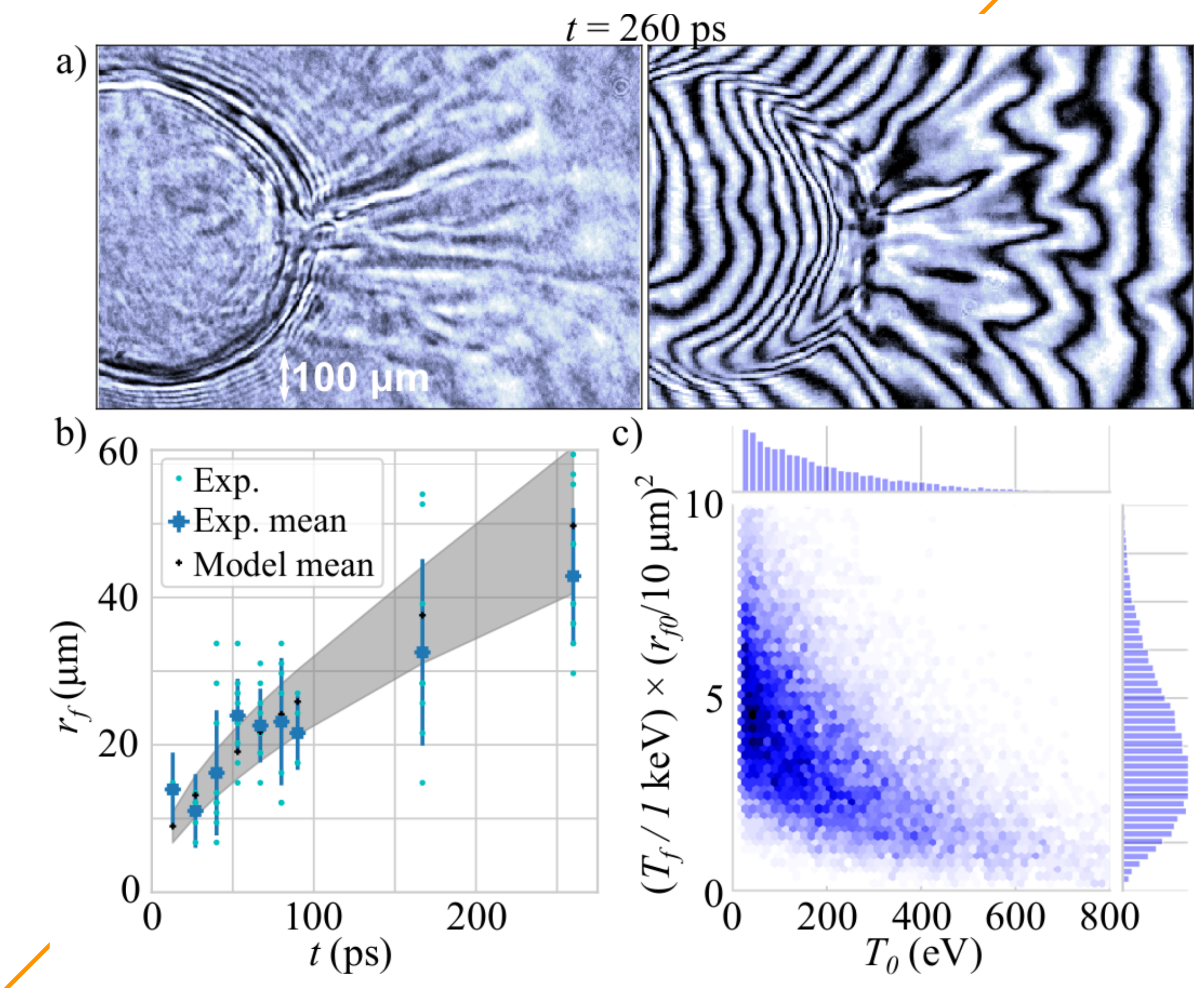
$$\frac{\delta}{\omega_L} \approx \alpha^{1/2}$$

The electrons driven by many-cycle CO2 pulse will therefore strongly drive the instability

Evidence of enhanced heating along filaments by energetic electrons



PIC simulation confirms generation of filamentation instability and shows energetic electron beam guiding along filaments



Optical probing after laser shows filament expansion, i.e. enhanced heating along filaments

Markov Chain Monte Carlo simulation of filament expansion model gives filament temperature of (6±3) keV, much higher than the (200±150) eV ambient plasma