Experimental demonstration of the acceleration of electrons from a linear accelerator by a laser driven plasma wakefield at CLARA

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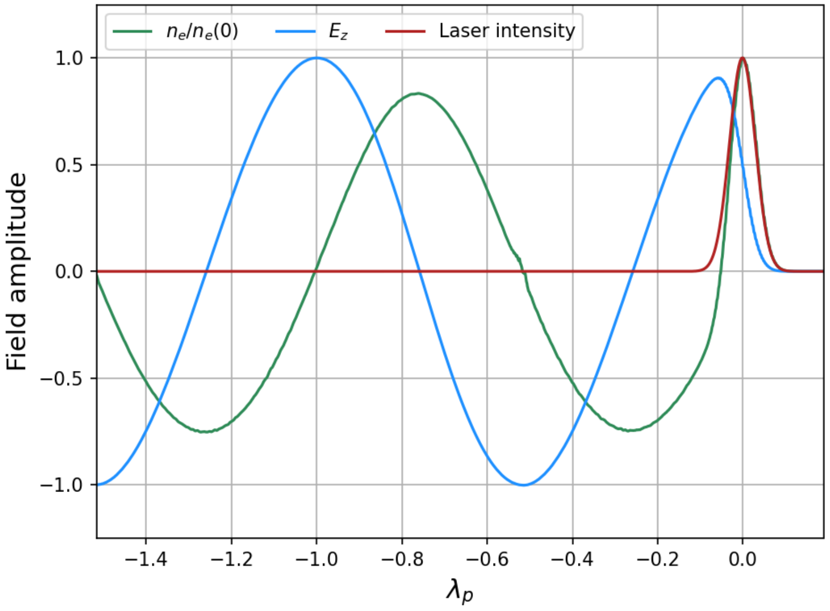
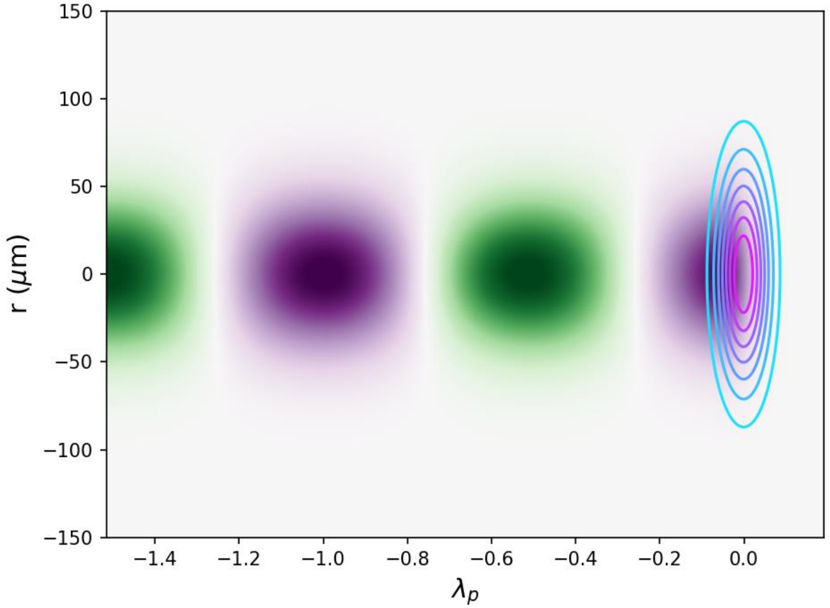
Laser wakefield acceleration

- Laser wakefield acceleration is a method of generating high energy (MeV – GeV) electrons.
- A high intensity laser pulse ionises gas into a plasma.
- Laser then drives a wake wave of electron density behind it.

- Accelerating field can reach 100s GVm^{-1}.





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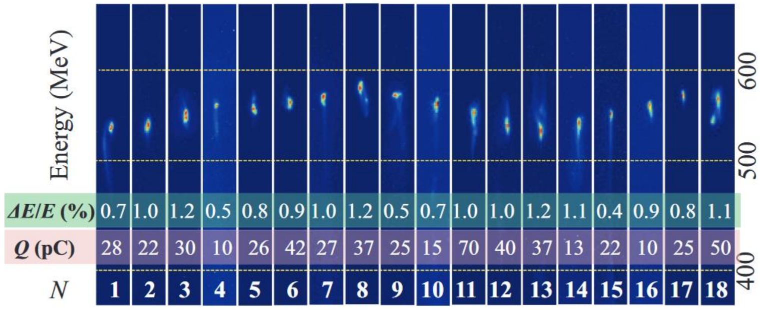
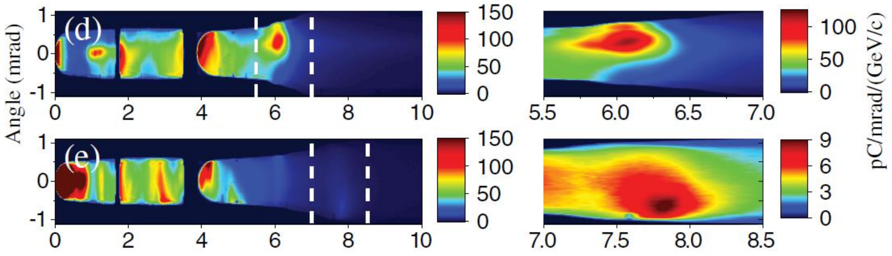
Achievements of LWFA



ΔE/E (%)	0.7	1.0	1.2	0.5	0.8	0.9	1.0	1.2	0.5	0.7	1.0	1.0	1.2	1.1	0.4	0.9	0.8	1.1
Q (pC)	28	22	30	10	26	42	27	37	25	15	70	40	37	13	22	10	25	50
N	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18

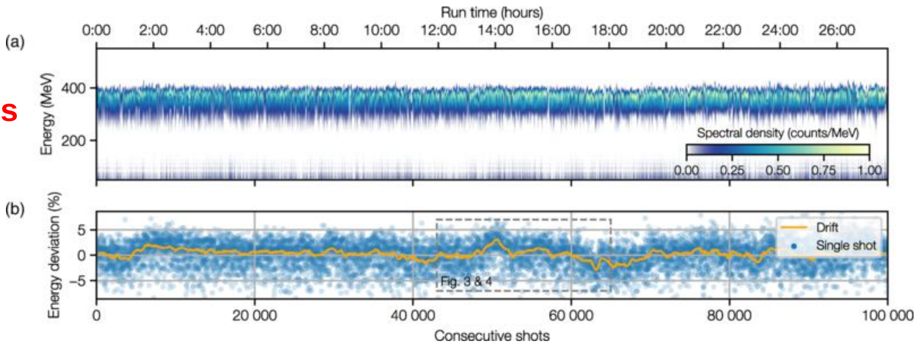
Sub-percent energy spread

Wang et al., Phys. Rev. Lett. 117, 124801 (2016)



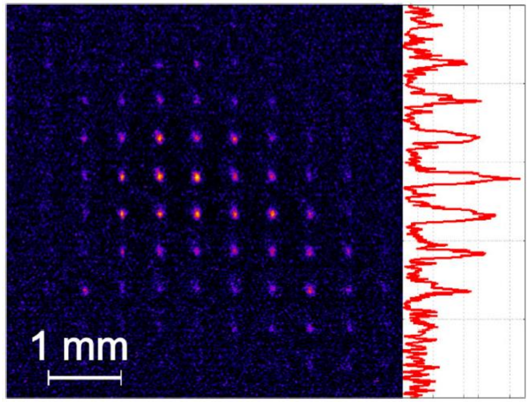
Electrons up to 8 GeV

Gonsalves et al., PRL, 122, 084801 (2019)



Stability over >24 hrs

Maier et al., PHYS. REV. X 10, 031039 (2020)

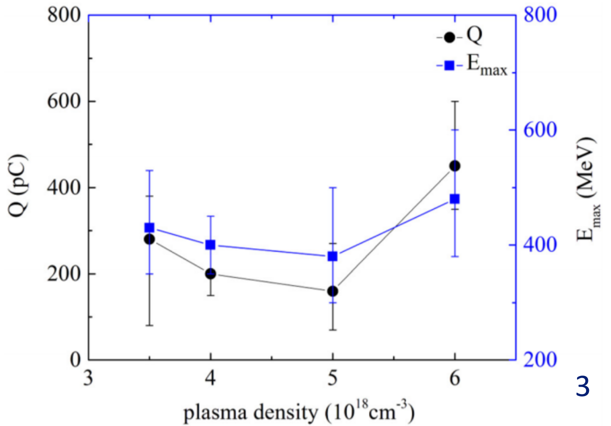


< 1 mm mrad emittance

Brunetti et al., Phys. Rev. Lett. 105, 215007 (2010)

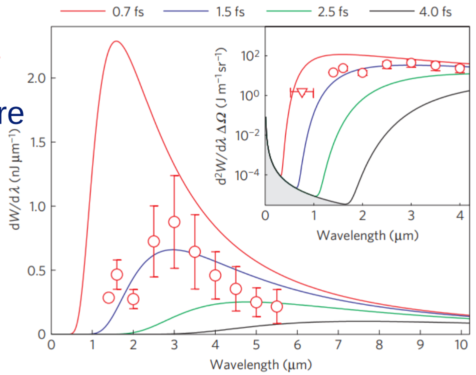
Up to 500 pC charge

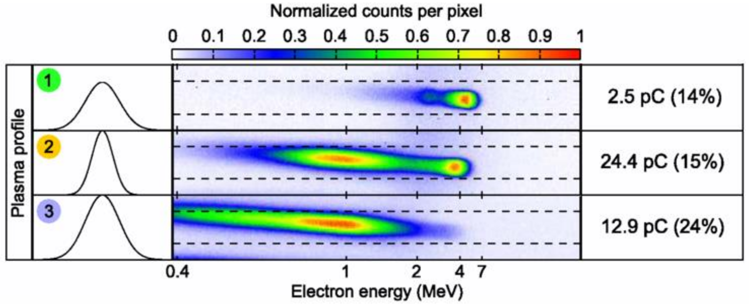
Li et al., Phys. Plasmas 24, 023108 (2017)



Ultrashort electron beams

Lundh et al., Nature physics, 7, 219–222 (2011)





Operation at 1 kHz

Gustas et al., Phys. Rev. Accel. Beams 21, 013401 (2018)

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External injection

- Combines advantages of conventional and plasma based accelerators.
- Beam quality preservation has been shown in simulation only.
- Ideal candidate for testing staged plasma acceleration.
- The CERN expert panel identified **beam quality** and **staged acceleration** of plasma accelerators as an important milestone for the field.
- In the EuPRAXIA conceptual design report, 3 out of 4 laser wakefield schemes require external or staged acceleration with beam quality preservation.
- Single demonstration to date with low charge beam.
- CLARA is one of the few facilities with electron beam and high power laser.

https://e-publishing.cern.ch/index.php/CYRM/issue/view/146
Assmann, R.W. *et al.* EuPRAXIA Conceptual Design Report. *Eur. Phys. J. Spec. Top.* **229,** 3675–4284 (2020).
Wu, Y. *et al.* Nature Physics volume 17, pages 801–806 (2021)

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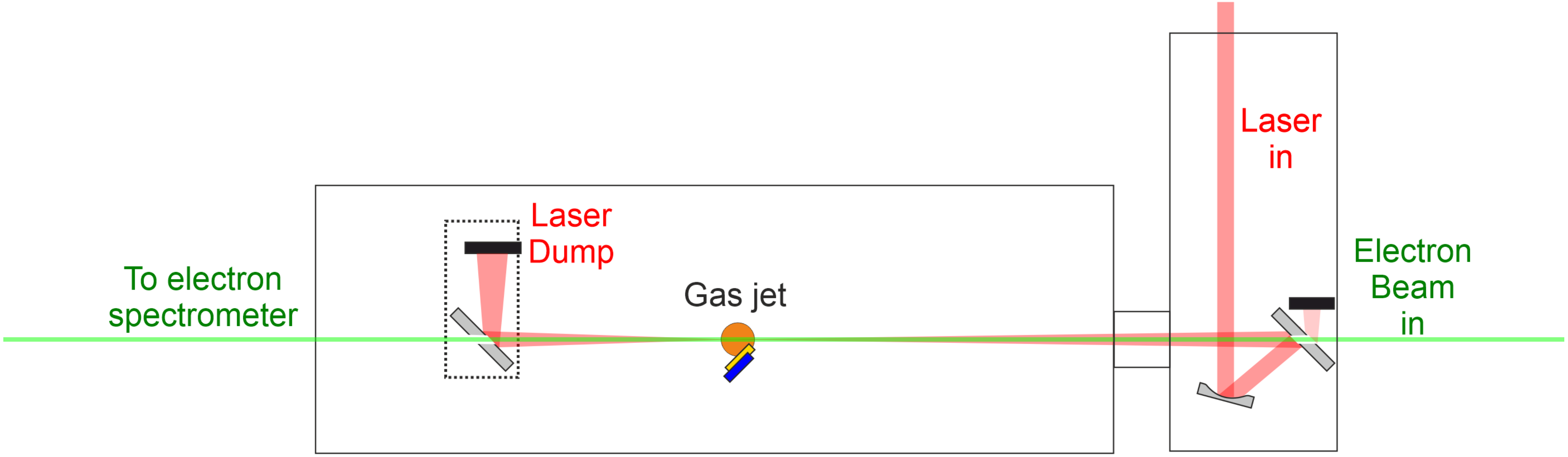
Experimental layout

Experiment performed on CLARA accelerator at Daresbury laboratory.



- Gas jet backed with Nitrogen gas at 6 bar. Laser ~ 5 mm above it.
- Laser & electron beam timed to arrive above the gas jet at the same time.
- Proof of principle experiment at CLARA – We aim to build on this.

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External injection at CLARA

Electron beam:

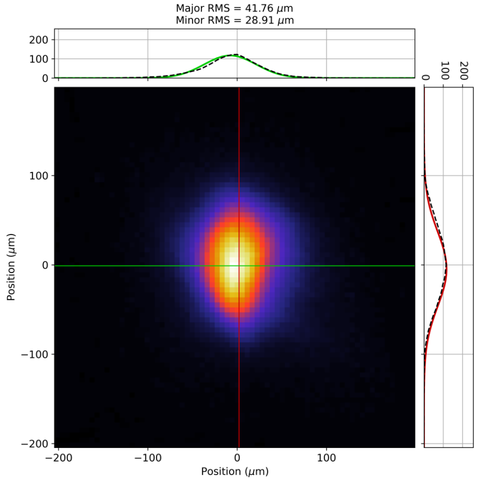
$E = 35$ MeV

$\sigma_r \sim 35$ μm

$\sigma_z \sim 450$ μm

$\sigma_E = 10 – 20$ keV

$Q = 20$ pC



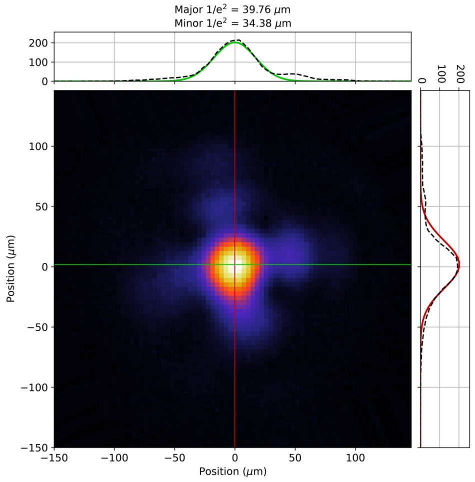
Laser:

$E = 8 – 40$ mJ

$\tau_{FWHM} = 90$ fs

$\omega_0 = 40$ μm

$a_0 = 0.04 – 0.08$

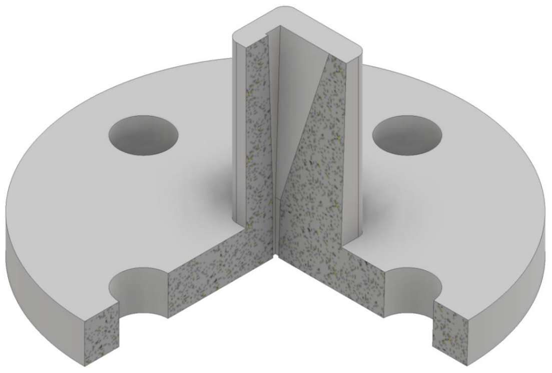


Plasma:

$n_e = 2.1\times10^{18}$ cm^{-3}

$\lambda_p = 23$ μm

$L_p \sim 8$ mm

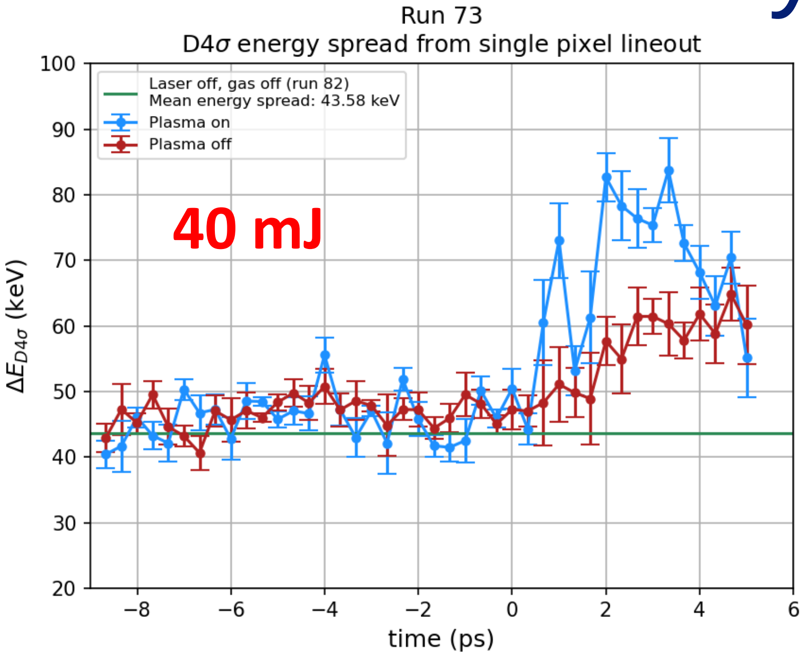


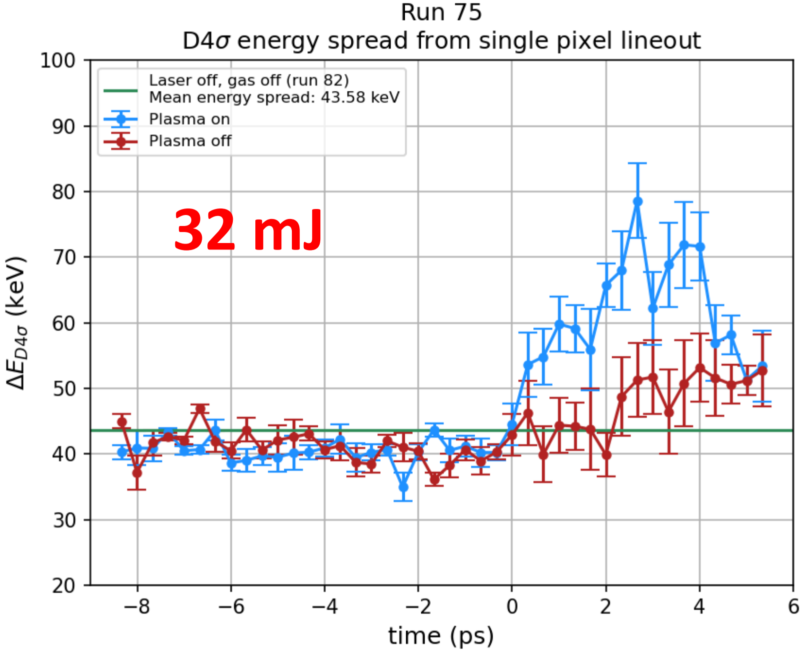
$\sigma_z >> \lambda_p$ – signature of a successful interaction is a **broadening** of the electron beam energy spectrum.

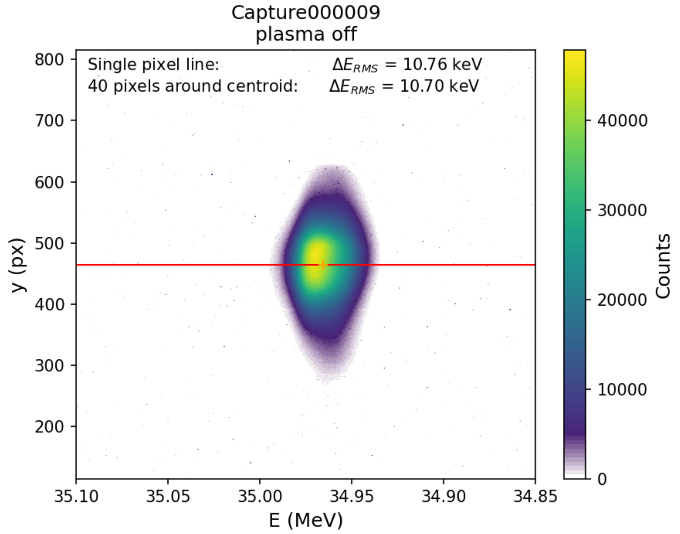
Results – Preliminary

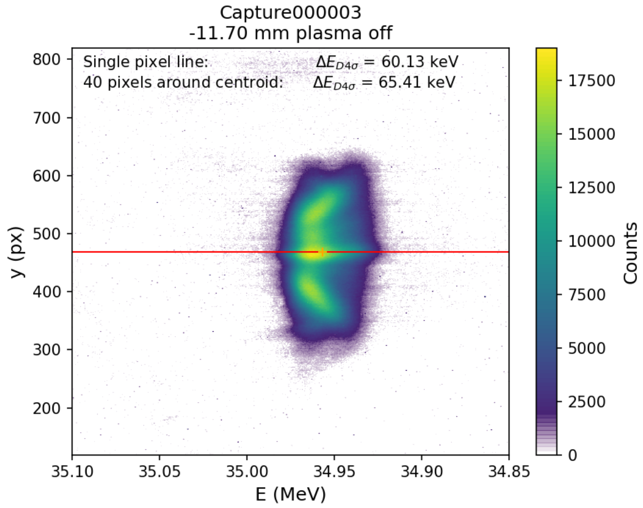
- Laser & electron beam – 10 Hz, gas jet opening – 5 Hz.
- Complicated by low density plasma in chamber when gas jet off.
- Looking at width (energy spread) of electron beam on e-spec with arrival time of laser & e$^-$ bunch.

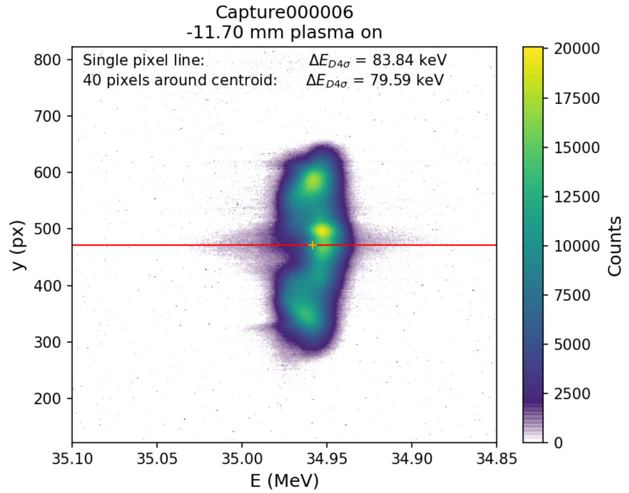
250 mJ in laser lab – 40 mJ on target


Run 73
D4σ energy spread from single pixel lineout


Run 75
D4σ energy spread from single pixel lineout

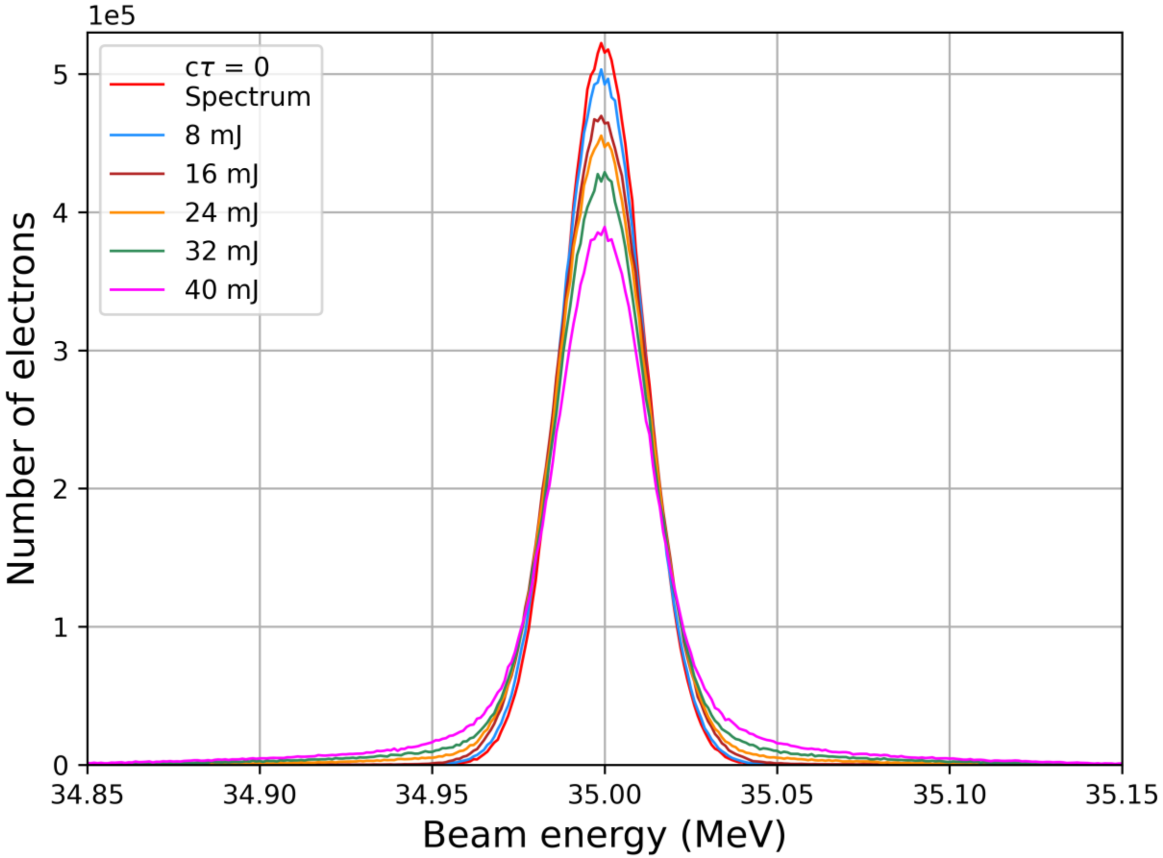

Capture000009
plasma off


Capture000003
-11.70 mm plasma off


Capture000006
-11.70 mm plasma on

Simulations

Experimental measurements were compared to **FBPIC simulations**.



- Laser & electron parameters taken from experiment.
- Gas profile taken from FLUENT simulation of target.
- ADK ionisation of N gas included to correctly model laser propagation.

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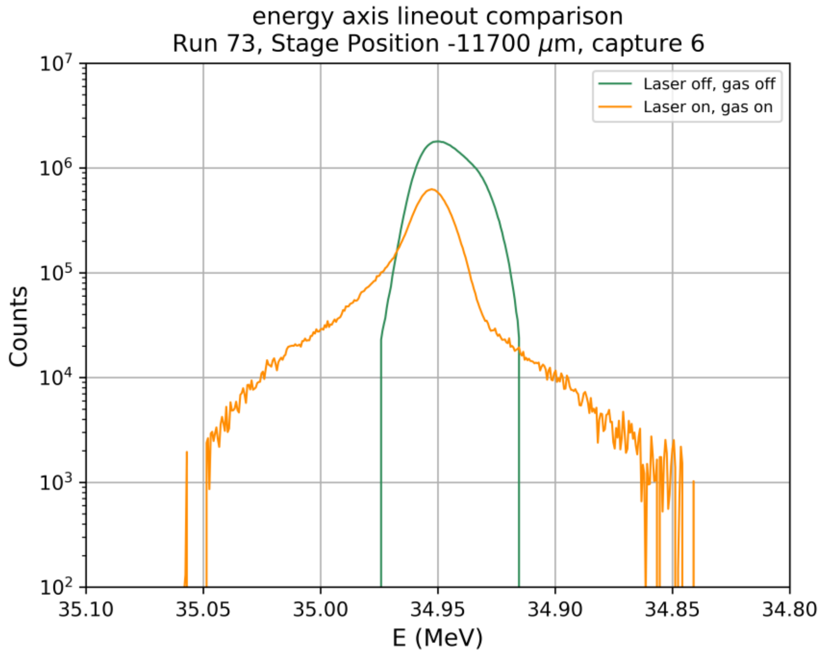
Accelerating gradient

Experiment:

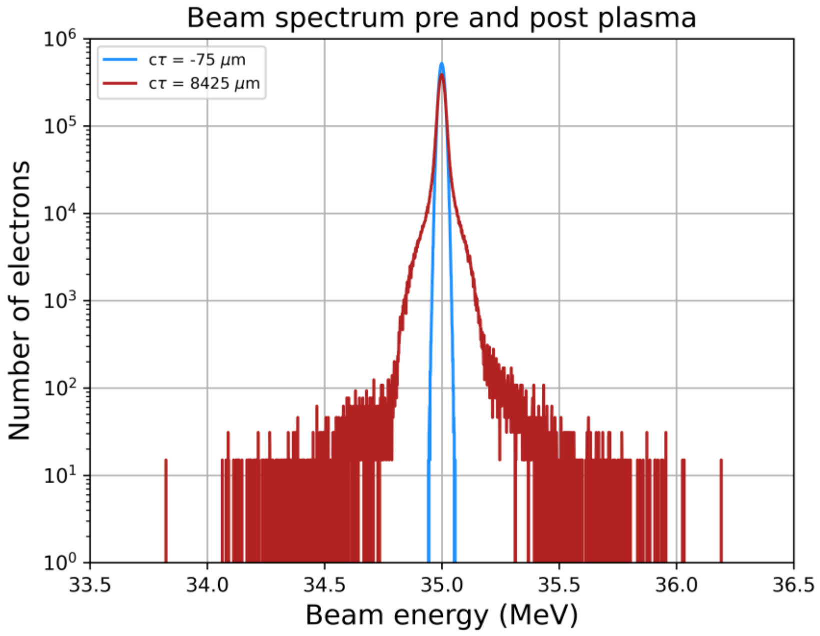
- Max. energy gain ~ **100 keV.**
- 8 mm plasma: gradient ~ **12.5 MV/m.**

Simulation:

- Max. energy gain ~ **900 keV.**
- 8 mm plasma: gradient ~ **112 MV/m.**
- Camera response must be taken into account.
- 12 bit camera, 200 keV energy gain: **25 MV/m**



energy axis lineout comparison
Run 73, Stage Position -11700 μm, capture 6



Beam spectrum pre and post plasma

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Accelerating gradient

Experiment:

- Max. energy gain ~ **100 keV.**
- 8 mm plasma: gradient ~ **12.5 MV/m.**

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- Max. energy gain ~ **900 keV.**
- 8 mm plasma: gradient ~ **112 MV/m.**
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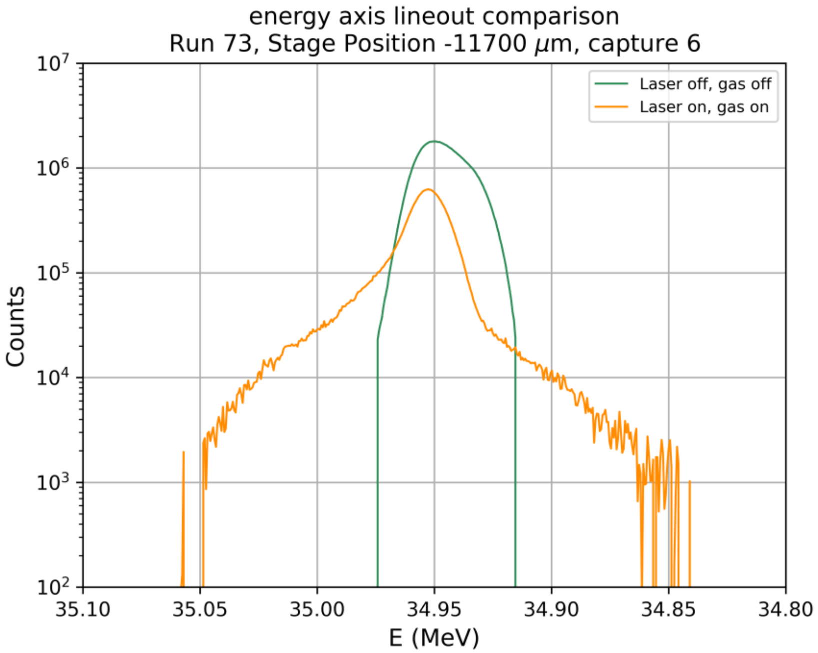

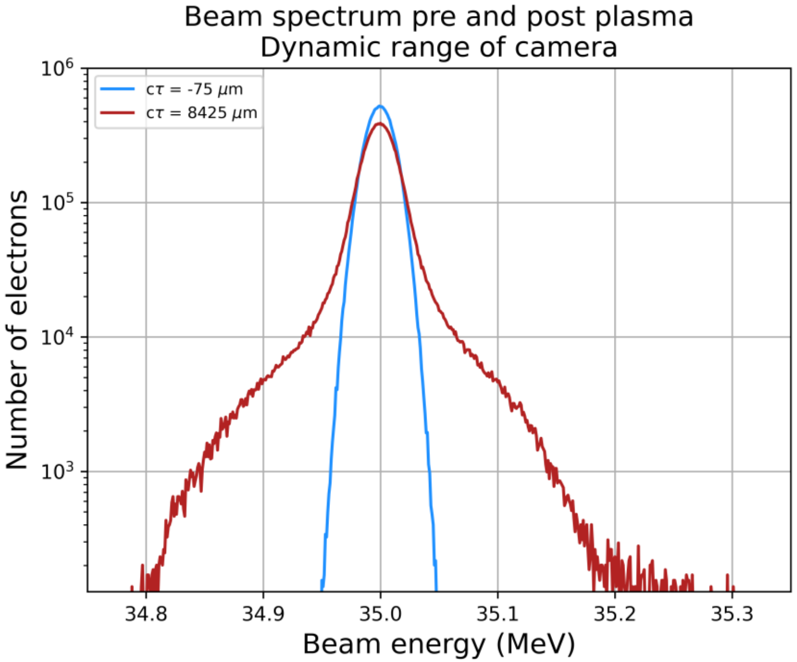

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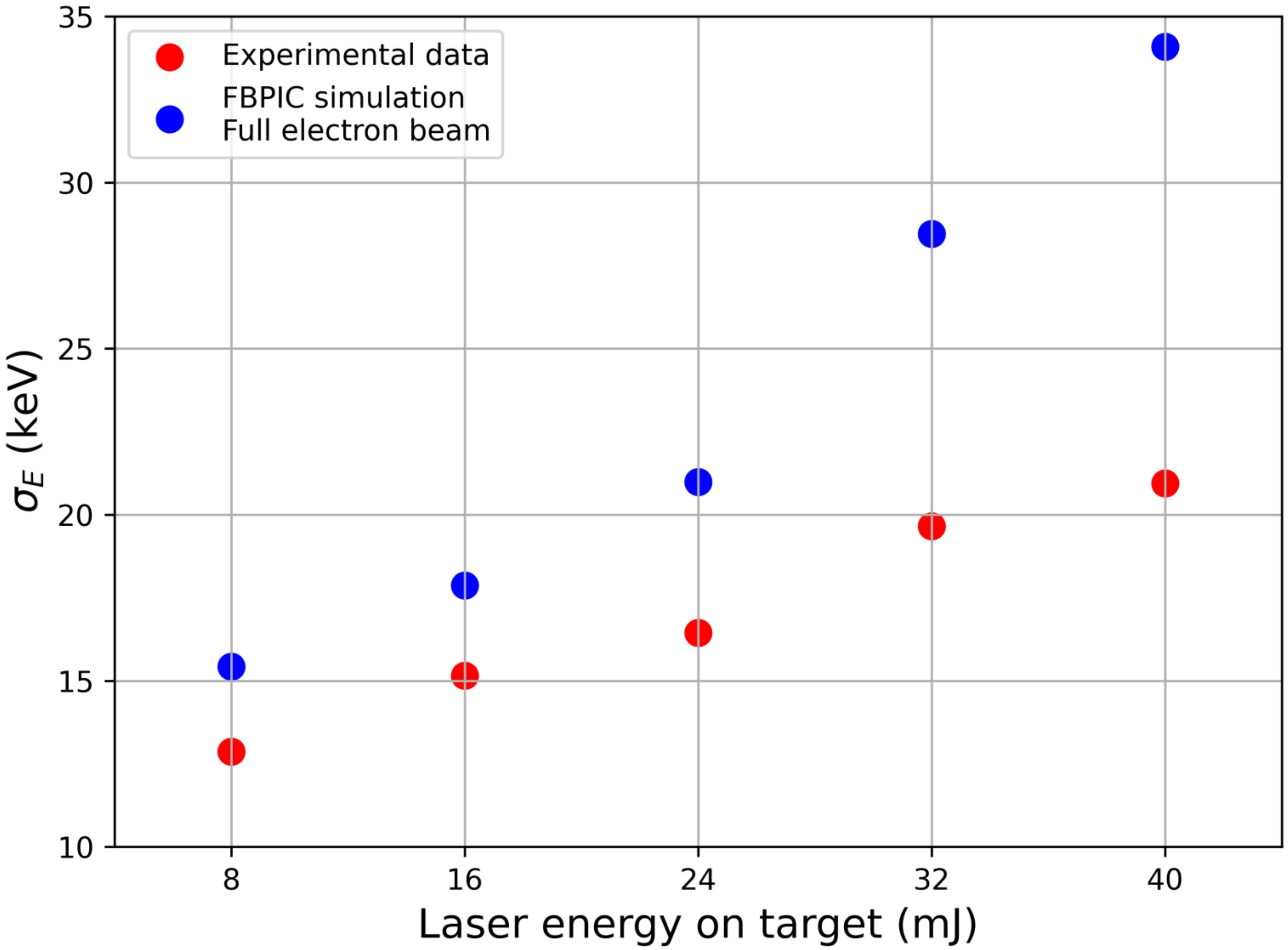
Scaling with laser energy

- Scan of laser energy delivered to interaction point
- Experimental measurements in **red**.
- FBPIC simulation results in **blue**.



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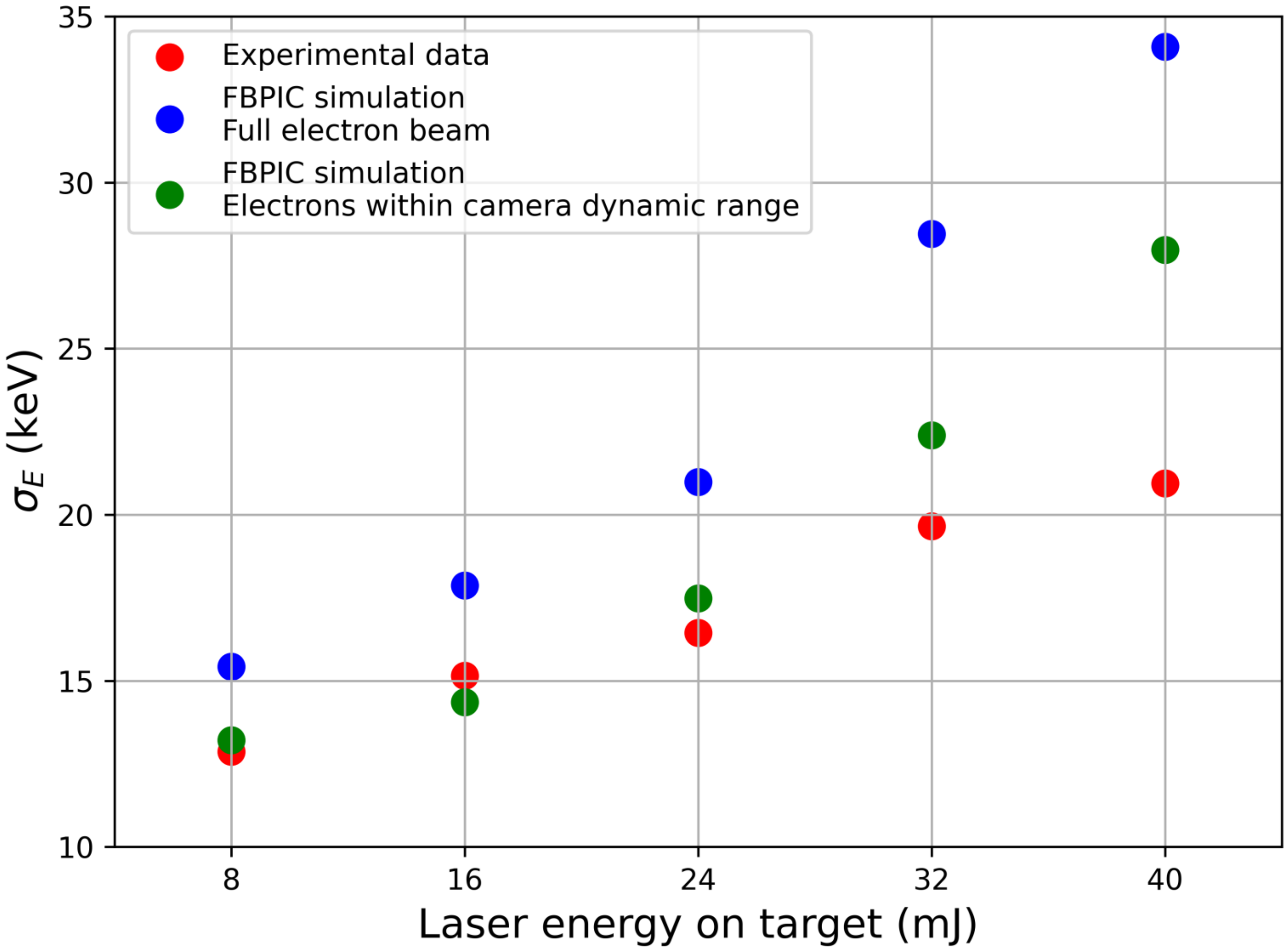
Scaling with laser energy

- Scan of laser energy delivered to interaction point
- Experimental measurements in **red**.
- FBPIC simulation results in **blue**.
- FBPIC simulation only taking electrons within the dynamic range of the camera in **green**.



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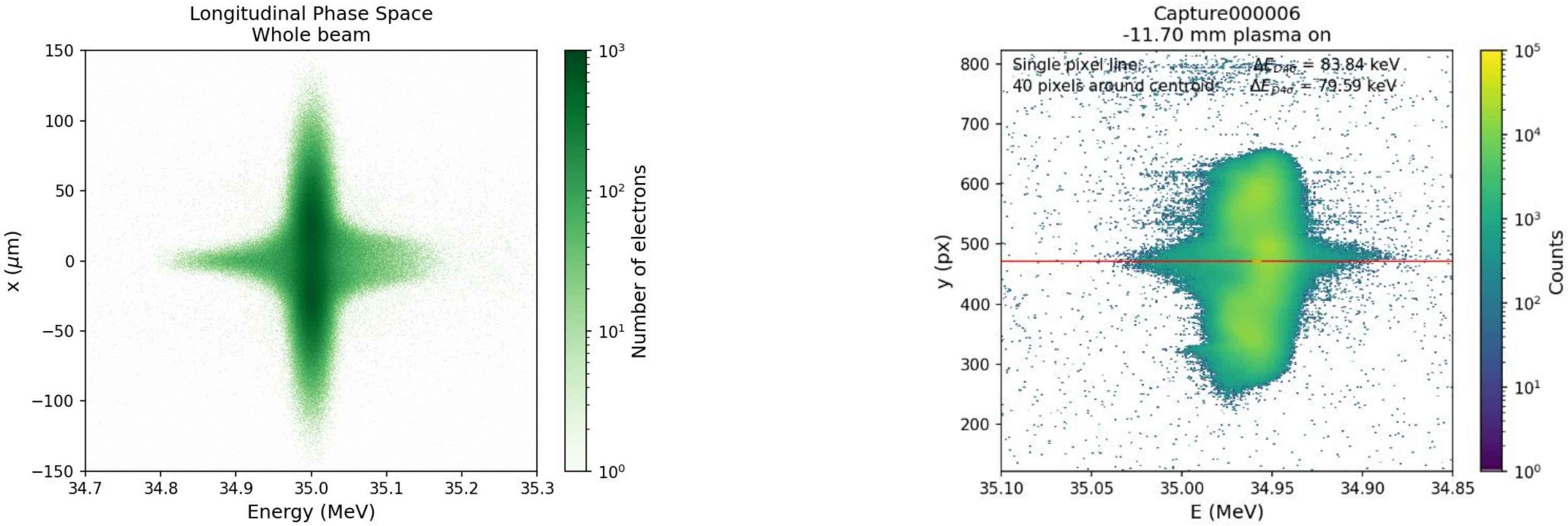
Projection of beam onto spectrometer



Simulated (left) and experimental (right) electron spectrometer images showing electron spectral broadening.

Conclusions

- External injection is a method to improve the quality and stability of accelerated electron beams from laser wakefield accelerators.
- Broadening of the electron beam spectrum was observed at CLARA.
- Accelerating gradient of ~12.5 $\mathrm{MVm^{-1}}$ observed but from simulations, we can extrapolate a gradient of **~110 $\mathrm{MVm^{-1}}$**.
- Next experiments will have a new laser and upgraded electron beam so $\mathrm{GVm^{-1}}$ gradients are expected with near perfect beam quality preservation.

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Acknowledgements

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Strathclyde: Bernhard Hidding

ASTeC: Tom Pacey, Will Okell, Dave Walsh, Ed Snedden, Keith Middleman, Andrew Vick, Matthew King, Duncan Scott

(and more!)

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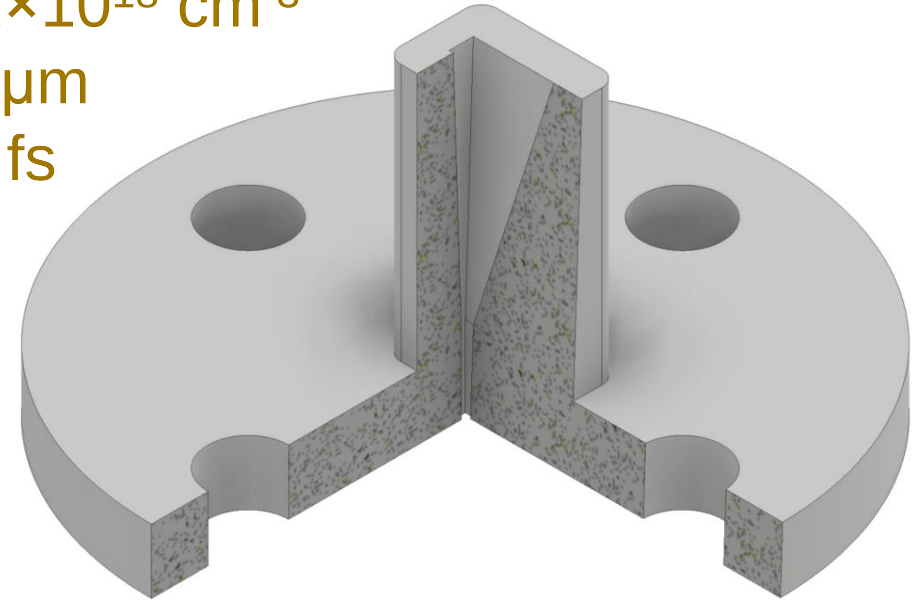
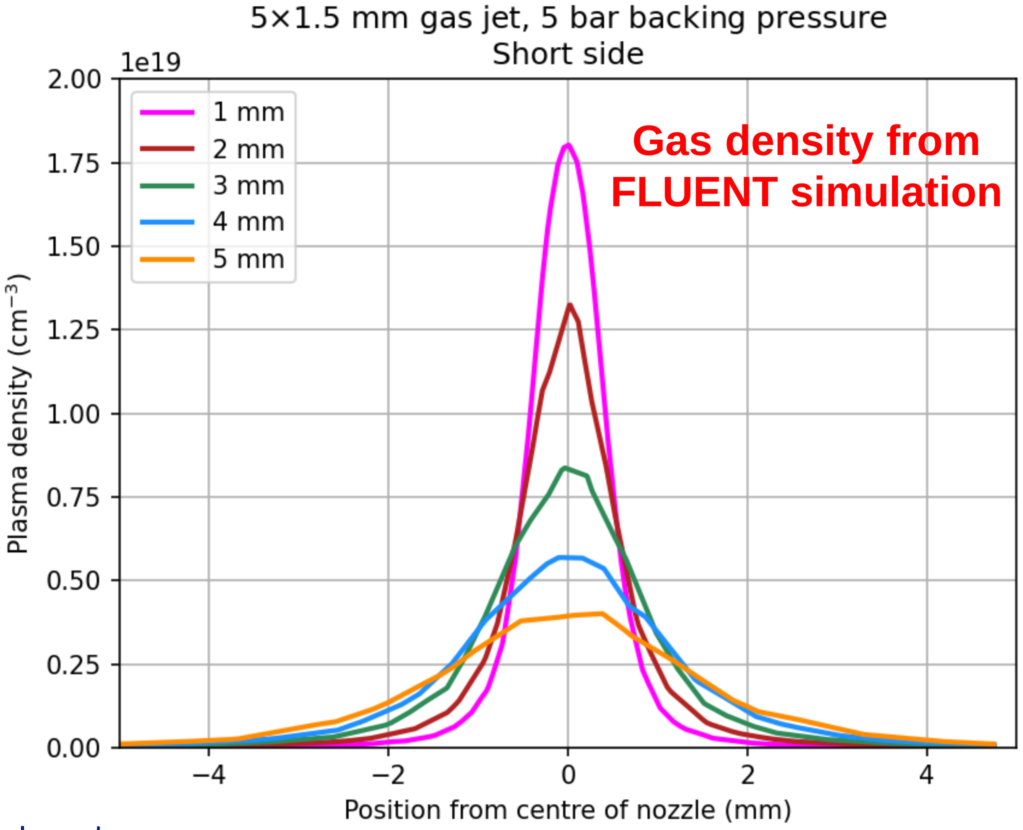
Backup slides

Gas target

- Target comprised of 1.5×5 mm asymmetric slit jet. The short side of the jet was used as well as positioning the laser well above the outlet of the nozzle.
- Longitudinal profile did not contain a region of constant density.
- Total plasma length ~8 mm.

$n_e = 2.1\times10^{18}\ \mathrm{cm}^{-3}$
$\lambda_p = 23\ \mu\mathrm{m}$
$T_p = 76\ \mathrm{fs}$





Gas density from FLUENT simulation

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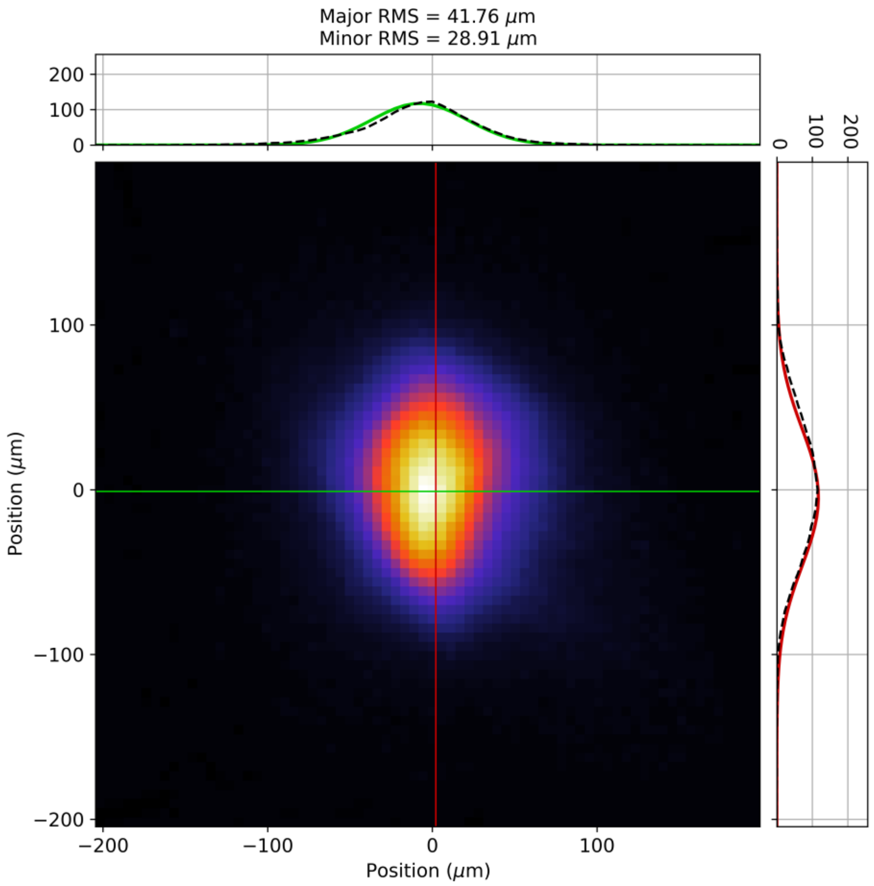
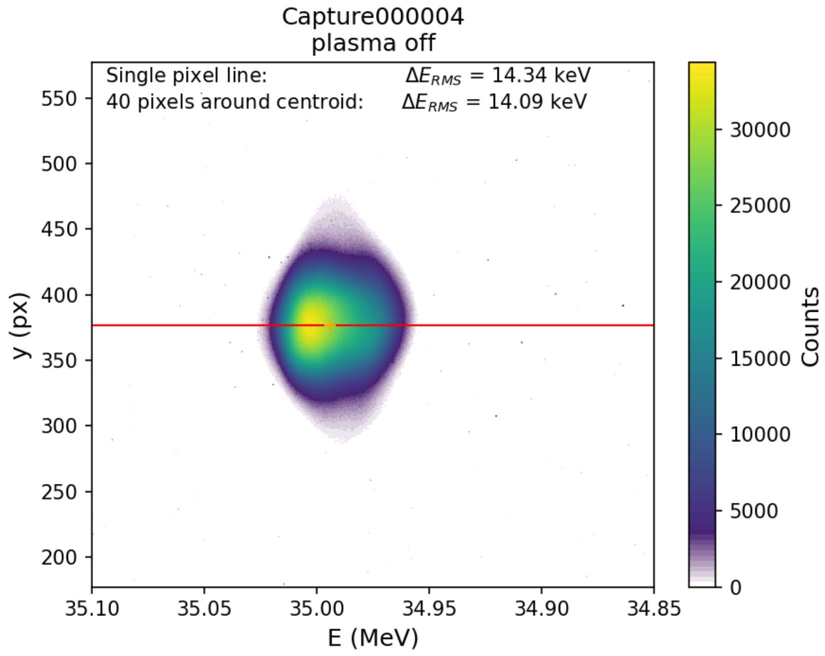
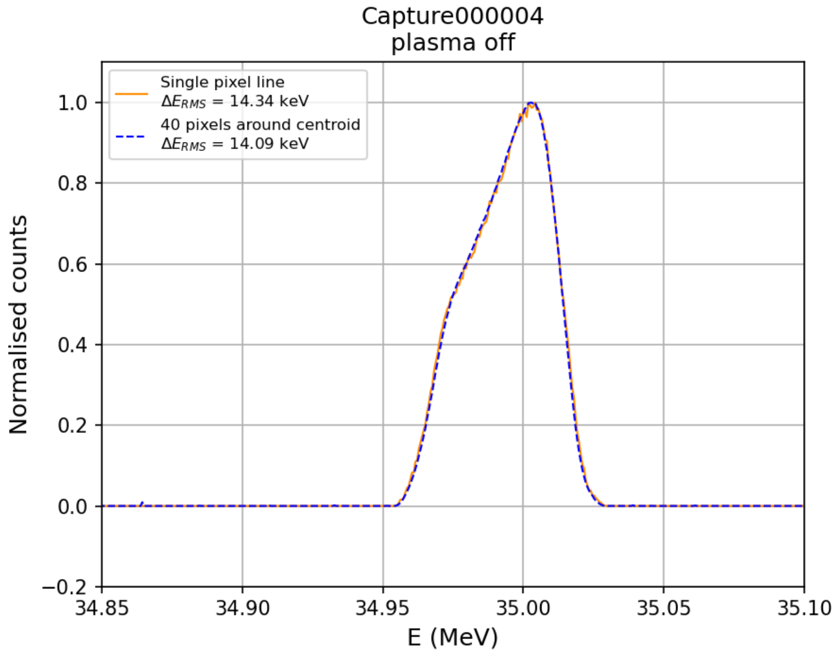
Electron beam

Electron beam was configured so that maximum radial focusing could be achieved. This gave a long electron beam with a narrow energy spread.



- σ_r ~ 35 µm
- σ_z ~ 450 µm (σ_z/c ~ 1.5 ps)
- σ_E = 10 – 20 keV
- Q = 20 pC
- $4\sigma_z/\lambda_p$ = 78 so the broadening of the energy spectrum indicates a successful interaction





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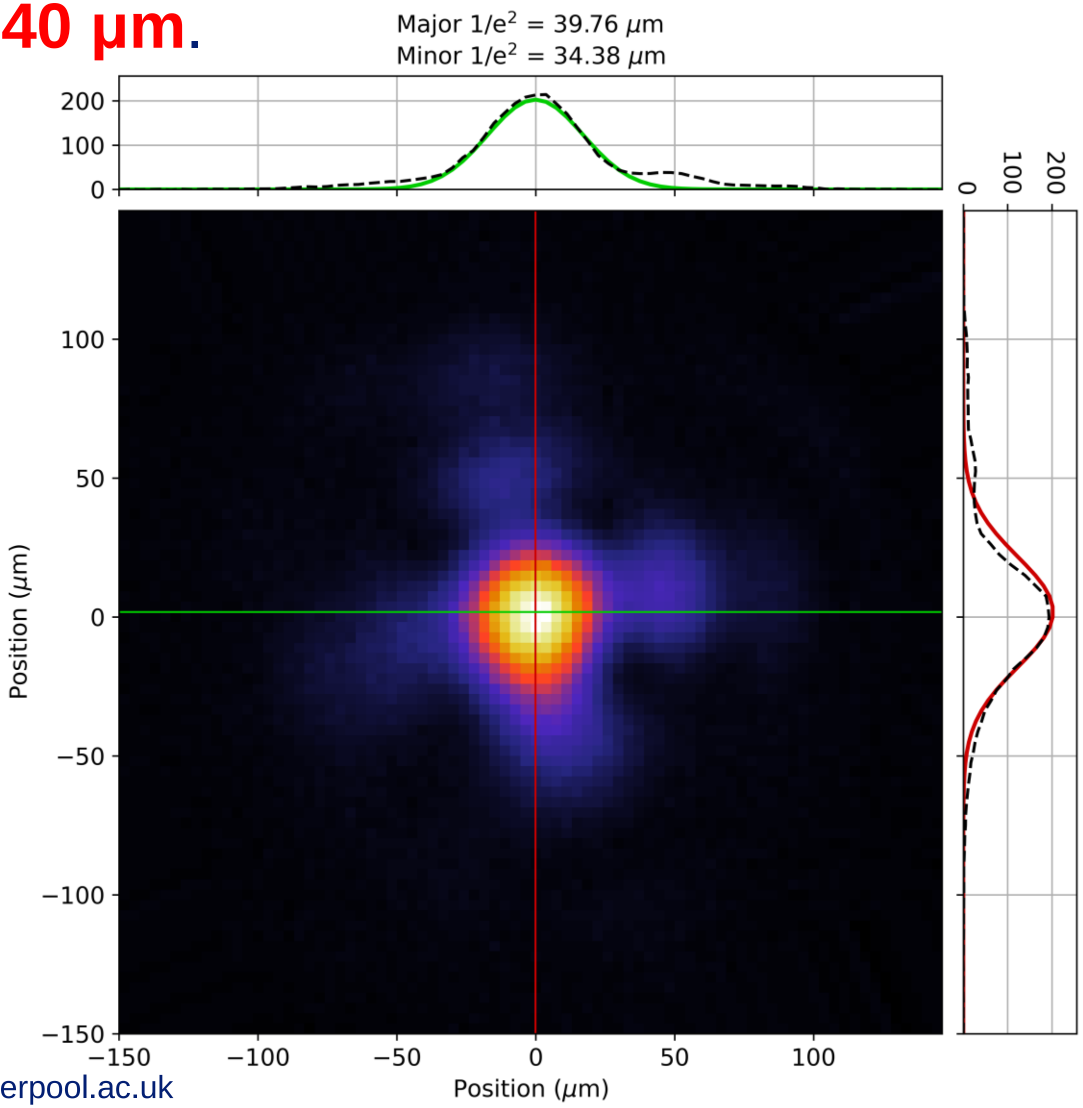
Laser

Laser pulses were delivered from the LATTE laser and focused with a f = 1780 mm off-axis parabola to a vacuum spot size of **ω_0 = 40 µm**.

- Laser energy on target varied between 15 – 75 mJ.
- 52.5% of the total laser energy is within $1/e^2$ diameter
- Laser pulse compressed to τ_{FWHM} = 90 fs.
- Normalised laser vector potential a_0 = 0.04 – 0.08.



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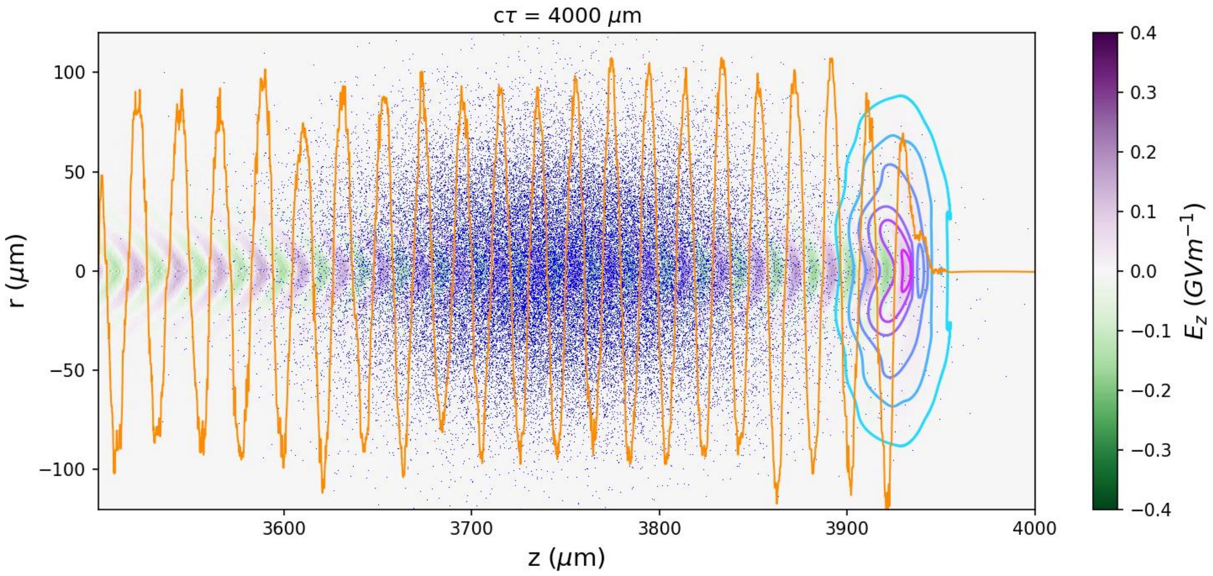
Simulations

Experimental measurements were compared to **fbpic simulations**.

The electron beam length makes simulating in unfeasible so a reduced electron beam of σ_z = 60 μm was chosen as a proxy.

Electron beam still extends over multiple plasma periods so we expect this to be valid and this was checked with a single full beam simulation.

The beam charge was also reduced so that the charge density of the electron beam was the same as the full length electron beam.



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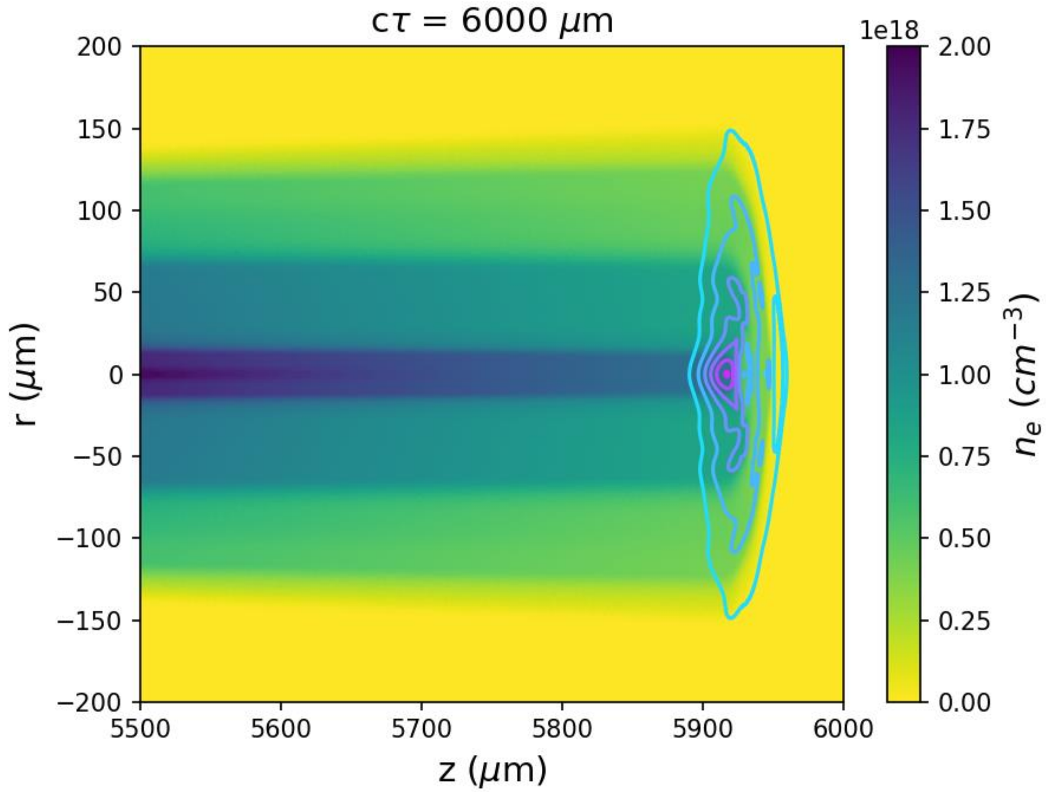
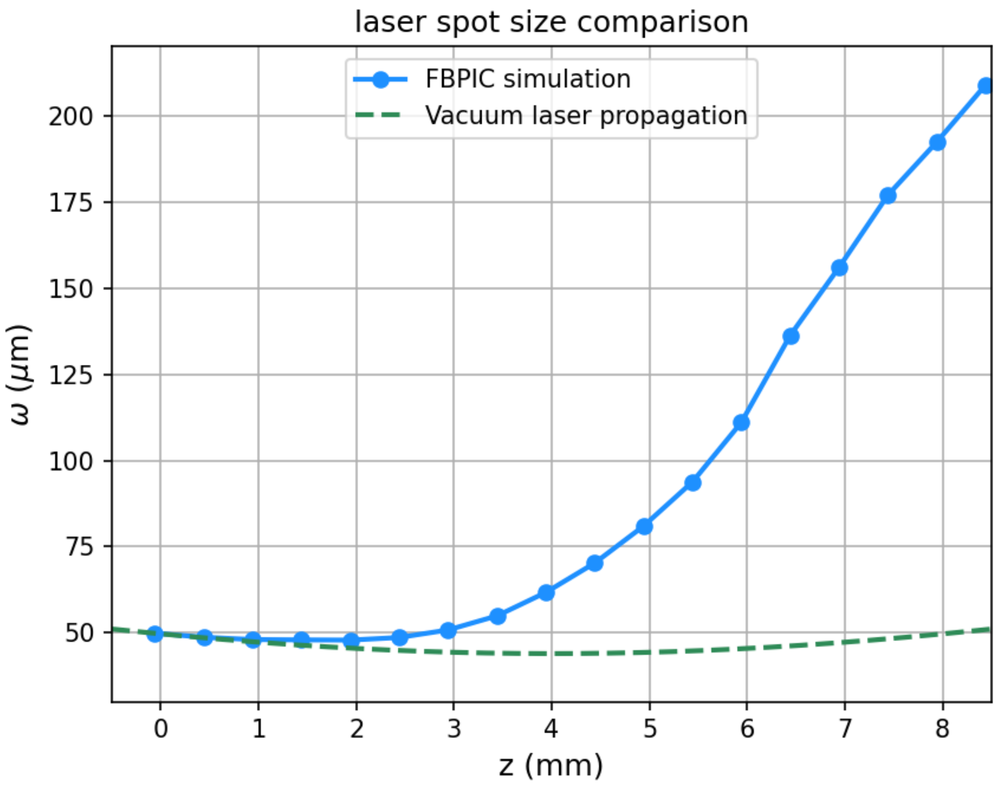
ADK ionisation

Due to the low laser intensity, the ionisation of the Nitrogen gas was included using the ADK model to correctly model the propagation of the laser through the target. The non-uniform radial ionisation of the gas made the plasma act as a negative lens which causes rapid laser pulse defocusing.





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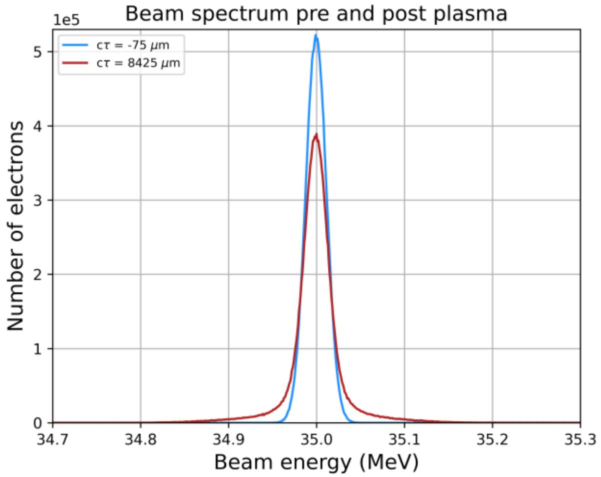
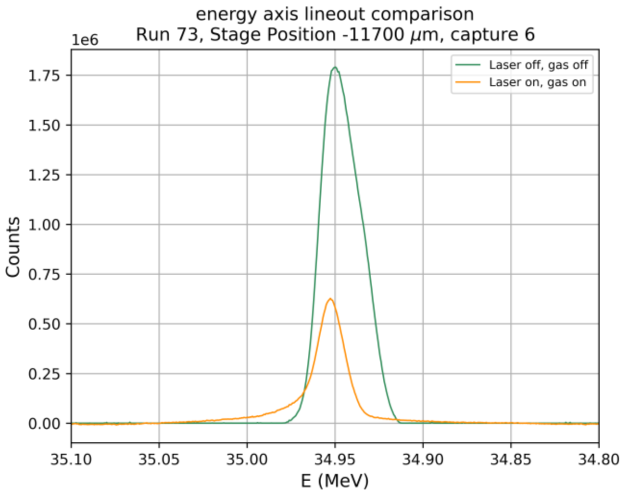
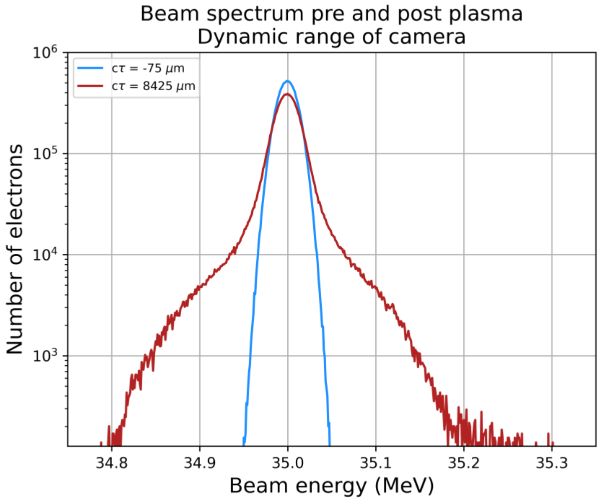
Simulation vs experiment

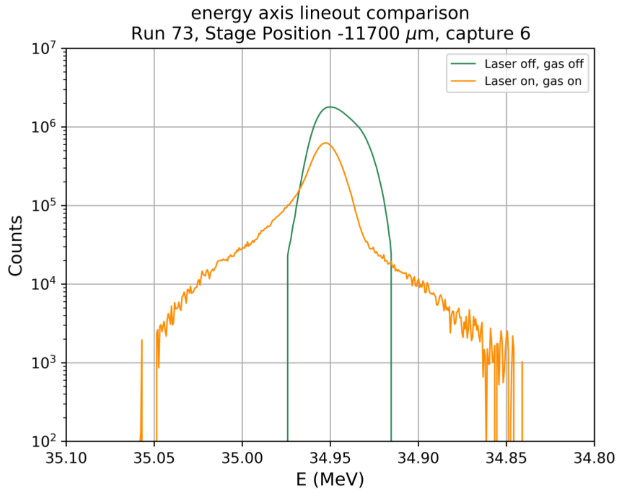




- FBPIC simulation predicts a 200 keV energy gain/loss within the dynamic range of the camera



400 keV



200 keV

- Measurement shows 100 keV energy gain/loss

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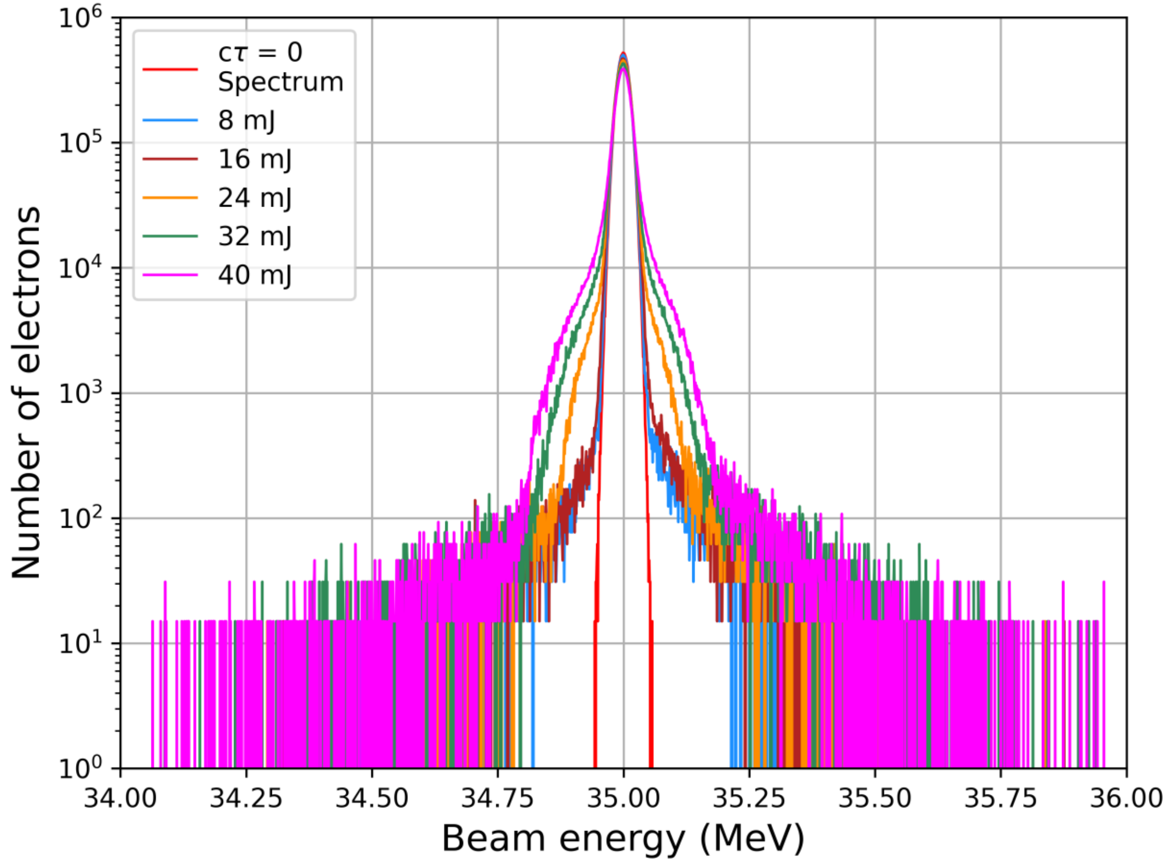
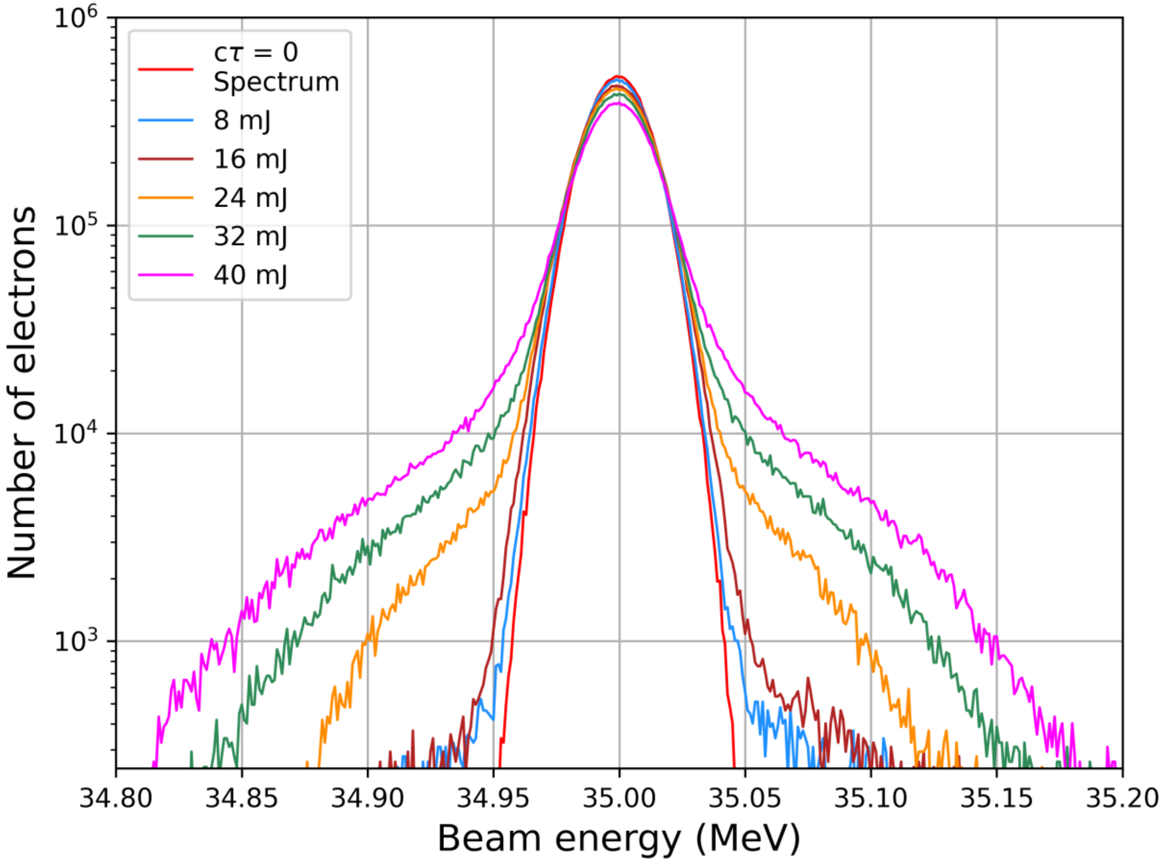
Simulation – Energy scan



Full electron beam spectra



Electrons within camera dynamic range

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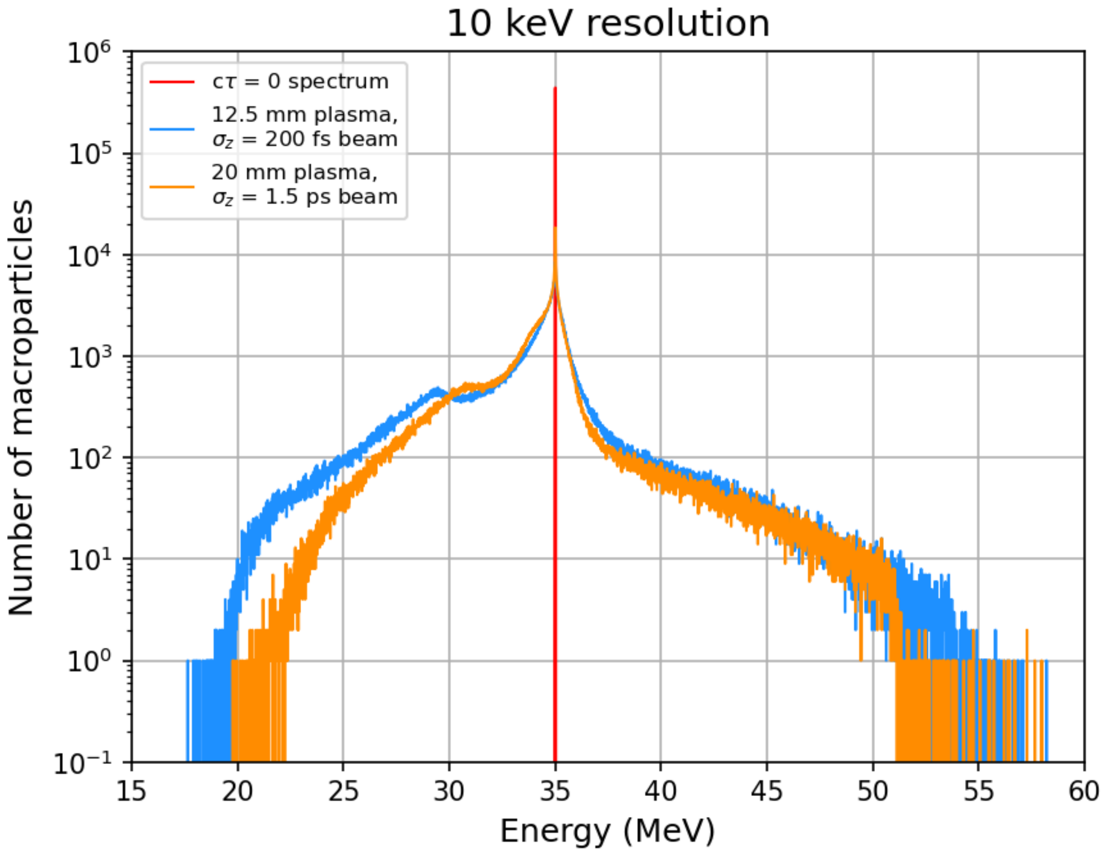
200 fs, 1.5 ps electron beam comparison



Ahead of the experiment, simulations were run with a longer plasma length and 300 mJ of laser energy on target.

Simulations were run for the full 1.5 ps electron beam and the reduced 200 fs beam.

The post-interaction energy spectrum is similar in each case.

This validates the assumption that the 200 fs simulations are is a good approximation because it is so much longer than the plasma wavelength.

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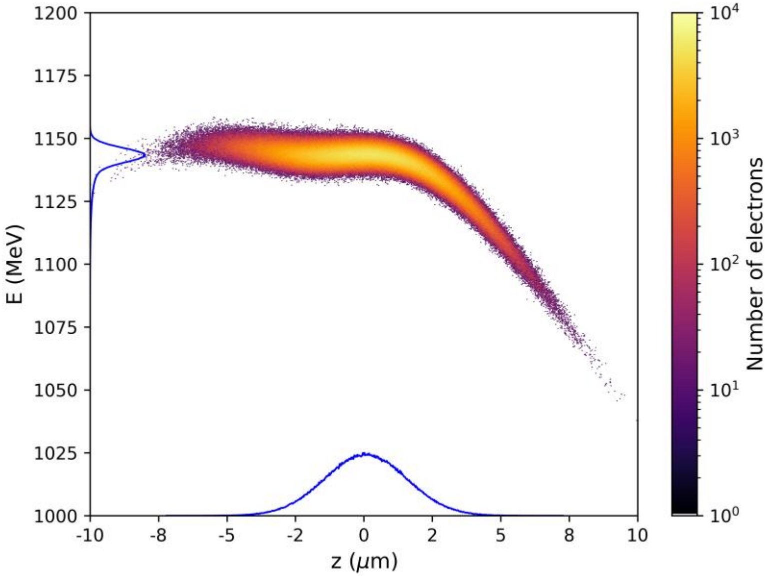
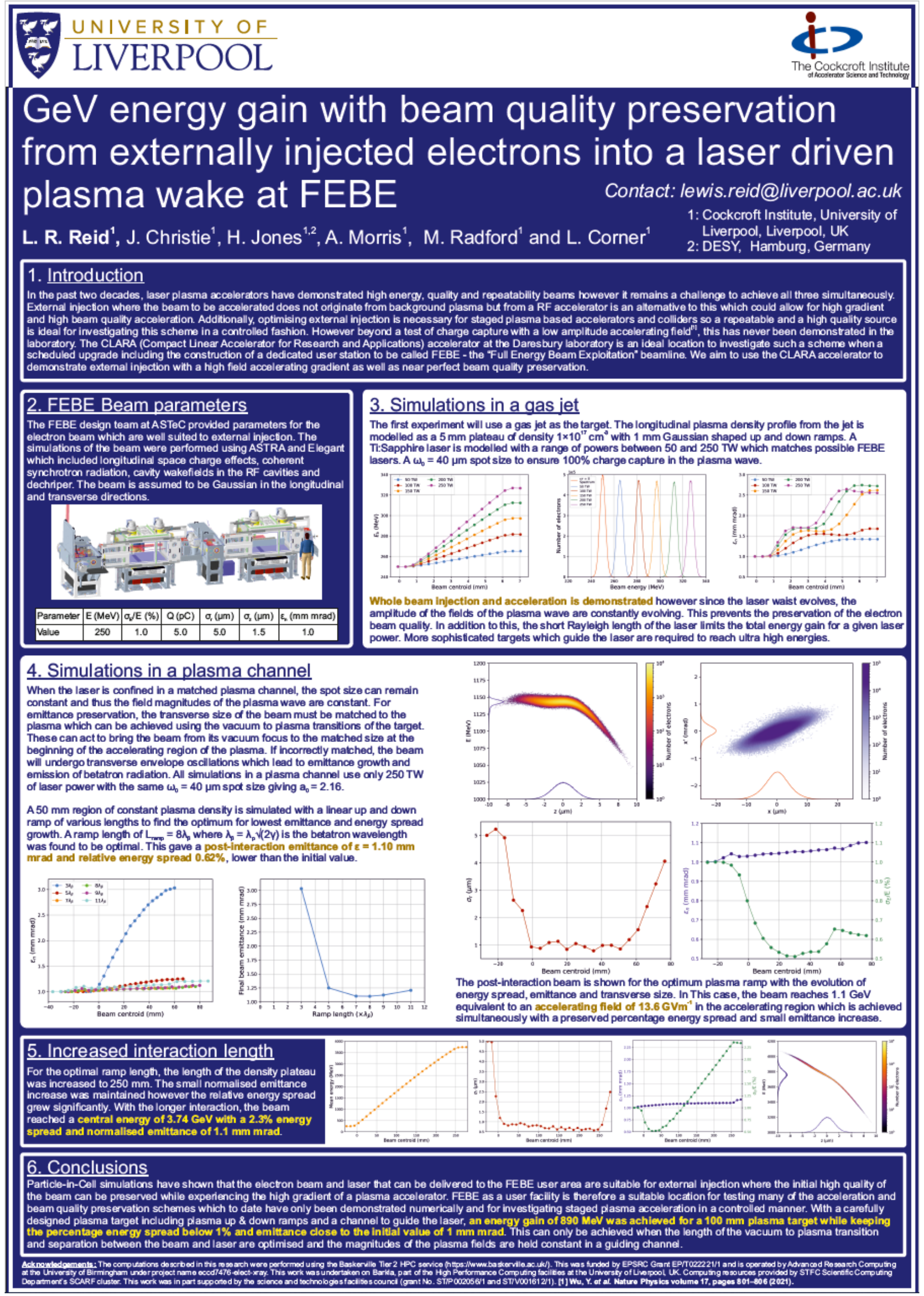
Future work

Next campaign will take place once the accelerator and infrastructure at Daresbury has been upgraded.
The laboratory will be far better optimised for external injection.

Whole beam capture and acceleration will be possible and by optimising the target, acceleration to several GeV is achievable without loss of electron beam quality.



For more information, see my poster during the poster session.


UNIVERSITY OF LIVERPOOL

The Cockcroft Institute of Accelerator Science and Technology

GeV energy gain with beam quality preservation from externally injected electrons into a laser driven plasma wake at FEBE

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2: DESY, Hamburg, Germany

1. Introduction

In the past two decades, laser plasma accelerators have demonstrated high energy, quality and repeatability beams however it remains a challenge to achieve all three simultaneously. External injection where the beam to be accelerated does not originate from background plasma but from a RF accelerator is an alternative to this which could allow for high gradient and high beam quality acceleration. Additionally, optimising external injection is necessary for staged plasma based accelerators and colliders so a repeatable and a high quality source is ideal for investigating this scheme in a controlled fashion. However beyond a test of charge capture with a low amplitude accelerating field[1], this has never been demonstrated in the laboratory. The CLARA (Compact Linear Accelerator for Research and Applications) accelerator at the Daresbury laboratory is an ideal location to investigate such a scheme when a scheduled upgrade including the construction of a dedicated user station to be called FEBE - the "Full Energy Beam Exploitation" beamline. We aim to use the CLARA accelerator to demonstrate external injection with a high field accelerating gradient as well as near perfect beam quality preservation.

2. FEBE Beam parameters

The FEBE design team at ASTeC provided parameters for the electron beam which are well suited to external injection. The simulations of the beam were performed using ASTRA and Elegant which included longitudinal space charge effects, coherent synchrotron radiation, cavity wakefields in the RF cavities and dechriper. The beam is assumed to be Gaussian in the longitudinal and transverse directions.

Parameter	E (MeV)	σ_E/E (%)	Q (pC)	σ_r (μm)	σ_z (μm)	ε_n (mm mrad)
Value	250	1.0	5.0	5.0	1.5	1.0

3. Simulations in a gas jet

The first experiment will use a gas jet as the target. The longitudinal plasma density profile from the jet is modelled as a 5 mm plateau of density 1×10^{17} cm^{-3} with 1 mm Gaussian shaped up and down ramps. A Ti:Sapphire laser is modelled with a range of powers between 50 and 250 TW which matches possible FEBE lasers. A ω_0 = 40 μm spot size to ensure 100% charge capture in the plasma wave.

Whole beam injection and acceleration is demonstrated however since the laser waist evolves, the amplitude of the fields of the plasma wave are constantly evolving. This prevents the preservation of the electron beam quality. In addition to this, the short Rayleigh length of the laser limits the total energy gain for a given laser power. More sophisticated targets which guide the laser are required to reach ultra high energies.

4. Simulations in a plasma channel

When the laser is confined in a matched plasma channel, the spot size can remain constant and thus the field magnitudes of the plasma wave are constant. For emittance preservation, the transverse size of the beam must be matched to the plasma which can be achieved using the vacuum to plasma transitions of the target. These can act to bring the beam from its vacuum focus to the matched size at the beginning of the accelerating region of the plasma. If incorrectly matched, the beam will undergo transverse envelope oscillations which lead to emittance growth and emission of betatron radiation. All simulations in a plasma channel use only 250 TW of laser power with the same ω_0 = 40 μm spot size giving a_0 = 2.16.

A 50 mm region of constant plasma density is simulated with a linear up and down ramp of various lengths to find the optimum for lowest emittance and energy spread growth. A ramp length of $L_{ramp} = 8\lambda_\beta$ where $\lambda_\beta = \lambda_p\sqrt{(2\gamma)}$ is the betatron wavelength was found to be optimal. This gave a **post-interaction emittance of ε = 1.10 mm mrad and relative energy spread 0.62%**, lower than the initial value.

The post-interaction beam is shown for the optimum plasma ramp with the evolution of energy spread, emittance and transverse size. In This case, the beam reaches 1.1 GeV equivalent to an **accelerating field of 13.6 GVm^{-1}** in the accelerating region which is achieved simultaneously with a preserved percentage energy spread and small emittance increase.

5. Increased interaction length

For the optimal ramp length, the length of the density plateau was increased to 250 mm. The small normalised emittance increase was maintained however the relative energy spread grew significantly. With the longer interaction, the beam reached a **central energy of 3.74 GeV with a 2.3% energy spread and normalised emittance of 1.1 mm mrad**.

6. Conclusions

Particle-in-Cell simulations have shown that the electron beam and laser that can be delivered to the FEBE user area are suitable for external injection where the initial high quality of the beam can be preserved while experiencing the high gradient of a plasma accelerator. FEBE as a user facility is therefore a suitable location for testing many of the acceleration and beam quality preservation schemes which to date have only been demonstrated numerically and for investigating staged plasma acceleration in a controlled manner. With a carefully designed plasma target including plasma up & down ramps and a channel to guide the laser, **an energy gain of 890 MeV was achieved for a 100 mm plasma target while keeping the percentage energy spread below 1% and emittance close to the initial value of 1 mm mrad**. This can only be achieved when the length of the vacuum to plasma transition and separation between the beam and laser are optimised and the magnitudes of the plasma fields are held constant in a guiding channel.

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[1] **Wu, Y. et al. Nature Physics volume 17, pages 801–806 (2021).**