Colinear Laser-Assisted Injection from a Foil

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Introduction

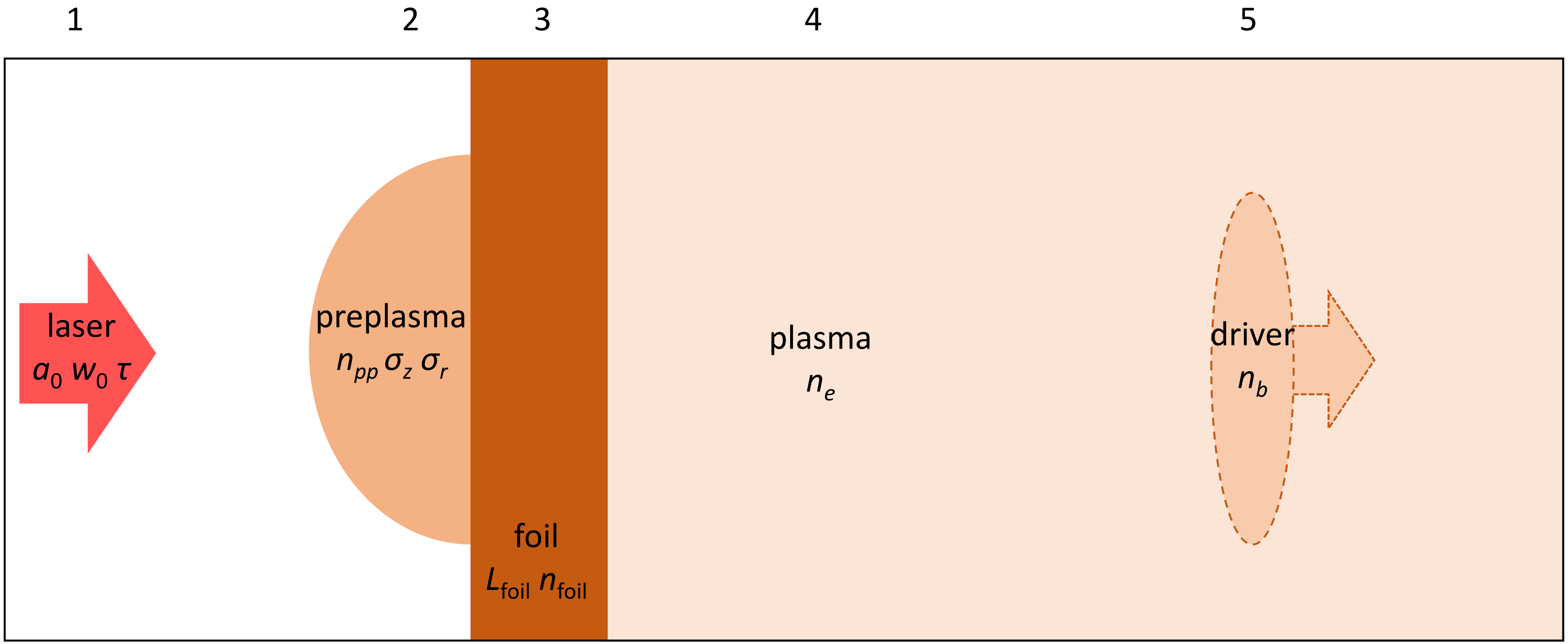
- Following on from the work of Khudiakov and Pukhov [1] examining laser-assisted injection from a foil at 45 degrees, we now look at a scheme employing normal incidence on the foil i.e. collinear with the driver

- We study this using FBPIC to carry out start-to-end simulations handling both the laser interaction with the foil, charge capture and subsequent acceleration
- We will present two specific cases, a low trapping potential/low charge case and a high trapping potential/high charge case

[1] *Phys. Rev. E* **105**, 035201 (2022)

Problem Setup

Five major components, many free parameters to choose



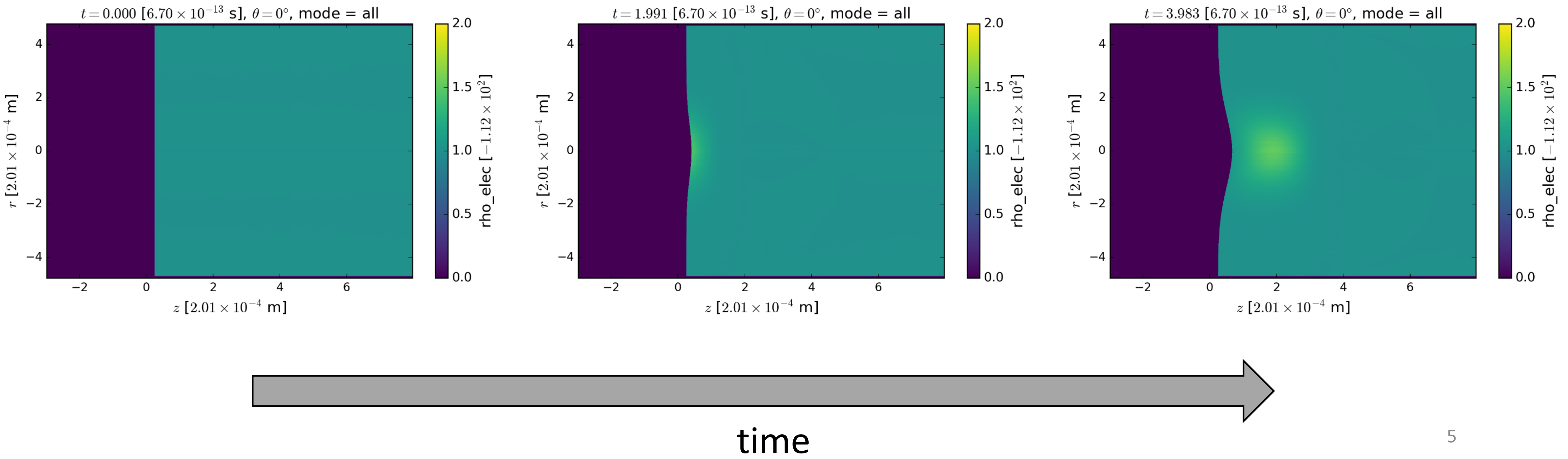
Simulation Parameters

- 200mJ Laser (a_0 = 2) incident on 50 micron Al foil
- small Gaussian shaped preplasma ~1n_c density for the laser to interact with
- Short proton driver passes through the foil and into uniform plasma n_e = 7x10^{14} cm^{-3} first to excite a wake with $\phi_0 \approx 0.2$
- Hot electrons are kicked through the foil by the laser and captured by the wake

- Grid Resolution of 6 cells/λ_0 or Δz = 133 nm

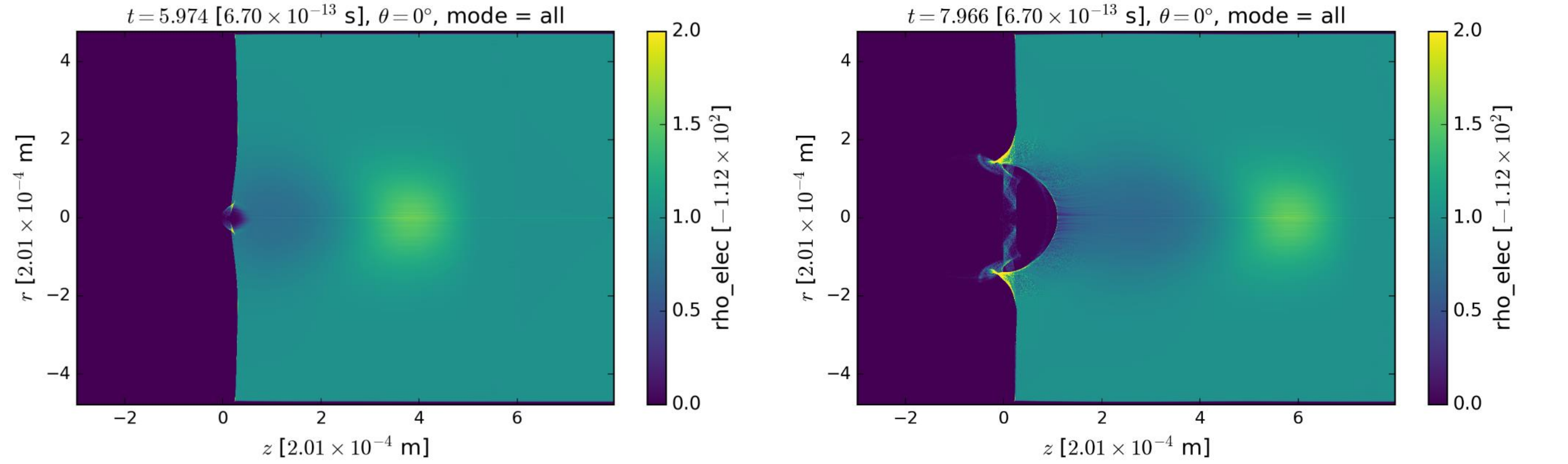
Early stages – Wake Formation

- As the driver passes through the foil and enters the plasma, ponderomotive force pushes plasma electrons away from the foil in order to begin the oscillations of the wake



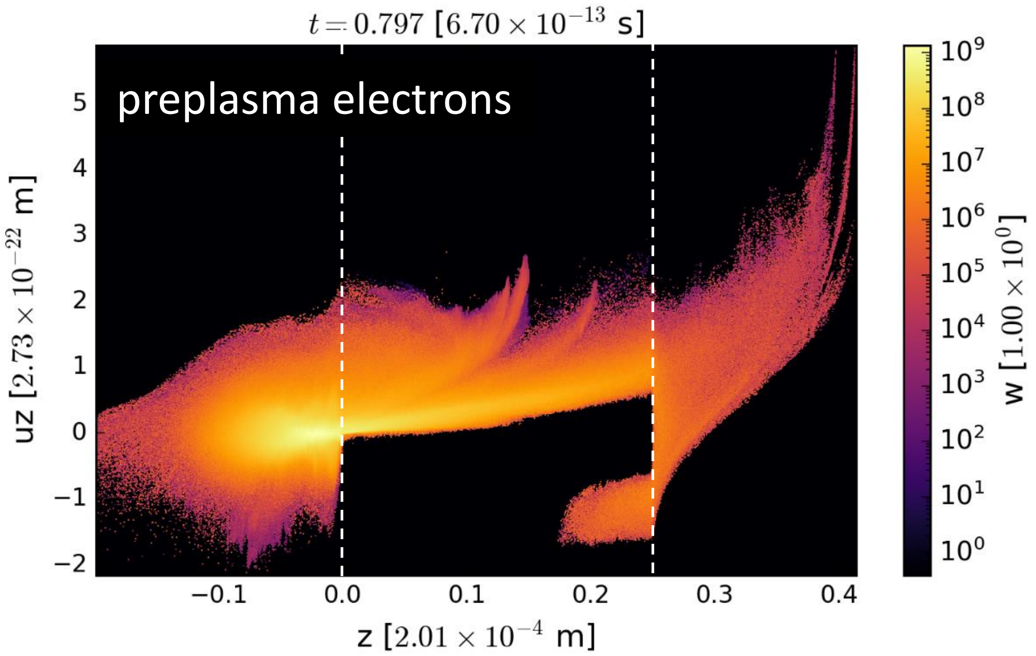
Early stages – Particle Injection

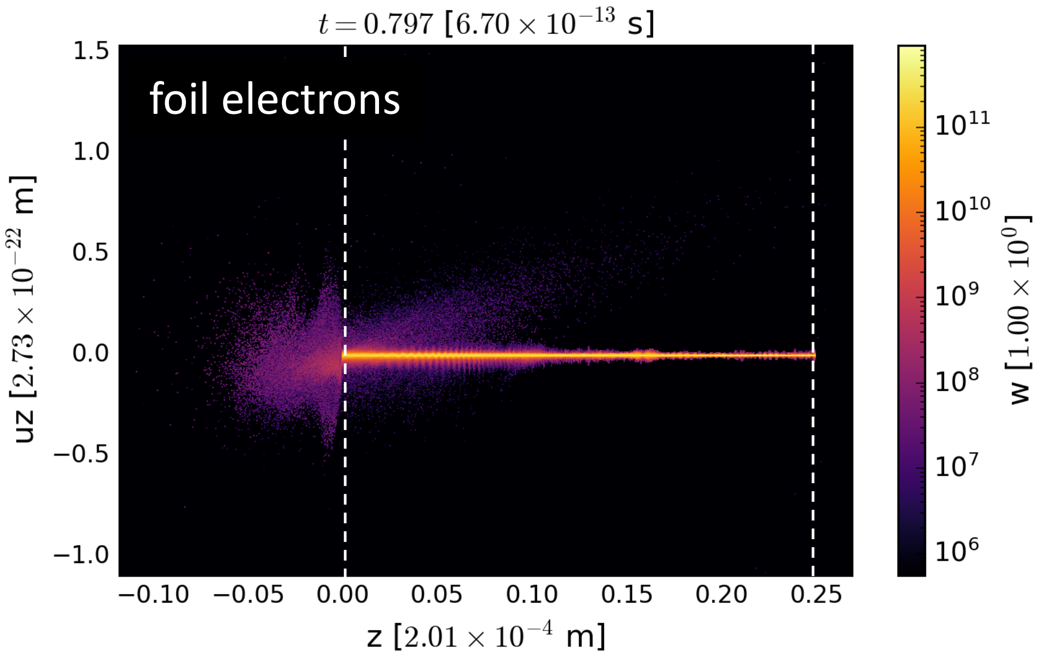
- When the laser hits the foil, a large amount of charge is pushed through the foil and into the very tenuous plasma on the other side.
- The plasma electrons are blown out from the foil as the electrons stream through.



Phasespaces of the Hot electrons by Source

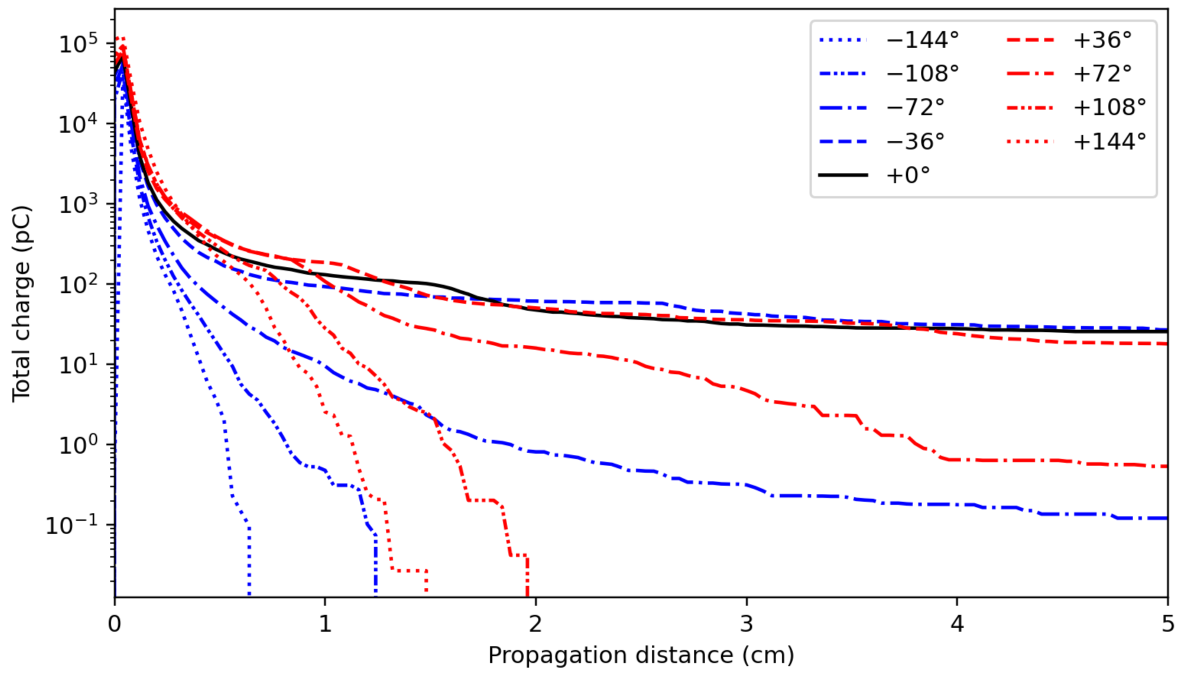
The preplasma, and its interaction with the laser is entirely responsible for the hot electrons

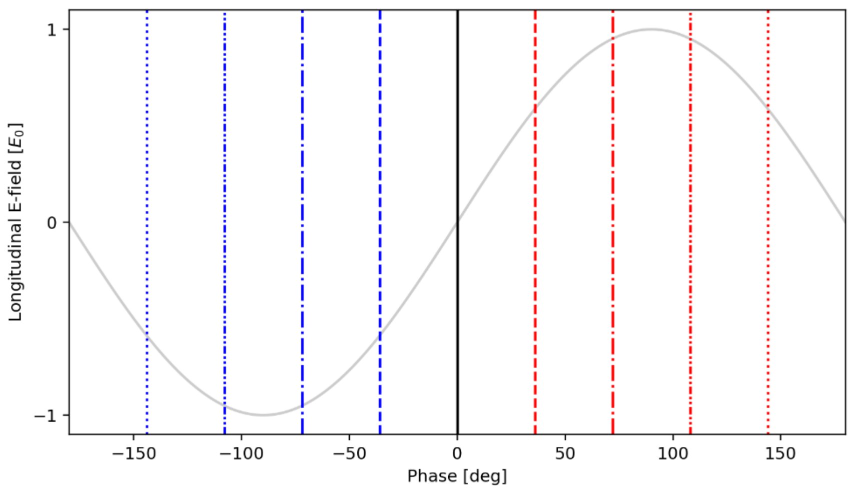




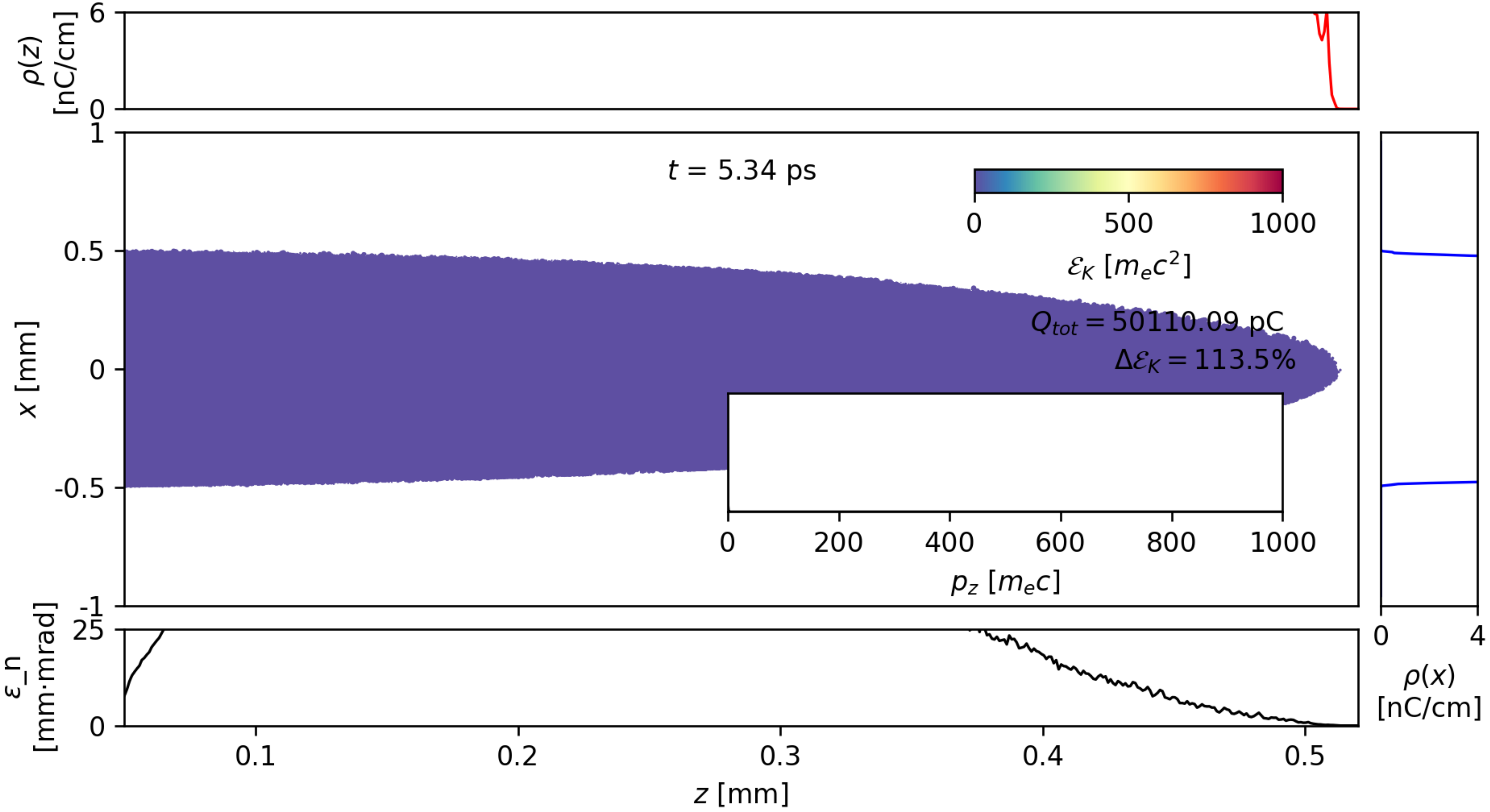
Delay Timing

- A scan of different delays between the driver and the laser were performed to examine the amount of charge captured
- Characterised by the position of the head of the bunch relative to the plasma wake phase
- The zero point here corresponds to the phase at which the wake swaps from being accelerating to decelerating
- Maximum charge capture round the zero point, as seen in previous work

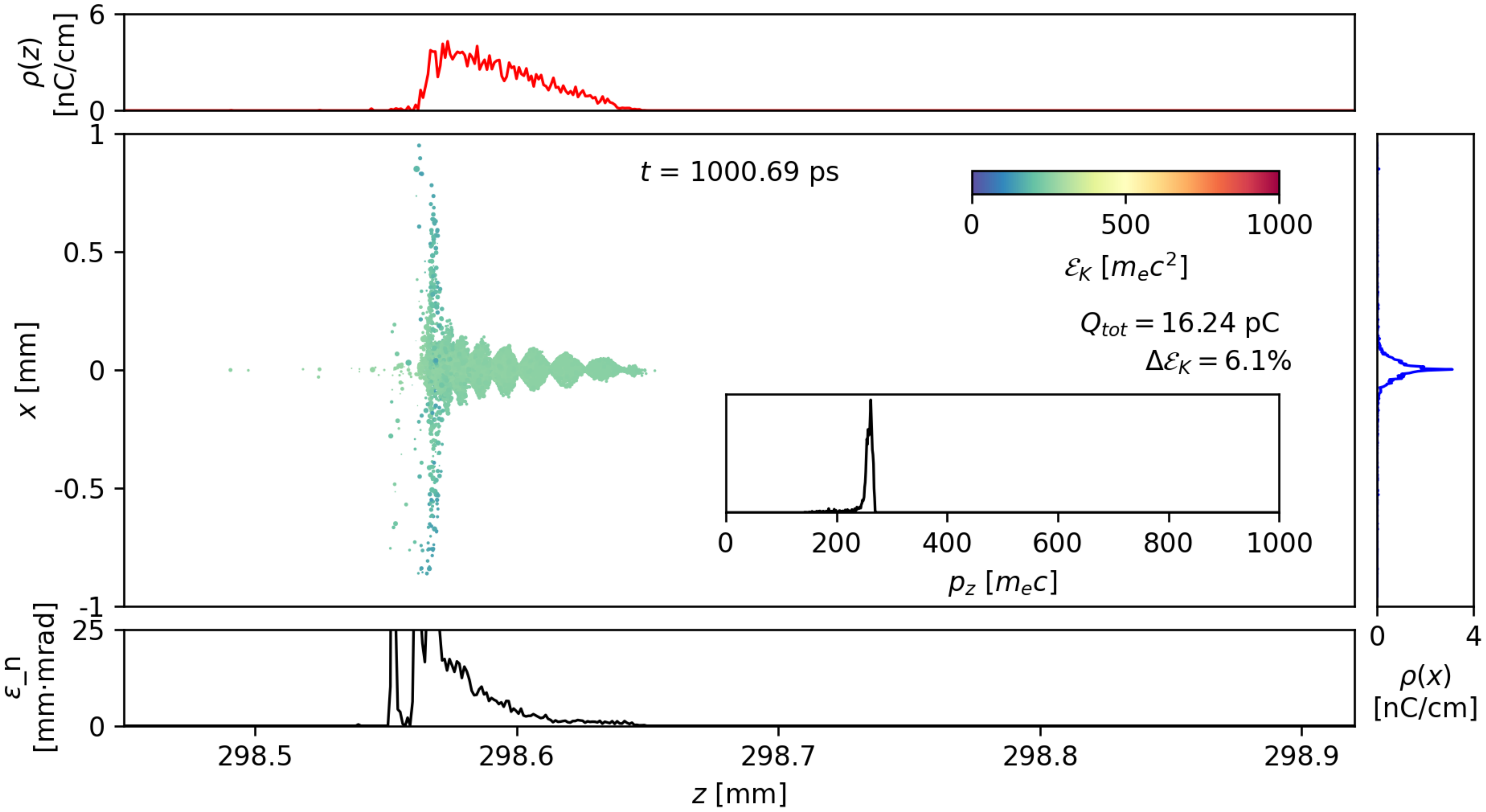




Acceleration Dynamics - Initial



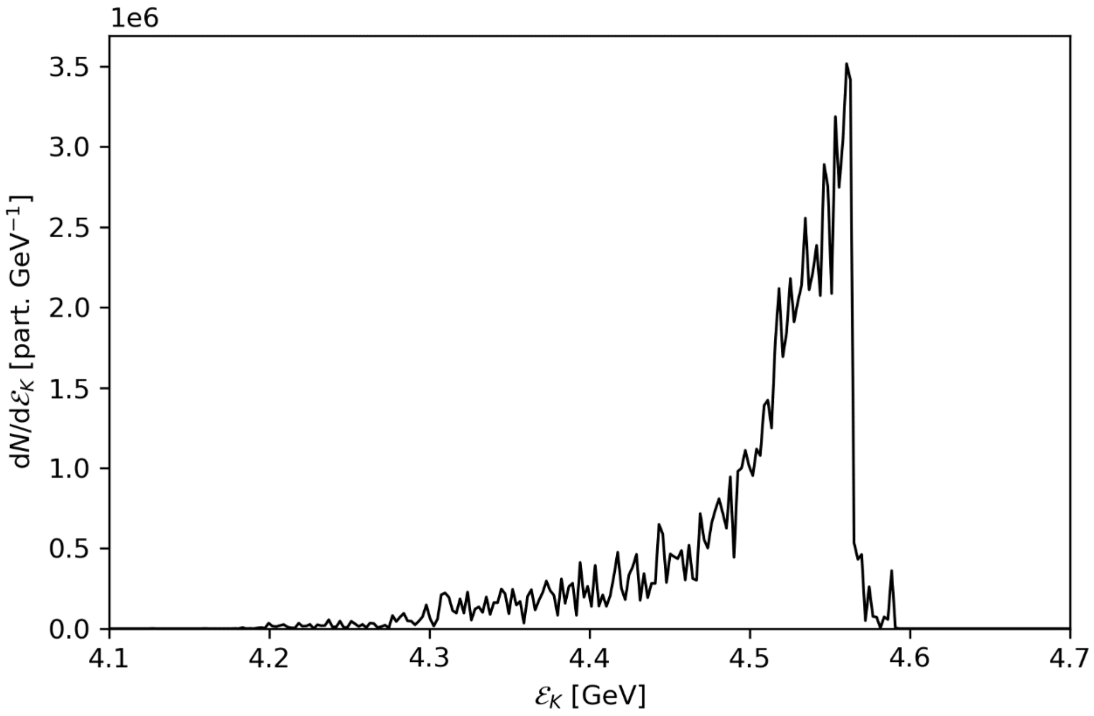
Acceleration Dynamics – 30cm

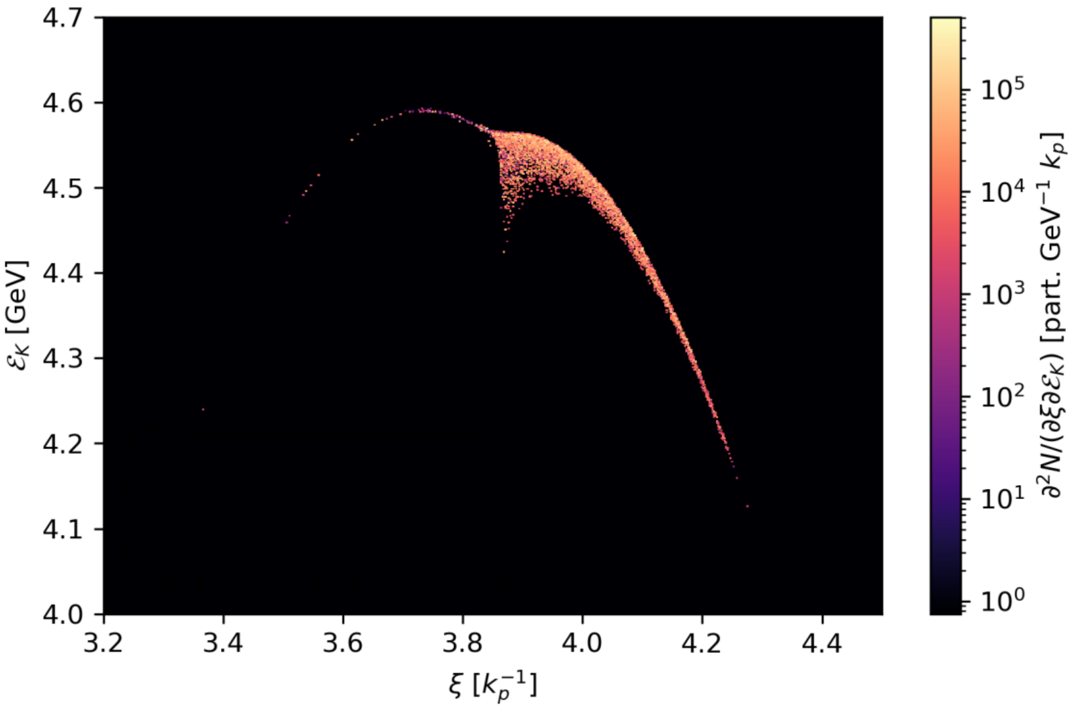


10m Summary – Low charge / Low wake

After 10 meters of acceleration

- 15 pC charge
- 4.5 GeV
- 1.5% energy spread
- 10 μm normalised emittance





Trapping Conditions

- Khudiakov and Pukhov determine the conditions for trapping from a solid target for a particle with initial momentum p_z, p_r as

$$\frac{(p_z - p_c)^2}{a^2} + \frac{p_r^2}{b^2} < 1$$

with

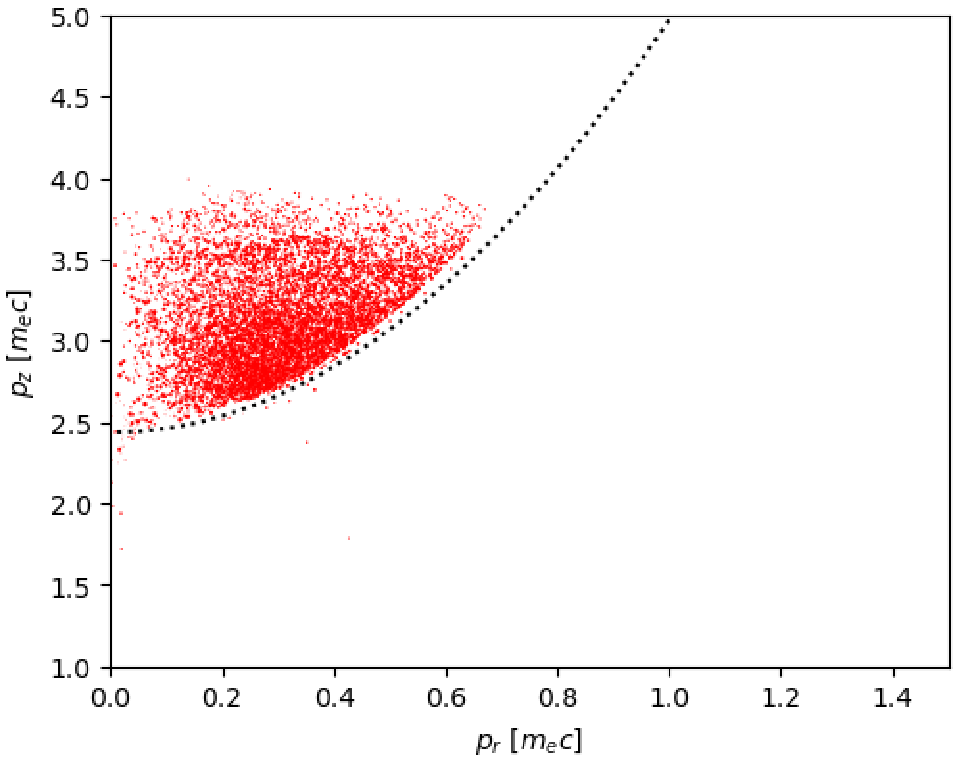
$$p_c = \gamma_b^2 \beta_b T$$
$$a^2 = \gamma_b^2 (\gamma_b^2 T^2 - 1)$$
$$b^2 = \gamma_b^2 T^2 - 1$$
$$T = \gamma_b^{-1} + \phi_0$$

Describing an ellipse in p_r-p_z

Particles falling within this ellipse as they are injected into the wake are trapped, those that fall outside it are eventually lost

Trapping – Simulation Results

- Particles sampled after 50cm of propagation are traced back to their injection point using their unique IDs
- Initial particle momentum is plotted against the trapping conditions, showing good agreement
- In this simulation, ~15 pC of charge is trapped



Momentum of the trapped particles at the point of injection into the wake

Parameter Scans

- The preplasma has a half-Gaussian shape centered on (0,0)

$$n_{pp} = n_c \exp\left(-\frac{z^2}{\sigma_z^2} - \frac{r^2}{\sigma_r^2}\right)$$

- We can vary σ_r and σ_z of the preplasma to determine optimal parameters for maximum charge capture
- We can also vary the laser amplitude and wake potential

Note: these simulation are still operating in a nonconverged regime for the laser – actual values will be underestimated!

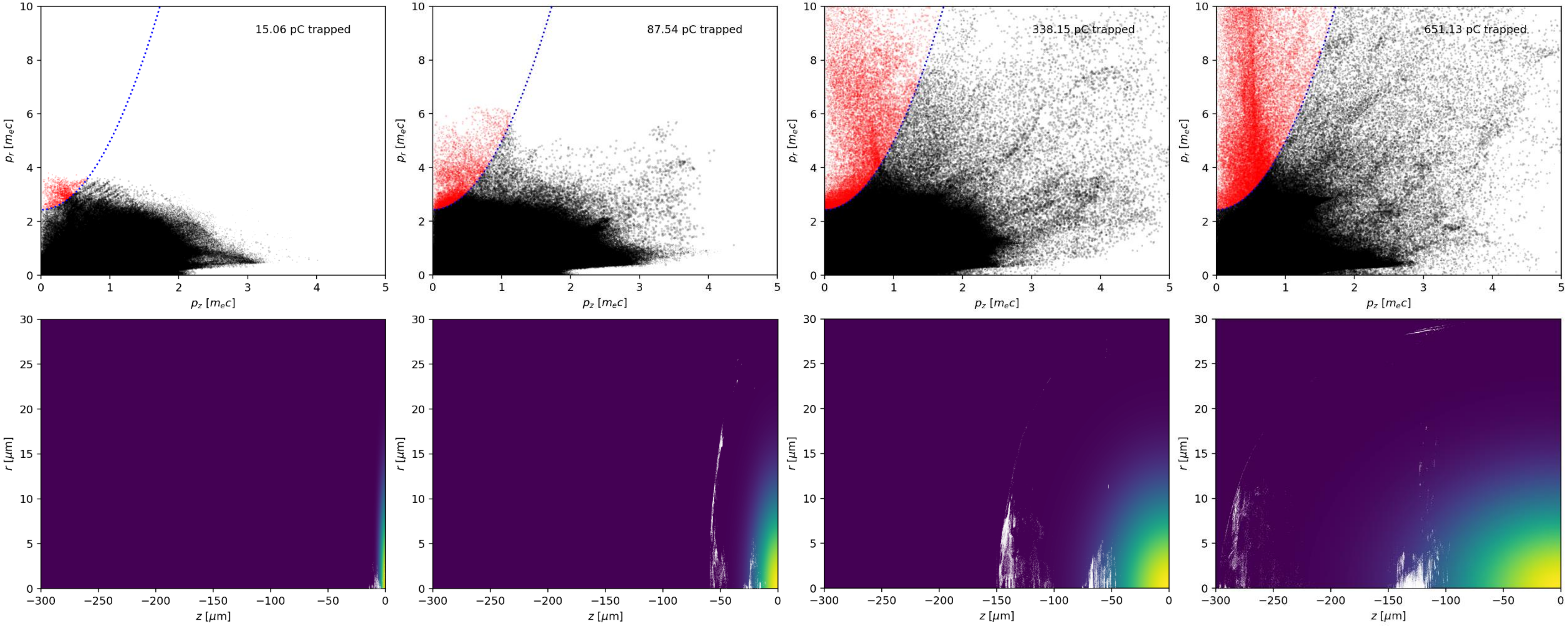
Scans – Preplasma longitudinal size

σ_r = 10µm, a_0 = 2, ϕ_0 = 0.2

σ_z = 5µm 20µm 50µm 100µm

Trapped particles

Trapped particle original locations



Trapped charge	15 pC	87 pC	338 pC	**651 pC**

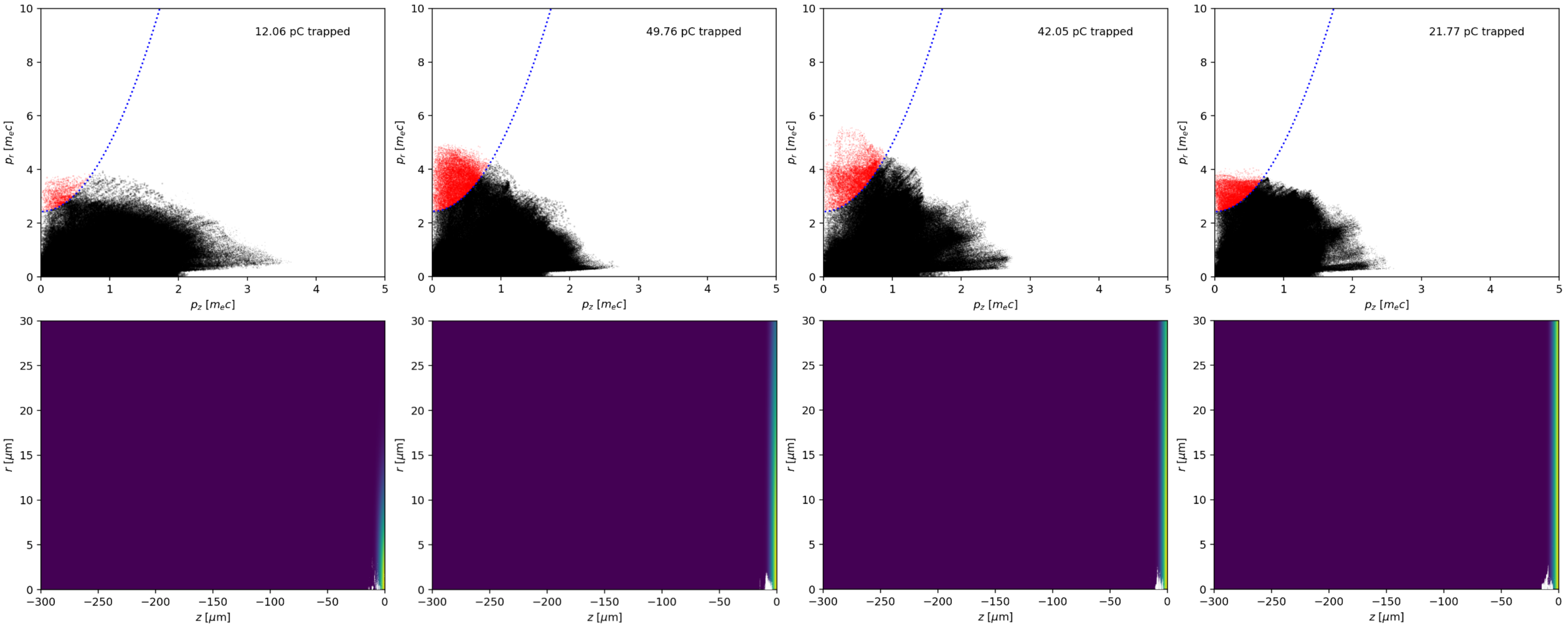
Scans – Preplasma radial size

σ_z = 5µm, a_0 = 2, ϕ_0 = 0.2

σ_r = 10µm | 25µm | 50µm | 100µm

Trapped particles

Trapped particle original locations



Trapped charge	12 pC	**50 pC**	42 pC	22 pC

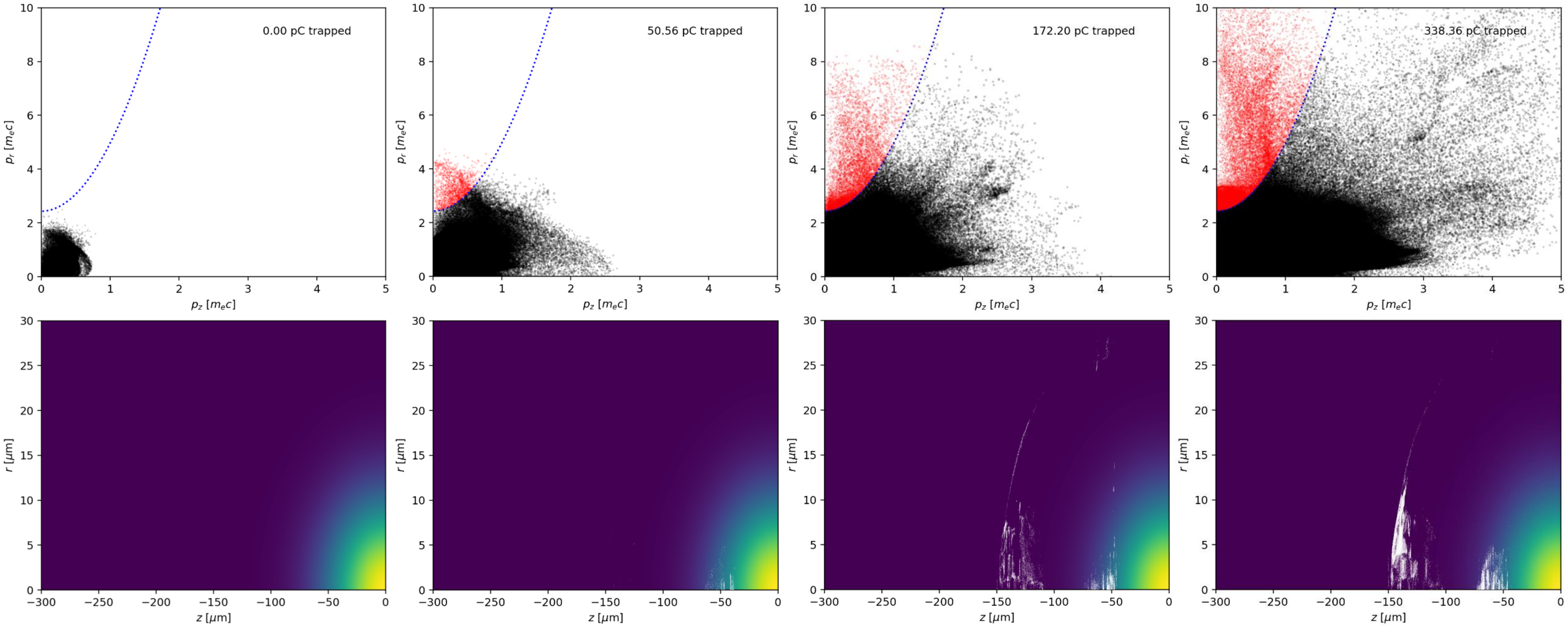
Scans – Laser Amplitude

σ_r = 10µm, σ_z = 50 µm, ϕ_0 = 0.2

a_0 =	0.5	1	1.5	2
$\mathcal{E}_0$ =	13.5 mJ	53.9 mJ	121.2 mJ	215.5 mJ

Trapped particles

Trapped particle original locations



Trapped charge	0 pC	51 pC	172 pC	**338 pC**

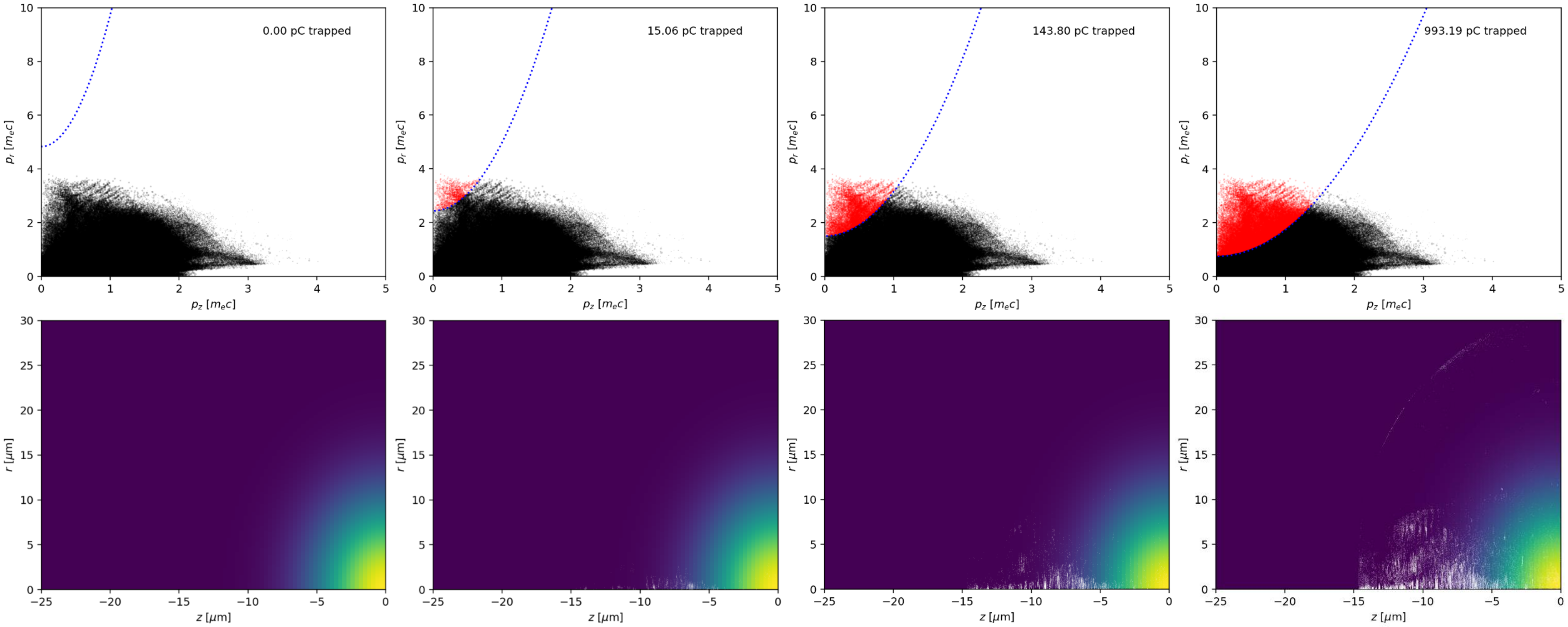
Scans – Wake Potential

σ_r = 10µm, a_0 = 2, σ_z = 5 µm

ϕ_0 = 0.1 | 0.2 | 0.3 | 0.5

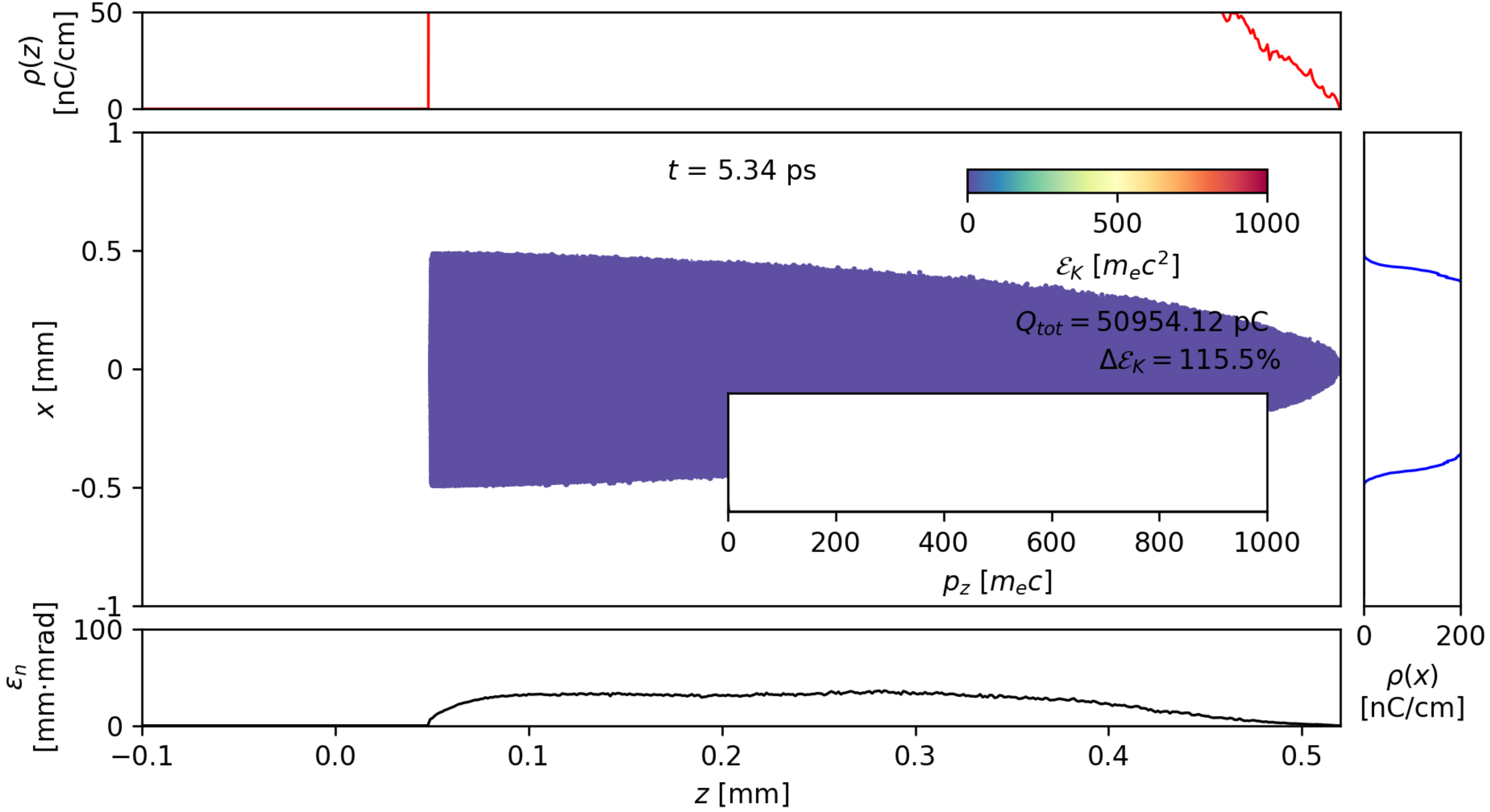
Trapped particles

Trapped particle original locations

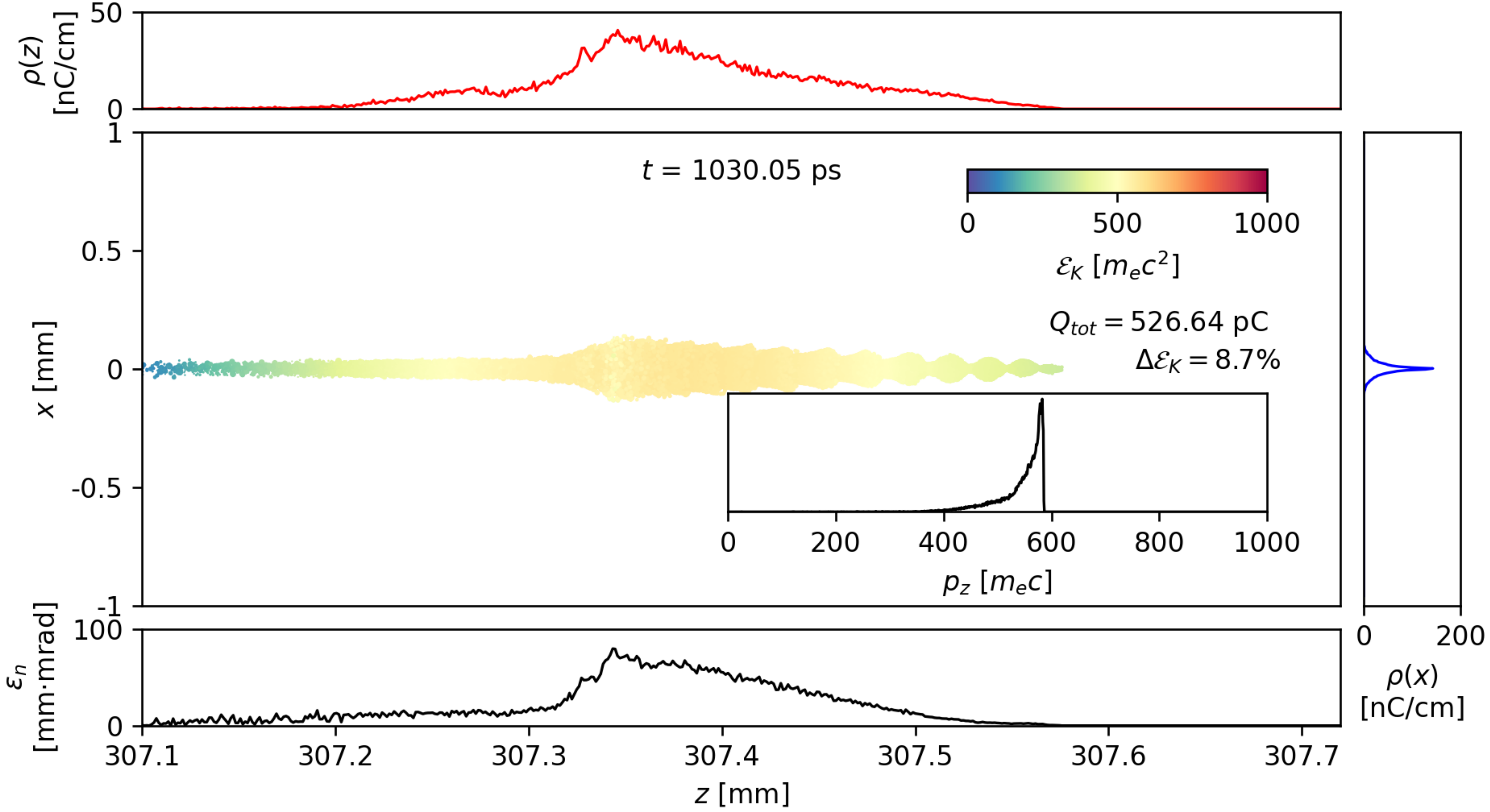


Trapped charge	0 pC	15 pC	143 pC	**993 pC**

High Trapping Acceleration Dynamics - Initial



High Trapping Acceleration Dynamics – 30cm

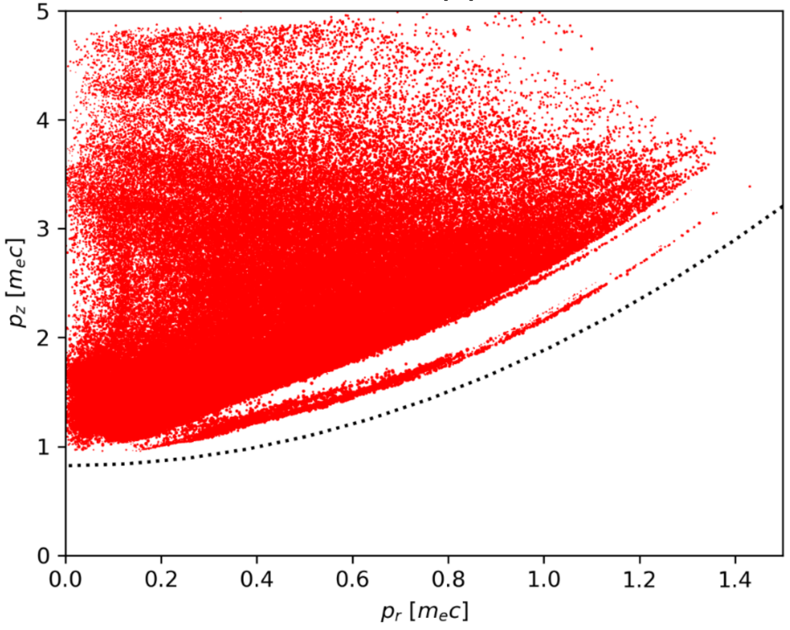


High Trapping Potential – High Charge

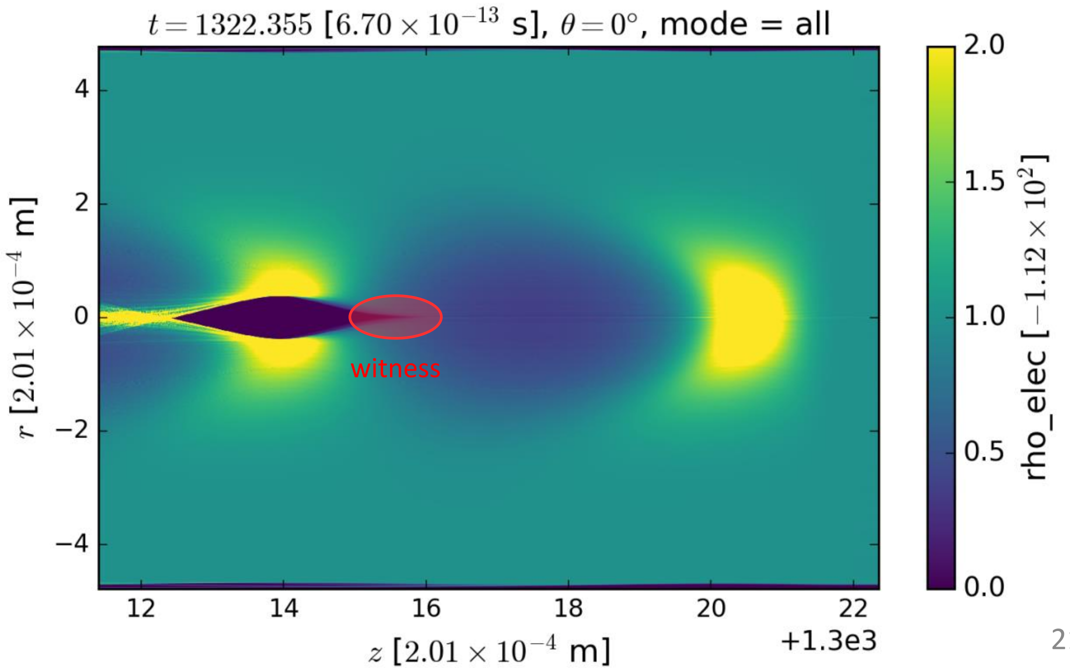
- Wake $\phi_0 \approx 0.5$ - Accelerating fields ≈ 1 GV/m
- Nearly 1nC trapped charge expected,

  Actually, we get about 500 pC

trapping conditions still give lower limits, but not all particles that 'should' be trapped are trapped

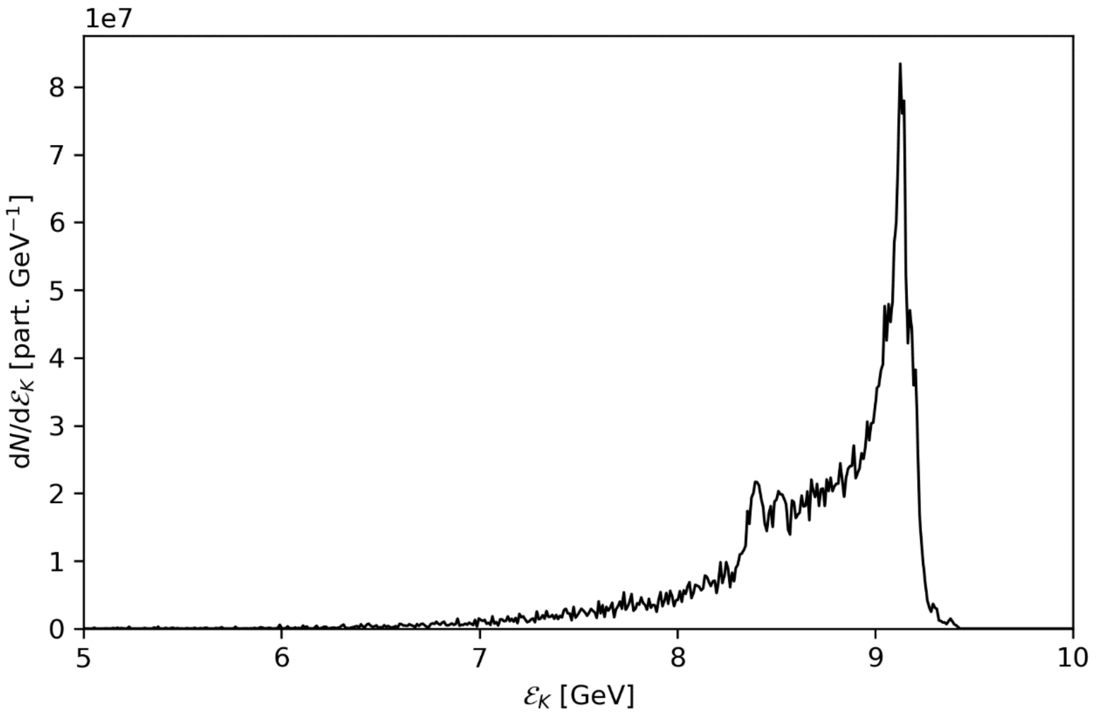


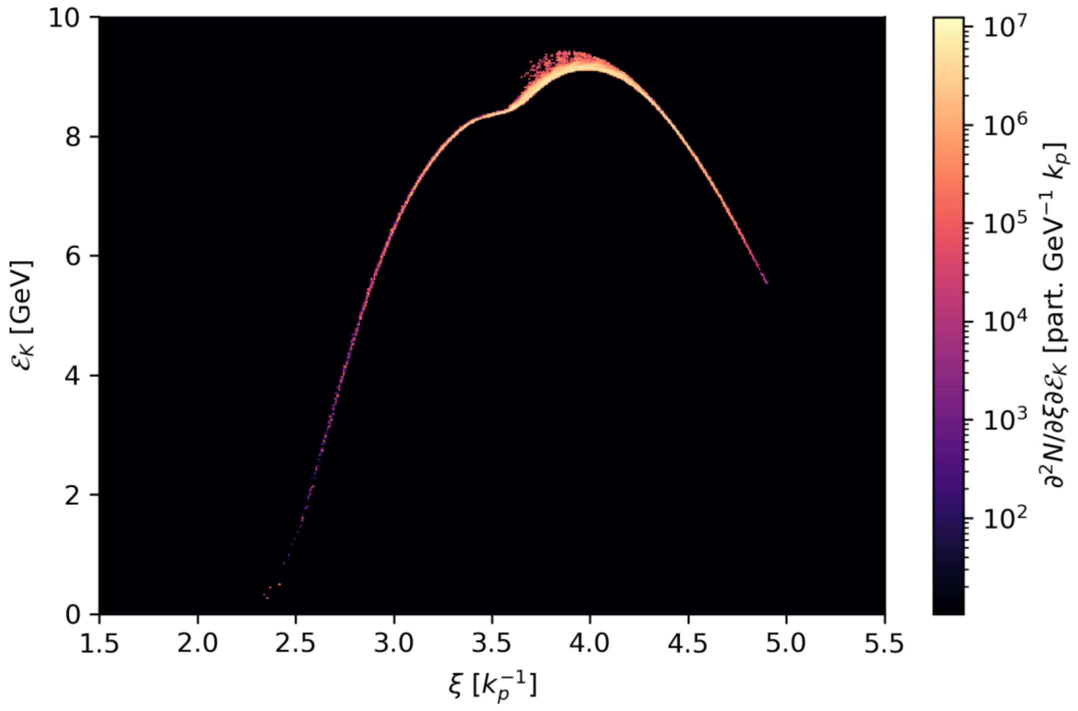
500pC bunch drives its own blowout



10m Summary – High charge / High wake

After 10 meters of acceleration
- 500 pC charge
- 8.6 GeV
- 6.5% energy spread
- 40 µm normalised emittance





Summary

- Colinear injection from a foil offers another alternative for injecting witness bunches with properties on par with existing laser-driven schemes

- Previously-derived trapping conditions provide a good estimate of the witness charge, but high resolution simulations are called for to verify this and examine the injection process in detail – specifically using a realistic preplasma profile would be most useful

- Toy model simulations on track to produce multi-GeV electrons after 10m with energy spread 1 – 10% and emittances in the 20- 50μm range, hybrid simulations to examine the full AWAKE beam would be interesting.

Thank you