A Compact Plasma Beam Dump for Next-Generation Particle Accelerators

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Aims

- To investigate the feasibility of using a plasma-based beam dump for future accelerators as an alternative to conventional beam dumps.

Objectives

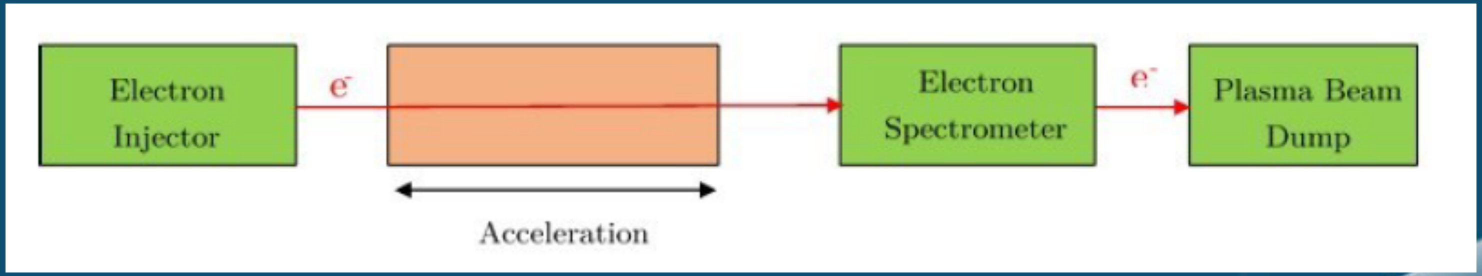
- To compare the advantages and disadvantages of a plasma-based to a conventional beam dump.
- To understand why structured plasma schemes can help further increase energy loss of a particle beam.
- Use EPOCH software to:
  - Create an electron beam using EUPRAXIA parameters
  - Trial different density regimes for uniform plasmas.
  - Test different structured plasma schemes to try and increase energy loss further by removing reaccelerated particles.

Motivation – Conventional Beam Dumps

- Particle accelerators continue to increase in energy and the beam must be disposed of safely.
- Normally achieved using a high density material, however interactions between this material and the beam can lead to production of radionuclides.
- In addition, high temperatures and pressures are produced, meaning larger amounts of coolant are required
- This means they tend to be both costly and cumbersome.

Motivation – Plasma Beam Dump

- A plasma beam dump uses the wakefields created as a driving pulse passes through a plasma to decelerate the incident beam.
- Previous studies have shown we can obtain far larger decelerating gradient for this compared to conventional beam dumps.
- More compact and cost effective than a conventional beam dump – would complement LWFA plasma accelerators well.



- Also produces fewer radionuclides due to low density of the plasma.

Theory – Stopping Power

- A conventional beam dump is based upon particle interactions with matter described by the Bethe Bloch Equation:

$$-\left(\frac{dT}{dx}\right) = \left(\frac{e^2 k_p}{\beta^2}\right)\left[ln\left(\frac{2m_e\gamma^2v^2}{I}\right) - \beta^2\right],$$

- In relativistic regime, energy loss due to Bremsstrahlung radiation dominates, Bethe Bloch equation for this simplifies to:

$$-\left(\frac{dT}{dx}\right)_{BR} = e^2 k_p\left(\frac{Z}{137\pi}\right)\left(\gamma - 1\right)ln\left(183Z^{-1/3}\right),$$

- For copper, this gives a decelerating gradient of ≈ 5 GeV/m.

Theory – Collective Deceleration

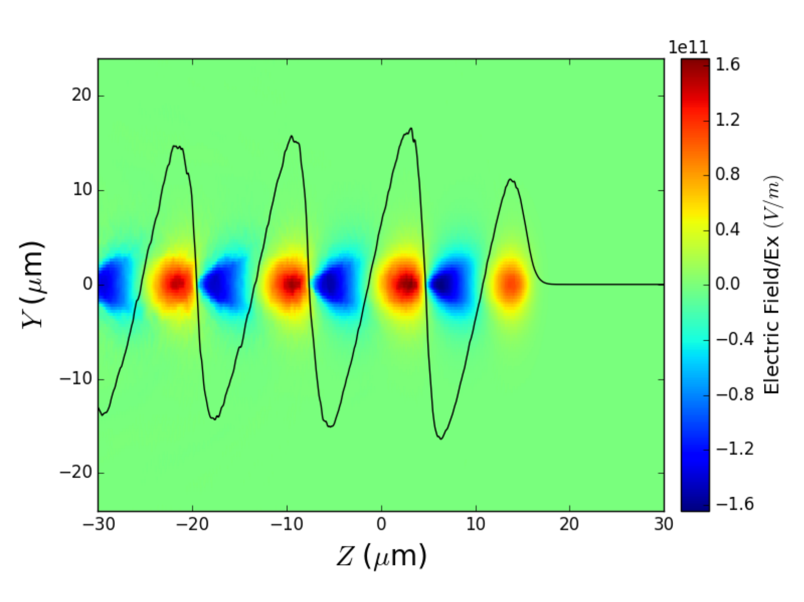
- Depending on the ratio of plasma and beam electron densities, we get three different regimes:
  - Linear: $n_b << n_p$
  - Quasi Linear: $n_b \sim n_p$ where $n_b = \frac{N_e}{(2\pi)^{\frac{3}{2}} \sigma_x \sigma_y \sigma_z}$,
  - Non-Linear: $n_b >> n_p$
- Collective Stopping Power: $-\left(\frac{dE}{dx}\right)_{C-Wake} = m_e c \omega_p \left(\frac{n_b}{n_p}\right)$
- To avoid self-injection, we require that $n_b \lesssim n_p$. However for a maximally decelerating wakefield, we want $n_b \gtrsim n_p$,. Compromise-quasi-linear regime.

Theory – Plasma Beam Dump Schemes

- Two types of beam dump: Active (ABD) and Passive (PBD).
- PBD more reliable so we will focus on this but drawbacks include no deceleration of head particles due to finite response time of plasma.
- There is a limit on the decelerating gradient achievable:

$$E_{max} = \frac{m_e c \omega_p}{e},$$

- For typical LWFA parameters, decelerating gradient of ≈ 75 GeV/m.



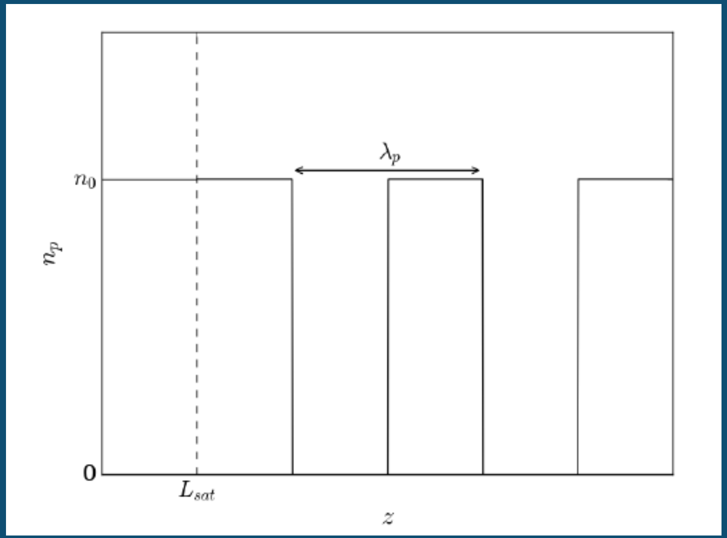
- Will begin with a uniform plasma to initially reduce energy of particles up to a saturation point approximately defined by:

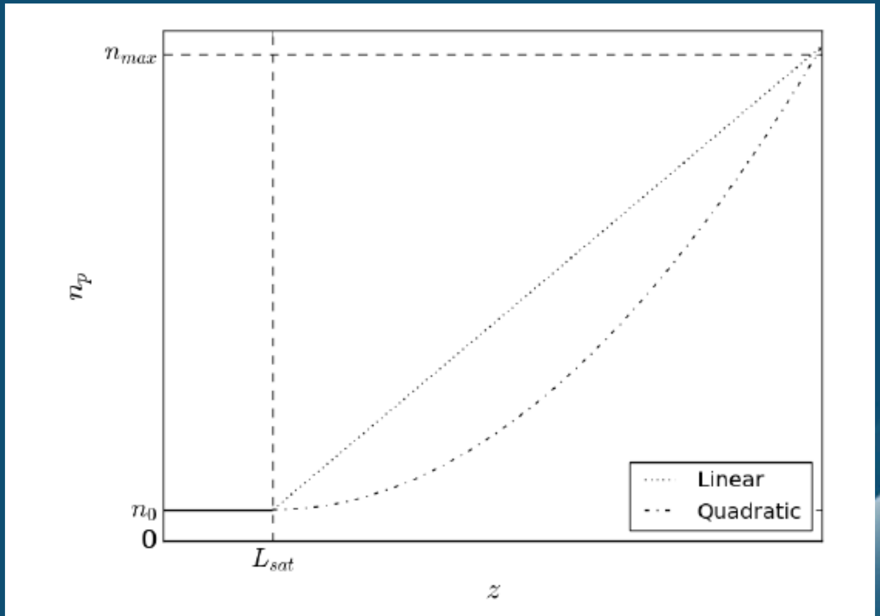
$$L_{sat} = \frac{T_0}{eE_{max}}$$

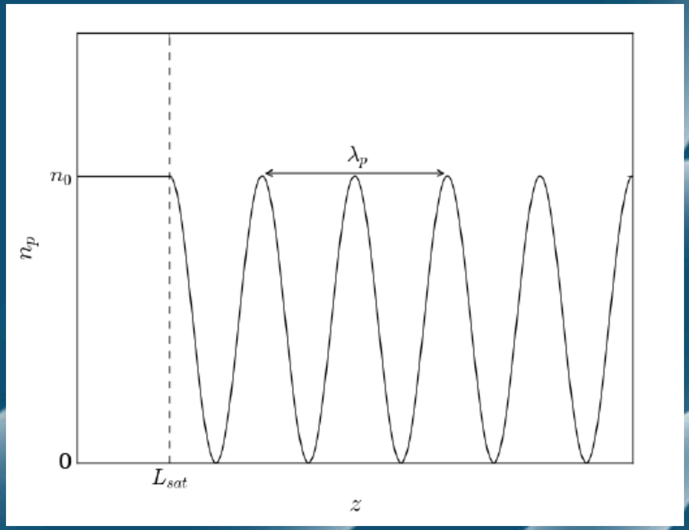
Theory – Plasma Beam Dump Schemes (2)

- Beyond this point, structured schemes will be investigated including:
  - Foils / Vacuum Gaps
  - Linearly / Quadraticaly Increasing Plasma Density
  - Sinusoidally Varying Plasma Density

$$\lambda_p = 2\pi c\left(\frac{\epsilon_0 m_e}{e^2 n_p}\right)^{\frac{1}{2}} \approx \frac{3\times 10^7}{\sqrt{n_p}},$$

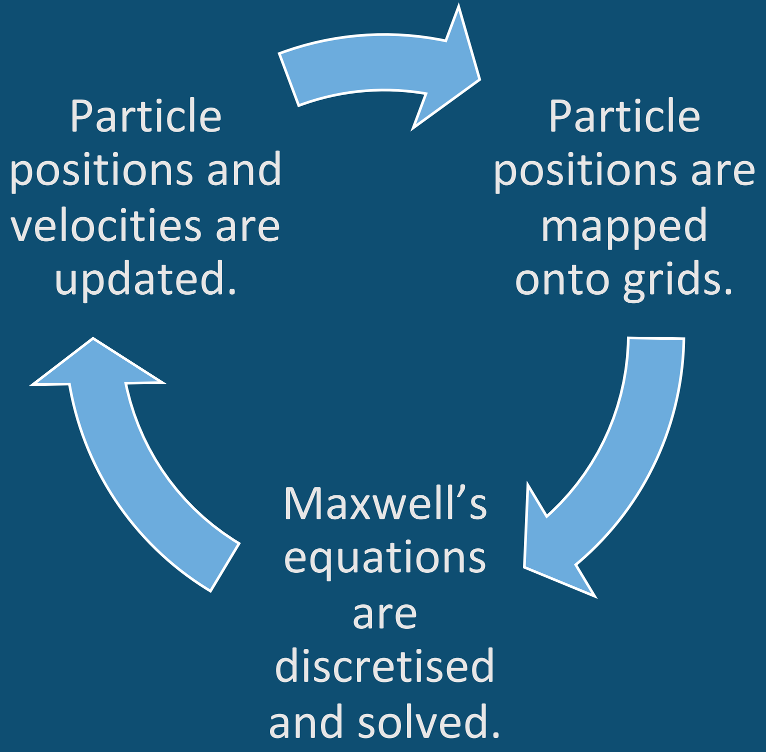






Software – EPOCH

- Used EPOCH in this project.
- Particle In Cell (PIC) code- uses a small number of macroparticles to represent plasma particles.
- Controlled using input decks - text files where properties of the particles and the simulation domain are defined.
- Outputted data is contained in SDF files. These can be processed using other software (e.g Python).




```
begin:species
  name = electronBeam
  charge = -1.0
  mass = 1.0
  npart_per_cell = ppc_e_beam
  density = beam_den_max* beam_profile_x * beam_profile_y
  density_min = 1000.
  temp = beam_temp
  drift_x = beam_central_px
end:species
```

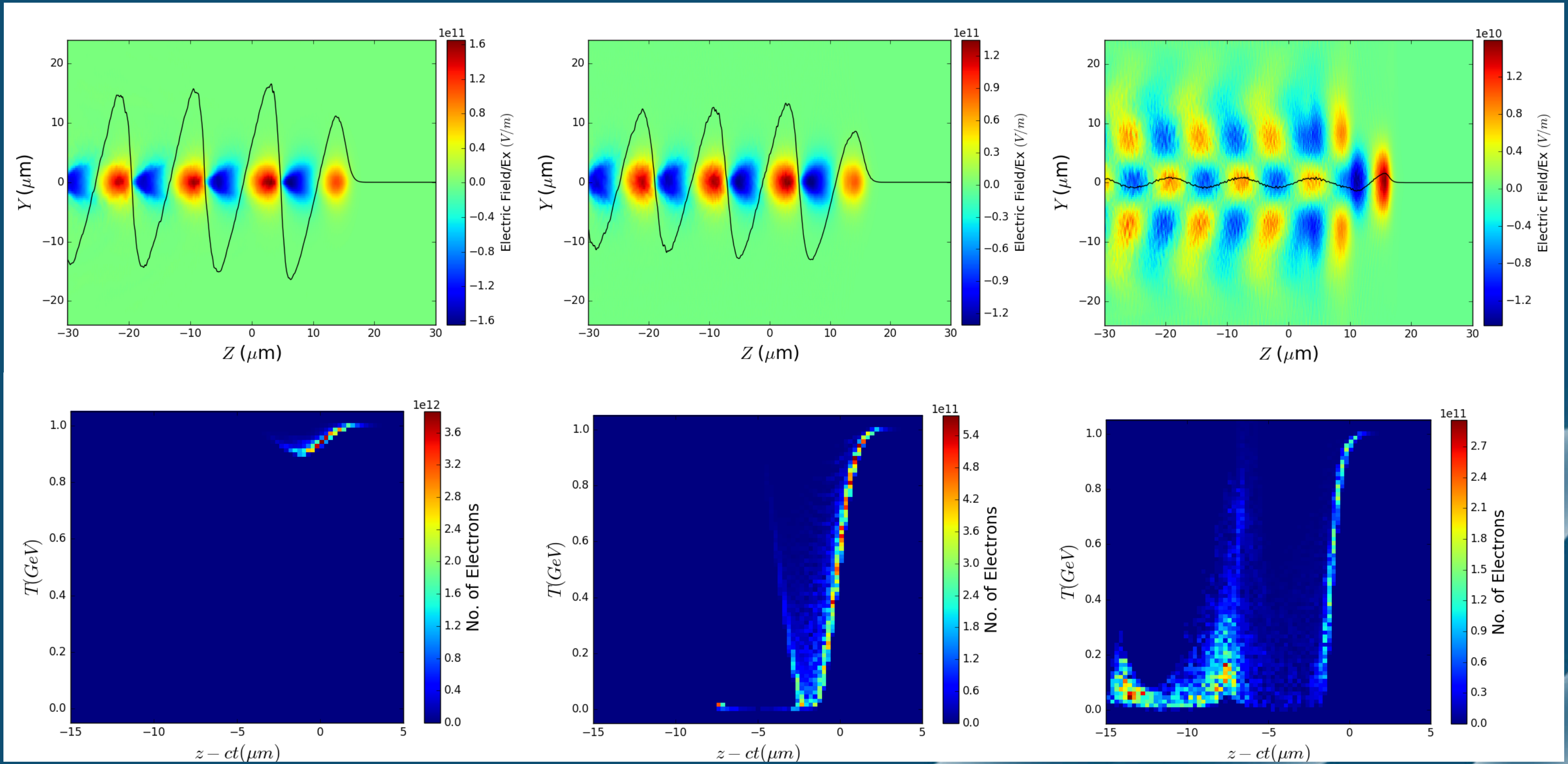
Method

- First, used EPOCH to simulate a Gaussian beam with the desired parameters (see table).
- Then studied the energy loss of a beam as it passed through a section of uniform plasma.
- Repeated this for a variety of plasma densities $(n_p/n_b = 1, 2, 5, 10, 0.1)$.
- Used the density that gave the best results to perform further simulations beyond saturation i.e different plasma structures.

Parameter	EUpraxia Beam	Simulation Beam
Mean beam energy, T_0	1-5 GeV	1 GeV
RMS energy spread	$\sim$5%	$\lesssim$ 1%
RMS bunch length, σ_z	$\sim$ 1.5μm (5 fs)	1.5 μm (5 fs)
RMS transverse beam size, $\sigma_{x,y}$	$\sim$0.3 μm	0.3μm
Bunch charge	100 pC	100 pC
Peak bunch density, n_b	10^{23} m^{-3}	10^{23} m^{-3}

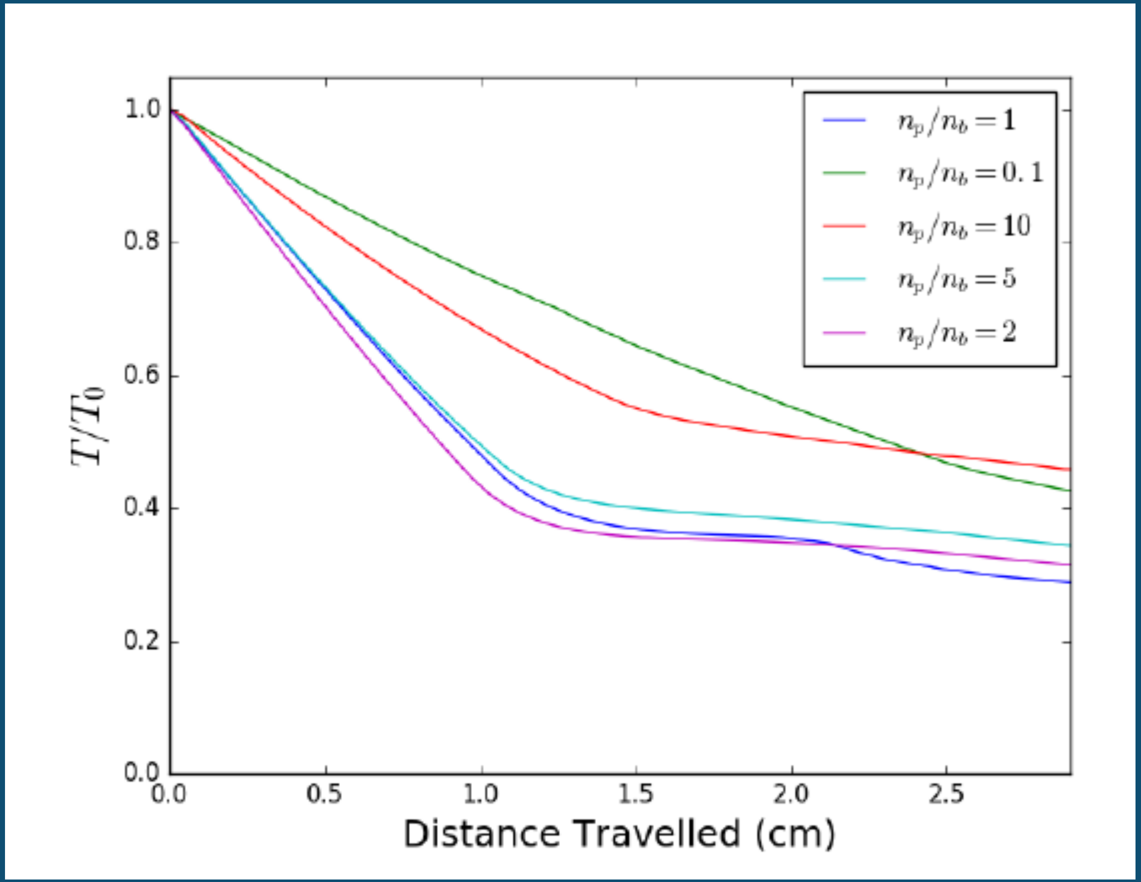
Results – Uniform Plasma Density

0.5cm | 1cm | 5cm



Results- Uniform Plasma Density

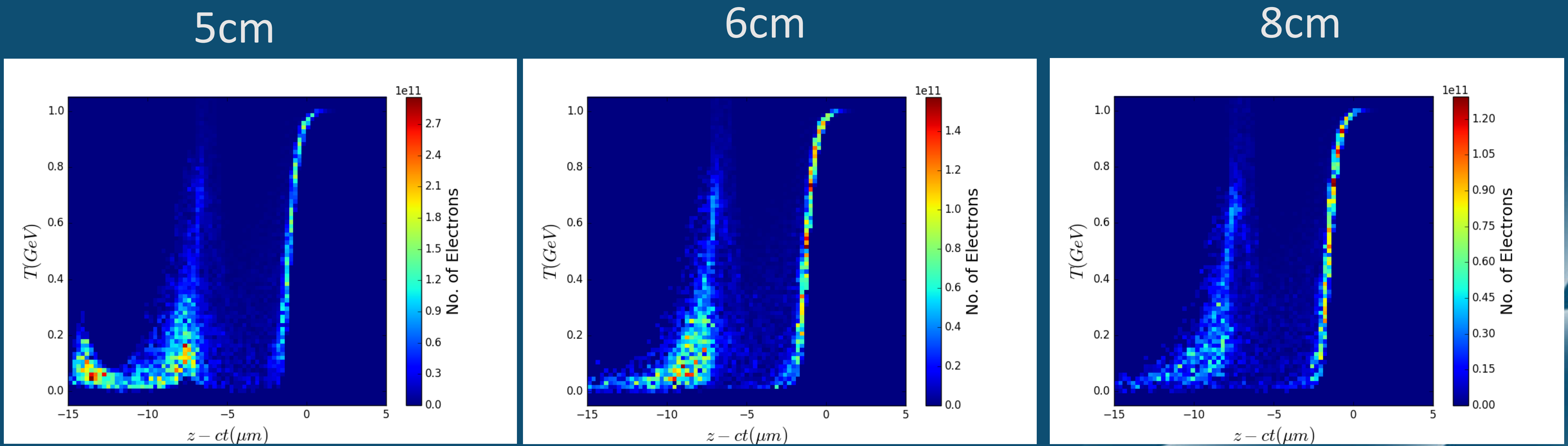
- Normalised Energy Loss:



- Quasi-linear schemes far more efficient at reducing energy of the bunch.
- Can see that the $n_p = 2n_b$ case reaches saturation first, so will use this.
- Energy loss of ≈ 75% after 5cm travelled.

Results – Structured Plasmas

Example: Periodic Vacuum Gaps

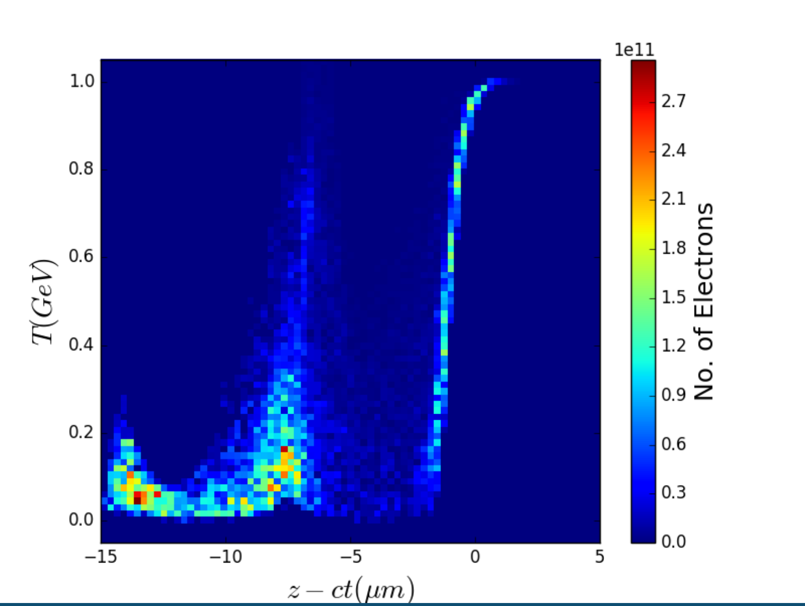


- Gradual removal of tail particles.
- Particles at the bunch head still remain.

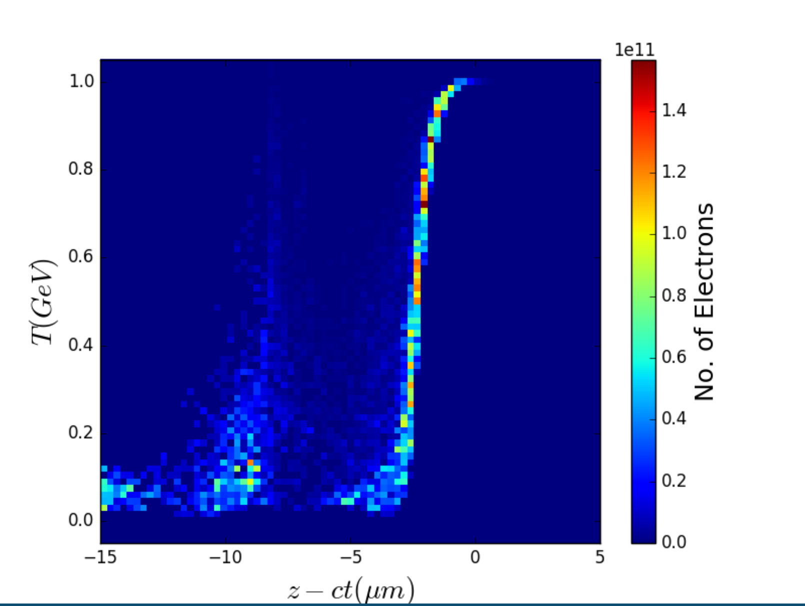
Results – Structured Plasmas

Example: Linearly Increasing Plasma Density

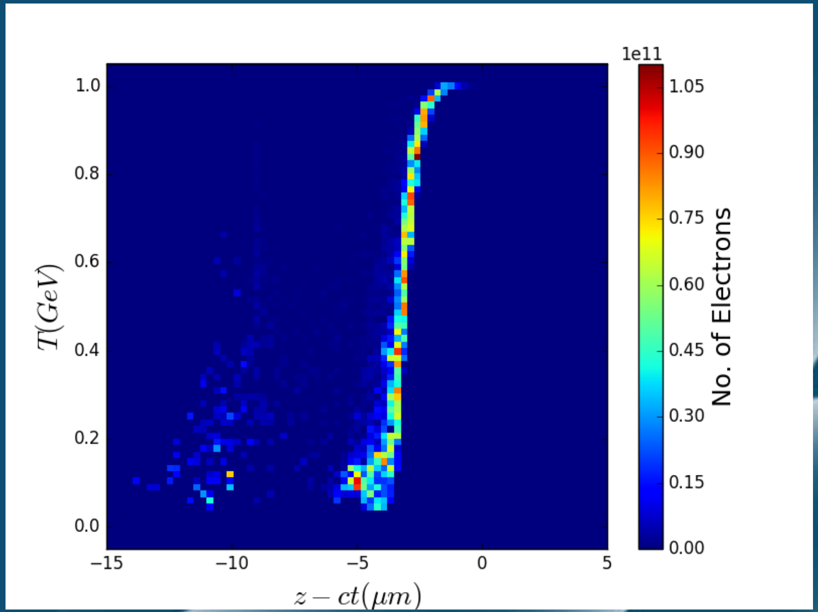
5cm



6cm



8cm

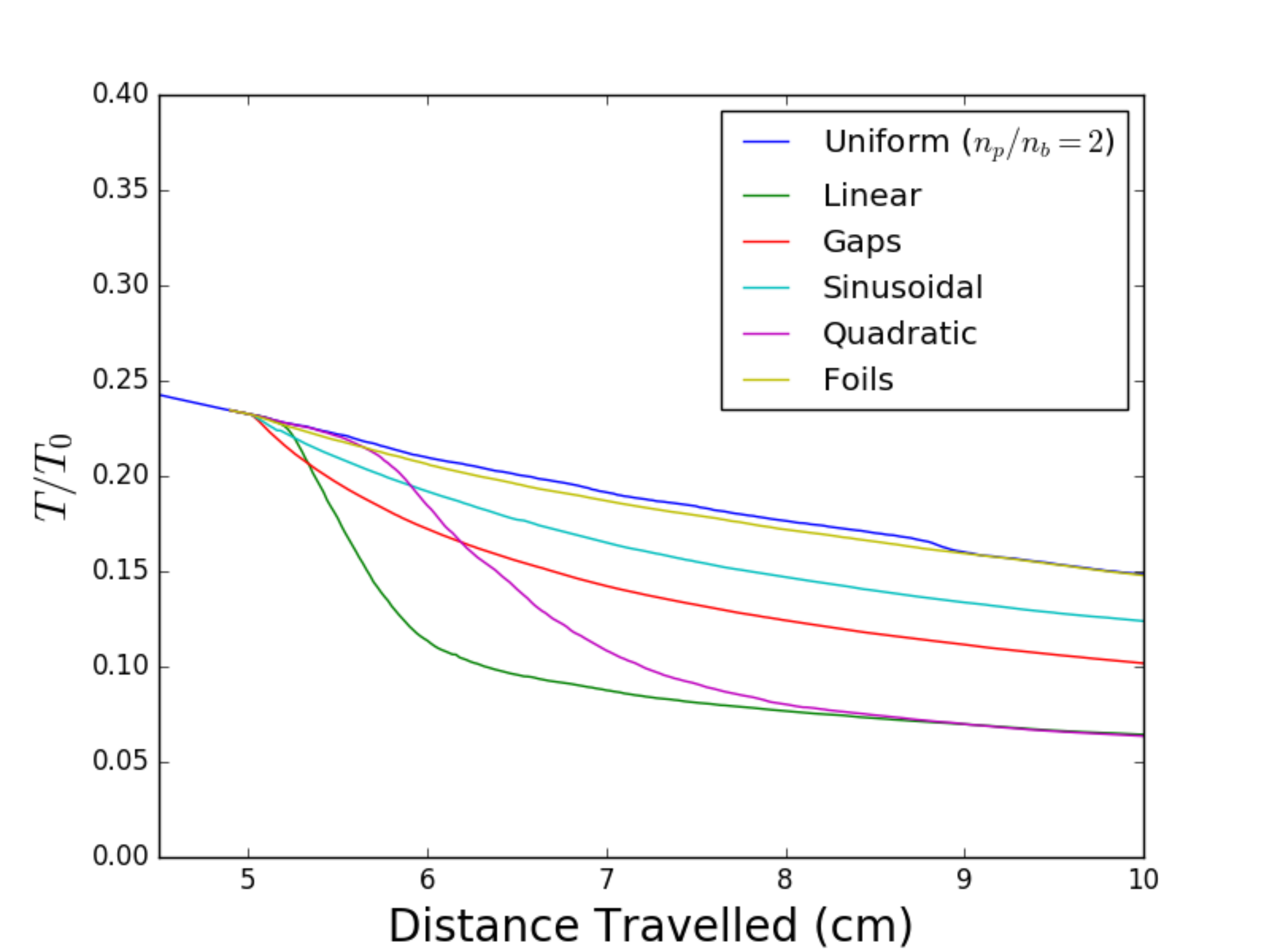


- Nearly all tail particles removed.
- Particles at the bunch head still remain.

Results – Structured Plasmas

Normalised Energy loss beyond saturation:

- Linearly and quadratically increasing densities provide the most efficient energy loss.
- Total energy loss of $\sim 93\%$ achieved.
- Foils performed badly - simulations not taking into account all of the physics.



Results – Summary & Discussion

- By passing a 1 GeV electron beam through a uniform plasma with density $n_p = 2n_b$, an energy loss of $\sim 75\%$ was achieved over a distance of ~ 5cm where the energy loss became completely saturated due to the reacceleration of the electrons.
- Following this with a linearly increasing plasma density to remove the reaccelerated electrons, a total energy loss of $\sim 93\%$ was achieved over a total distance of ~ 10cm.
- This beam dump is much more compact than conventional counterpart e.g copper beam dump would need to be around 15 times longer.

Improvements & Possible Extensions

- Implementation of an active beam dump to reduce the energy of particles at the head of the bunch.
- Investigating solid interactions in more depth to improve results for the foils simulation.
- Investigation of hybrid schemes of the structured plasmas.
- Producing beam with correct energy spread to replicate a EUPRAXIA beam.
- Investigating self-injection of plasma electrons.
- All would require high performance computing so this is vital for future extensions of the project.