A passive plasma beam dump using non-uniform plasma density

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13/12/2016

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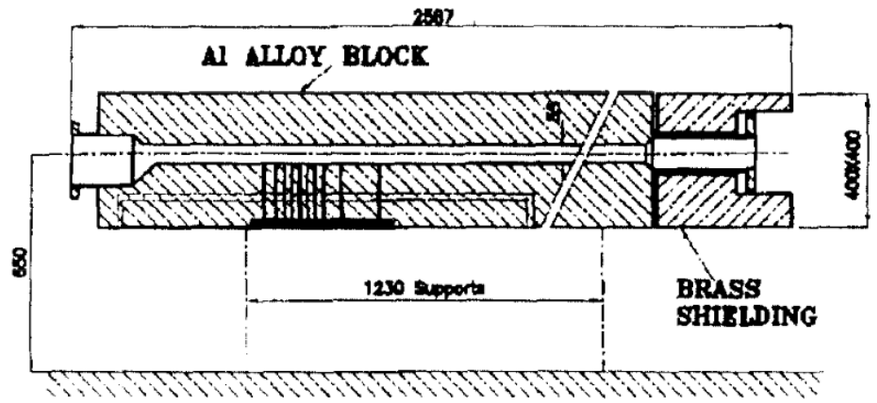
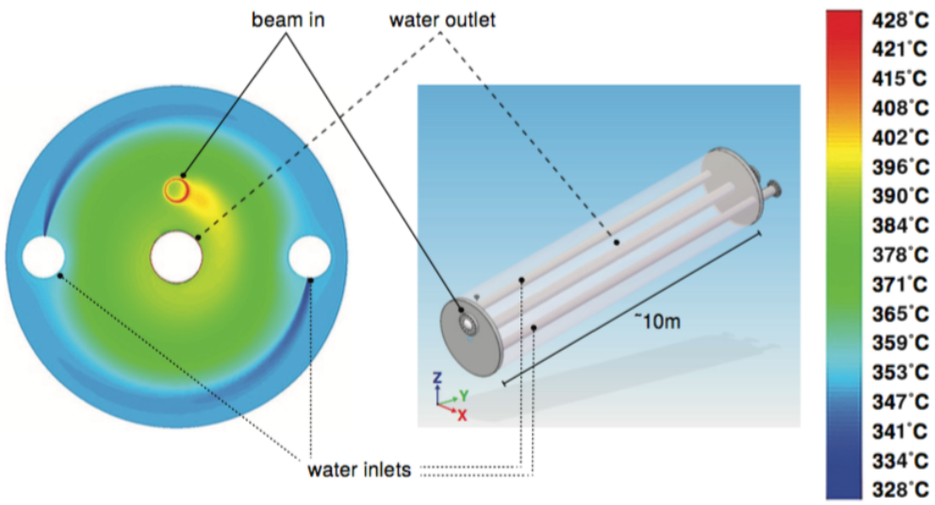
Conventional beam dump

Conventional beam dumps use high density materials - metal, water etc.

Planned ILC beam dump is based on SLAC design:



LEP beam dump
- 2 m aluminium alloy
- Additional brass shielding
- Air cooled



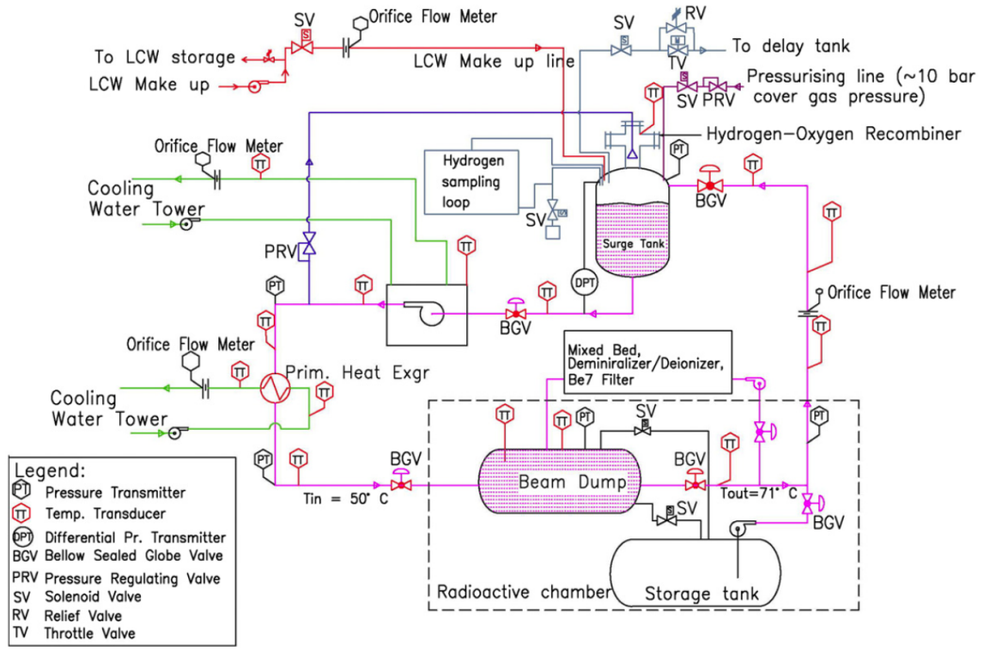
ILC beam dump (proposed)
- 11 m long steel pressure vessel
- Max water temperature 155 °C
- Pressure 5 bar

E. Carlier et al. Proc. EPAC94, 2494 (1994)
P. Satyamurthy et al. NIM A 679, 67 (2012)

Conventional beam dump

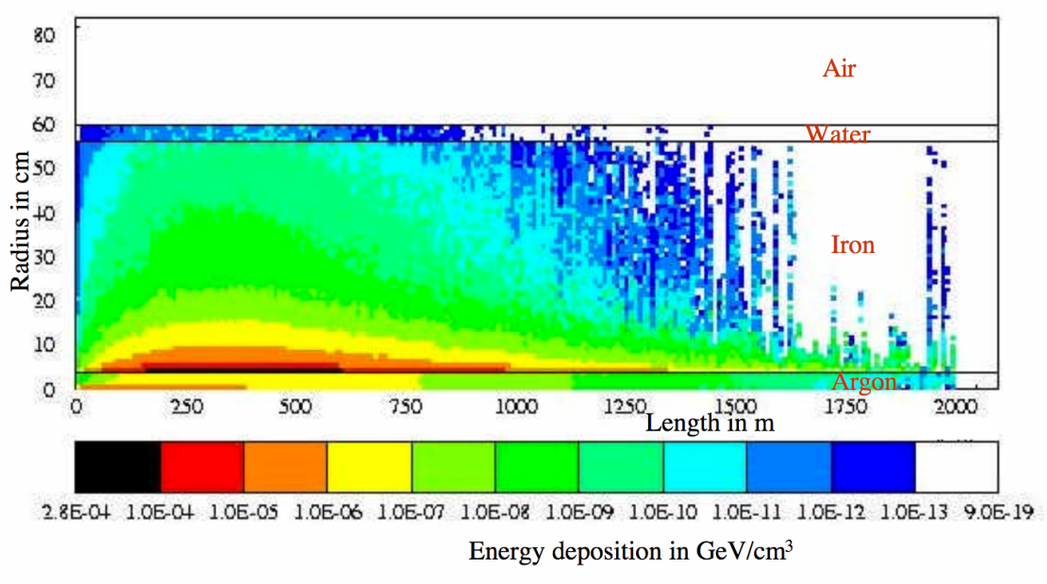
There are a number of drawbacks to conventional beam dumps:

- Radionuclide production
- Hydrogen/oxygen production
- Size and cost of cooling systems



Noble gas beam dump

A. Leuschner, LC-ABD dump meetings, Sept. 2005



- Very long length, but low power density.
- Reduced radionuclide production.
- No hydrogen/oxygen gas production.

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Plasma beam dump

A plasma beam dump offers high decelerating gradients in a low density medium:

$$E_{\mathrm{wb}} = \frac{m_{\mathrm{e}} c \omega_{\mathrm{p}}}{e} = 9.6\sqrt{\frac{n_e}{10^{22}}}\ \mathrm{GV\ m^{-1}}$$

For n_e=10^{23} m^{-3}, E_{wb}=96 GV/m.

c.f. density of air at 1 atm ~10^{25} m^{-3}

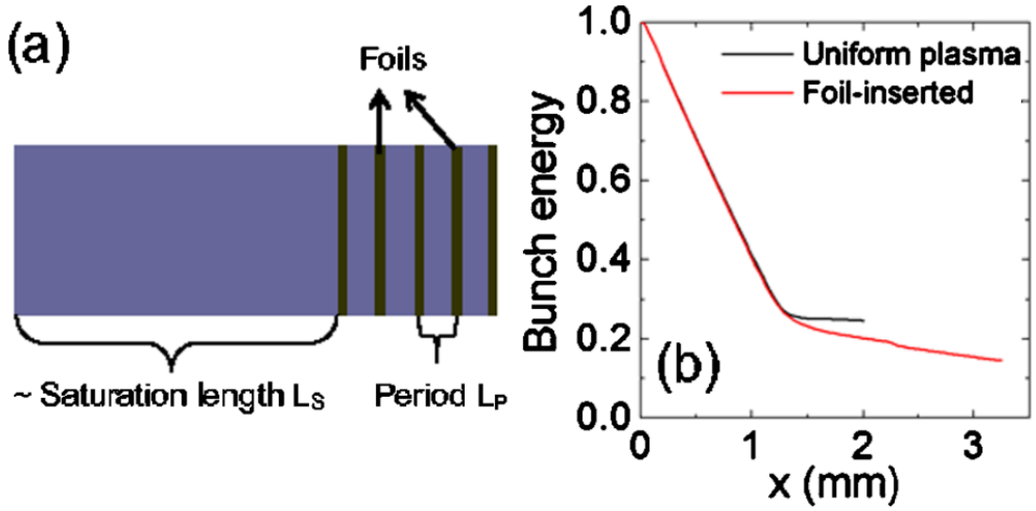
- Compared with the stopping power in a solid material e.g. ILC beam dump 500 GeV in 11 m = 45 GV/m.
- Plasma density is orders of magnitude lower than solid e.g graphite ~ 10^{29} m^{-3}.
- Plasma beam dump also decelerates muons at the same gradient.

Passive plasma beam dump

Decelerating gradient saturates after some distance as a portion of the bunch is re-accelerated.

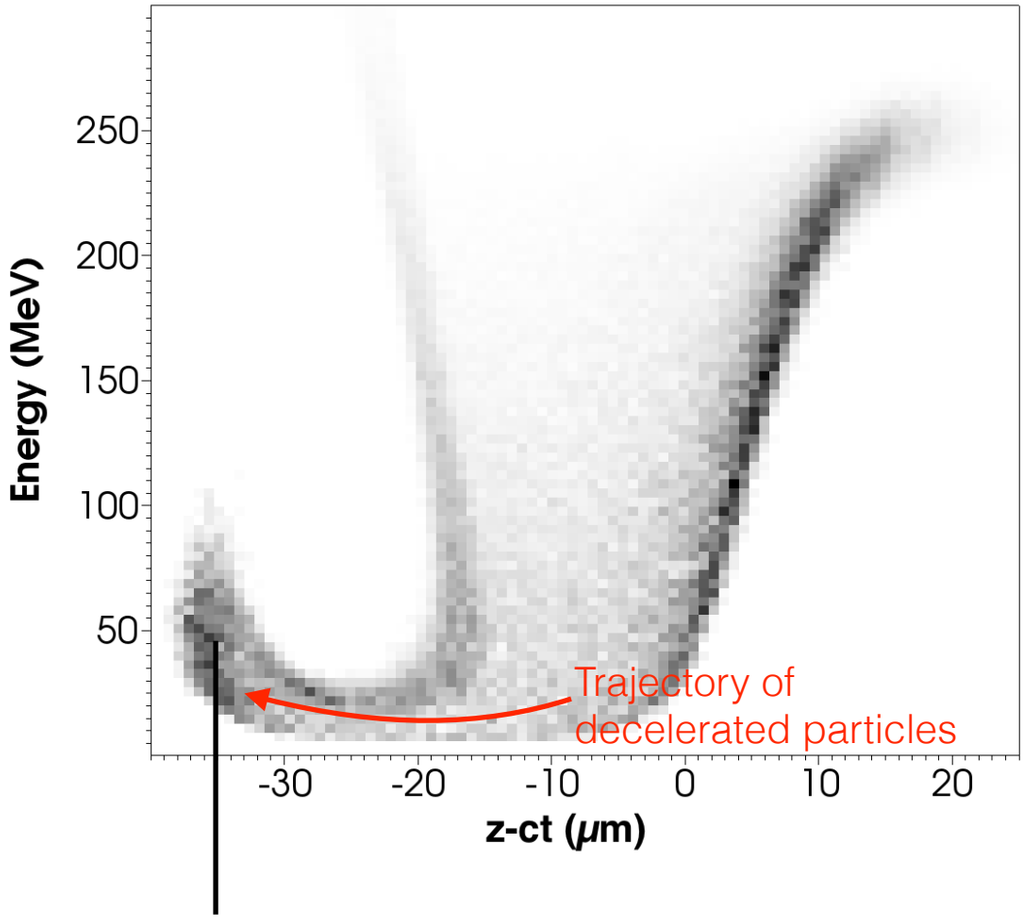
The low energy particles need to be removed.

Wu et al. proposed using a series of foils after the saturation length.



H.C. Wu et al. PR-STAB 13, 101303 (2010)

Longitudinal phase space of plasma decelerated bunch

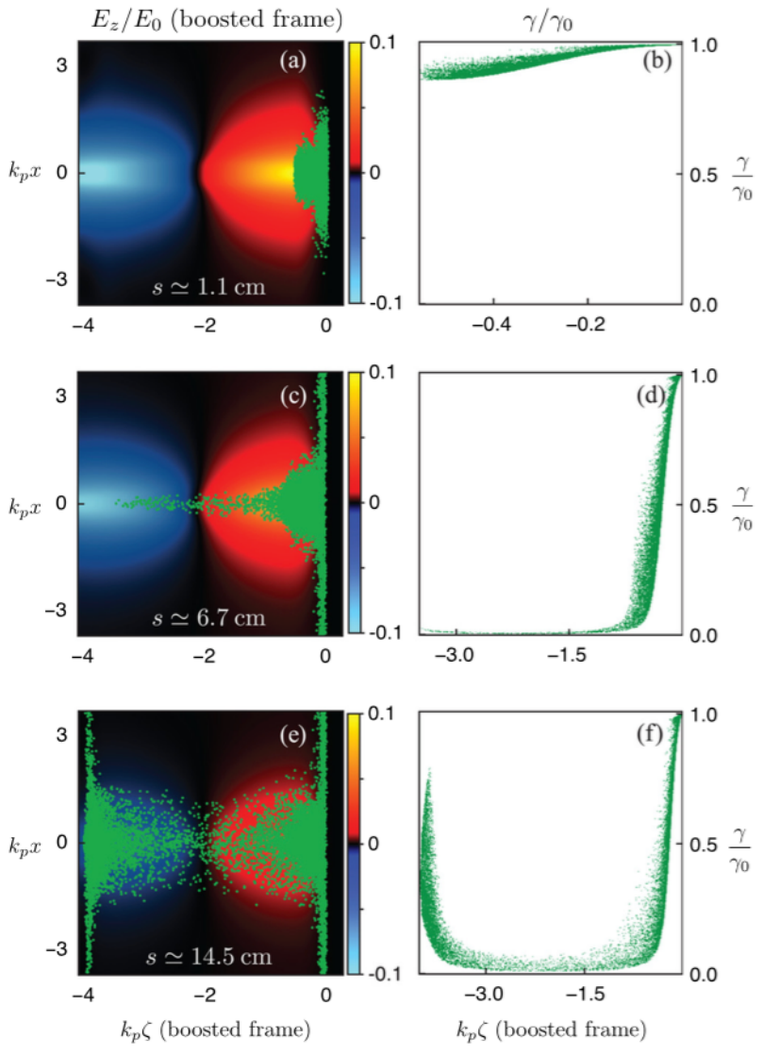


Re-accelerated portion of bunch

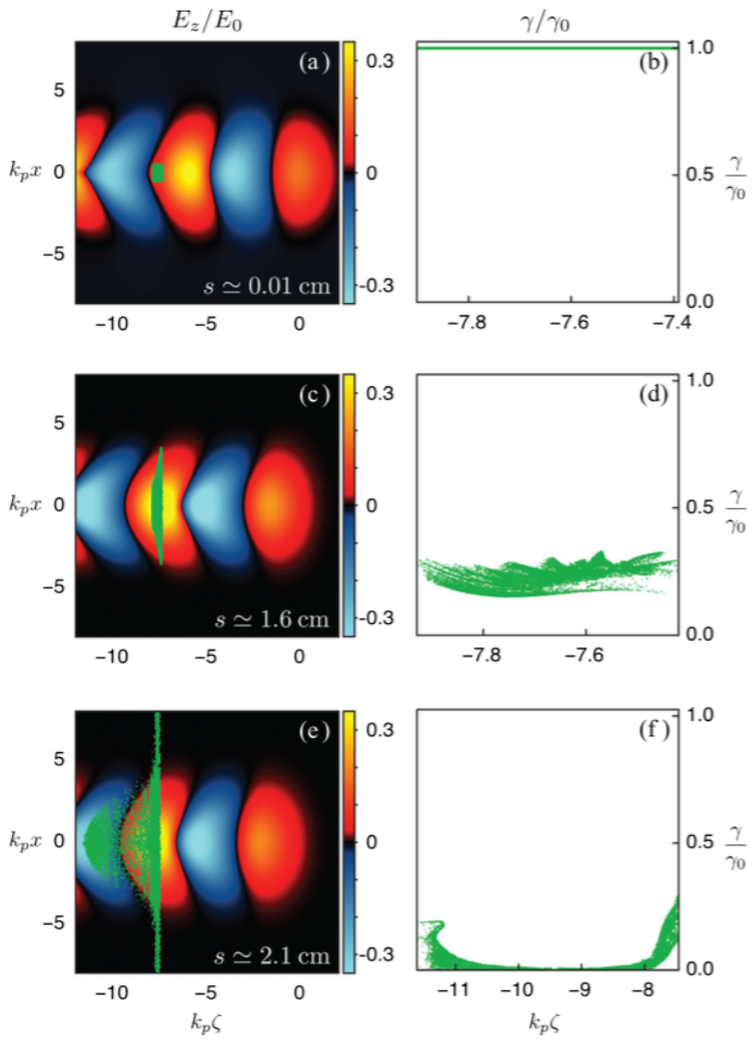
Active plasma beam dump

In an active beam dump, the wakefield of a laser pulse is used to stop the beam.

Passive dump



Active dump

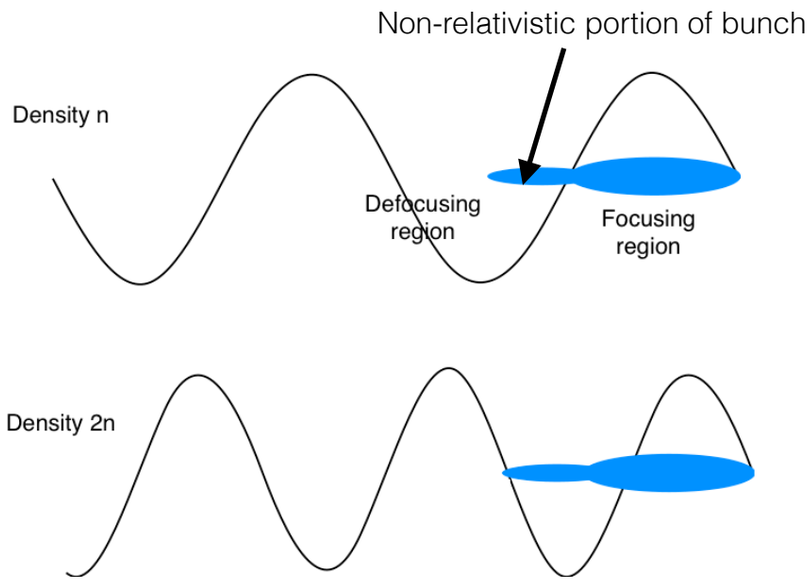


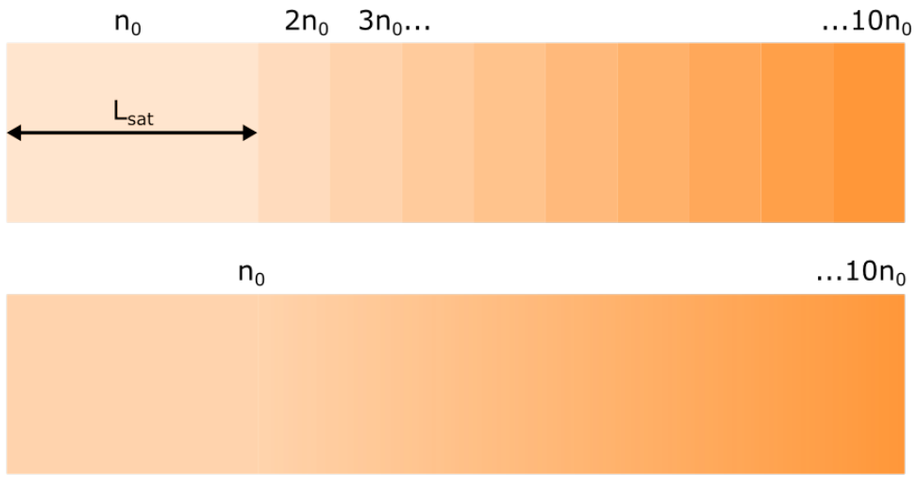
A. Bonatto et al., Phys. Plasmas 22, 083106 (2015)

Modified plasma density

An alternative to absorbing the low energy particles is to move them into a defocusing region of the wakefield by reducing the plasma wavelength.

When the density increases, the decelerated portion of the bunch passes into a defocusing region.



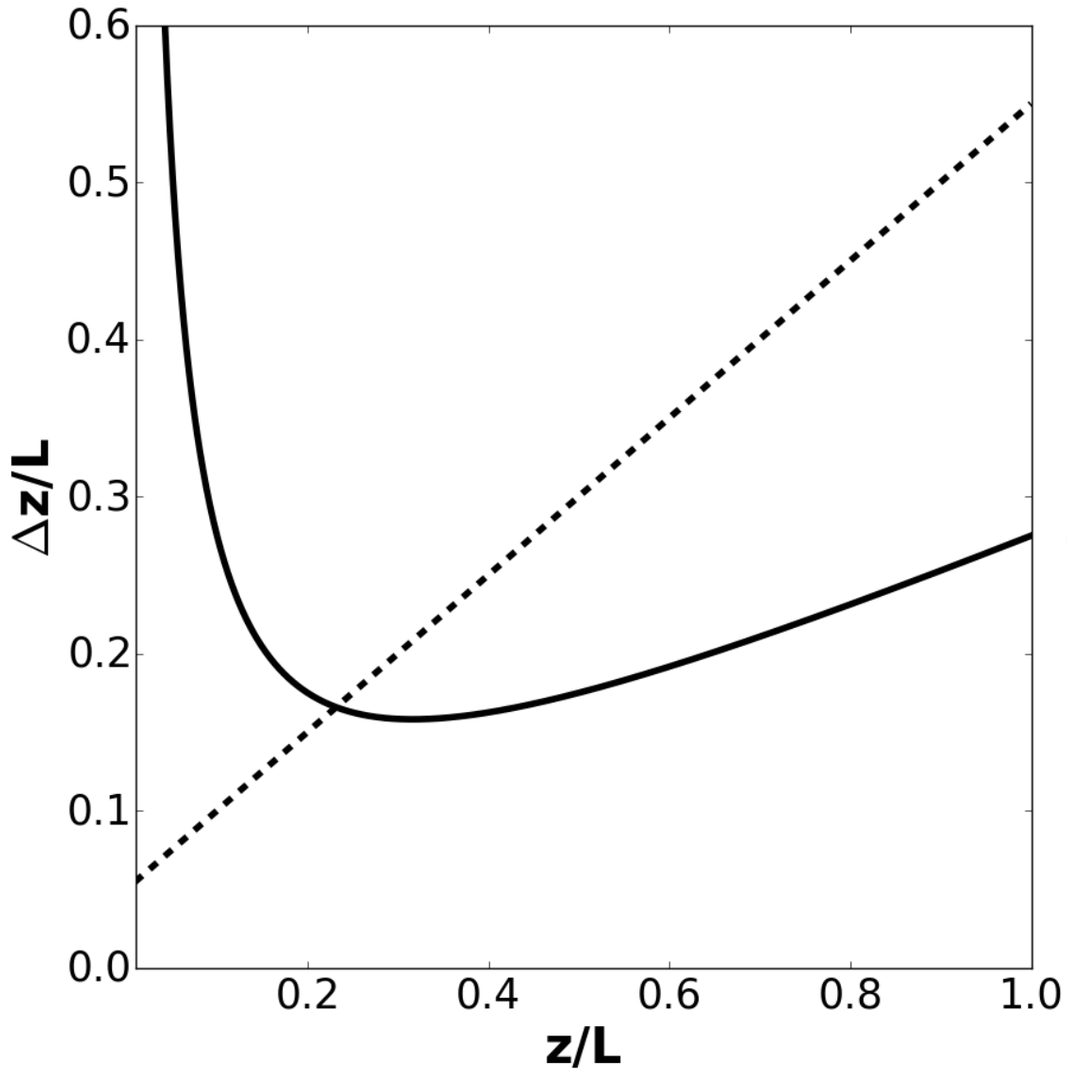


Stepped profile gives instant shift in wavelength while gradient shifts wavelength gradually.

Gradient density profiles

For a gradient plasma density the decelerated particles must pass through the accelerating region without becoming highly relativistic.

The functional form of the plasma density determines how quickly the wavelength changes.



Linear

Quadratic

$$\lambda_{\mathrm{p}} \propto n_{\mathrm{e}}^{-\frac{1}{2}}$$

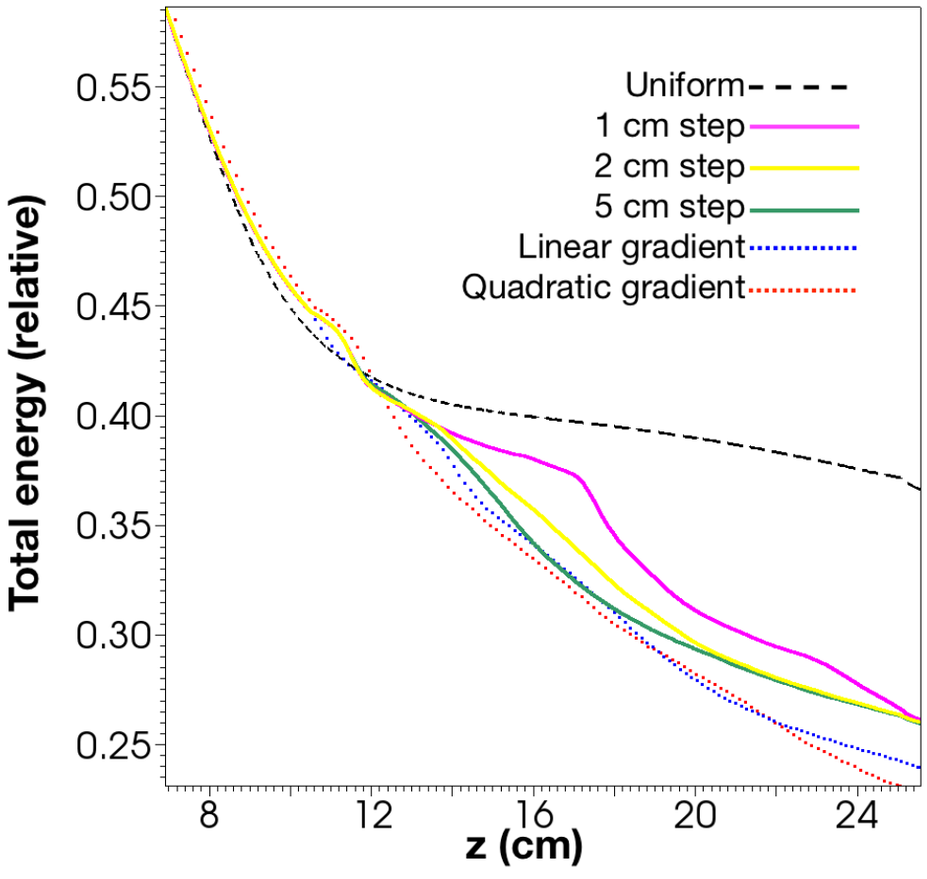
Left: Plot showing distance required for plasma wavelength to change by a factor of 2

CLARA simulations

J. Clarke et al., J. Instrum. 9, T05011 (2013)

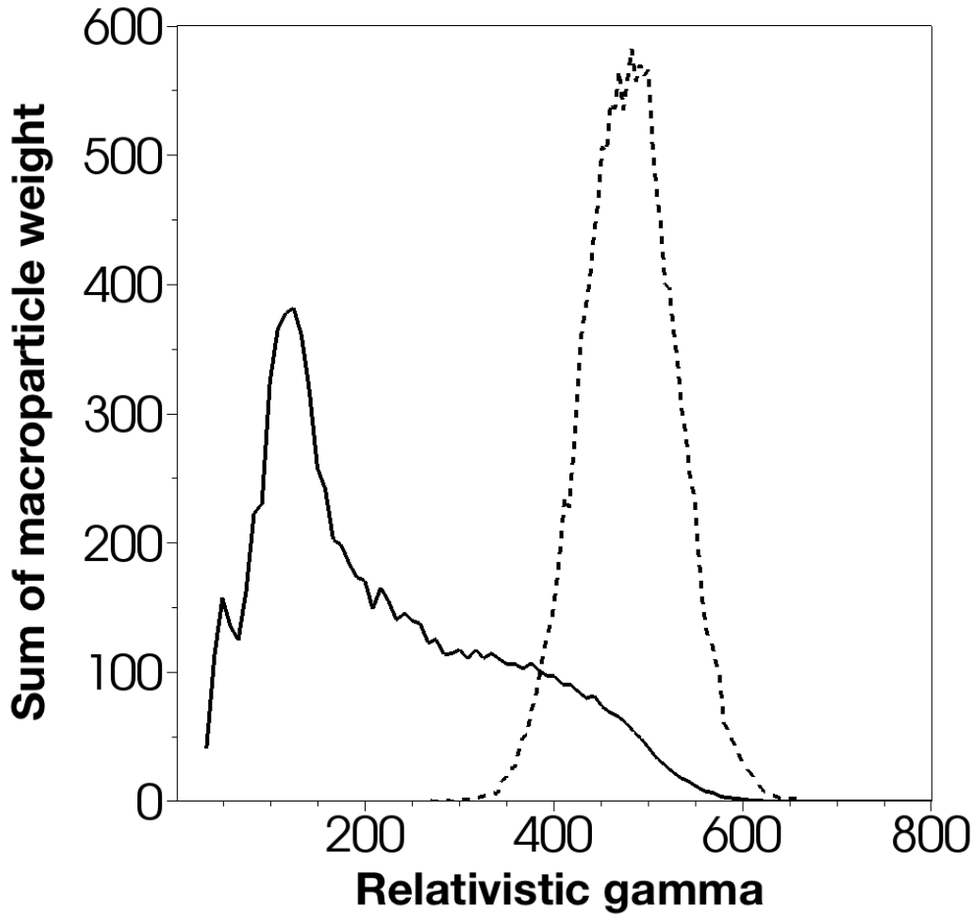
Simulations carried out for CLARA ultrashort bunch: 7.5 μm rms bunch length, 100 pC, 250 MeV; also representative of LWFA.

Initial decelerating gradient 4.5 GV/m (peak), 1.5 GeV/m (average).



Left: Energy loss for different plasma profiles

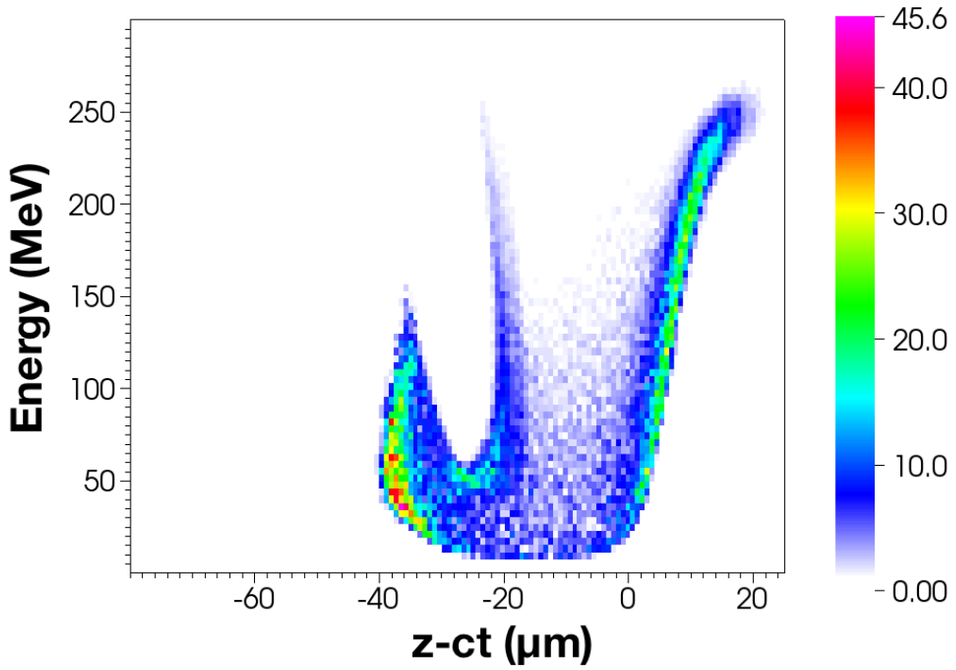
Right: Initial and final energy spectra for linear gradient plasma.



Defocusing

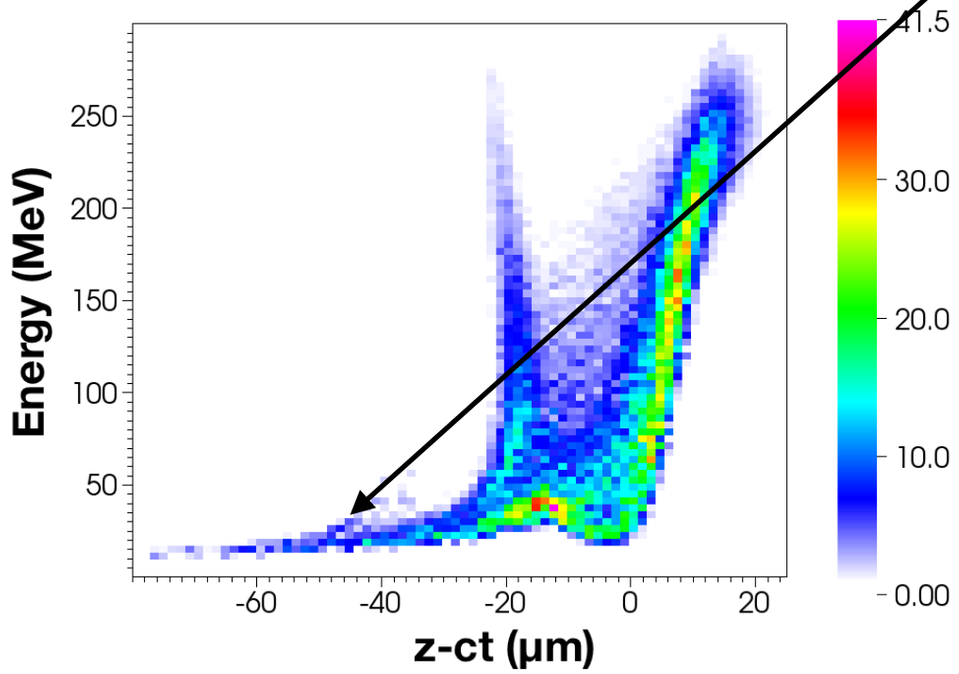
Longitudinal

Uniform

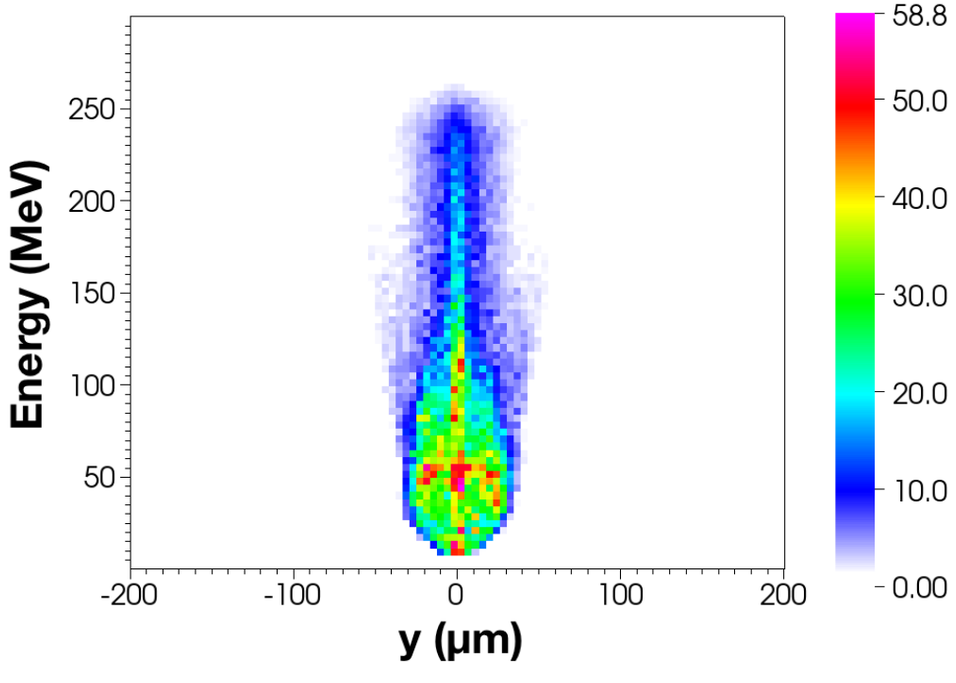


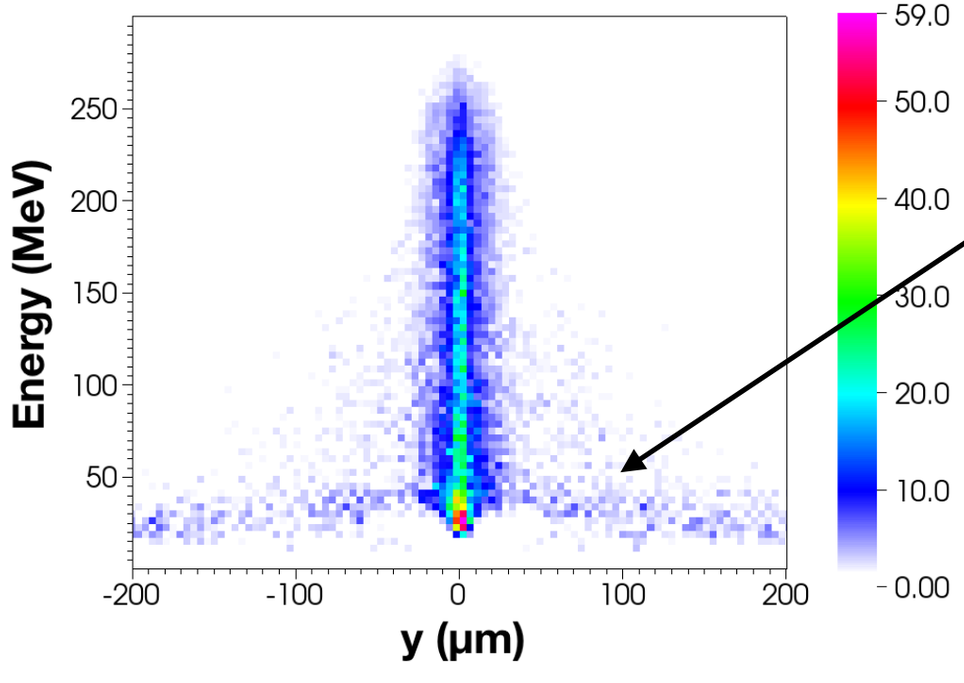
Stepped

Less charge re-accelerated



Transverse





Low energy particles defocused

Conclusion

- Plasma beam dumps are a promising alternative to conventional dumps.
- They offer high decelerating gradients despite having low densities, while being much more compact than a gas dump.
- Changing plasma density can improve performance compared to a uniform plasma.
- Gradient plasma performs as well as stepped plasma, and may be easier to achieve in practice.