Simulation study of plasma acceleration/deceleration by tuning the plasma density

Guoxing Xia
on behalf of collaboration team

August 2018

Introduction

- Introduction and background
- Plasma wakefield acceleration with CLARA and CLARA-FE
- Plasma beam dump
- Conclusion

Background

LEP - the highest energy e^-/e^+ collider to date:

- Up to 100 GeV beam energy
- 27 km circumference
- Energy limited by RF power

LEP RF module (Chris Foster/MOSI)

D. Brandt et al., Rep. Prog. Phys. 63, 939 (2000)

Energy (GeV)	45.6	65	97.8
Population ($\times 10^{11}$)	1.18	2.20	4.01
Charge (nC)	18.9	35.2	64.2
Vertical rms (μm)	197	247	178
Horizontal rms (μm)	3.4	2.8	3.3

Background

MANCHESTER
1824
The University of Manchester

Beam energy of a circular electron accelerator is limited by energy losses:

Energy loss per turn

$$U \propto \frac{\gamma^4}{\rho}$$

Relativistic gamma

Bending radius

Solutions:

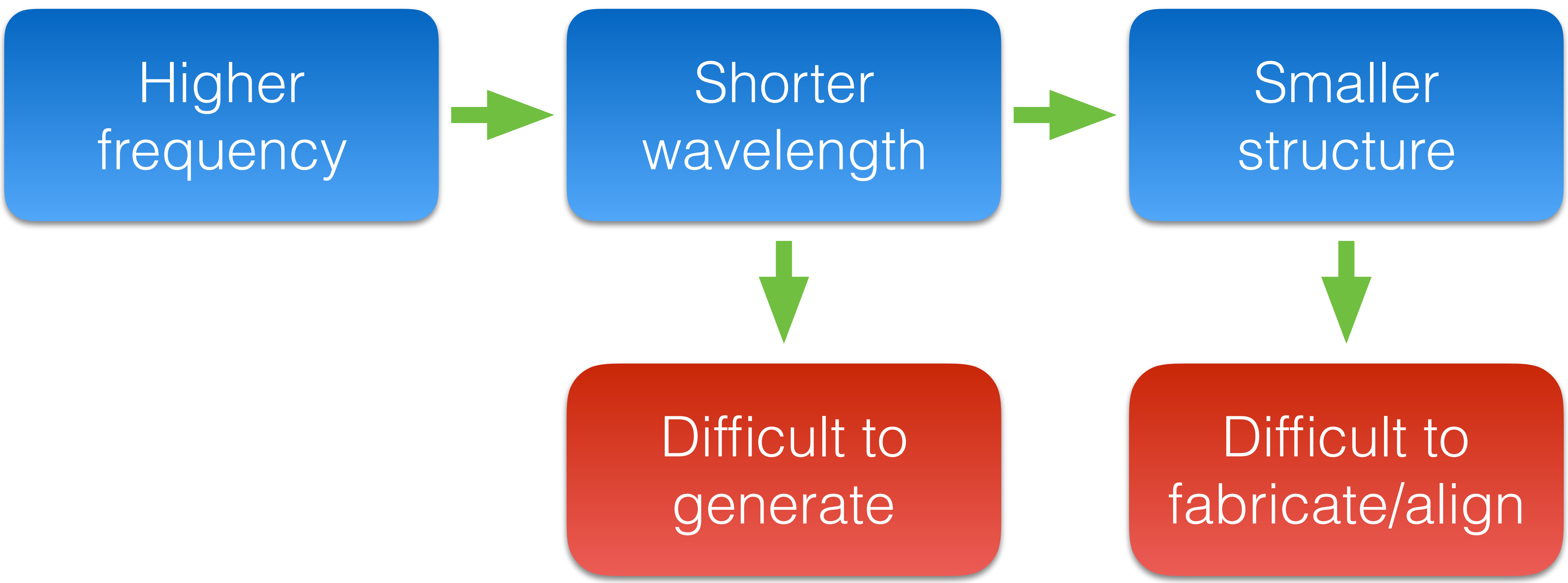
- Increase bending radius -> expensive
- Use higher mass species e.g. muons -> new difficulties
- Accelerate in a straight line -> size now limited by gradient

ILC/CLIC: > 500 GeV energy, but ~30 km length

Plasma acceleration

Higher accelerating gradient is needed to keep machine size small.

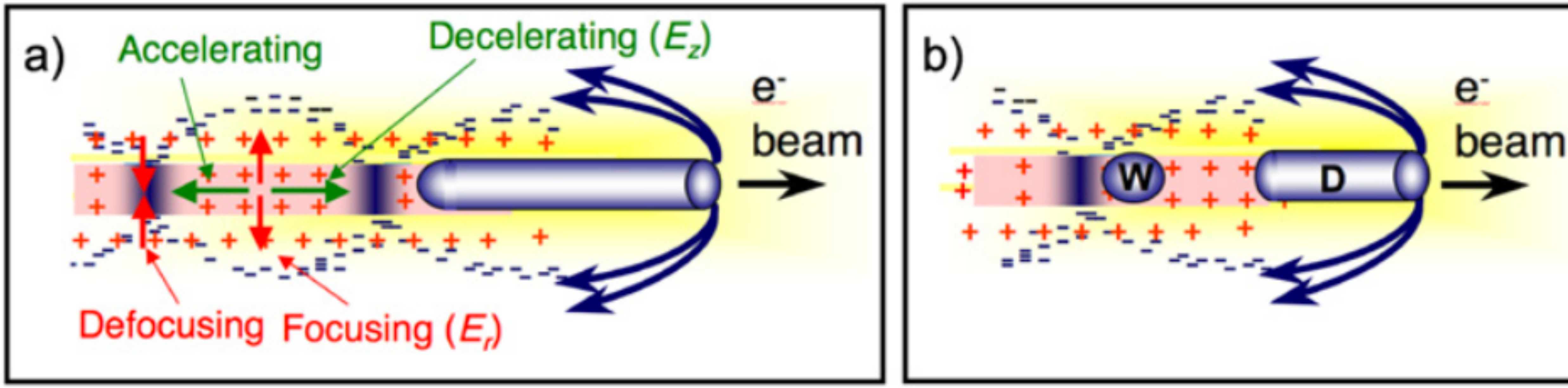
Kilpatrick breakdown limit proportional to square root of frequency.



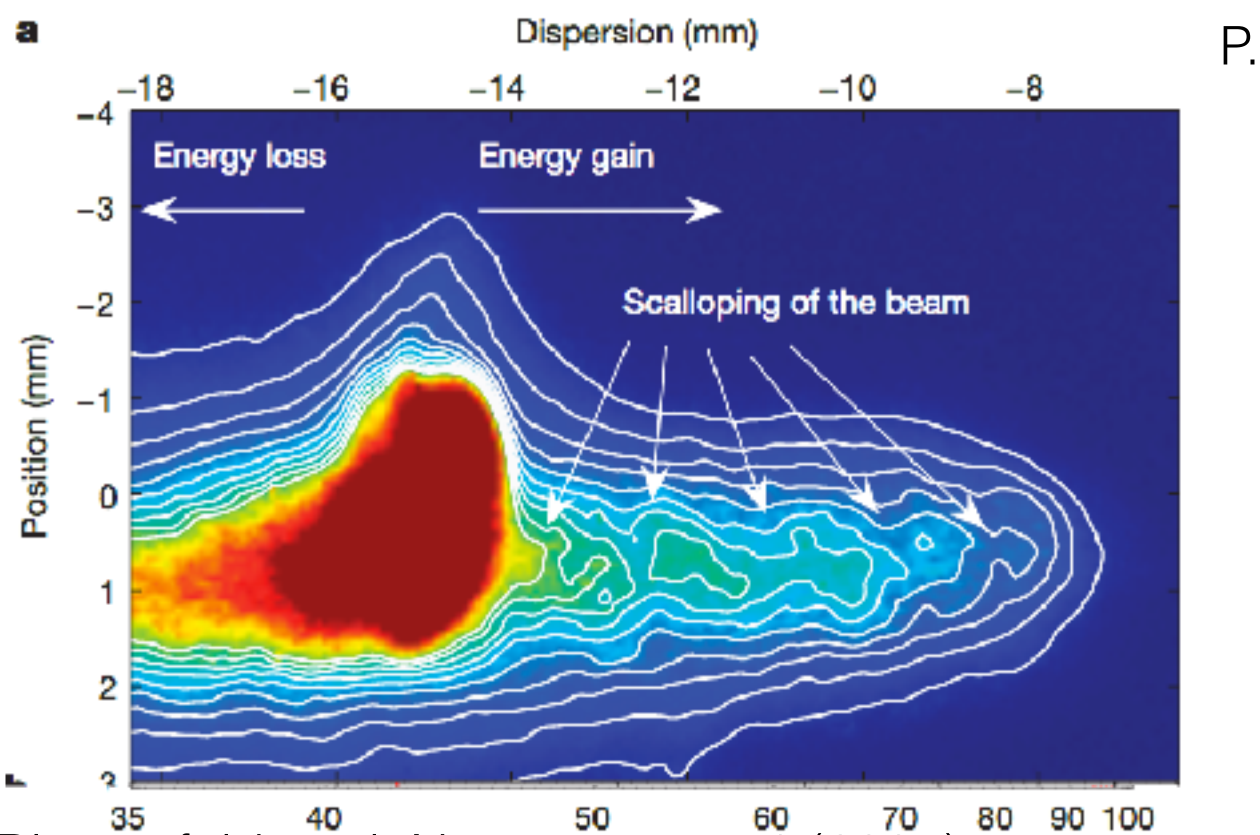
Plasma acceleration

Laser driver via ponderomotive force

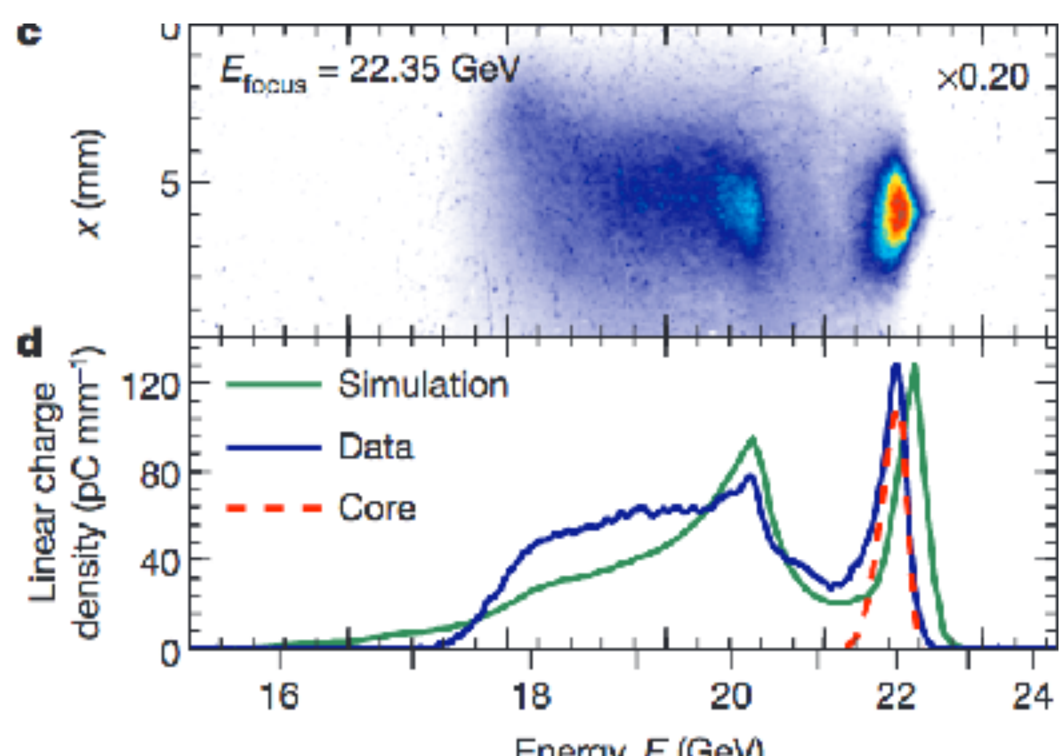
Beam driver via space charge force



P. Muggli and M. Hogan, C. R. Physique 10, 116 (2009)



Blumenfeld et al. Nature 445, 741 (2007)



Litos et al. Nature 515, 94 (2014

Plasma acceleration in the UK

MANCHESTER 1824
The University of Manchester

Laser wakefield acceleration

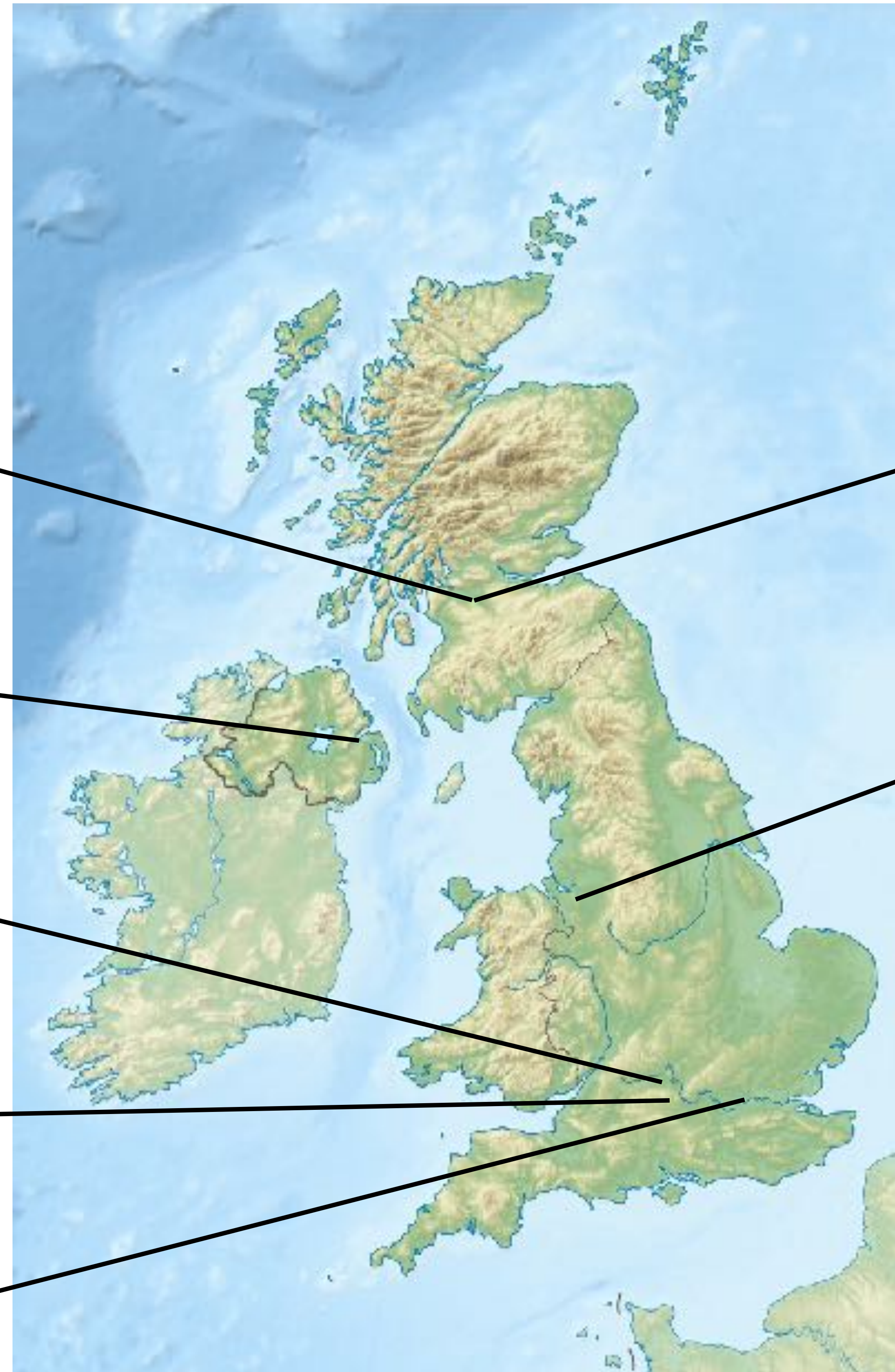
University of Strathclyde Glasgow

Queen's University Belfast

JAi John Adams Institute for Accelerator Science

STFC Central Laser Facility

Imperial College London



Beam driven plasma wakefield acceleration

University of Strathclyde Glasgow

The Cockcroft Institute of Accelerator Science and Technology

Plasma wakefield accelerator

The University of Manchester

Dephasing: plasma has a refractive index while accelerated electrons travel very close to the speed of light.

→ As long as drive and witness beams are ultra-relativistic, dephasing is less of a problem.

Diffraction: Gaussian laser pulse spreads out after passing through its focal point.

→ Relativistic self-focusing

Charged particle beams are focused by a plasma and thus can propagate without losing intensity.

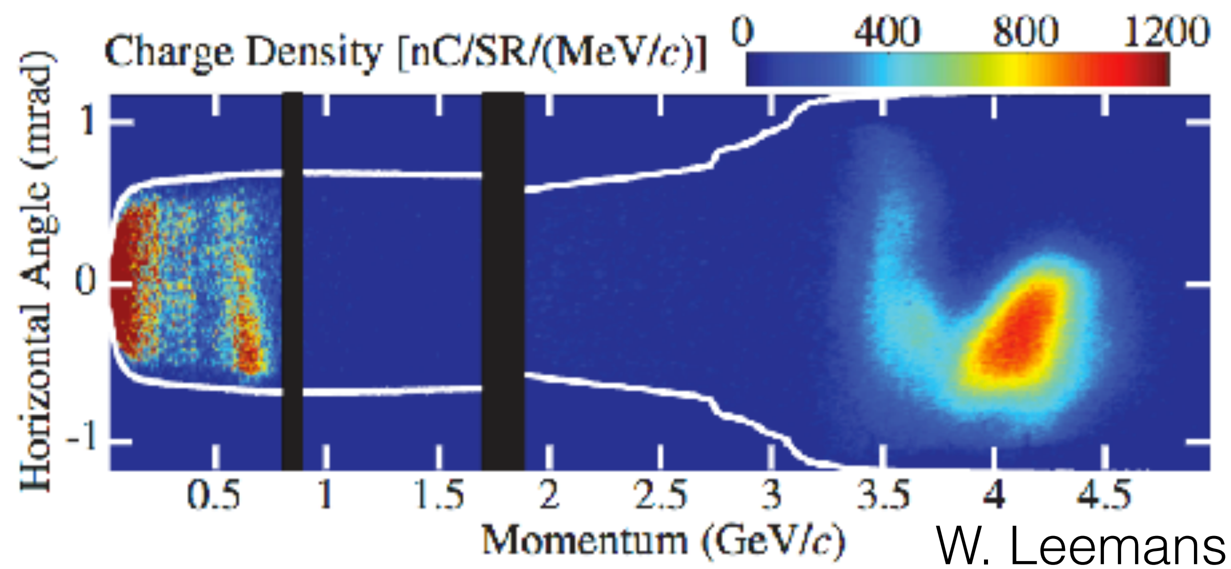
Depletion: the amount of energy in an ultrashort laser pulse is limited.

→ Particle beam total energy can be orders of magnitude larger than laser pulses

Laser wakefield accelerator

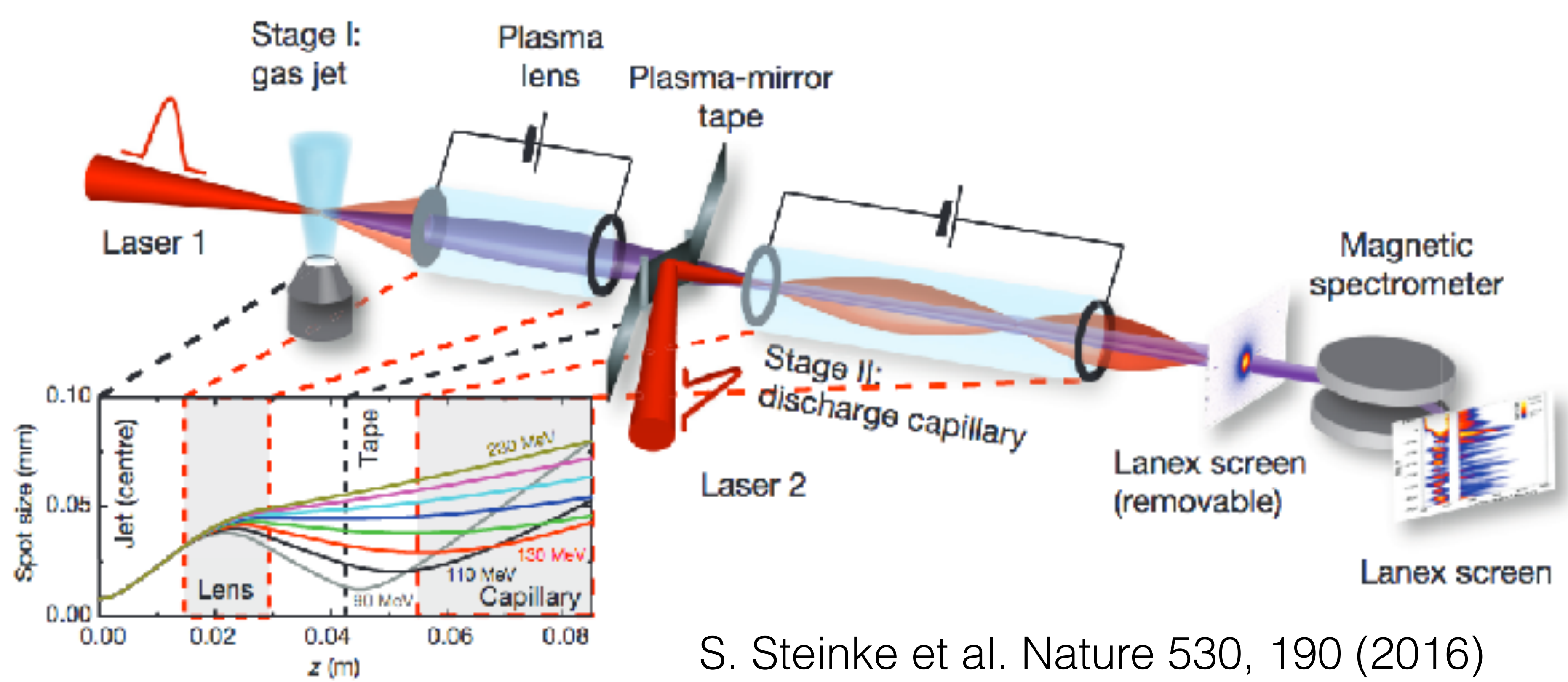
MANCHESTER 1824
The University of Manchester

Single stage laser wakefield accelerator, 6 pC at 4.2 GeV:



W. Leemans et al. PRL 113 245002 (2014)

Two-stage LWFA, up to 100 MeV energy gain:



S. Steinke et al. Nature 530, 190 (2016)

Linear regime

Maxwell's laws and the continuity equation can be applied to obtain an expression for the longitudinal electric field due to a point charge moving in a plasma:

$$E_z = -\frac{Qk_p^2}{2\pi\varepsilon_0} K_0(k_p r) \cos\left[k_p(z - ct)\right] H(t - z/c)$$

Traverse variation is a Bessel function

Longitudinal variation is a cosine

Heaviside step function for causality

For a low-aspect-ratio bunch (W. Lu 2005):

$$E_z \approx 529\ \mathrm{MVm}^{-1}\, \frac{q}{e} \frac{N}{10^{10}} \left(\frac{200\ \mu\mathrm{m}}{\sigma_z}\right)^2 \log\left(\sqrt{\frac{10^{22}}{n_\mathrm{e}}} \frac{50\ \mu\mathrm{m}}{\sigma_r}\right)$$

Transformer ratio

The University of Manchester

In the linear regime, conservation of energy can be applied to show that the energy gain of the witness bunch is:

Drive bunch energy

Witness bunch pop.

$$\Delta E_2 = E_1 \left(2 - \frac{N_2}{N_1} \right)$$

Witness bunch energy

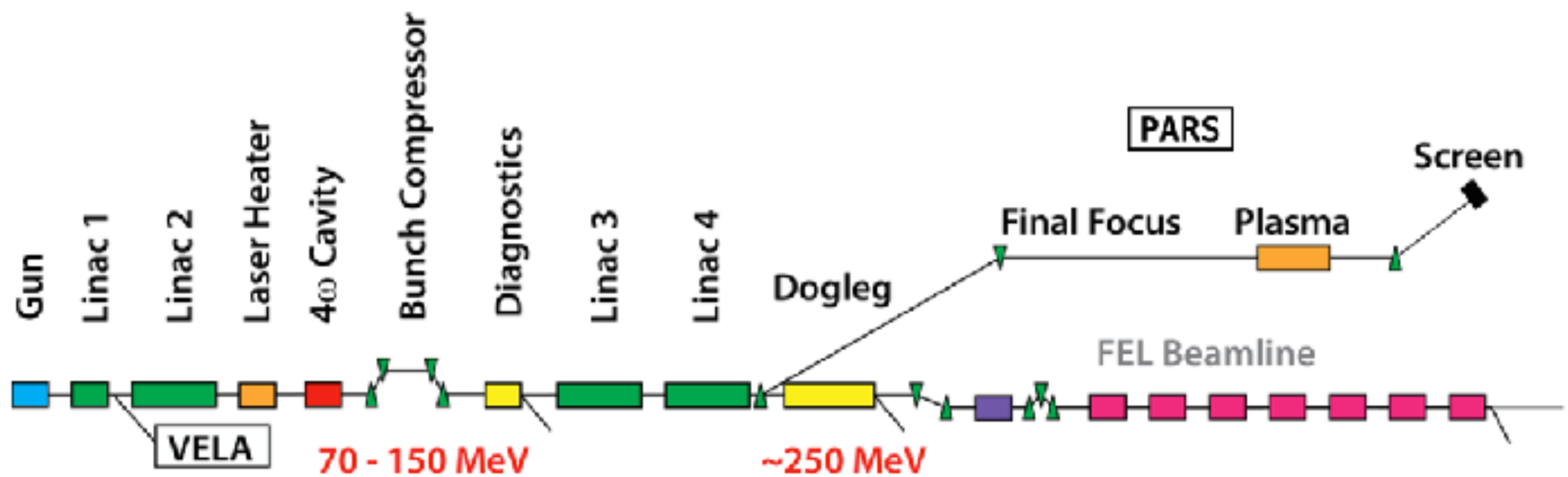
Drive bunch pop.

Energy gain is maximized for zero witness bunch charge, and limited to a factor of 2.

$$\eta = \frac{N_2}{N_1} \left(2 - \frac{N_2}{N_1} \right)$$

Efficiency is maximized for equal witness and drive bunch charges.

PWFA proposal at Daresbury

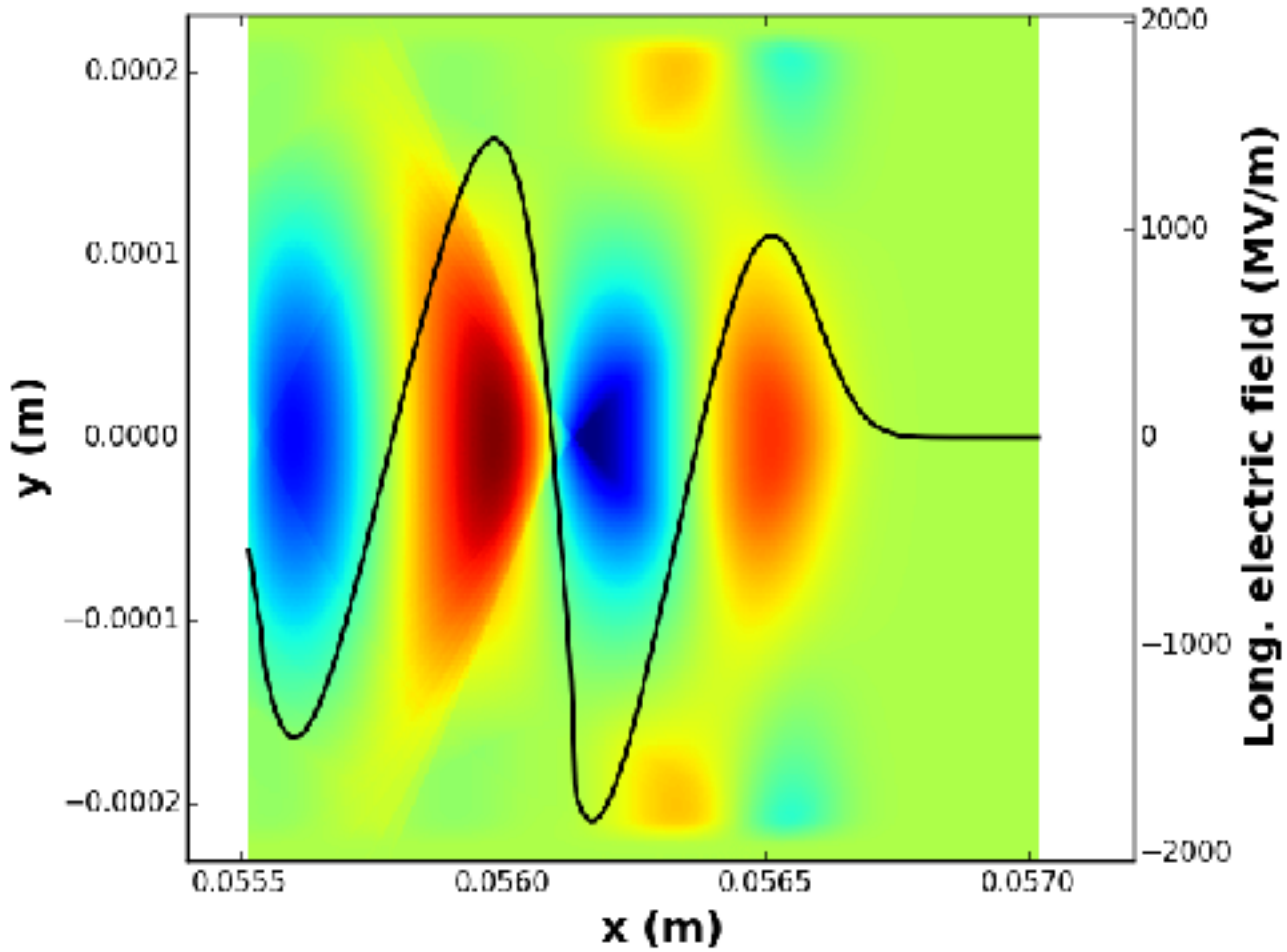


J. Clarke et al., CLARA Conceptual Design Report, J. Inst. 9 (2014)

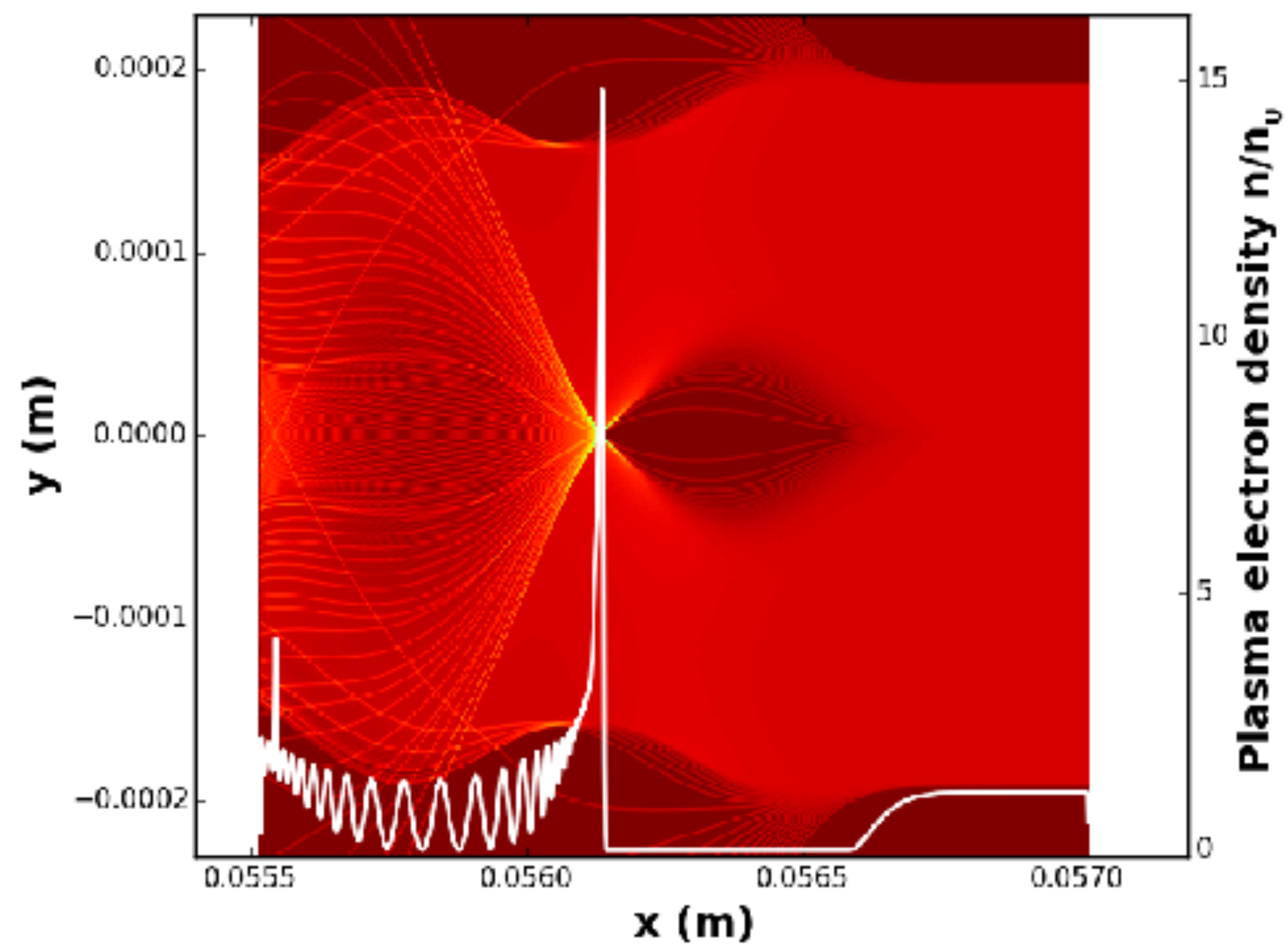
Mode	SASE	Ultrashort
Energy (MeV)	250	250
Population ($\times 10^9$)	1.56	0.125-0.625
Charge (pC)	250	20-100
Trans. rms (μm) (assumed)	20-100	20-100
Long. rms (μm)	75	<7.5

PWFA with CLARA

Electric field



Plasma electron density



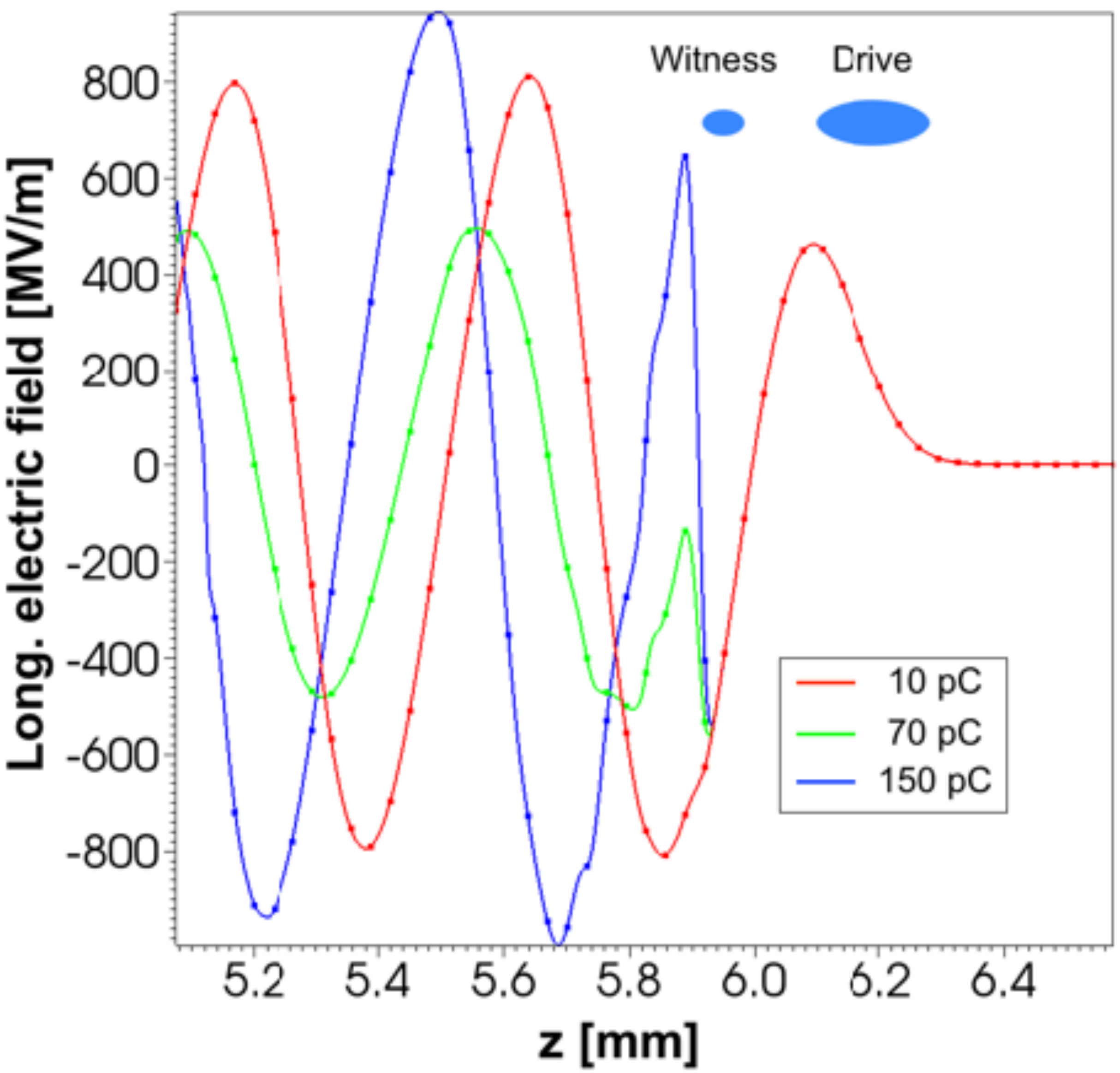
75 μm bunch length

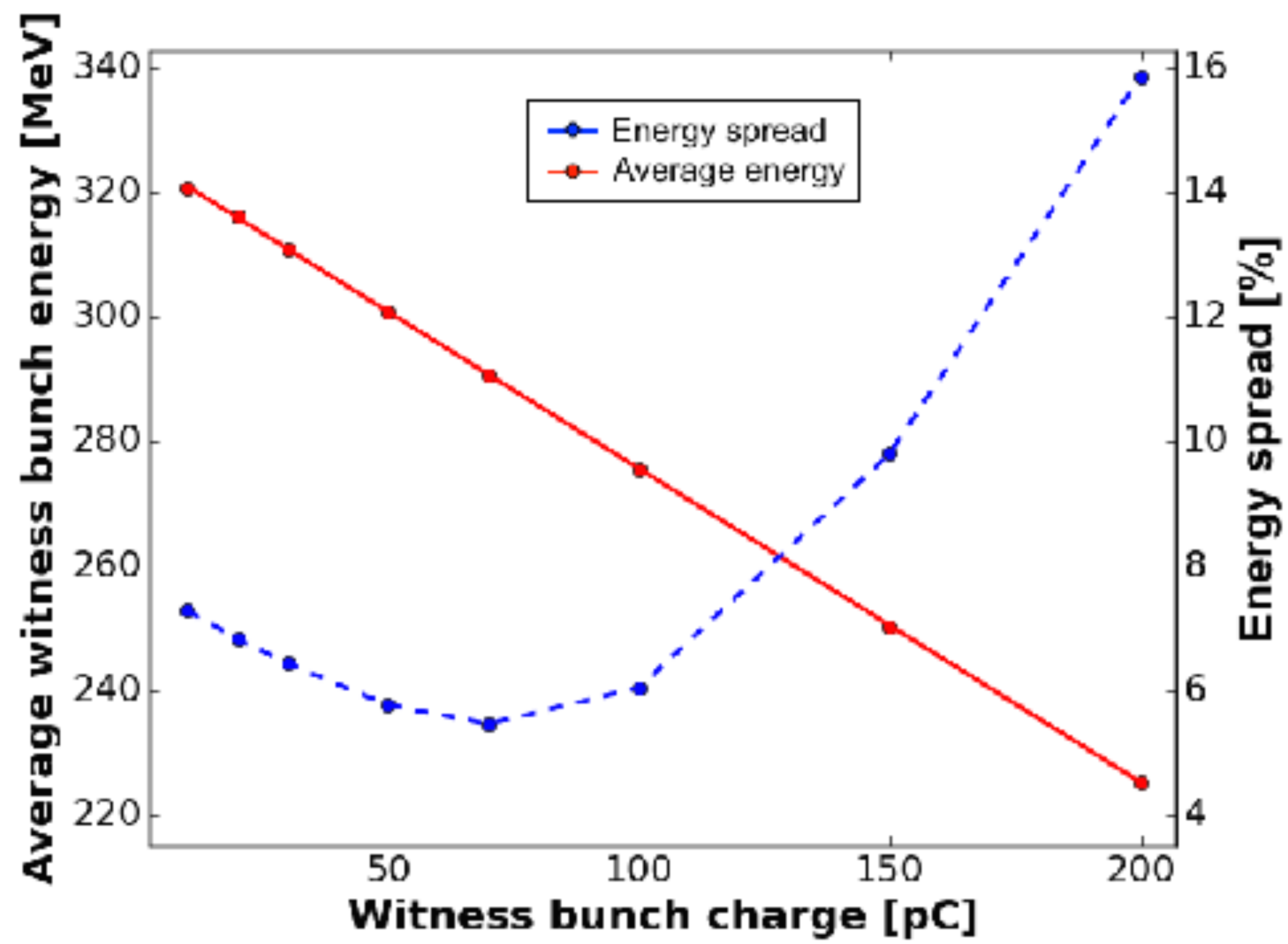
Accelerating gradient: 1.8 GV/m

Plasma density: $3{\times}10^{21}$ m^{-3}

G. Xia et al., NIMA 829, 43-49 (2016)

Beam loading





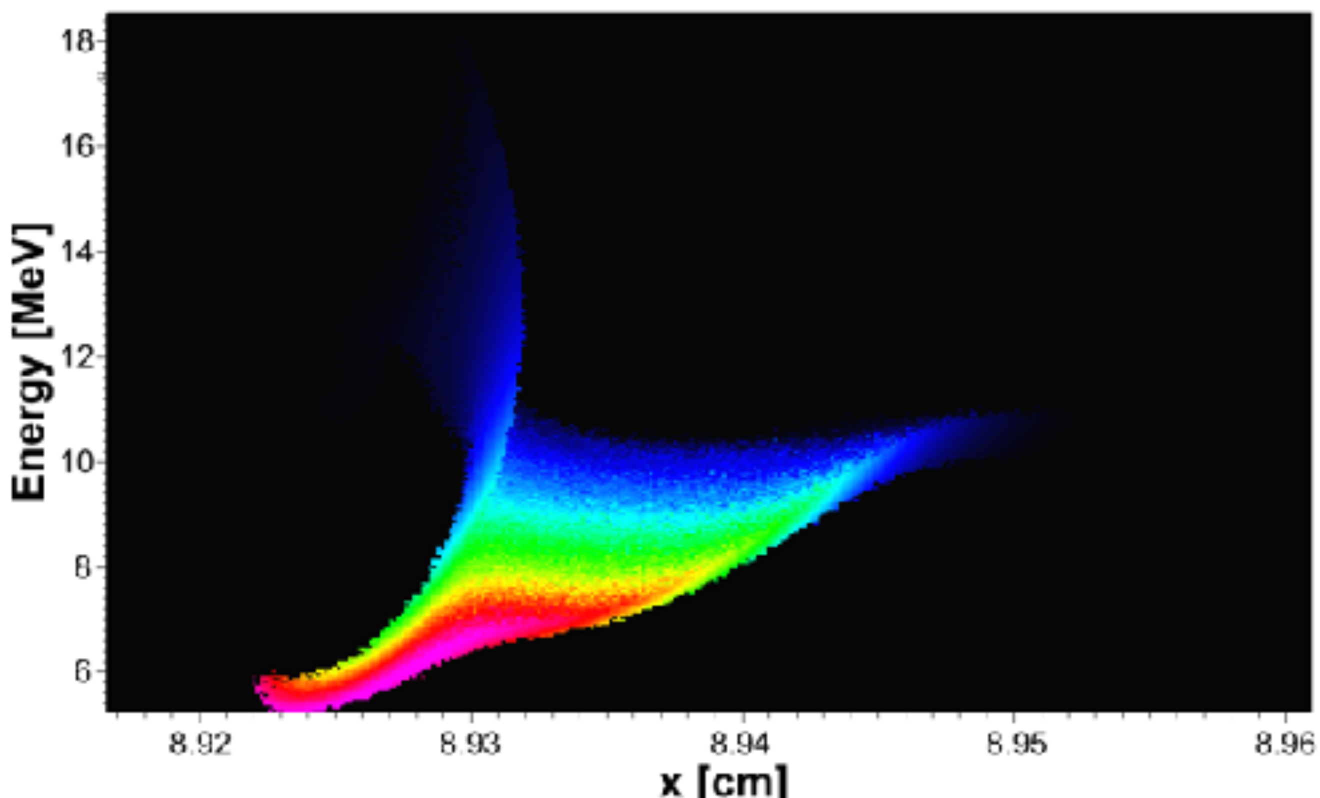
Higher witness bunch charge leads to a lower average accelerating gradient.

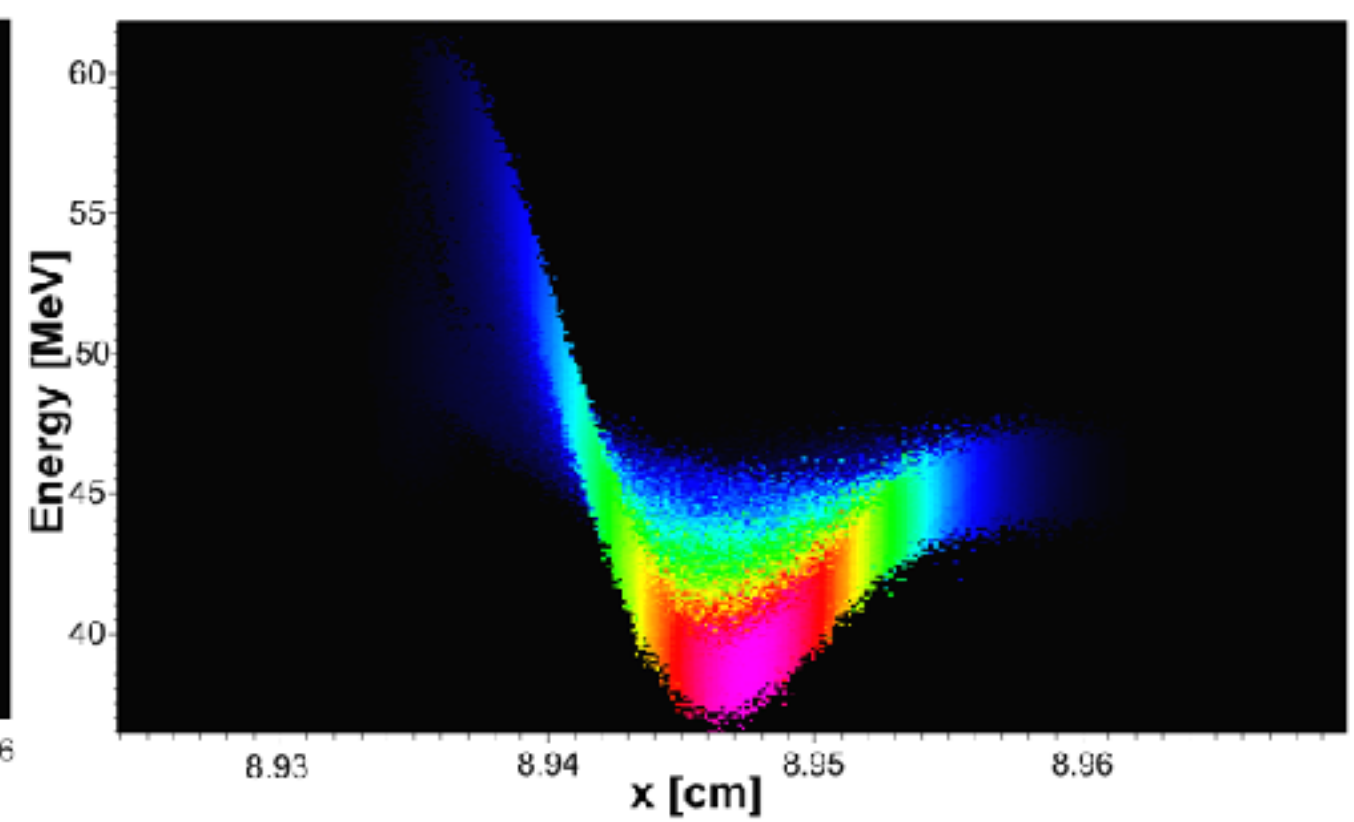
Energy spread is minimized for intermediate charge.

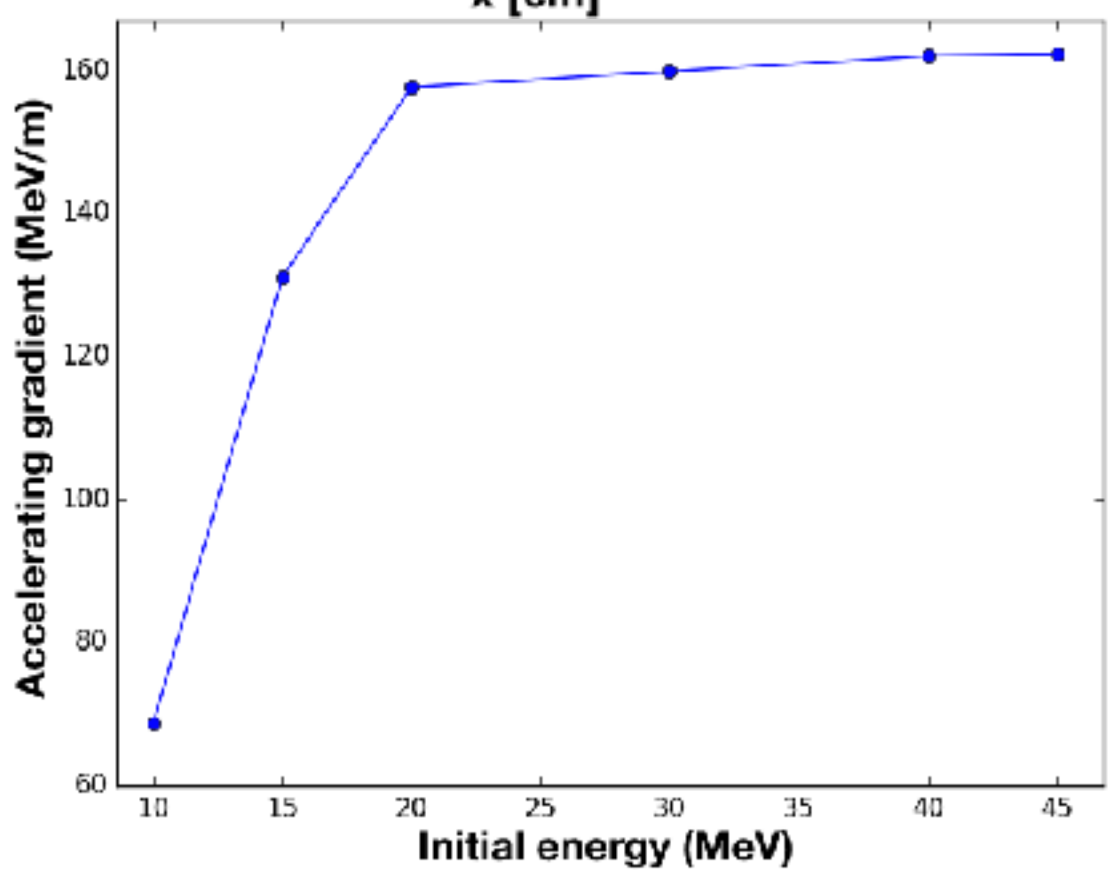
CLARA Front End

10 MeV

45 MeV







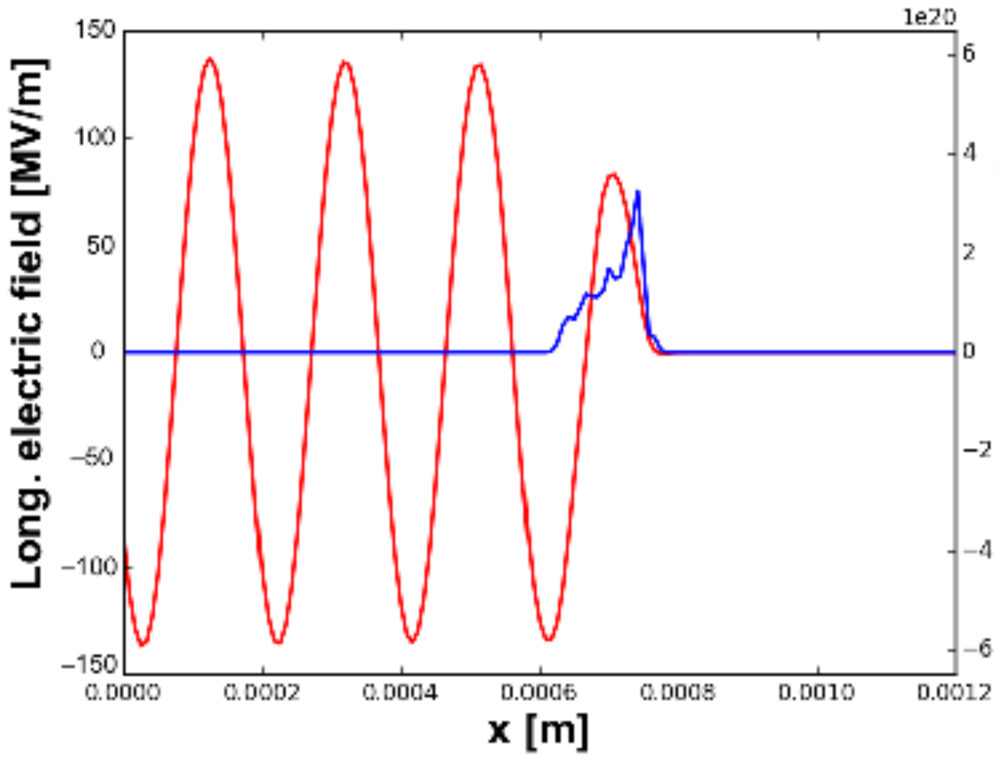
250 pC, 270 μm bunch length

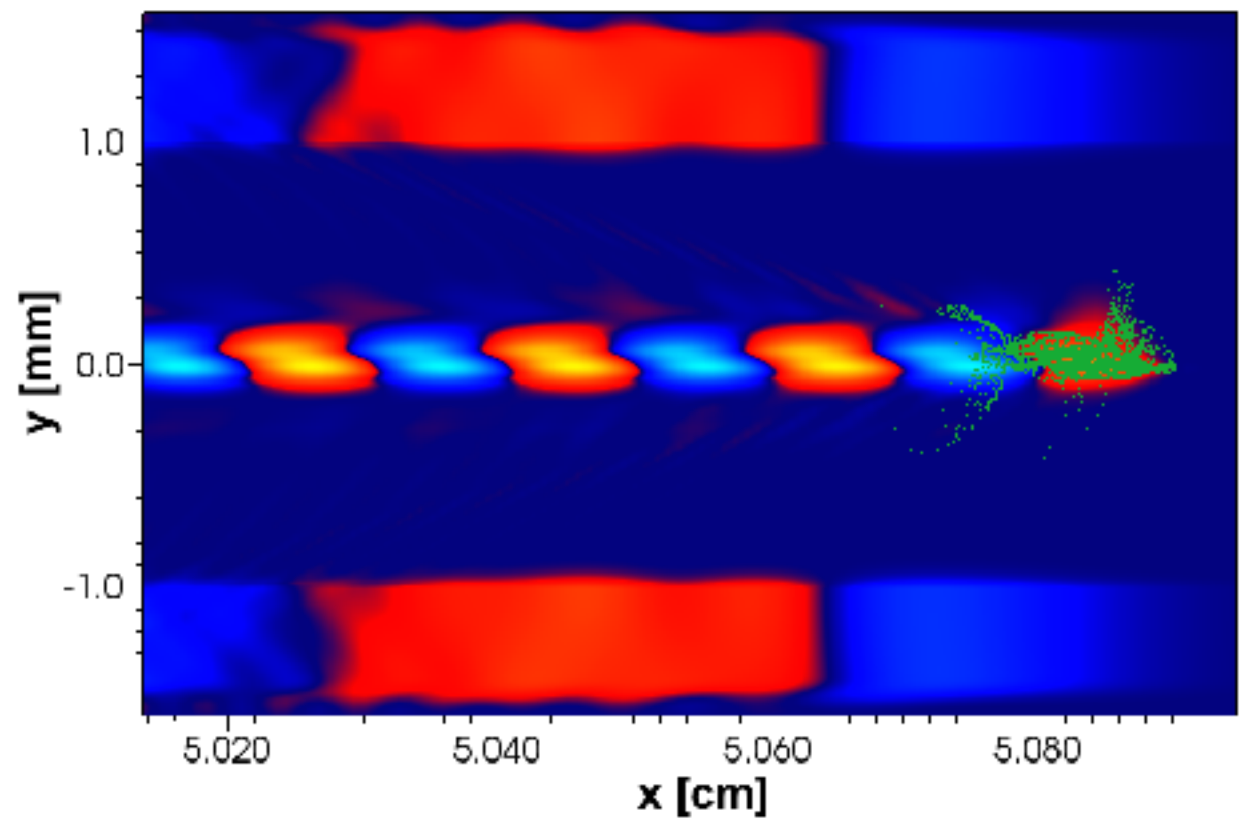
Dependence of average accelerating gradient on initial beam energy.

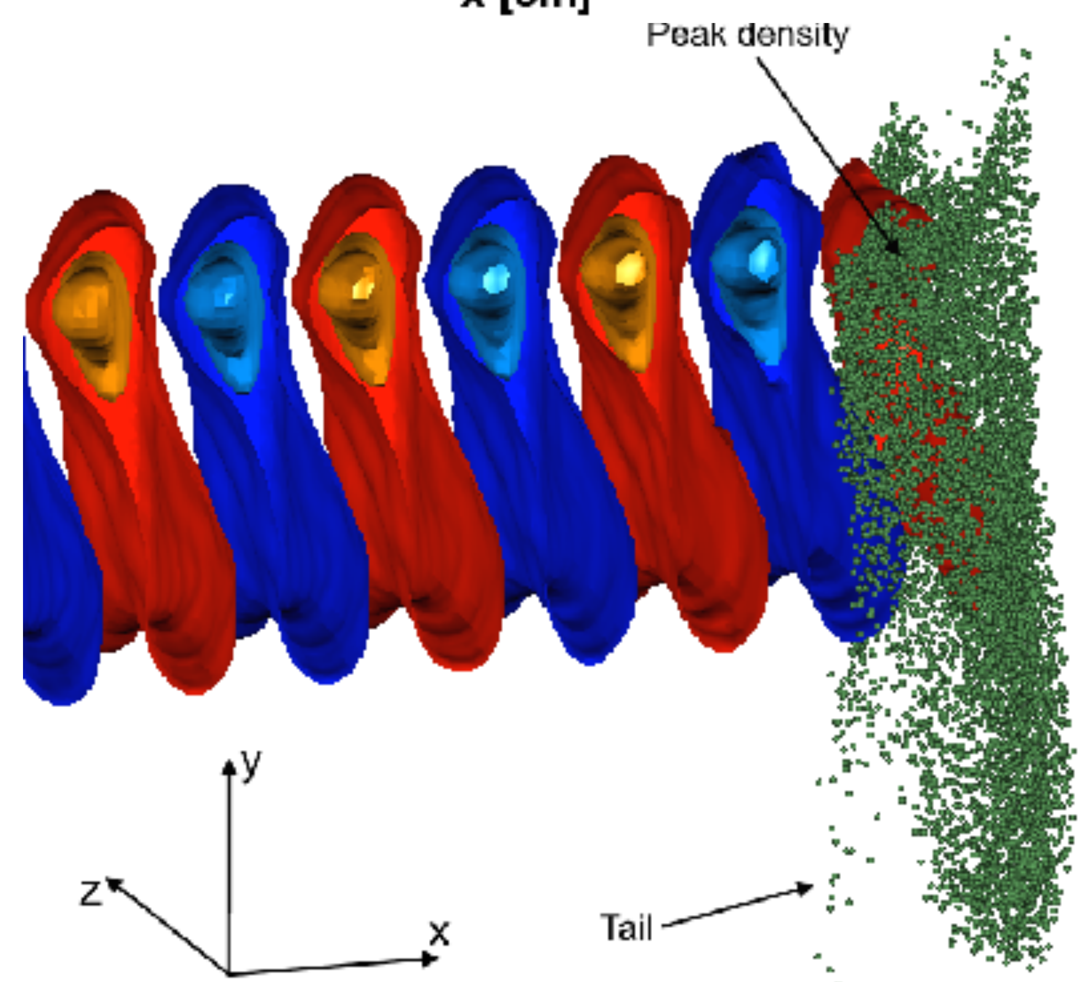
45 MeV initial -> ~15 MeV gain

10 MeV initial -> ~ 6 MeV gain

CLARA Front End







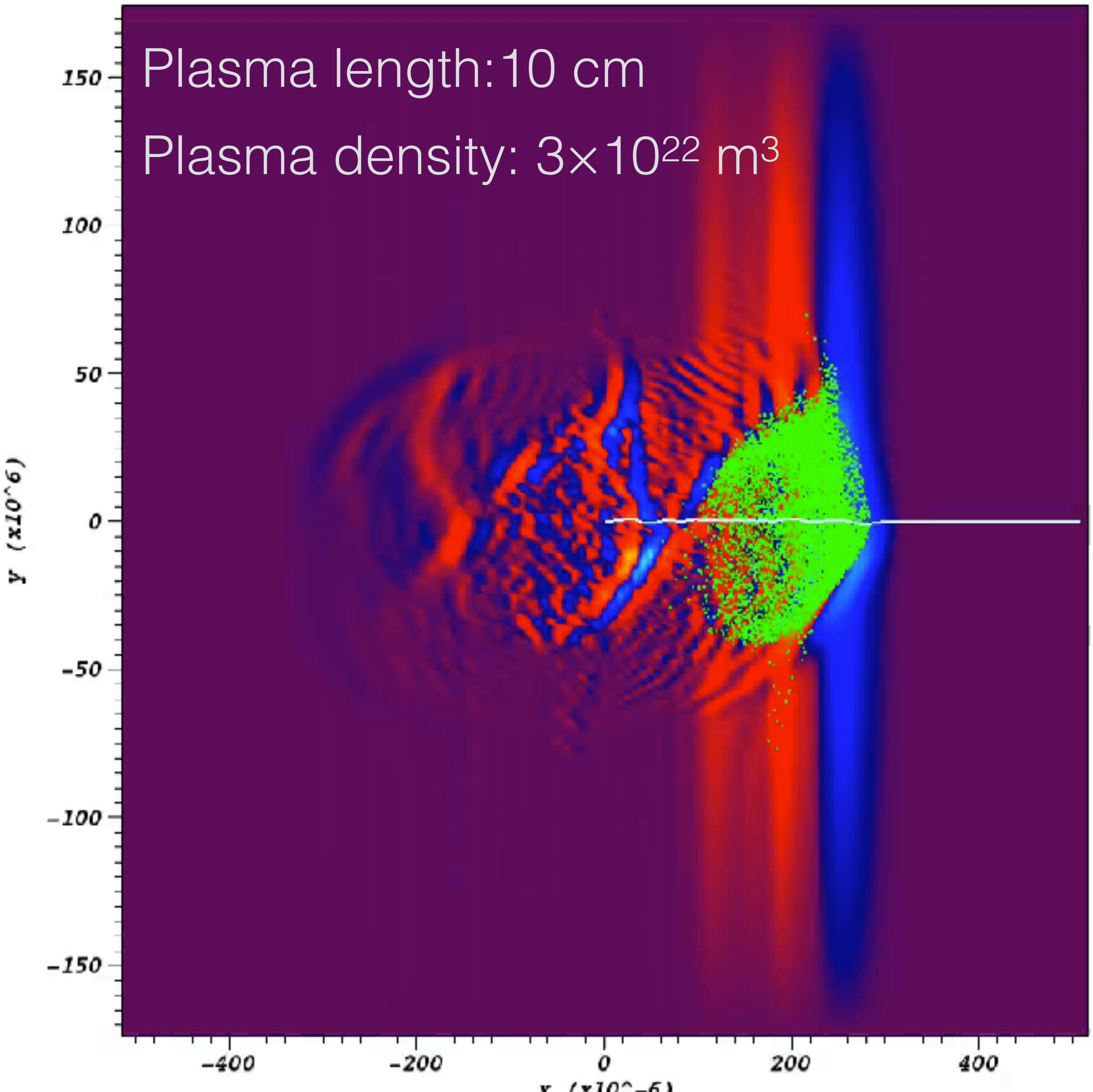
Average accelerating gradient:

2D - 120 MeV/m

3D - 147 MeV/m

CLARA-FE ASTRA simulation data from B. Kyle

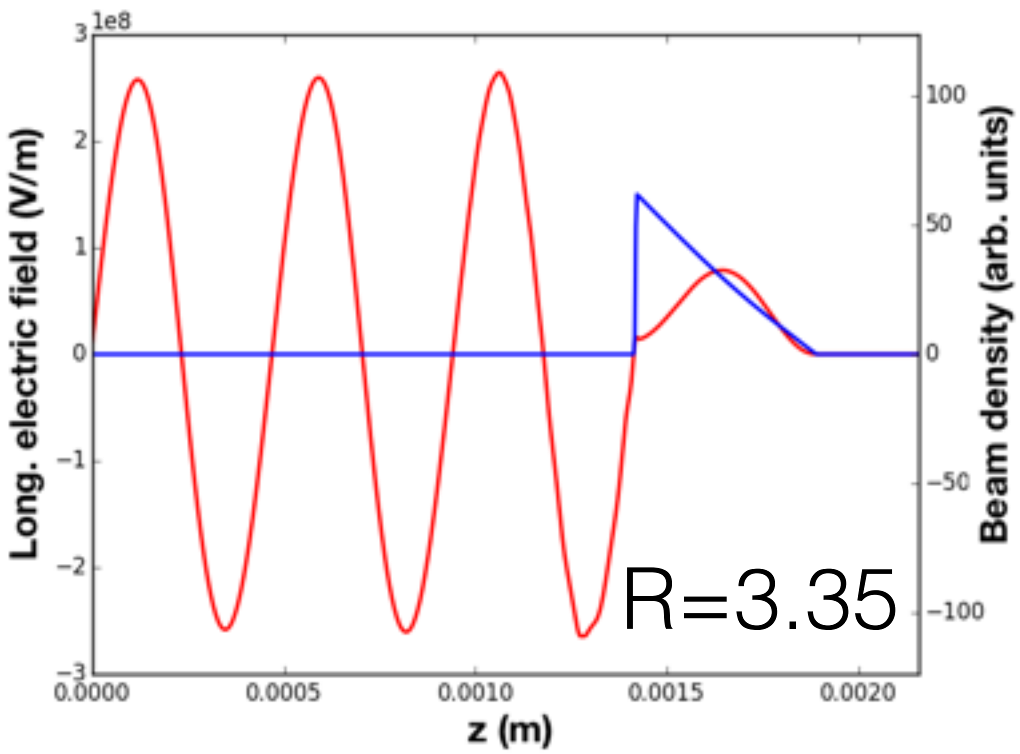
CLARA Front End



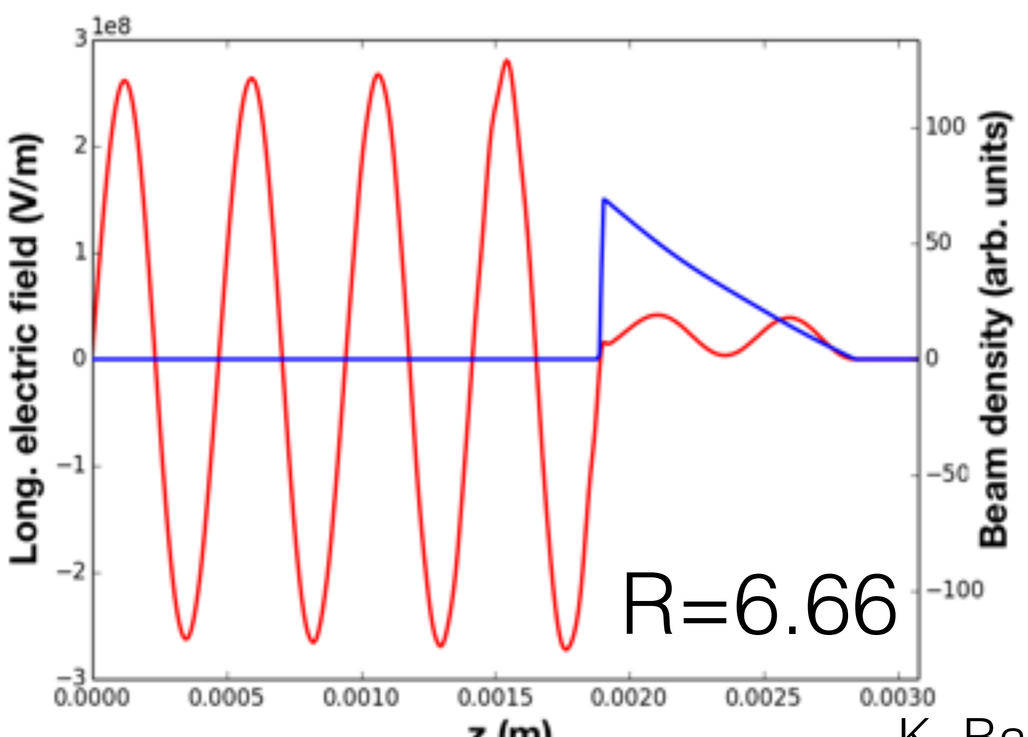
Ramped drive bunch

The University of Manchester

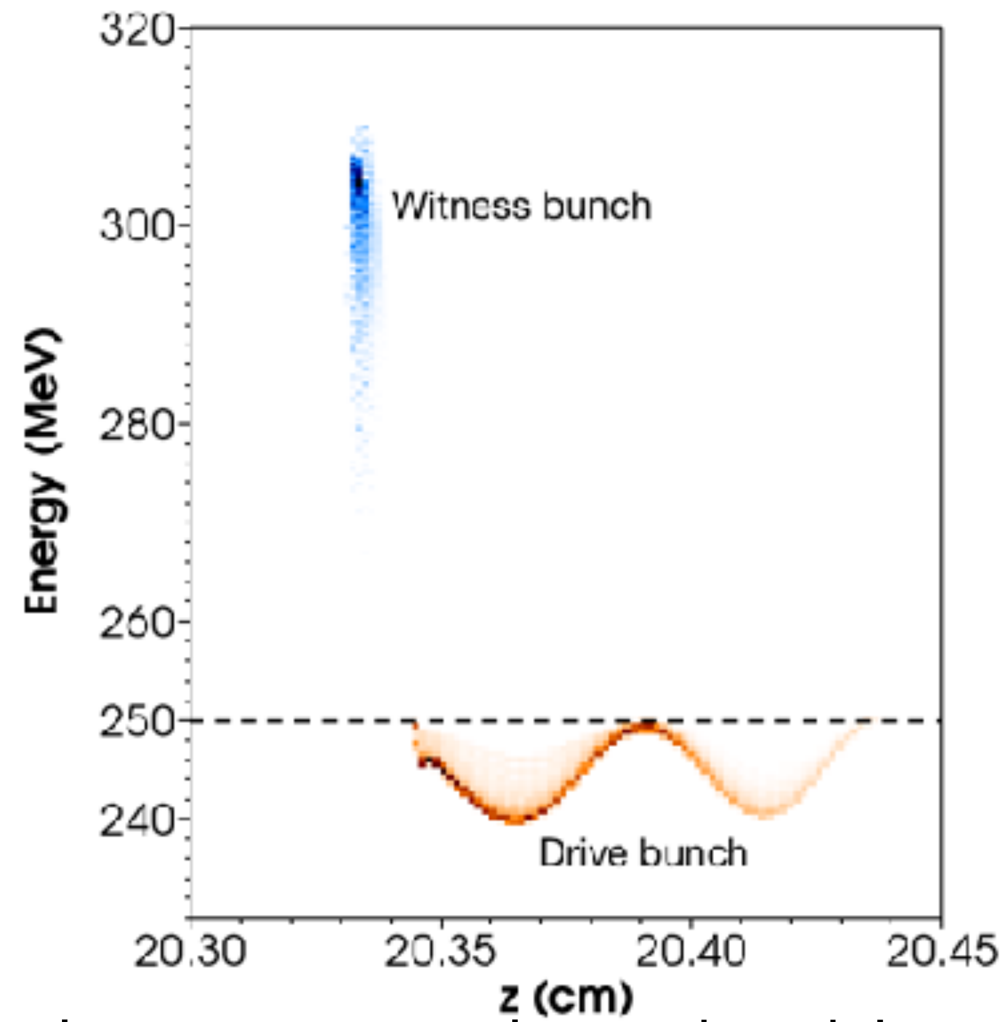
One plasma wavelength



Two plasma wavelength



Bane: transformer ratio of Nπ for linear ramp of N plasma wavelength.



Two plasma wavelength: drive bunch charge of 320 pC. Could sustain acceleration over 4.8 m.

K. Bane, P. Chen, P. Wilson, IEEE Trans. Nuc. Sci. NS-32, 3524 (1985)

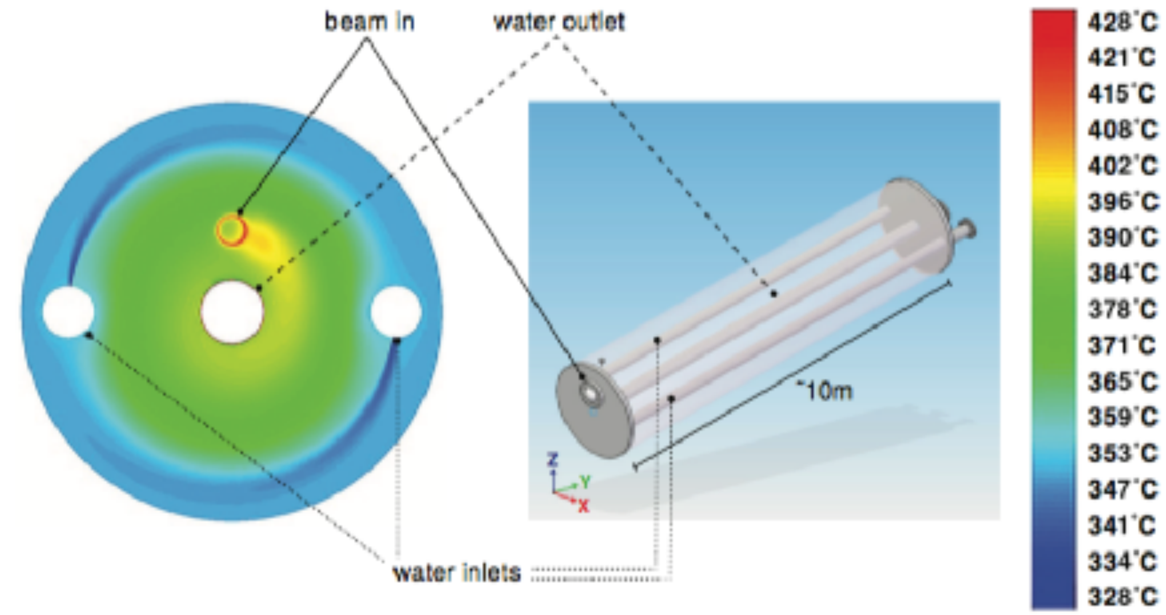
Beam dump

ILC beam dump design:

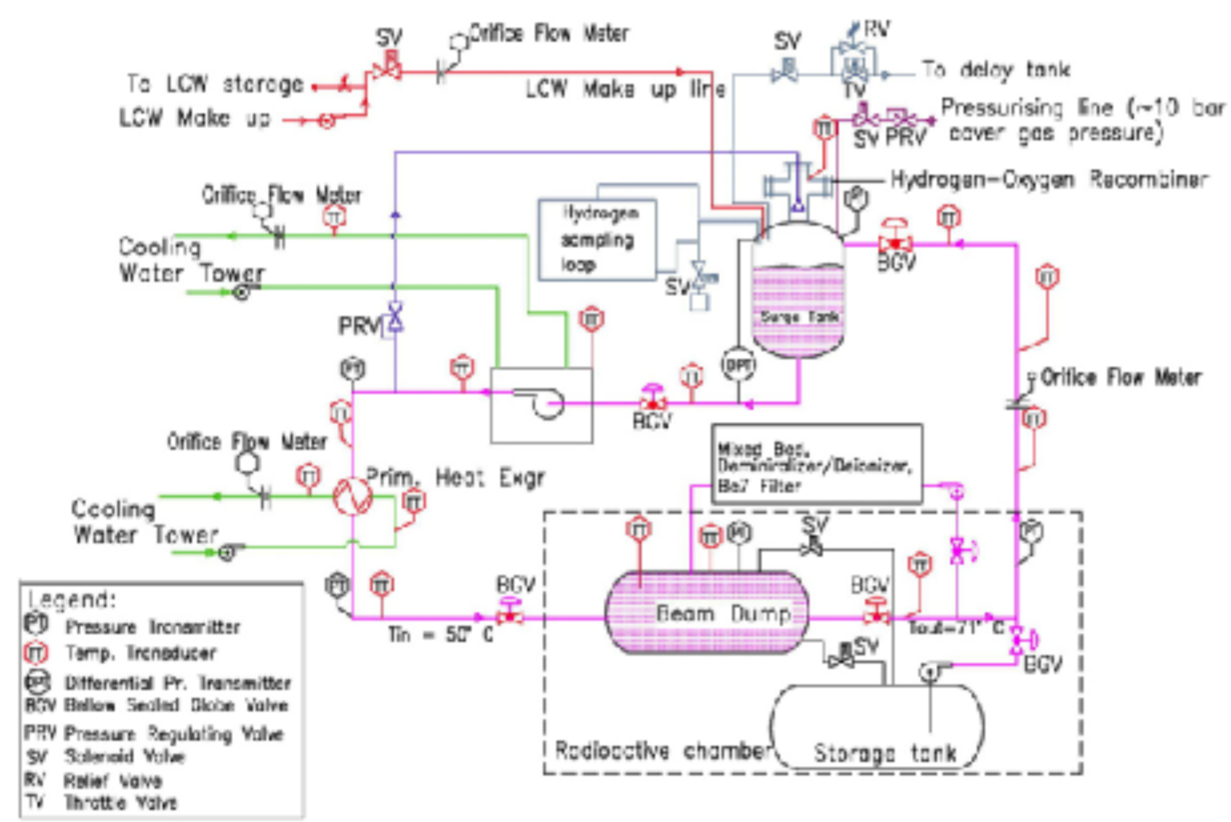
- Stainless steel pressure vessel
- 12 m length
- 5 bar pressure, plus 100% safety margin
- 155 °C water temperature

Challenges:

- Dump window must allow passage of beam while withstanding high pressure
- Radioactivation by photospallation
- Hydrogen/oxygen production

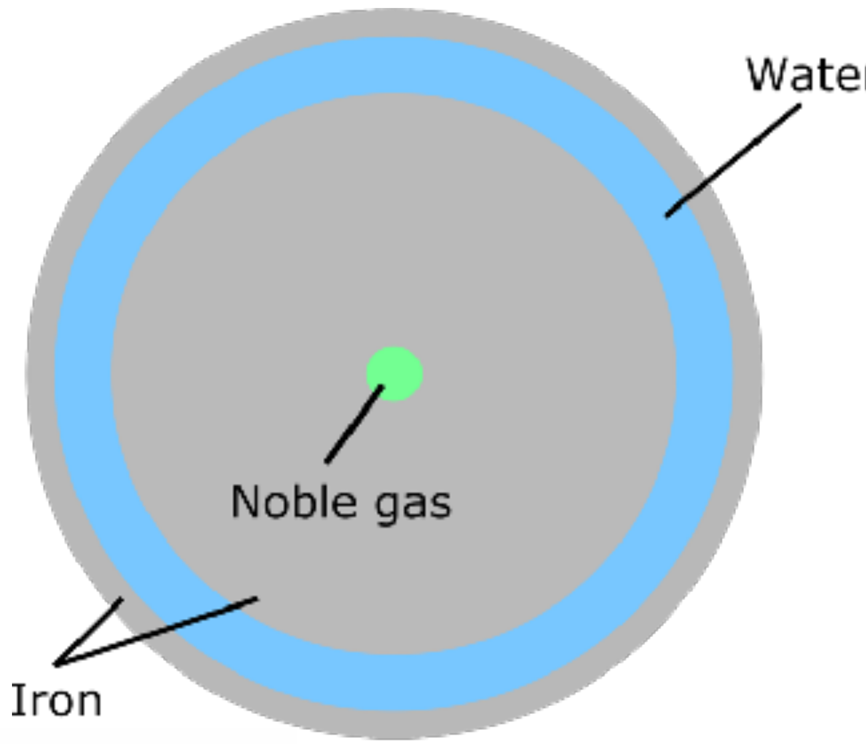


P. Satyamurthy et al., NIMA 679, 67 (2005)

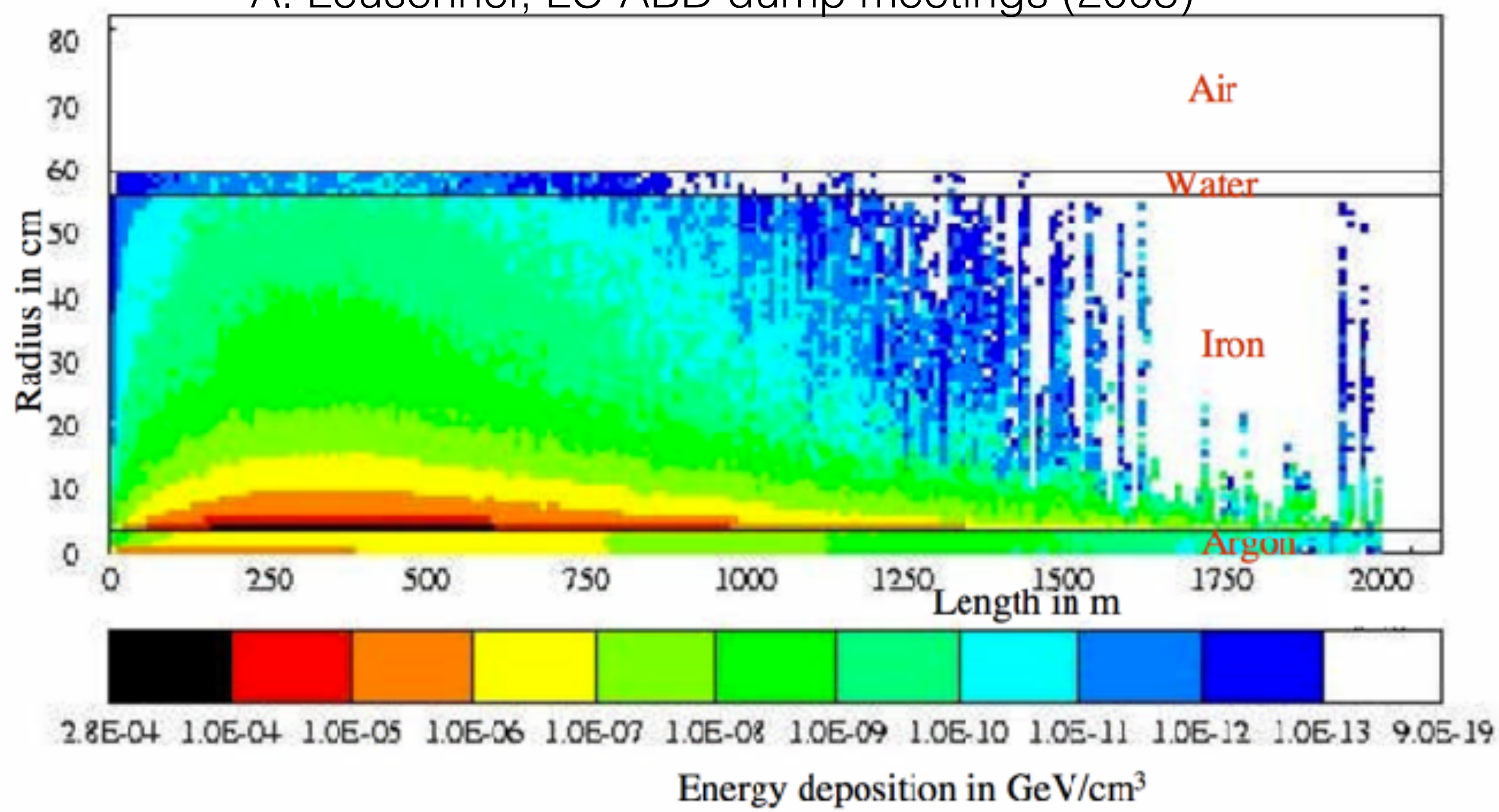


Noble gas beam dump

- Noble gas at atmospheric density
- 2 km length
- Low power density
- Inert gas means no reactive chemicals



A. Leuschner, LC-ABD dump meetings (2005)



Plasma beam dump

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

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

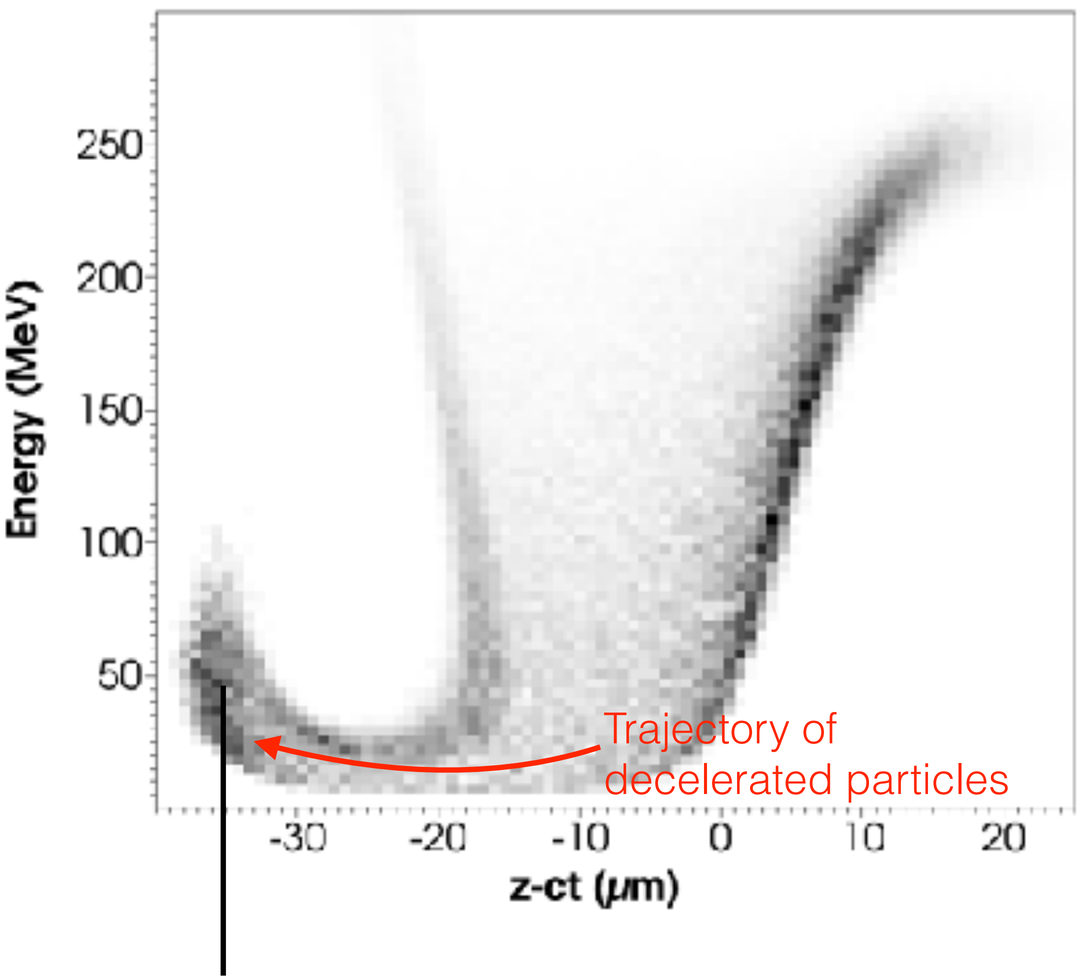
For $n_e = 10^{23}$ m^{-3}, E_{wb}=96 GV/m.

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.

Plasma beam dump

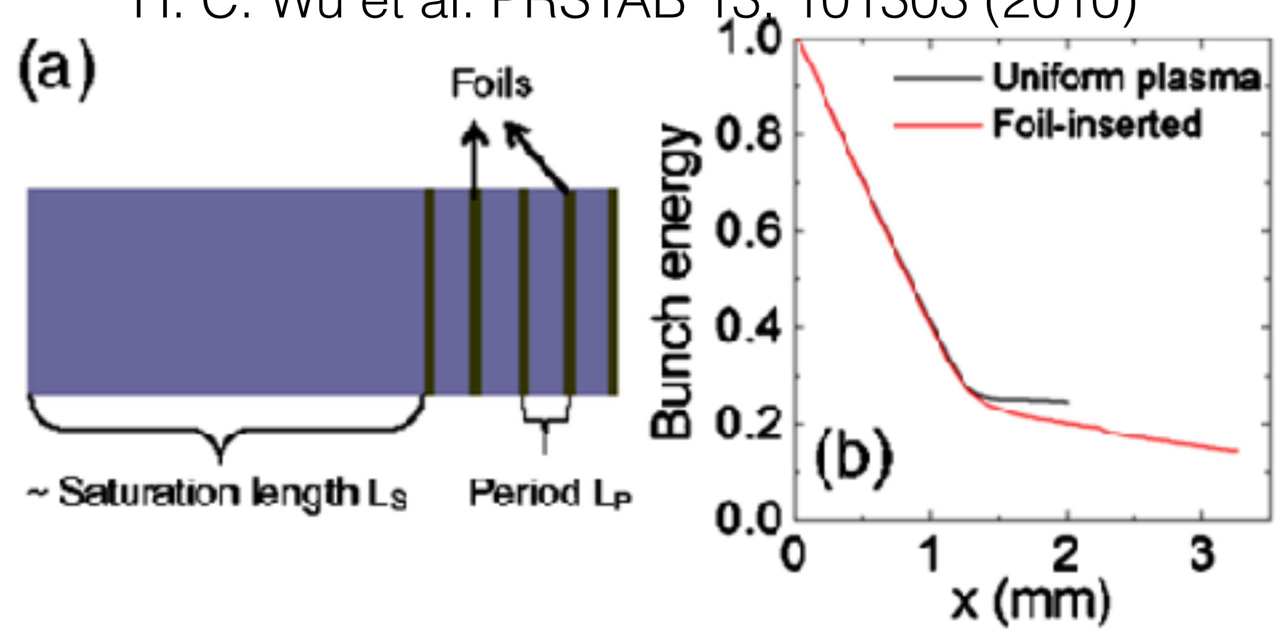
Longitudinal phase space of plasma decelerated bunch



Re-accelerated portion of bunch

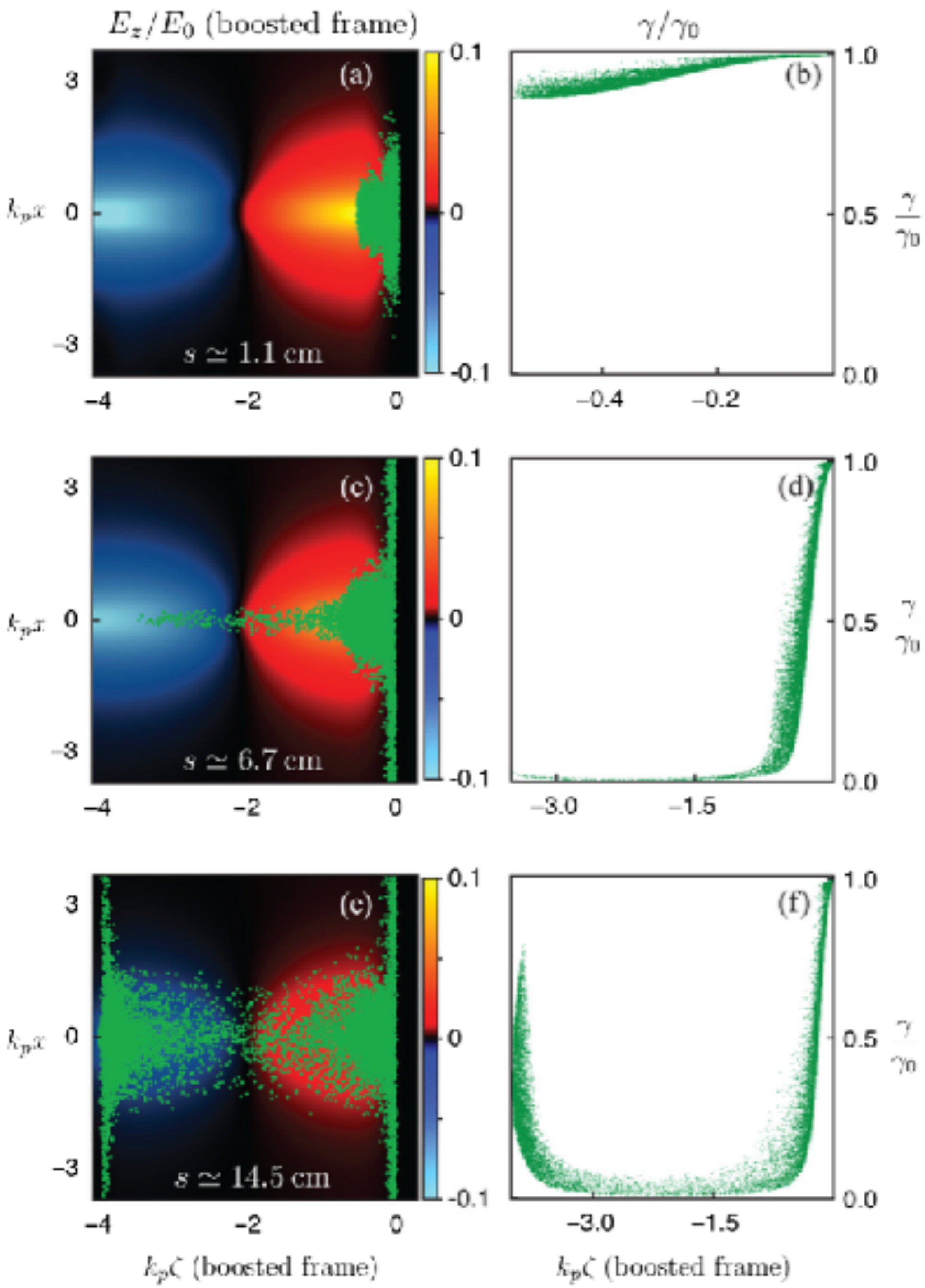
Wu et al. proposed using foils to absorb low-energy particles.

H. C. Wu et al. PRSTAB 13, 101303 (2010)

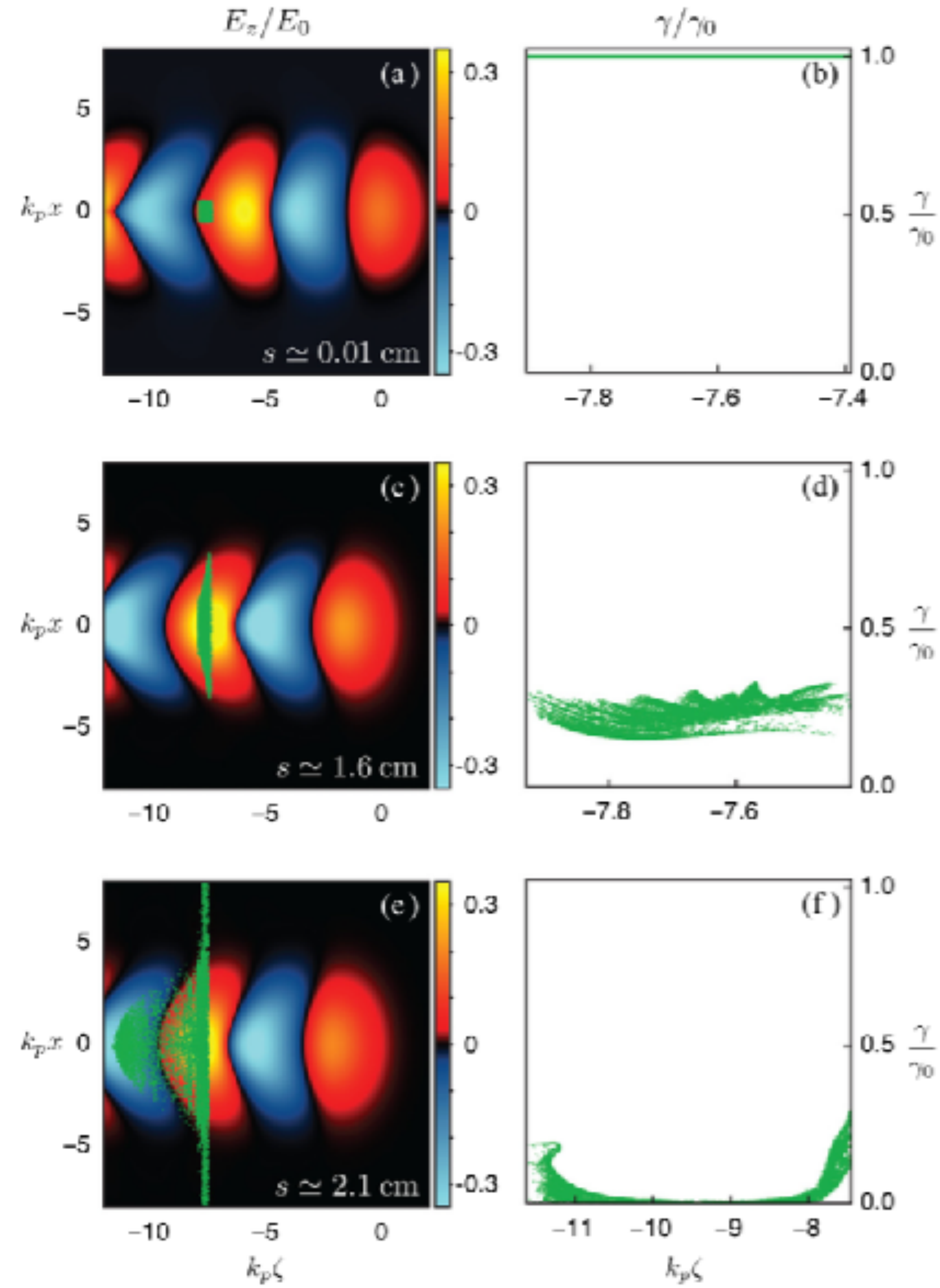


Active beam dump

Passive beam dump

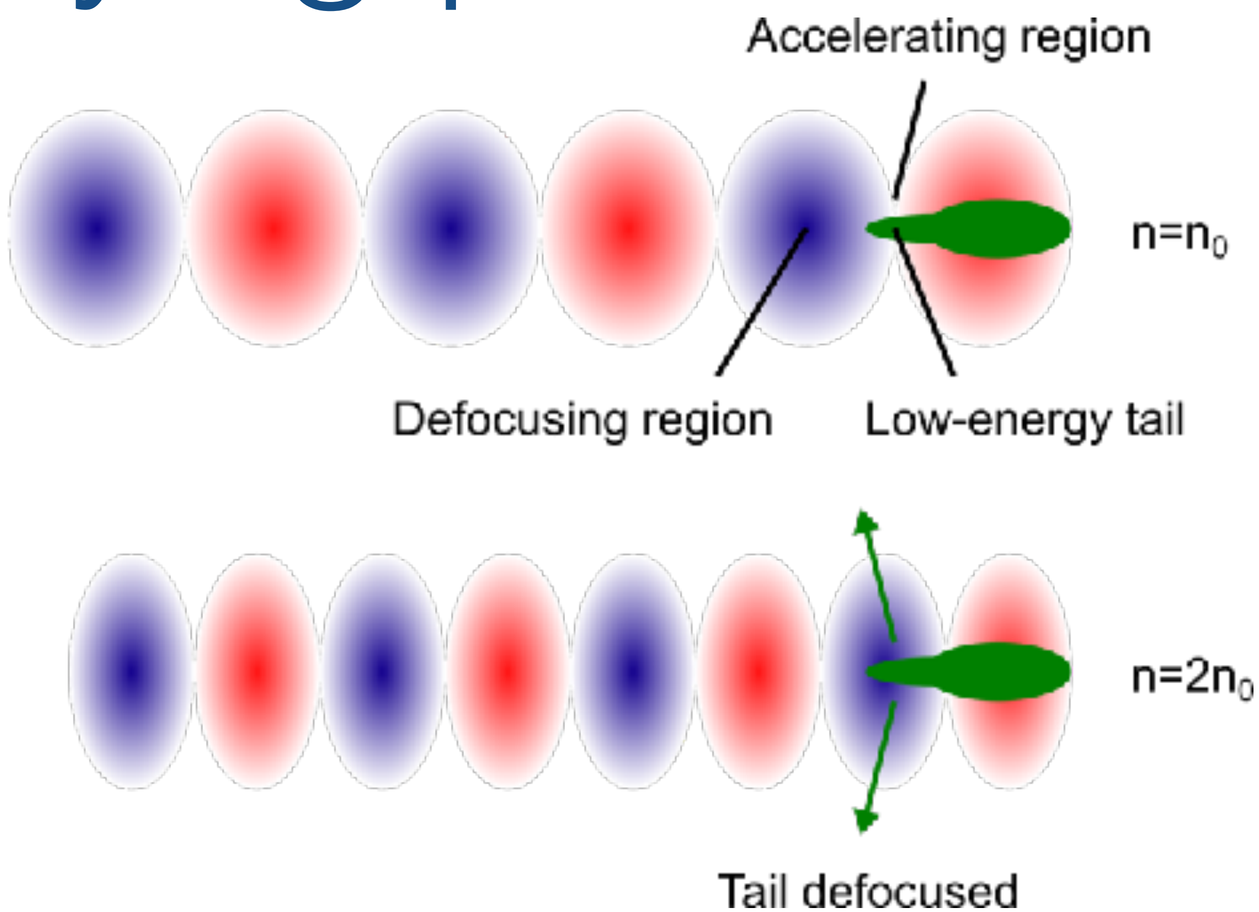


Active beam dump

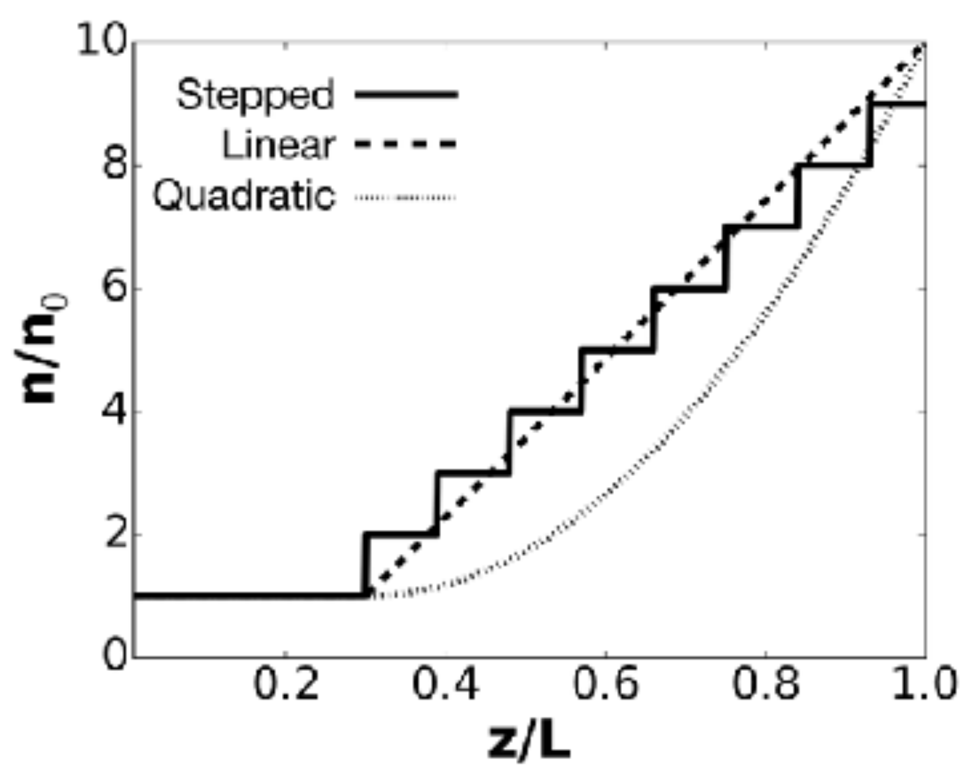


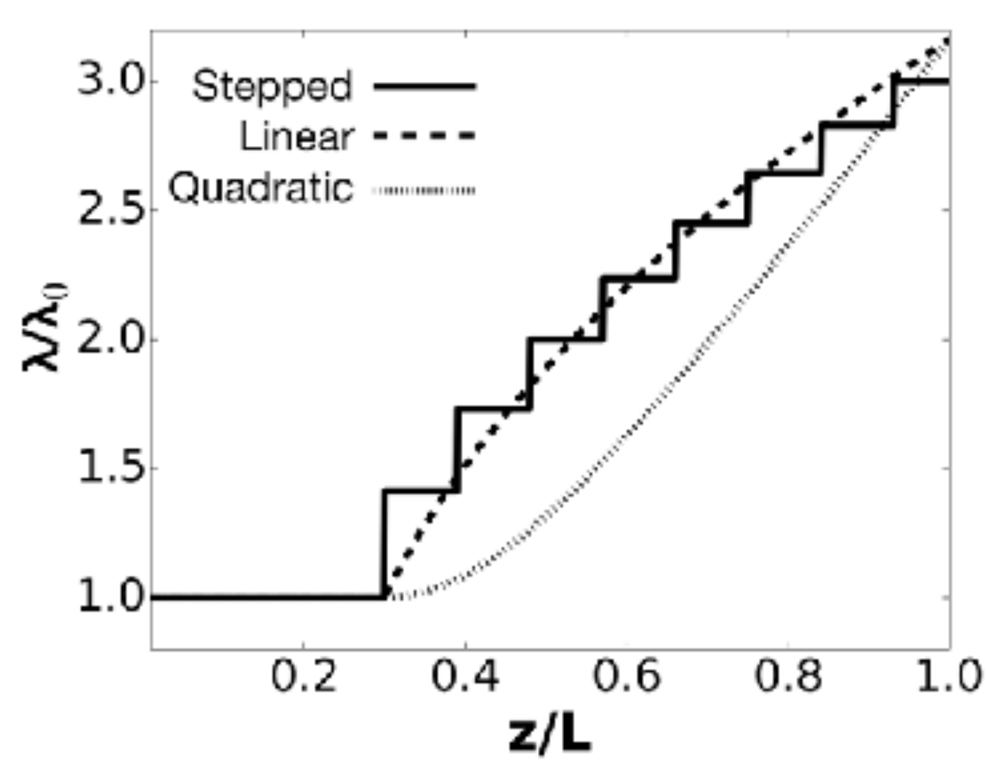
A. Bonatto et al. Phys. Plasmas 22, 083106 (2015)

Varying plasma density



Plasma density increase puts low energy tail of the bunch into defocusing region





K. Hanahoe, G. Xia, M. Islam, Y. Li, O. Mete-Apsimon, B. Hidding and J. Smith, Phys. Plasmas 24, 023120 (2017)

Saturation of deceleration

$$E_{\rm wb} = \frac{m_{\rm e} c\, \omega_{\rm p}}{e}$$

$$\omega_{\rm p} = \left(\frac{e^2 n_{\rm p}}{\epsilon_0 m_e}\right)^{\frac{1}{2}}$$

$$L_{\rm sat} \approx \frac{T_0}{e E_{\rm dec}}$$

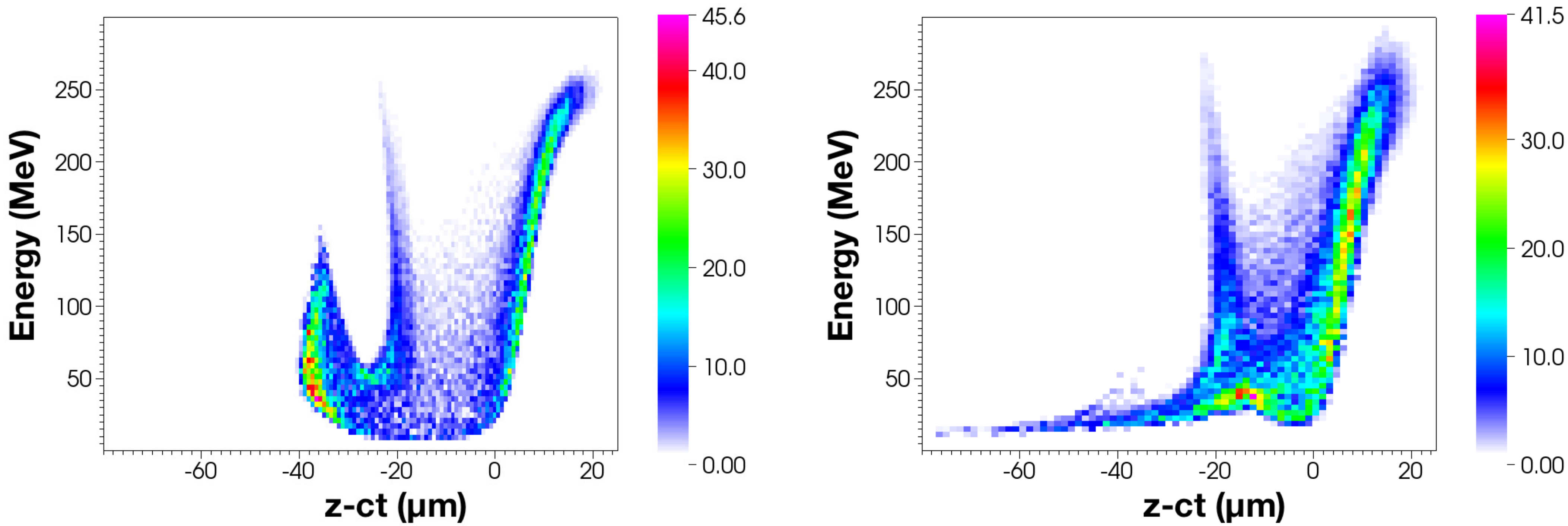
L_{sat} is the saturation length, T_0 is the beam initial energy, E_{dec} is the maximum decelerating gradient

Decelerating gradient of a passive beam dump depends on the bunch dimensions but not on the initial energy, a higher energy beam can be dumped using a longer plasma

Simulation study-VSim

MANCHESTER 1824 The University of Manchester

For a typical LWFA generated bunch, E=250 MeV, rms bunch length of 7.5 microns, rms radius of 20 microns and charge of 100 pC. Initial plasma density of 2e17cm^(-3), which corresponds plasma wavelength of 75 microns. Plasma density increased by a factor of 10



(a) (b)

FIG. 4: Longitudinal phase space histogram at $z = 16.3$ cm for a uniform plasma (a) and a linear gradient plasma profile (b). The energy scale corresponds to $\gamma/m_e c^2$ and as such is not accurate for non-relativistic velocities. The color scale gives the sum of macroparticle weight for each bin.

Simulation study-VSim

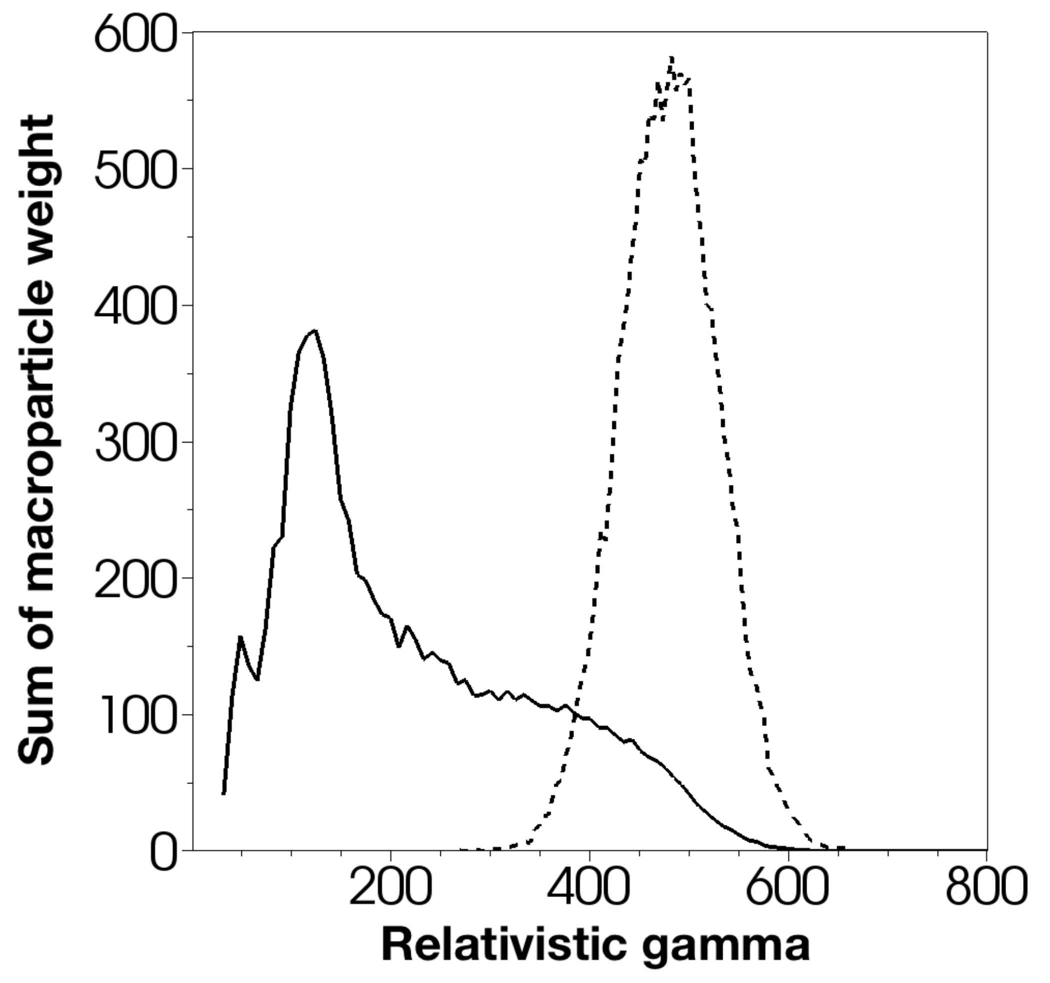
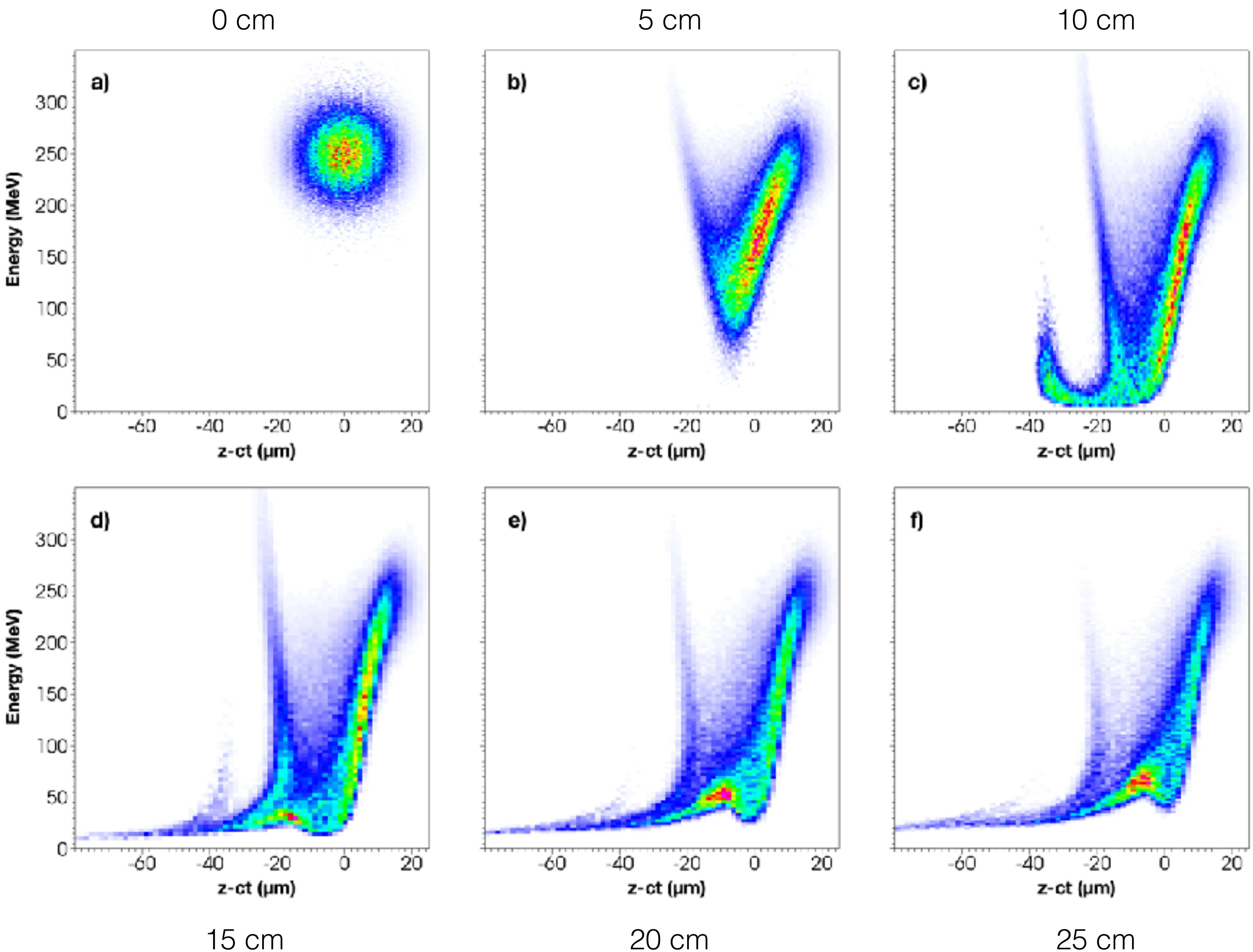


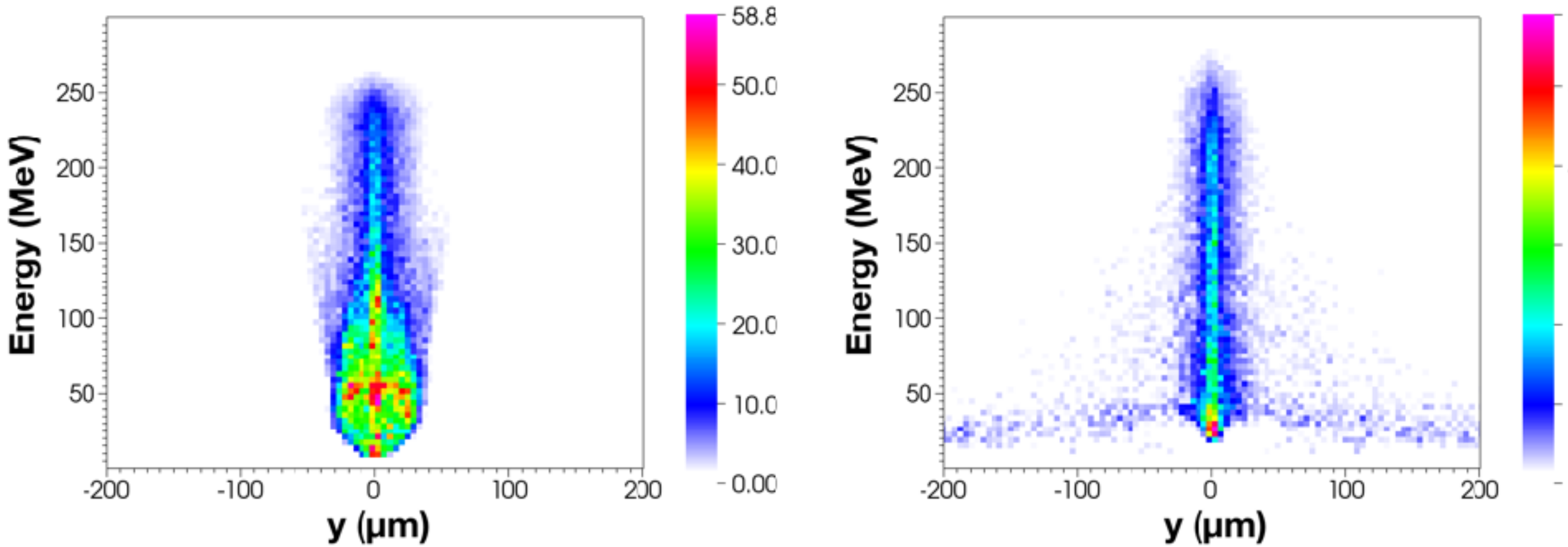
FIG. 6: Histogram of γ of the electron bunch at $z = 0$ (dashed line) and after 25 cm (solid line) for a linear gradient plasma profile. The y-scale is the sum of macroparticle weight in each bin. 100 equally-sized bins were used.

Linear density increase



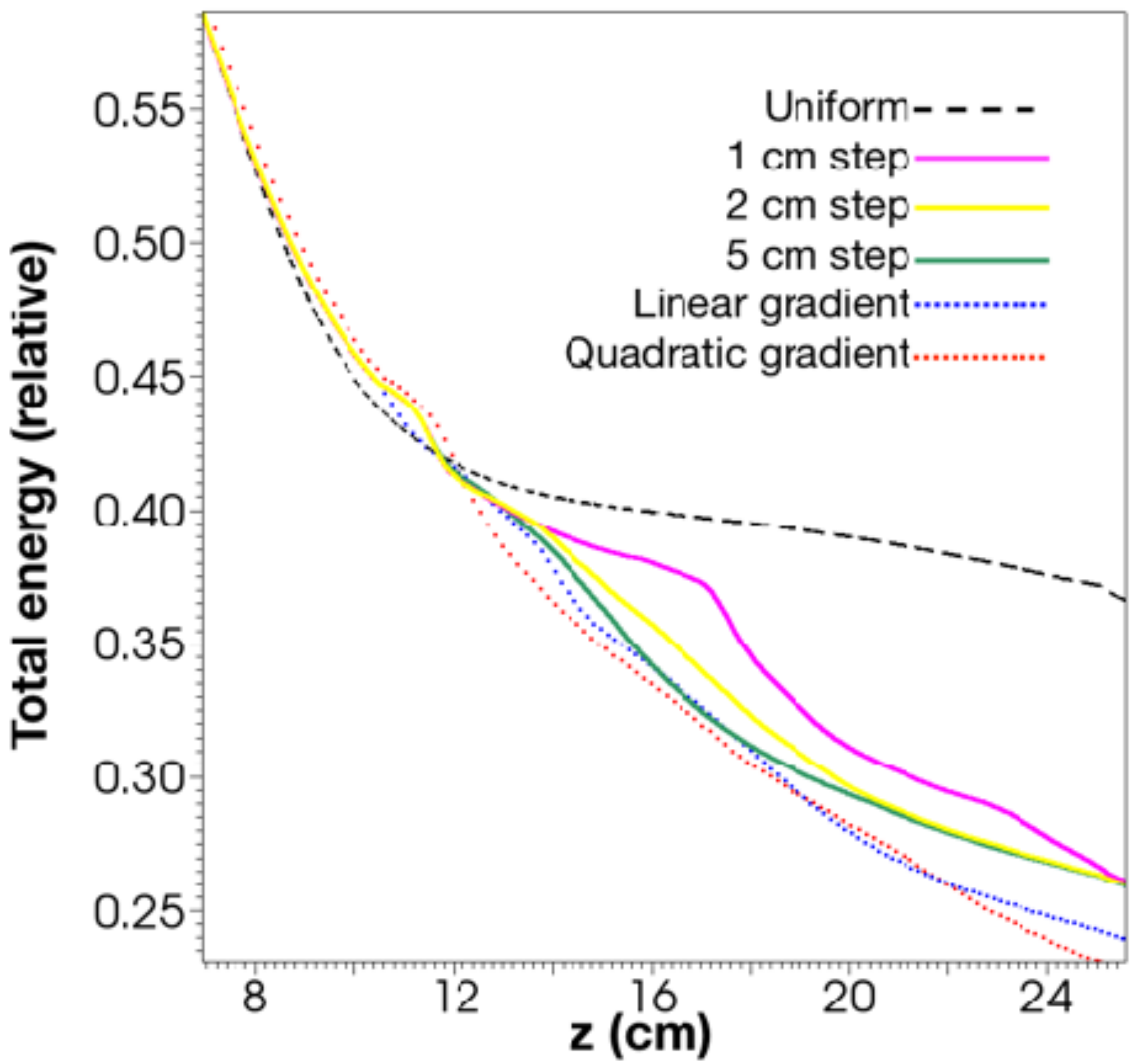
Varying plasma density

Energy/transverse position plots after saturation length for uniform plasma (L) and gradient plasma (R).



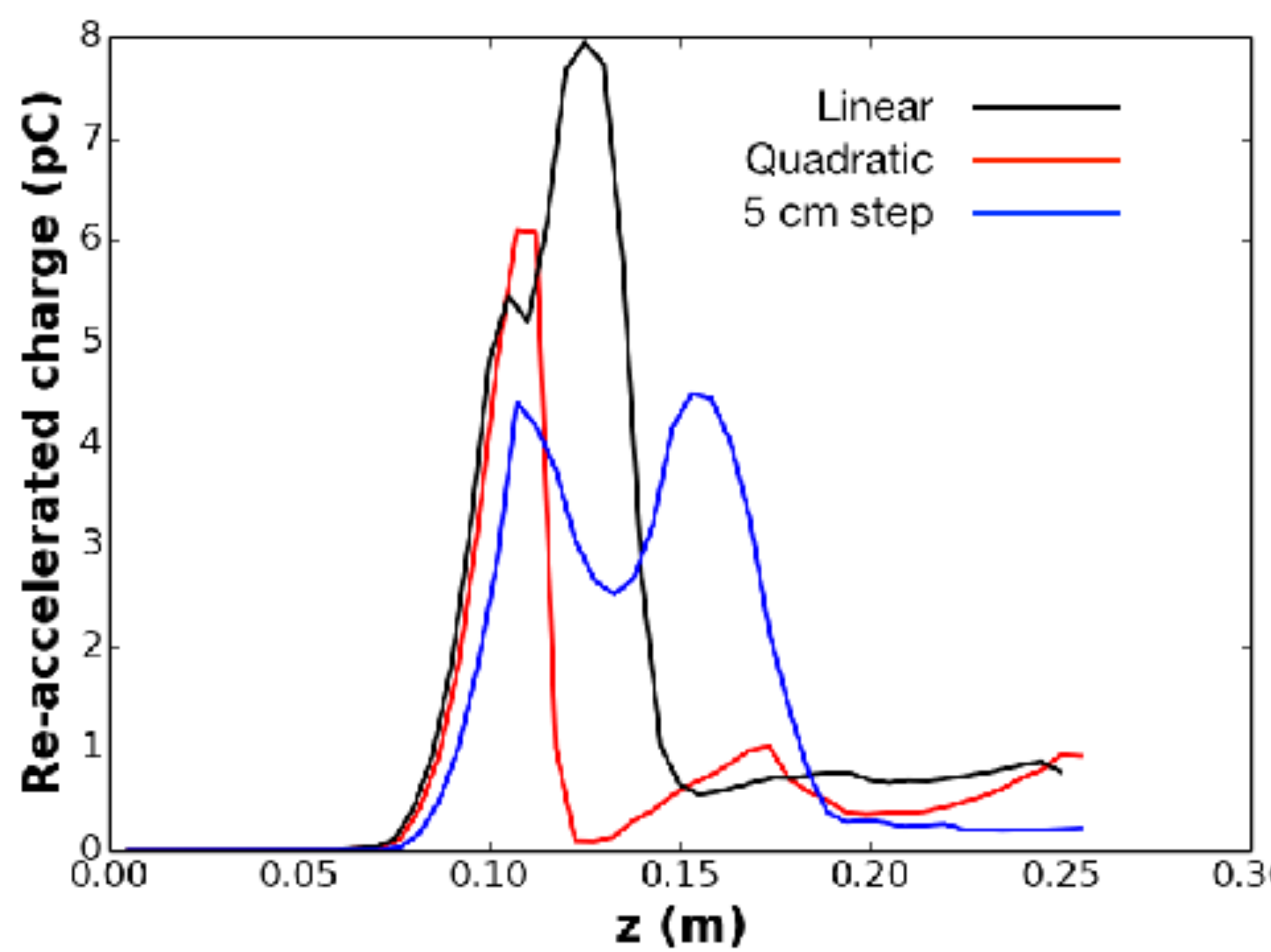
K. Hanahoe, G. Xia, M. Islam, Y. Li, O. Mete-Apsimon, B. Hidding and J. Smith, Phys. Plasmas 24, 023120 (2017)

Varying plasma density



Total bunch energy loss for different plasma density schemes

Quantity of charge in a region 30 μm behind bunch head with energy > 30 MeV



Conclusion

- Plasma wakefield acceleration is a promising means of achieving ultra-high accelerating gradients.
- Plasma wakefield acceleration is possible using CLARA and CLARA-FE.
- Investigating tailored bunch shapes to achieve high transformer ratio would be viable using modified CLARA beam parameters.
- Plasma beam dump can absorb beam energy with reduced radioactivation.
- Varying plasma density can be used to improve the energy loss of a passive plasma beam dump.