Laser wakefield acceleration in a heterogenous plasma

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Outline

- Introduction
- Concepts in *wakefield accelerators* and *laser-cluster interaction*
- Cluster injection
- Experimental Results
  TA2 2016
- Simulations
- Conclusion and outlook

Heterogeneous plasma

A heterogeneous plasma consists of over dense plasma locally with under-dense plasma globally.

Heterogenous plasmas have some useful effects which have been observed.

- **Pulse guiding** [1,2,3]
- **Charge enhancement** [4]

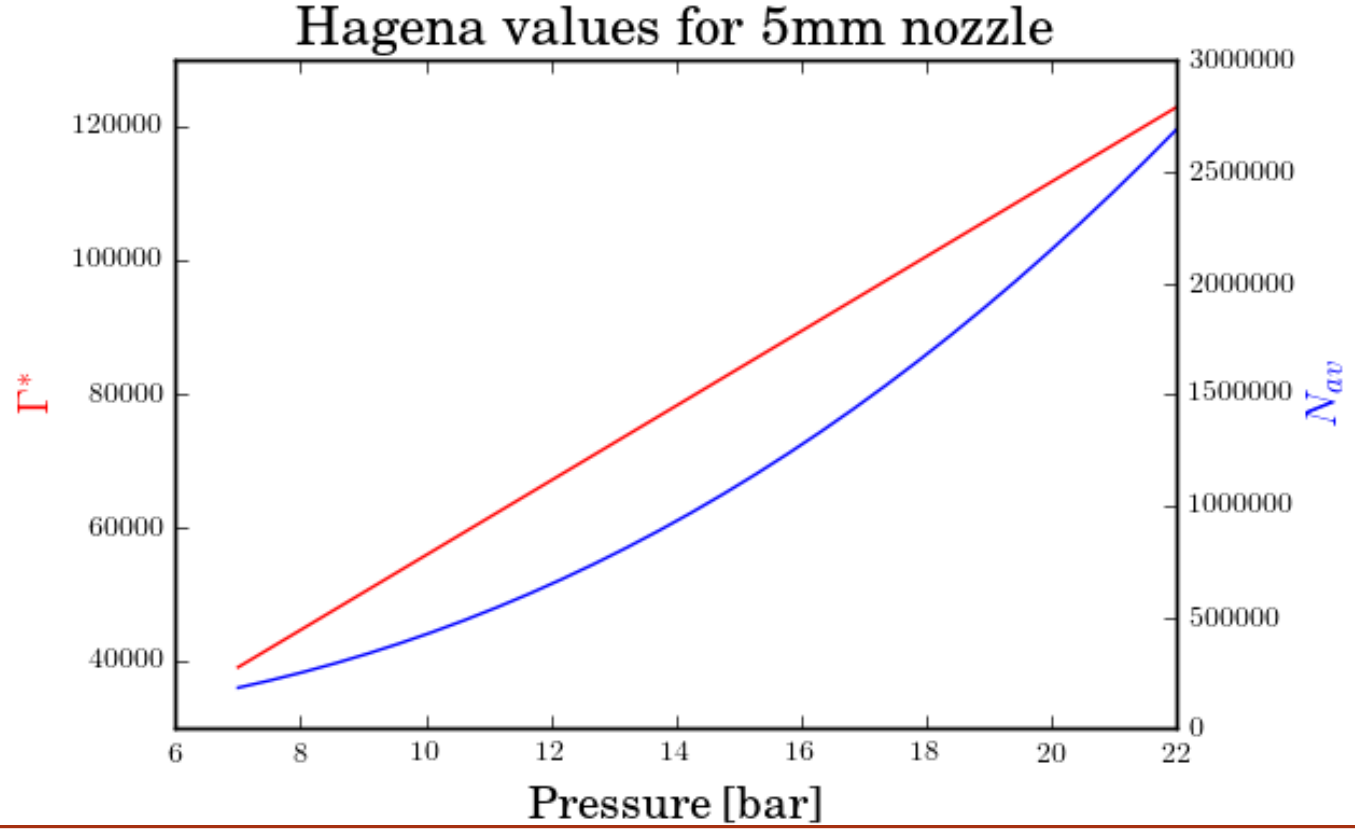
These plasmas can be created by the ionization of a clustered medium using an intense laser pulse.

[1] Kim, A. V. et. al.(1998). Self-confinement plasma effect in intense laser interaction with a cluster gas,
[2] Alexeev, T. M., PRL, 2004
[3] Ditmire, T et. al. , Optics Letters, 1998
[4] Fukuda, Y et. al (2007). Ultrarelativistic electron generation during the intense, ultrashort laser pulse interaction with clusters

Background: Laser-cluster interactions

<u>What is a cluster?</u>
A cluster is a collection of bound atoms/molecules which can be 100's -1e9 atoms large held by Van-der-Waals forces

[5] Hagena O. F., The Journal of Chemical Physics, 1972

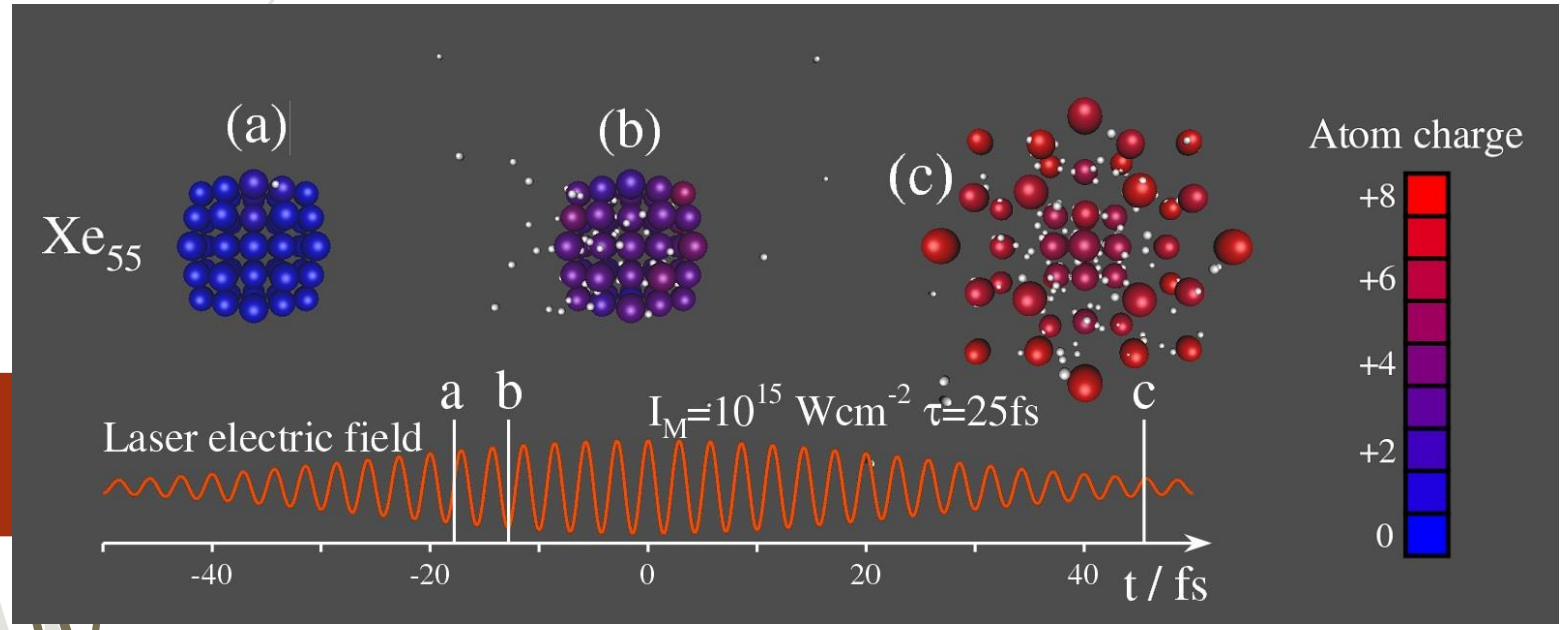


<u>Cluster formation</u>
Clusters are formed when gases undergo rapid cooling.
- Supersonic gas jets

$$\Gamma^* = k\frac{(0.74 * d/tan(\alpha))^{0.85}}{T_0^{2.29}}P_0 \qquad N_{av} = 33\left(\frac{\Gamma^*}{1000}\right)^{2.35}$$

Hagena parameter for supersonic nozzles with Γ^*>1000
[4] Boldarev et. al, Review of scientific instruments ,2006

Background: Laser-cluster interactions



[5] http://www.ehu.eus/chemistry/theory/2_research/1_res_lines/5_coulomb/1_coulomb/

Coulomb explosion

- Laser pulse strips electrons from a cluster causing it to become charged resulting in a expansion driven by space charge.

$$\tau_{ex} \approx r_0 \left(\frac{m_i}{Z k_b T_e}\right)^{1/2} \left(\frac{n_0}{n_e}\right)^{1/3}$$

[6] Kim A. V. 1998 AIP conference proceedings

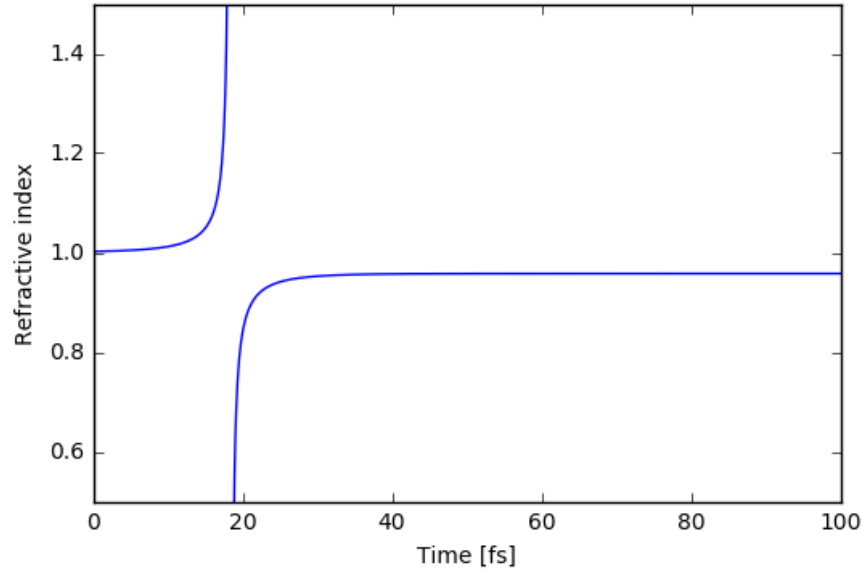
$\boldsymbol{\tau}_{ex}$ is the cluster expansion timescale. For T=1keV, n_e=2e19cm^{-3} with a methane cluster we obtain $\boldsymbol{\tau}_{ex}$=600 fs

Cluster enhanced guiding

$$p_\omega = \frac{\epsilon - 1}{\epsilon + 2} r_{cl}^3 E_\omega$$

$$\chi_{pl} = -\frac{n_e}{3n_{cr} - n_e} r_{cl}^3 N_{pl}$$

$$\eta = \sqrt{1 + \chi_{pl}}$$



Transient beam self-focusing
The susceptibility of the medium changes sign(+ve to -ve) as the cluster expands. The clusters act as a focusing lens initially.

[7] Alexeev, T. M., PRL, 2004

Plasma waveguide formation in predissociated clustering gases
Low intensity pre-pulse disassociates clusters in the middle.
High intensity main pulse is strongly absorbed by clusters at the edge resulting in the formation of a waveguide structure.

[8] Ditmire, T et. al. , Optics Letters, 1998

Critical power for self-focusing in heterogeneous plasma

$$P_{SF} \approx 112 \left(\frac{r_0}{r_{cl}(t)} \right)^7 \left(\frac{n_e}{\omega} r_0 \right)^2$$

[9] Symes, D.R. , AIP, 2007

Injection mechanism

- Self injection

Advantage: Easy to achieve with a sufficiently intense laser

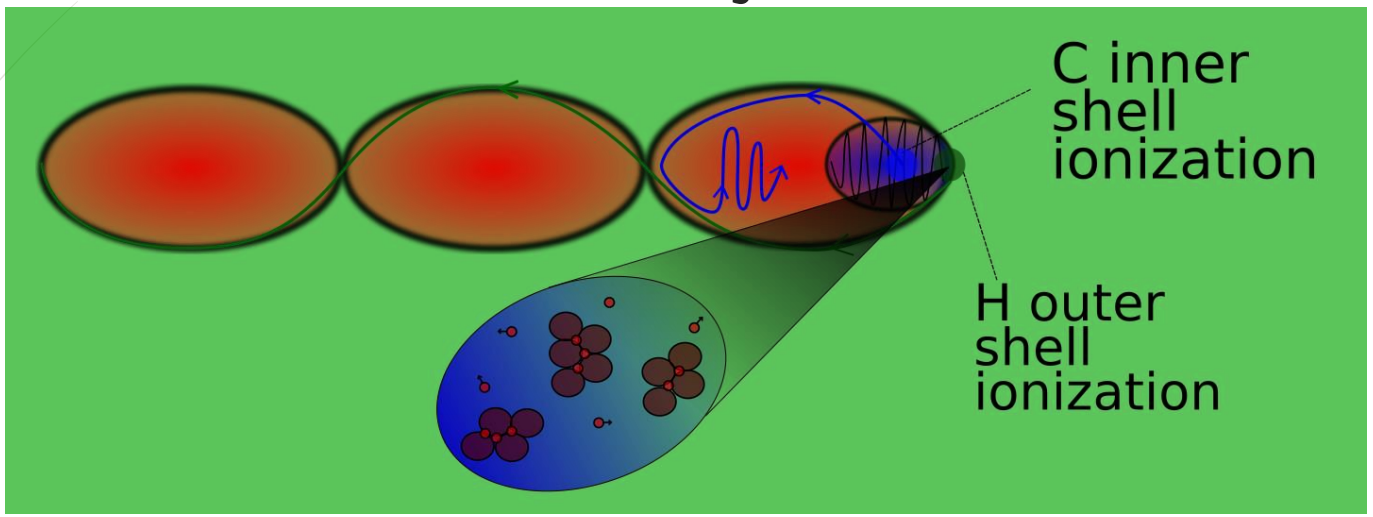
Disadvantages: Operates in the non-linear regime. Beam parameters are sensitive to laser stability.

- Ionization injection

Advantage: Improves on the stability and charge of the injected electron beam

Disadvantages: Discrete energy levels mean finding suitable ionization levels can be difficult.

Cluster injection



Cluster injection

- Clusters act like large sources of electrons
- Ionization levels are tuneable with the size of a cluster.

Experiments on clustered LWFA

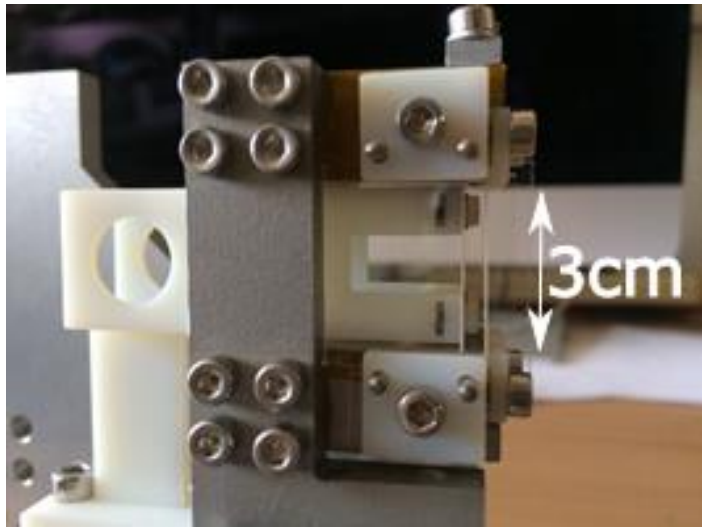
- This idea has been examined by others but typically operating in different regimes.

Experiment	Laser Power [TW]	Electron plasma density[cm^{-3}]	Mean cluster size[No. of atoms]	Charge [pC]	Max energy [MeV]
Y. Fukuda 2007	20	9.1e19	6.6e9	2100	58
TA2 2012	10	1e19-2.2e19	3e5-5e6	27	173
M. Mirzaie 2016	50	5e18-1.2e19	500-3000	3000	17-50
This work	10	5e18-5e19	1.8e5-2.6e6	50	180

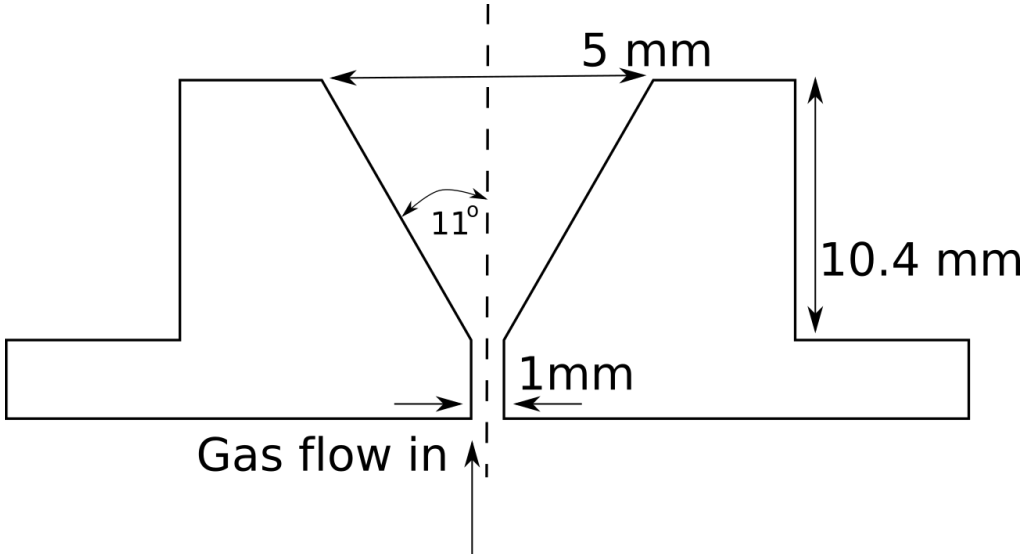
Imperial College London Experiment details- *TA2 2016*

Distinguishing the effects of clustering using targetry

- Compare wakefield acceleration in a gas jet to a gas cell.
- *Clustering occurs in a gas jet* whereas it **does not** in a gas cell.
- This is due to adiabatic cooling of the fluid in a gas jet.
- Methane clusters readily at room temperature.
- Both targets have trapezoidal longitudinal profiles.



Gas cell used in this experiment



Gas jet used in this experiment

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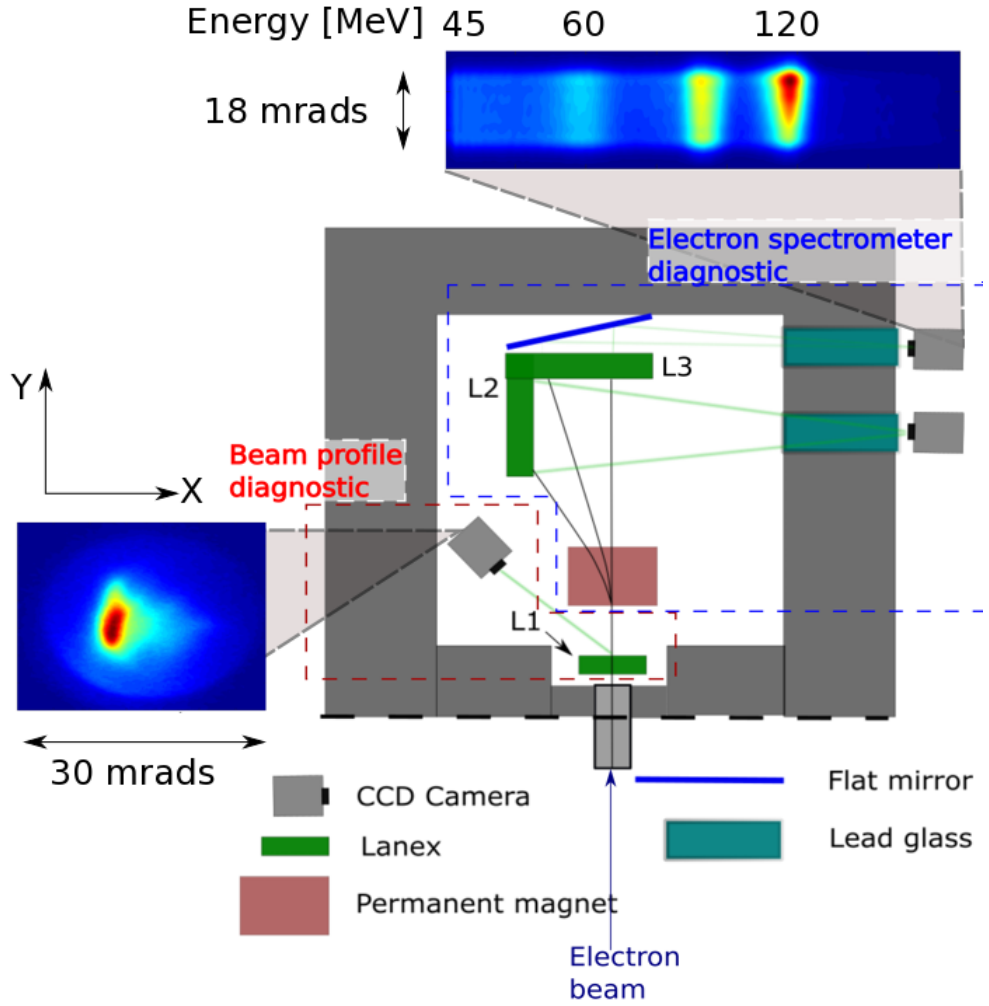
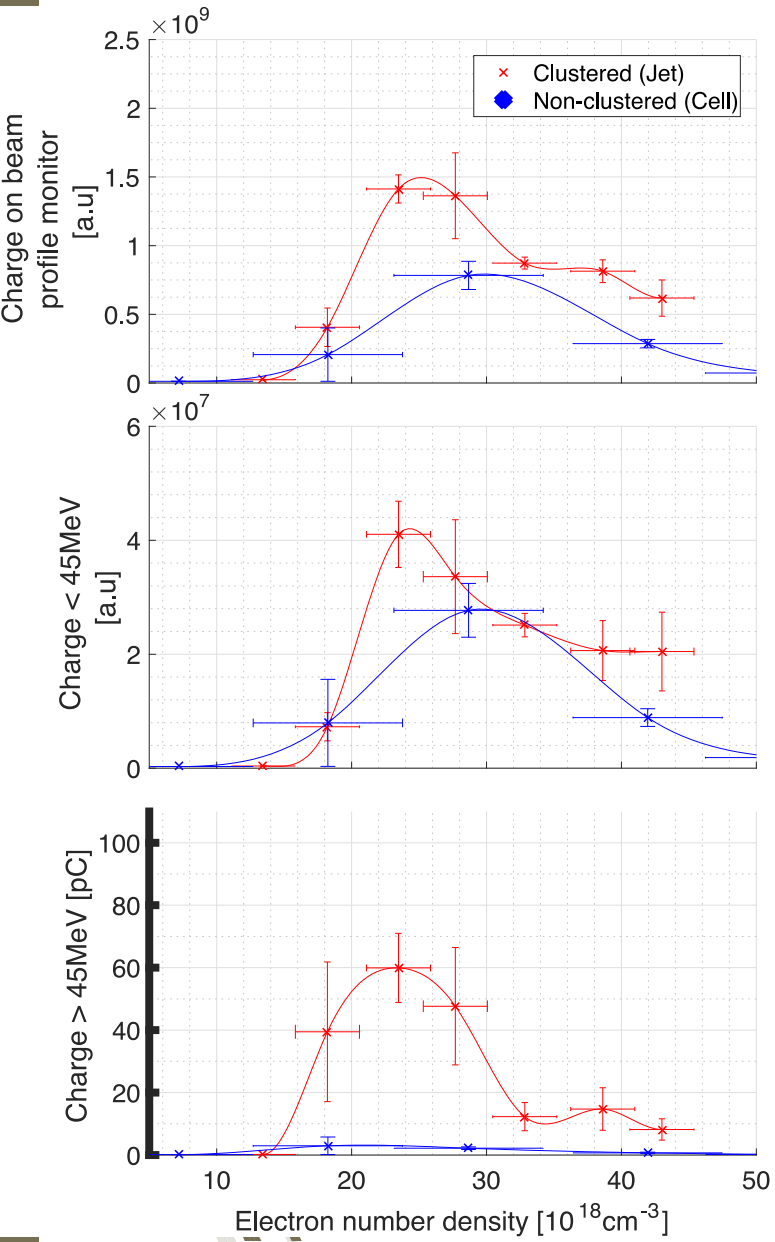
Experiment details- ***TA2 2016***



Laser parameters	
Laser energy [mJ]	500+/-10
Pulse duration [fs]	45 +/- 5
Spot size (w0) [μm]	15+/- 3
Vacuum a_0	0.9

Target parameters	Gas jet	Gas cell
Backing pressure [bar]	7-22	0.03-0.35
Electron number density [10^{18} cm^{-3}]	6-50	10-50
Length [mm]	5	4.4
Reduced Hagena parameter – Γ^*	4e4-1.2e5	N/A
Mean cluster size [No. of atoms]	1.8e5-2.7e6	N/A

Results: Beam charge enhancement



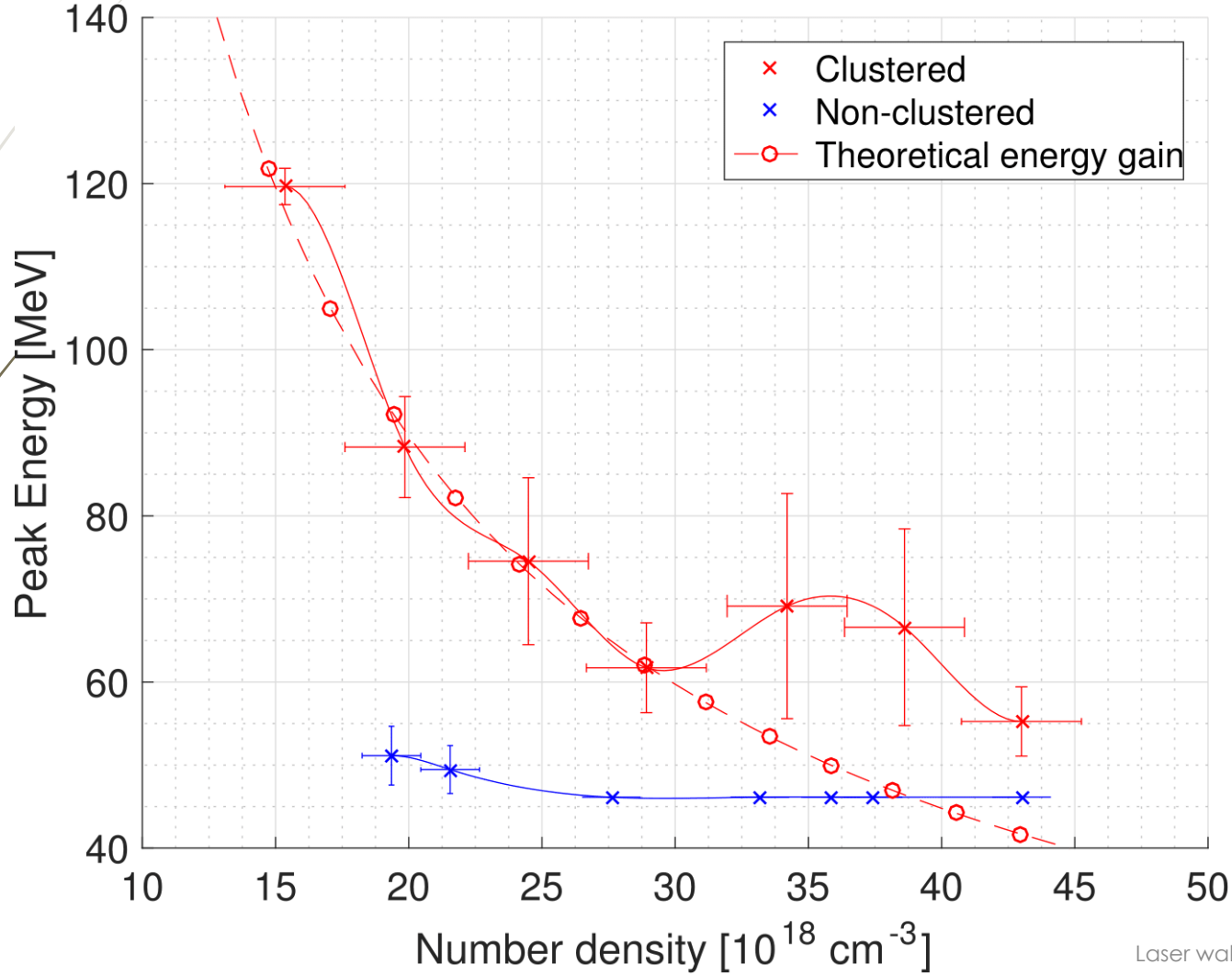
Beam profile monitor

Low energy electron spectrometer

High energy electron spectrometer

Charge above 45MeV is being enhanced. This suggests that the charge inside the beam (as opposed to the halo) is being enhanced.

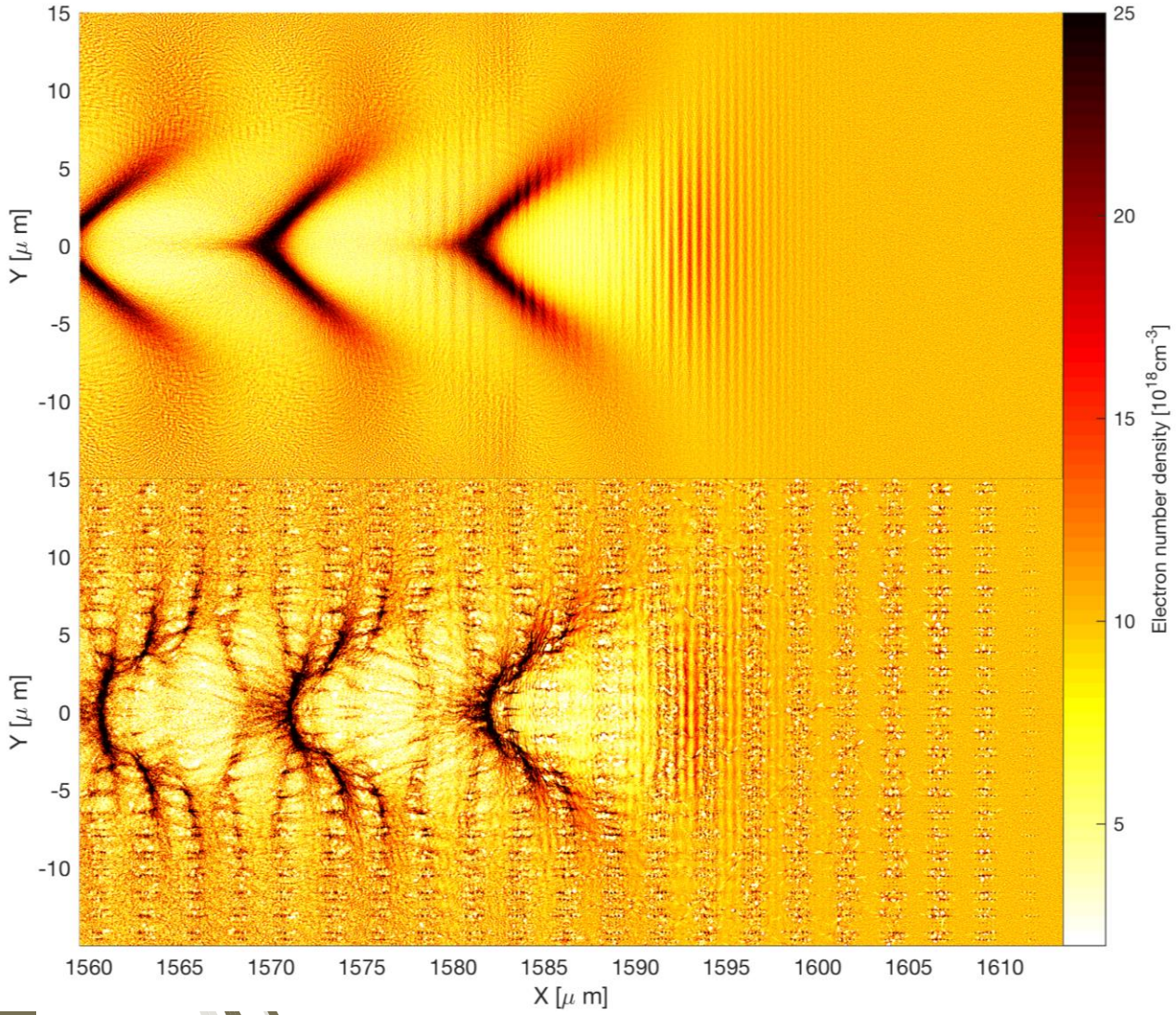
Results: Beam energy enhancement



Peak energy follows linear energy gain equation. Suggestive of guiding enhancement. W_{max} is the linear energy gain.

$$W_{max} = 2mc^2 \frac{n_c}{n_e}$$

Simulation results: Plasma wave structure



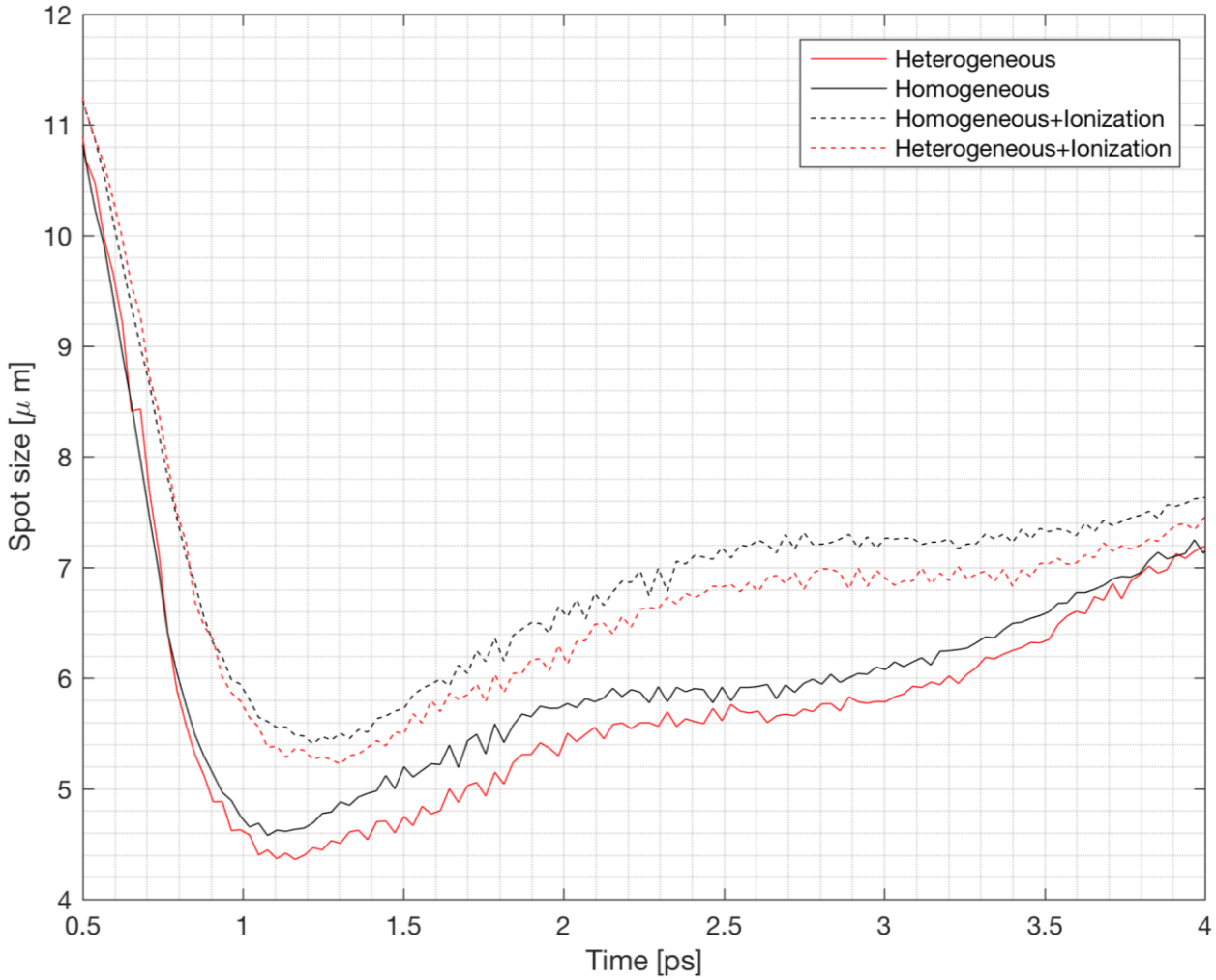
Top: Plasma wave with ***homogeneous*** plasma

Bottom: Plasma wave with ***heterogeneous*** plasma

Particle-in-cell simulations were performed (using EPOCH) to ascertain differences in evolution of the plasma wave between the two cases

Non-clustered number density	1.25e19 cm^{-3}
Cluster density	1.29e13 cm^{-3}
Mean cluster separation	0.43 μm
Energy	0.5 J
Atoms per cluster	9.7e5
Cluster mass fraction	0.5
Peak Cluster density	8.74e20 cm^{-3}
Cluster FWHM	225 nm

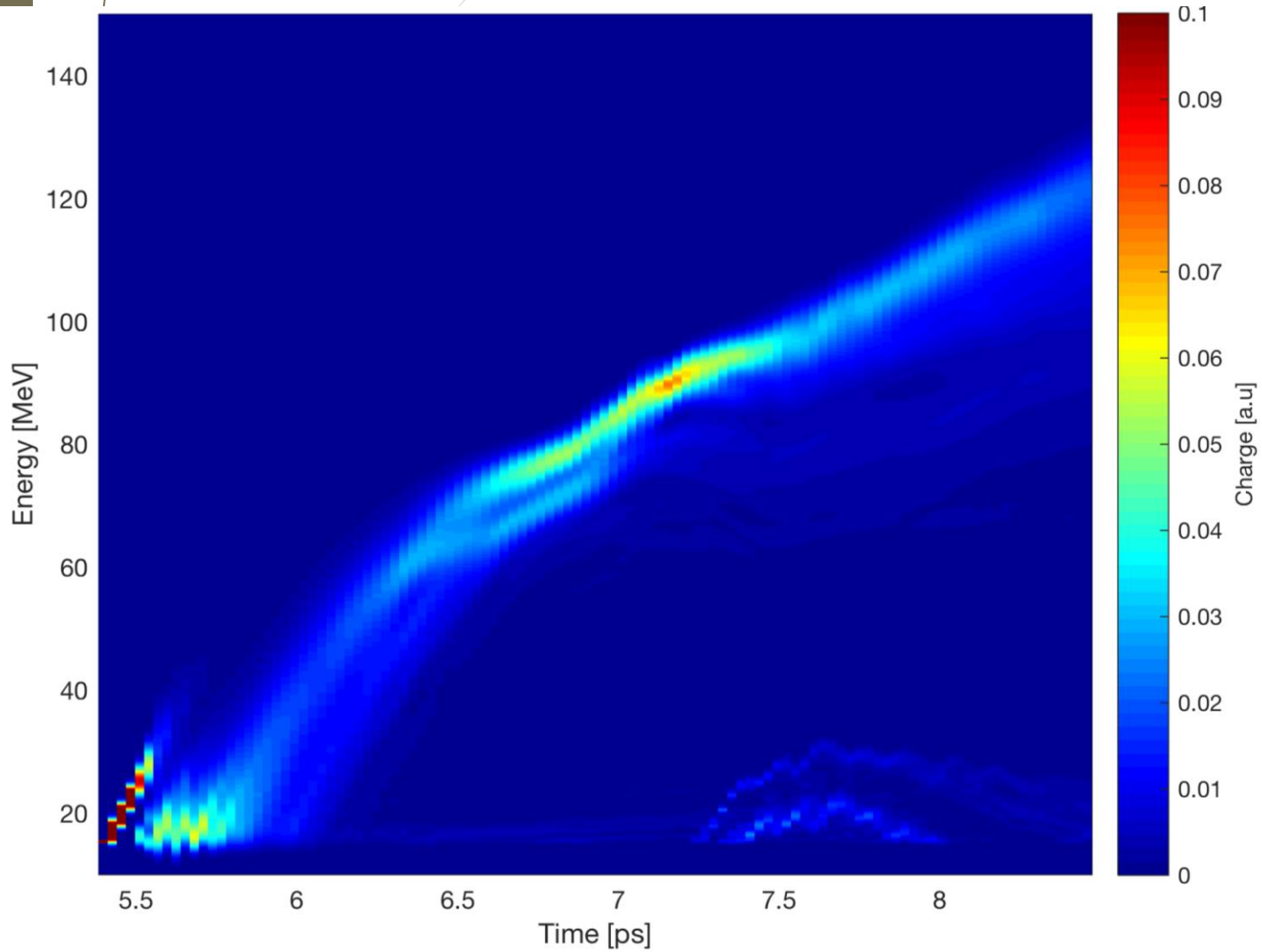
Simulation results: Spot size evolution



In the heterogeneous medium PIC simulations indicate that the pulse experiences some self-focusing.

Ionization induced defocusing is the reason why (for methane in a gas cell) lower energies are observed.

Simulation results: Energy gain



PIC simulations show electrons are injected and accelerated from clusters.

Conclusion

- Cluster injection *enhances* the charge of the injected beam.
- Self-focusing component of clusters may assist guiding of laser pulse.
- Future experiments will aim at control of cluster size through temperature. Possibility of tailoring injection using temperature.

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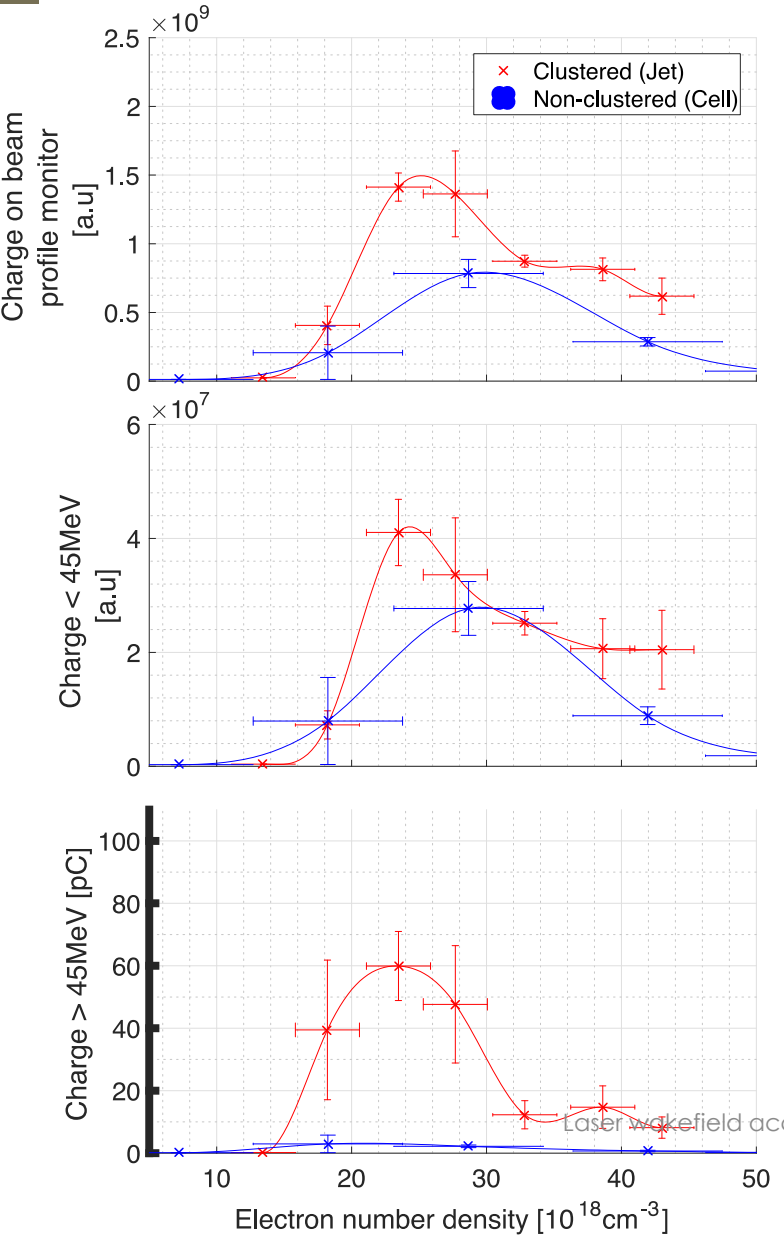
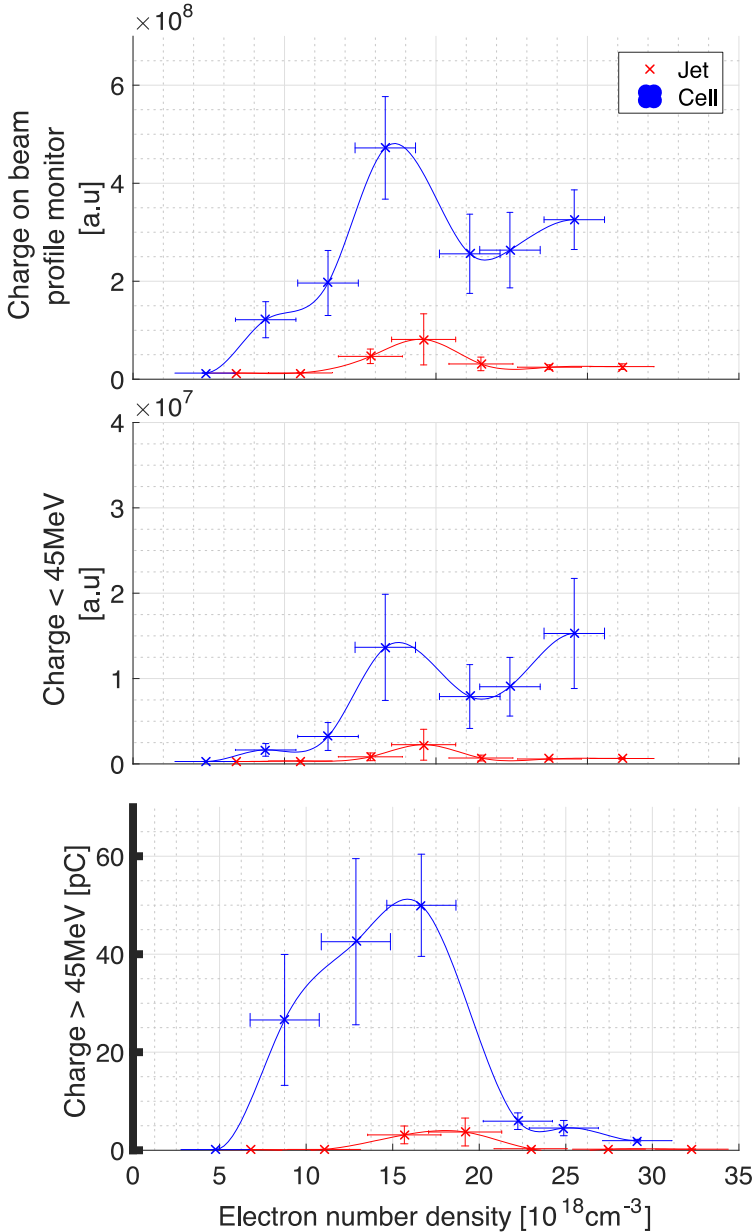
Additional slide 1: Targetry effect

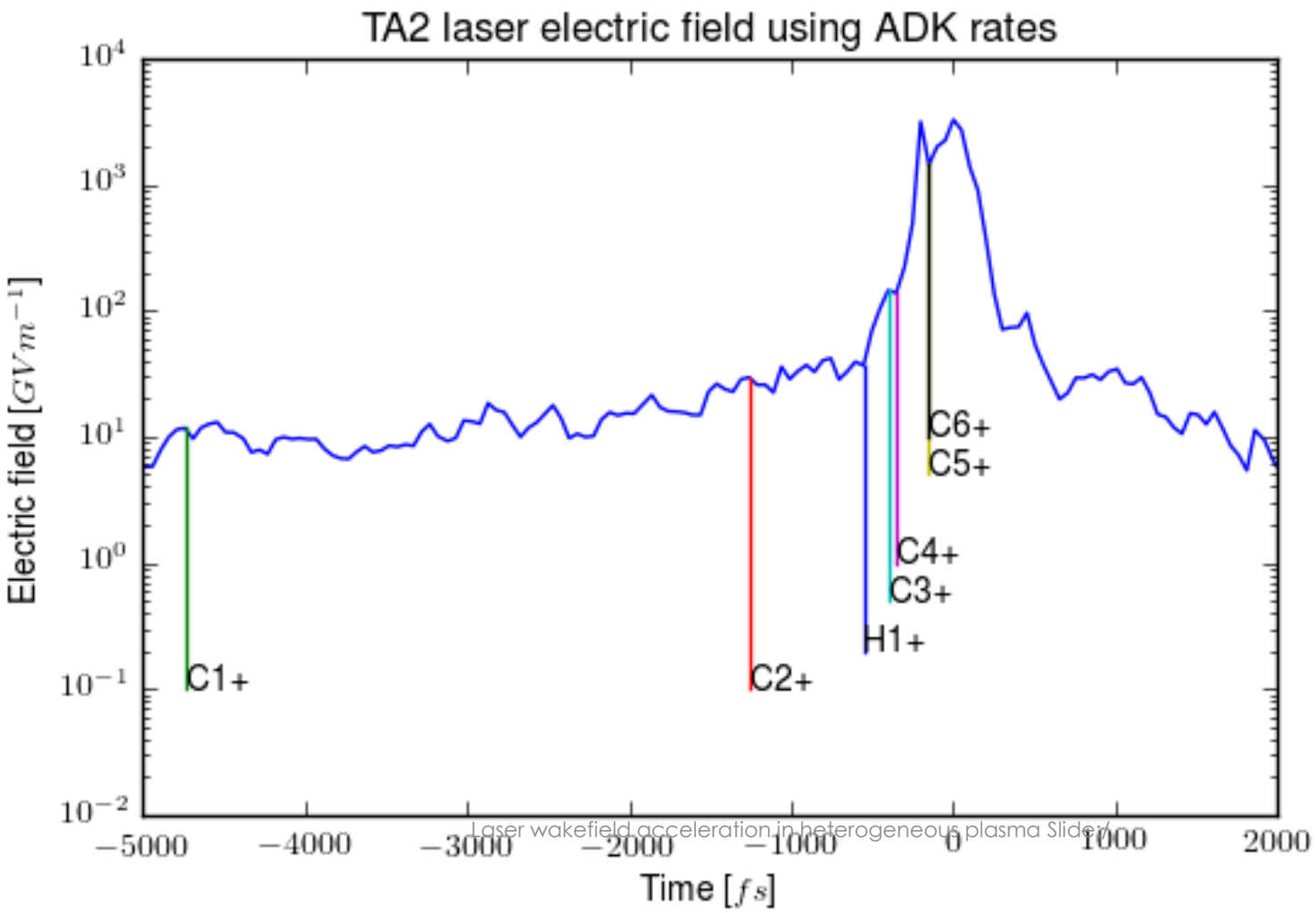
Methane



Helium

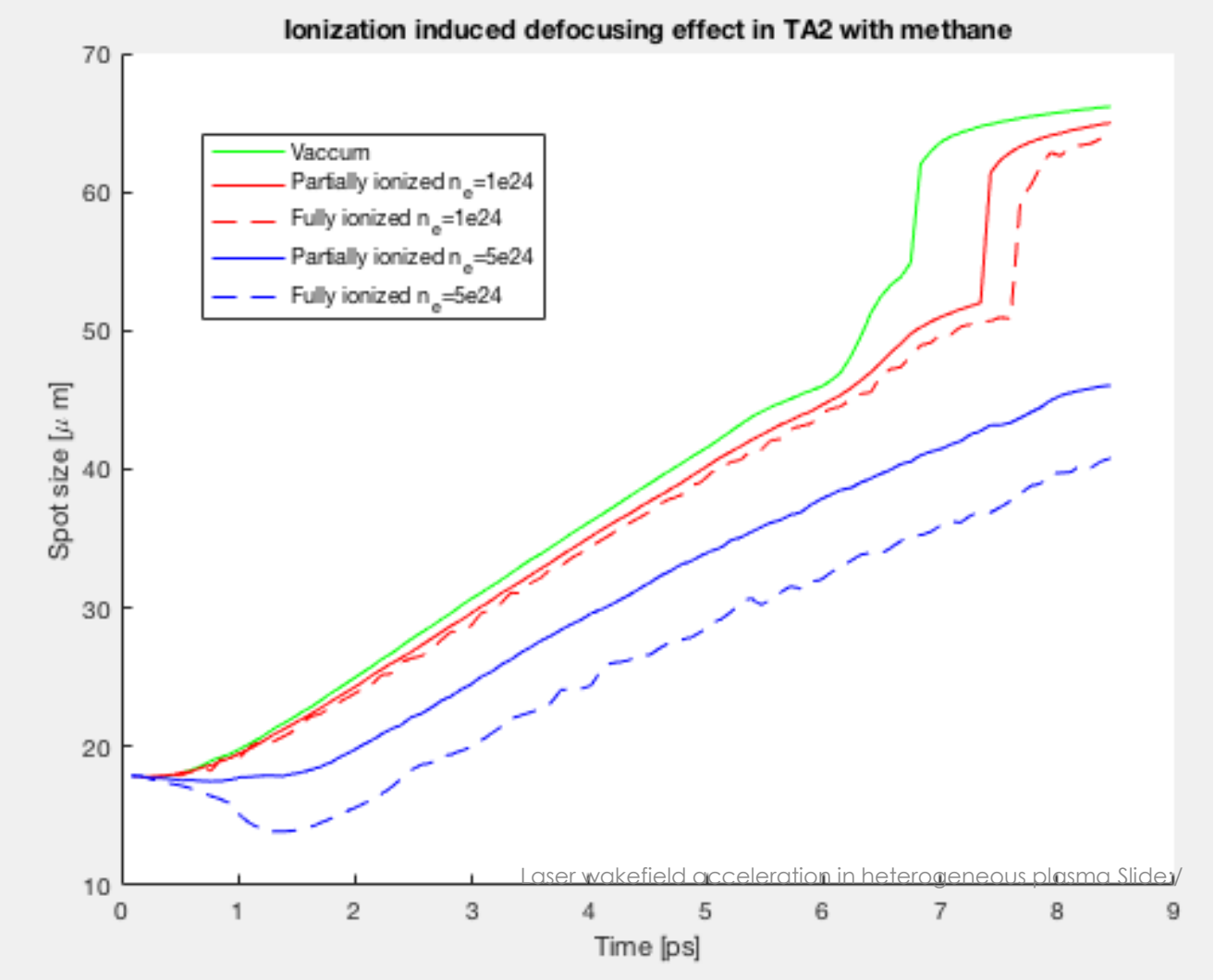


Additional slide 2: TA2 prepulse



Energy levels	1	2	3	4	5	6
Carbon [eV]	11.3	24.4	47.9	64.5	392.1	490
Hydrogen [eV]	13.6					

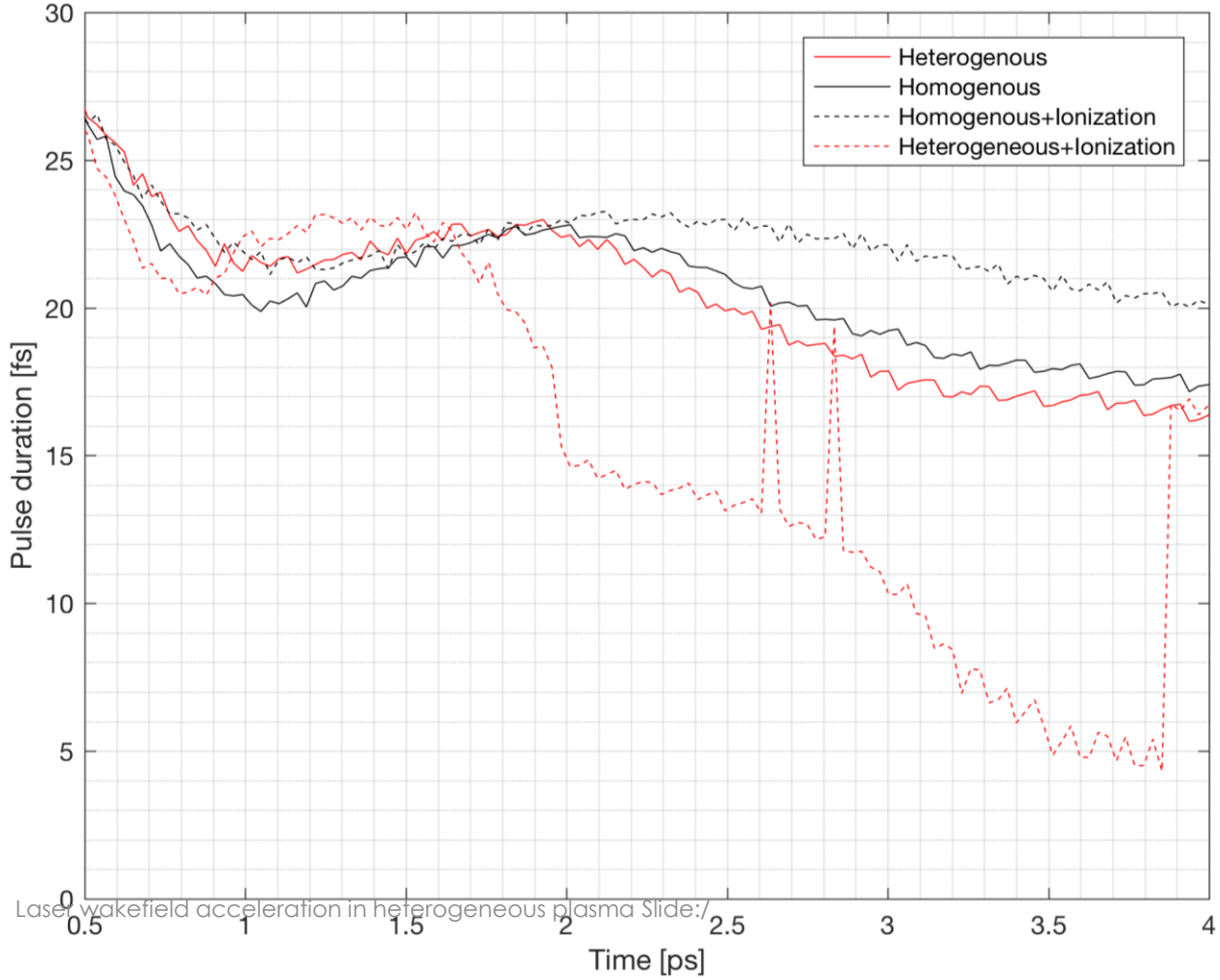
Additional slide 3: Ionization induced defocusing



Carbon ions are not fully ionized. This has a defocusing effect on the laser pulse at a critical number density.

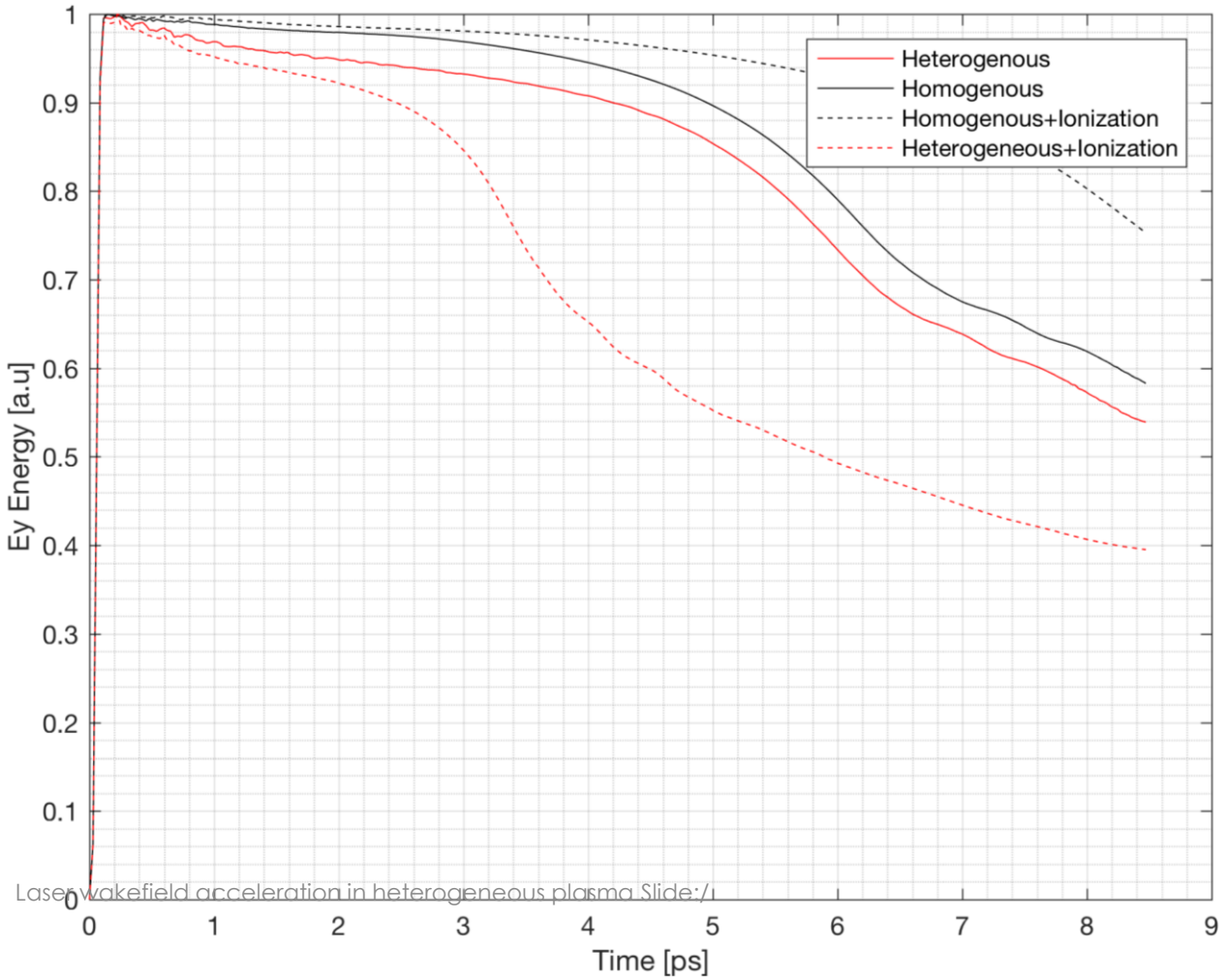
$$n_{IID} \approx n_{cr}\left(\frac{\lambda_0^2}{2w_0^2}\right)$$

Additional slide: Pulse duration for heterogenous LWFA



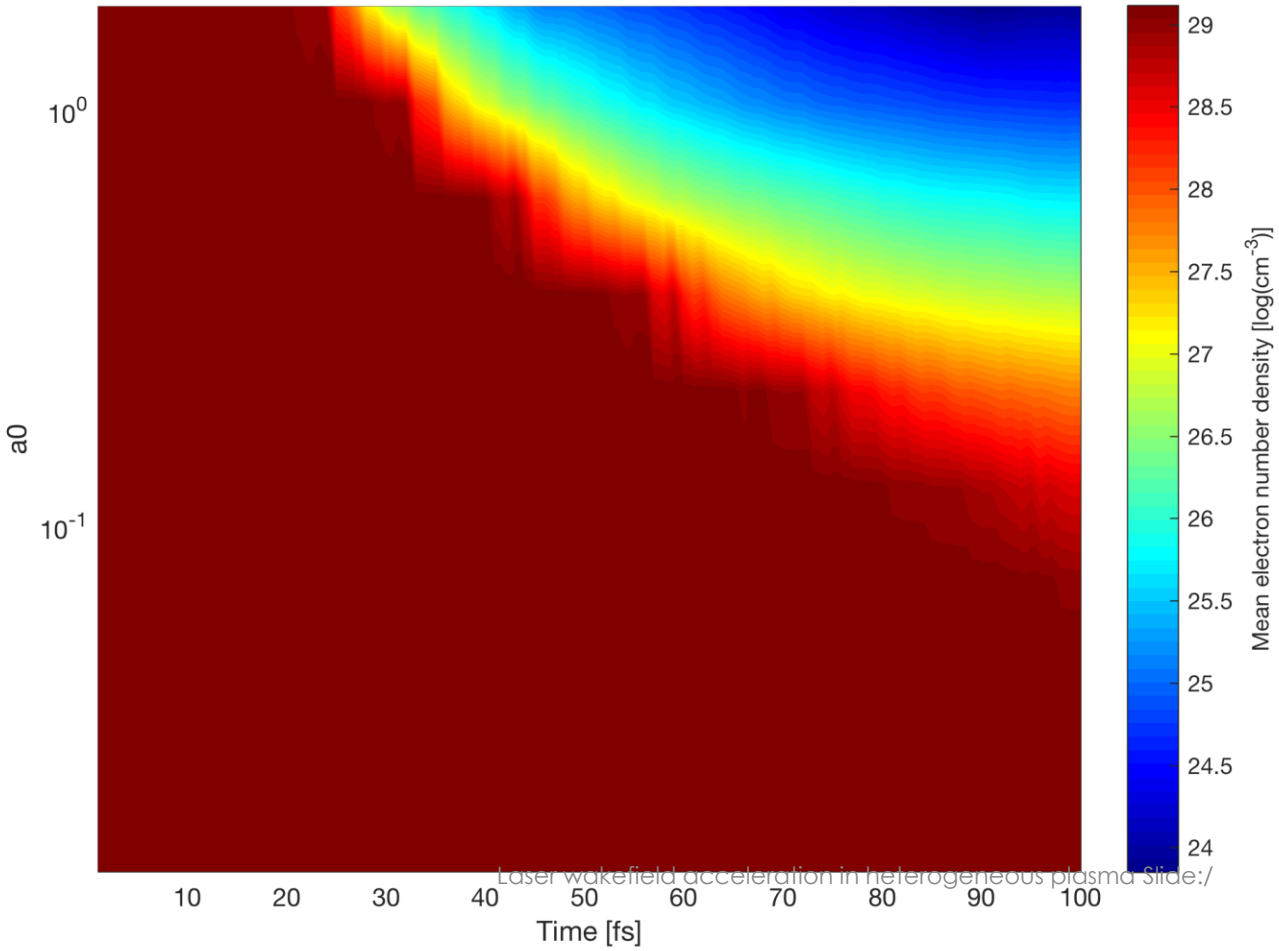
Pulse experiences more temporal compression.

Additional slide: Pump depletion for heterogenous LWFA



Heterogenous plasmas deplete the pulse faster than homogenous plasmas

Additional slide: Single cluster simulation



Mean electron cluster density inside cluster rapidly varies as a function of a0