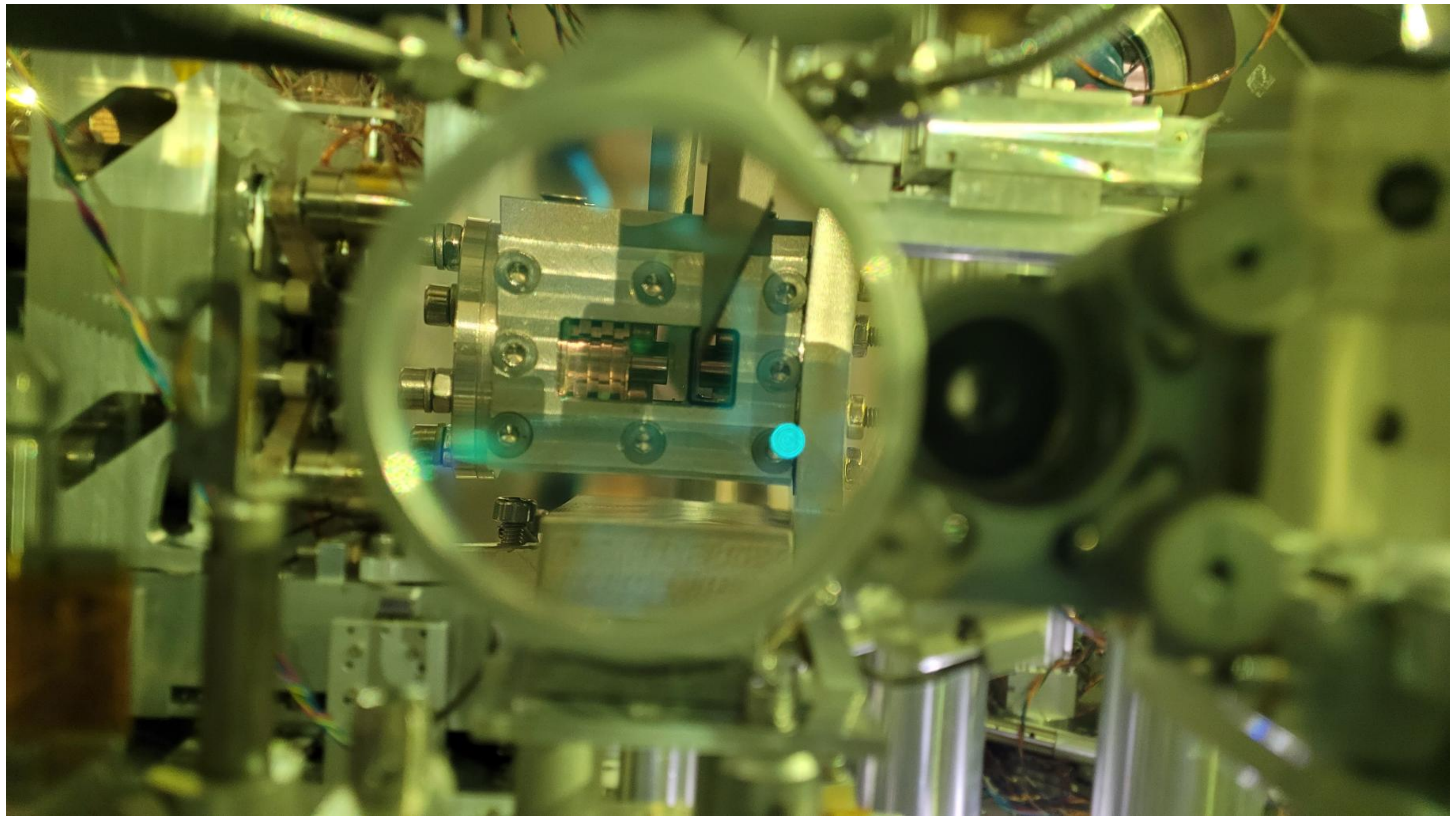
LABORATOIRE DE PHYSIQUE DES GAZ ET DES PLASMAS

HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

université PARIS-SACLAY

Observation of improved electron beam quality from a laser plasma accelerator by post acceleration beam shaping



Lodewyk Steyn LPGP, Orsay France

European Advanced Accelerators concepts worshop 2025 ,Elba, Italy

https://arxiv.org/abs/2506.18047

Achieving high quality beams is a general goal of laser wakefield acceleration

- Source for applications
  - Eupraxia
  - FEL
  - Multistage acceleration

Arie Irman Talk
Wed PS5 17:20
Coxinel FEL

High quality beam in our context

- High Charge — $Q > 100\ pC$
- High mean energy — $\bar{E} > 100\ MeV$
- Low energy spread — $\frac{\Delta E}{E} < 1\%$
- Low emittance — $(\epsilon_{\perp} < 1\ mm\ mrad)$
  - Low Divergence — $\theta_{rms} < 1\ mrad$
  - Small Spot size — $\sigma_{\perp} \approx 10\ \mu m$
- Repetition rate — $f > 1\ Hz$
- Repeatability — Stability shot to shot

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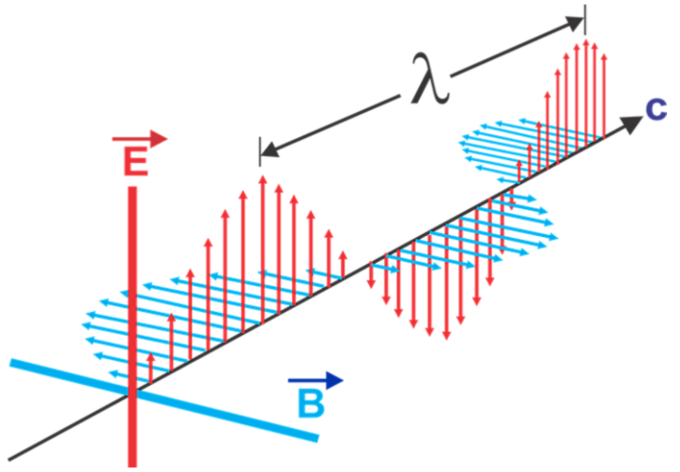
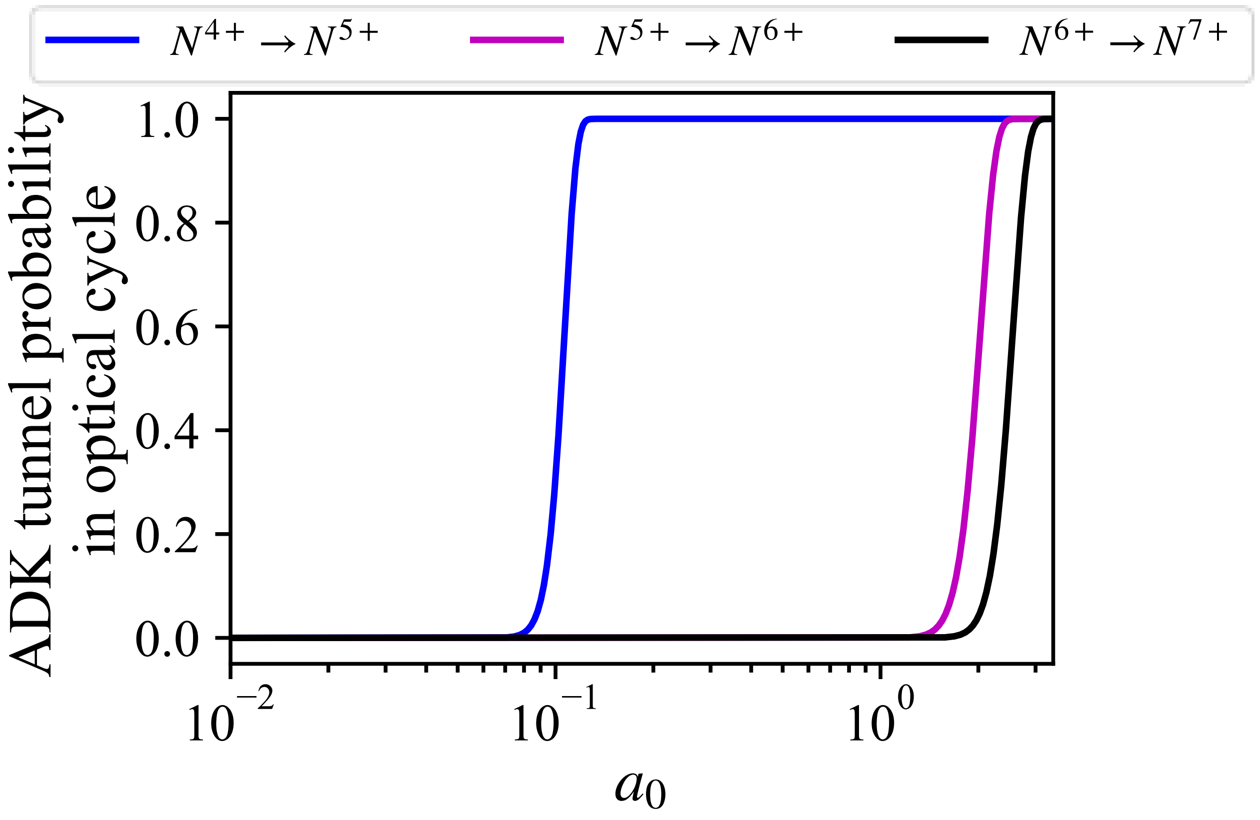
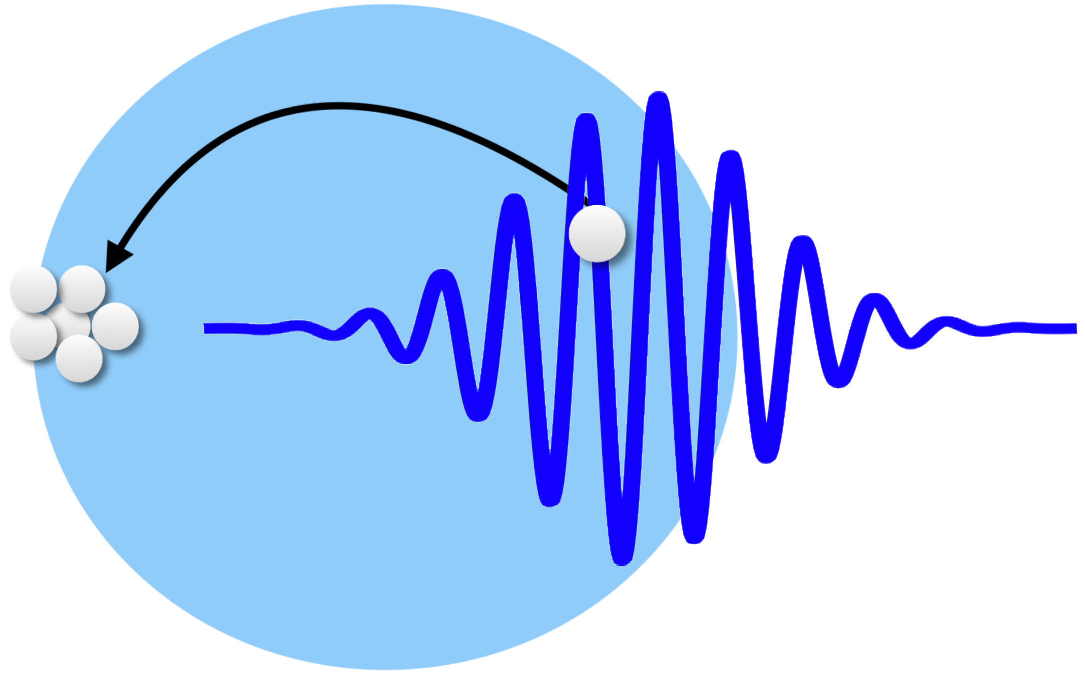
Ionisation combined with tailored density profile is useful to control electron injection

- Ionization injection allows high charge at low laser intensity
  - $a_0 \gtrsim 1.4$ ionize $N^{5+} \rightarrow N^{6+} + e^-$
- Possible at low gas densities
  - $n_e \approx 10^{18} cm^{-3}$
- Low nonlinearities in laser-plasma interaction
- Straightforward tailoring of density profile in gas cells
  - Making and manipulating plateaus and density ramps

$$a_0 = \frac{eE_0}{m_e \omega c}$$

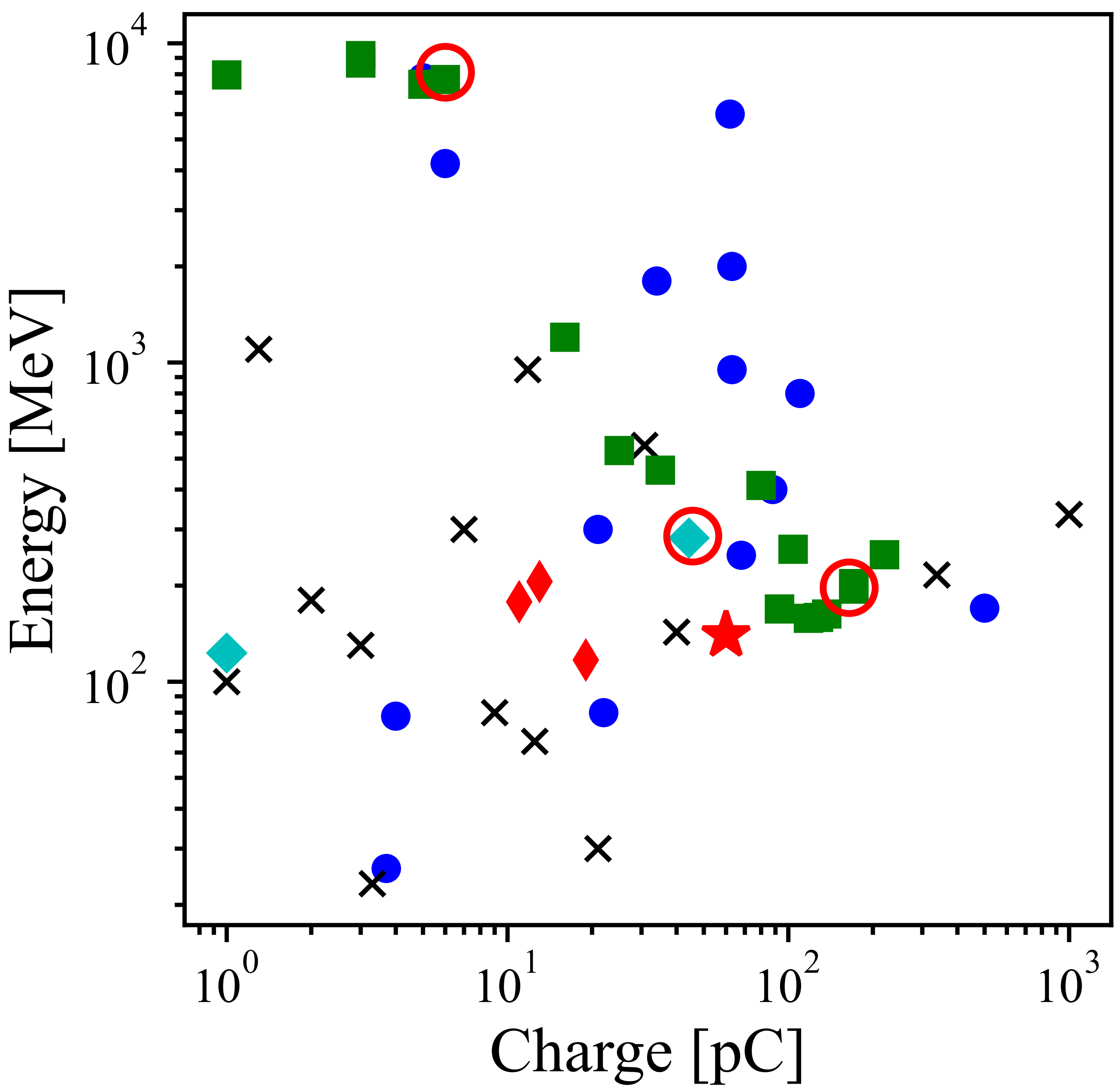


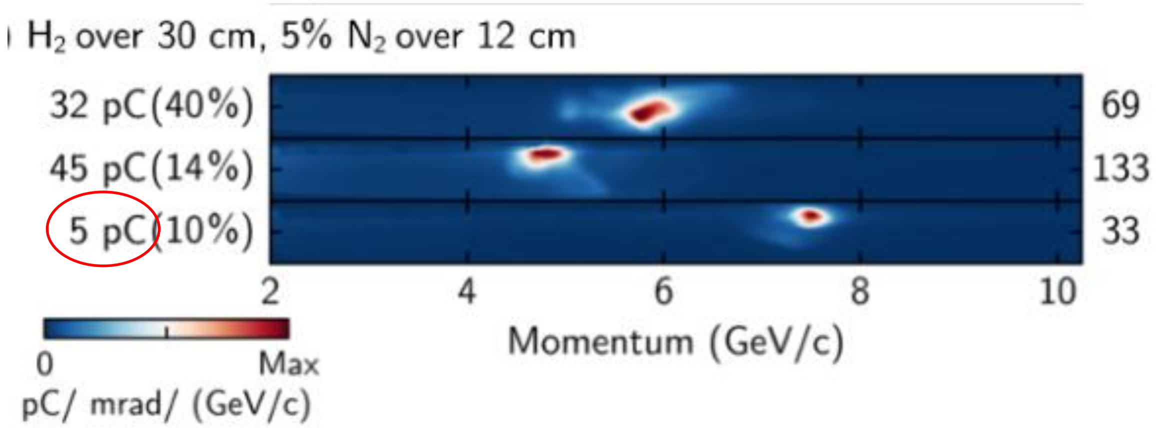




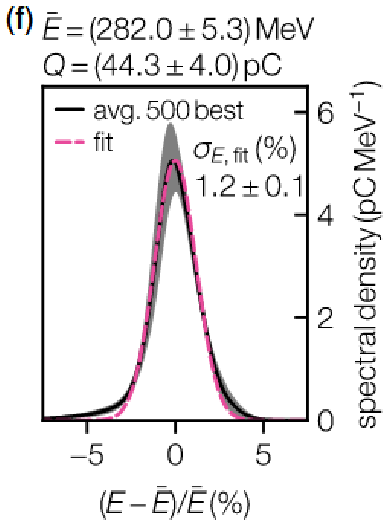
Examples Laser wakefield results

Biagioni Arxiv *2024*
arXiv:2412.16910

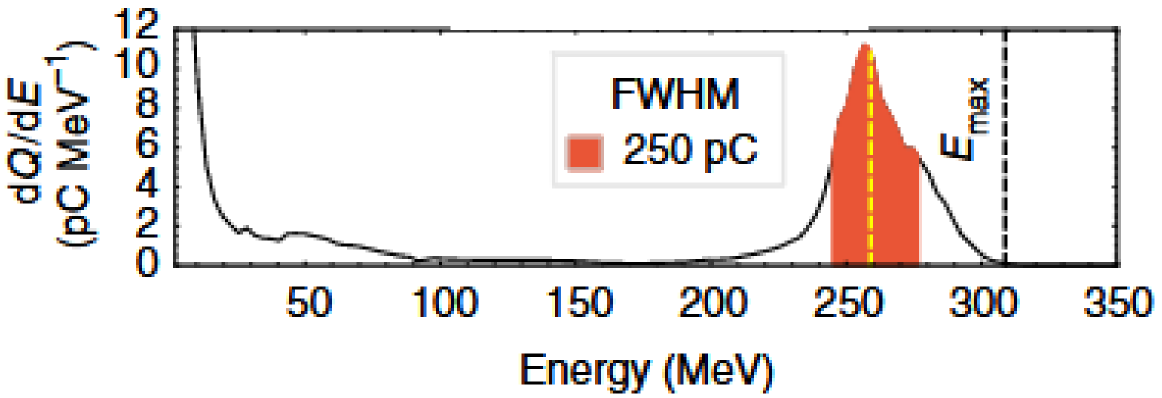




Picksley PRL 2024
Hofi Channel



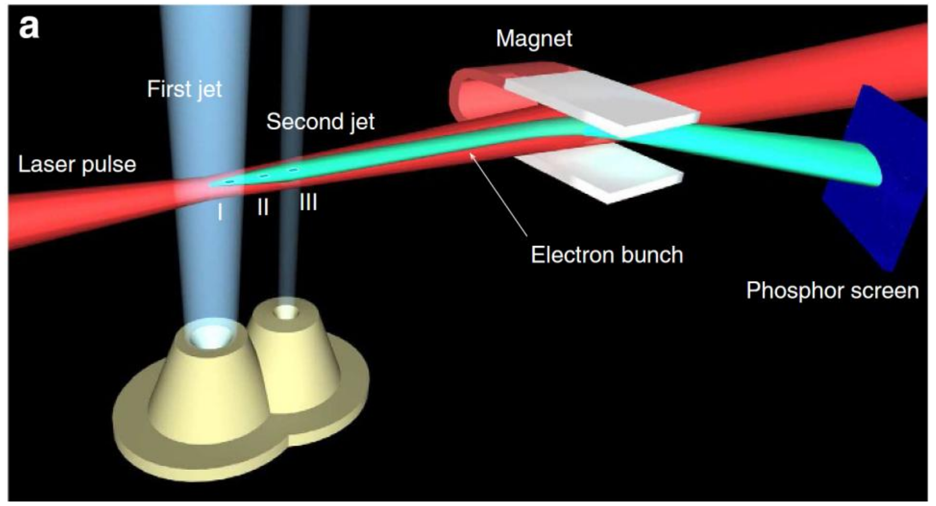
M Kirchen PRL 2021
Gas cell



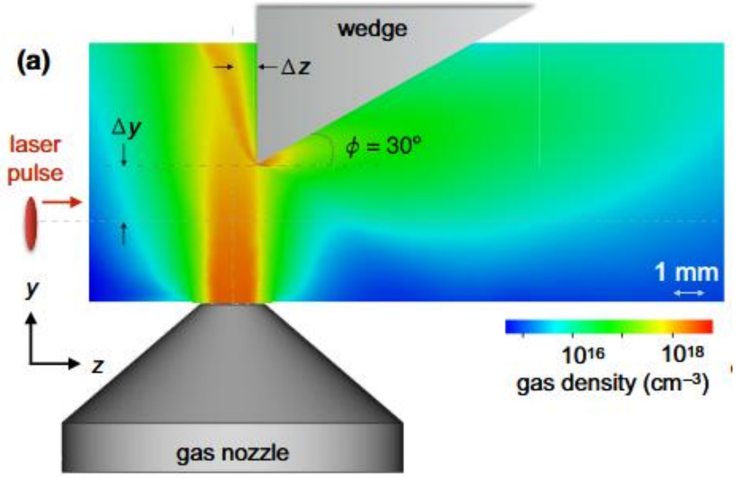
Couperus Nat Comm 2017
Gas jet

Plasma lenses are used to decrease divergence after acceleration

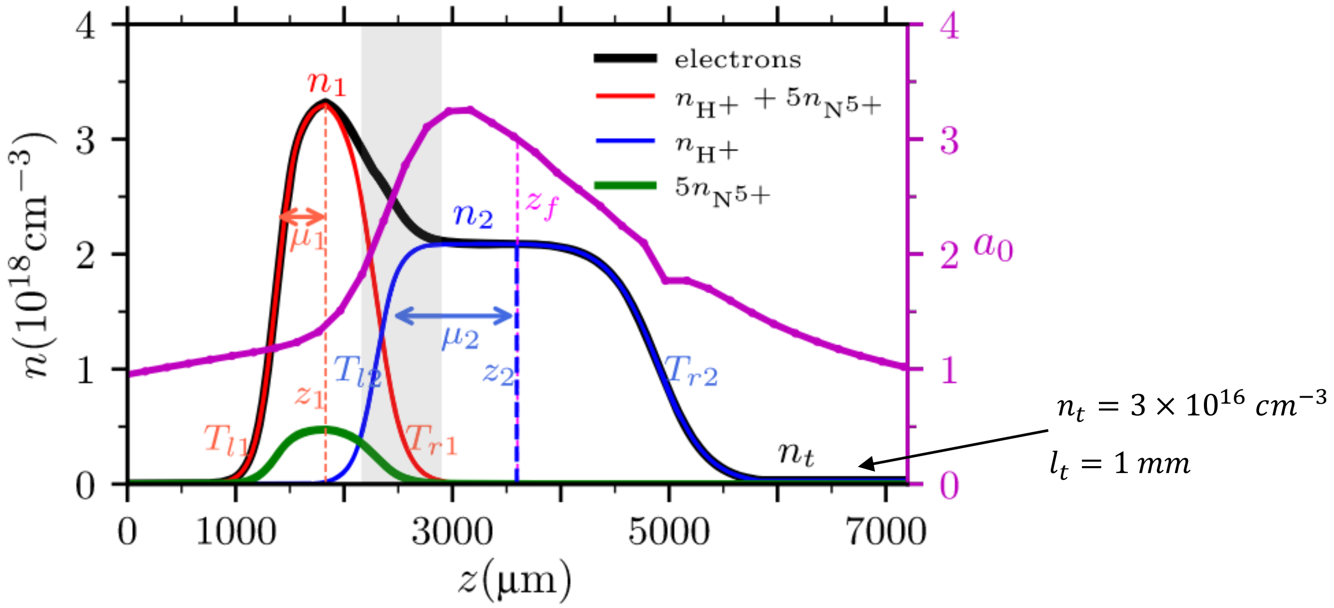
P. Chen, Part. Accel. 1987
Lehe PoP 2015



Thaury N. Com 2015

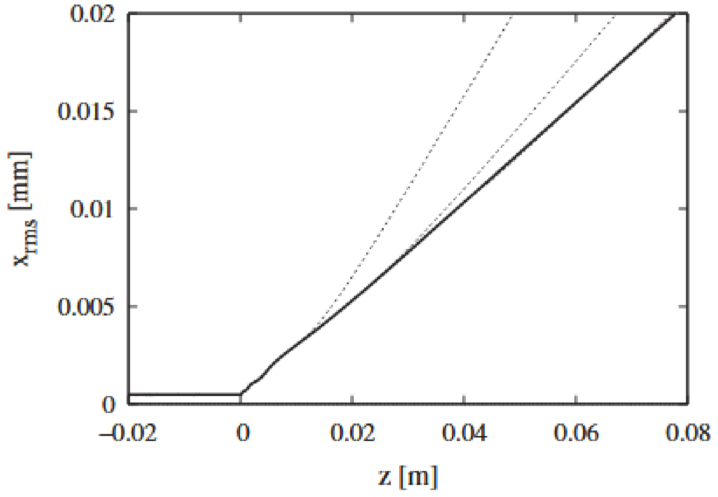


Chang PR Applied 2023

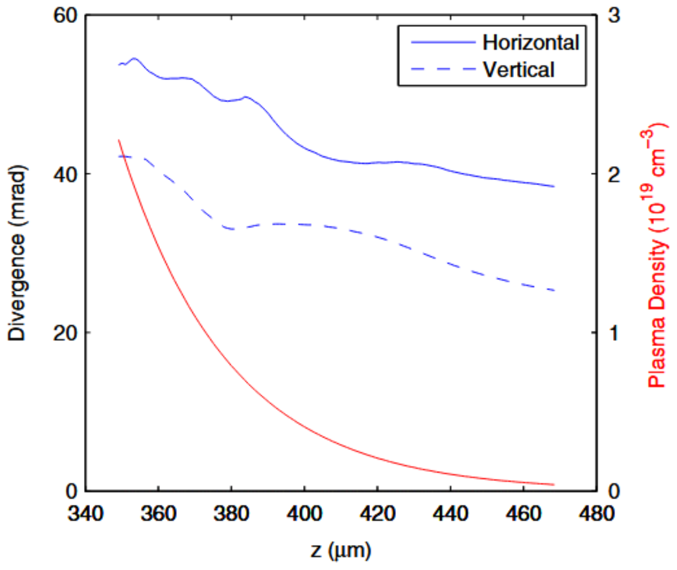


Marini PR AB 2024

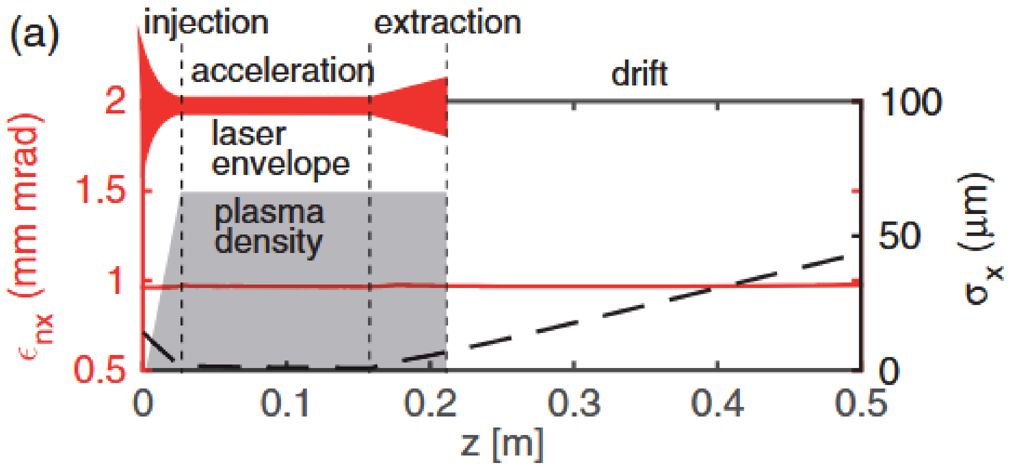
« Adiabatic Matching » i.e. Emittance preservation



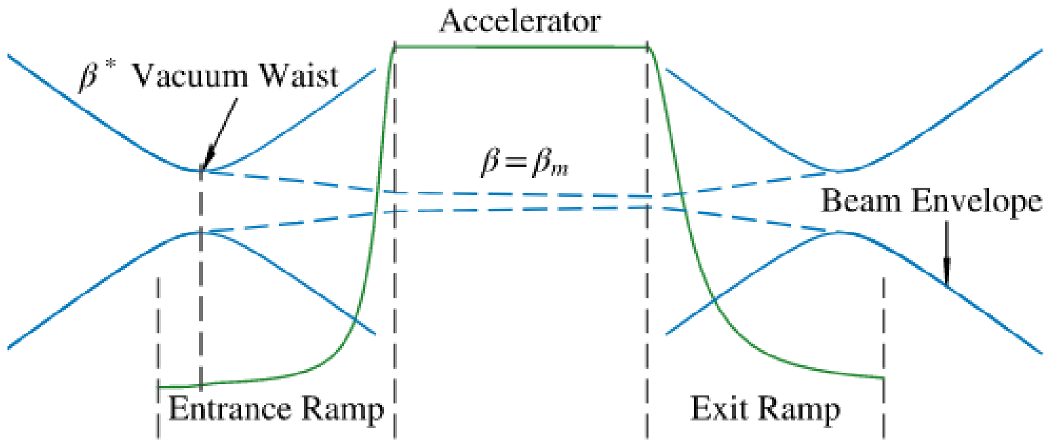
Floettmann PR AB 2014



Sears PR AB 2010

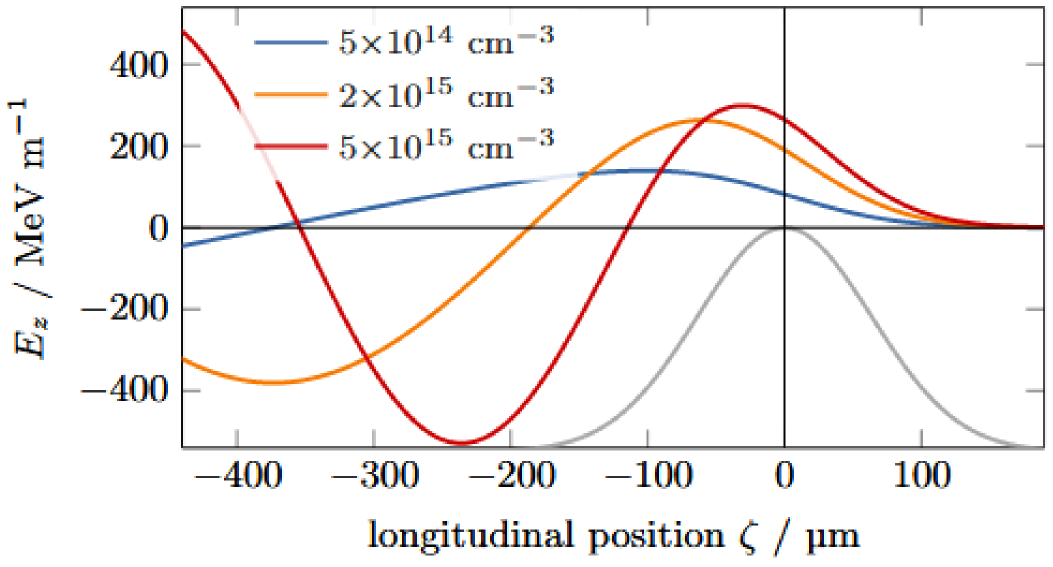


Dornmair 2015

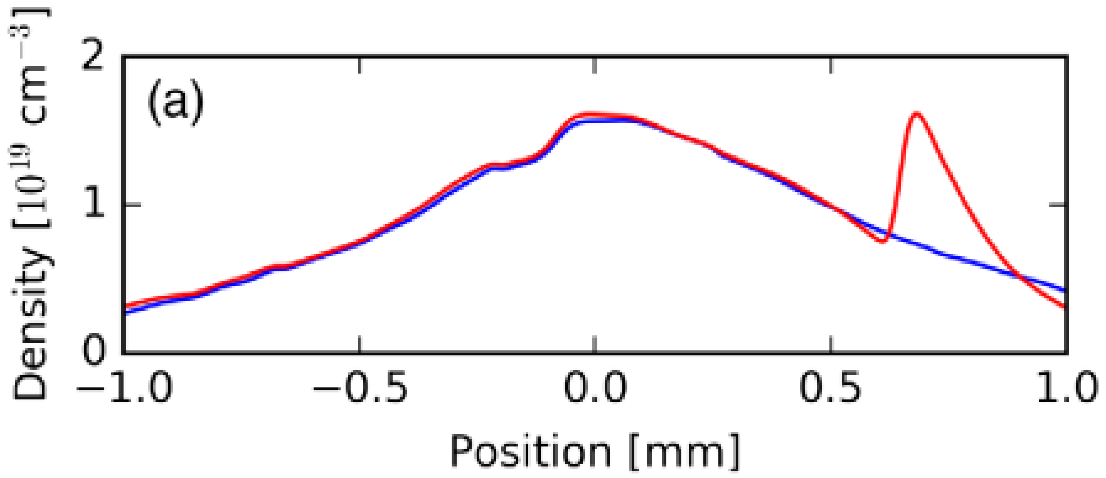


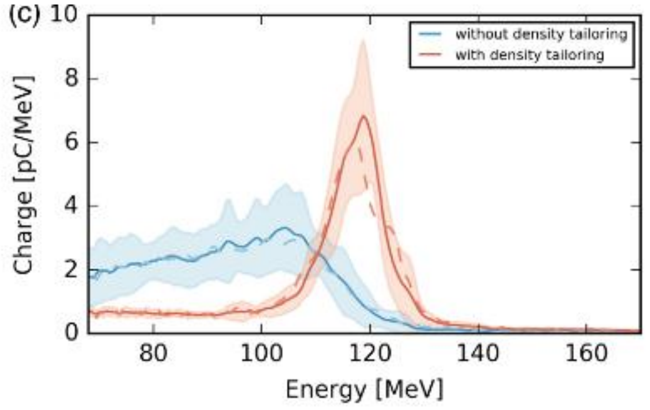
Ariniello PR AB 2019

Plasma Dechirper is used to decrease energy spread

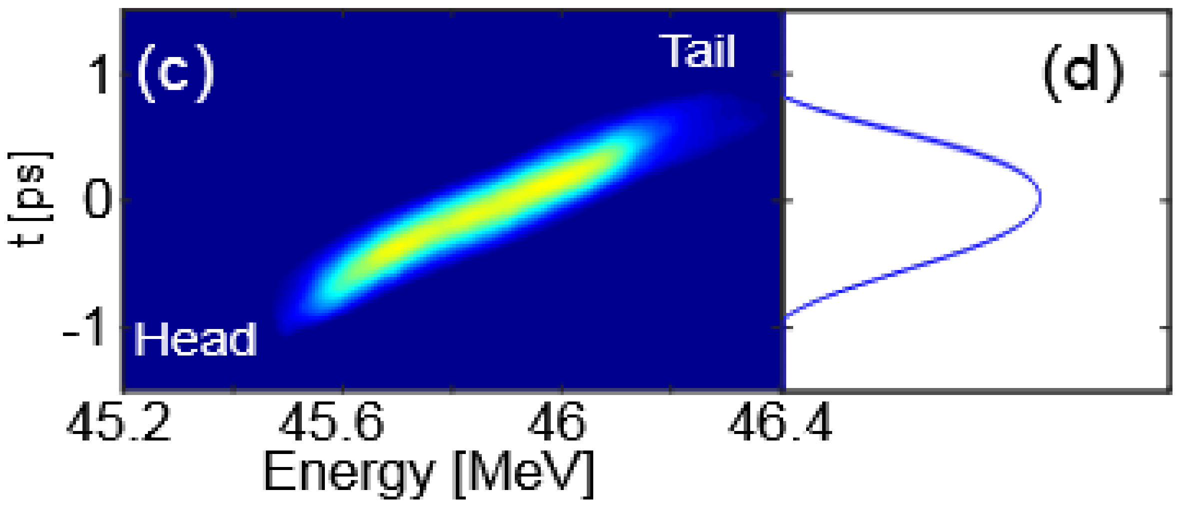


D'Arcy PRL 2019

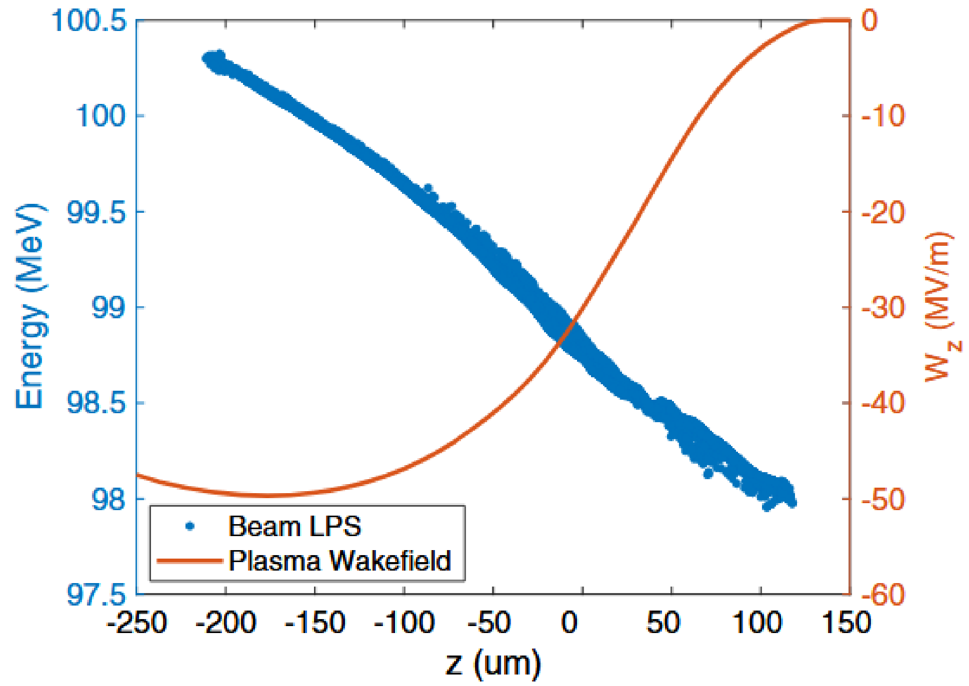




Döpp PRL 2019



Wu PRL 2019



Shpakov PRL 2019

Experimental setup and laser parameters

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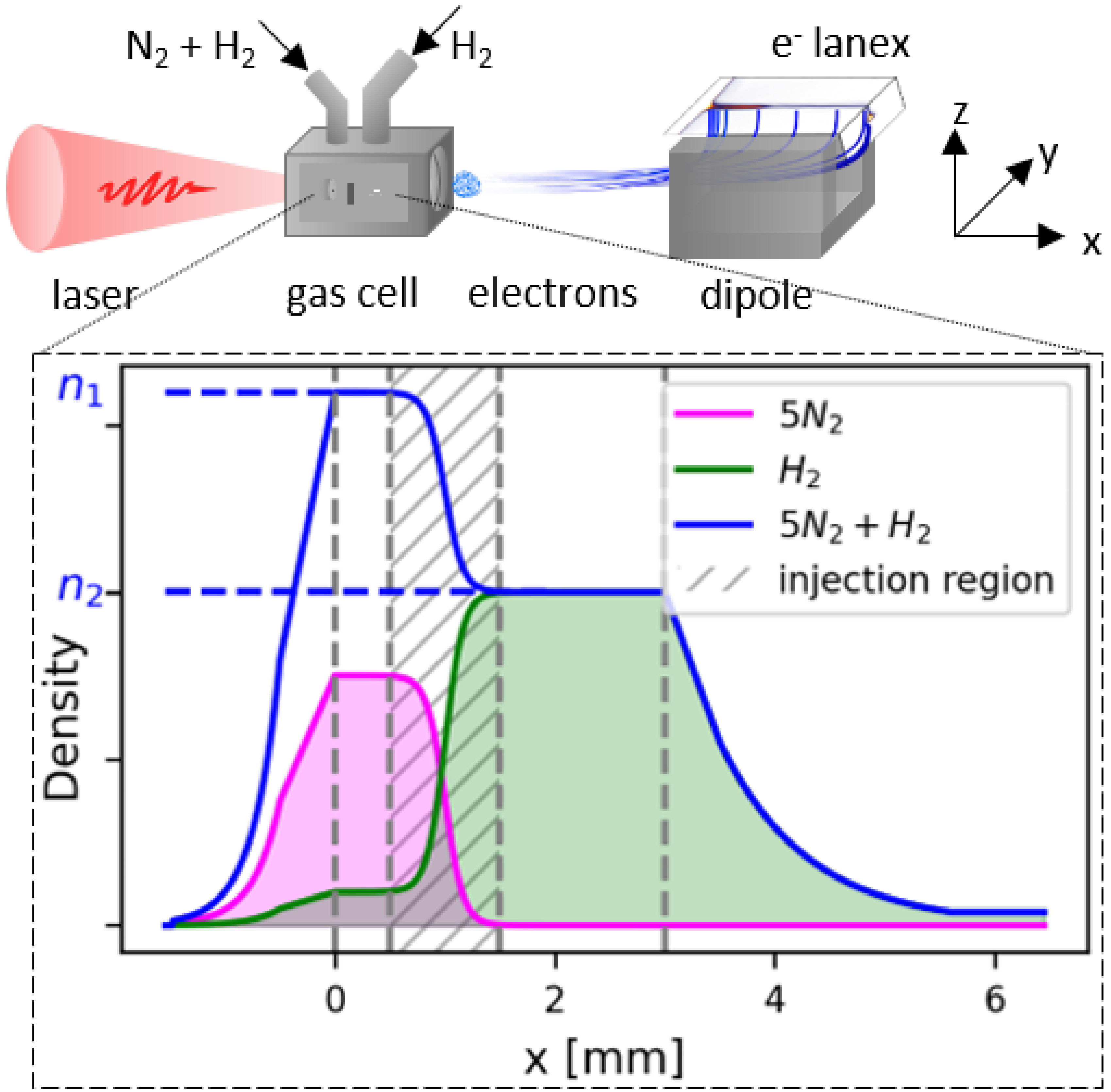
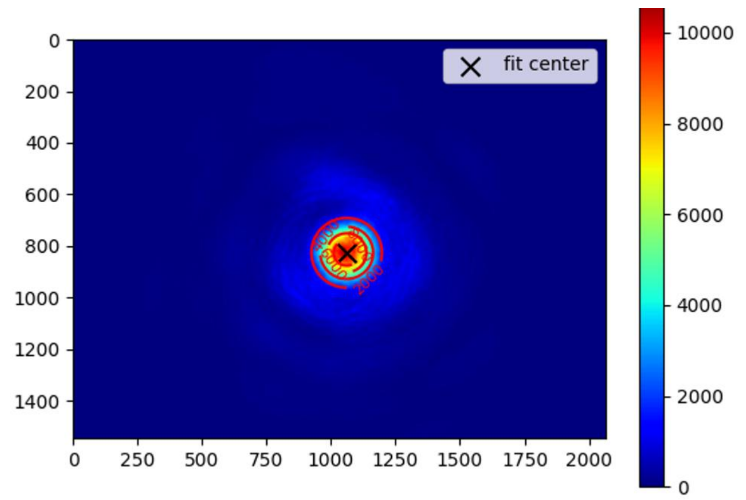
DRACO Laser
- $\lambda_0 = 0.8\ \mu m$
- 2.5 J
- 24 µm FWHM spot size
- 30 fs FWHM duration

- Modelled as a Flattened Gaussian beam
  - N=8,
  - $w_0 = 14\ \mu m$

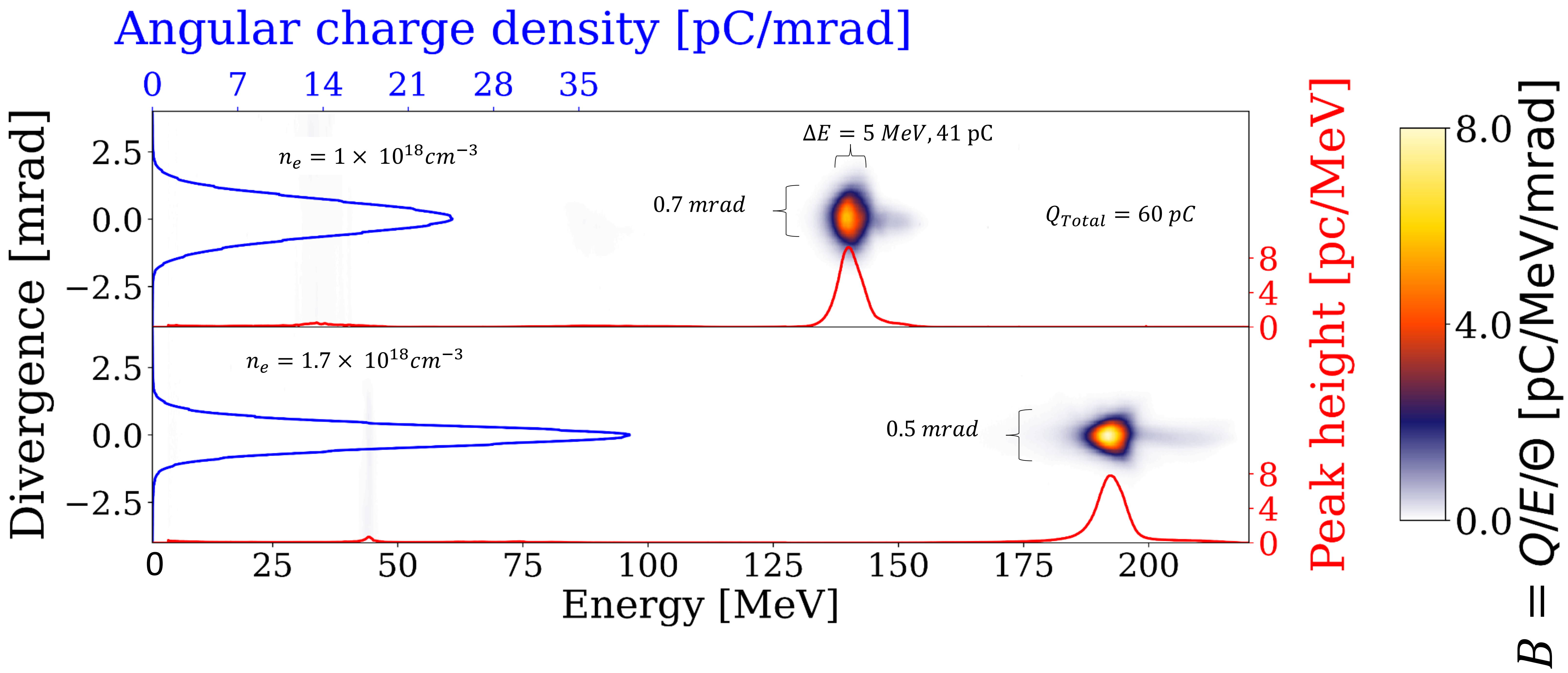




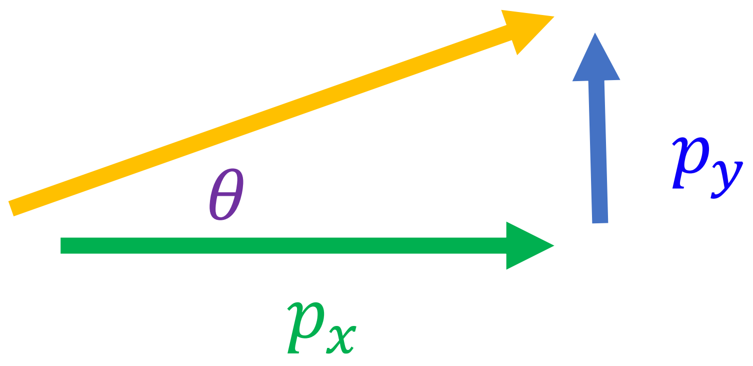
- Injection on the Nitrogen downramp
- Acceleration in the Hydrogen Plasma in second compartment.
- No intermediate focusing equipment between source and Lanex.

Pollock PRL 2011
Drobniak RSI 2025

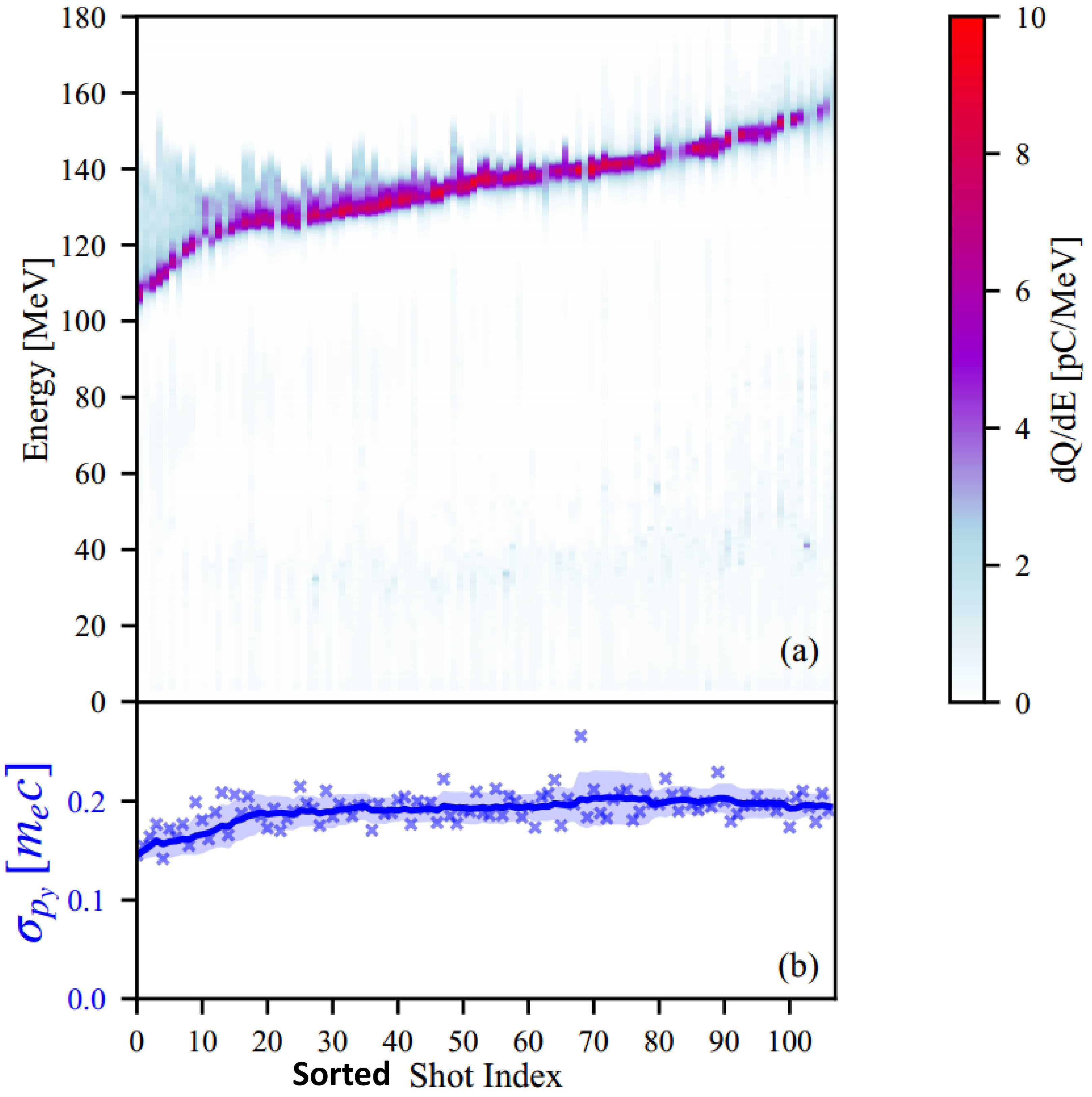
High spectral brightness beams observed at different plasma densities



Spectra of 107 shots plotted with increasing peak energy values for $n_e = 10^{18}\ cm^{-3}$



$$\sigma_{p_y} \approx (\theta_y)_{rms}\,\bar{\gamma}$$
$$\approx 0.2\ m_e c$$



All spectra obtained for the same input parameters

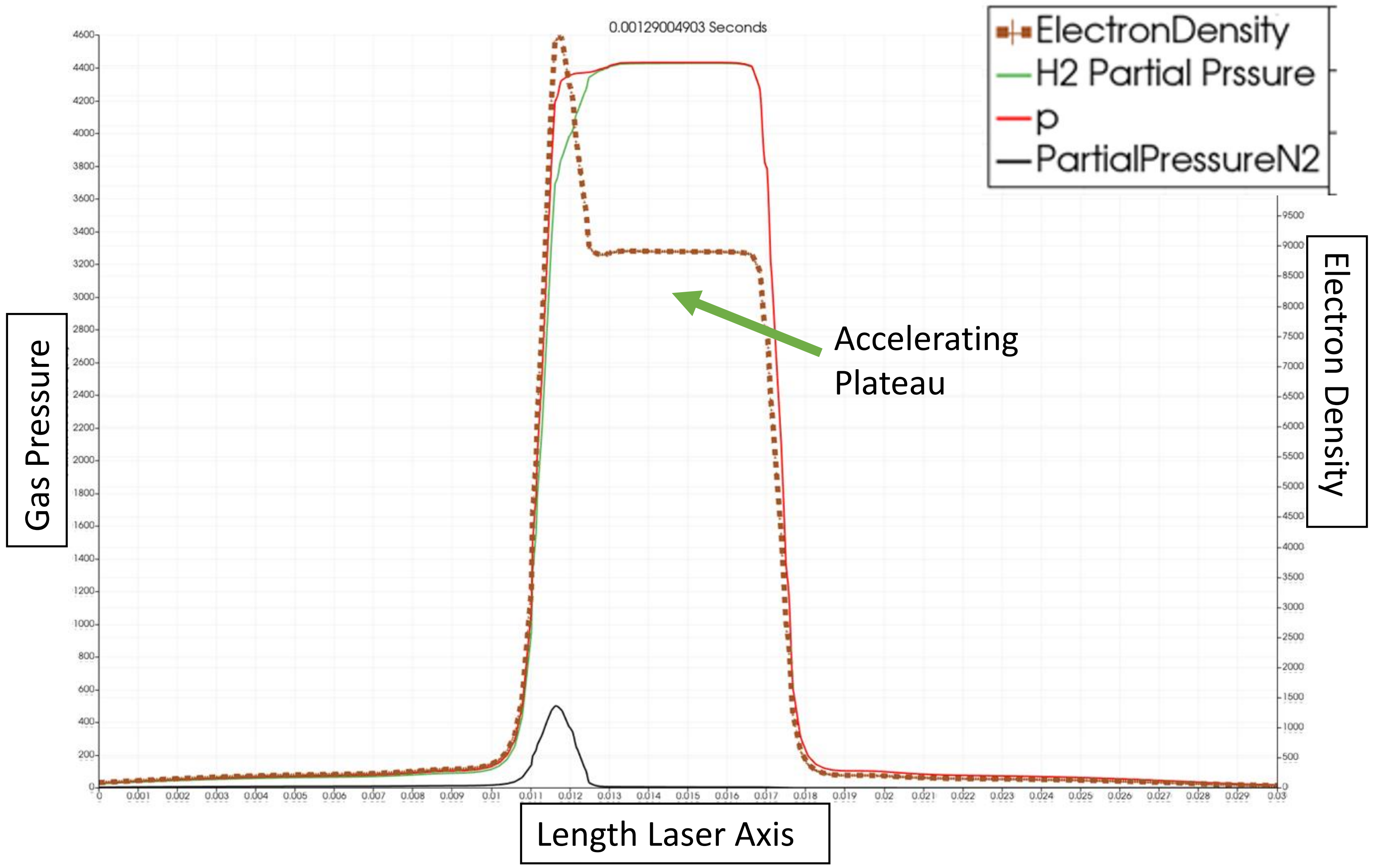
Laser focus and down-ramp location fluctuations lead to injected charge variations

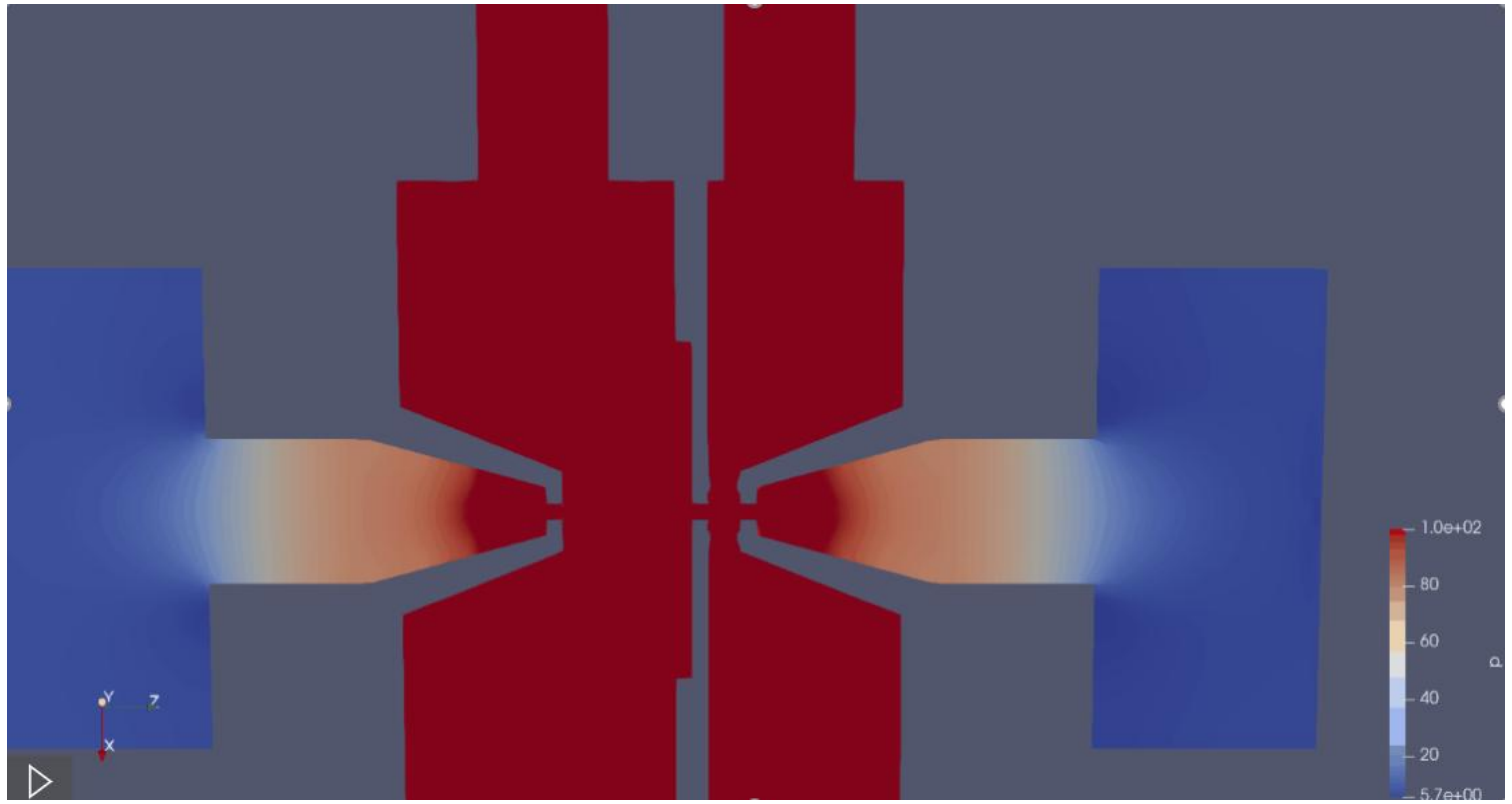
$$Q_{max} = 100\ pC, \bar{E} = 100\ MeV$$
$$Q_{min} = 50\ pC\ , \bar{E} = 160\ MeV$$

See Poster

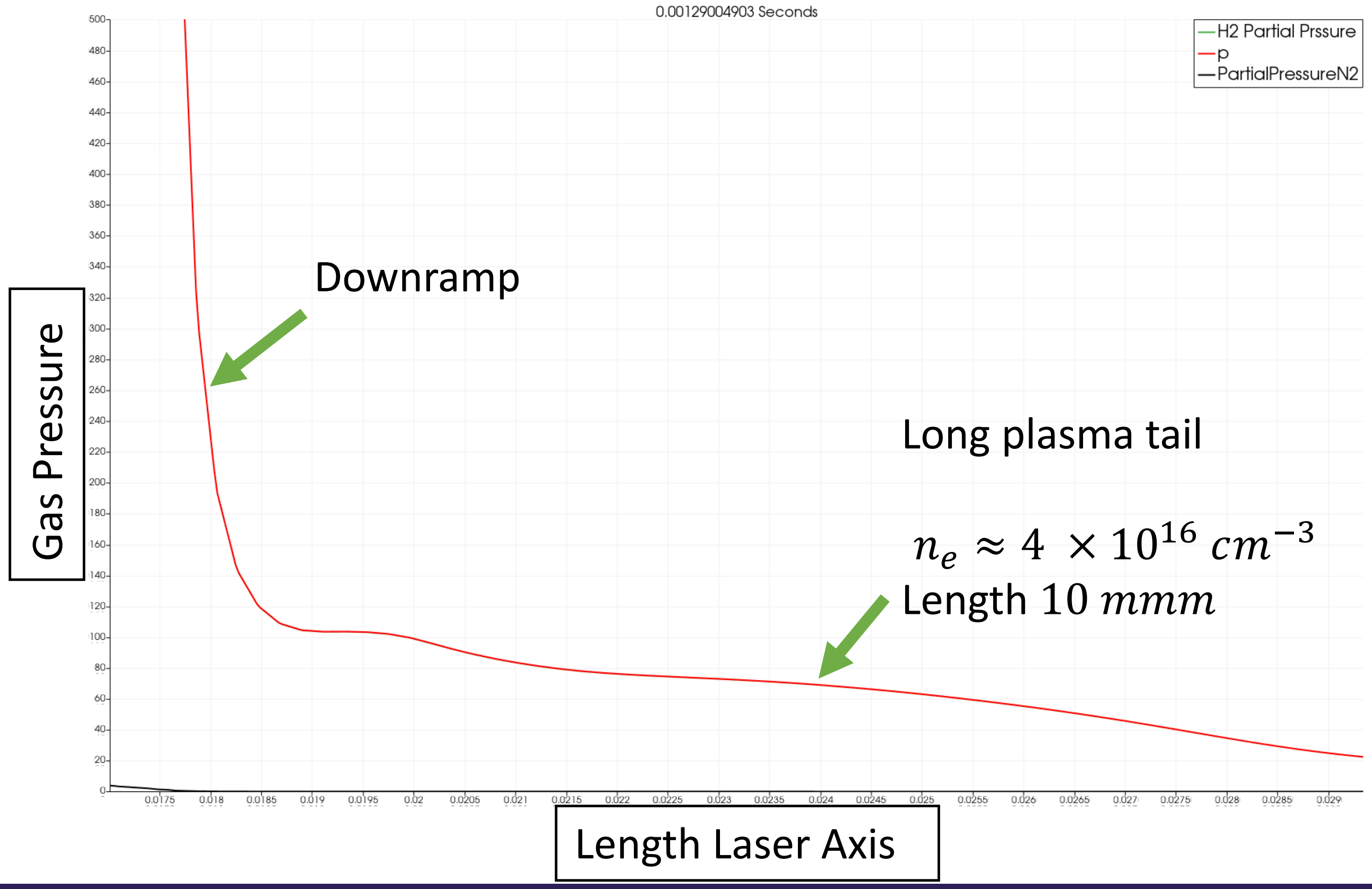
CFD : Creating a downramp and long plasma tail

Overall Density Profile



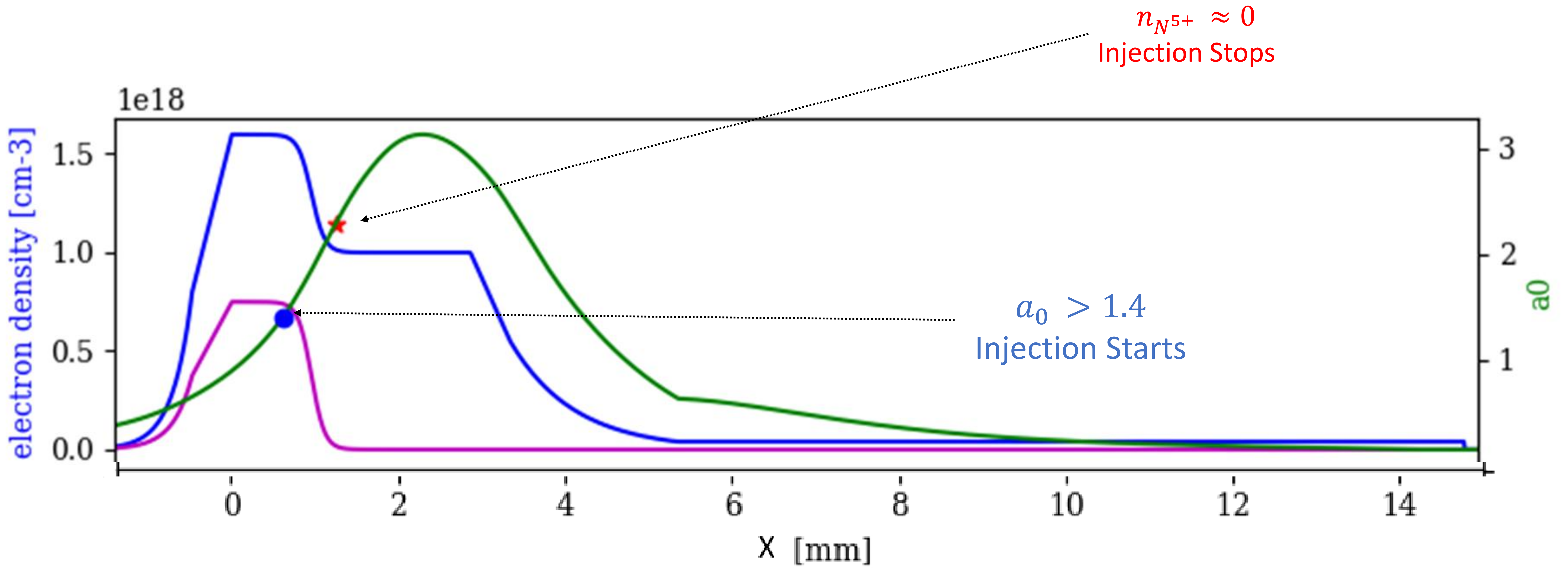


Detail of Outlet Density Profile

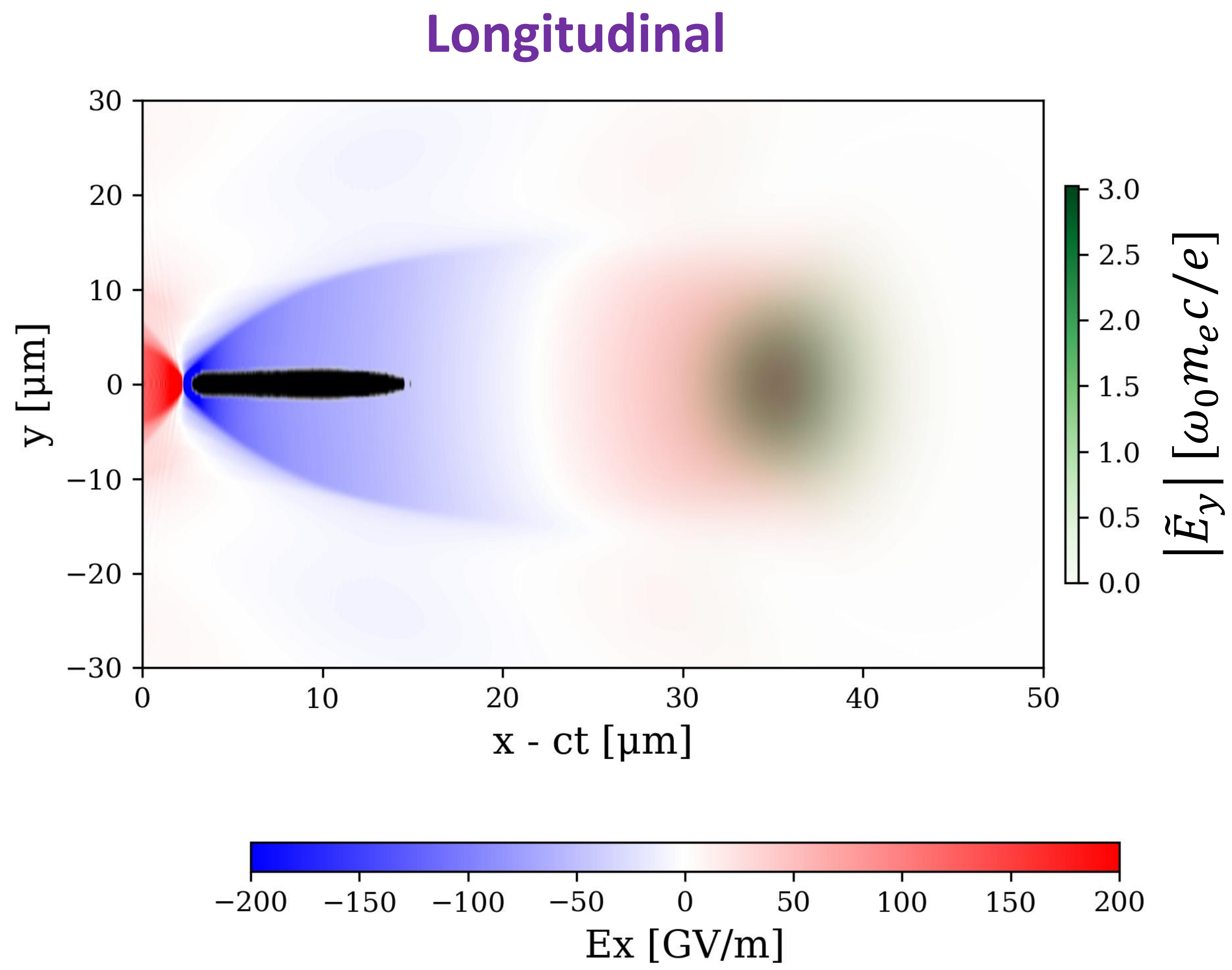


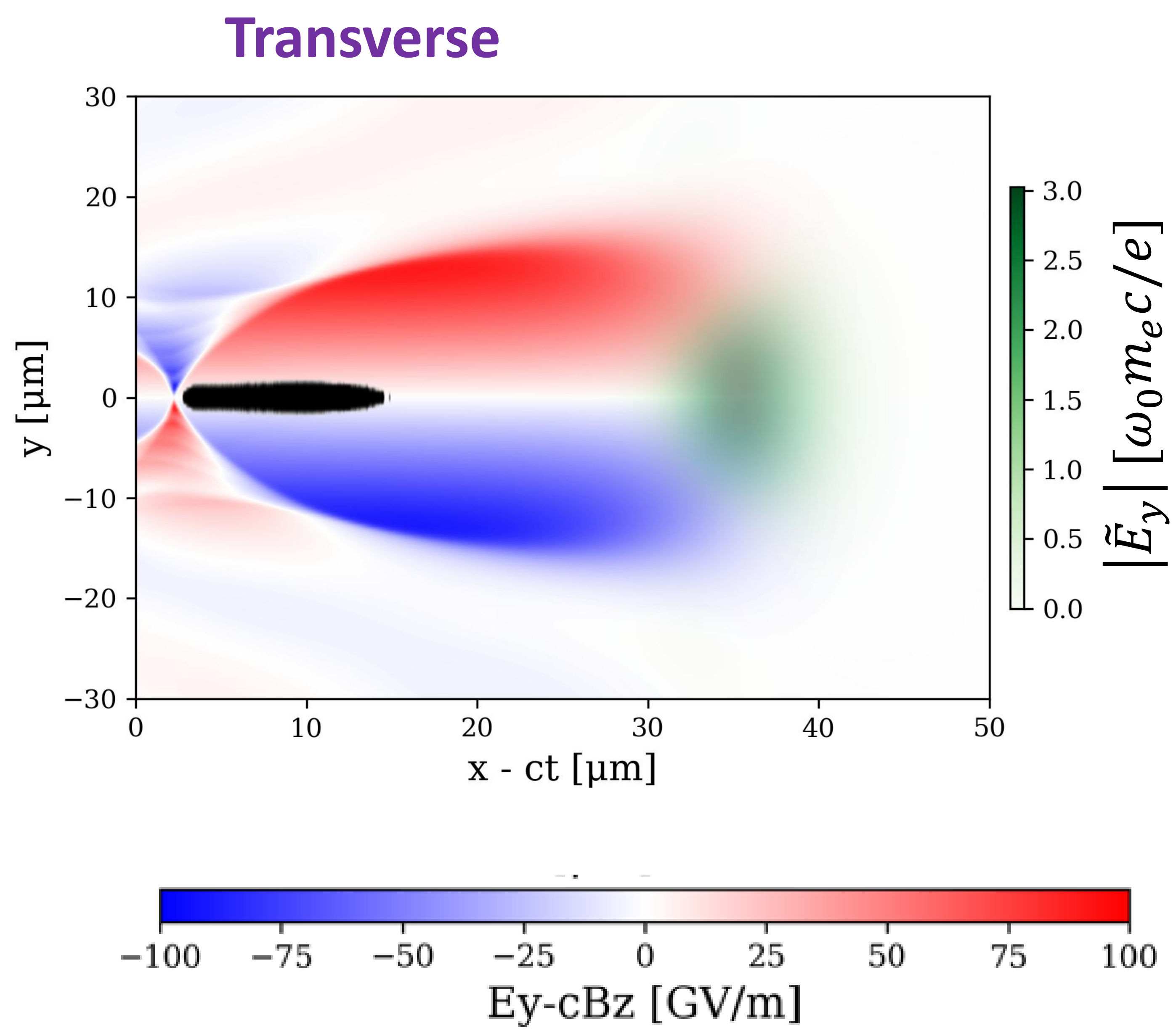
OPENFOAM density profile to SMILEI (PIC code)

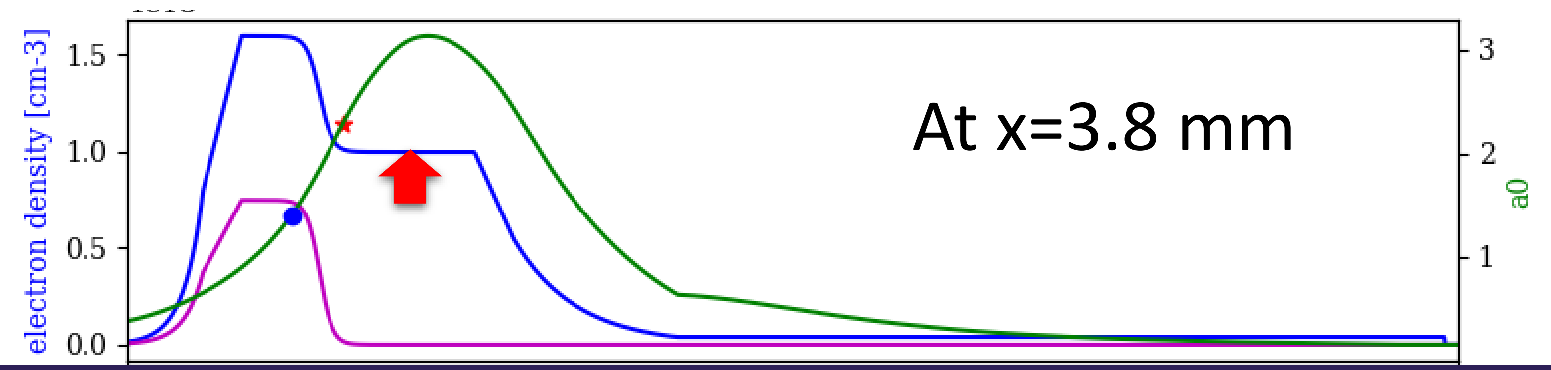
Electron trapping is controlled by laser focusing in the nitrogen density downramp



The electron beam is accelerated with a chirp



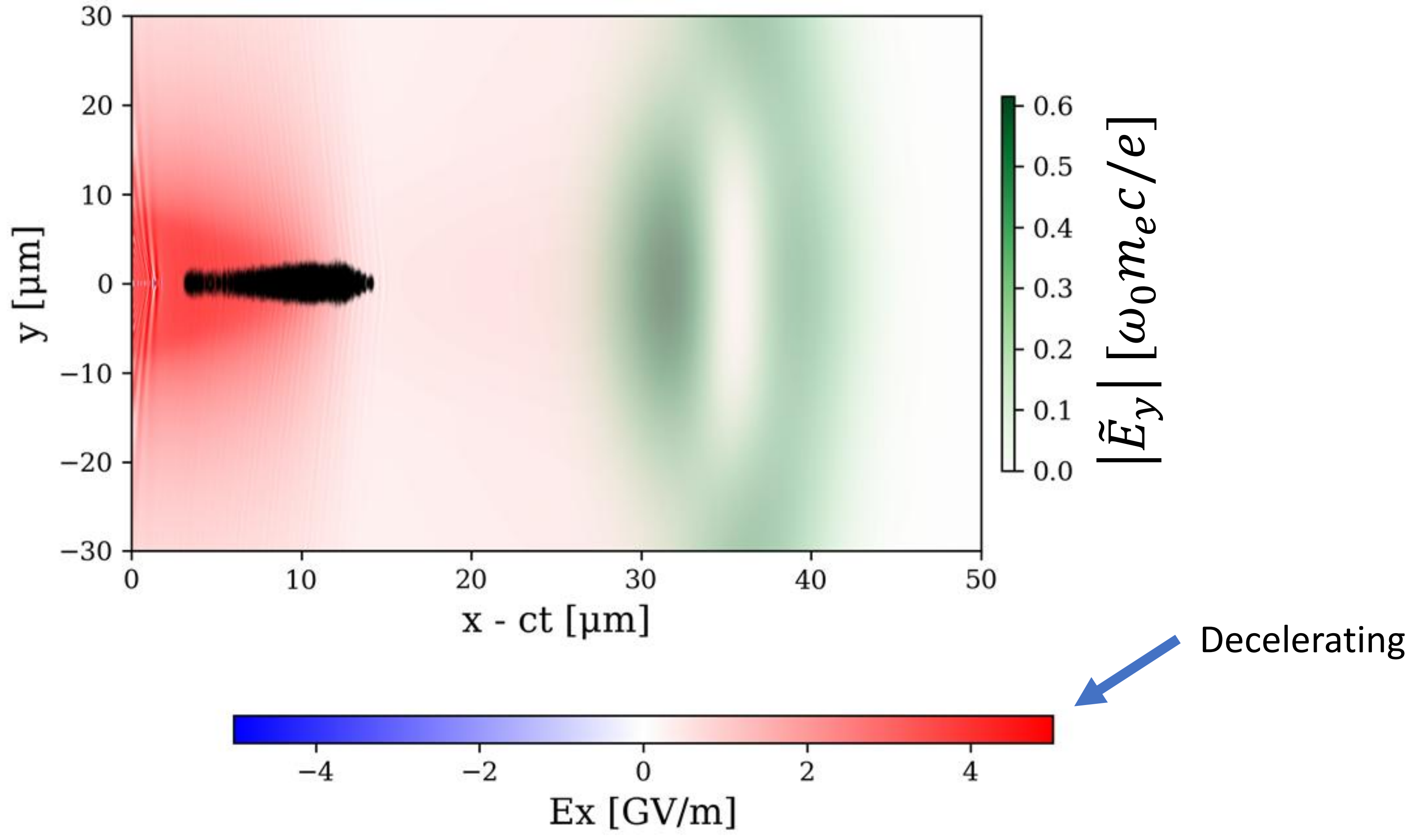




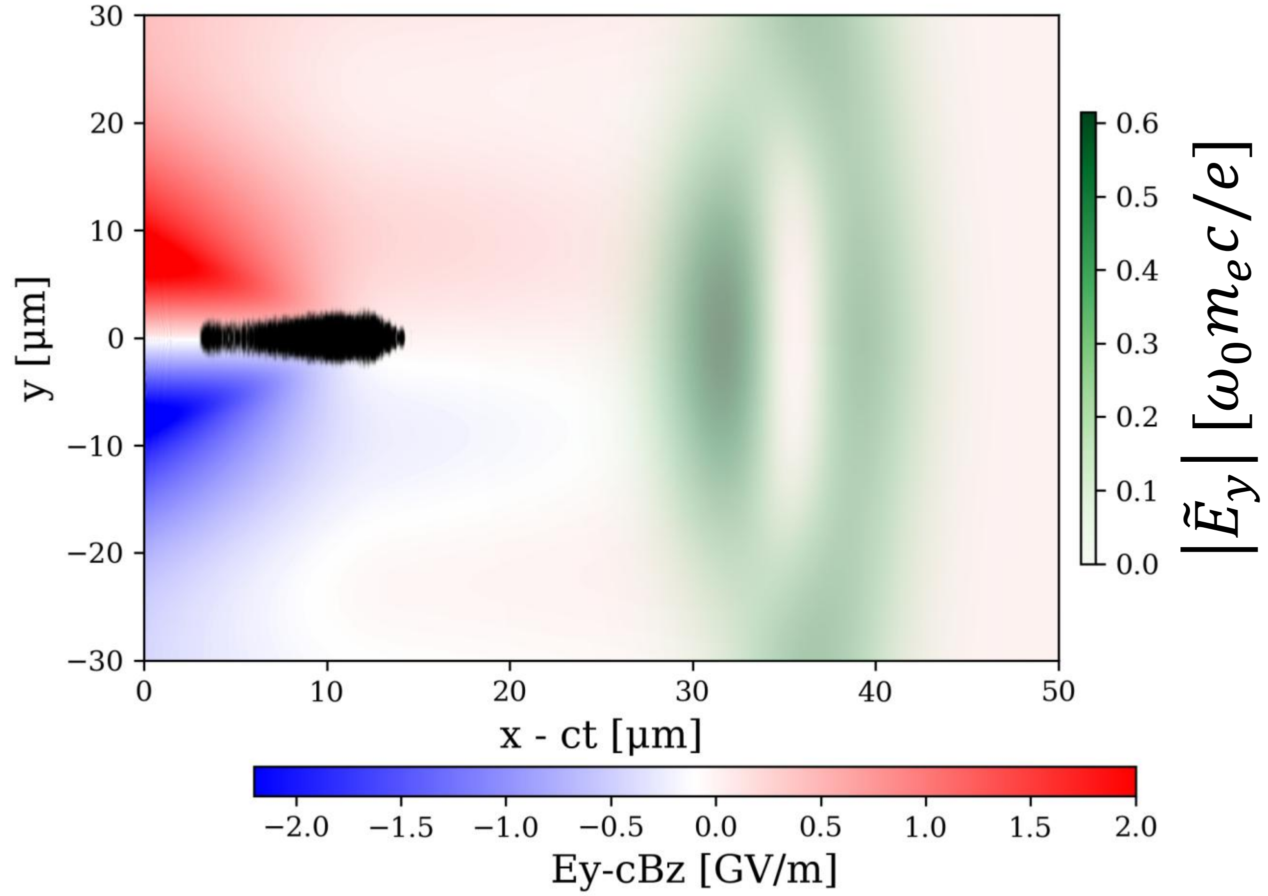
- Longitudinal forces impose a space-energy chirp
- Transverse forces generate betatron oscillations

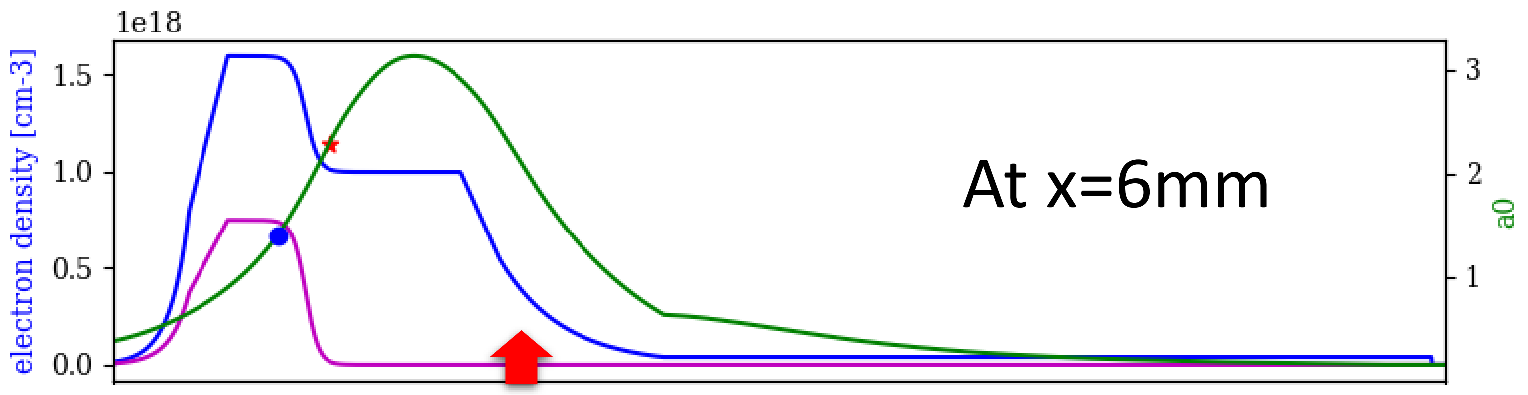
Transition from laser to beam driven wakefield occurs in the downramp

Longitudinal



Transverse



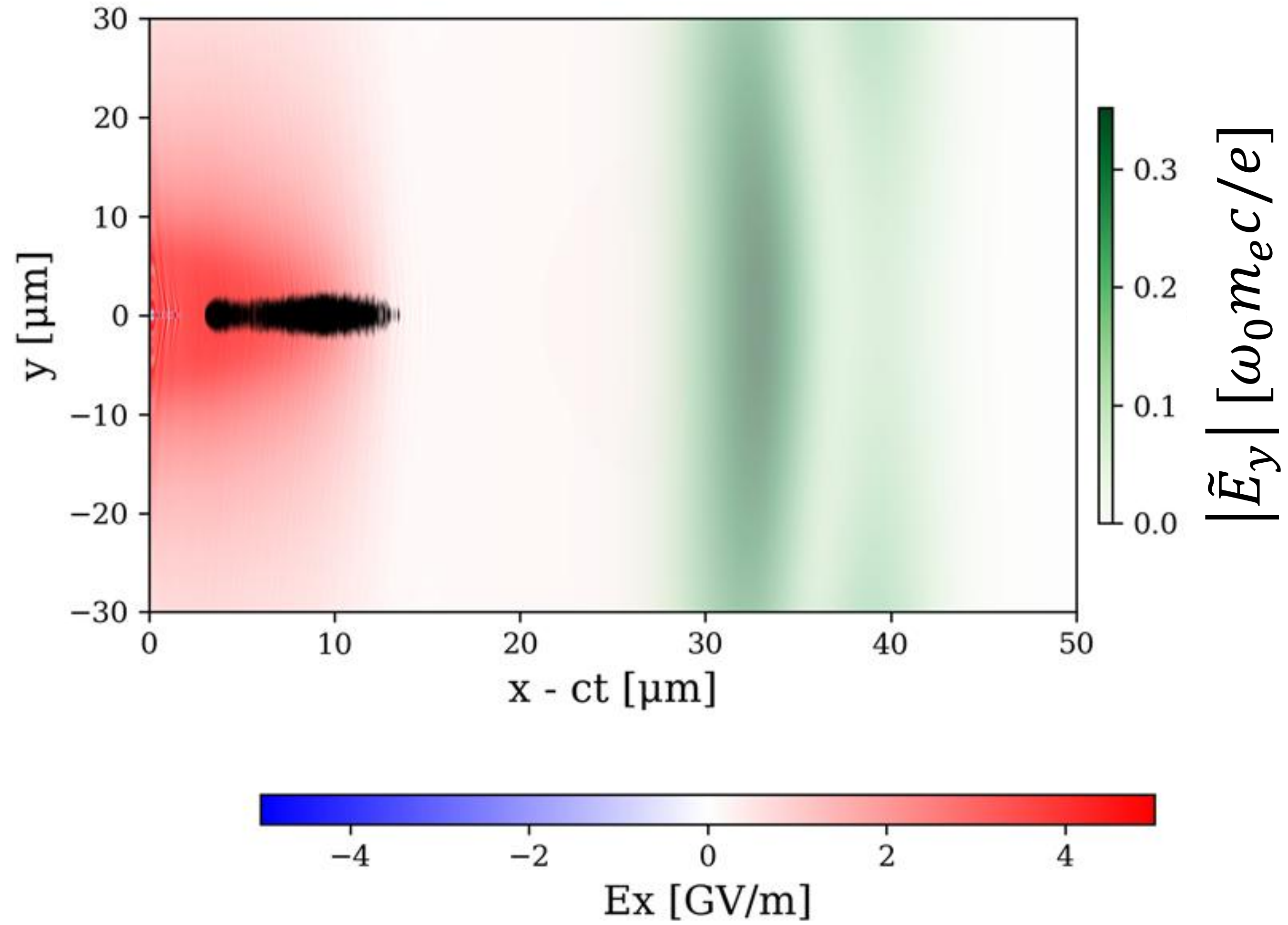


- Laser intensity and Plasma decrease simultaneously
- Transition for laser to beam excitation of wakefield
- Longitudinal field has become decelerating

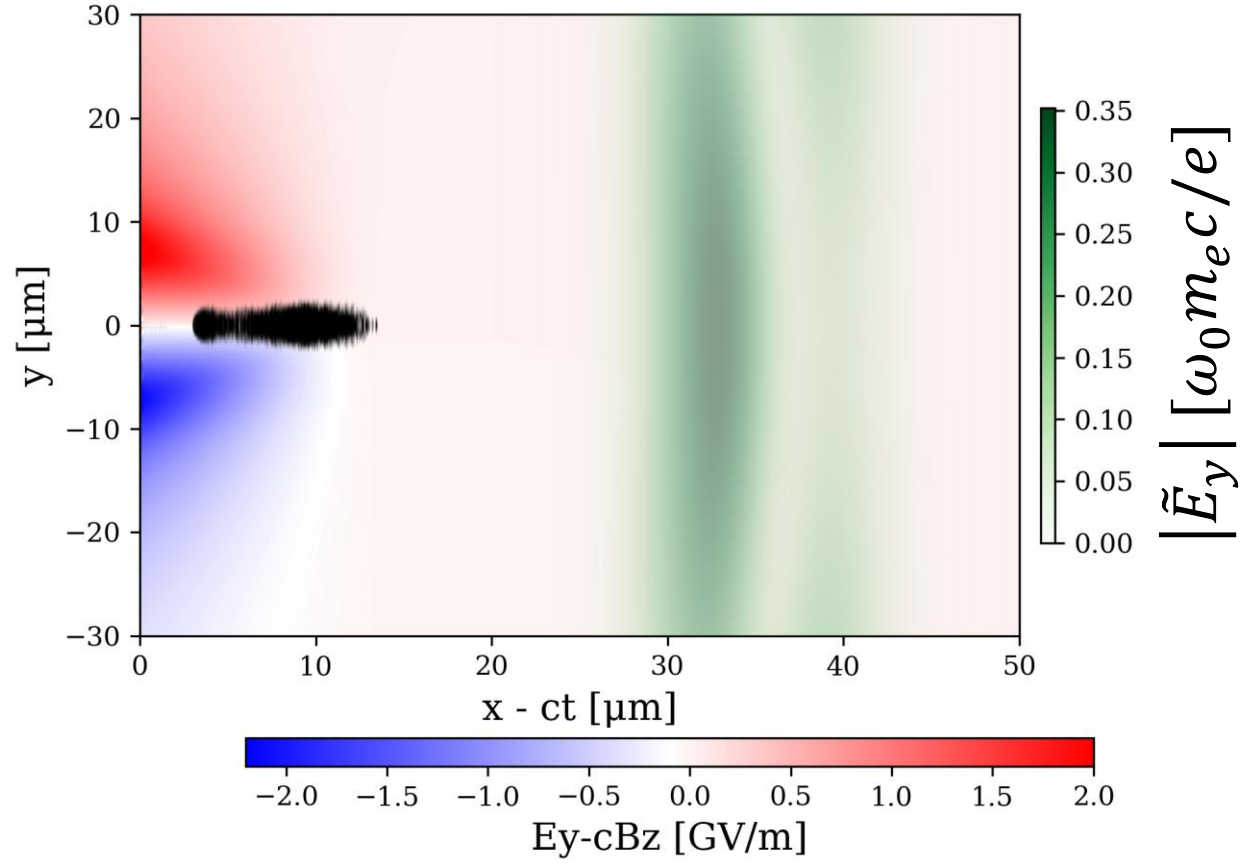
Dechirper and plasma lens occur in the long plasma tail

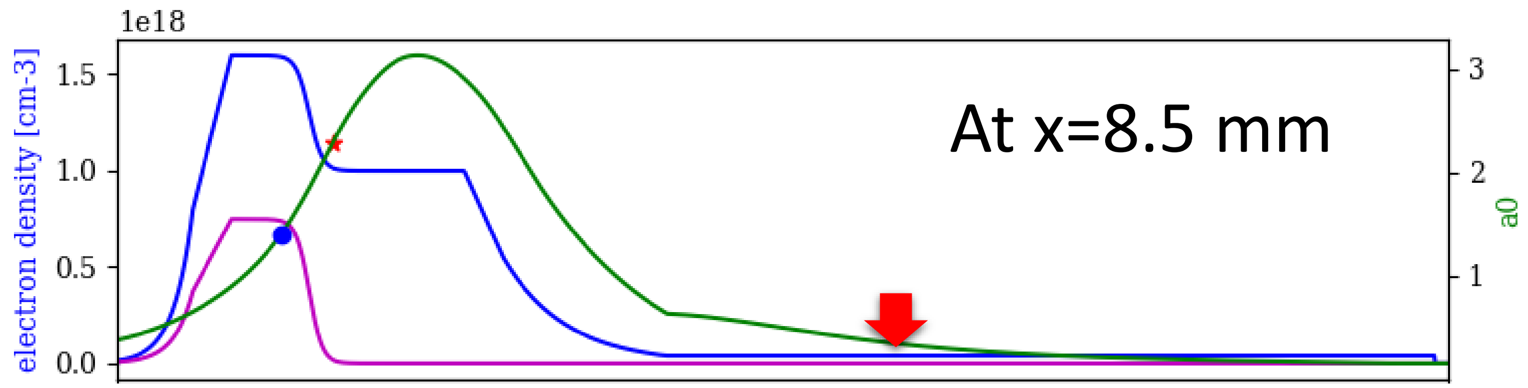
Smilei)

Longitudinal



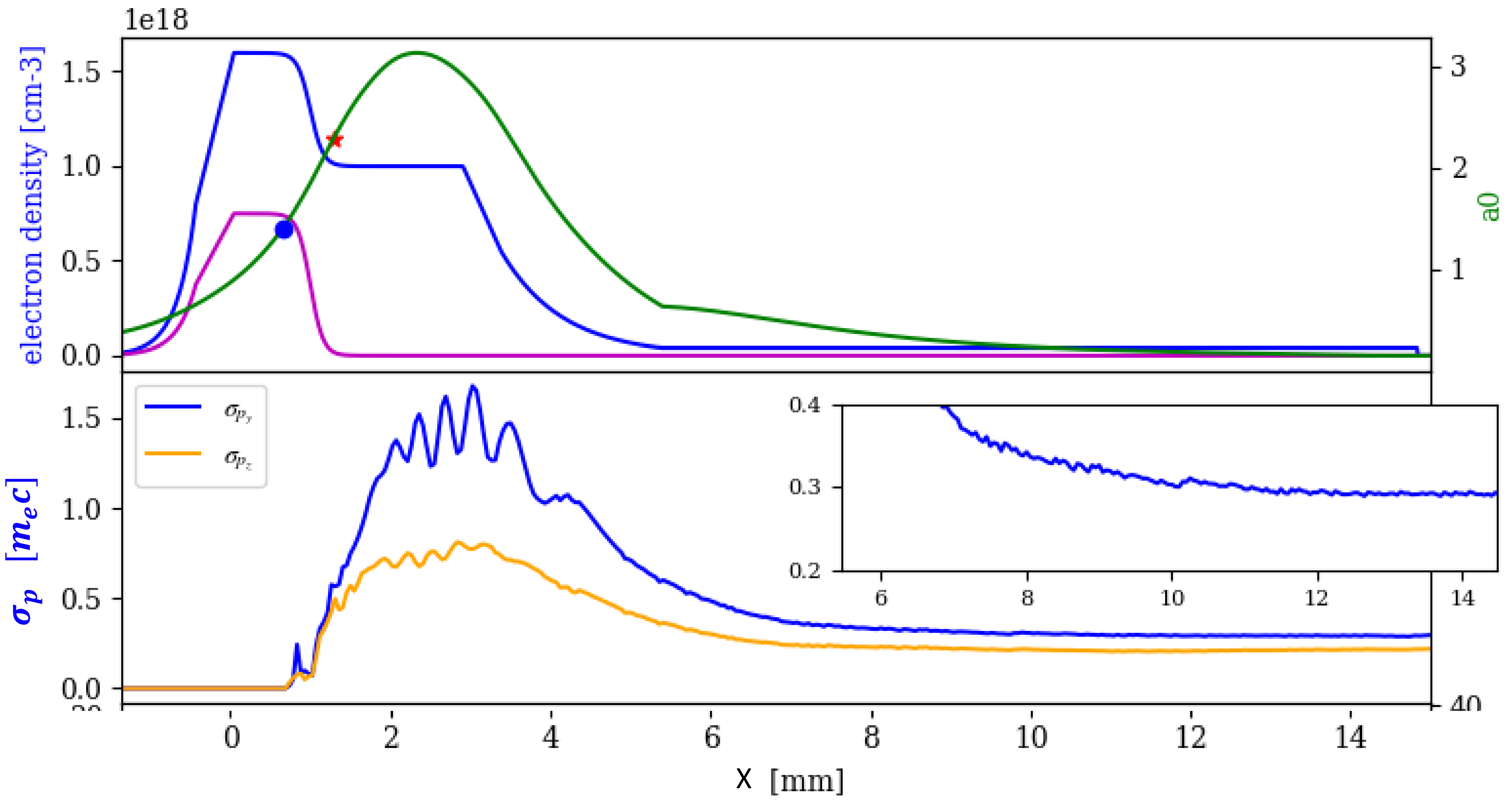
Transverse

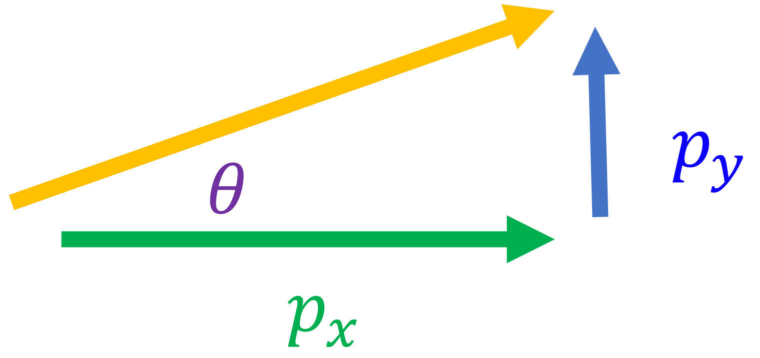




- Wakefield is dominated by beam driven effects
- The longitudinal field is dechirping due to wakefield from the front of the beam
- Rear of the beam experiences higher transverse forces

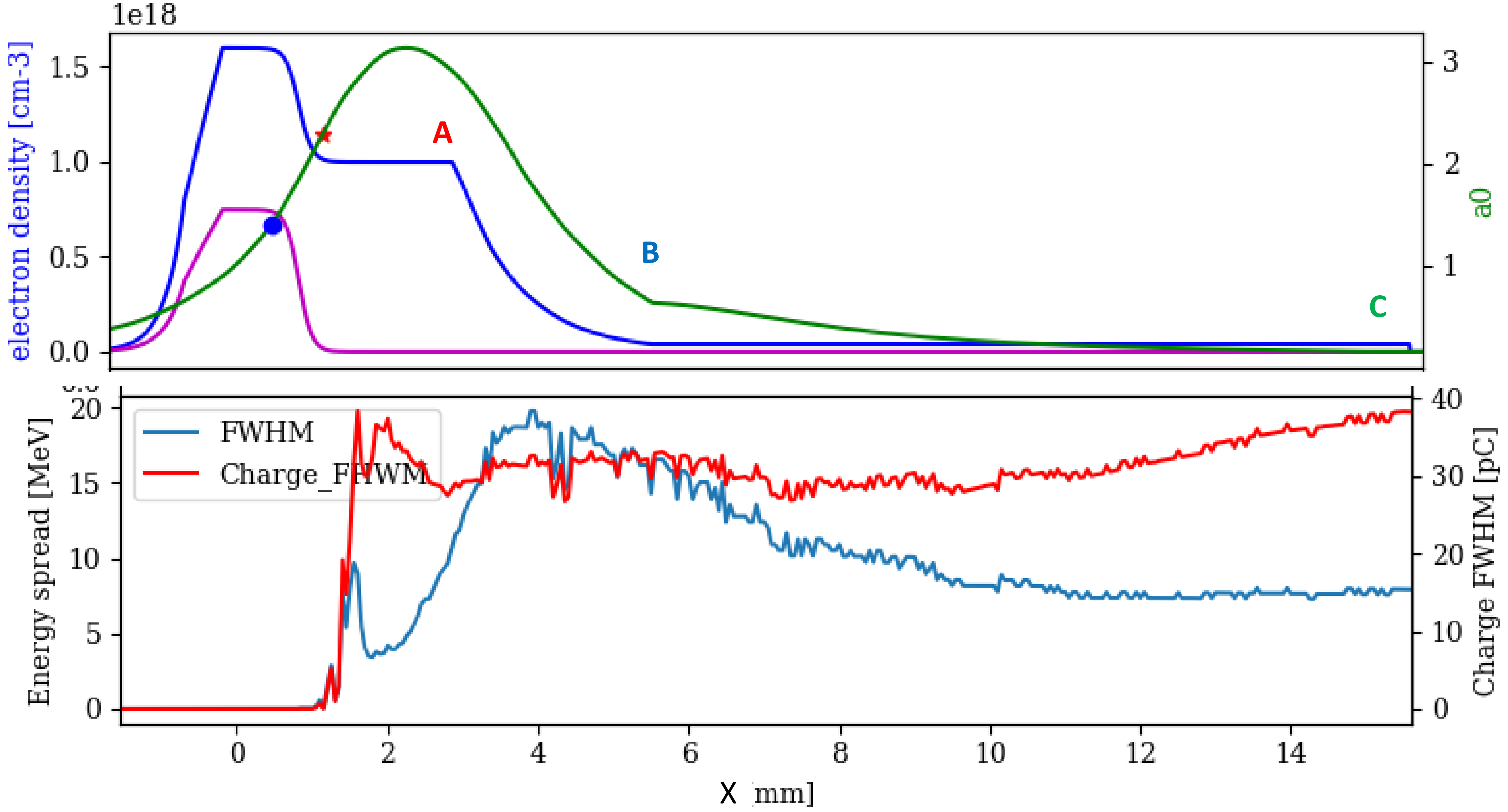
Transverse momentum spread is reduced in down ramp and long plasma tail





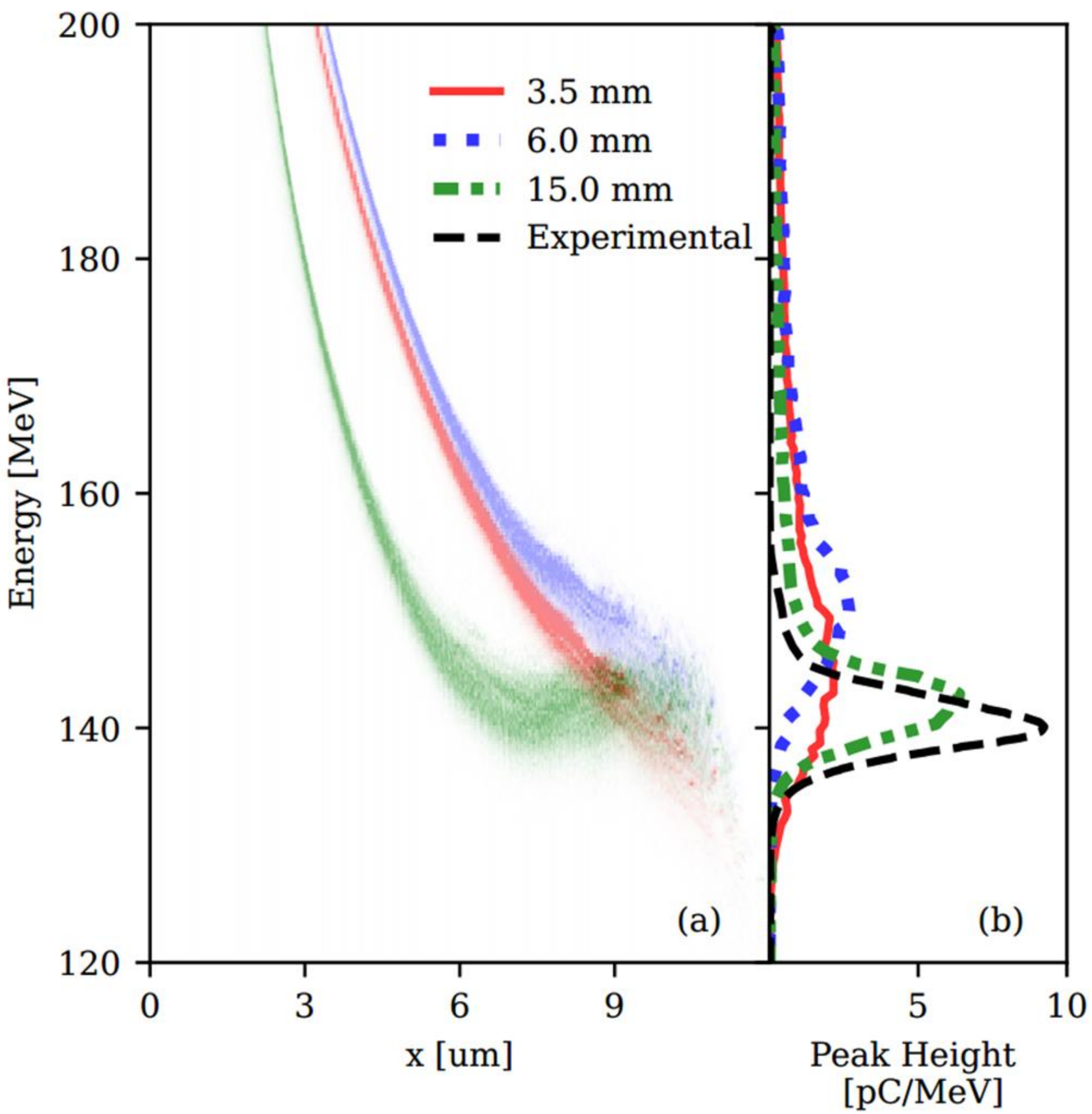
- x : 1.5 → 2 mm Growth of σ_{p_y}
- x: 2 → 4 mm Betatron oscillations
- x > 4 mm Decay lens effect

Dechirping results in higher spectral intensity : Q_{FWHM} ↑ , ΔE_{FWHM} ↓



- The FWHM represents the front of the beam
- x = 1.5 – 4mm Acceleration (up to 180 MeV)
  - Full Width Half Maximum ΔE grows in this zone
- x>4 mm ΔE decreases
- x>10 mm Q inside ΔE increases

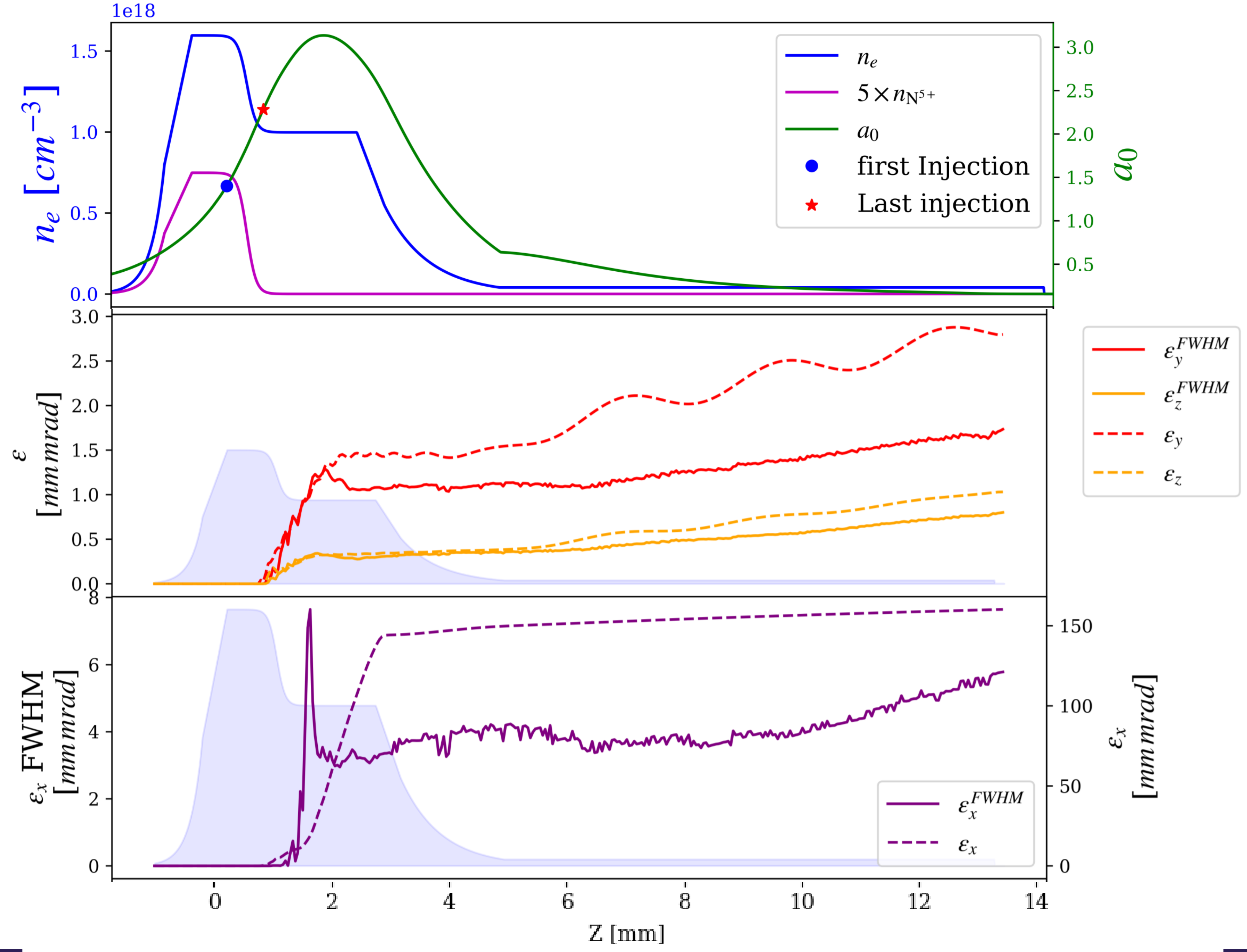
Comparison of simulation with experiment



Emittance is conserved for FWHM electrons

$$\varepsilon_{n,rms} = \frac{1}{m_o c}\sqrt{\sigma_x^2\sigma_{p_x}^2 - \sigma_{xp_x}^2}$$

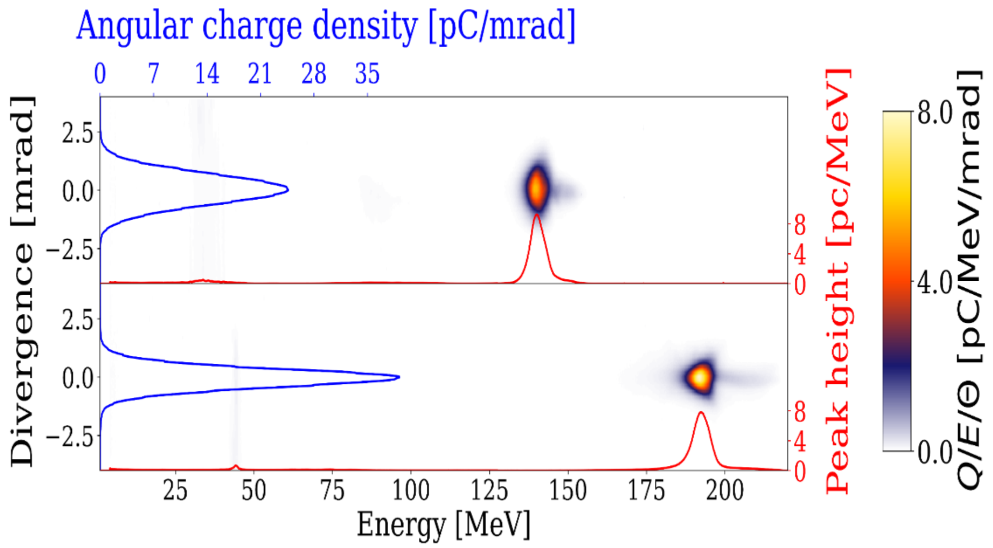
- Phase space shows that FWHM electrons are at the front of the bunch.
- $x < 6\ mm$, full emittance is conserved which means adiabatic matching.
- $x > 6\ mm$, the full emittance is not conserved
- $x : 6 \rightarrow 9\ mm\ \varepsilon^{FWHM}$ is constant
- $x : 9 \rightarrow 14\ mm\ \varepsilon^{FWHM}$ increases as Q_{FWHM} increases.
- Thus in LPT the emittance is:
  - conserved in the front of the bunch.
  - slightly degraded in the rear of the bunch.



Summary

Experimental observation of high quality beam with:

- 180 MeV
- 40 pC [FWHM]
- Divergence 0.5 mrad
- Low Transverse Momentum Spread
- ΔE= 6 MeV



Density profile that allows:

- Shape beam
  - Longitudinally
  - Transversely

Simulation reproduces closely experimental observation

Perspectives:

- Redesign for improved quality and stability
- Use of source for applications

Preprint

Observation of laser plasma accelerated electrons with transverse momentum spread below the thermal level

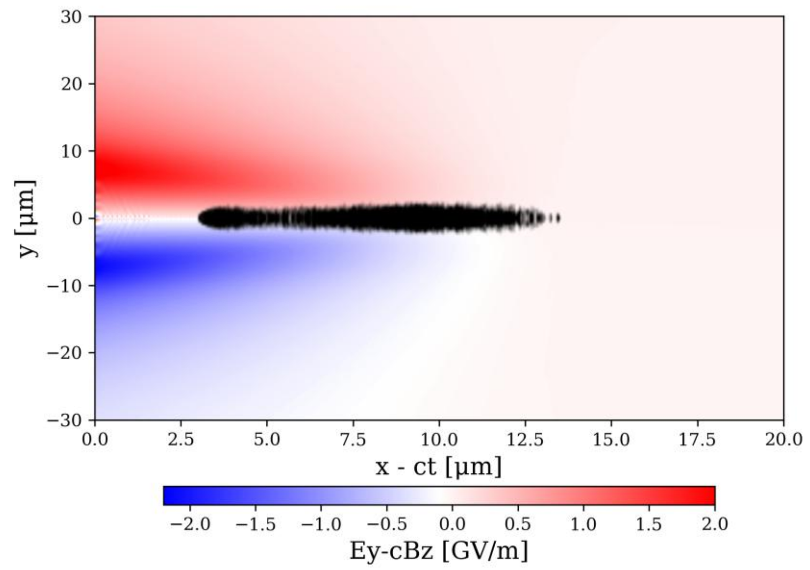
https://arxiv.org/abs/2506.18047

Related Posters

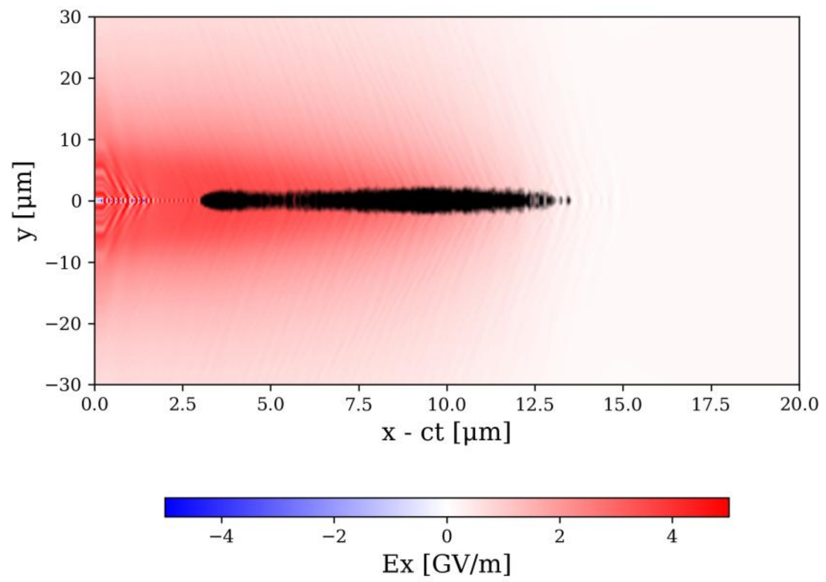
Independent Control of Electron Injection and Acceleration in a Laser Plasma Accelerator –
A. Panchal et al

Enhancing Electron Beam Quality Through Customized Density Gradients in Laser Wakefield Acceleration
- L Steyn et al

Plasma Lens effect



Plasma Dechirper



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