Injection, Acceleration and Collimation of Electrons in Laser-Plasma Accelerators

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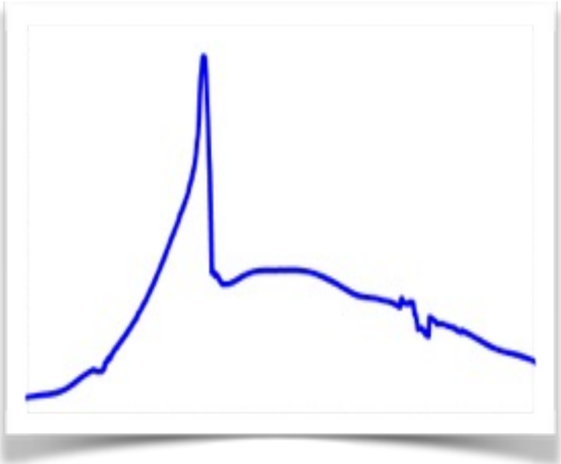
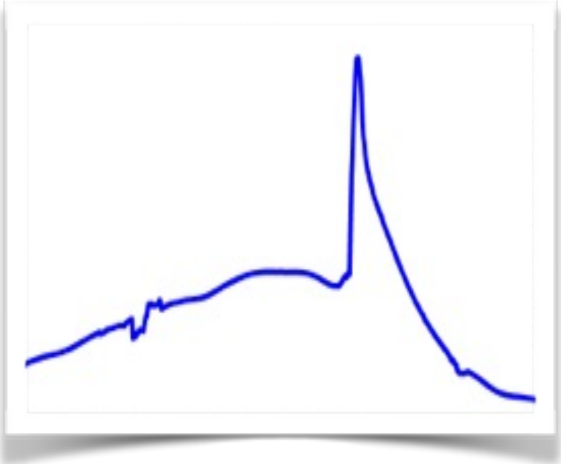
2nd European Advanced Accelerator Concepts Workshop, Elba, Italy, September 14-19 (2015)

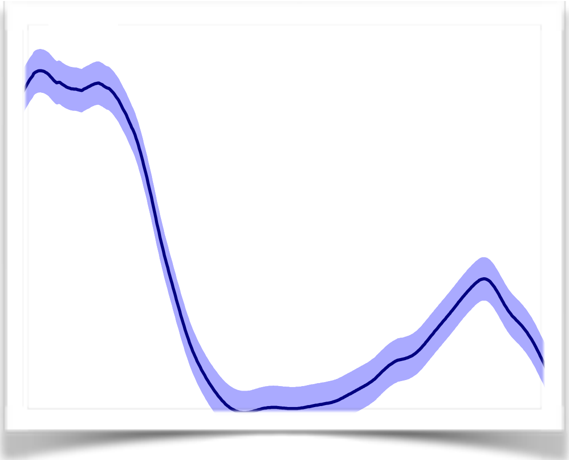
Outline



I. Injection in a shock front w/wo ionization assistance



II. Electron beam rephasing



III. Laser plasma lens

Outline

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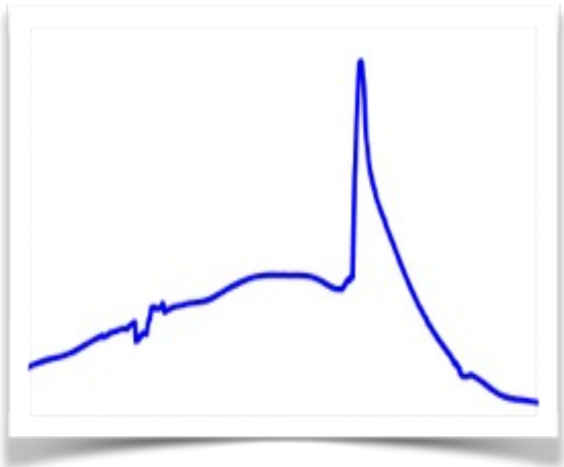

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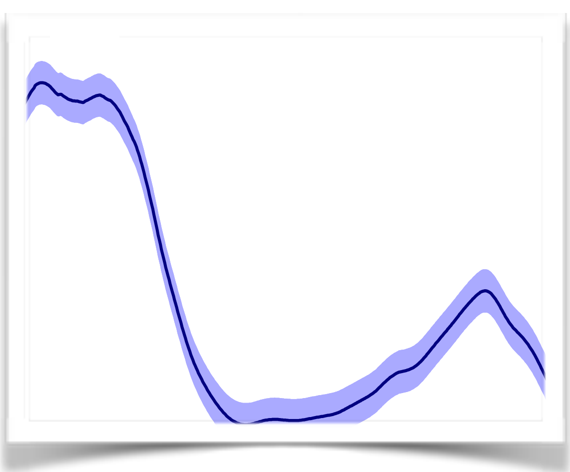
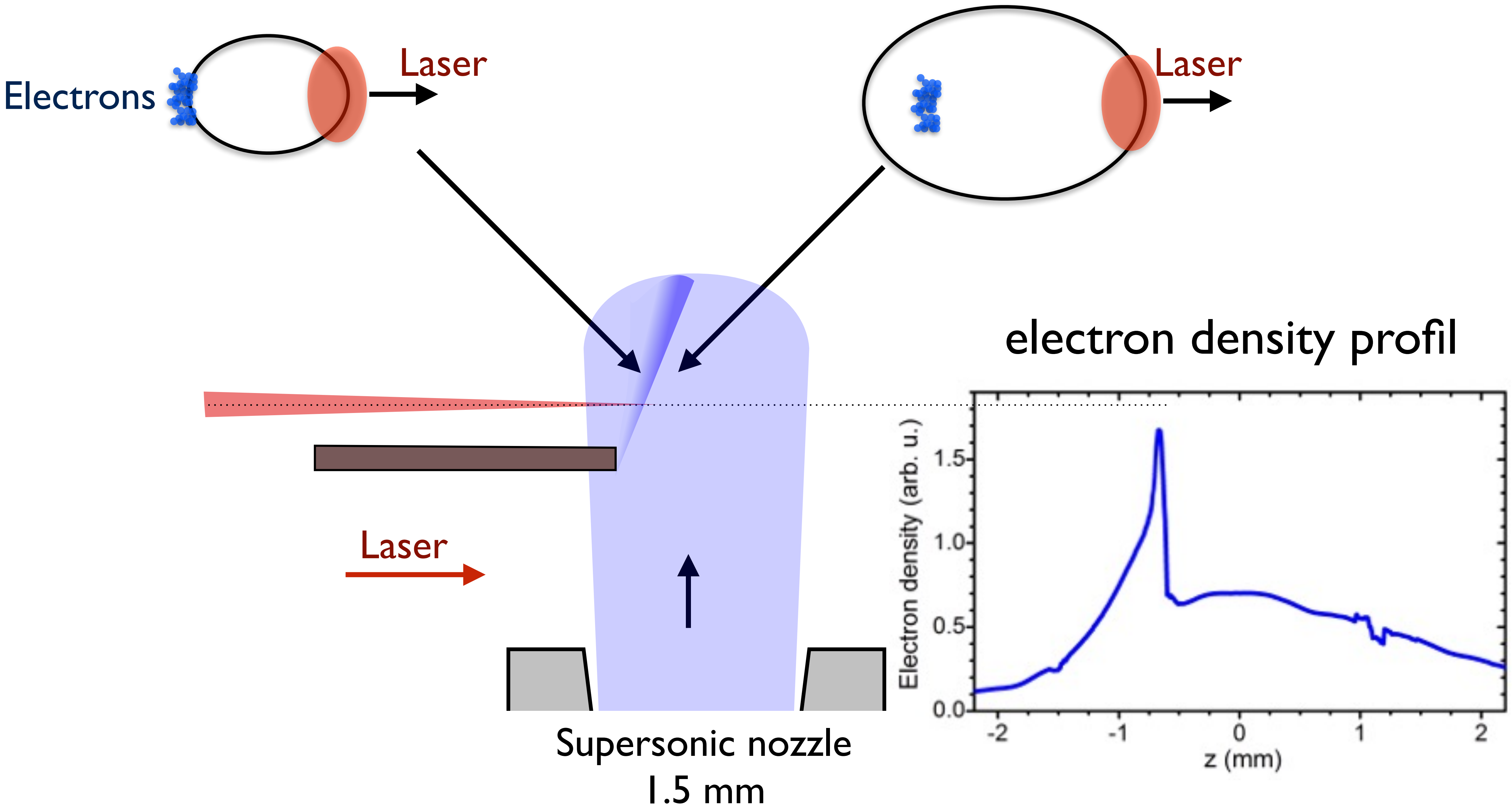
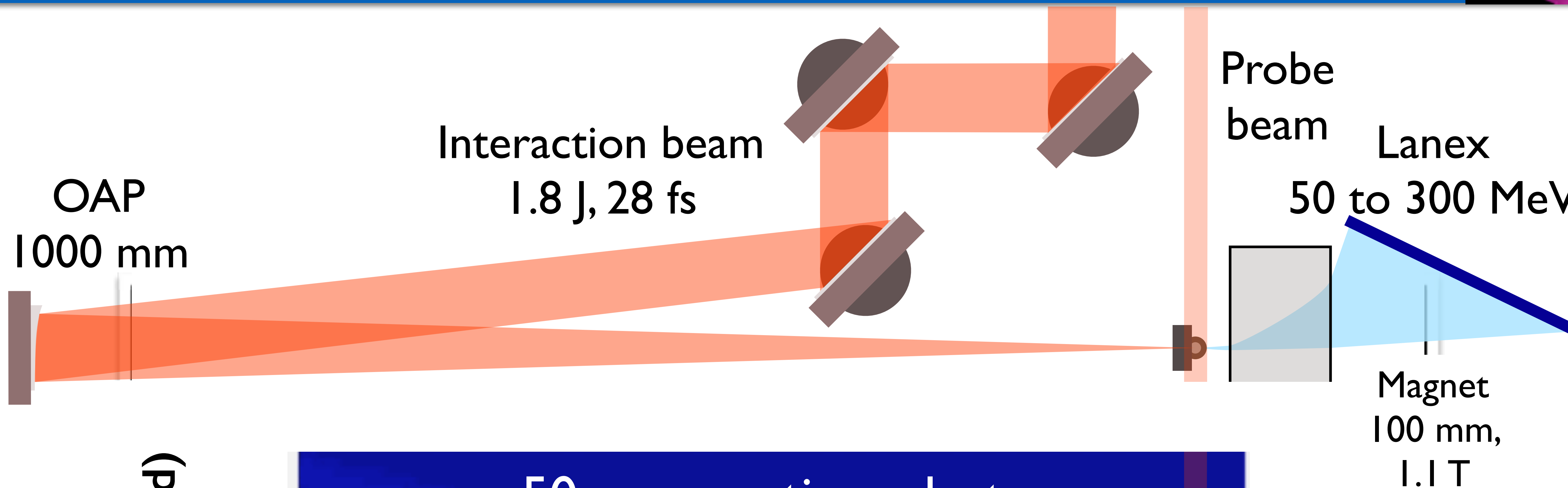


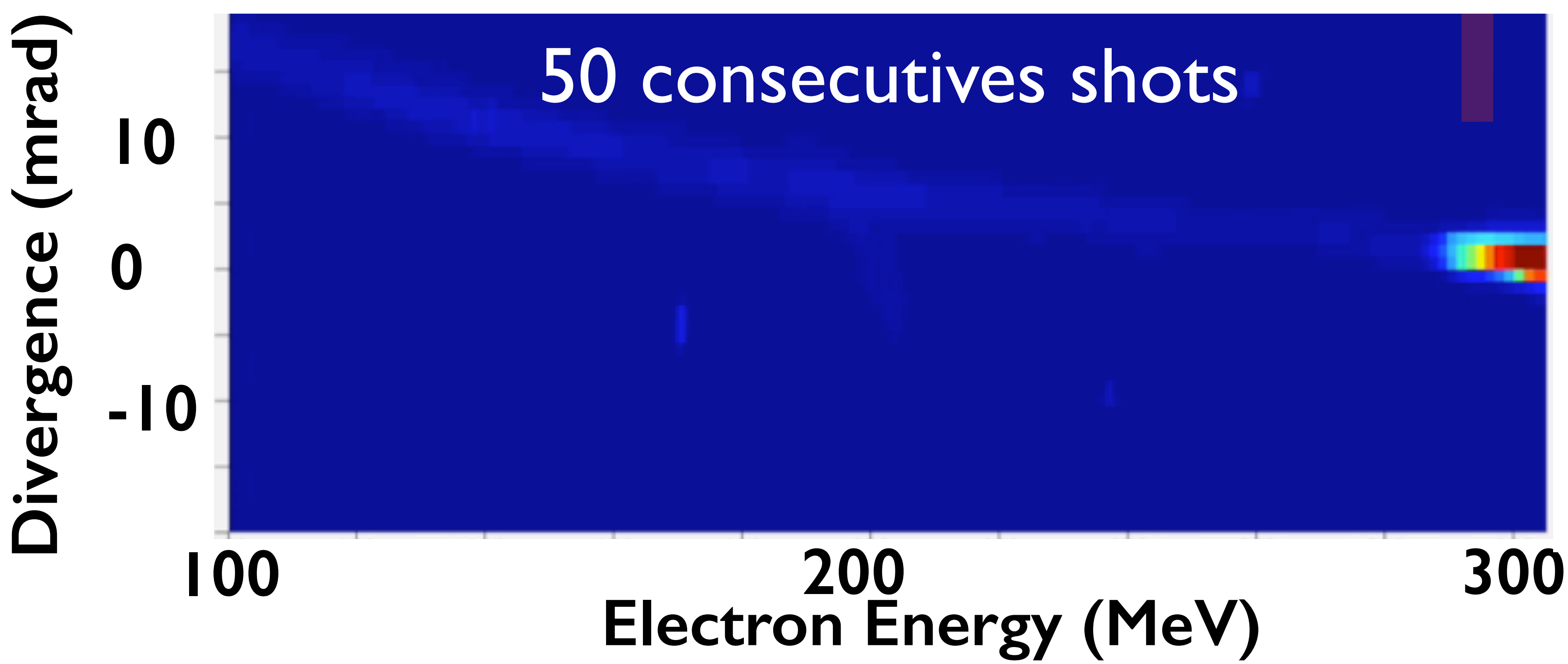
III. Laser plasma lens

Injection in a shock front : principle



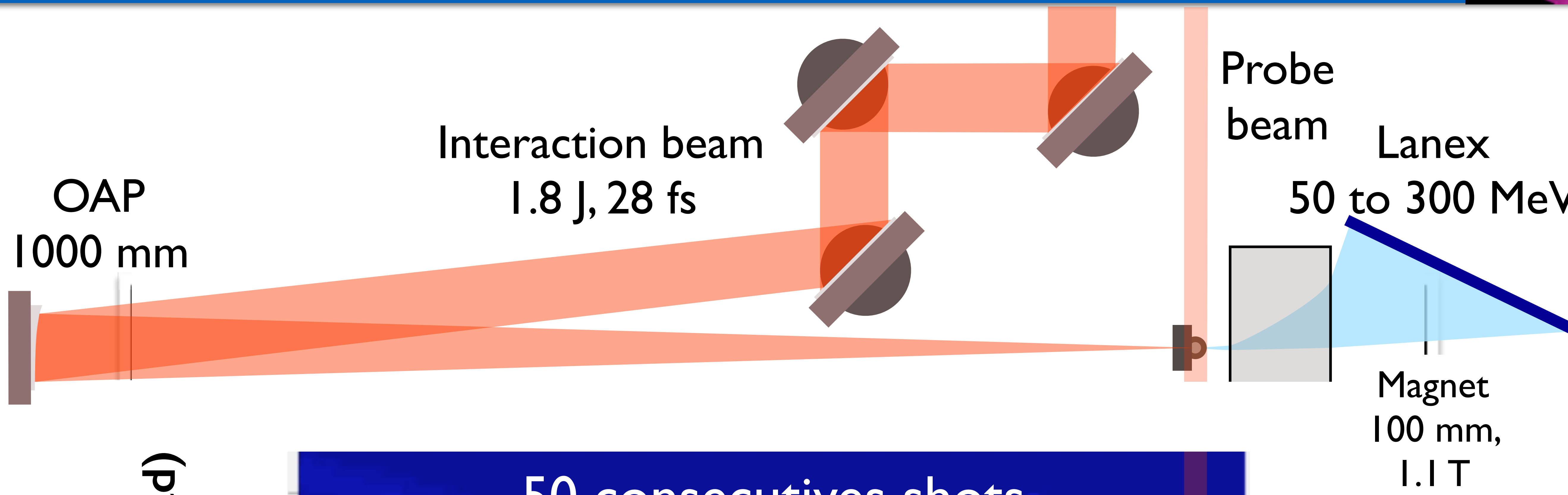
Experimental Set-up and Results

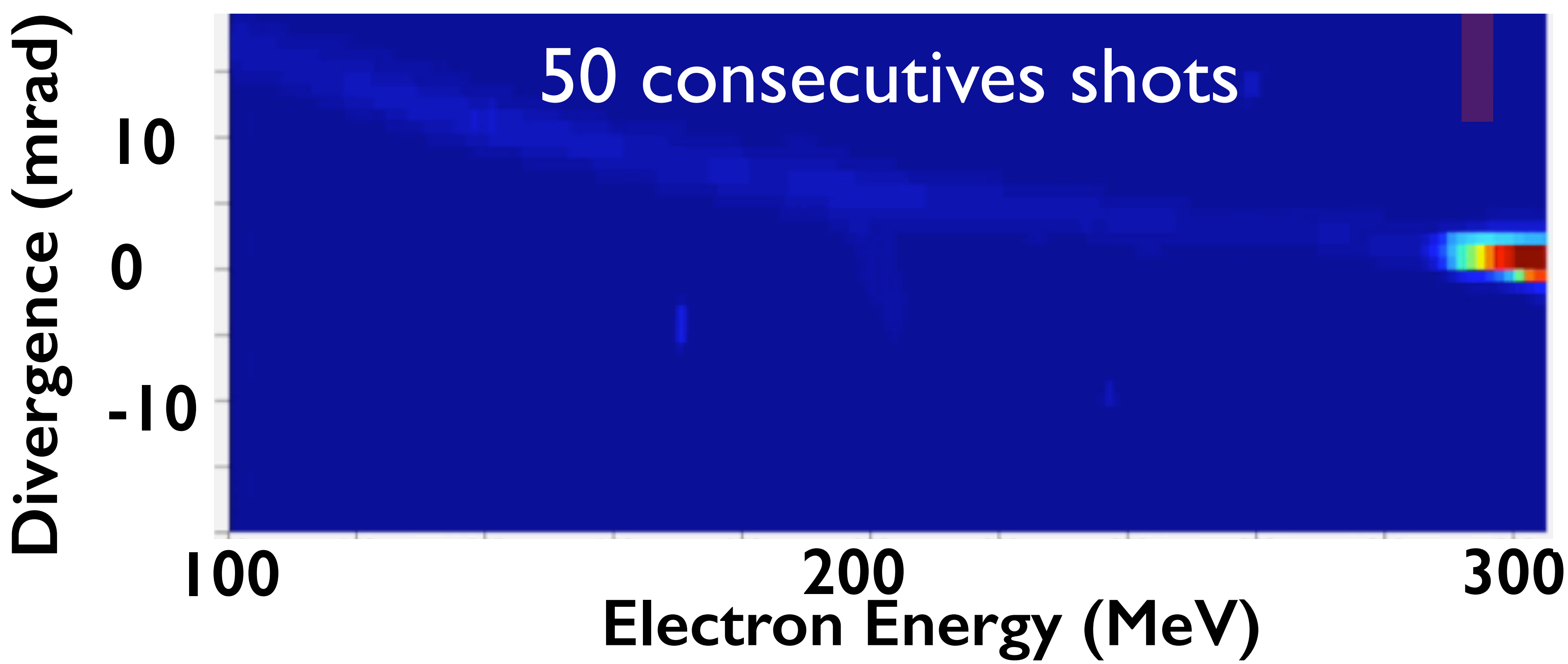




Peak energy : ~ 290 MeV **Energy spread : ~ 20 MeV (6%)**

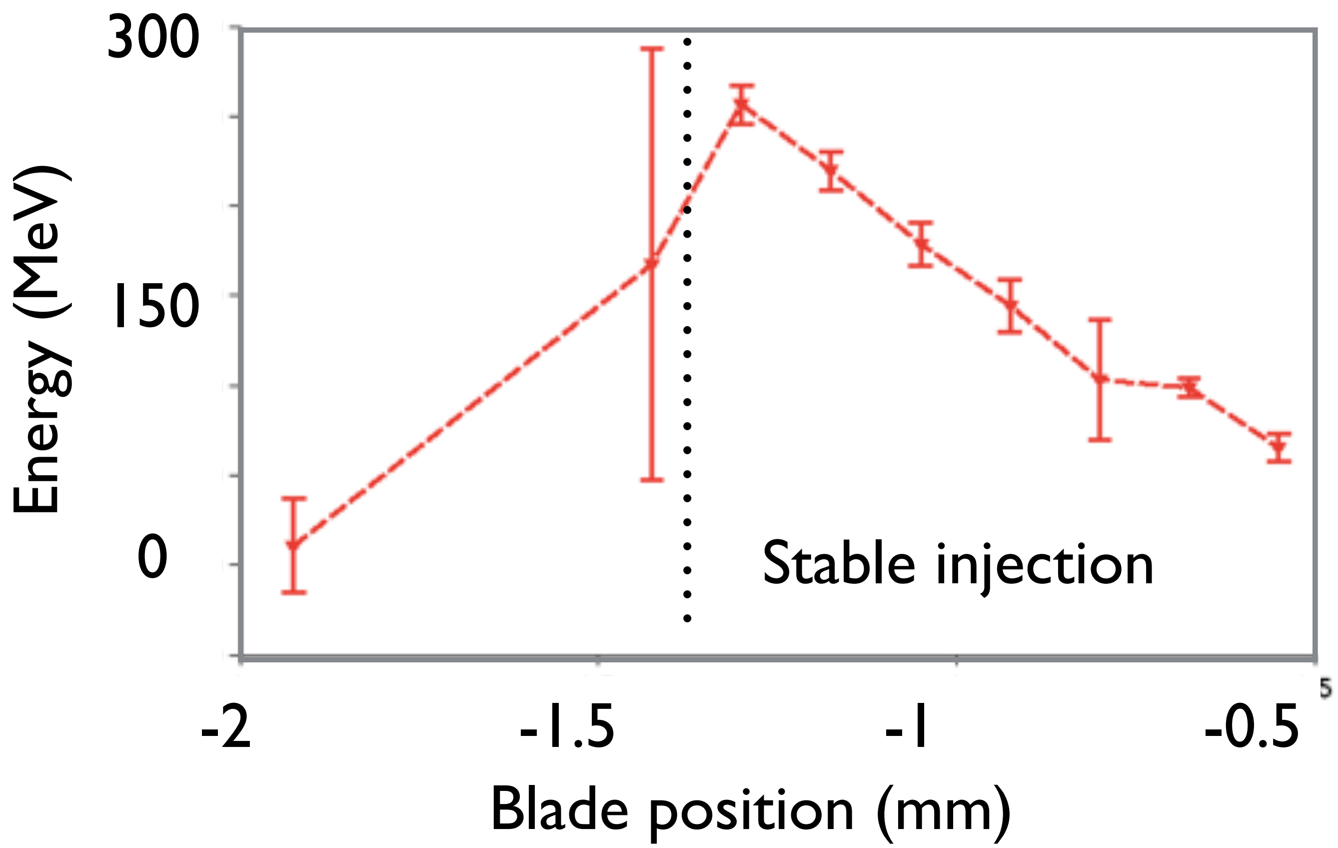
Experimental Set-up and Results

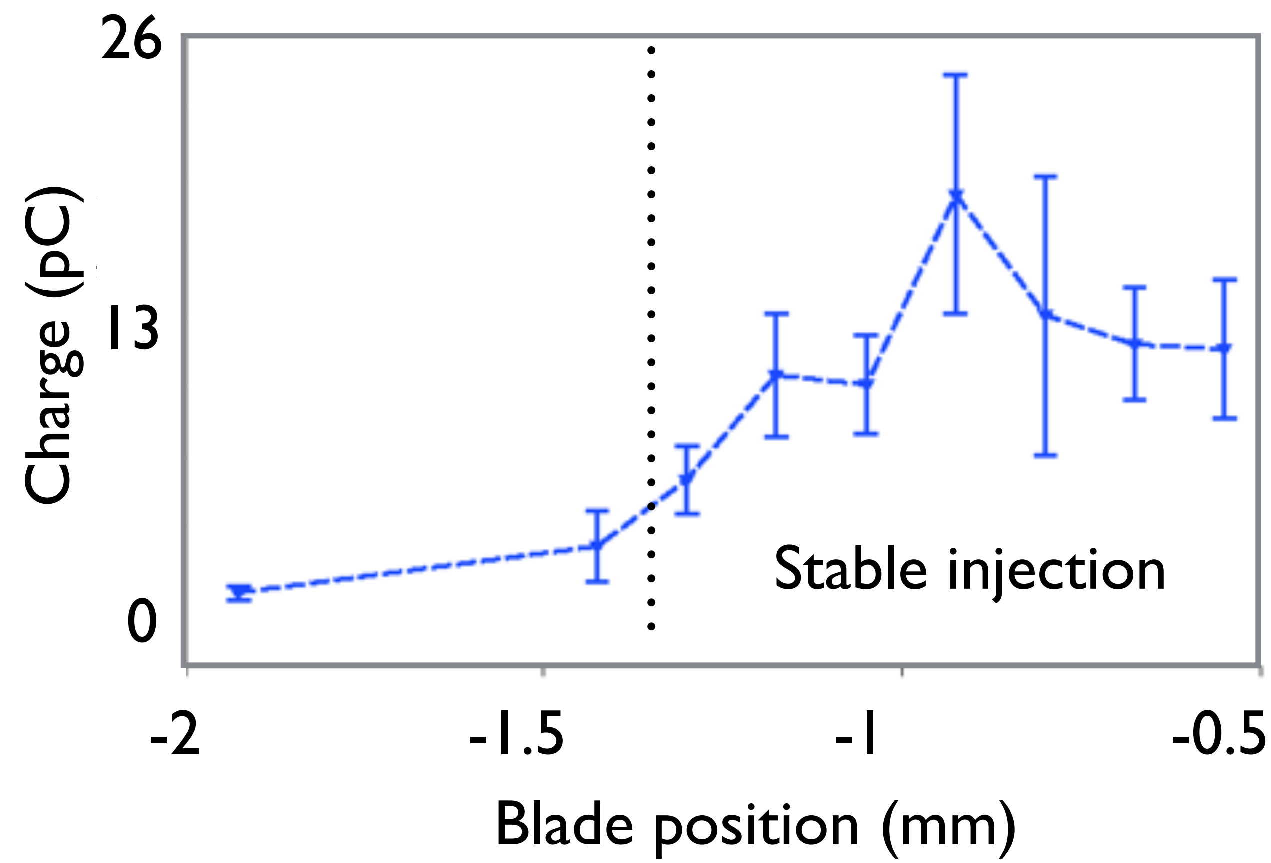




Peak energy : ~ 290 MeV **Energy spread : ~ 20 MeV (6%)**

Experimental Results on Tunability



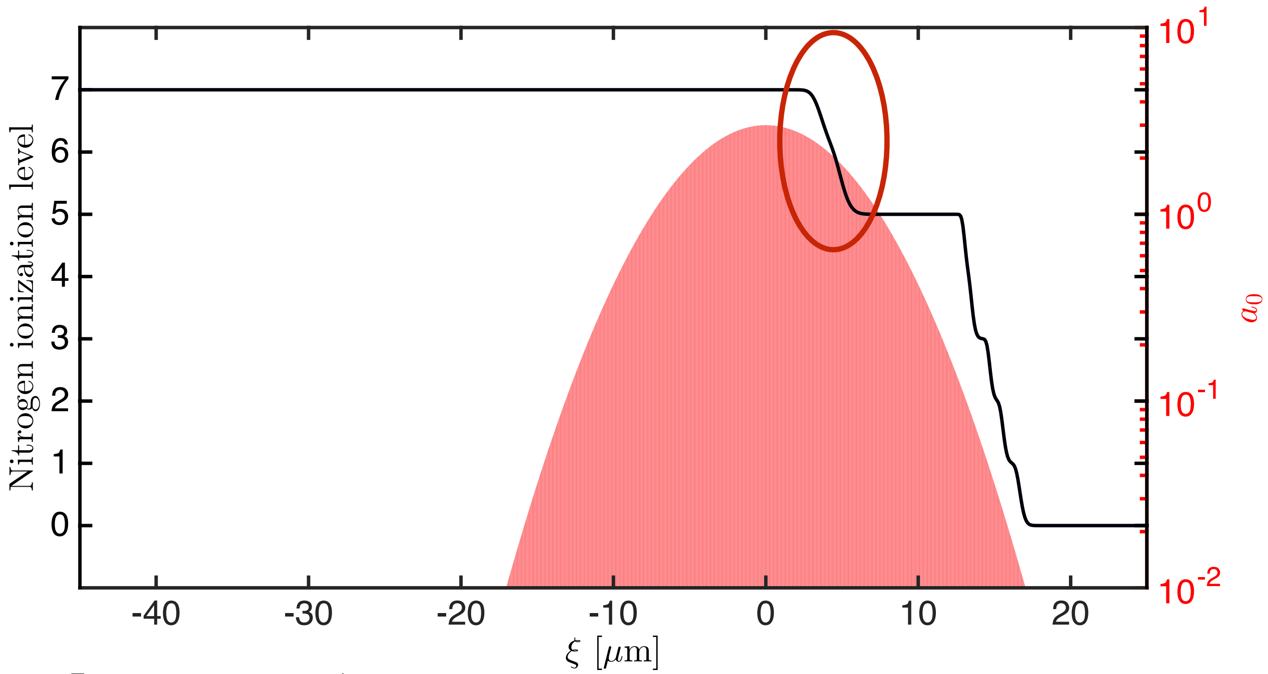


Tunable energy from 75 to 275 MeV
ΔE=20 MeV (10MeV for best shots)

Charge ~10 to15 pC

Injection in a shock front with ionisation assistance

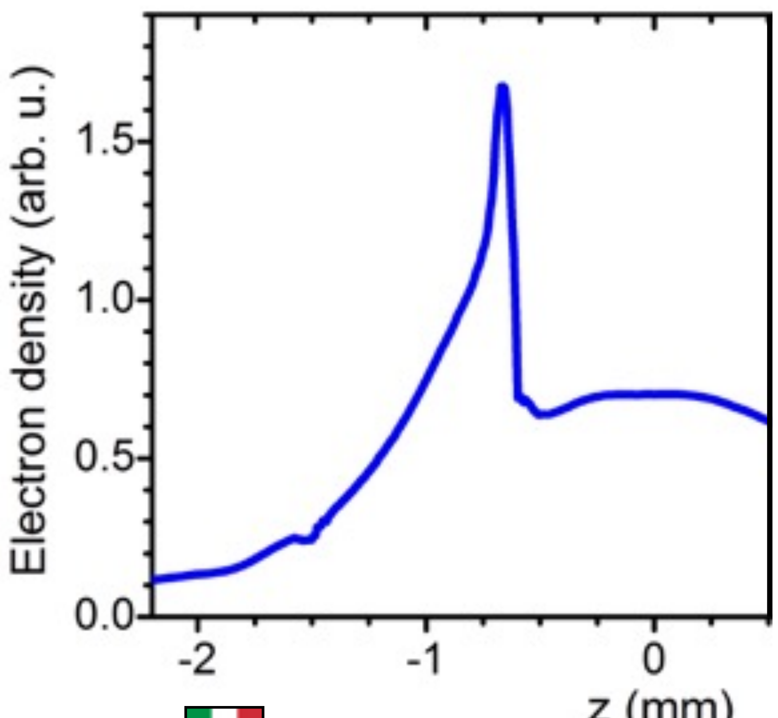
Principle of ionization injection



N^{5+} and N^{6+} are ionized only when the laser intensity is maximum

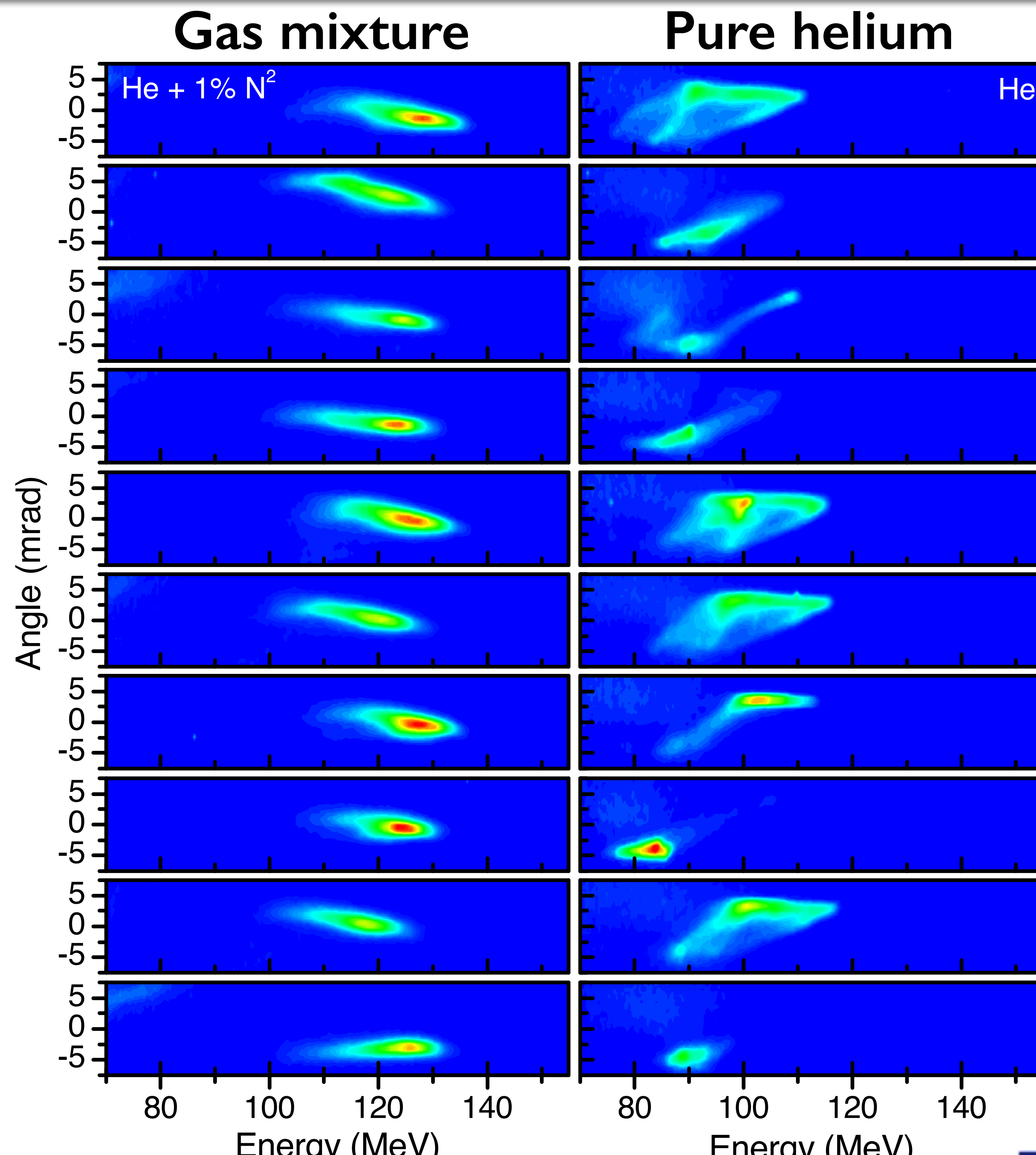
Properties

- Possibly high charge (>100 pC)
- Low transverse emittance
- Stable
- Large energy spread



Electrons ionized when the laser crosses the shock front spend more time in the accelerating eld, they are therefore more likely to be be trapped. They can thus be injected below the threshold for classical ionization injection, leading to localized trapping and low energy spread

Experimental Results : Pure helium vs gas mixture (1% N_2)



RMS Stability
$\delta E/E = 2.5\%$
$\delta Q/Q = 12\%$

Pointing
1.5 mrad RMS
(down to 0.7)

Divergence
2.6 x 5 mrad^2

Energy spread
14 ± 2 MeV

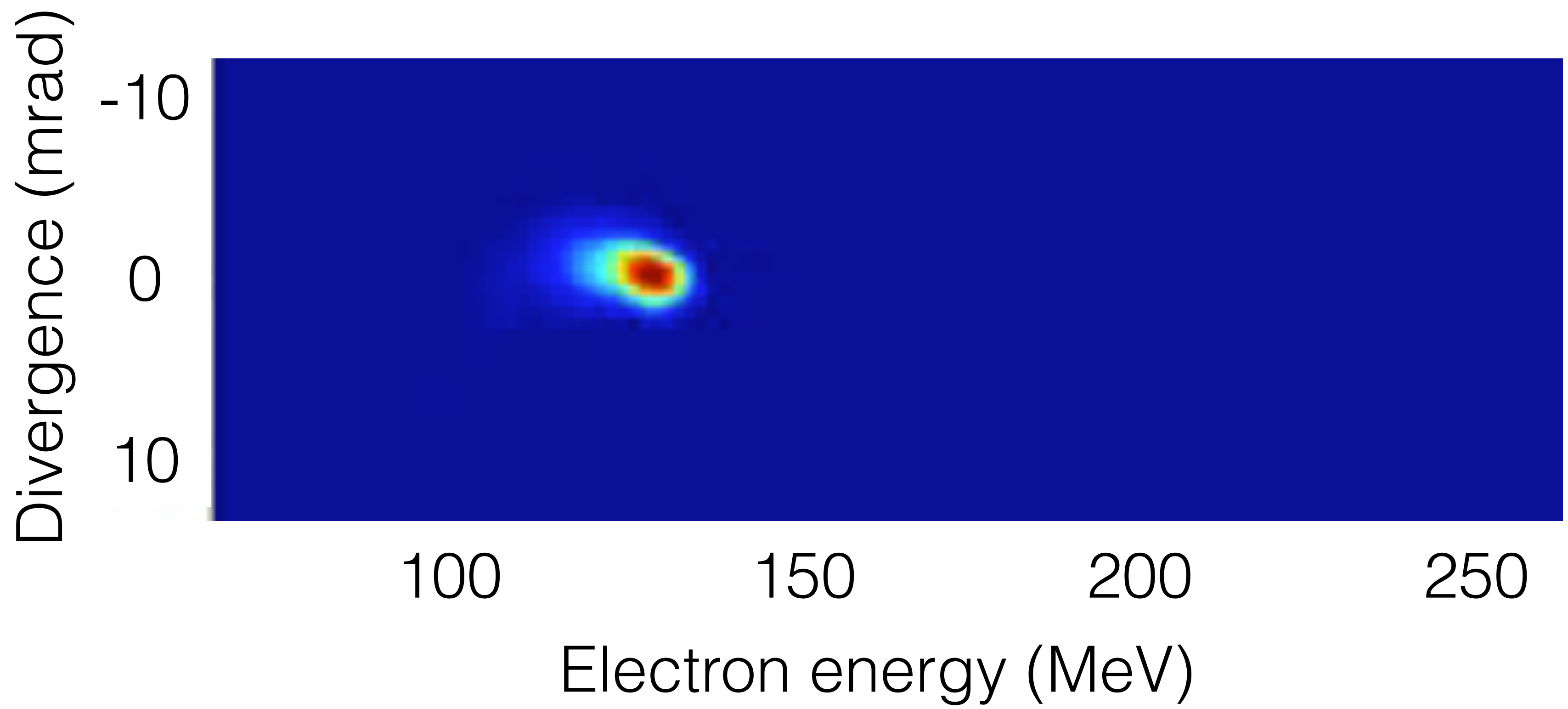
RMS Stability
$\delta E/E = 7\%$
$\delta Q/Q = 24\%$

Pointing
3.2 mrad RMS

Divergence
3.2 ± 0.7 mrad

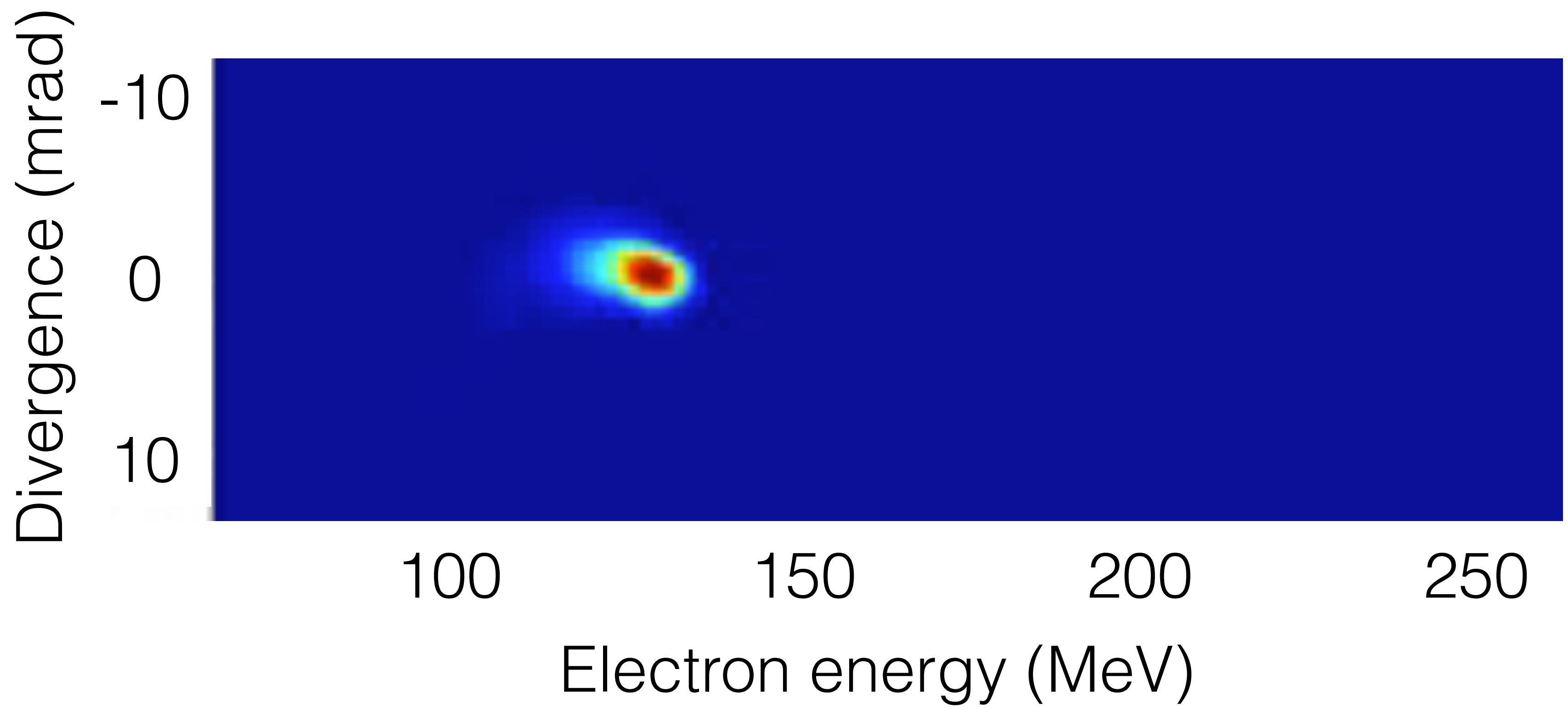
Energy spread
20 ± 10 MeV

50 consecutive, dispersion-corrected spectrum

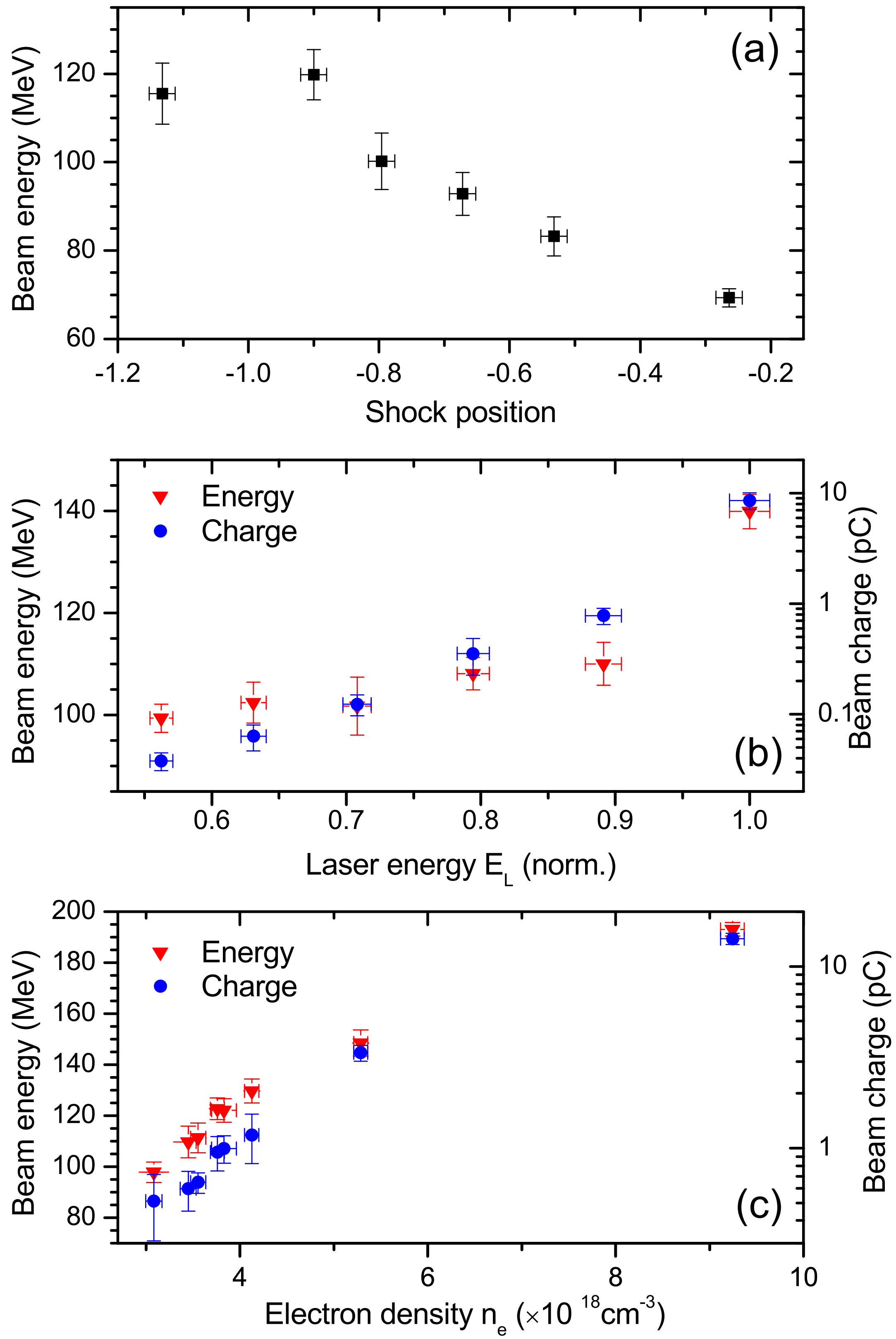


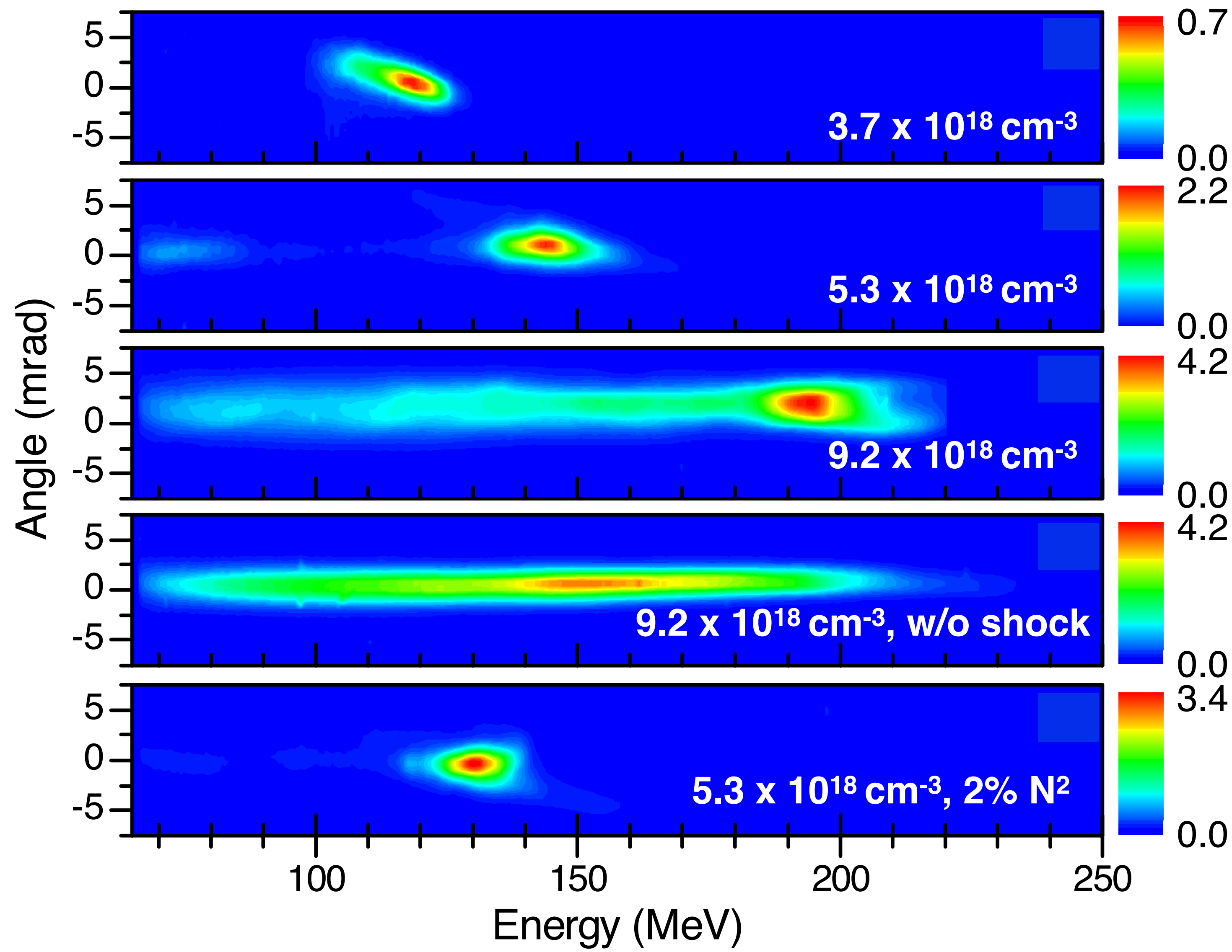
Experimental Results : Stability Improvements

50 consecutive, dispersion-corrected spectrum

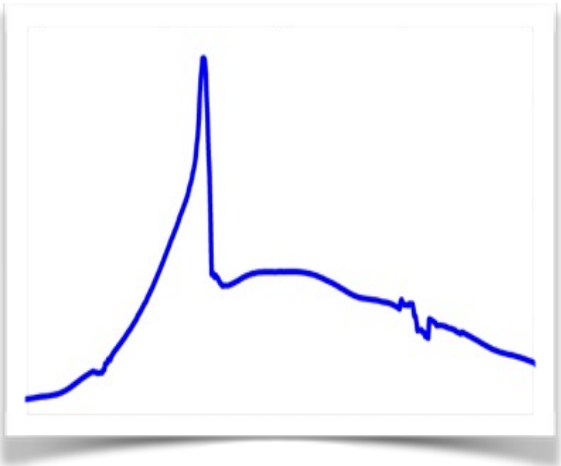


Experimental Results : Charge and Energy Tunability





Outline



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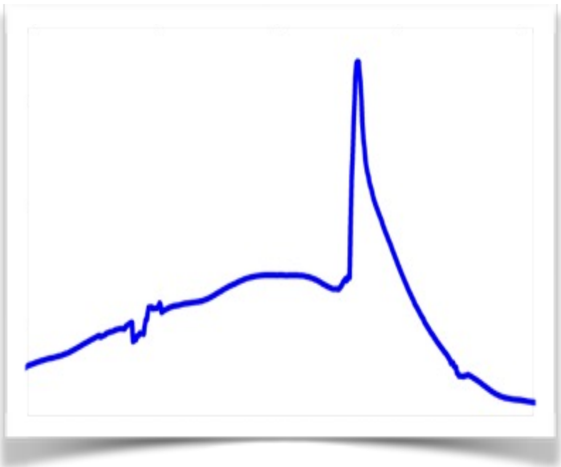
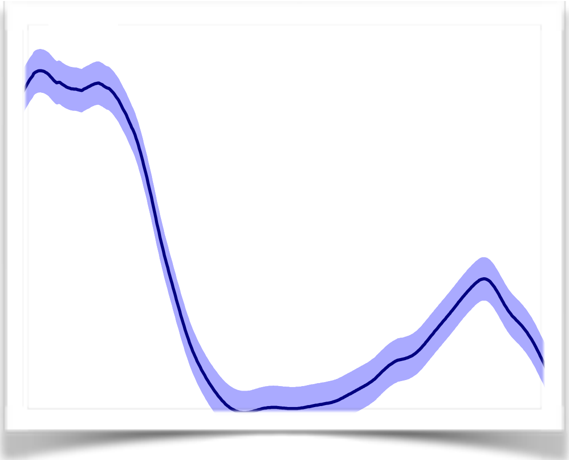
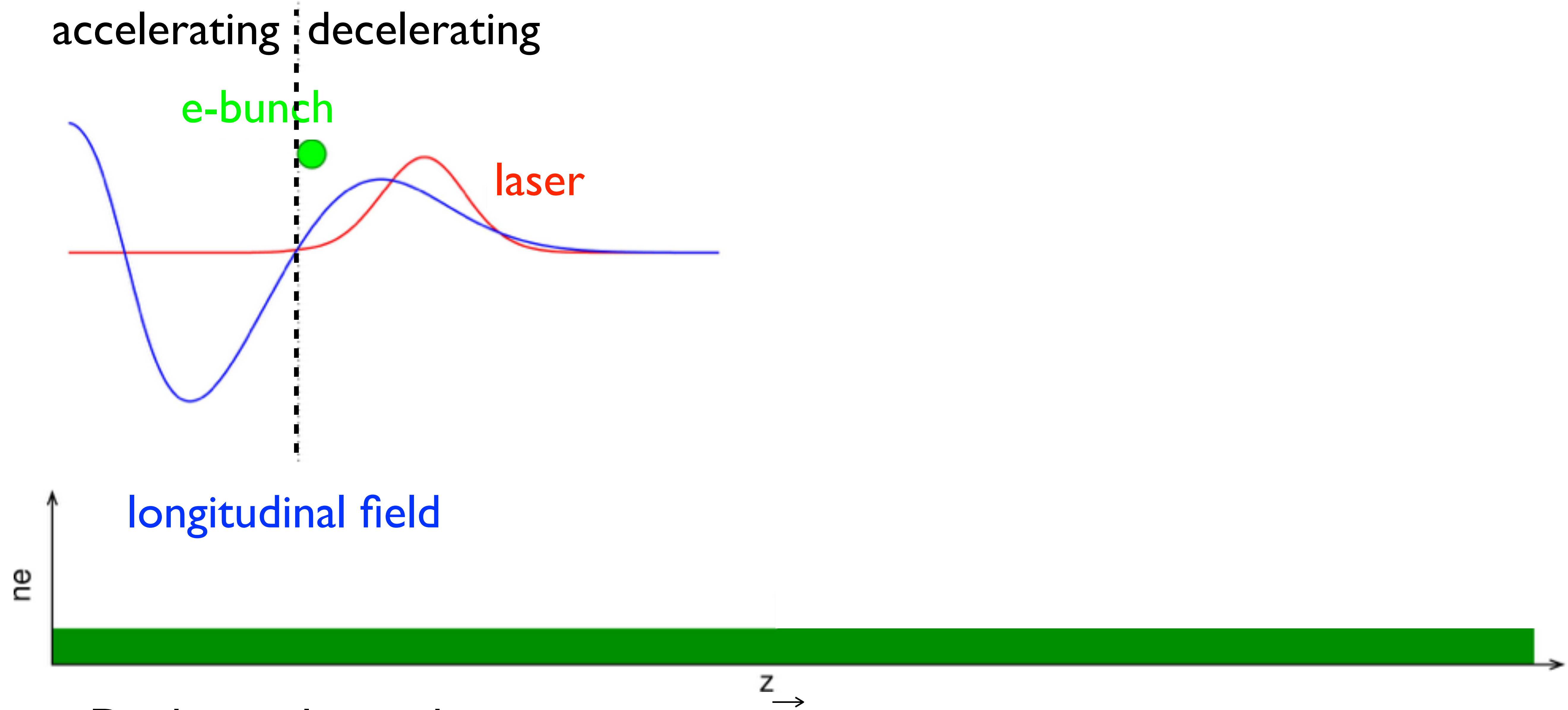


II. Electron beam rephasing



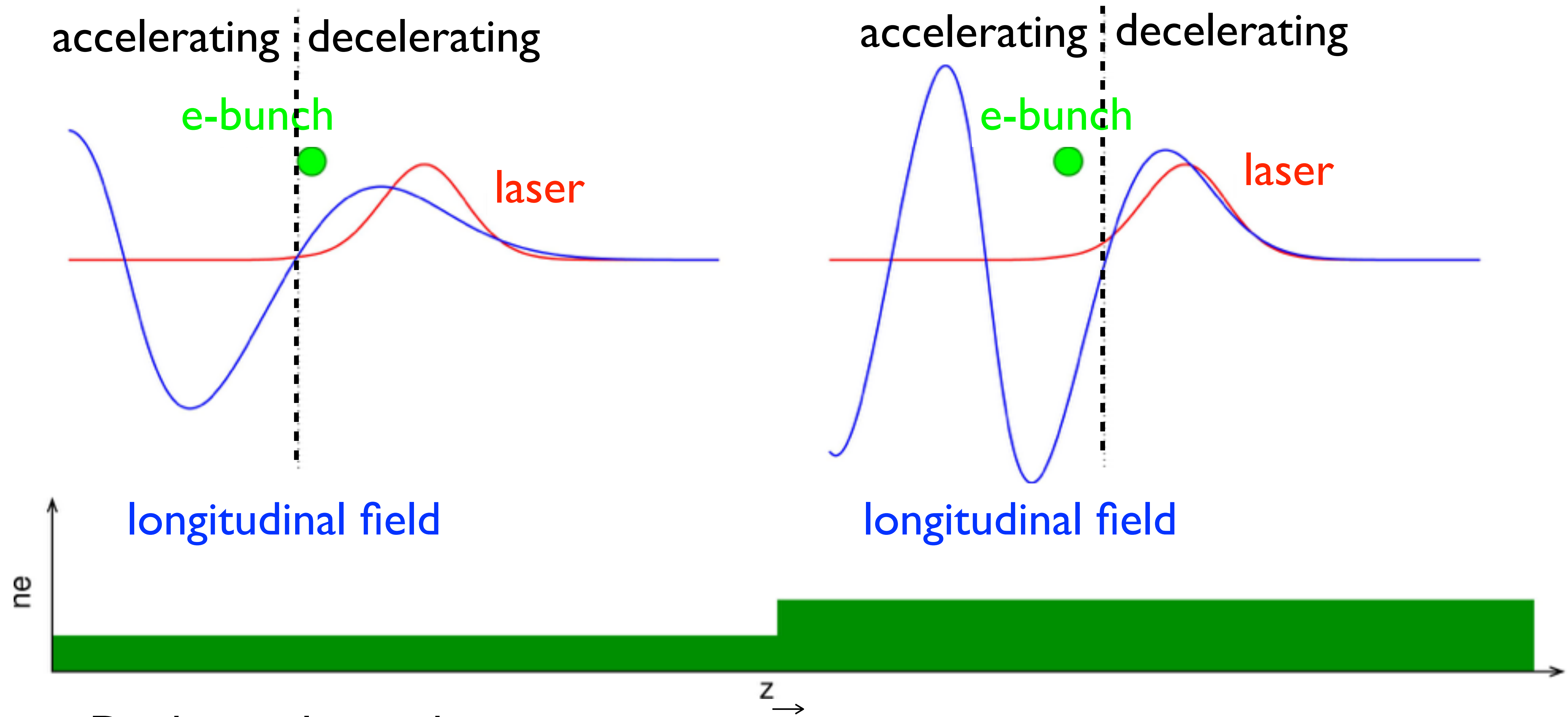
III. Laser plasma lens

Electron Rephasing



Dephasing limits the maximum attainable energy

Electron Rephasing



Dephasing limits the maximum attainable energy

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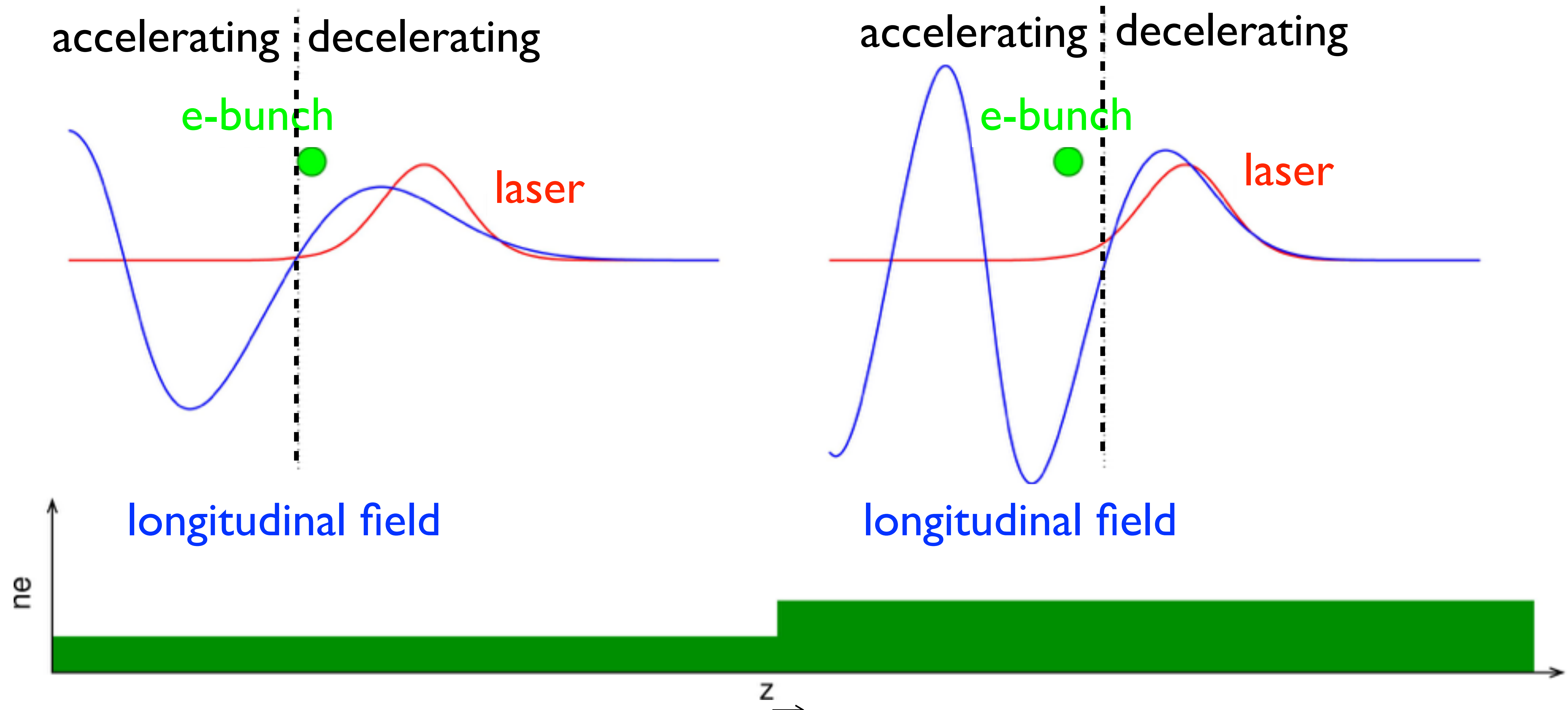
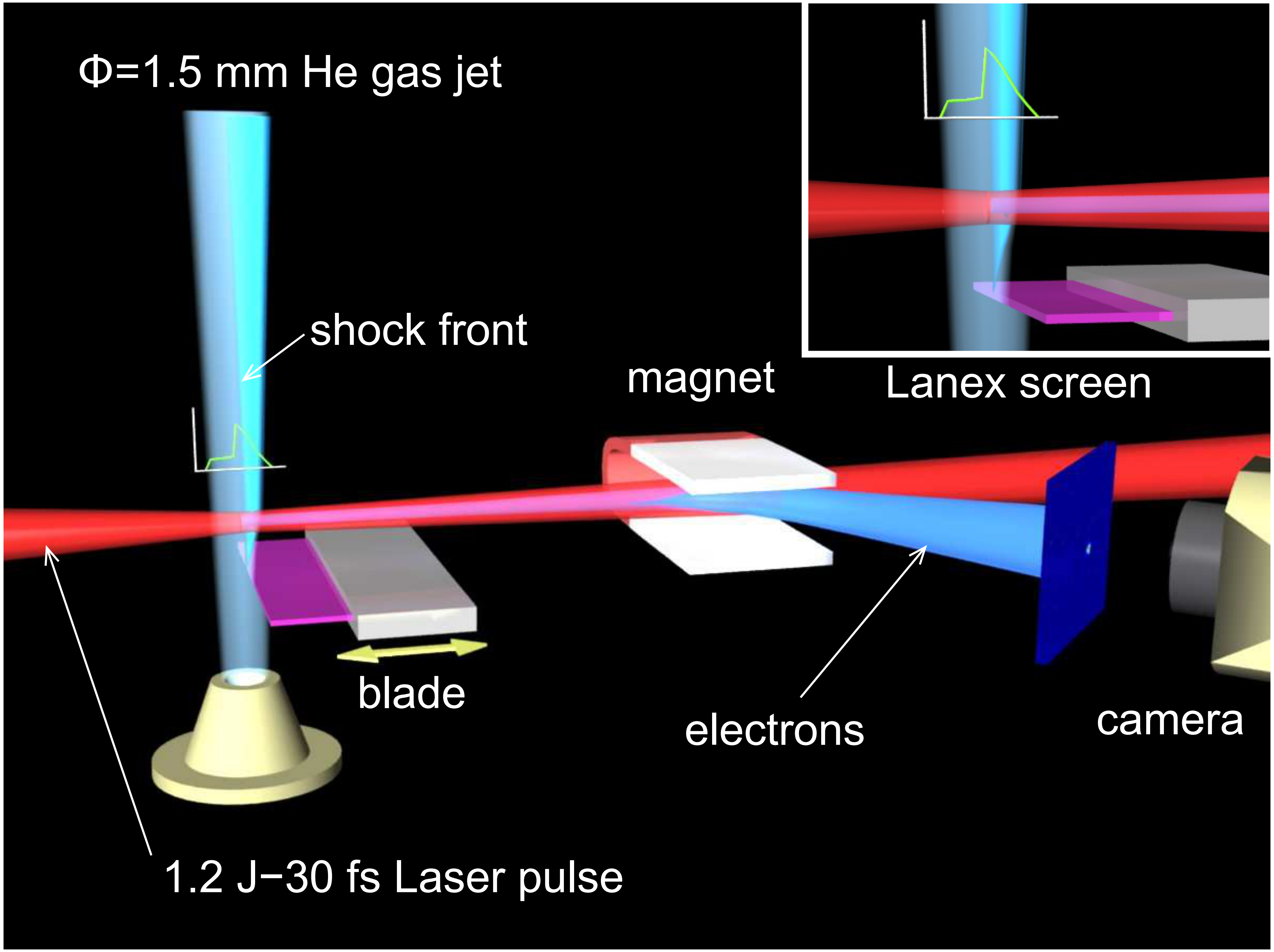


Dephasing limits the maximum attainable energy

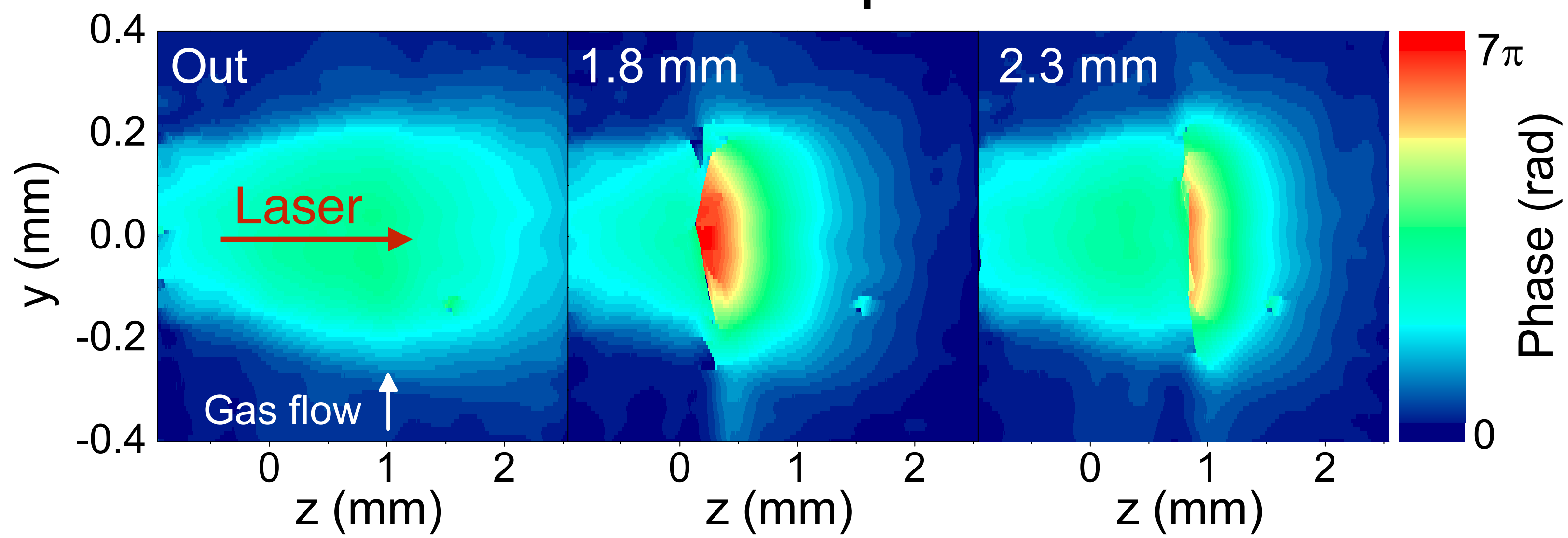
A density step rephases the electron bunch

Experimental set-up

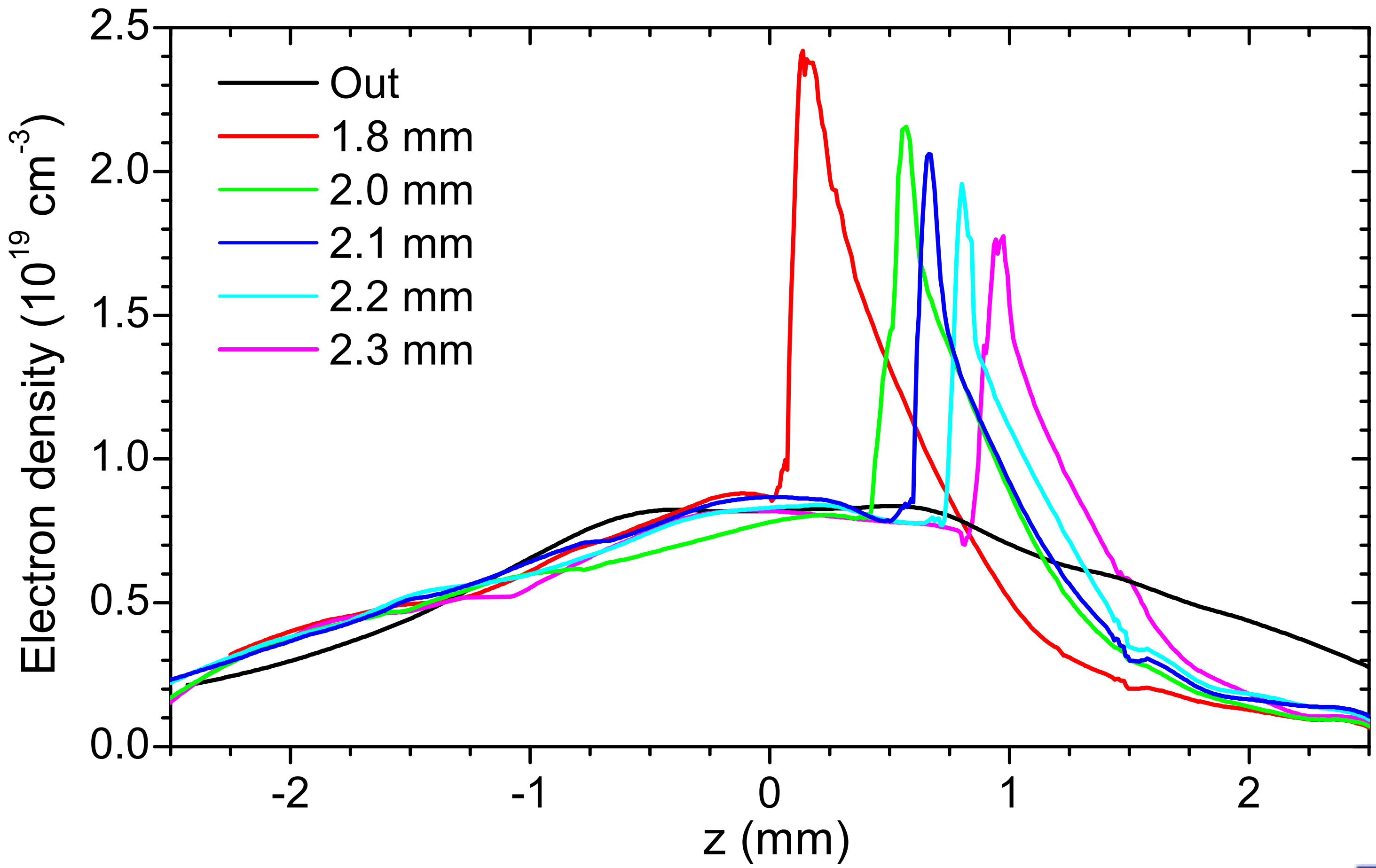


Density profil measurements

Phase maps

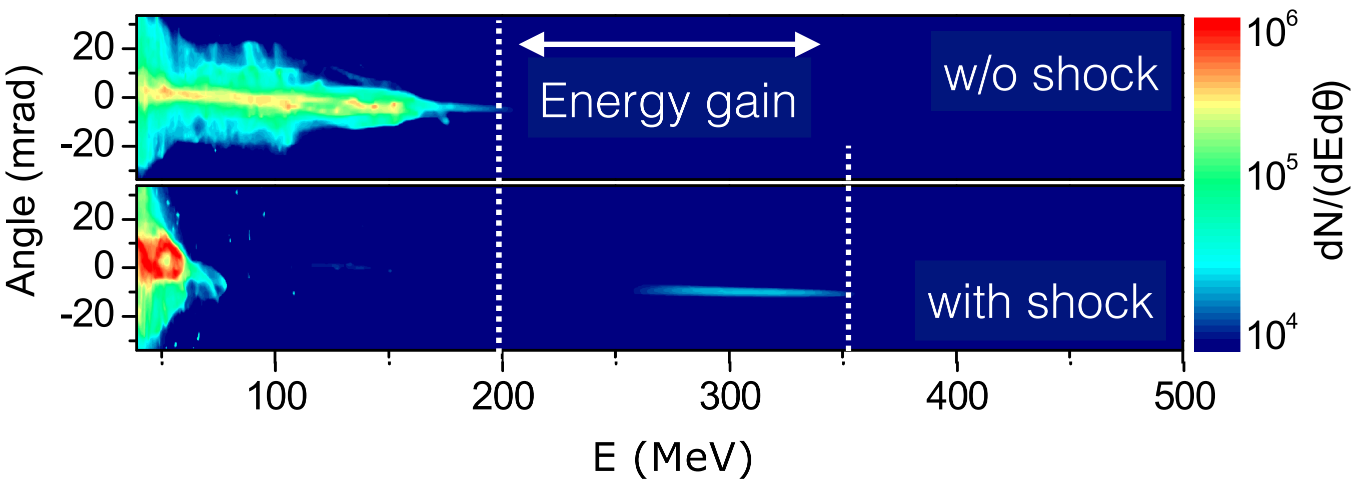


Plasma density profiles after Abel inversion

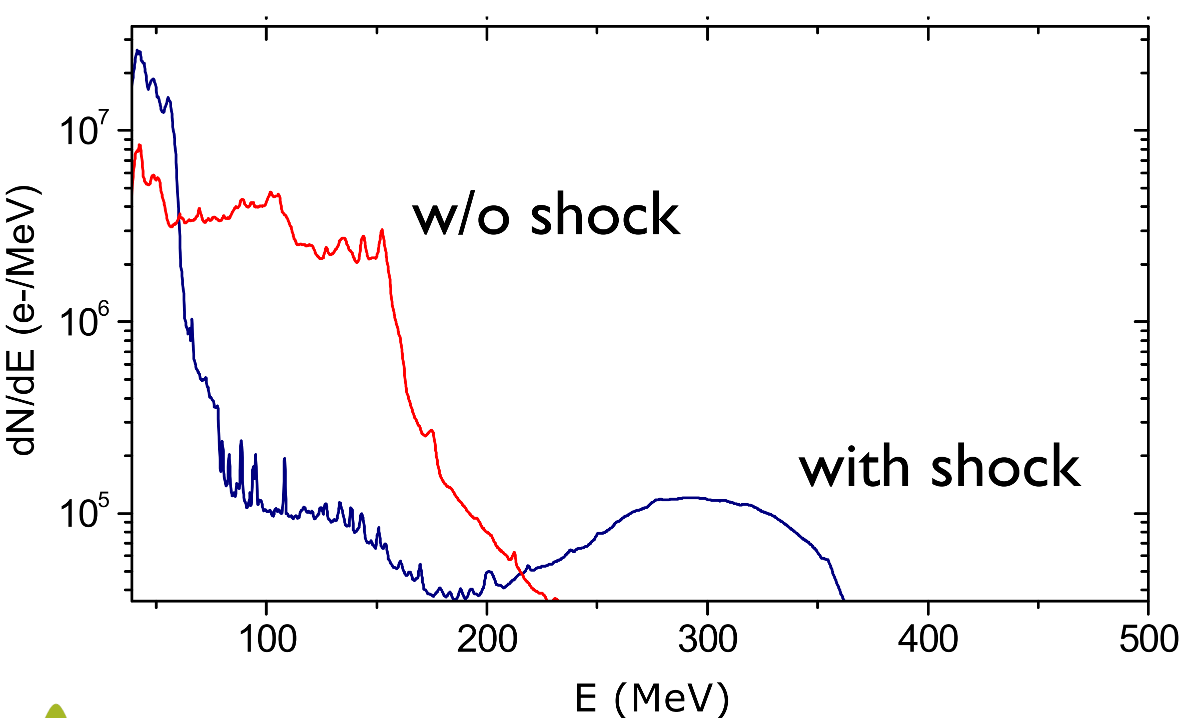


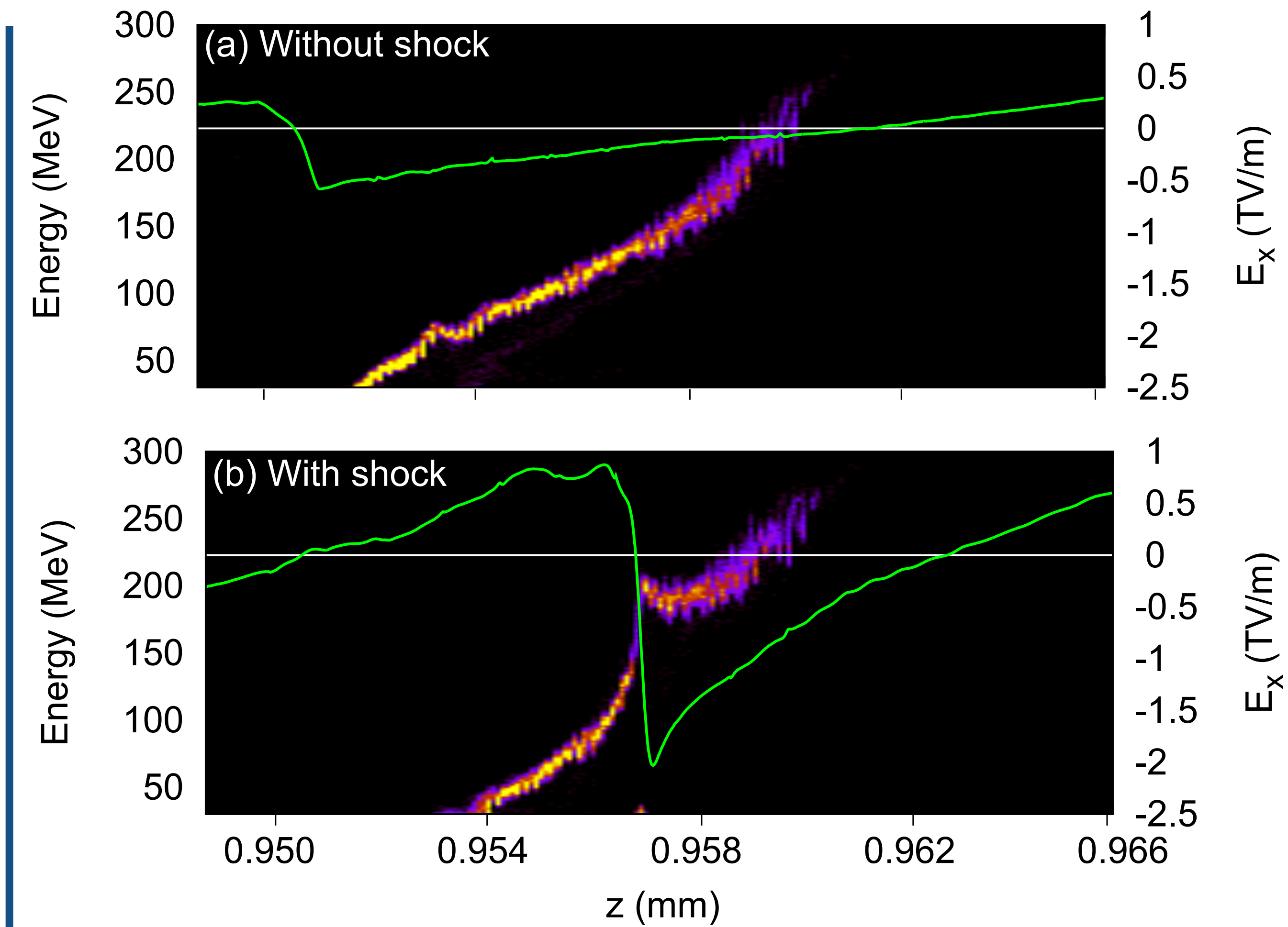
Rephasing AND Energy Boost: exp./PIC CalderCirc Sim.

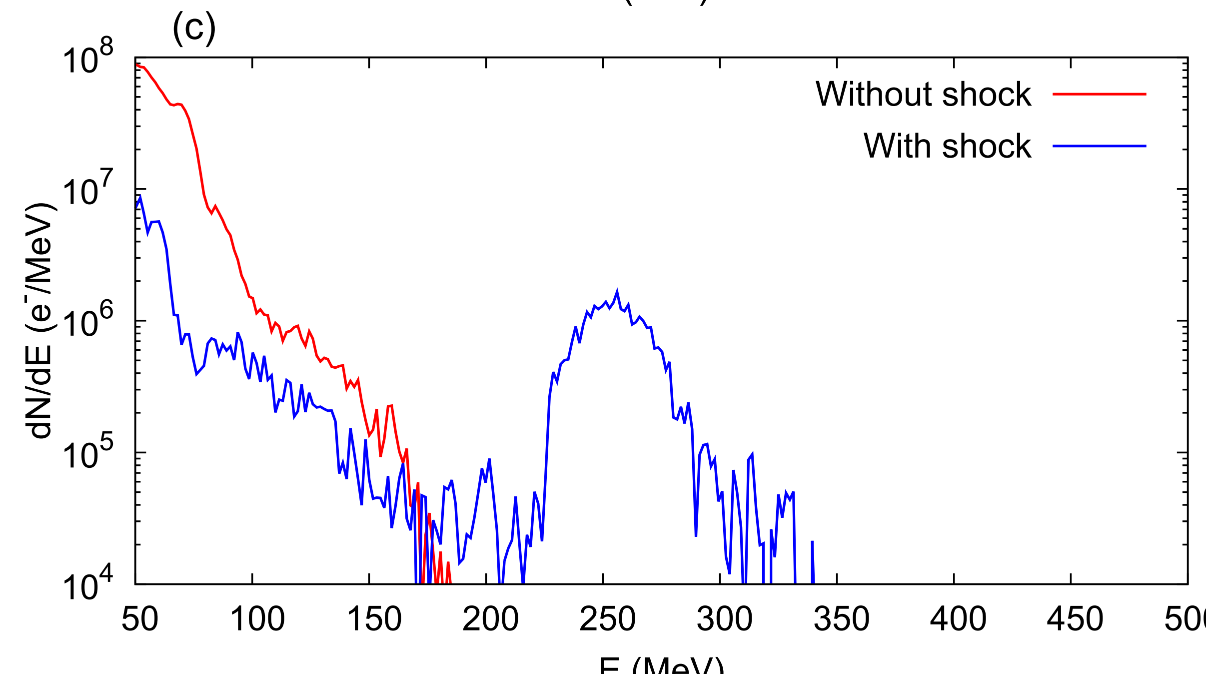
2D dispersion corrected spectra



Angularly integrated spectra



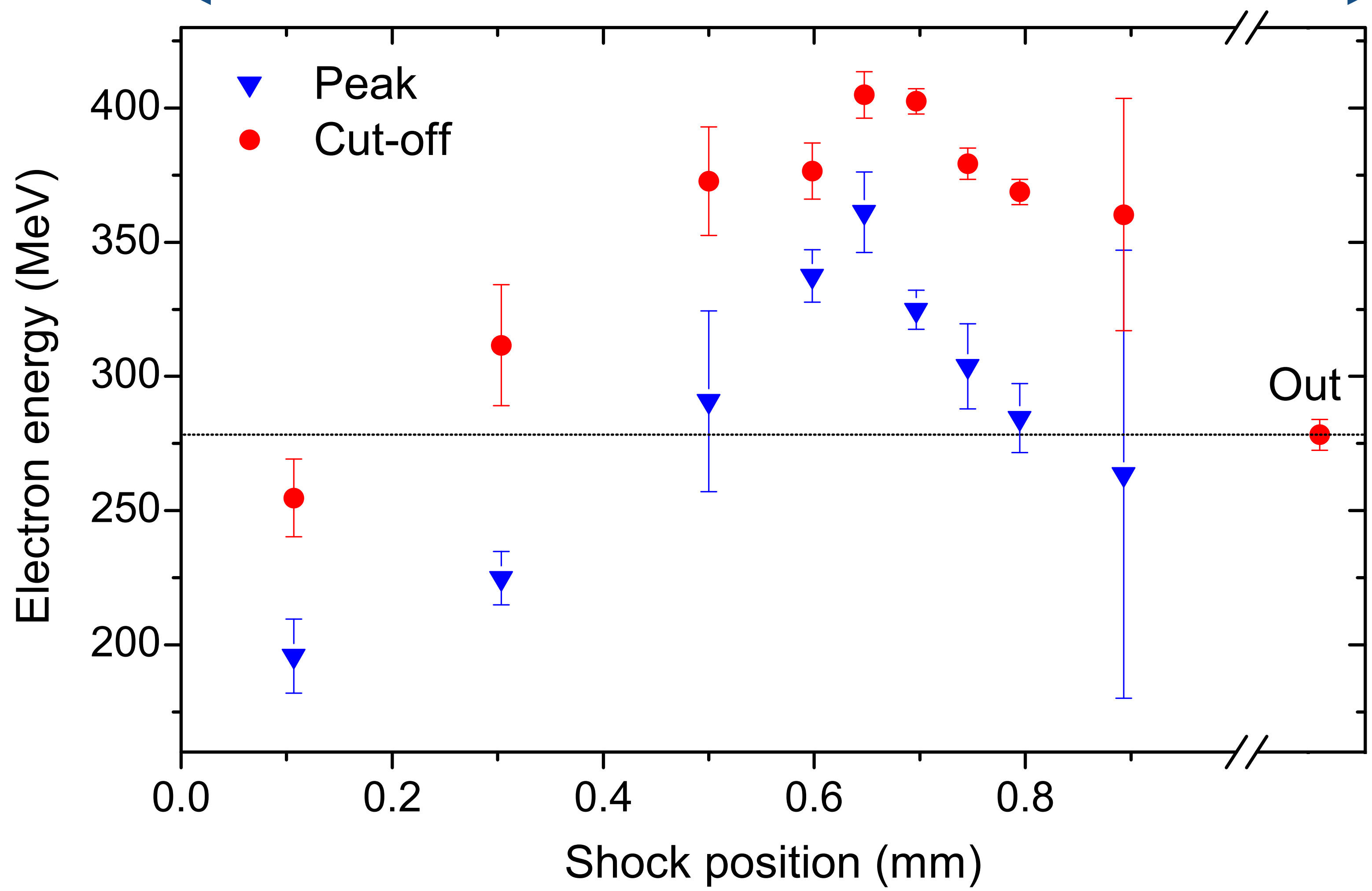




Rephasing AND Energy Boost

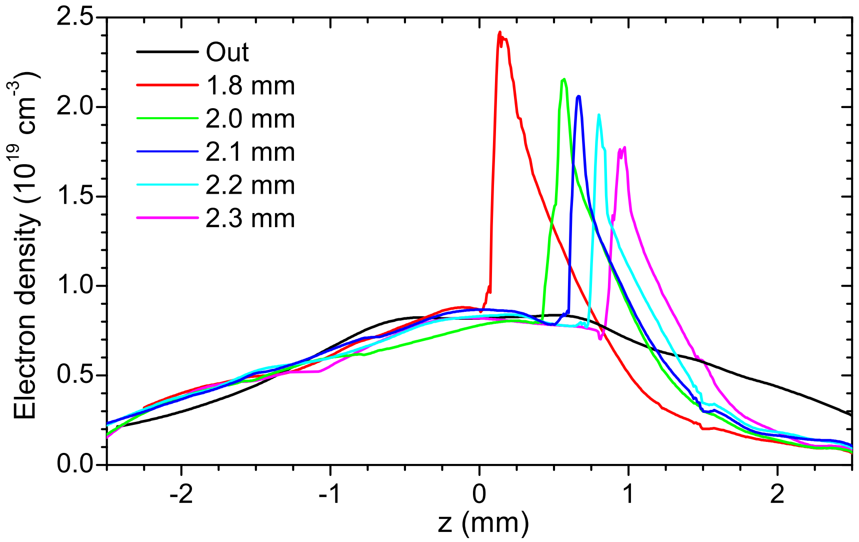
Shorter acceleration length in the first stage

Electrons reach the dephasing region in the first stage



Density and length of the second stage decreases with increasing shock position

Energy gain = 130 MeV (~50%)



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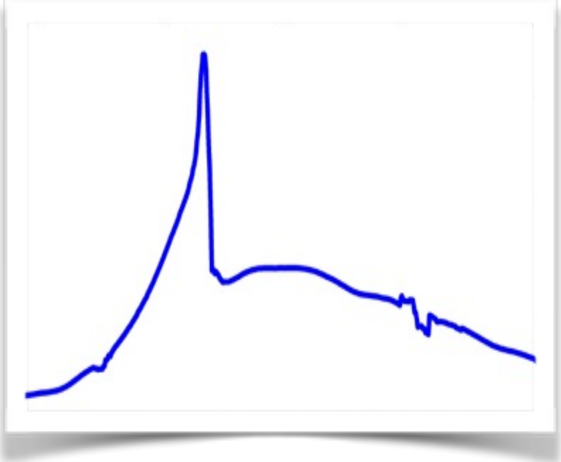

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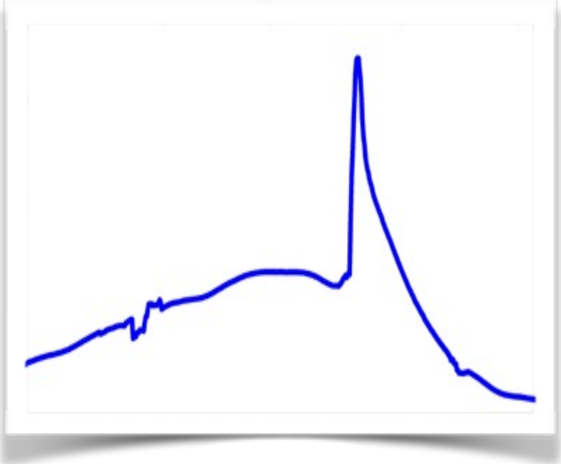

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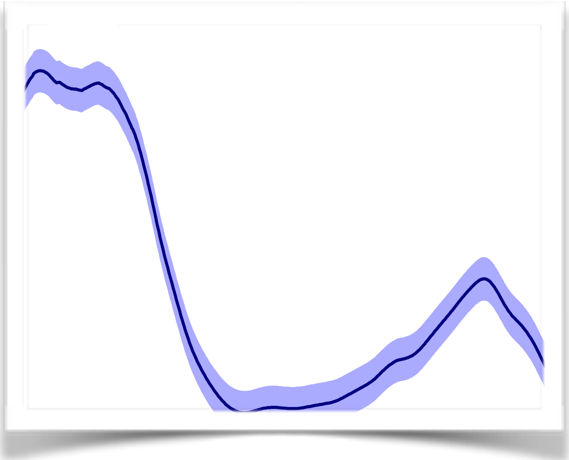
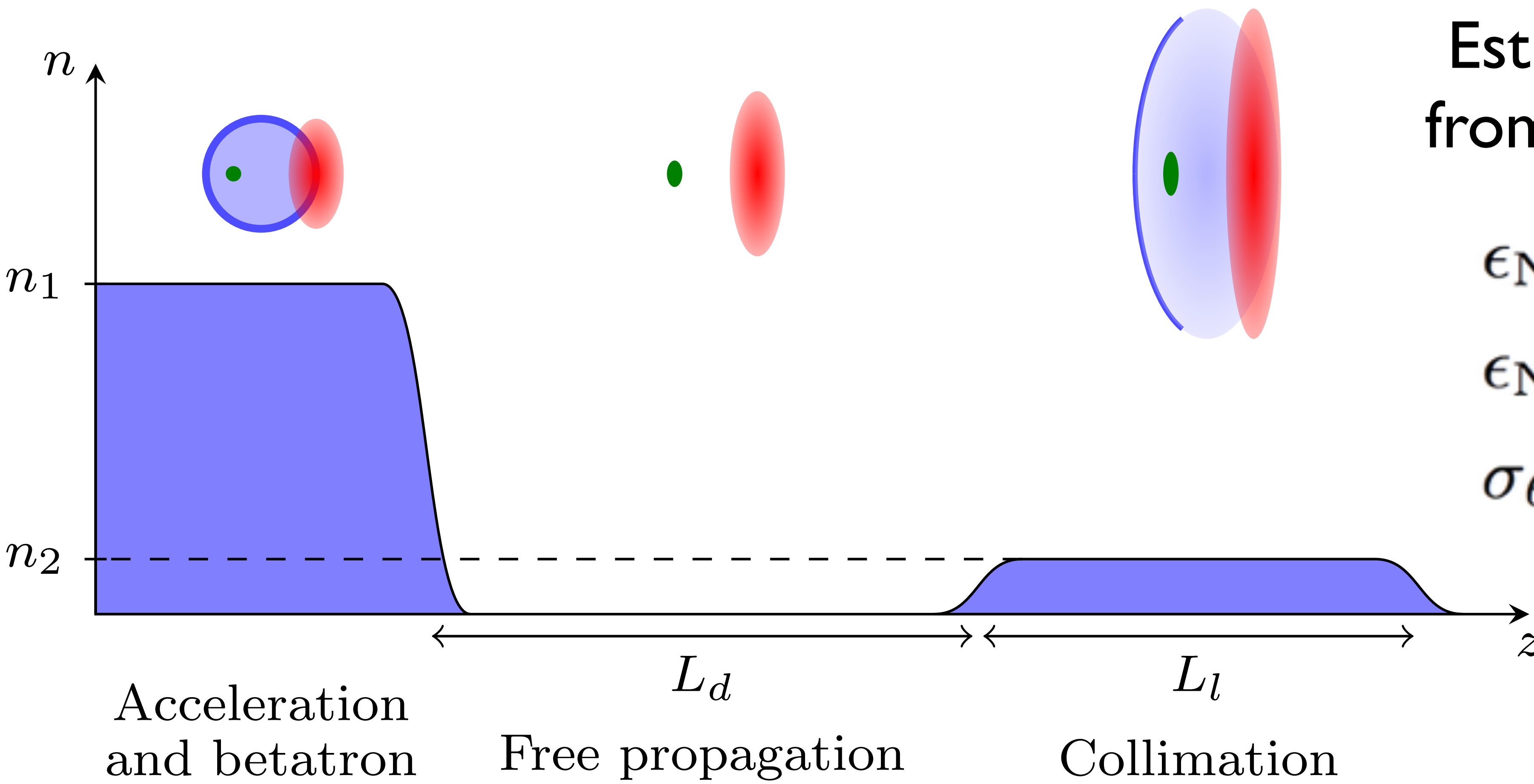


III. Laser plasma lens

Principle of Laser Plasma Lens



Estimate of final divergence from emittance conservation

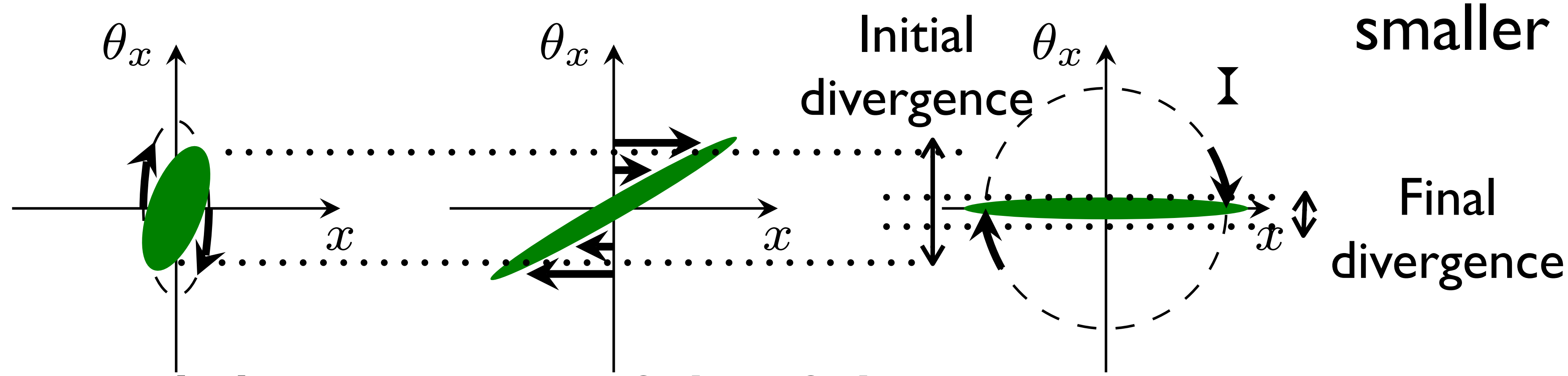
$$\epsilon_{\mathrm{N}} \approx \gamma \sigma_{\mathrm{x}} \sigma_{\theta}$$

$$\epsilon_{\mathrm{N}} \approx \gamma (\sigma_{\theta \mathrm{ini}} L_d) \sigma_{\theta \mathrm{min}}$$

$$\sigma_{\theta \mathrm{min}} \approx \epsilon_{\mathrm{N}} / (\gamma \sigma_{\theta \mathrm{ini}} L_d)$$

⬇

Longer drift lenght smaller possible divergence



No correlation between x and θ_x

$x = x_0 + \theta_x L_d \sim \theta_x L_d$ ($x_0 \sim 0.1$ µm, $\theta_x \sim 3$ mrad)

R. Lehe *et al.*, Phys. Rev. ST Accel. Beams **17**, 121301 (2014)

Experimental setup

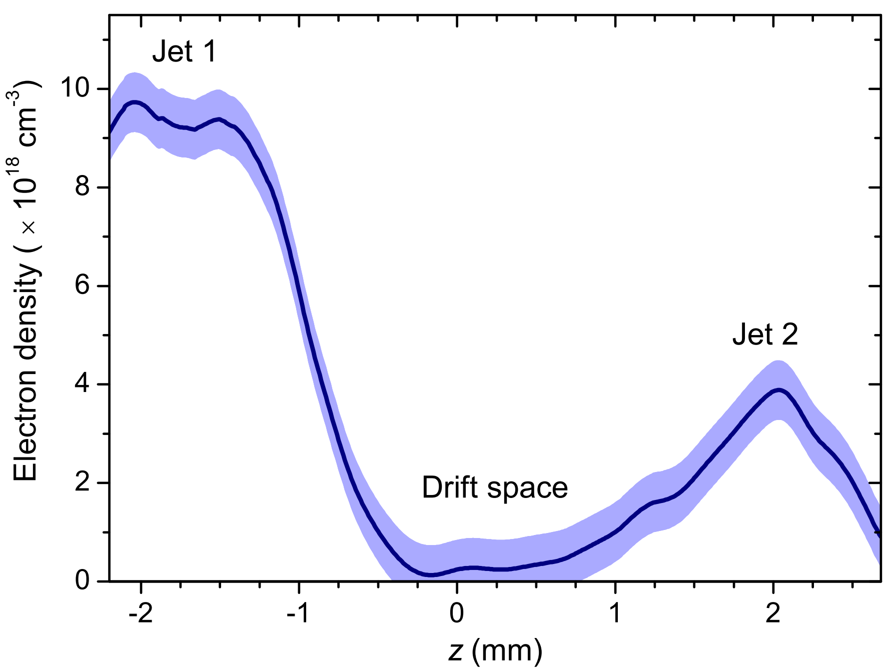
Acceleration stage

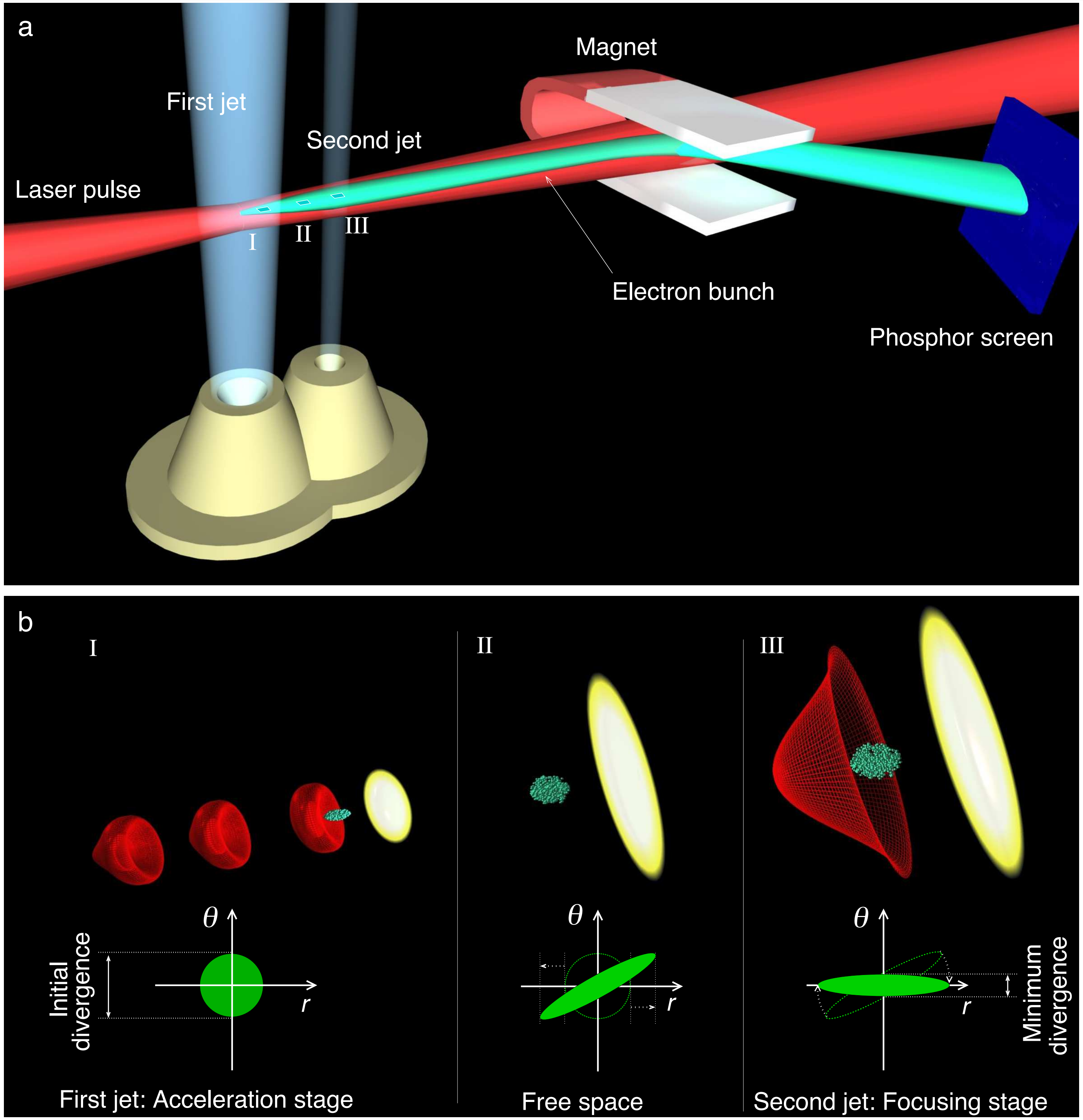
Laser beam
0.9 J, 28 fs, 12 microns FWHM

Focused with a 1 m OAP at the entrance of a 3 mm gas jet
$$n_1 = 9.2 \times 10^{18}\ \mathrm{cm}^{-3}$$

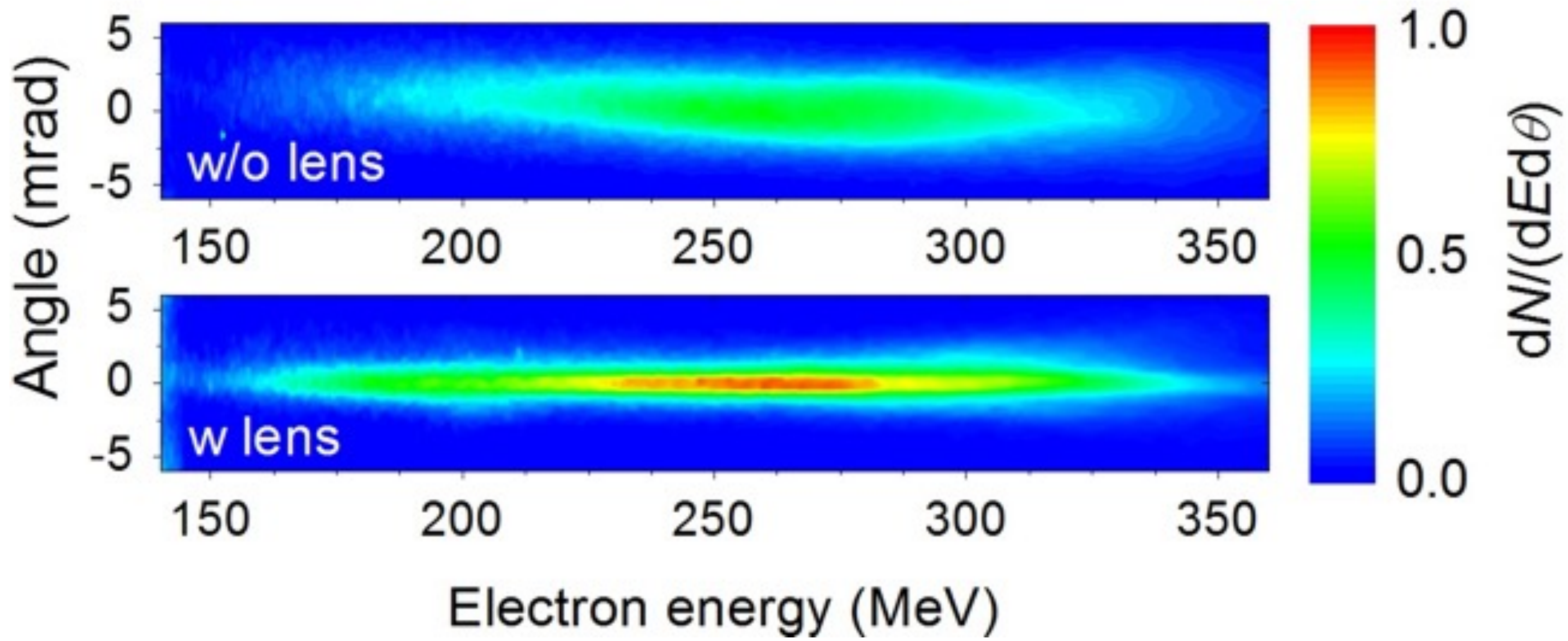
Focusing stage

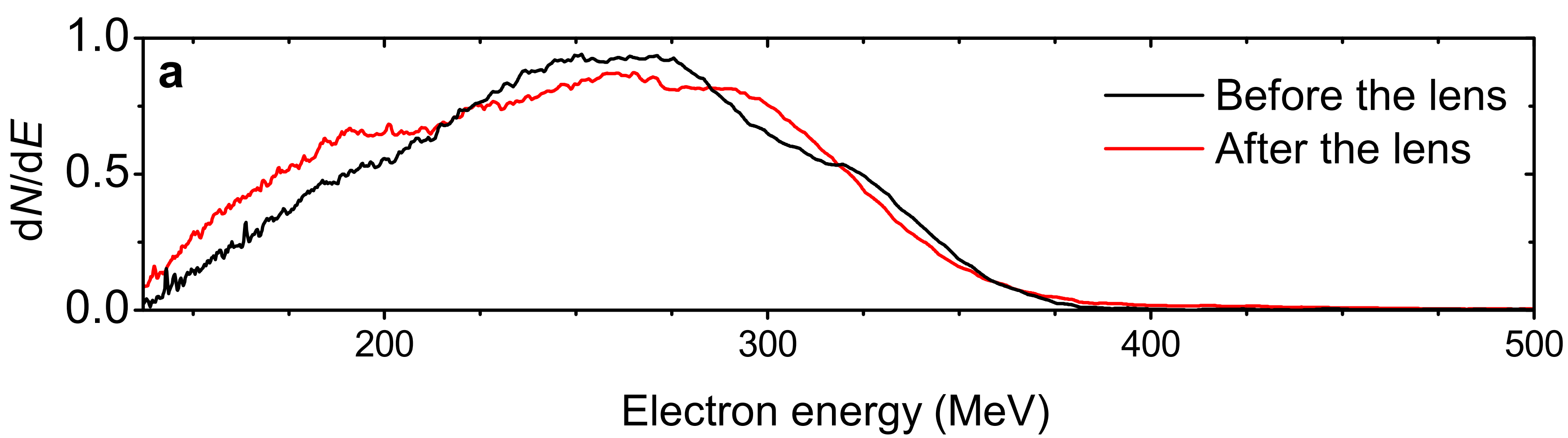
1 mm nozzle with variable n_2
Variable L_d





Demonstration of beam focusing





Focusing stage parameters :

L_d = 1.8 mm

n_2 = 3.9 x 10^{18} cm^{-3}

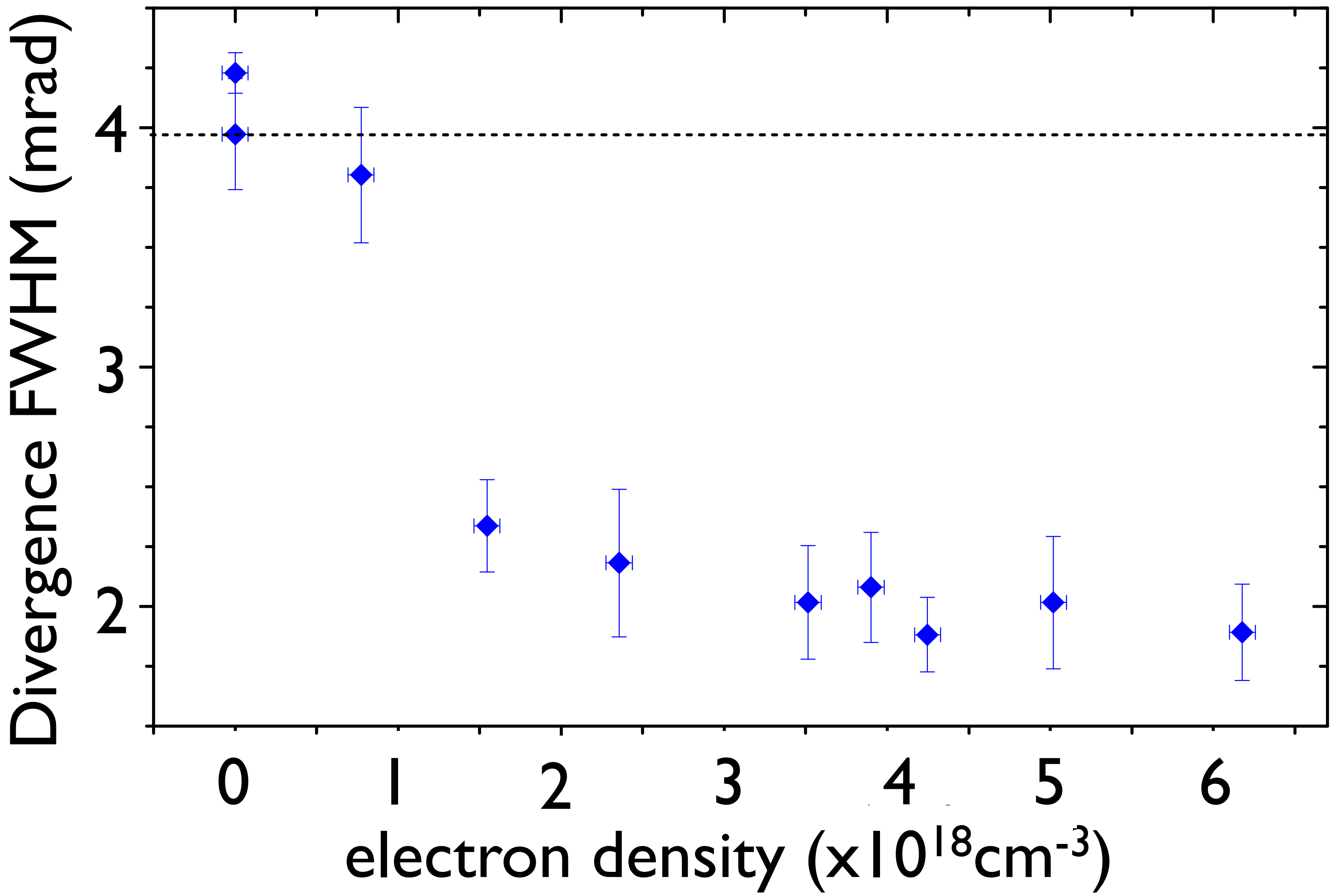
Divergence after the lens (FWHM)

$$\sigma_\theta = 1.6 \pm 0.2 \text{ mrad}$$

Divergence reduction ~ 2.6 ± 0. 7

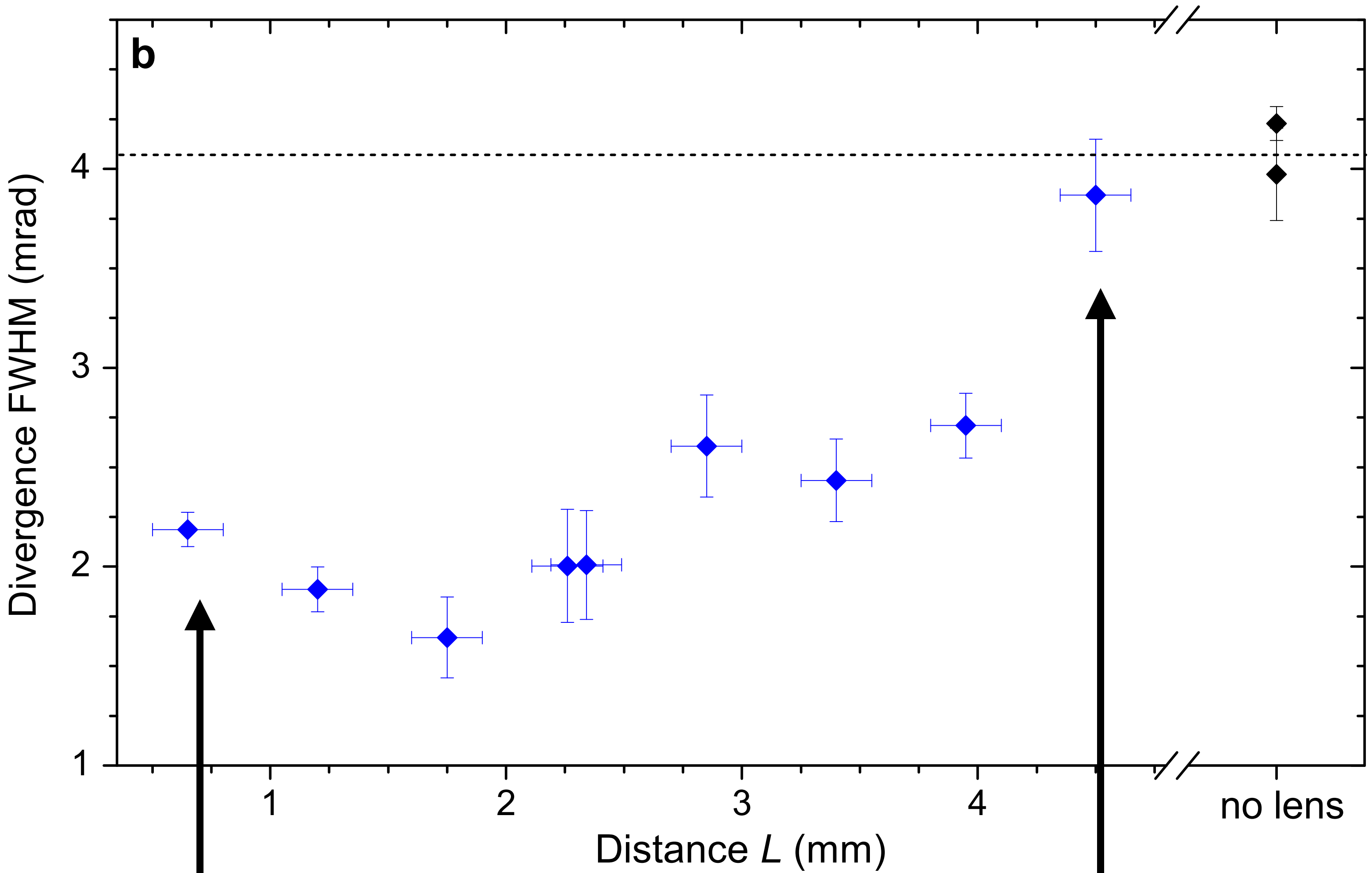
C. Thaury *et al.*, Nature Comm. 6, 6860 (2015)

Influence of the lens density



$$F_x \sim \underbrace{k_p \sigma_z \exp(-k_p^2 \sigma_z^2/2)}_{\text{Amplitude of the wakefield}} \underbrace{\sin(k_p d)}_{\text{Position of the electron beam in the wakefield}}$$

Influence of the free drift length



excessive focusing
L_d too short

insufficient focusing
L_d too long

Two effects governed the divergence reduction :

- decrease of the minimum achievable divergence $\sigma_{\theta,min} = \varepsilon_x / \gamma \sigma_\theta L_d$
- decrease of the laser intensity with increasing L_d

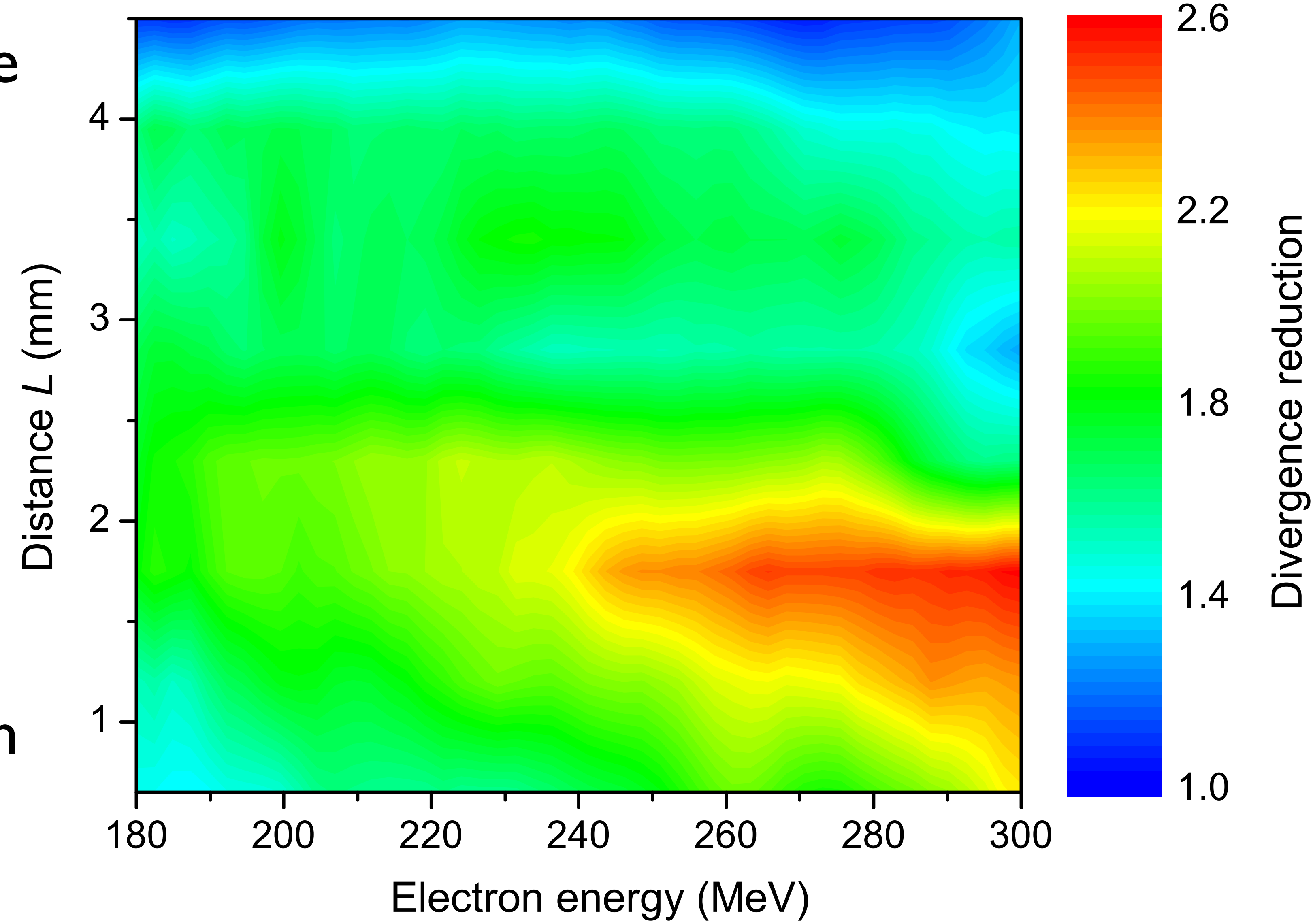
Chromaticity of the laser-plasma lens

Electrons of different energies are not focused to the same extend

Stronger divergence reduction at higher energies

$$\sigma_{\theta,min} \propto (\sigma_\theta \gamma)^{-1}$$

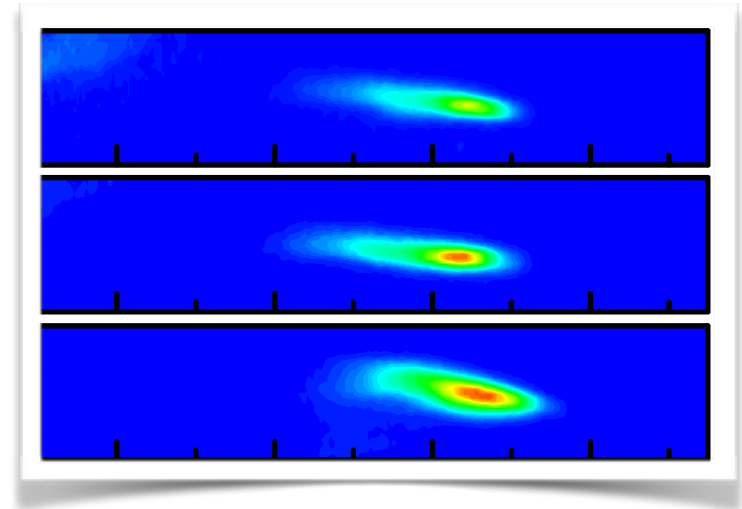
Optimal L_d decreases as electron energy increases



Conclusion

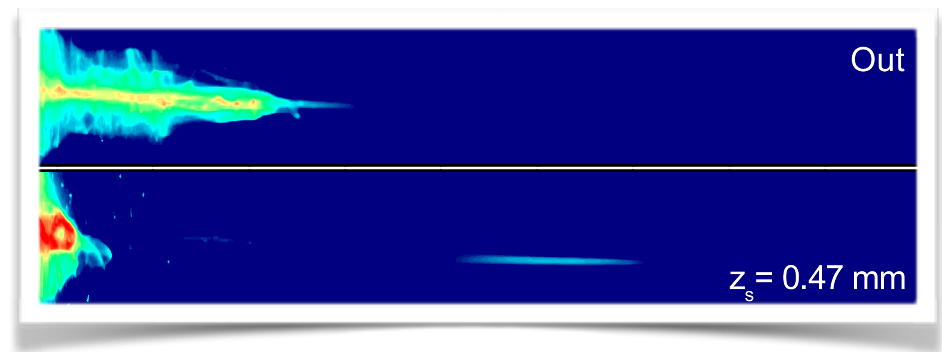
Shock assisted ionization injection

- More stable than shock front injection
- Much smaller energy spread than ionization injection



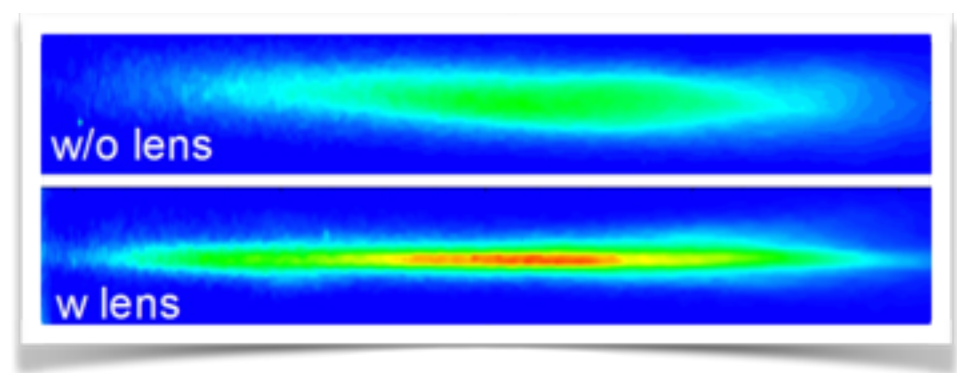
Electron beam rephasing

- Simple setup to increase the beam energy by 50%



Laser plasma lens

- Divergence reduced by 2,6
- No emittance growth for drift length <10 cm (and $\Delta E/E<2\%$)



Acknowledgements

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Laboratoire d'Optique Appliquée, ENSTA ParisTech – Ecole Polytechnique – CNRS, Palaiseau, France

PhD and post-doctoral positions at LOA
Permanent position for Laser Engineer, Technician
PhD and Post-doc at WIS

ERC/X-five, Charpac/Laserlab³ & Anac²/Eucard²