LASER WAKEFIELD ACCELERATION IN TAILORED UNDERDENSE PLASMAS

E. Guillaume[1], A. Döpp[1], C. Thaury[1], K. Ta Phuoc[1], A. Lifschitz[1] and V. Malka[1]

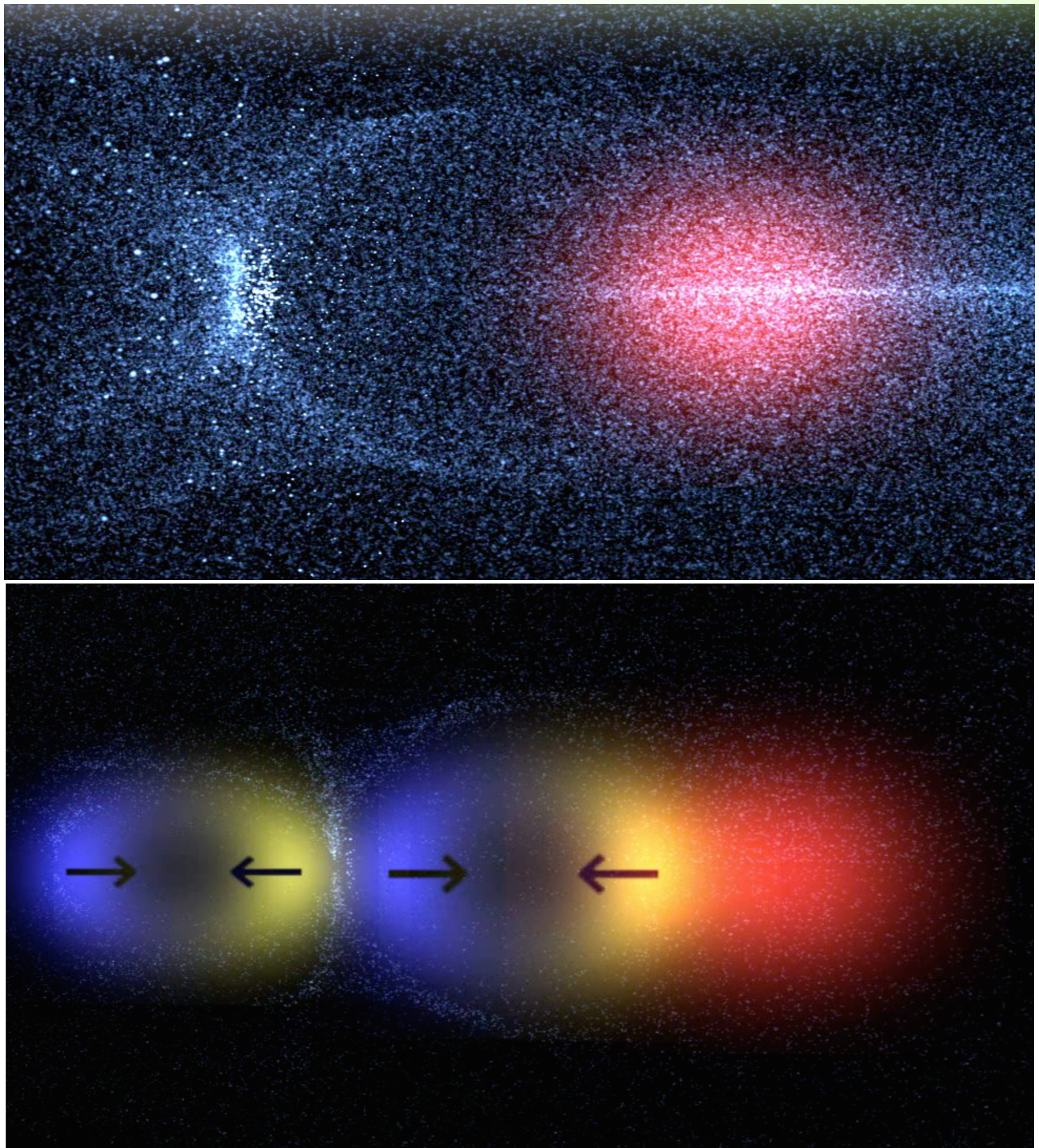
[1] *Laboratoire d'Optique Appliquée, École Polytechnique - CNRS UMR7639 - ENSTA ParisTech, Palaiseau, FRANCE*

 emilien.guillaume@polytechnique.edu

Outline

1. Laser-plasma electron acceleration
2. Electron energy boost by tailoring the plasma density
3. The laser-plasma lens

Electron acceleration

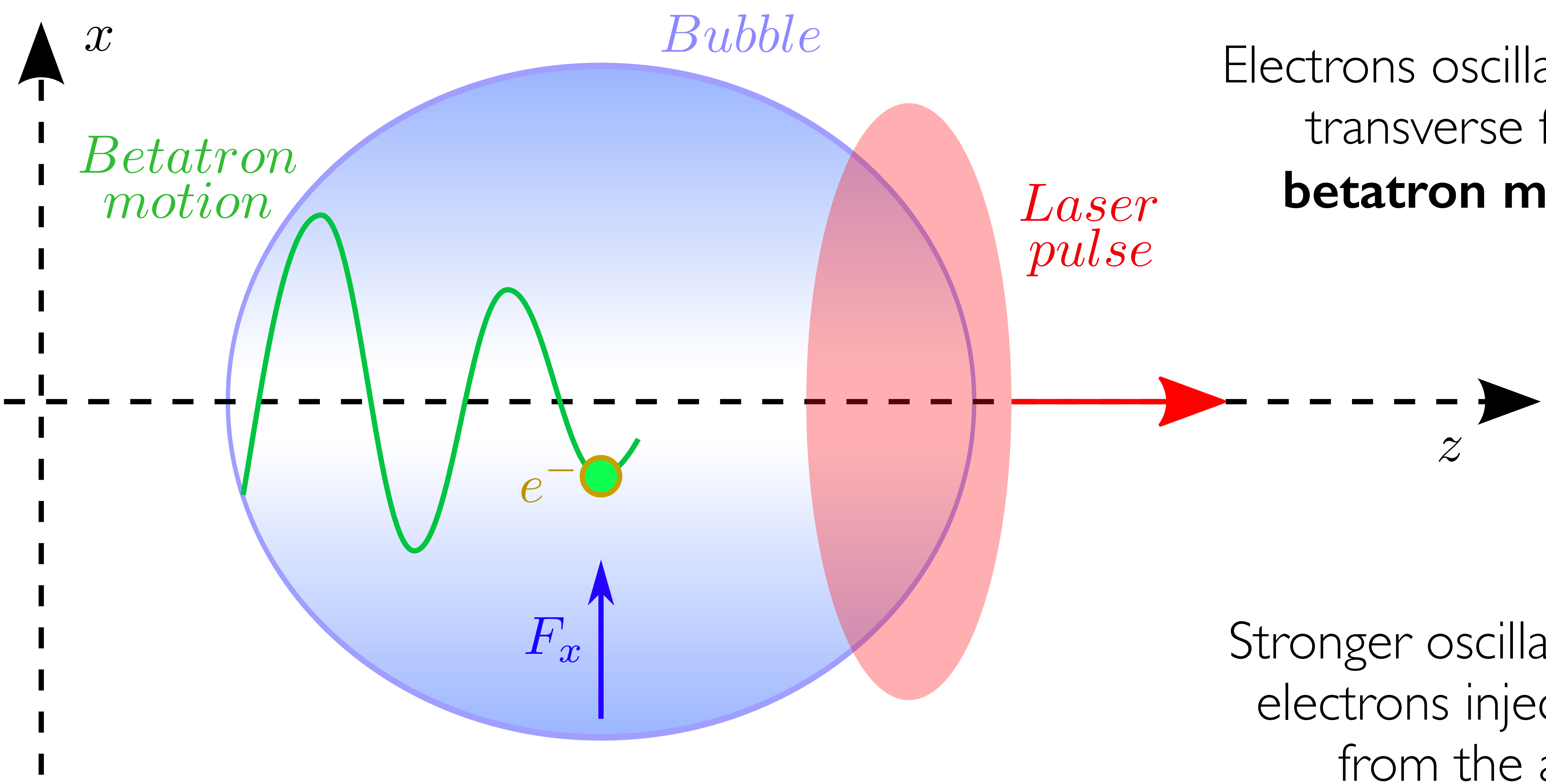


Laser :
Power : multi TW
Pulse duration ~ 30 fs
Focal spot size ~ 10 µm

Plasma :
Gas density ~ 10^{18} -10^{19} cm^{-3}
Wakefield λ_p ~ 30 µm
Longitudinal field : ~ 100 $GV.m^{-1}$

Electrons :
Energy 10 MeV - 3 GeV
Charge 1 - 100 pC
Duration 1 - 50 fs

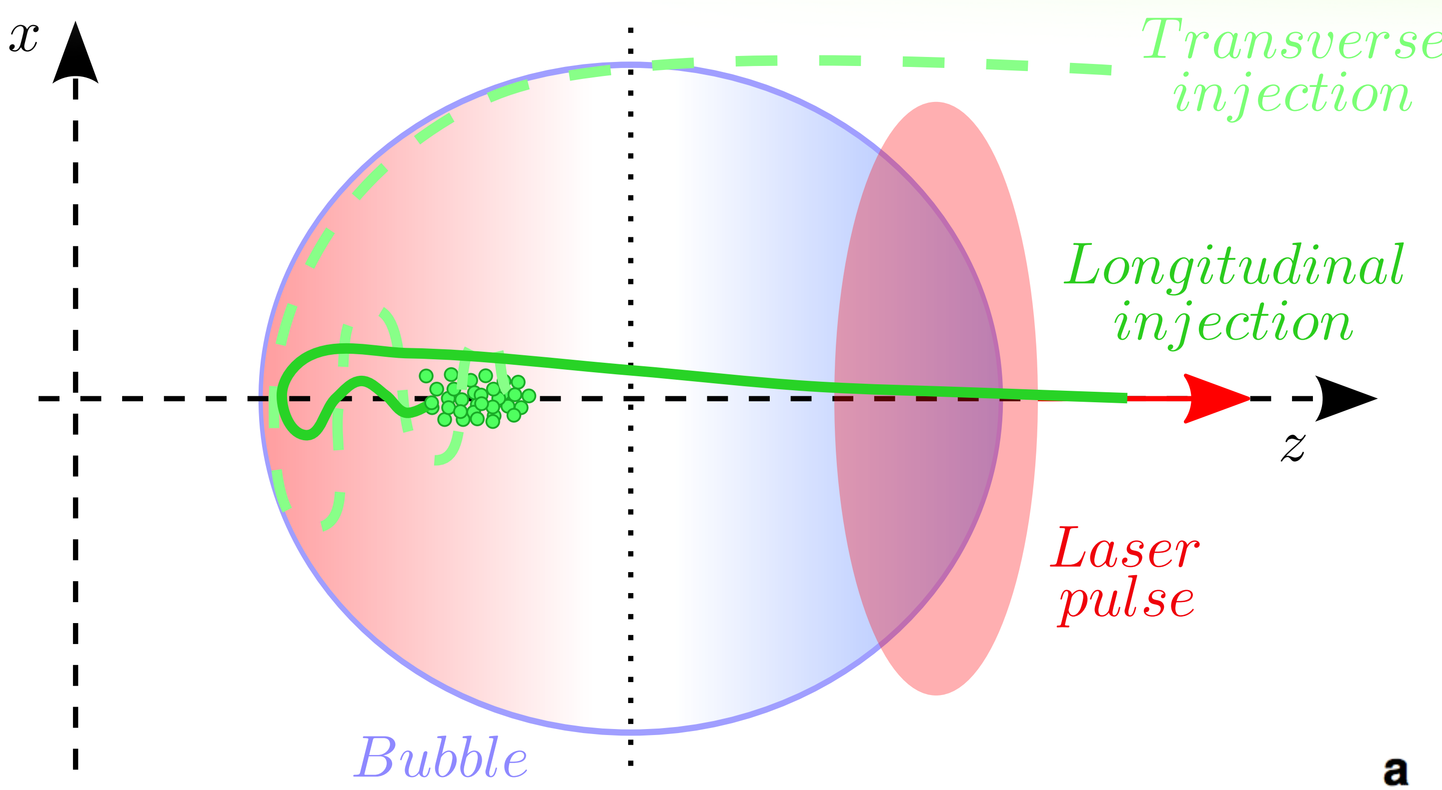
Transverse fields and Betatron oscillations



Electrons oscillate in the transverse field : **betatron motion**

Stronger oscillations for electrons injected far from the axis

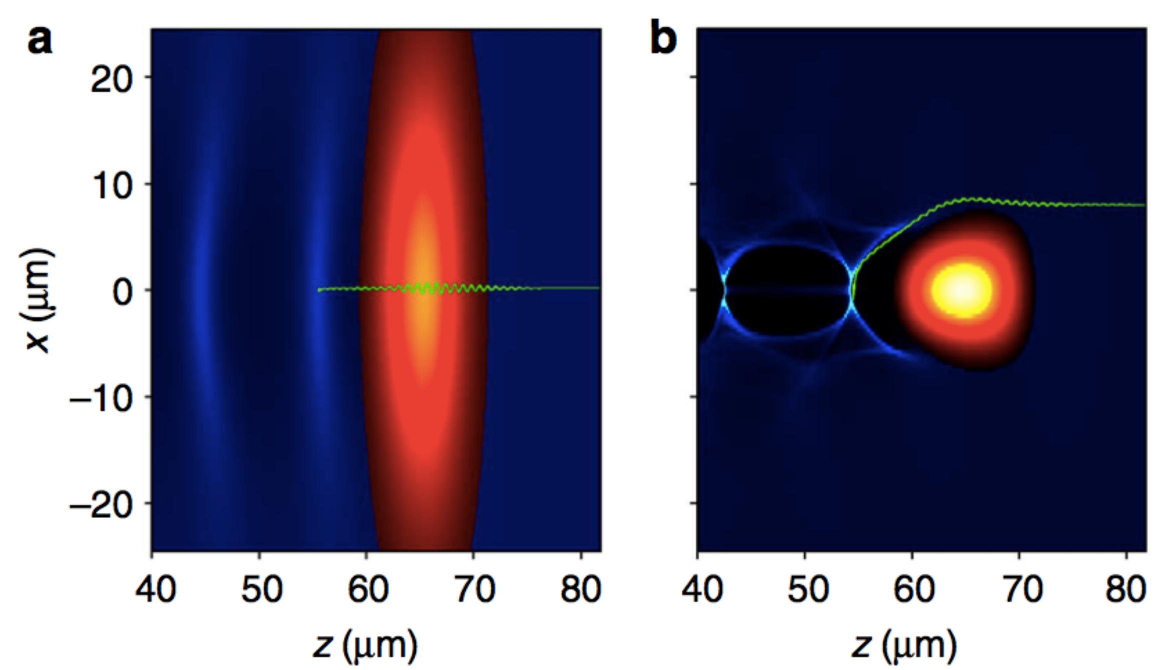
Longitudinal self-injection



Self-injection (wave-breaking process) : most common and easier method of injection

Transverse self-injection : off-axis, strong oscillations, high charge, unstable

Longitudinal self-injection : on-axis, weak oscillations, low charge, stable



Corde *et al.*, (2013), **Nat. Comm. 4**, 1501 loa

2. Electron energy boost by tailoring the plasma density

Pushing the limits of the accelerator

After some acceleration distance, electrons are faster than the plasma wave and enter the decelerating phase of the wakefield

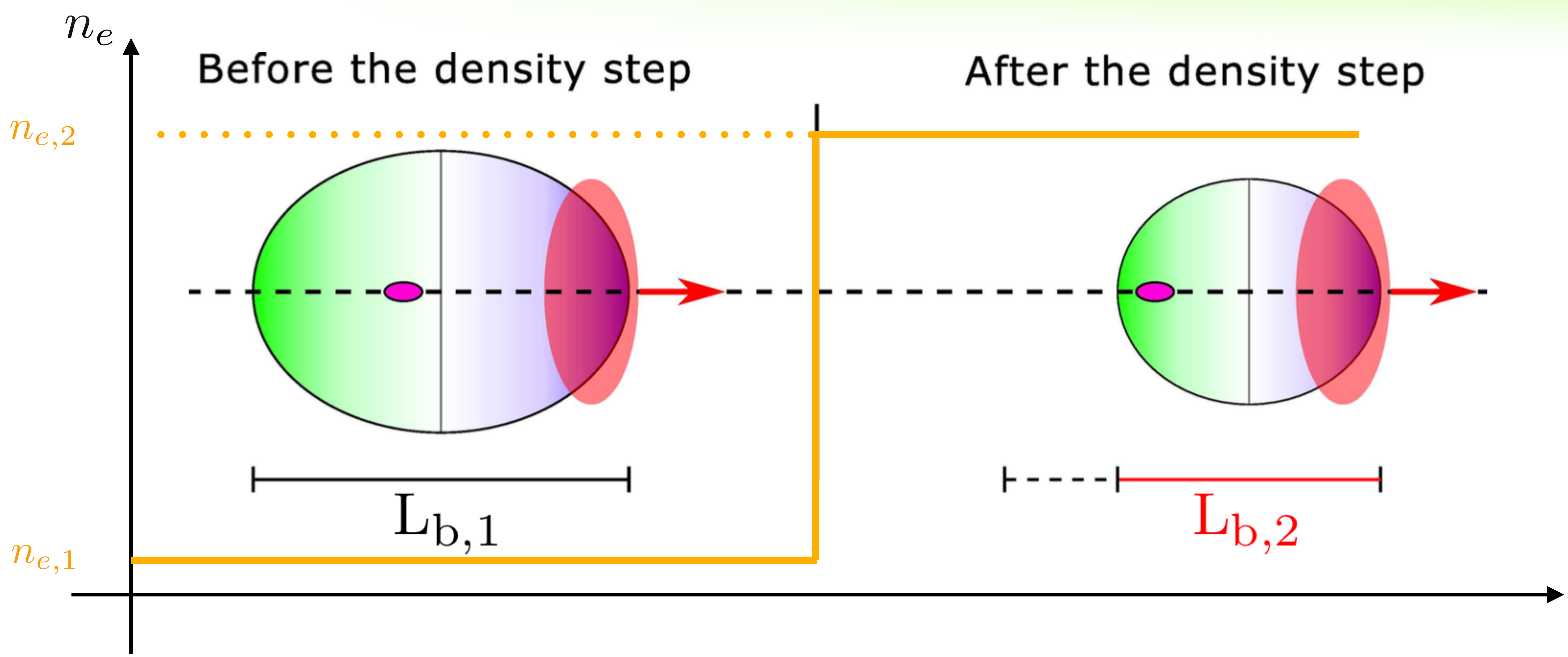
↓

Dephasing limits the maximum attainable energy in a laser-plasma accelerator

Objective

Mitigate the dephasing effects by resetting the phase of electrons before reaching the dephasing length

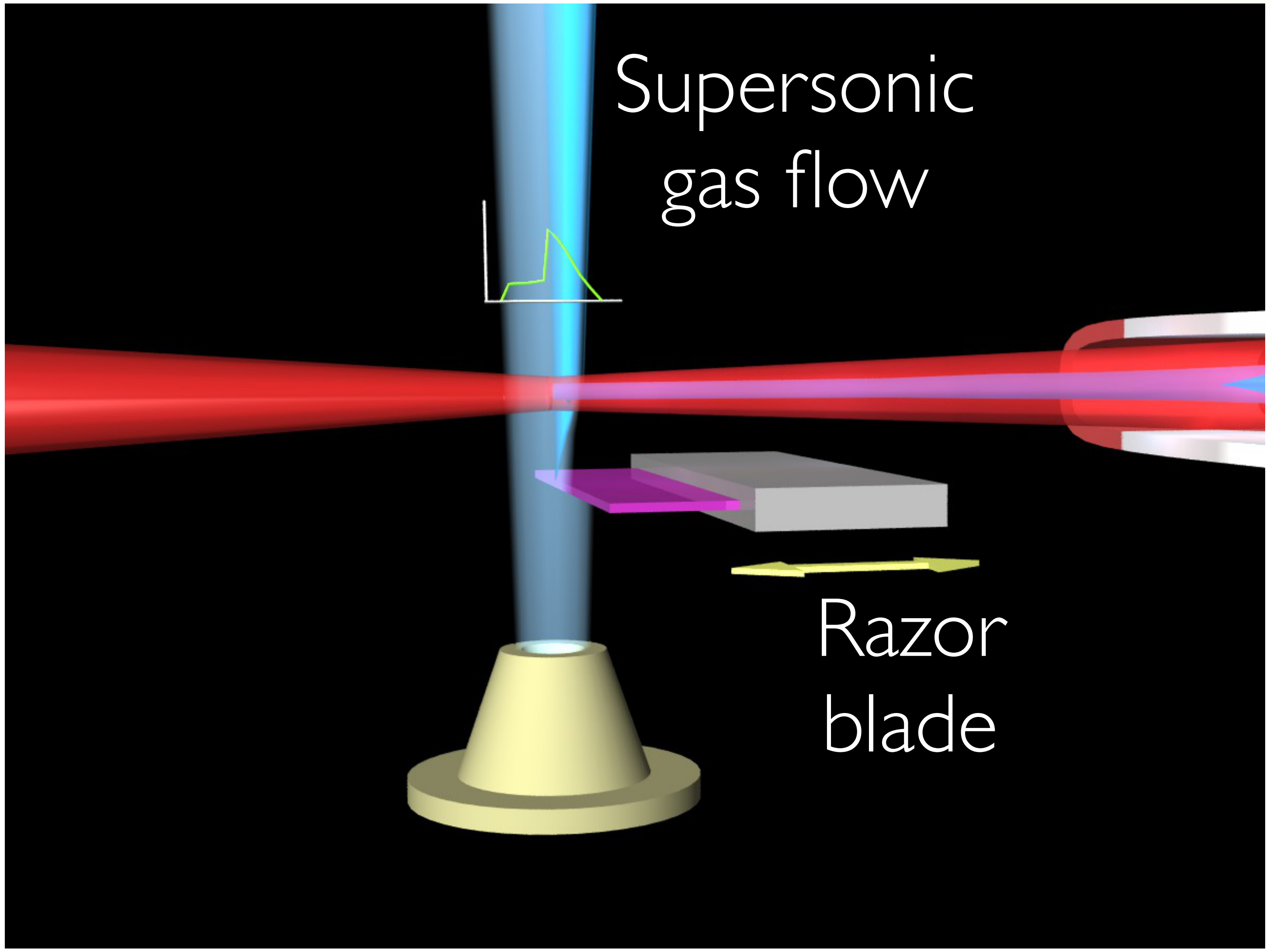
Pushing the limits of the accelerator

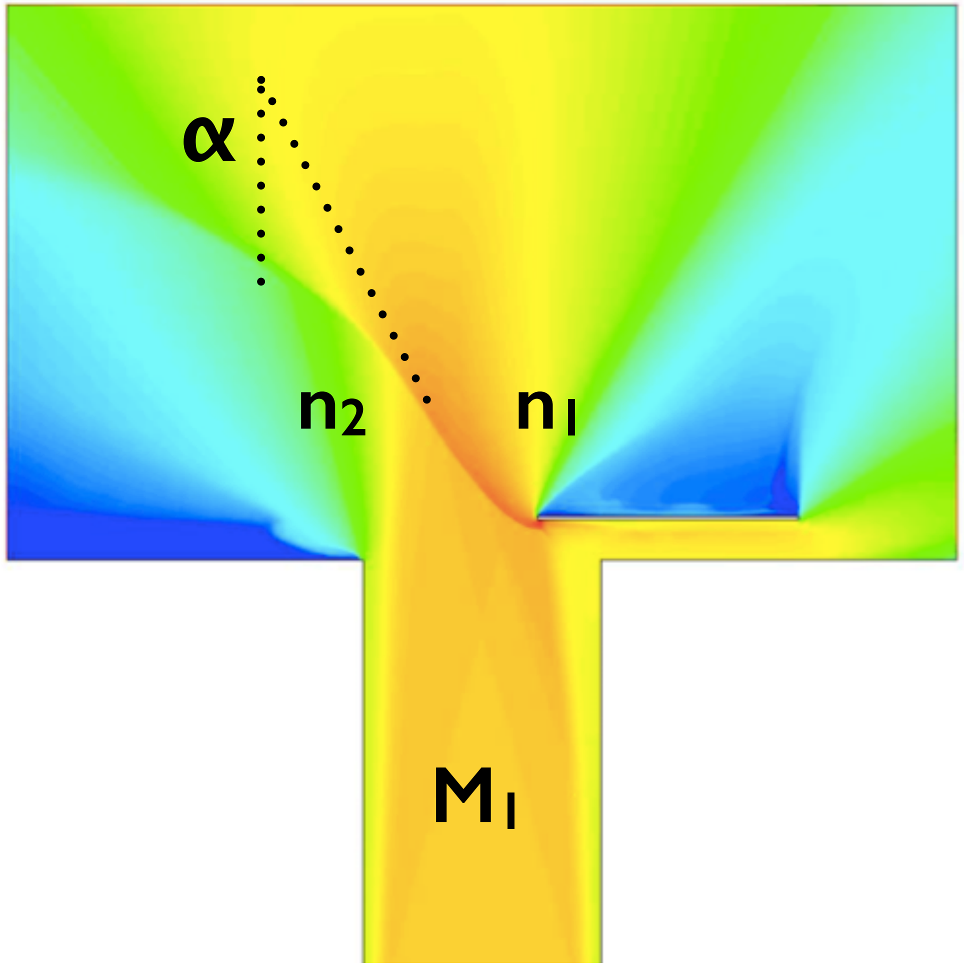


Phase resetting by crossing a sharp upward density transition : the electrons phase slippage is compensated by reducing abruptly the cavity size L_b

$$L_b \sim \lambda_p \propto n_e^{-1/2}$$

Gas jet machining : formation of a two densities plasma

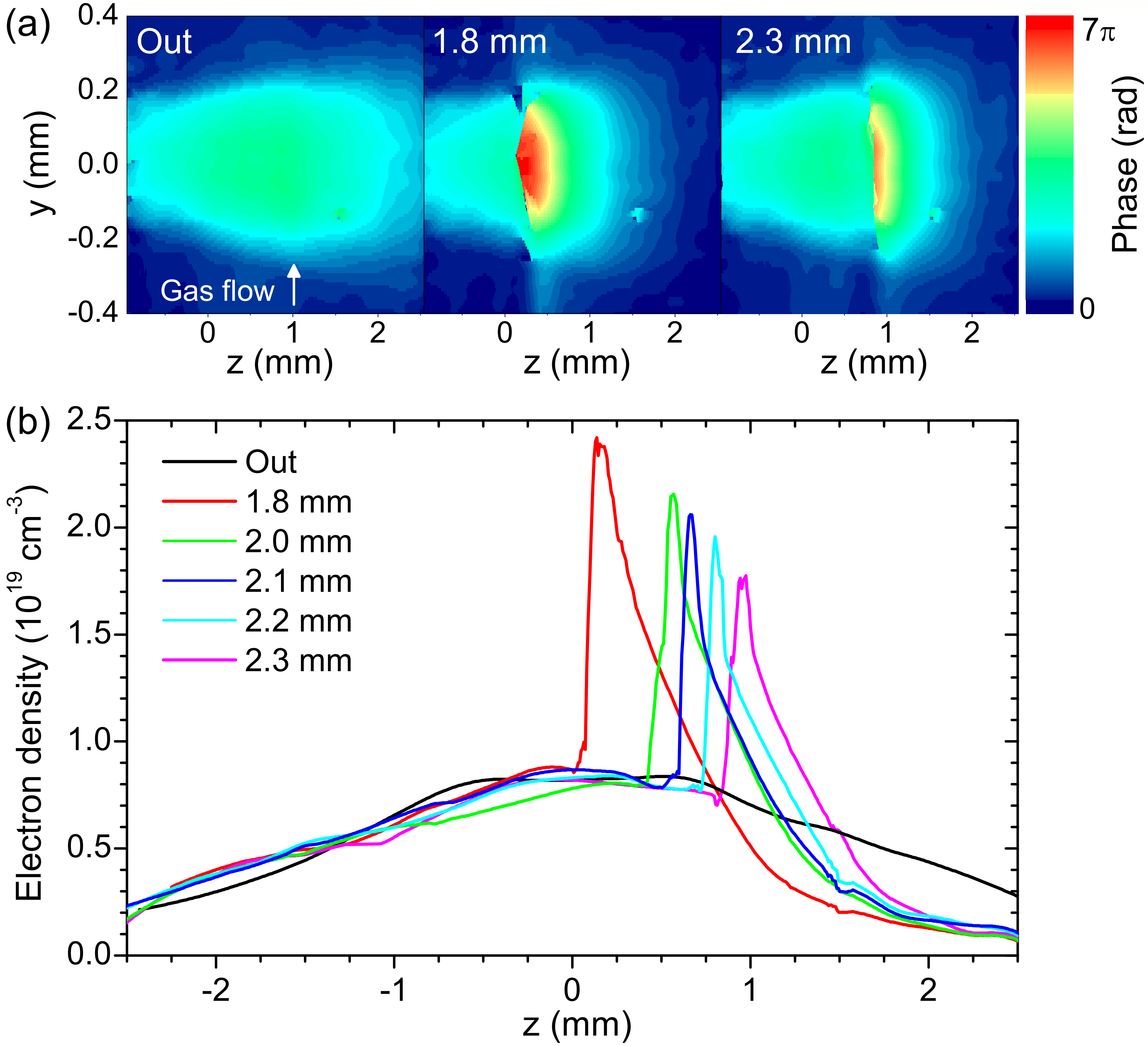




$$\frac{n_1}{n_2} = 1 - \frac{2}{\kappa + 1}\left(1 - \frac{1}{(M_1 \sin\alpha)^2}\right),$$

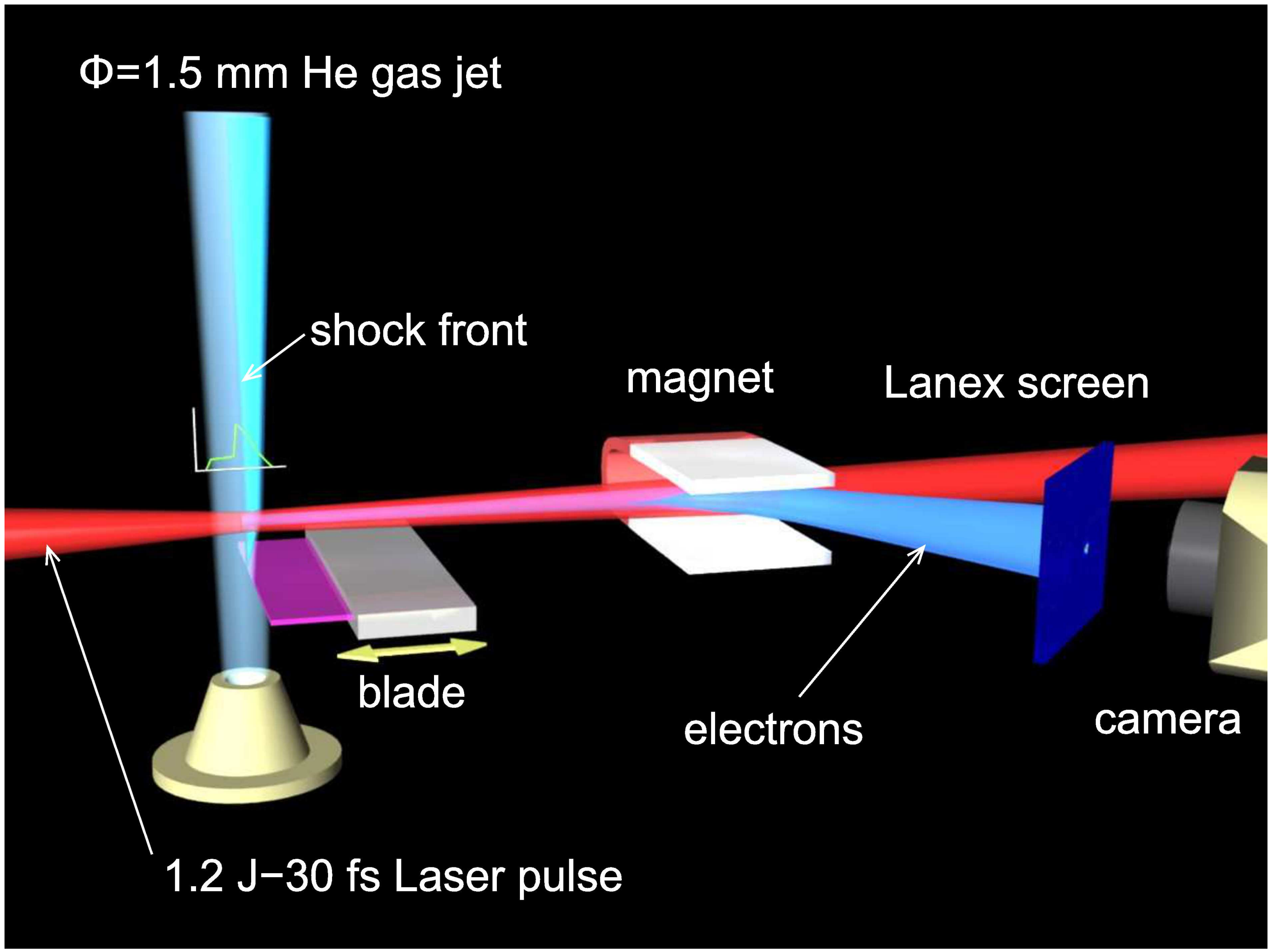
Sharp upward density transition created by a shock front with a razor blade inserted in a supersonic gas jet (setup from Schmid *et al.* (2010), PRSTAB **13** 091301)

Plasma density profile



Density profiles measured with a Nomarski interferometer and Abel inversion

Experimental setup



Interaction beam :
1.2 J, 30 fs, 15 microns FWHM

$$I = 1 \times 10^{19}\ \mathrm{W.cm}^{-2}$$

Focused with a f/10 OAP at the entrance of a 1.5 mm supersonic gas jet

$$n_e = 8 \times 10^{18}\ \mathrm{cm}^{-3}$$

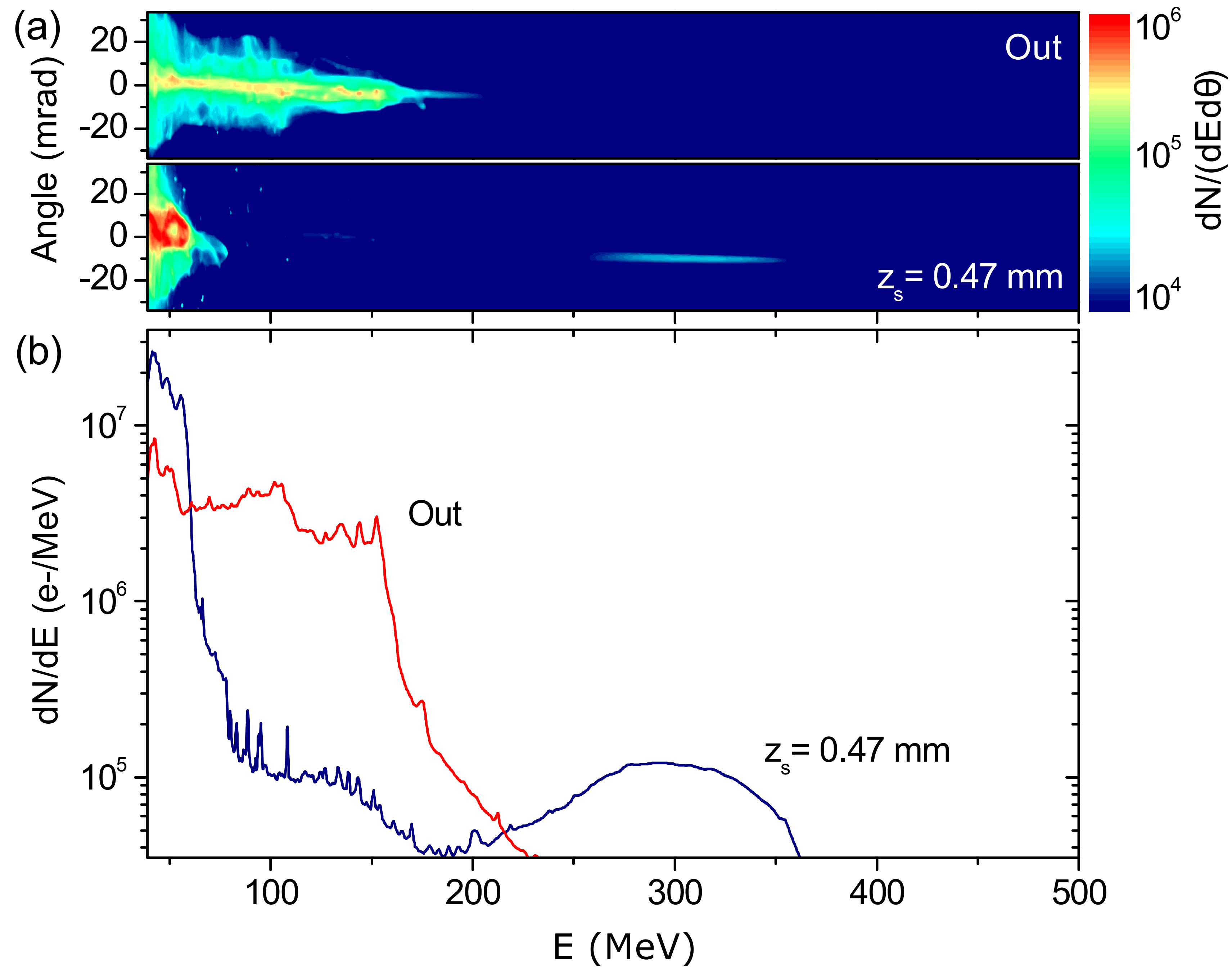
500 µm thick Silicon blade to create the shock

Transverse self-injection

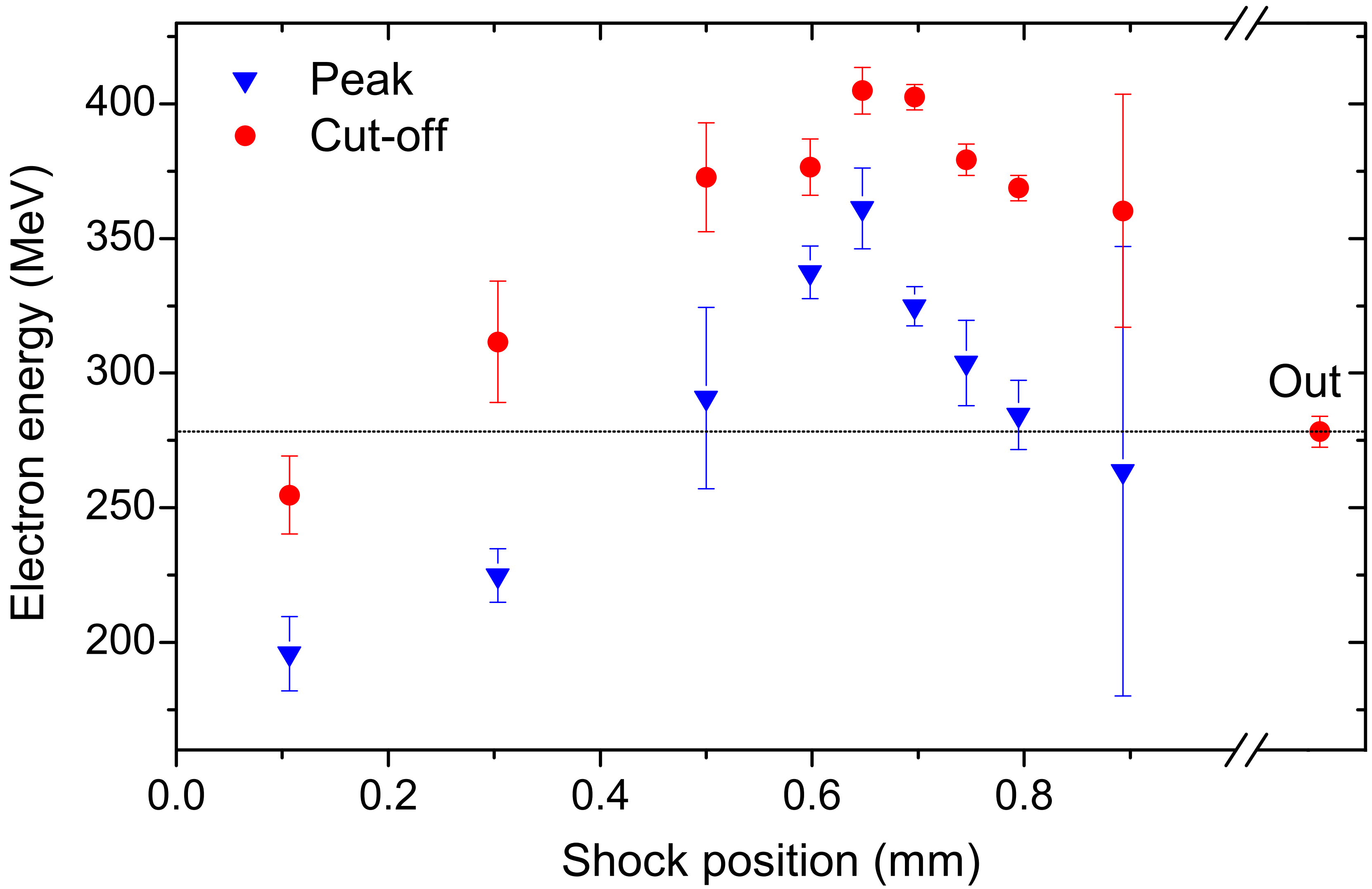
Electron spectra measurements

Blade out : electron spectrum rather flat, cut-off energy around 230 MeV

Blade in : part of electrons slow down and defocus and apparition of a quasi **mono-energetic peak at 300 MeV**



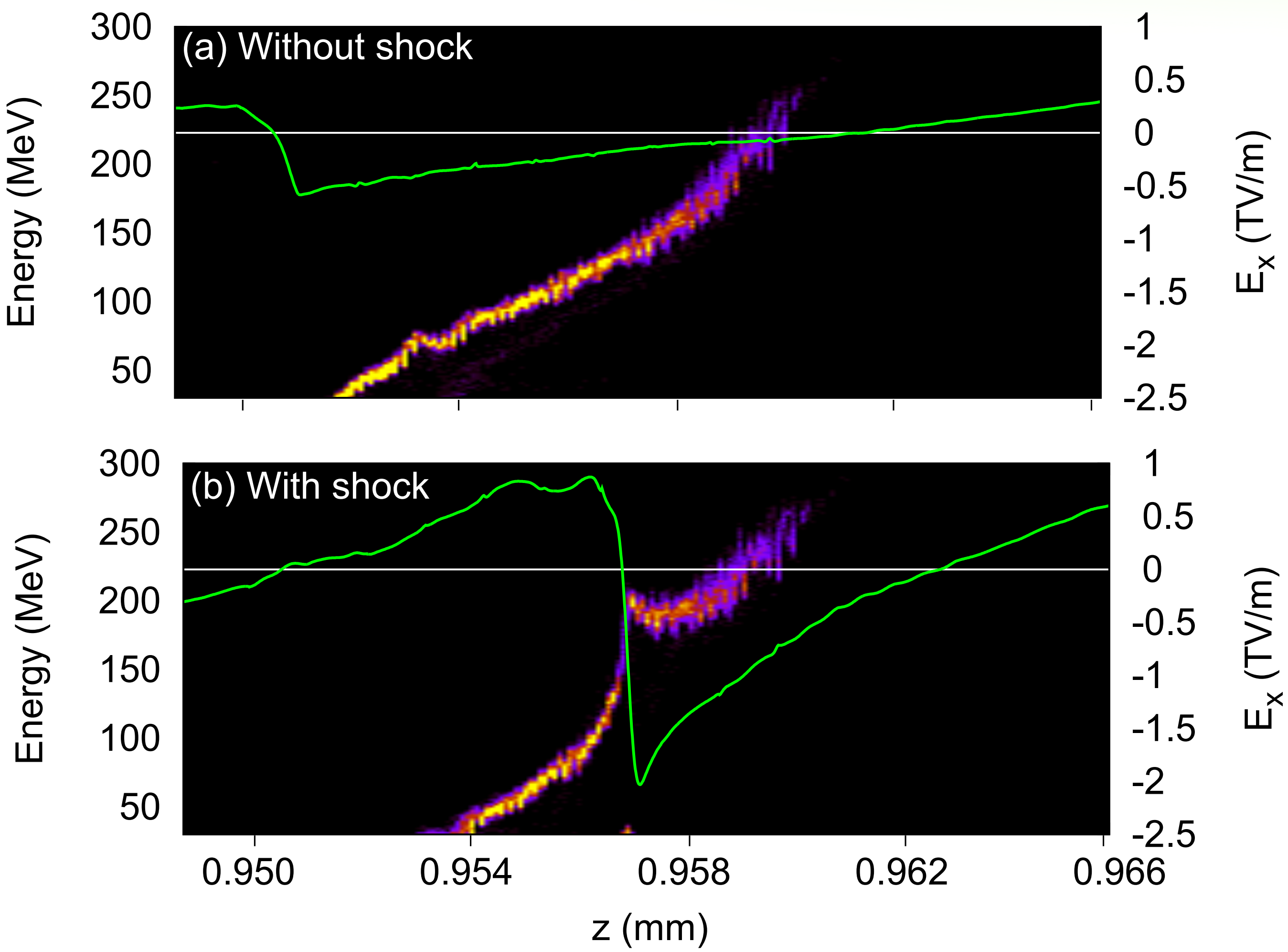
Changing the position of the shock

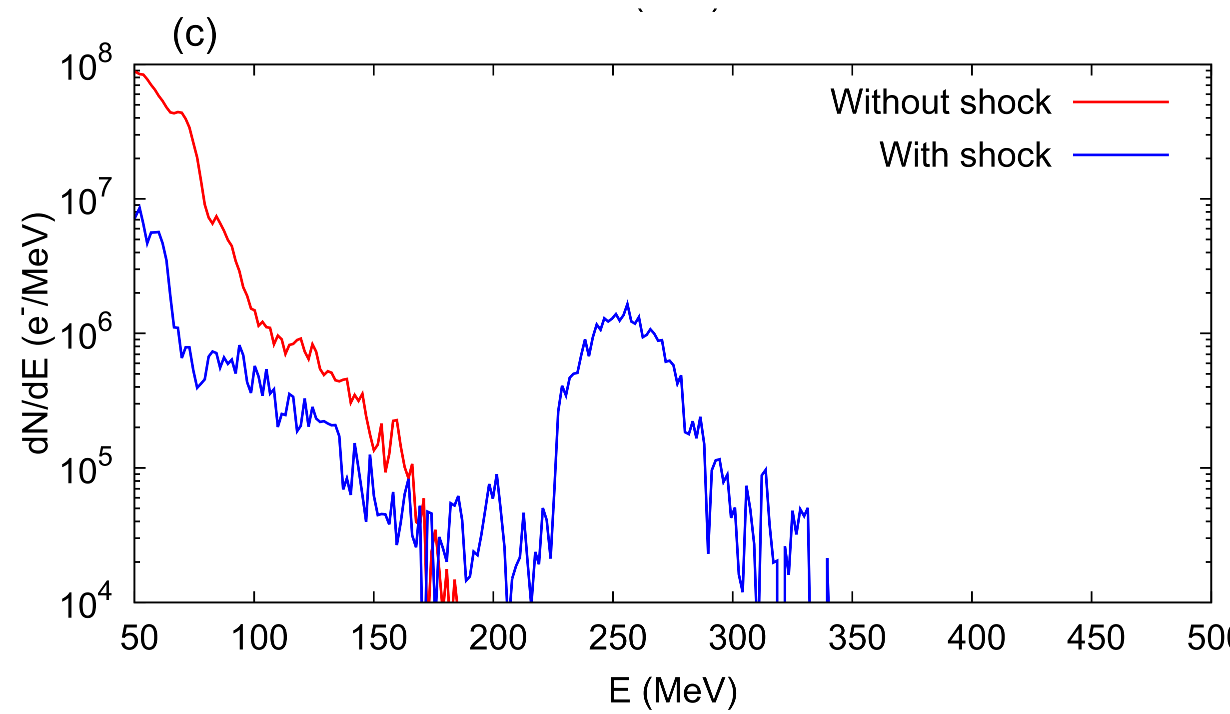


By changing the position of the shock, it is possible to change the energy gain of the peak

Optimum position of the shock : 150 MeV energy increase (**gain ~ 50%**)

Phase-space in PIC simulations





Without shock : lengthly self-injection creates a long electron bunch

Head of the bunch **decelerates** when reaching the center of the cavity

With shock : bubble shrinks after the density jump, its center is shifted

Head of the bunch shifts back at the tail of the bubble and is **accelerated**

3. The laser-plasma lens

Electron beam divergence and emittance

Emittance of the electron beam :

$$\varepsilon_{rms} = \sqrt{\underbrace{\langle x^2 \rangle}_{\text{Bunch size}} \underbrace{\langle x'^2 \rangle}_{\text{Beam divergence}} - \langle x x' \rangle^2}$$

Typical size of electron bunches : **< 1 µm**

Typical divergence of electron beams : **~ 4 mrad**

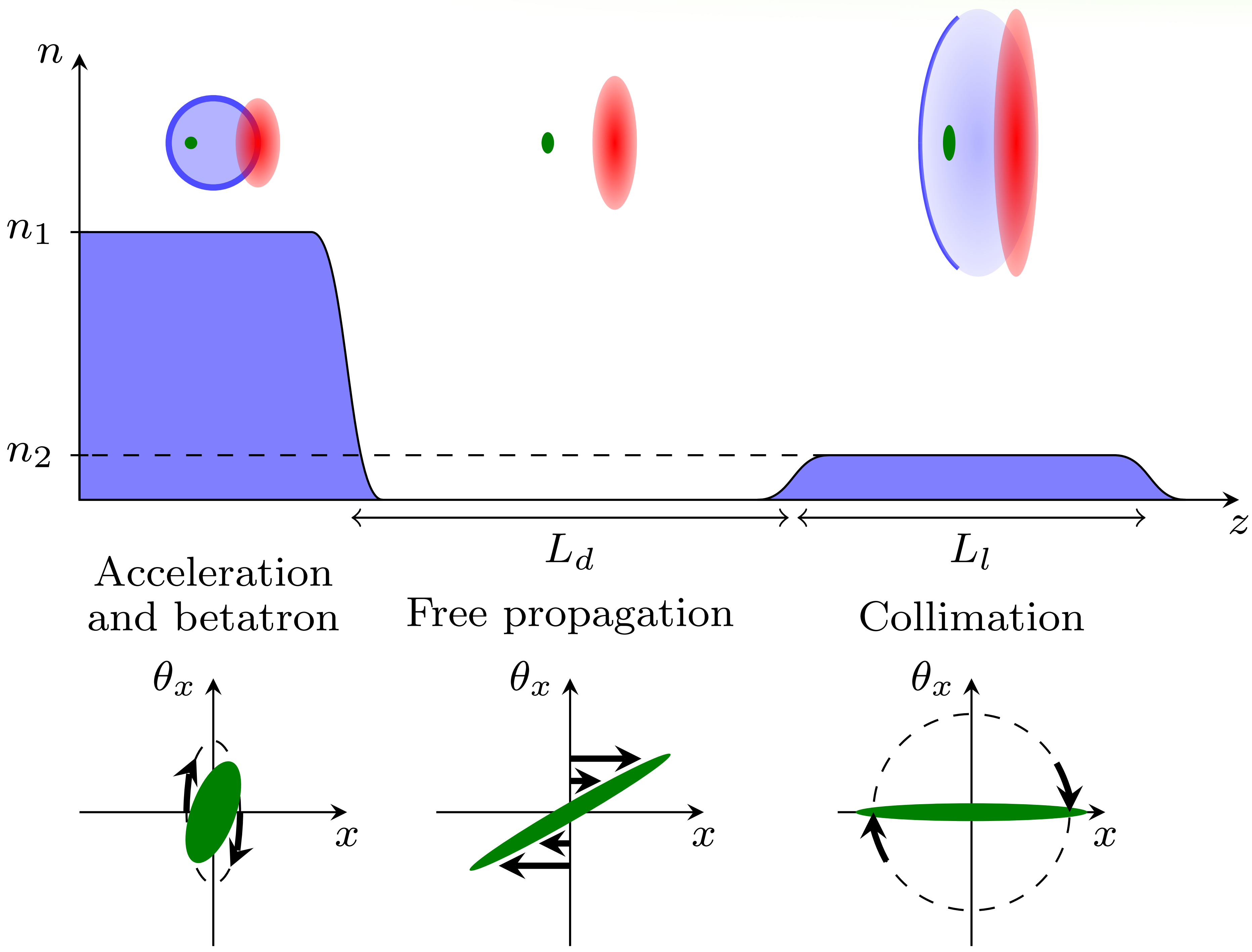
} Emittance dominated by the rather large divergence

→ Not convenient for applications (FEL, synchrotron radiation)

Objective

Reduce the divergence of the beam down to 1 mrad

Principle of the laser-plasma lens



Parameters of the laser-plasma lens :

- free propagation length L_d
- plasma lens length L_l
- plasma lens density n_2

tunability for optimal collimation

Experimental setup

Acceleration stage

Interaction beam :
0.9 J, 28 fs, 12 microns FWHM

$$I = 1.8 \times 10^{19}\ \mathrm{W.cm}^{-2}$$

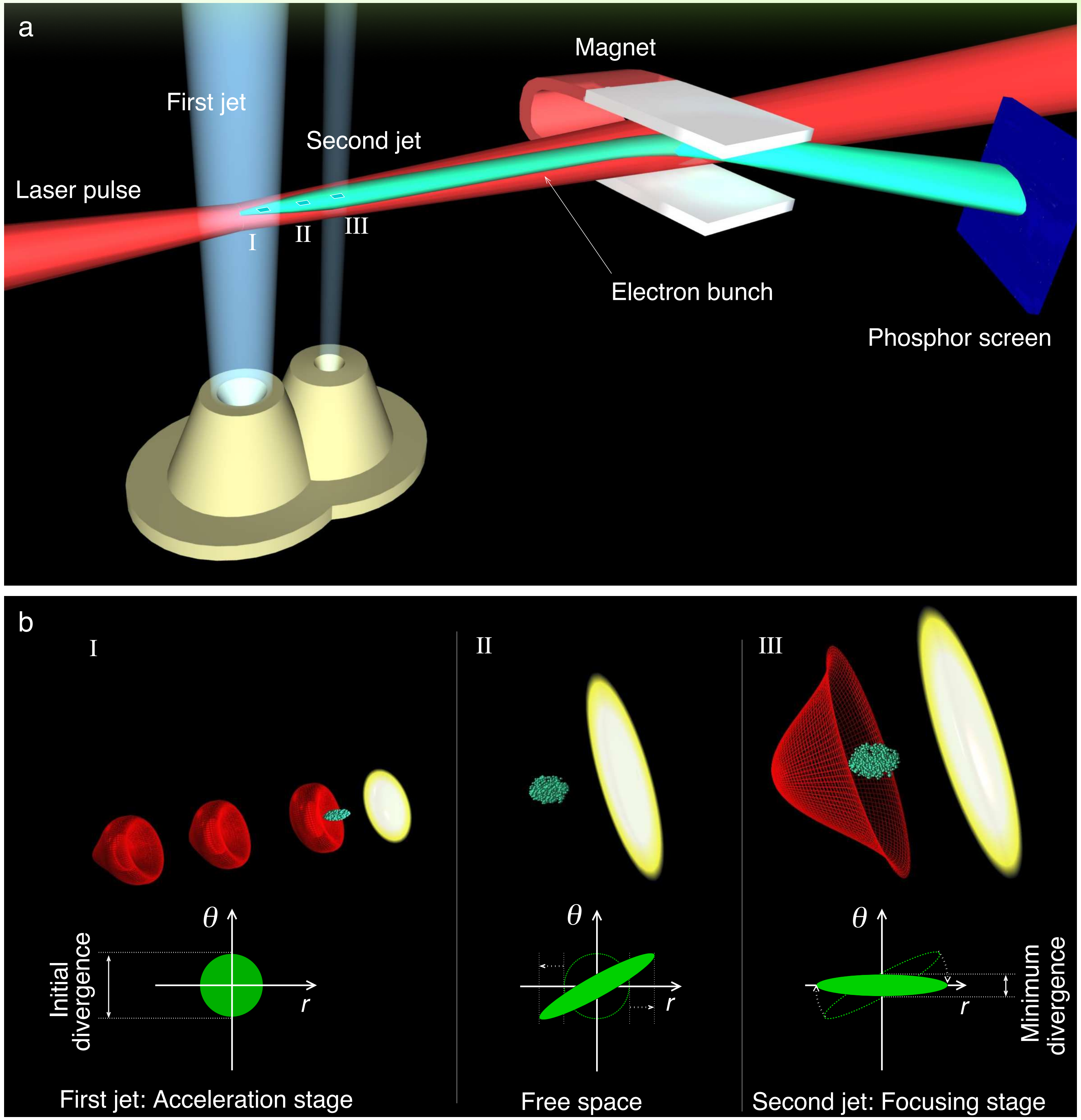
Focused with a 1 m OAP at the entrance of a 3 mm gas jet

$$n_1 = 9.2 \times 10^{18}\ \mathrm{cm}^{-3}$$

Longitudinal self-injection

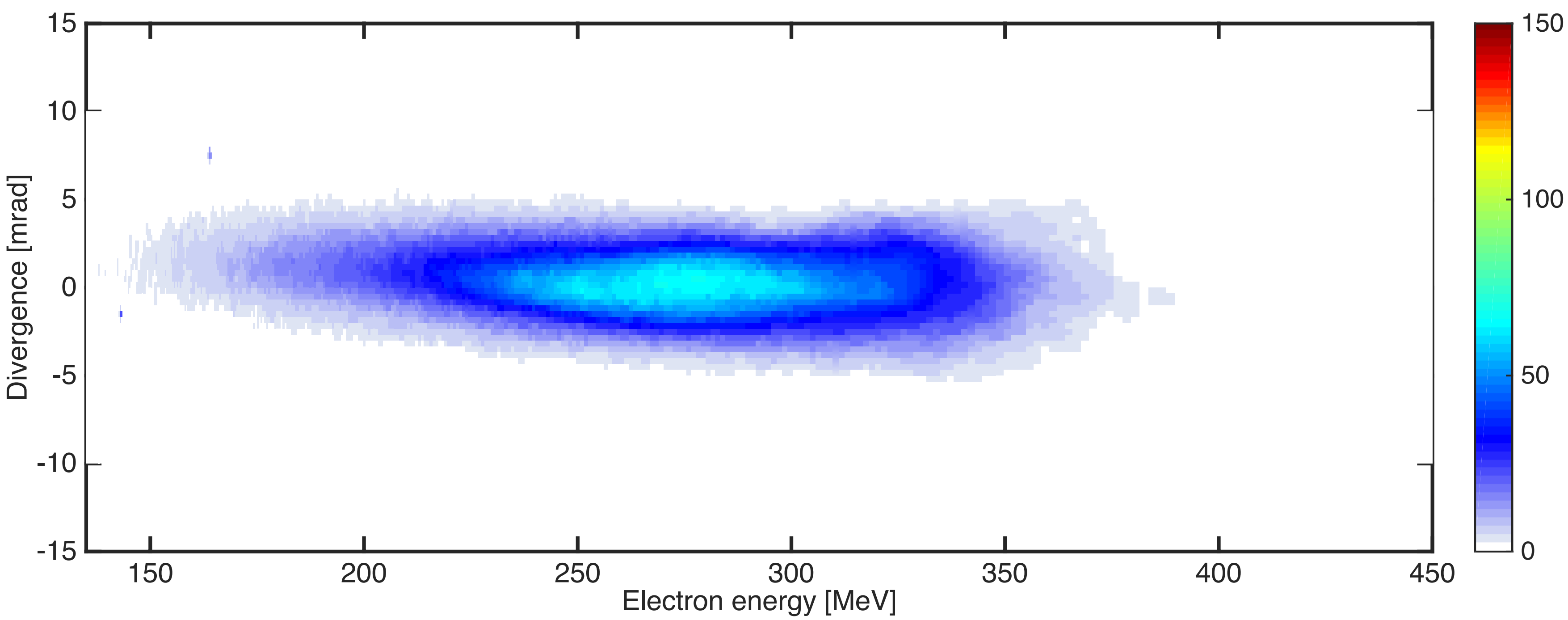
Focusing stage

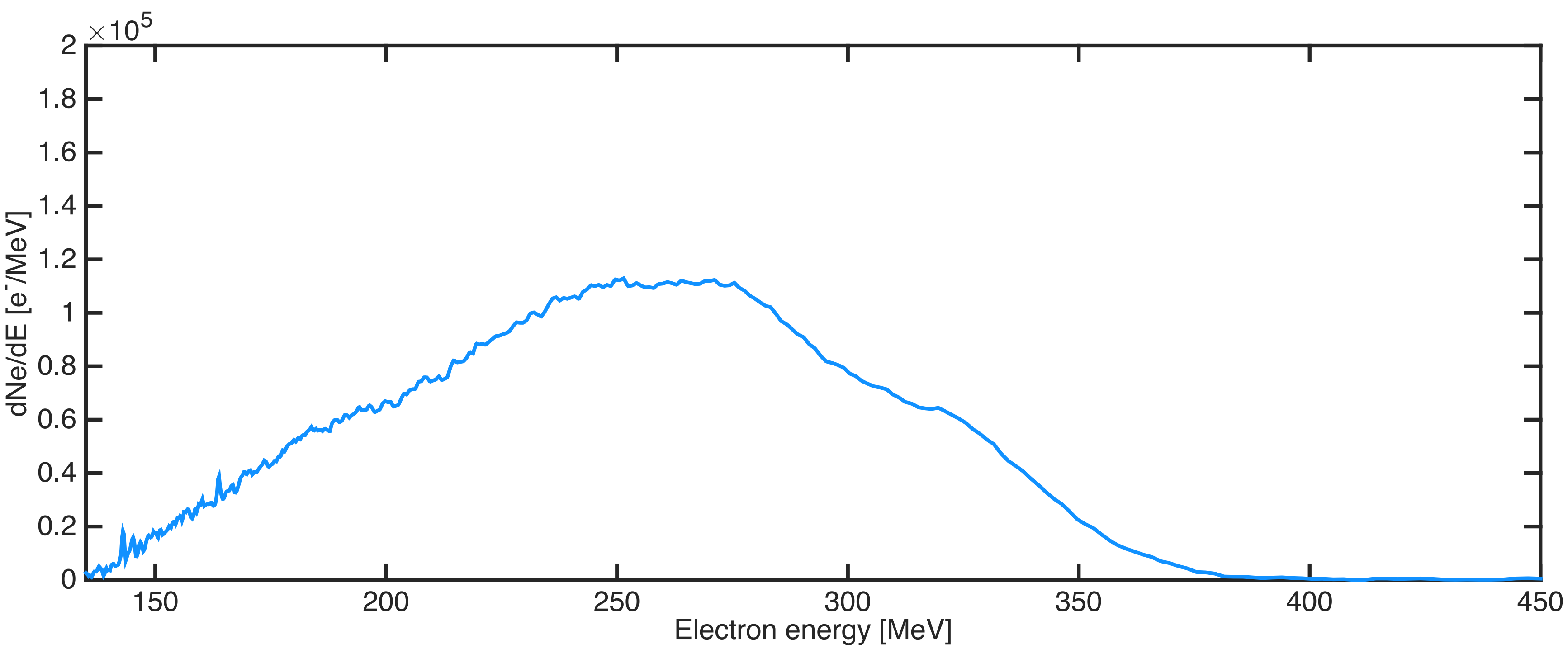
1 mm nozzle with variable n_2
Variable L_d



Longitudinal injection

Thaury C. *et al.*, to Nature Communications





Mean energy over 10 shots :

$$E = 241 \pm 12 \text{ MeV}$$

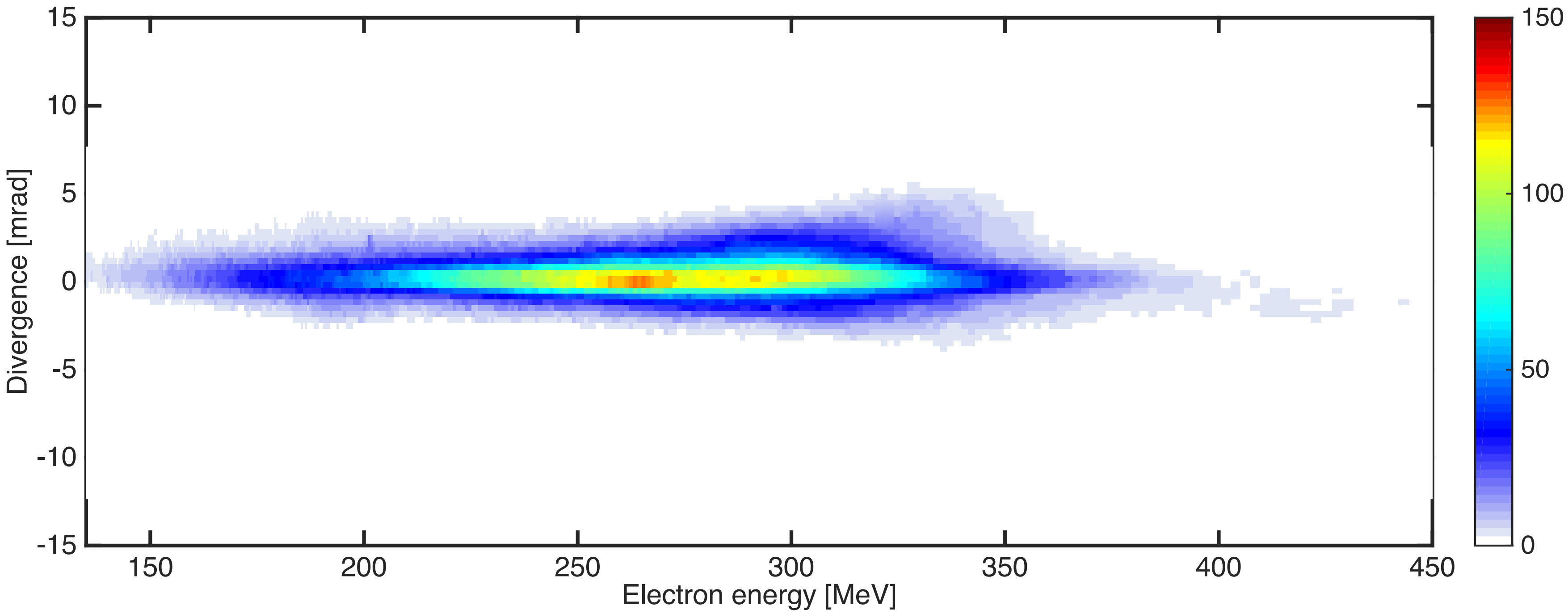
Mean divergence over 10 shots :

$$\sigma_\theta = 4.1 \pm 0.6 \text{ mrad}$$

Few pC charge, stable shot-to-shot

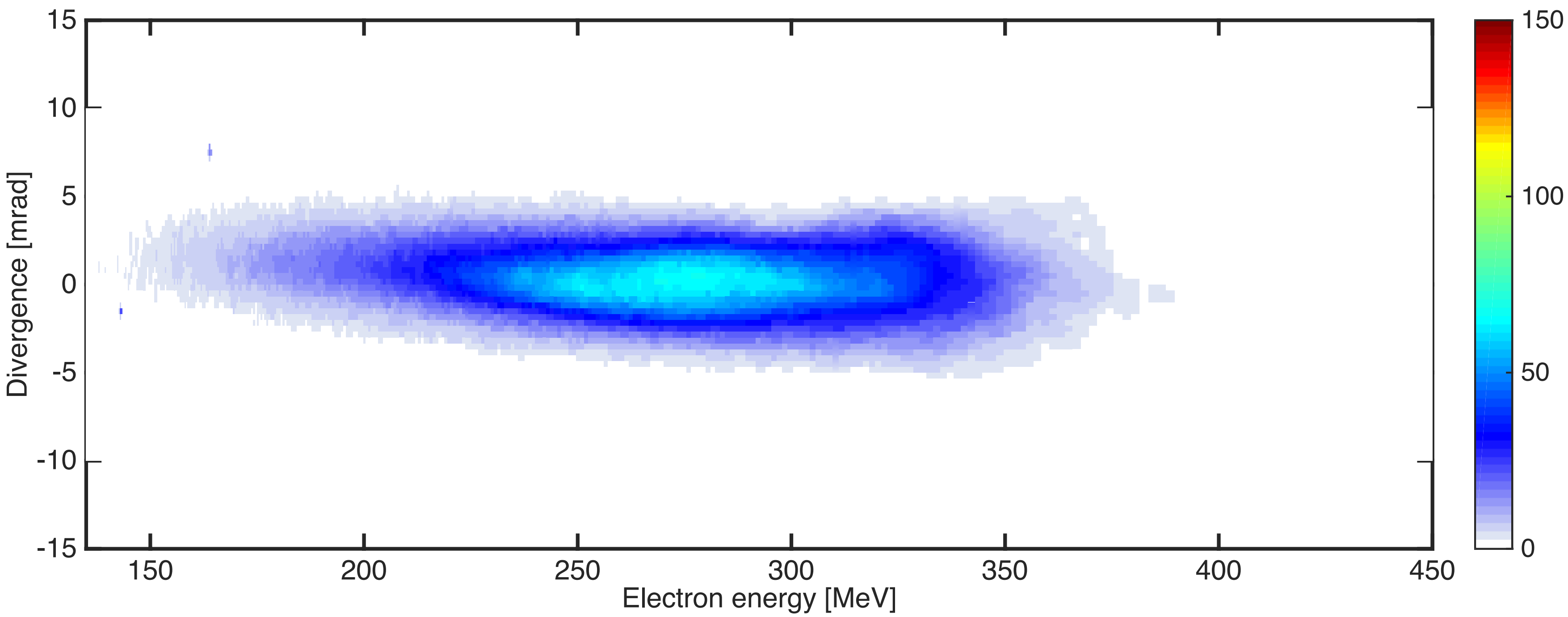
Experimental focusing of the beam

Thaury C. *et al.*, to Nature Communications



Focusing stage parameters :

L_d = 1.8 mm
$n_2 = 3.9 \times 10^{18}$ cm^{-3}



Divergence reduction at 270 MeV

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

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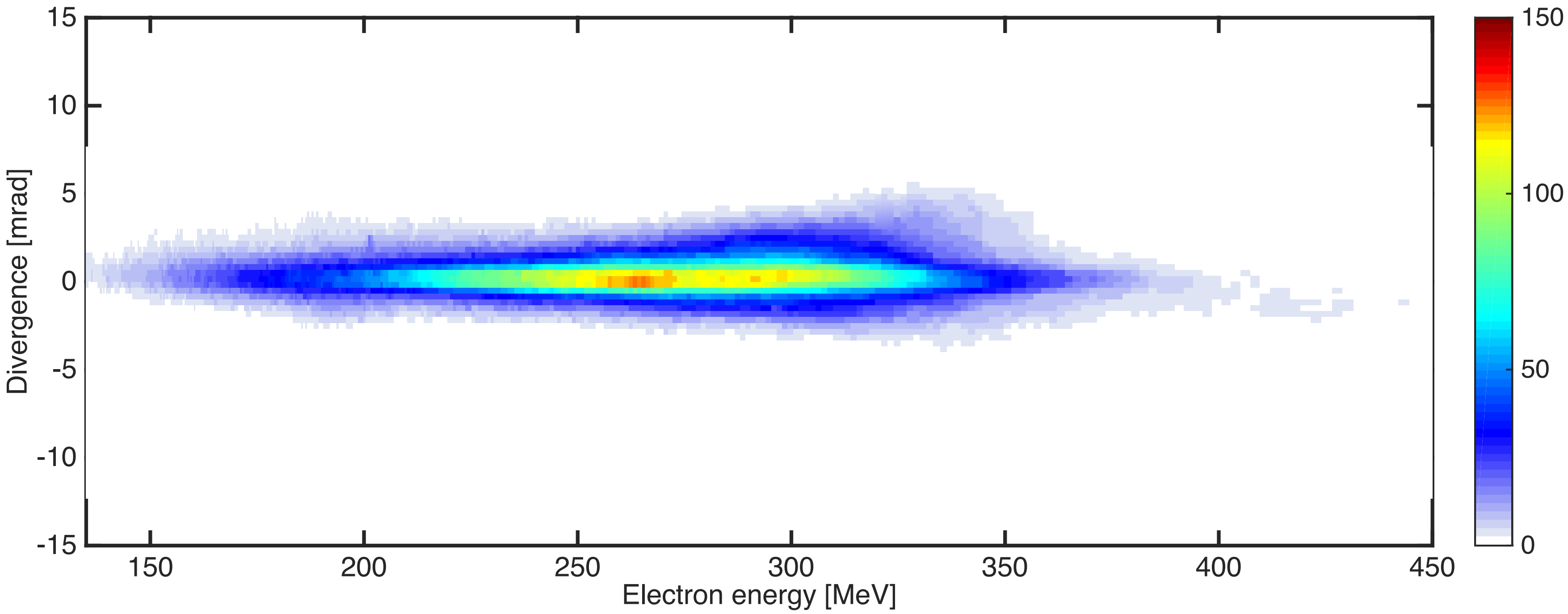

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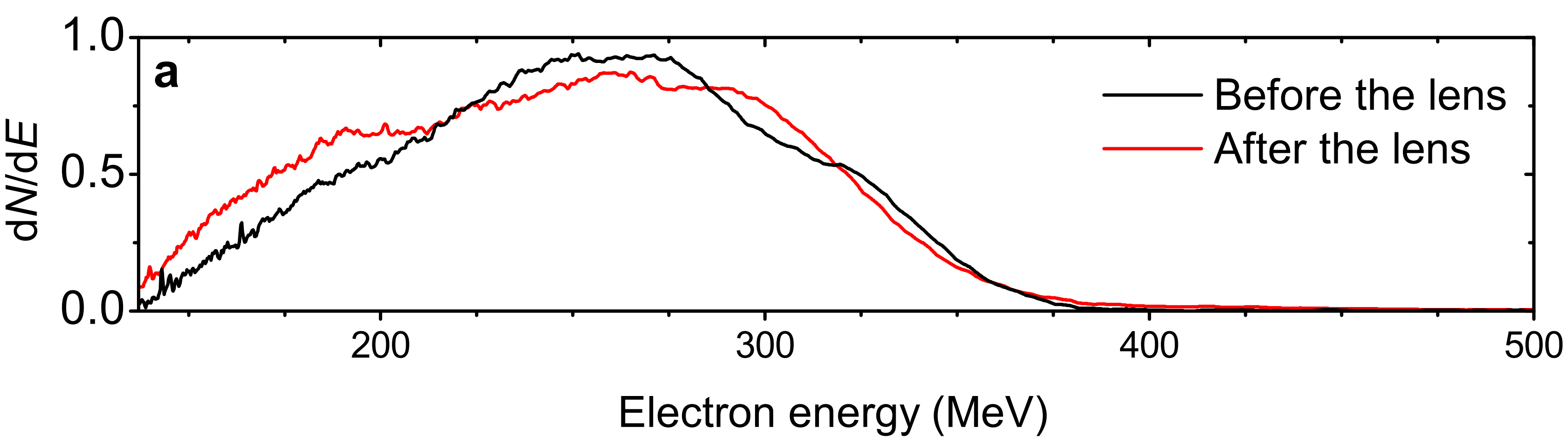
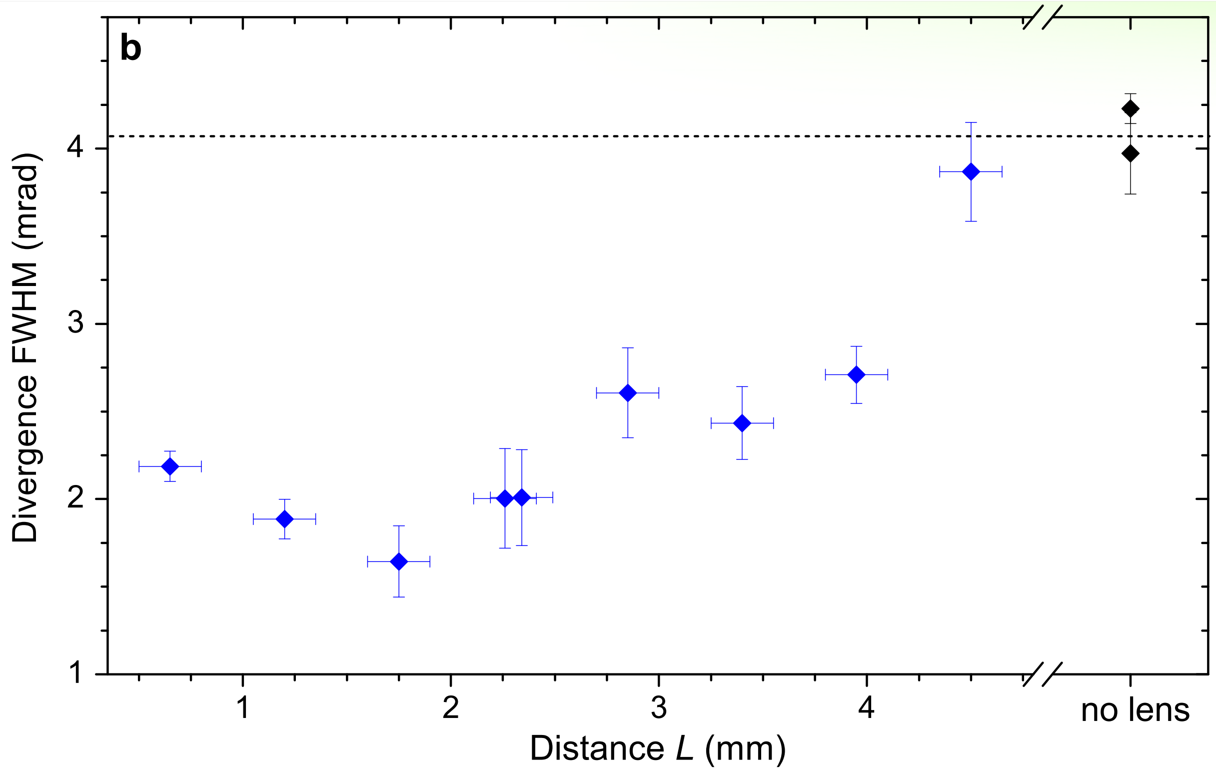
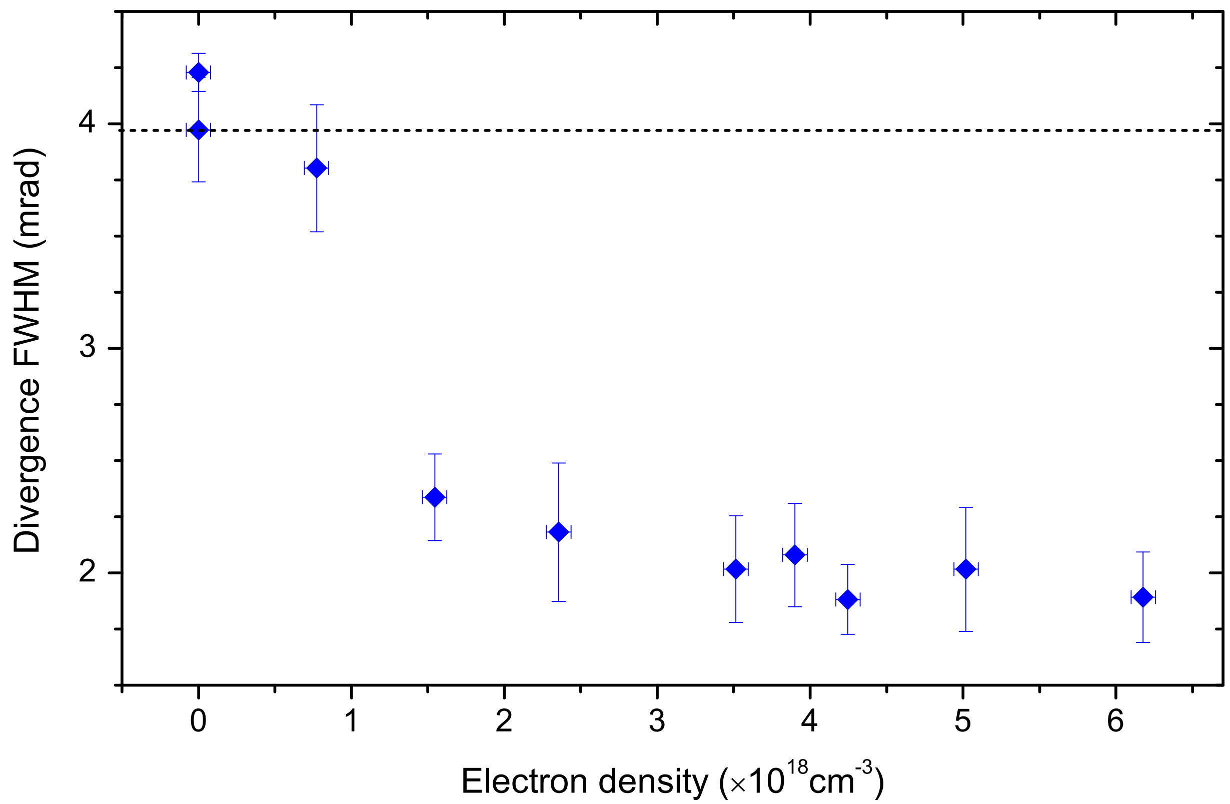


Laser-plasma lens doest not disturb the electron energy distribution

Drift length and density influence





Evolution of divergence governed by two effects :

- decrease of the minimum achievable divergence

$$\sigma_{\theta,min} = \varepsilon_x/\gamma\sigma_\theta L_d$$

- decrease of the laser intensity

Gradient of the focusing fields of the lens evolves as z^{-4} :
excessive focusing if L_d too short
insufficient focusing if L_d too long

Low density : weak focusing fields, divergence hardly reduced

High density : stronger focusing fields

Conclusions

Electrons rephasing : energy boost of a quasi mono-energetic peak by almost **50 %** BUT only the head of the bunch is rephased

→ Solutions : **upward parabolic** density gradient to create a tapered phase-locked laser-plasma accelerator

The laser-plasma lens : divergence reduced by a factor of **2**, but reduction limited by the fast decrease of laser intensity in the lens

→ Solutions : shorter gas jet for the acceleration stage, **sharper gradients** for the lens stage or a more energetic laser pulse

Need of more advanced machining on gas jet targets for further improvement of electron beam quality