Articulation between fundamental questions and their applications in laboratories in the the field of accelerators

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www.youtube.com/watch?v=qVO65x2lGbk

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Laser Plasma Accelerators : Outline

- Introduction : context and motivations

- Injection in a density gradient

- Manipulating the longitunal momentum

- Manipulating the transverse momentum

- Conclusion and perspectives

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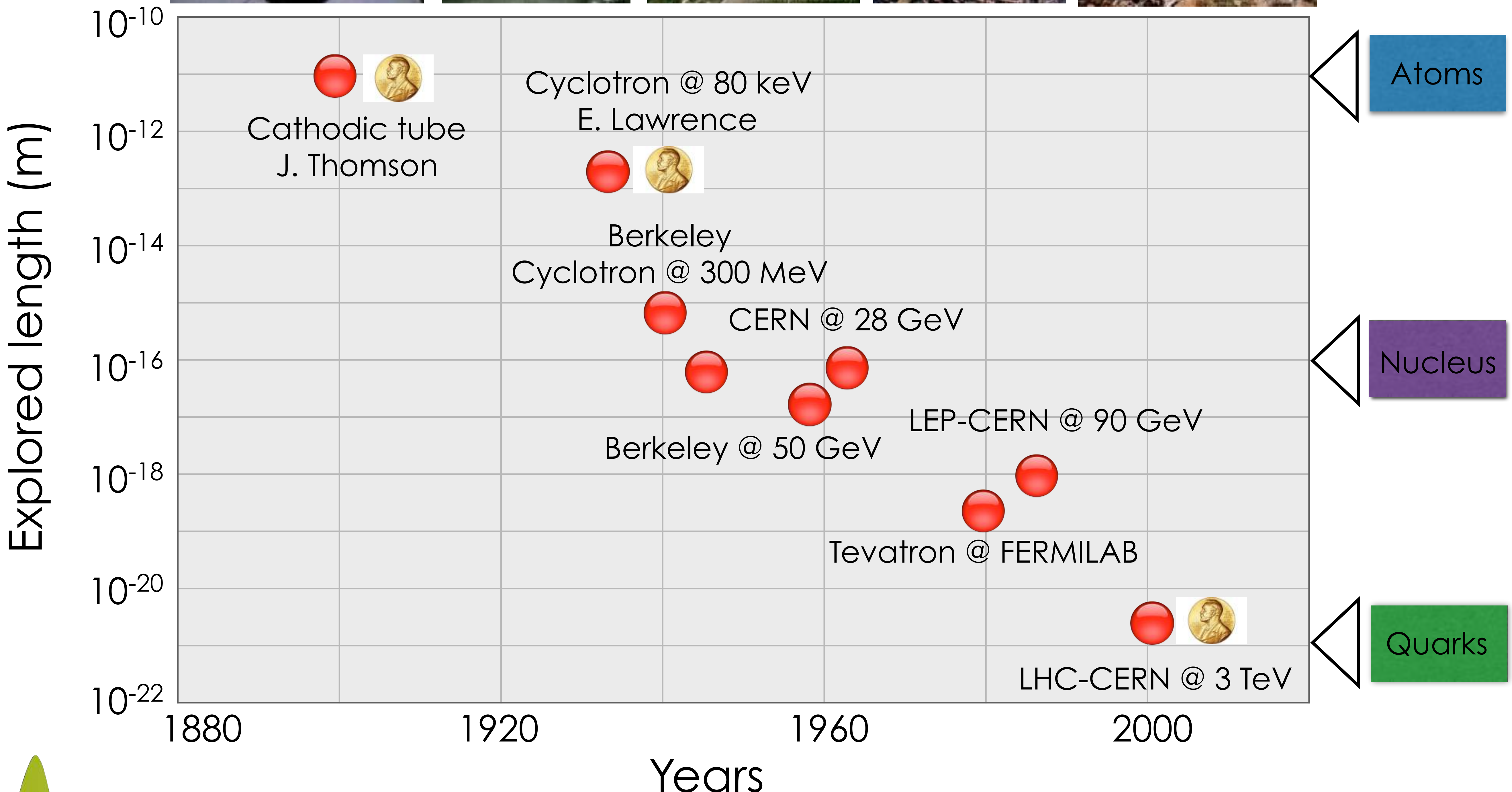
Fundamental Research



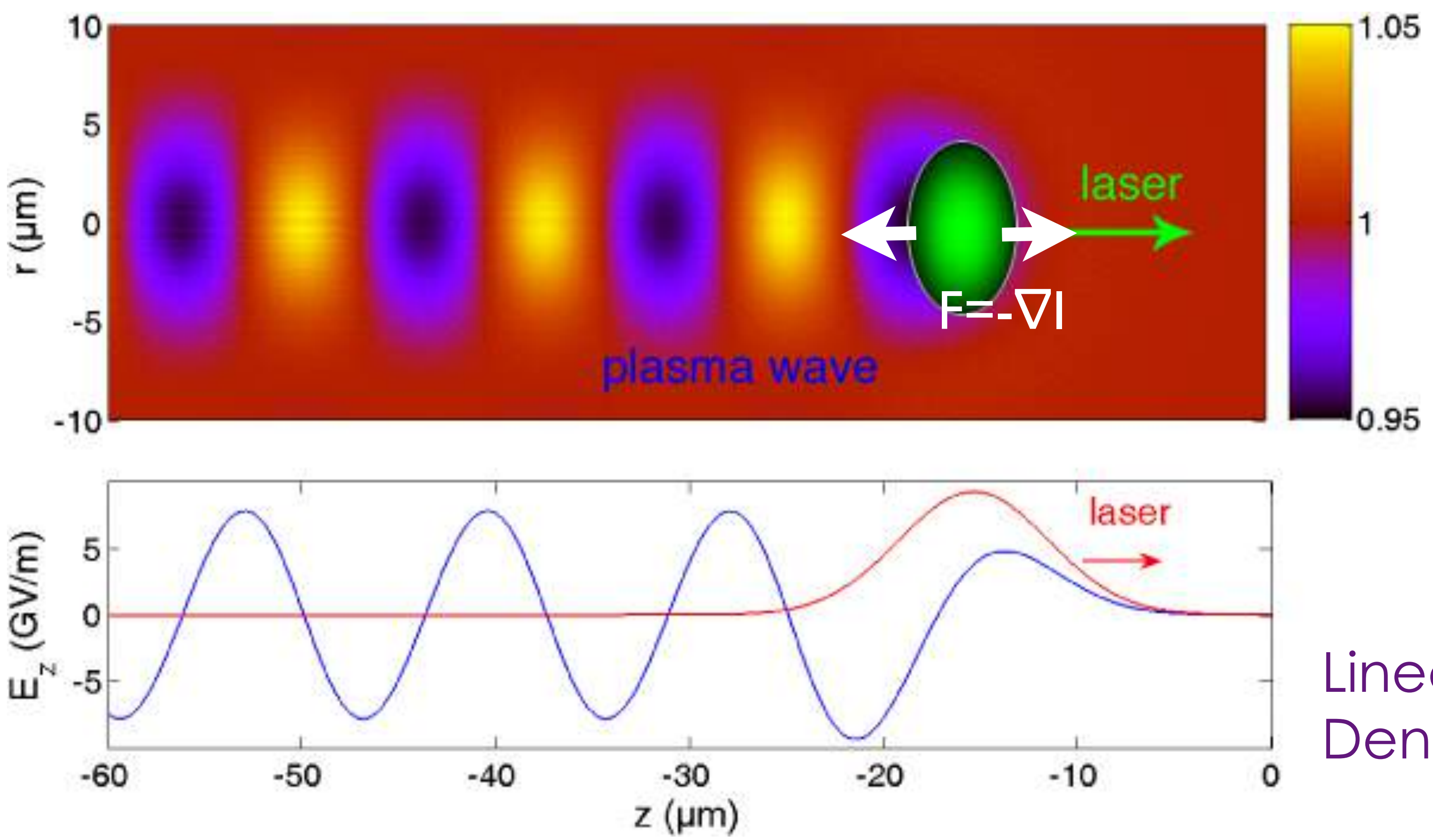
Industrial Market for Accelerators

Application	Total syst. (2007) approx.	System sold/yr	Sales/yr (M$)	System price (M$)
Cancer Therapy	9100	500	1800	2.0 - 5.0
Ion Implantation	9500	500	1400	1.5 - 2.5
Electron cutting and welding	4500	100	150	0.5 - 2.5
Electron beam and X rays irradiators	2000	75	130	0.2 - 8.0
Radio-isotope production (incl. PET)	550	50	70	1.0 - 30
Non destructive testing (incl. Security)	650	100	70	0.3 - 2.0
Ion beam analysis (incl. AMS)	200	25	30	0.4 - 1.5
Neutron generators (incl. sealed tubes)	1000	50	30	0.1 - 3.0
Total	27500	1400	3680	

The laser wake field : broad resonance condition

$\tau_{laser} \sim \pi/\omega_p$ with $\omega_p \sim n_e^{1/2}$ i.e. $\lambda_p \sim 1/n_e^{1/2}$

electron density perturbation & longitudinal wakefield



wave in the wake of a boat

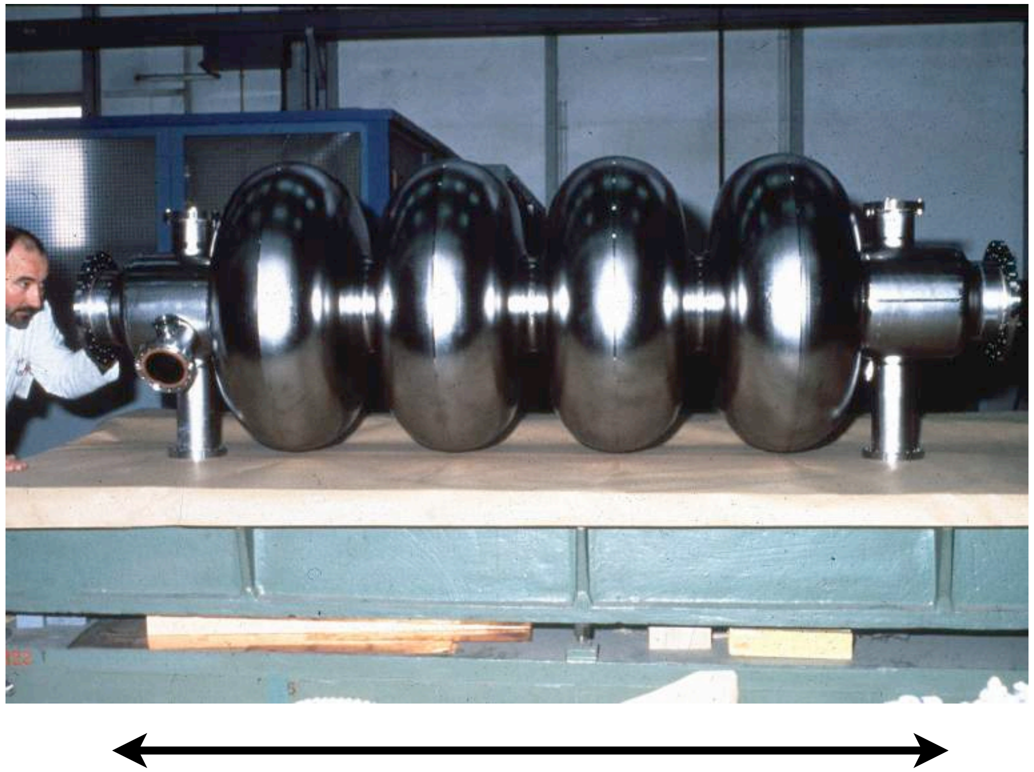
Linear wakefield : E_z = 1 GV/m for 1 % Density Perturbation at 10^{18} cc^{-1}

$v_{phase}^{epw} = v_g^{laser} \sim c$

T. Tajima and J. Dawson, PRL **43**, 267 (1979)

The non-linear wakefield regime : 100's GV/m electric field

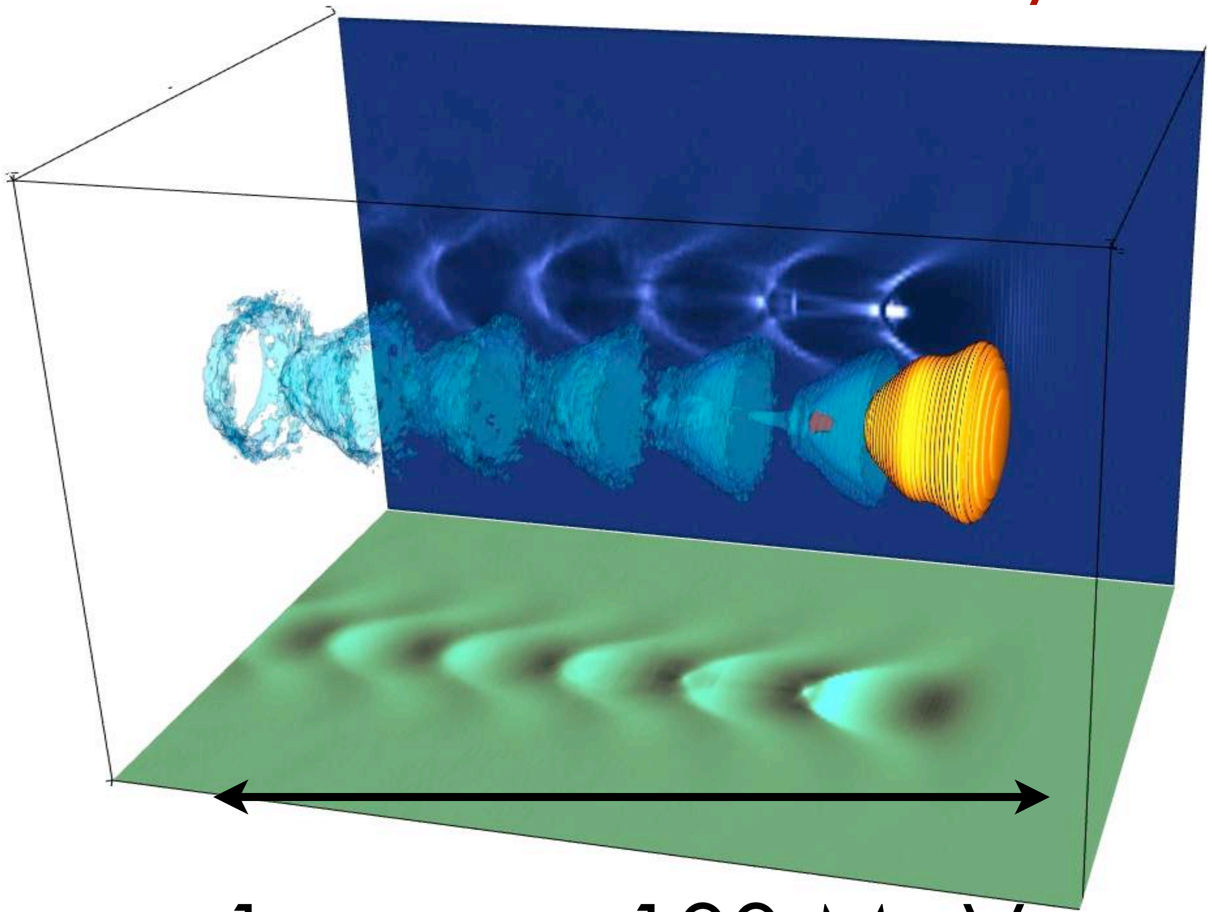
RF Cavity



1 m => 100 MeV Gain

Electric field < 100 MV/m

Plasma Cavity

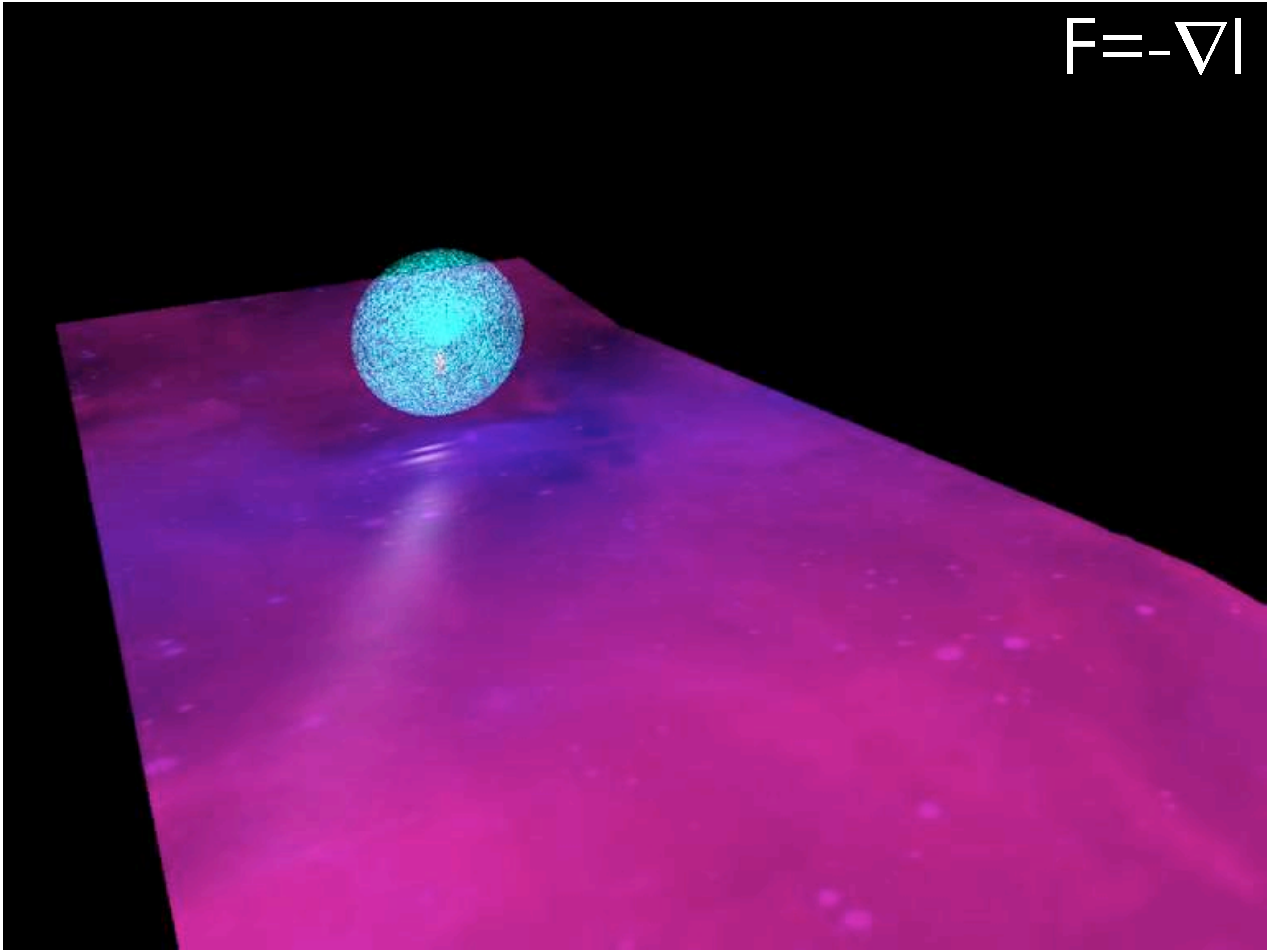


1mm => 100 MeV

Electric field > 100 GV/m

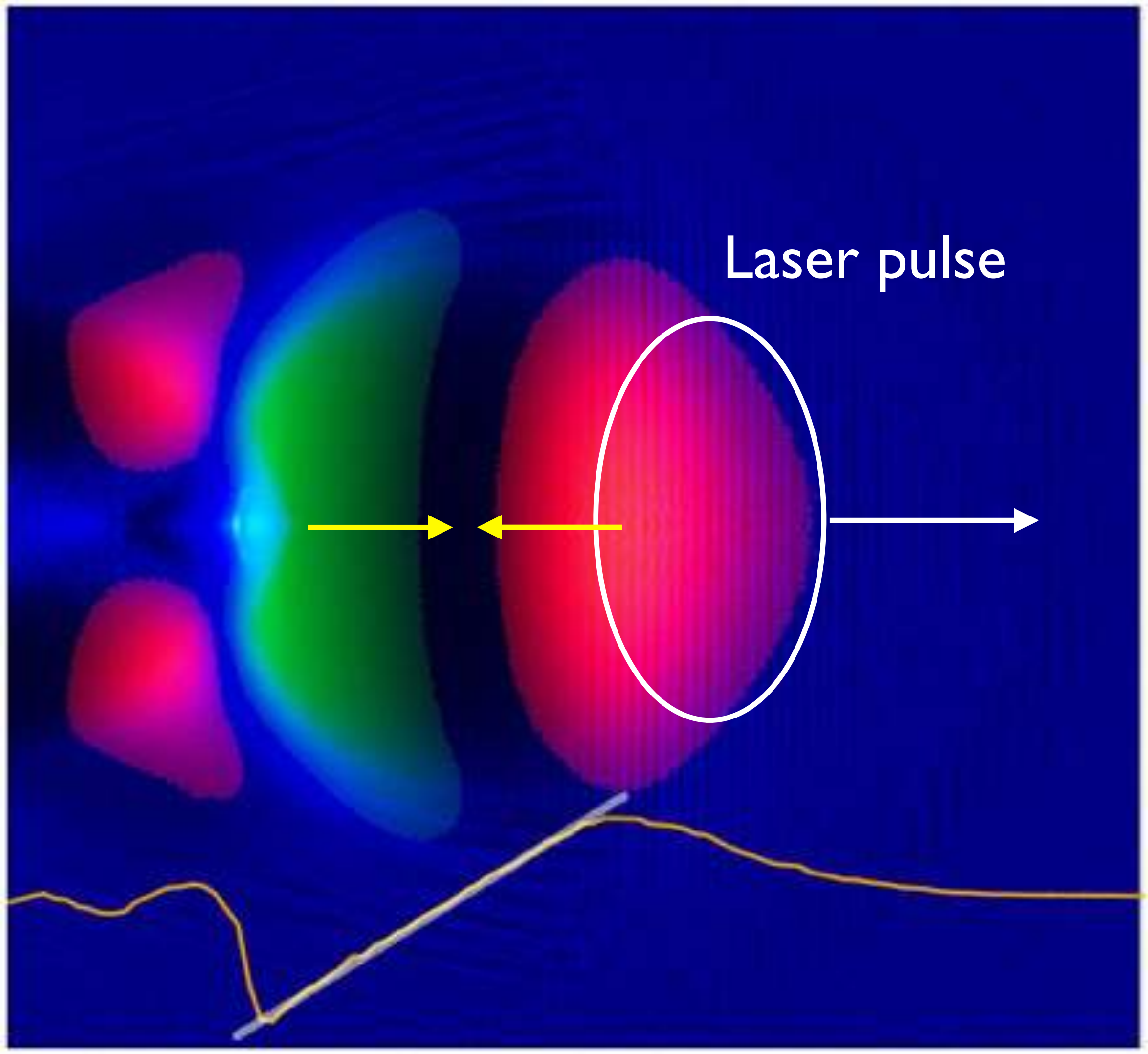
Non Linear Wakefield
V. Malka *et al.*, Science **298**, 1596 (2002)

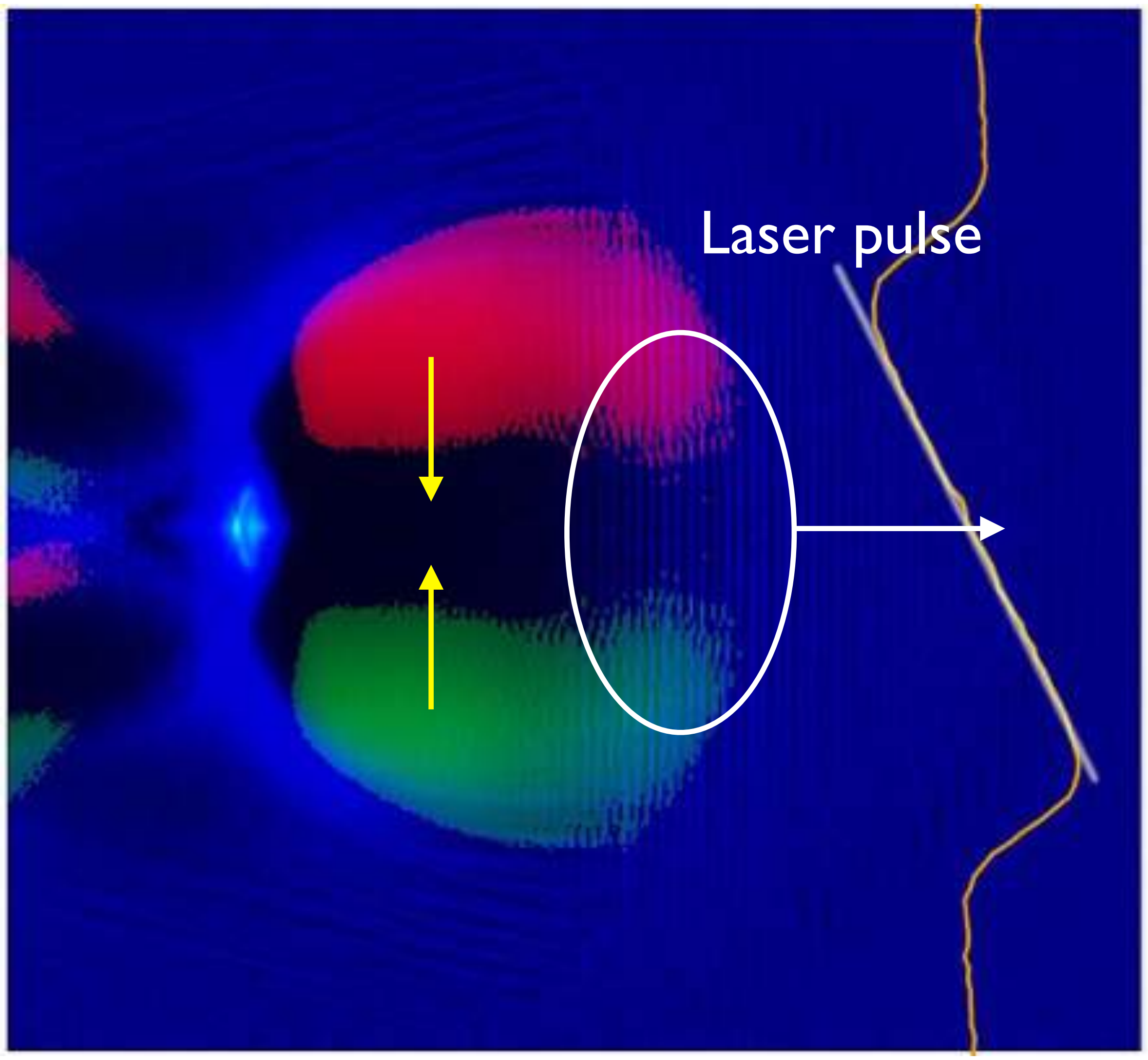
The Non Linear Regime



Laser Plasma Accelerator: Non linear regime

Electric field components : Longitudinal and Transverse



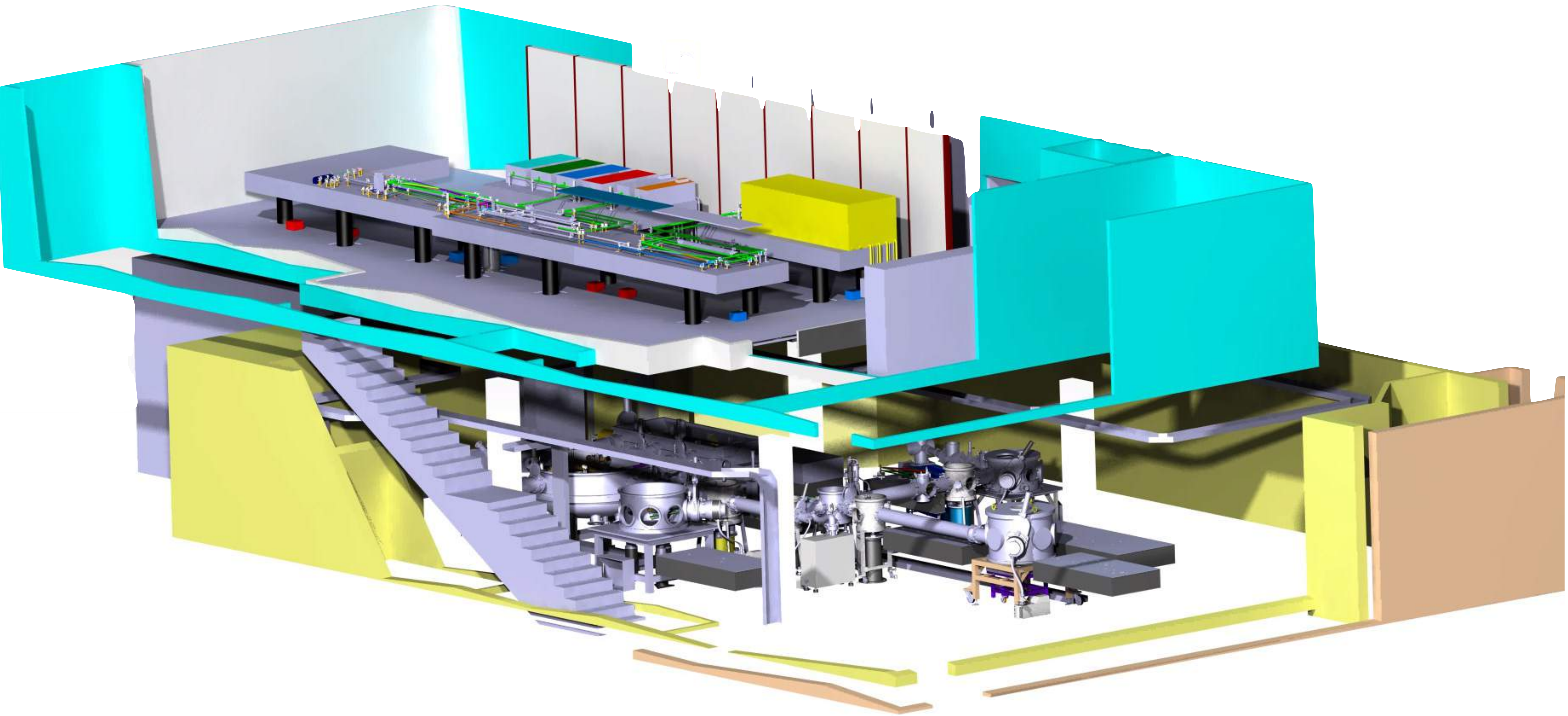


Linear accelerating gradient

Linear Focusing gradient

« Salle Jaune Laser » : Home made laser

2 Joules in 2 laser beams of 30 fs duration delivered at 1 Hz



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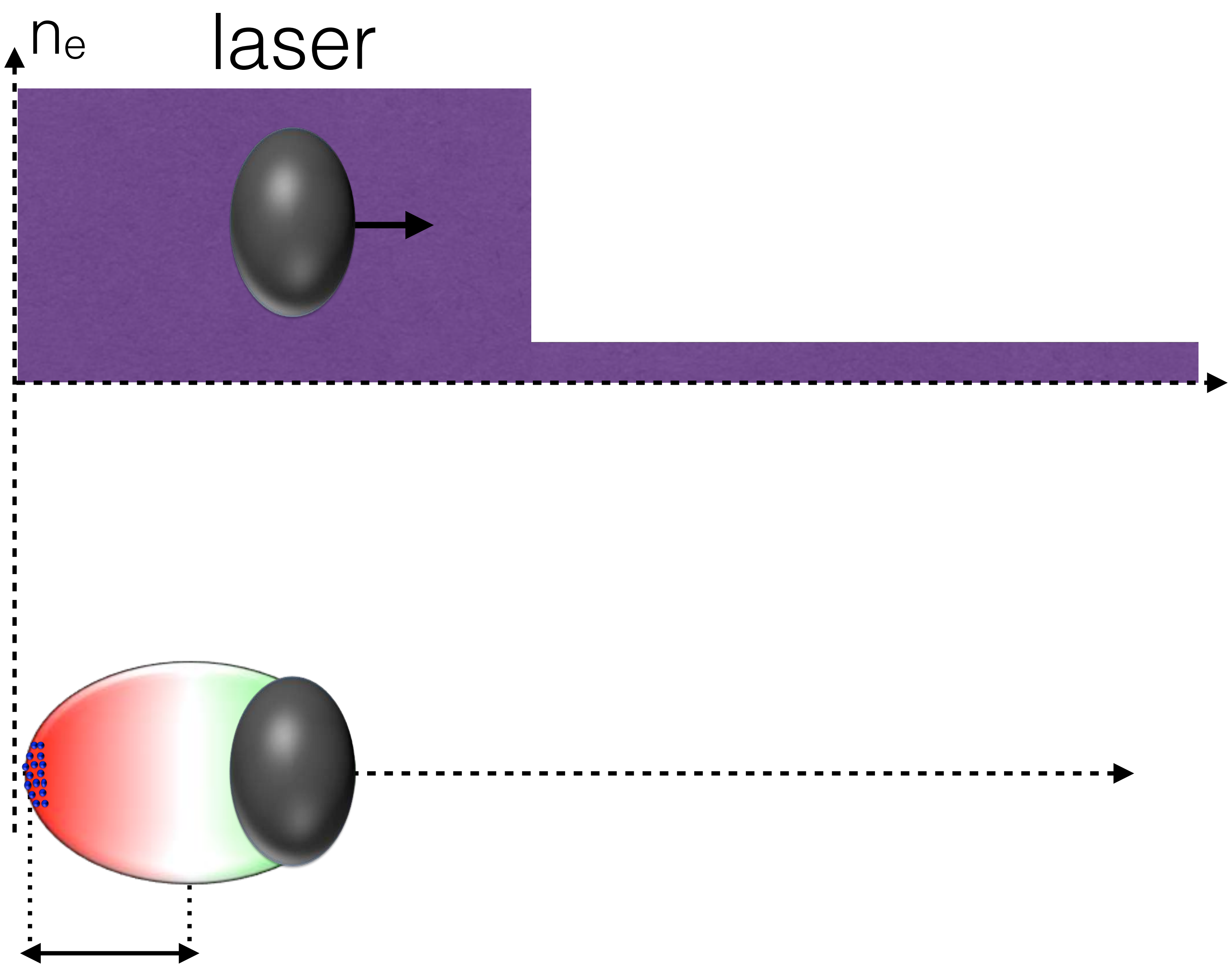
Injection in a sharp density gradient



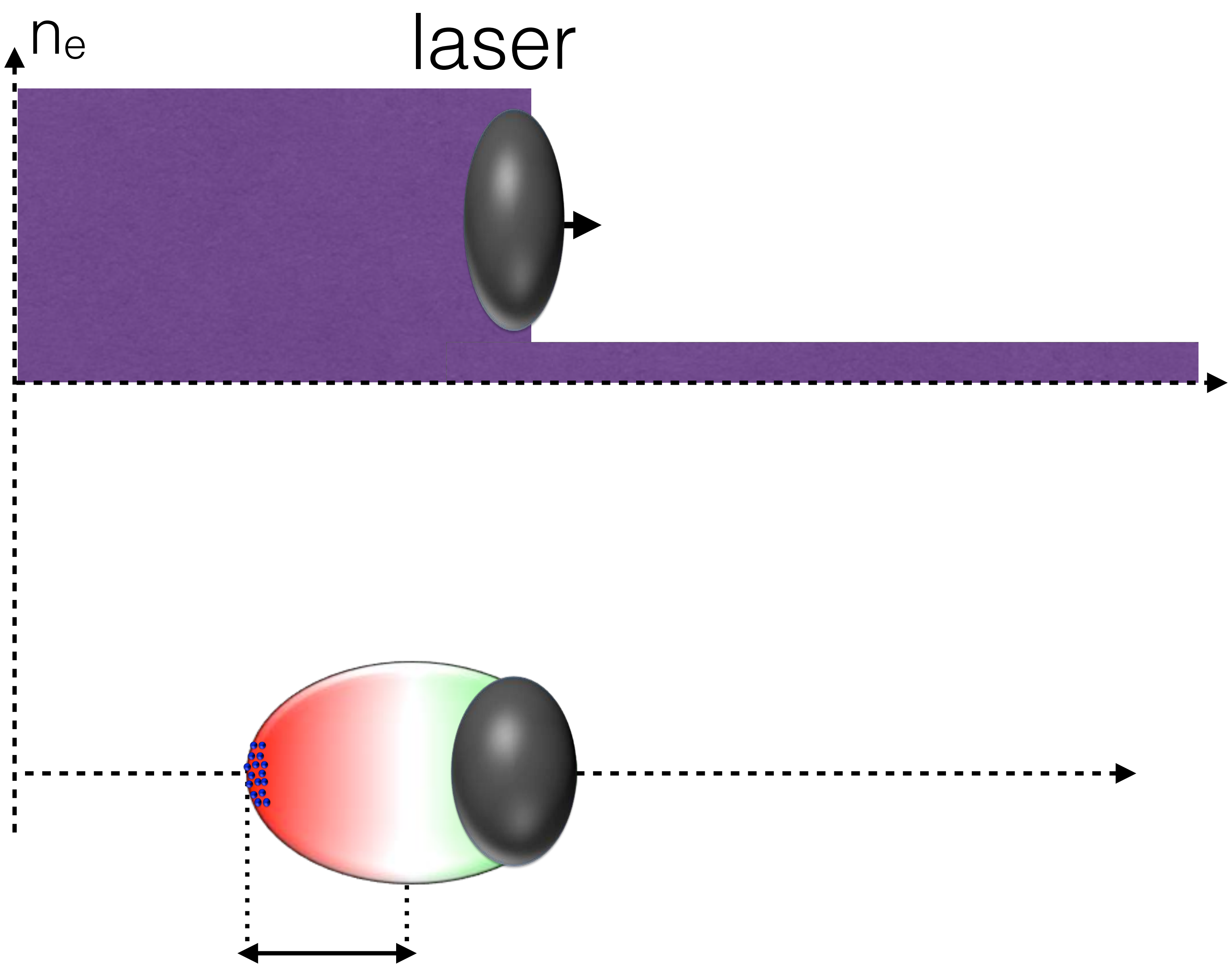
Density drop => increase of the cavity lenght

the bubble expansion allows electrons injection and energy gain.

Sharp density ramp is requires to localize the injection and reduce the energy spread !

[Schmid et al., 2010; Buck et al., 2013]

Injection in a sharp density gradient



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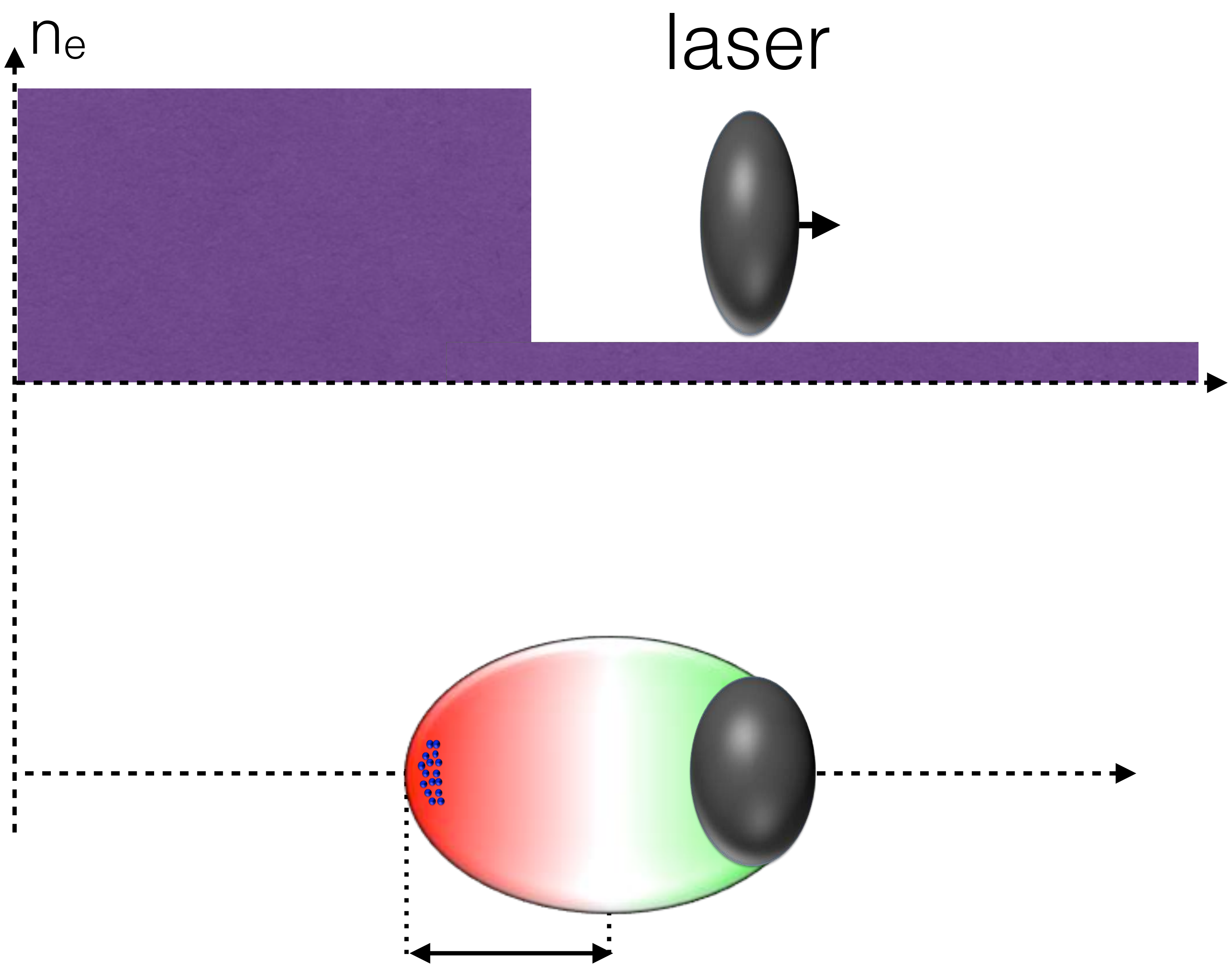

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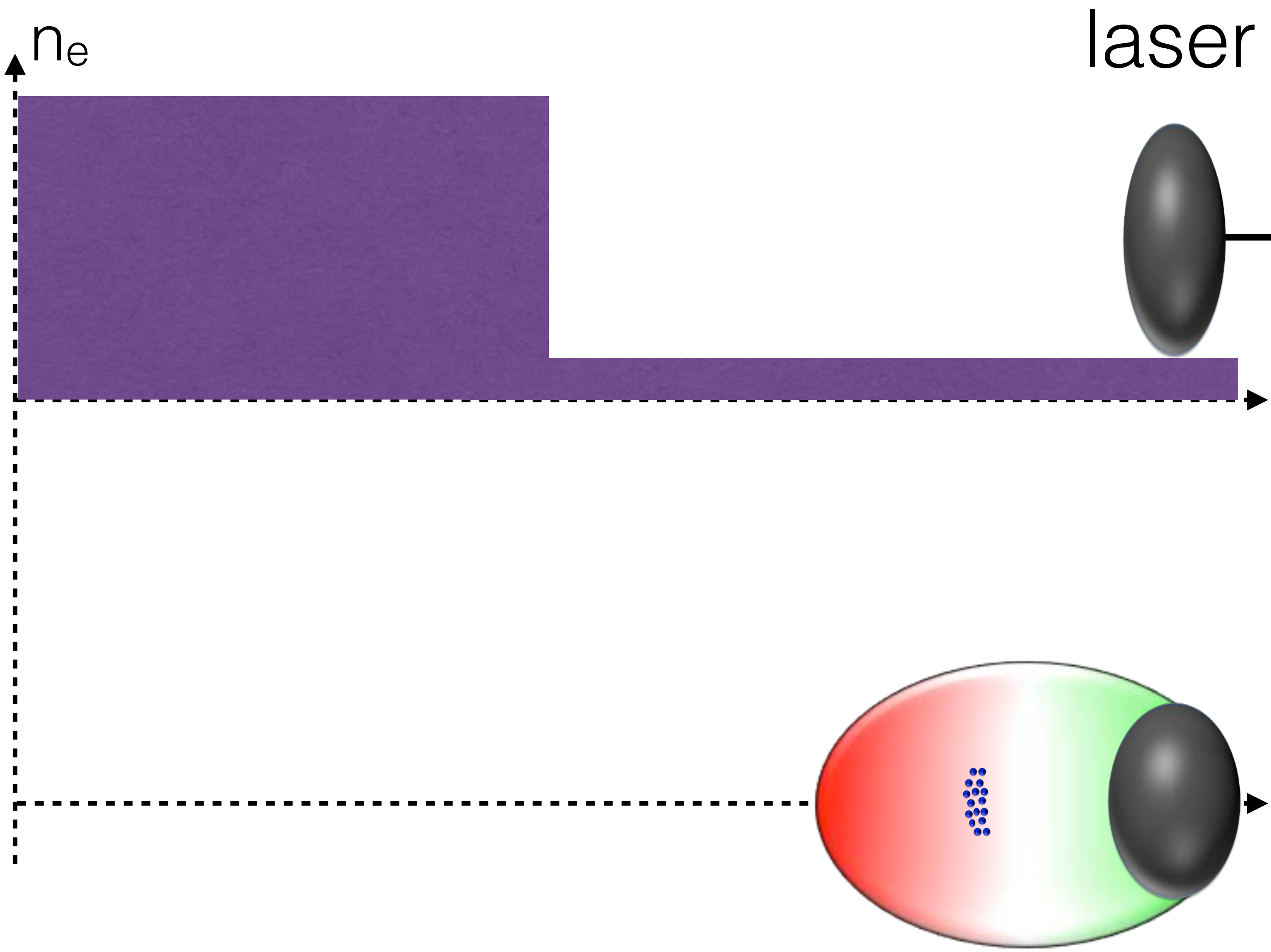

Density drop => increase of the cavity lenght

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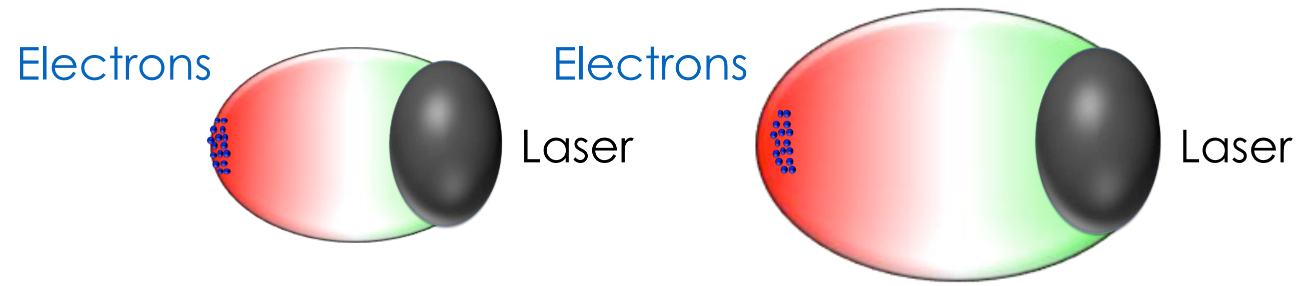
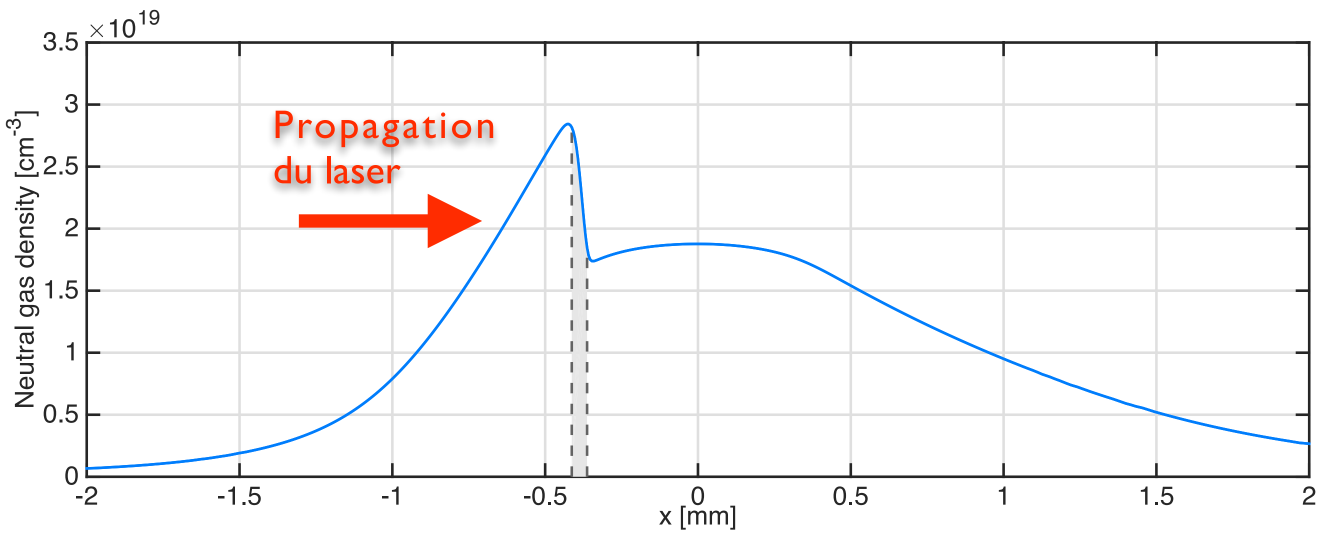
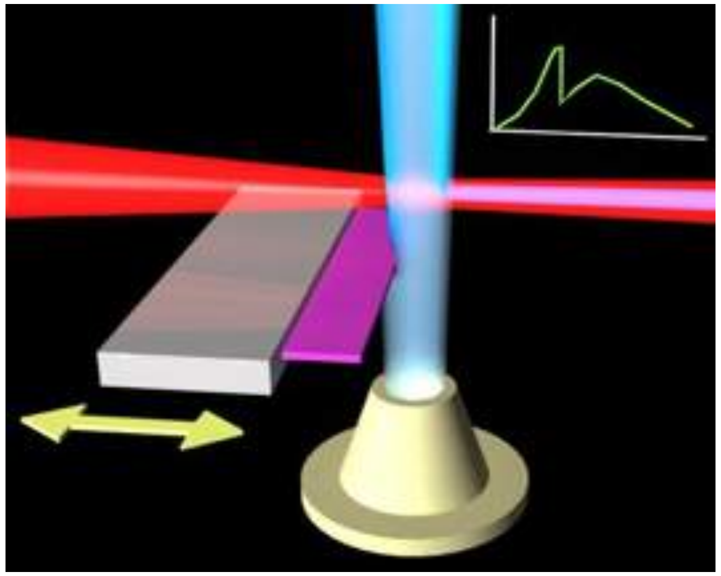
Injection in a shock front : principle

Plasma cavity before the shock front

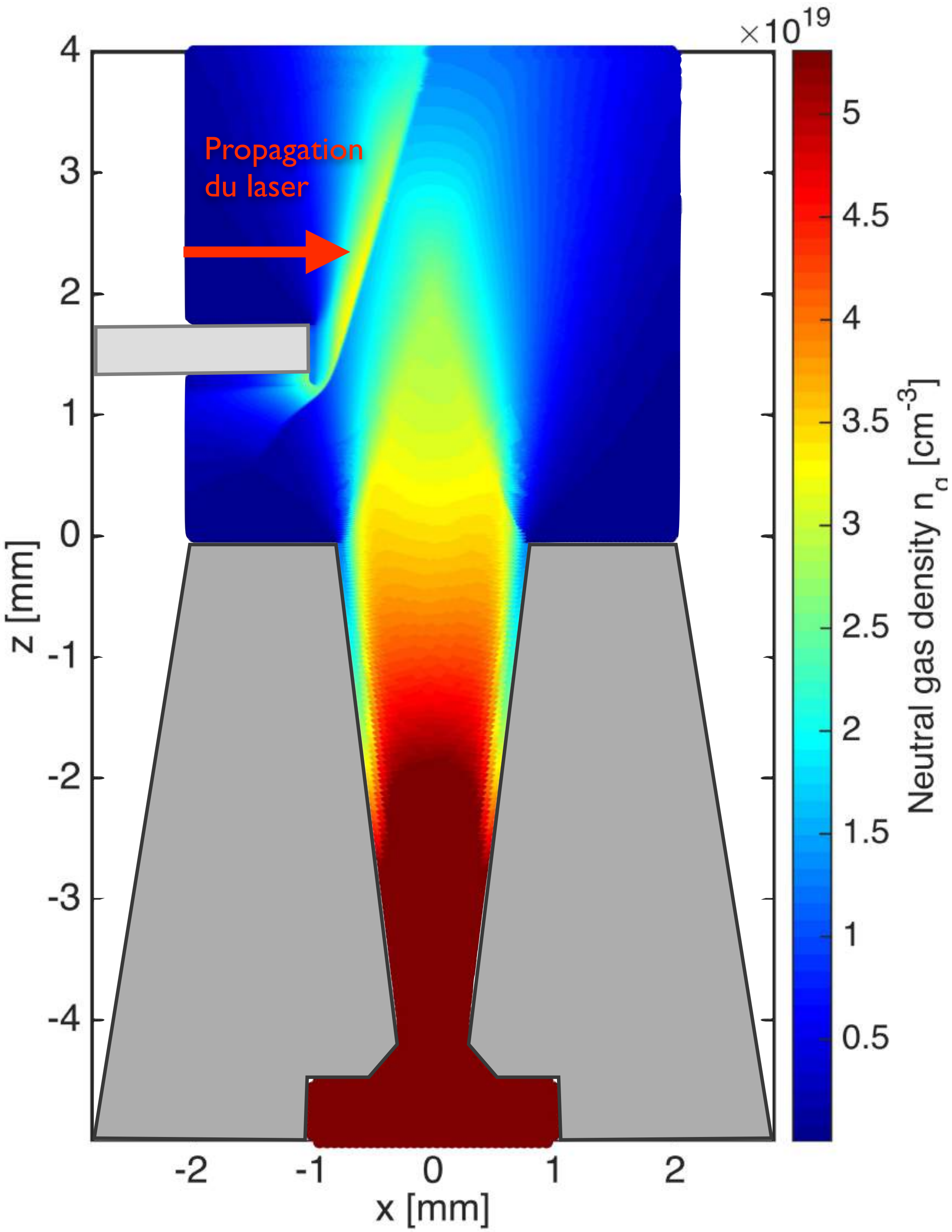
Plasma cavity after the shock front



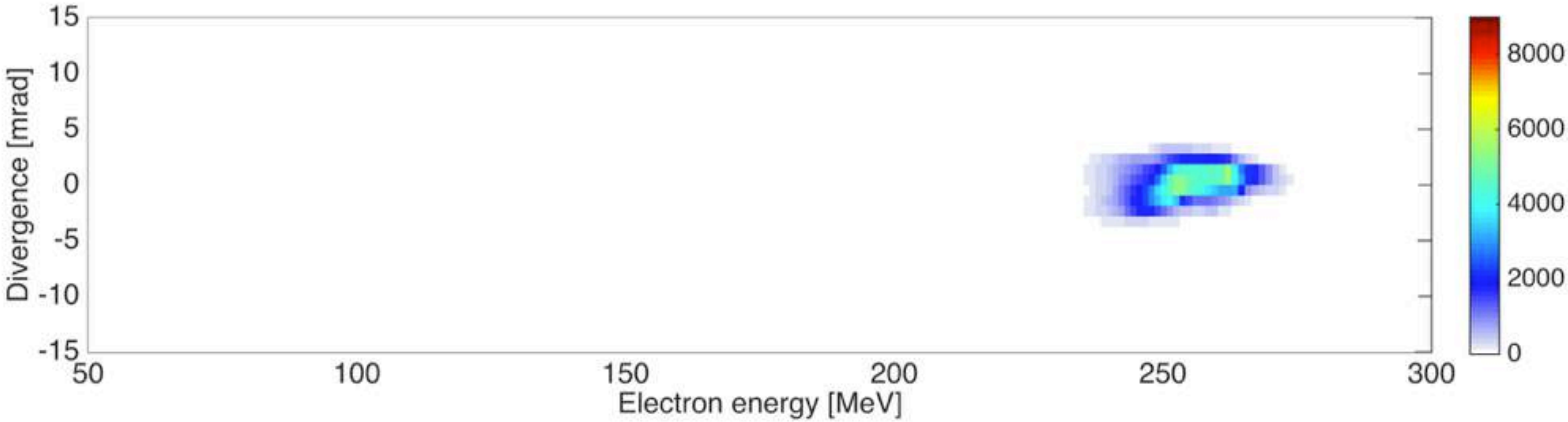




Simulations ANSYS Fluent



Injection in a shock front : pur helium gas



Generation of a stable e-beam ($n_2 = 7.5 \times 10^{18}$ cm^{-3}) :

$$E_{peak} = 256.5 \pm 4 \text{ MeV}$$

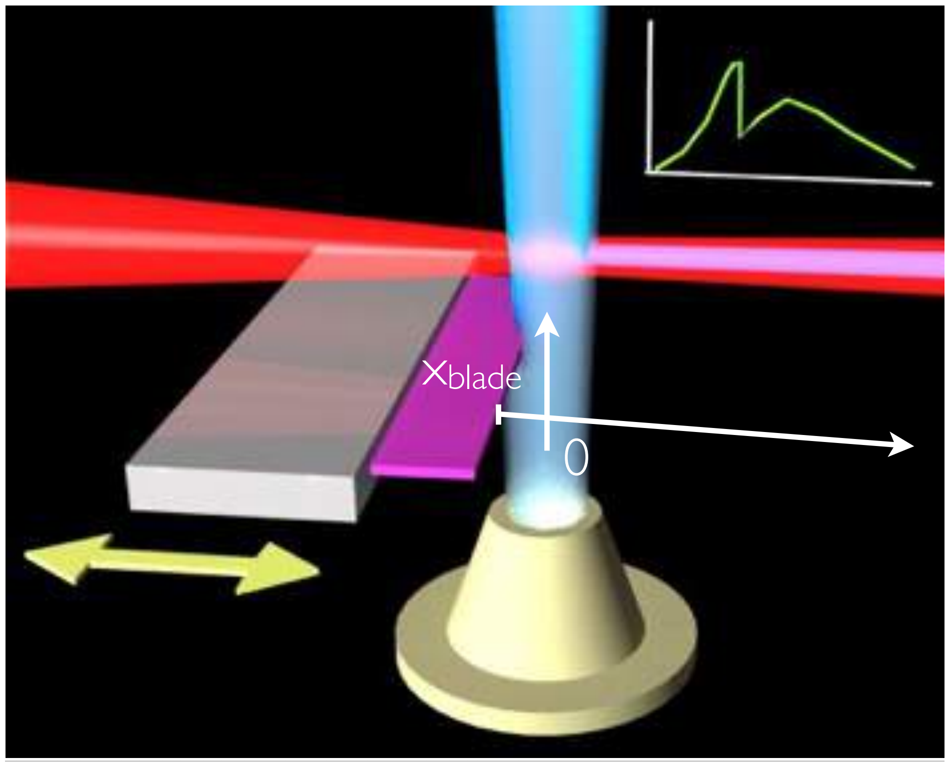
$$\Delta E = 15.5 \pm 2 \text{ MeV}$$

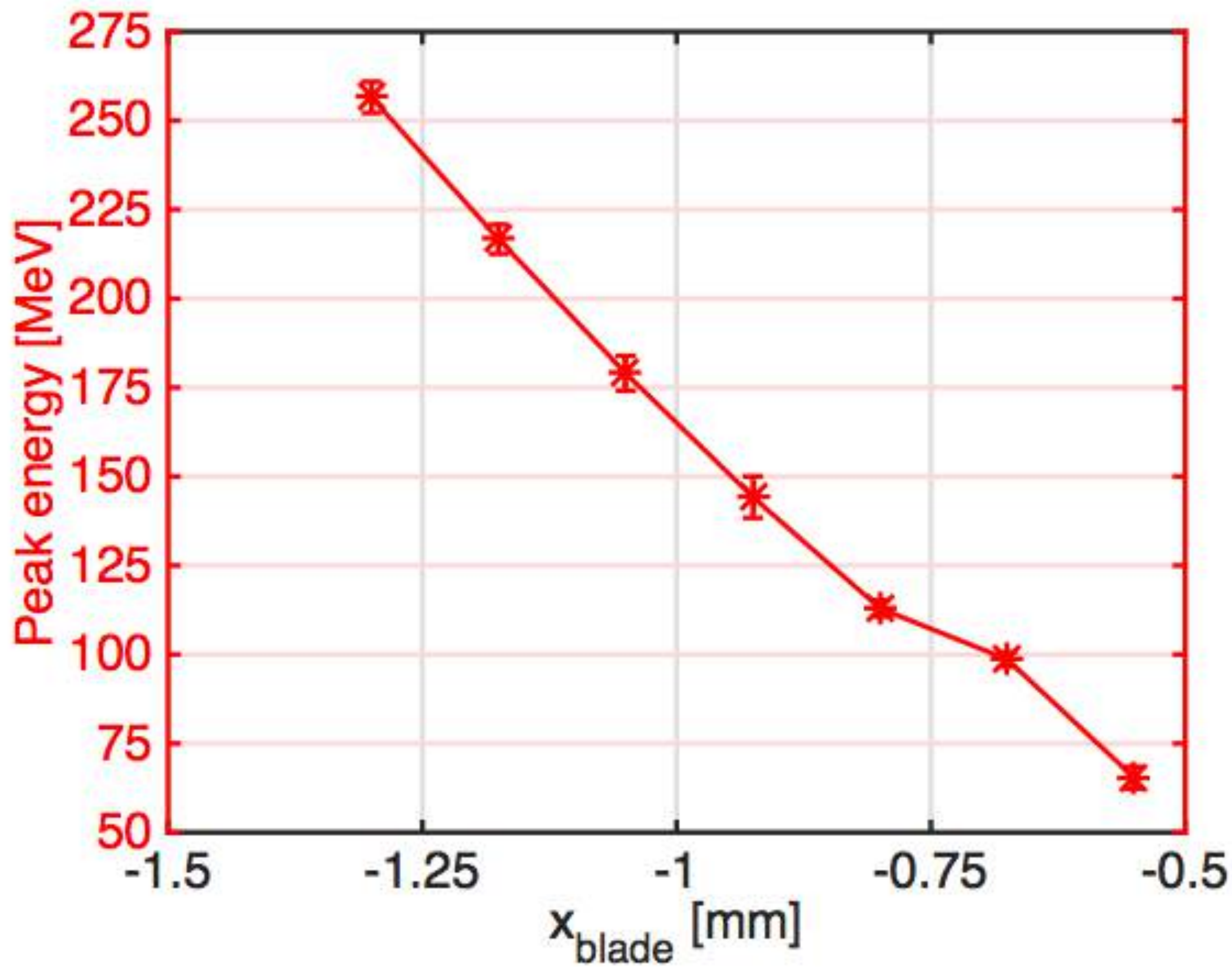
$$\Delta E/E = 6 \pm 1\%$$

$$Q_{peak} = 3.2 \pm 0.4 \text{ pC}$$

$$\text{Divergence} = 2.0 \pm 0.3 \text{ mrad}$$

Injection in a shock front : pur helium gas

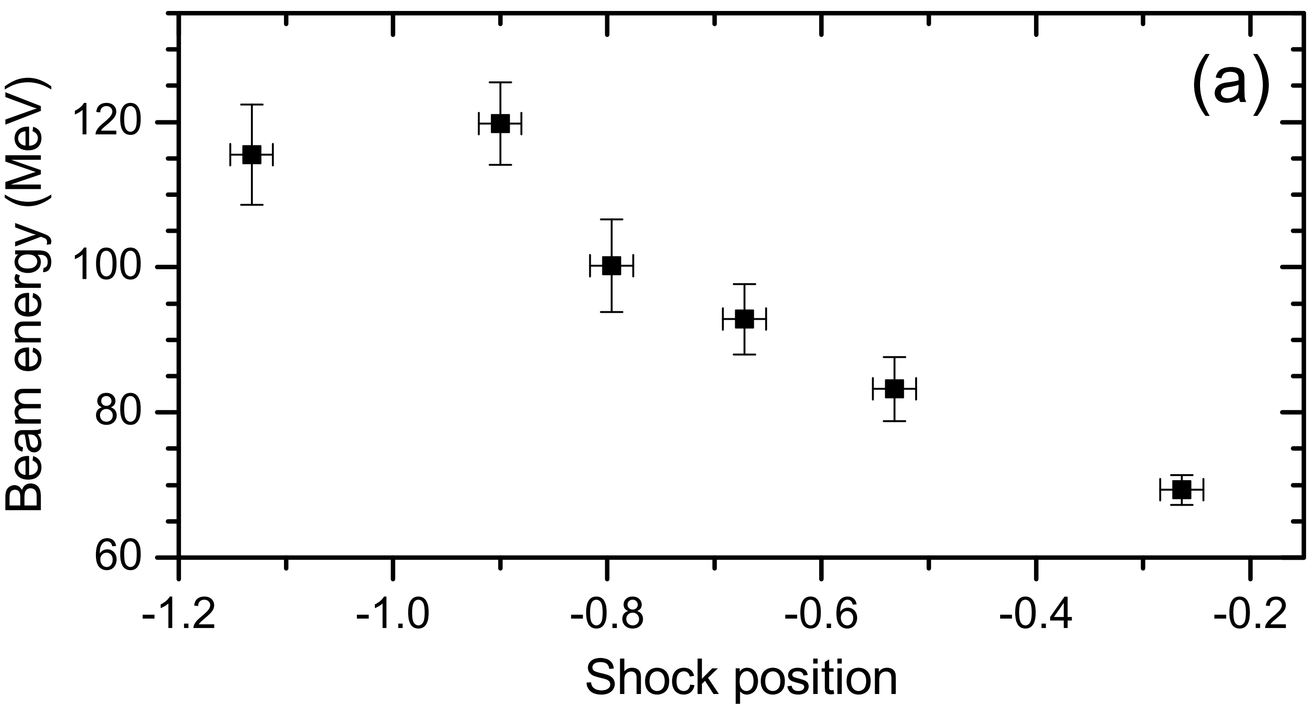


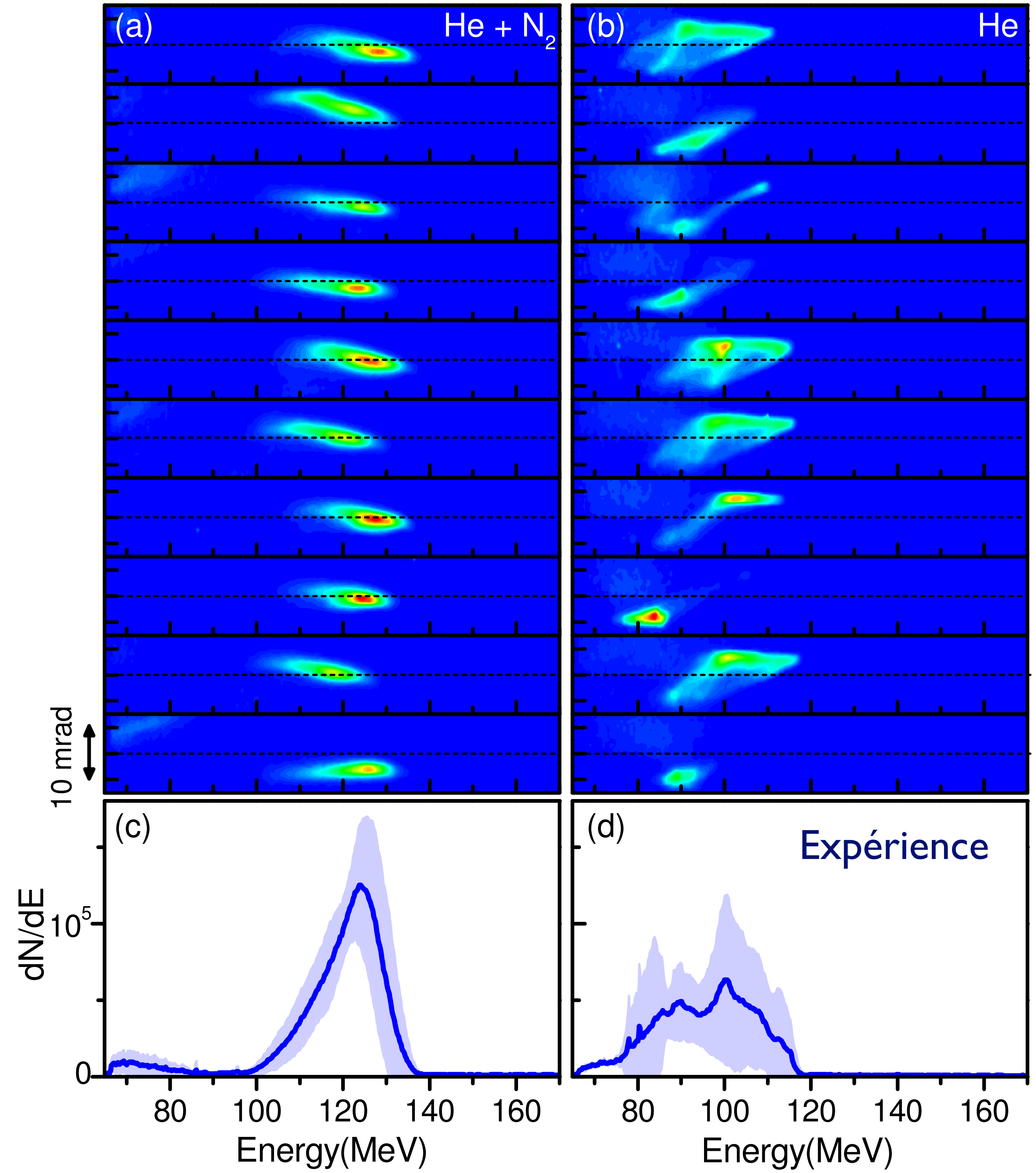


Electron energies is controlled by the position of the blade

Injection in a shock front : helium/nytrogene mixture

Combinaison of two injection method (shock and ionization) to generate better beam quality with better stability





Thaury C., Guillaume E. et al., Scientific Reports **5** (2015)

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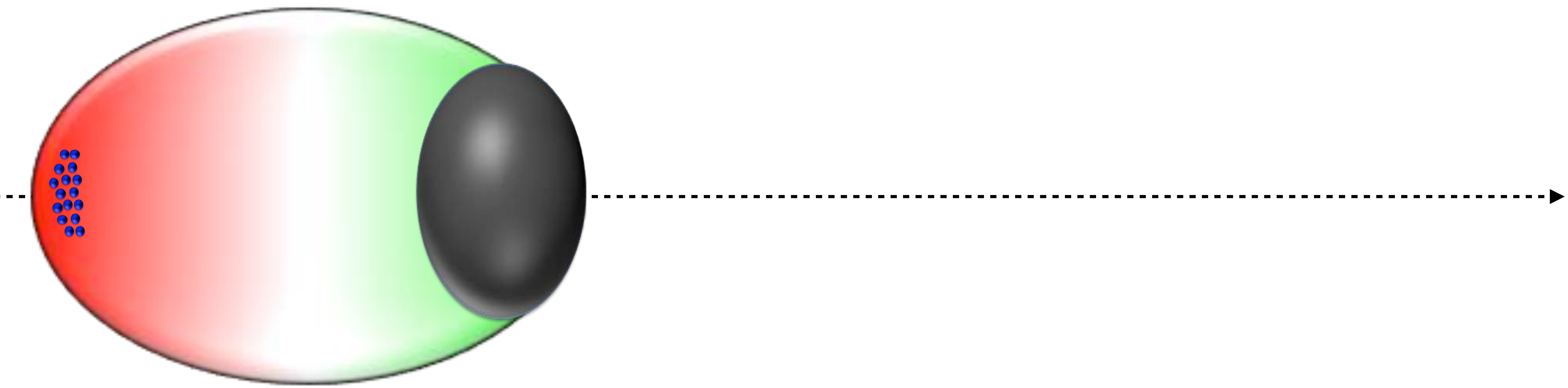
Overcoming the dephasing limit

since the laser group velocity is < c, when electrons energy is getting ~c they dephase

→ electrons reach the center of the cavity and start to be deccelerated



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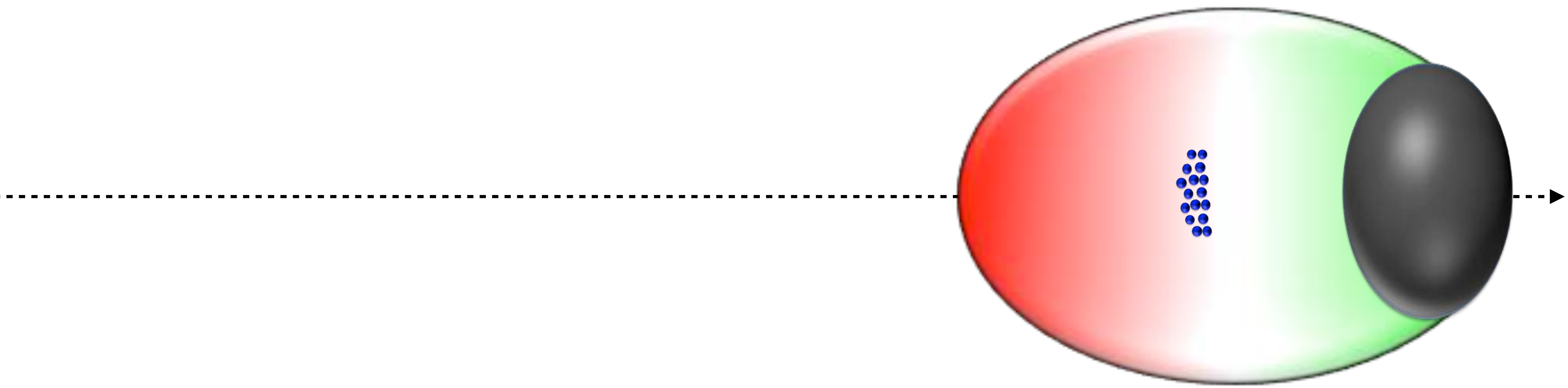

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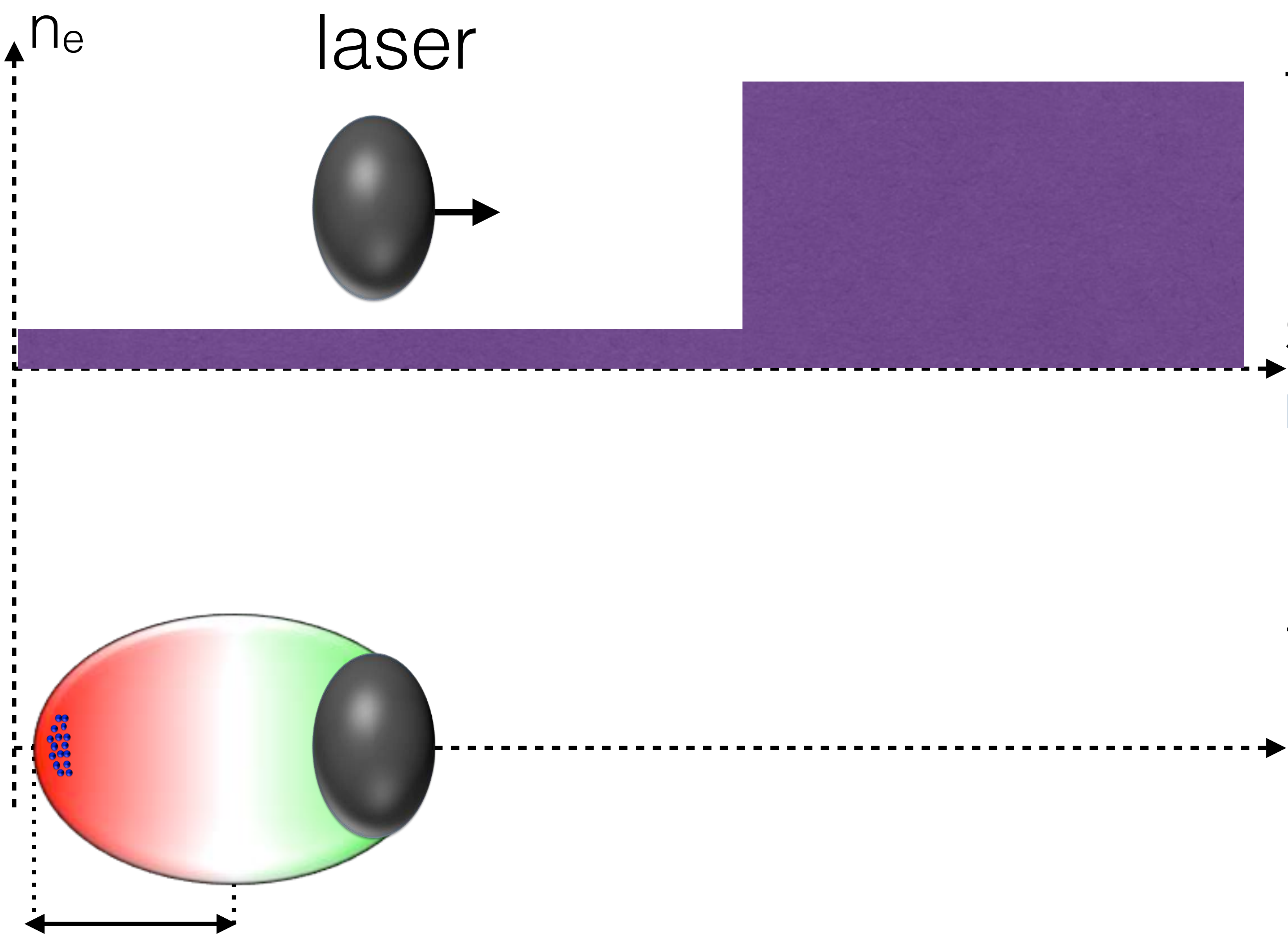
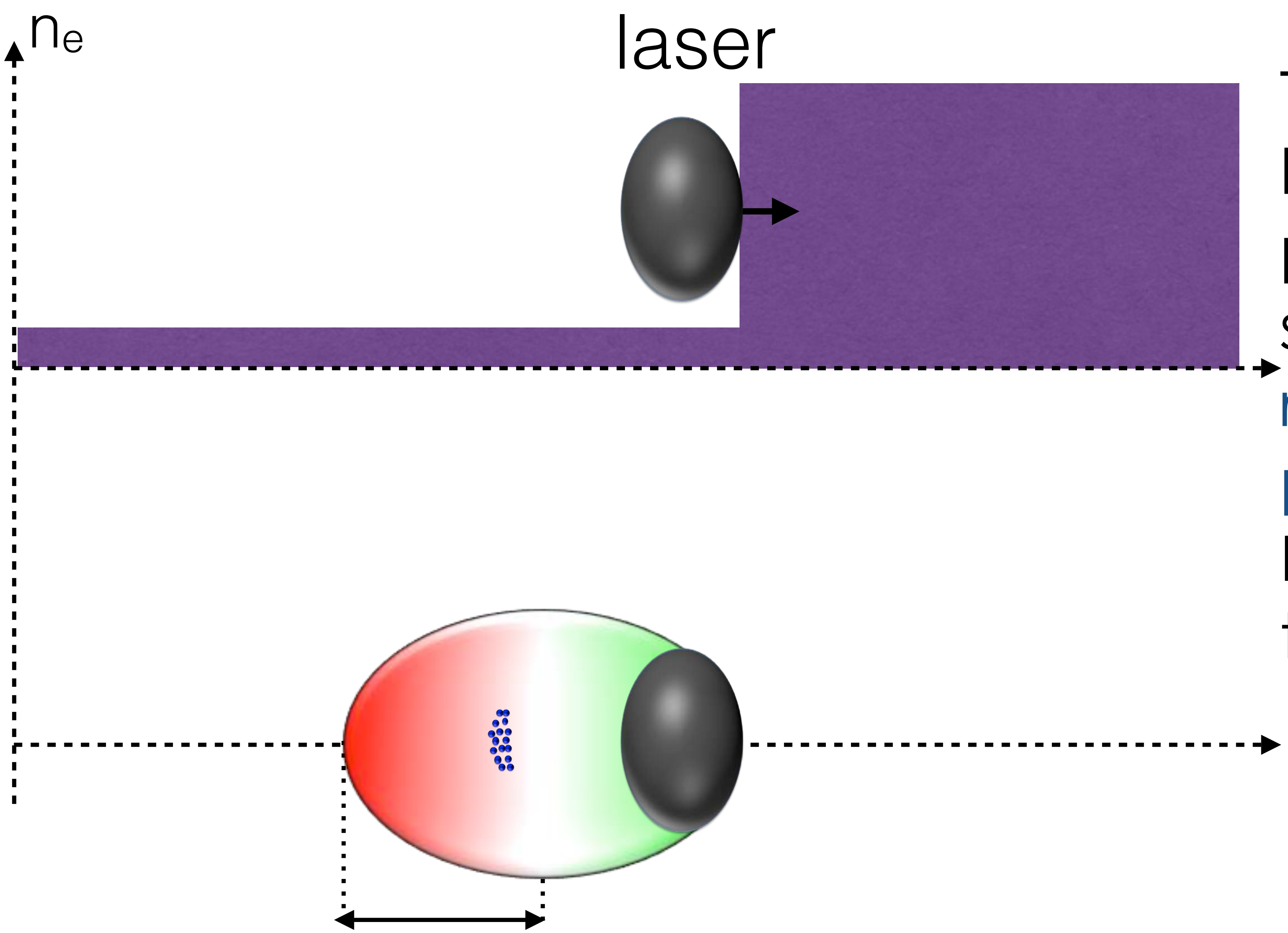


The reduction of the bubble size at the right position by increasing suddently the density resets the electrons phase.
Electrons can start again to gain energy.

[Katsouleas et al., 1986; Sprangle et al., 2001]

Overcoming the dephasing limit



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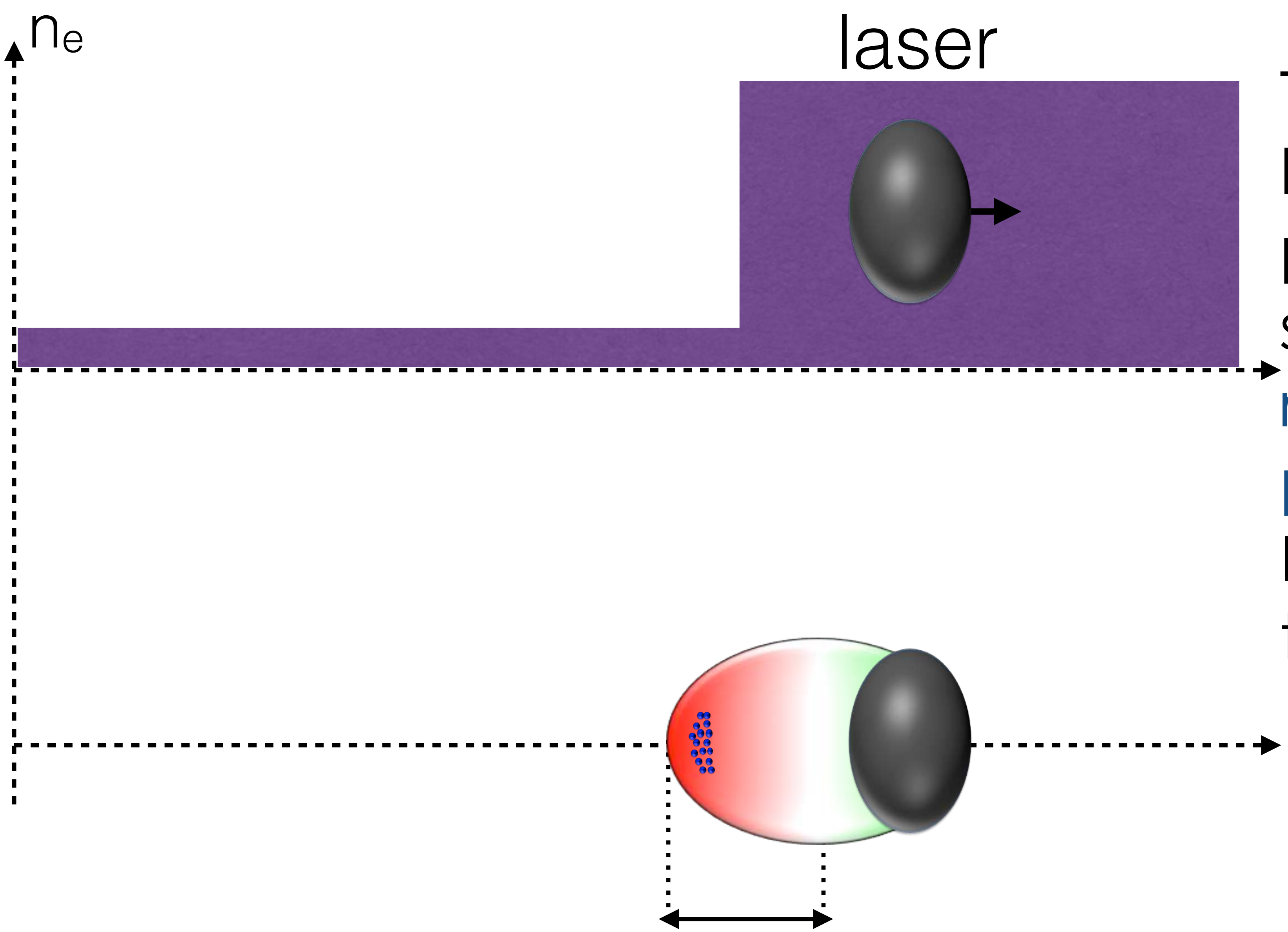

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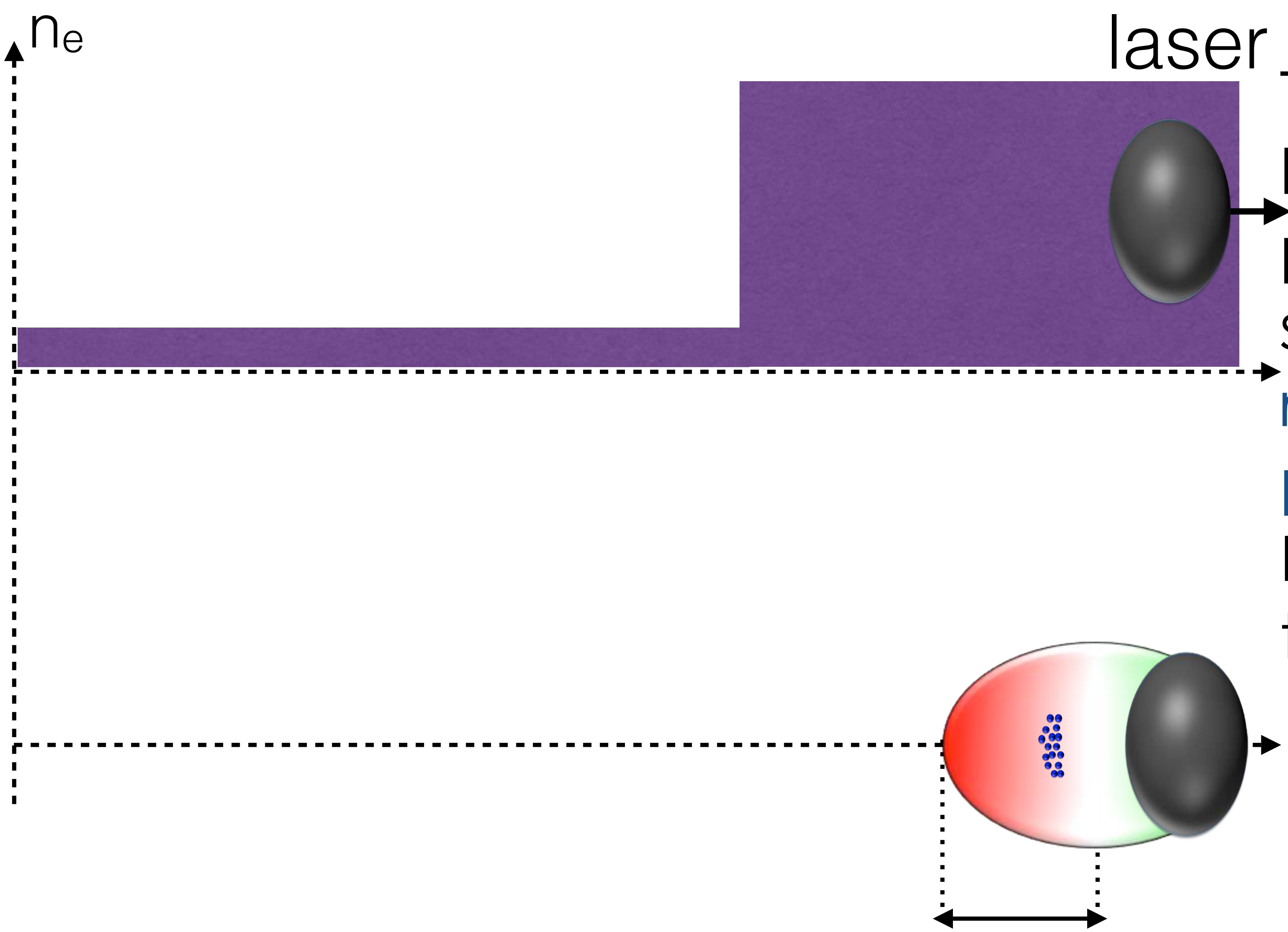

The reduction of the bubble size at the right position by increasing suddently the density resets the electrons phase.

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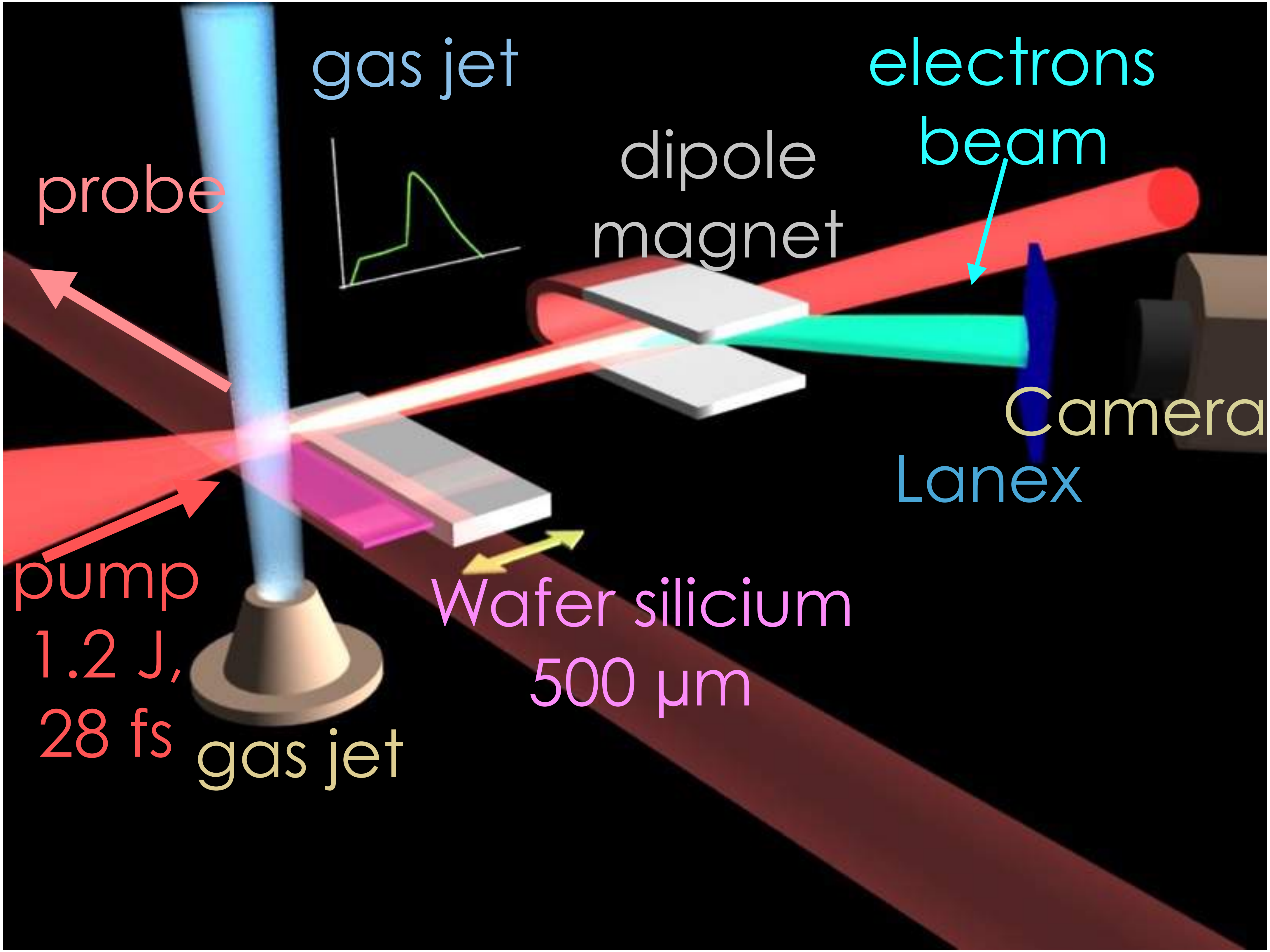
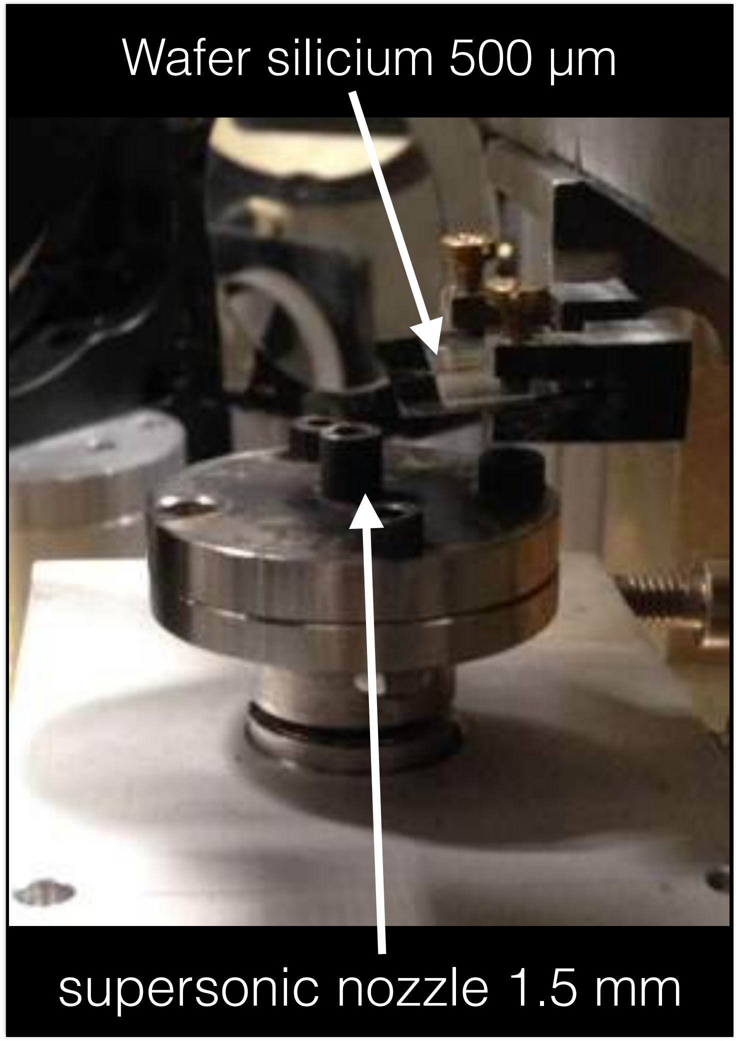
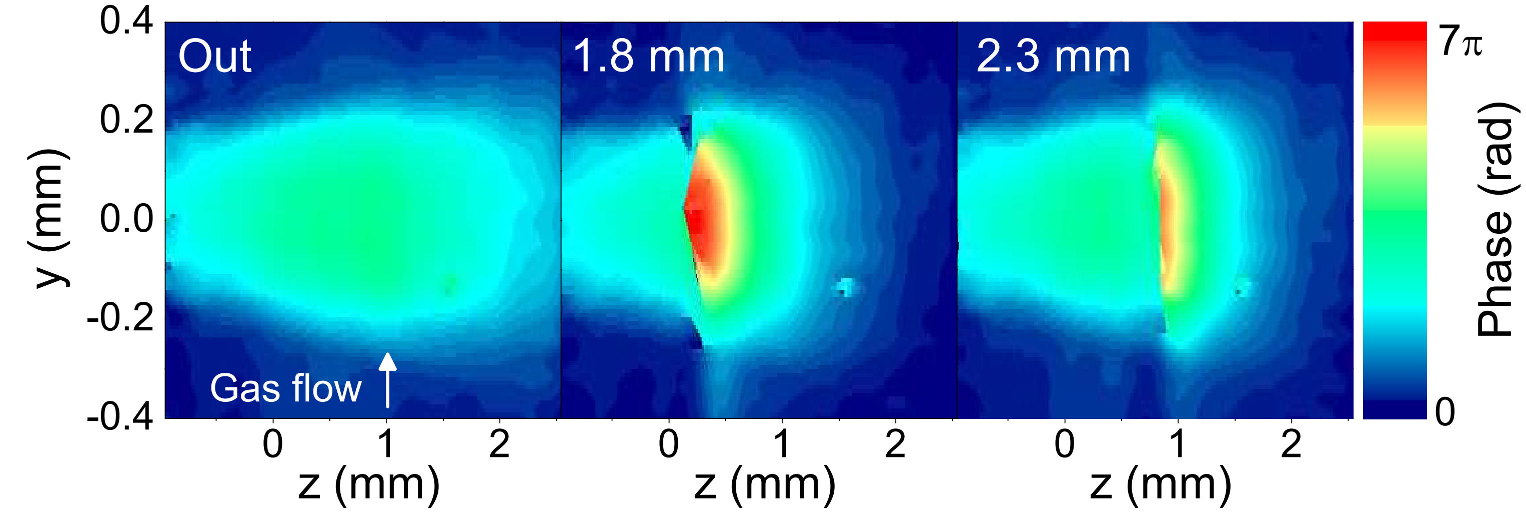
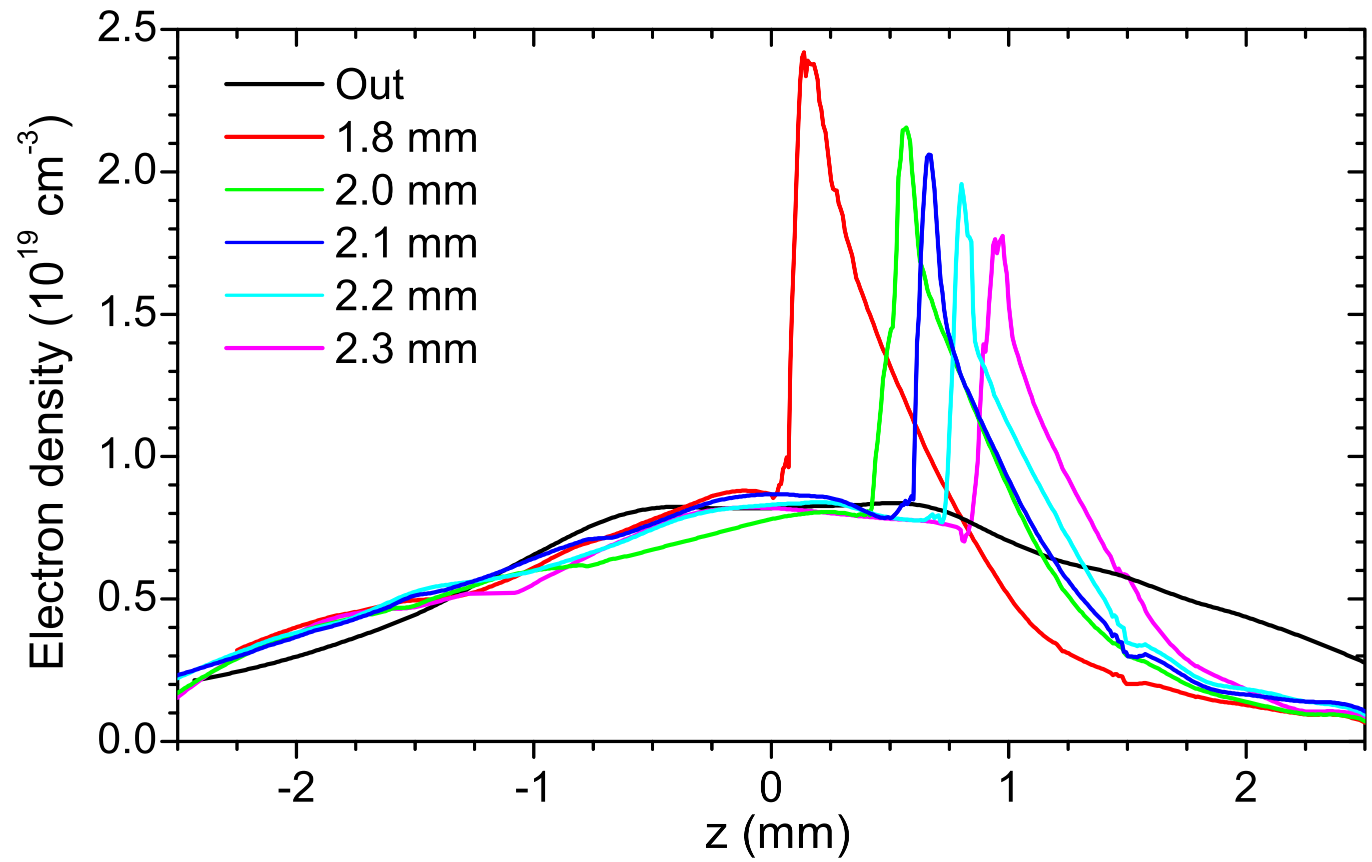
Overcoming the dephasing limit: experimental set-up



Overcoming the dephasing limit: results





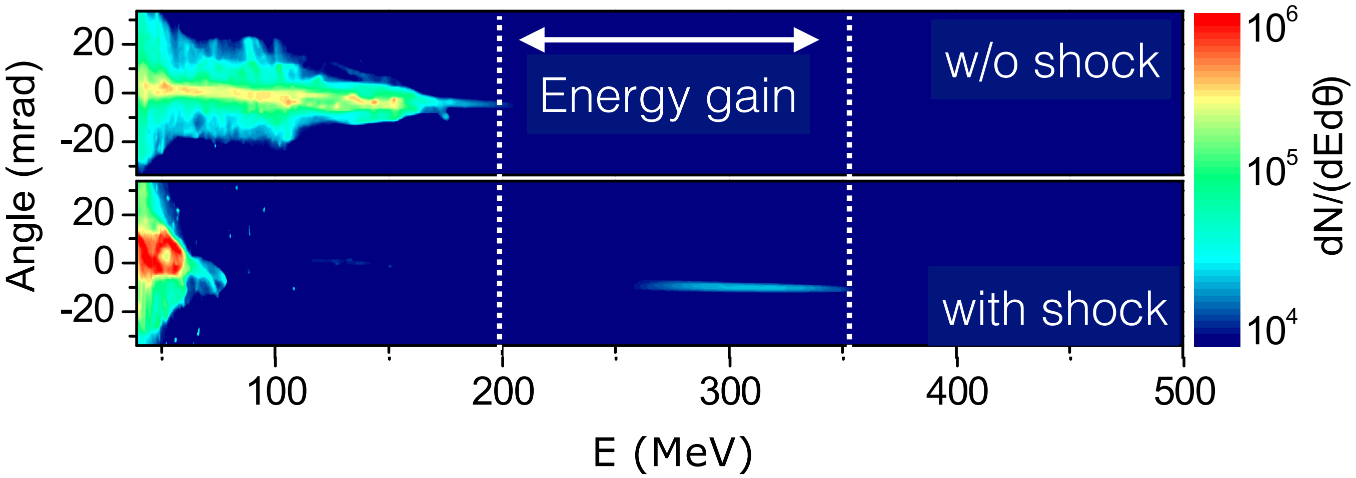


The density transition is controlled by changing the wafer position

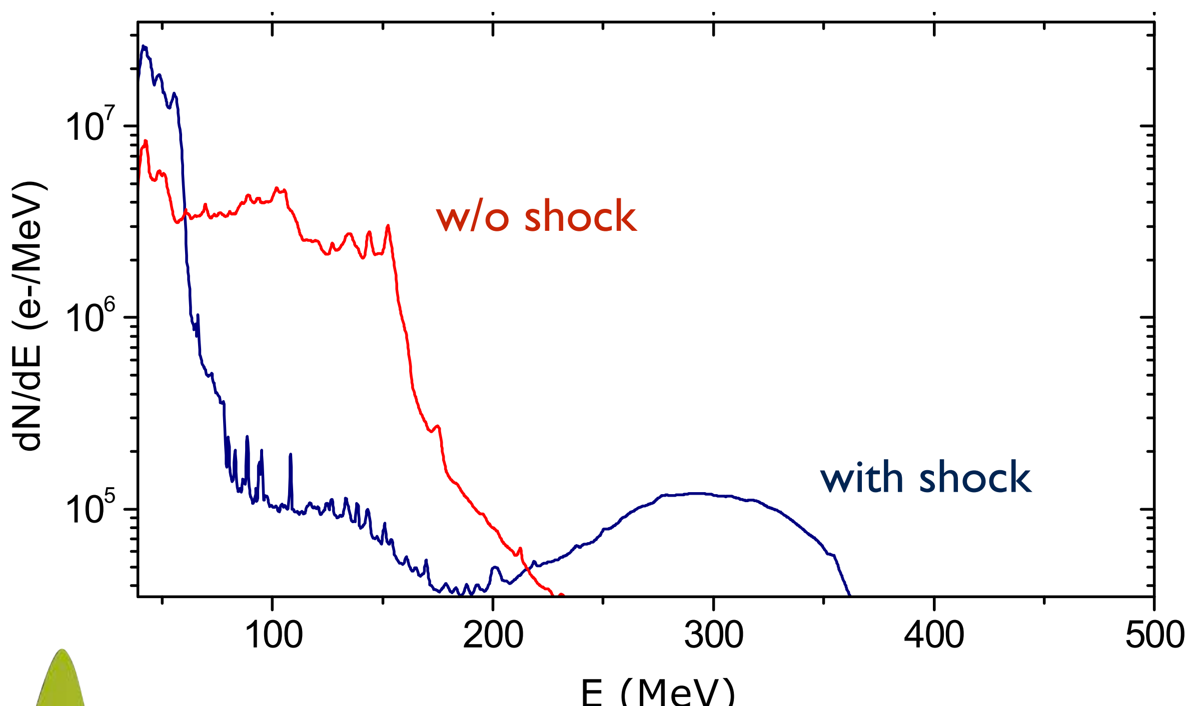
Overcoming the dephasing limit: experimental results & simulations

Experiment

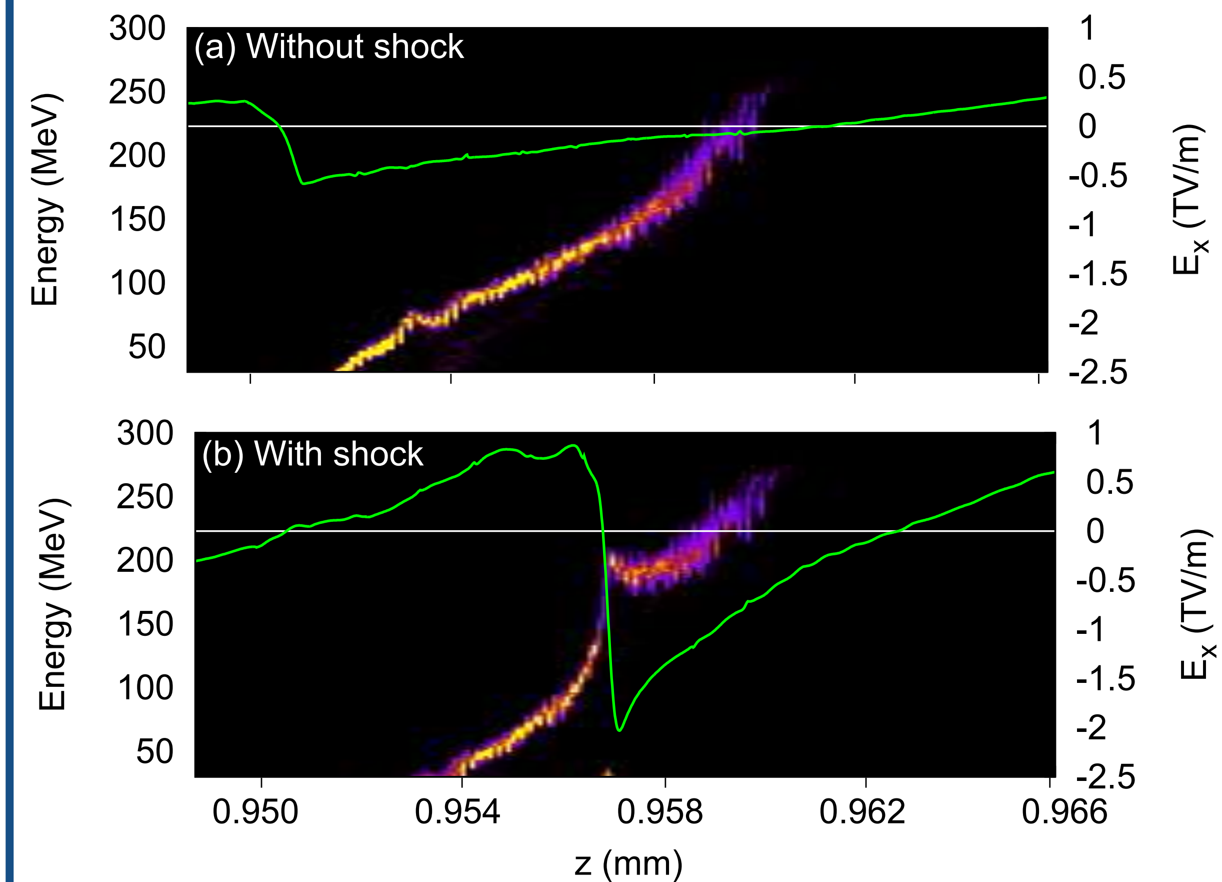
2D dispersion corrected spectra

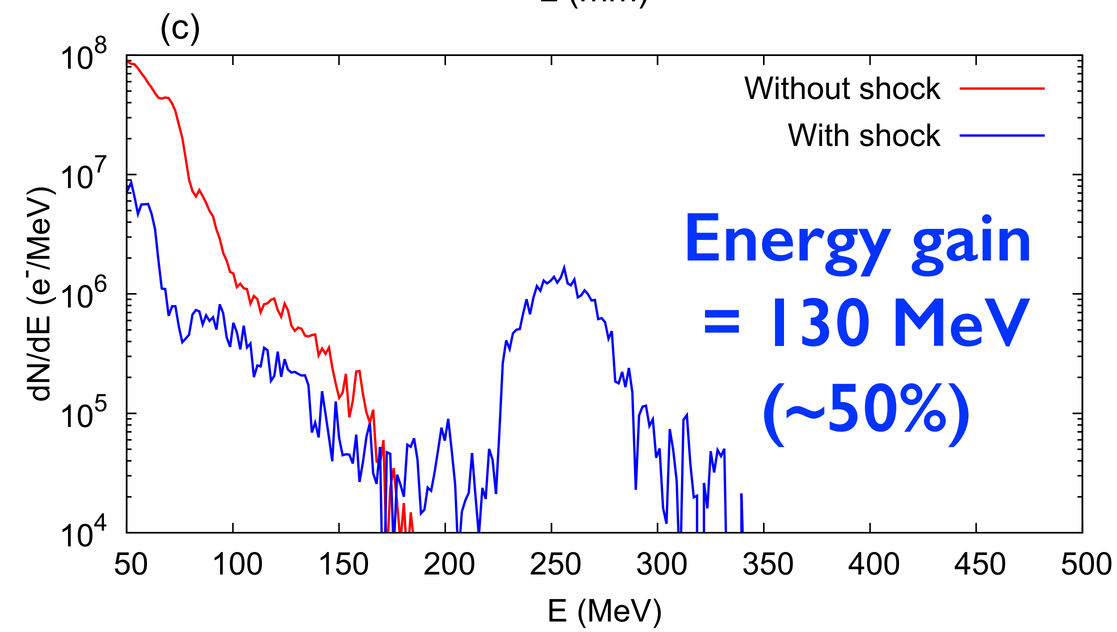


Angularly integrated spectra

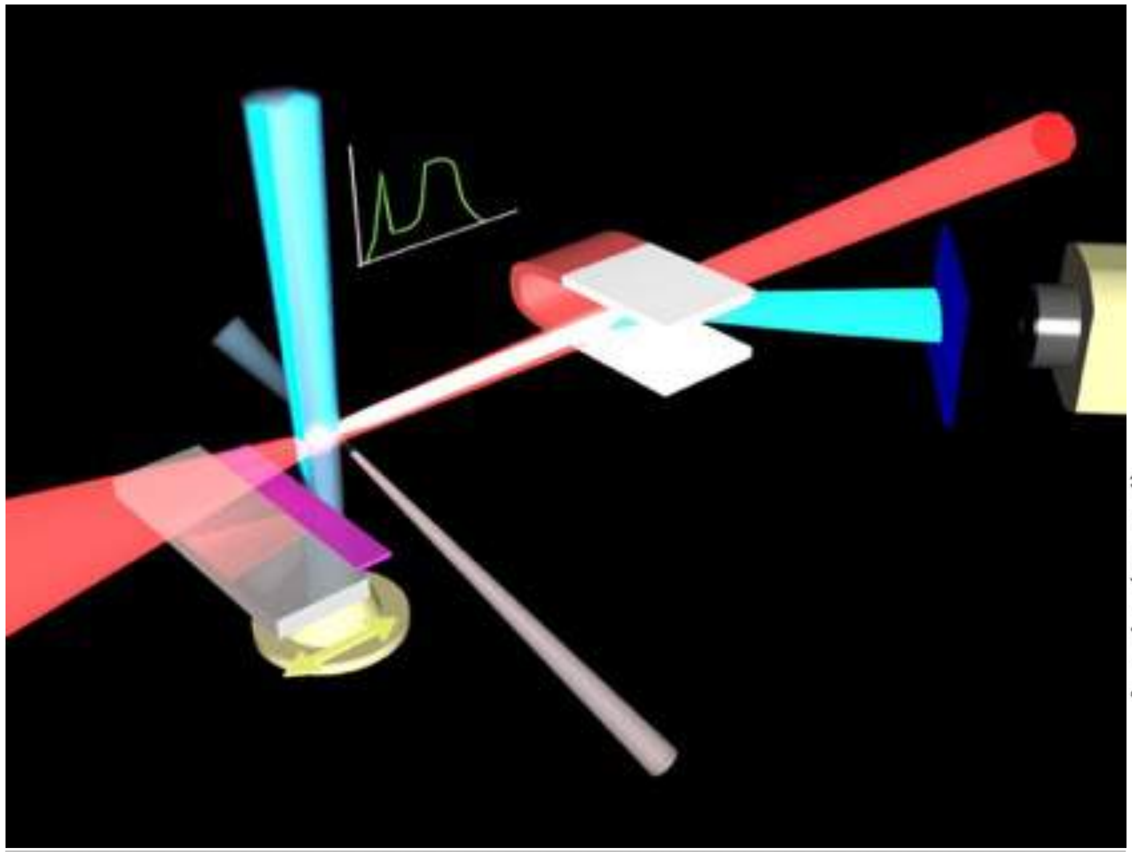


Calder-Circ PIC Simulations

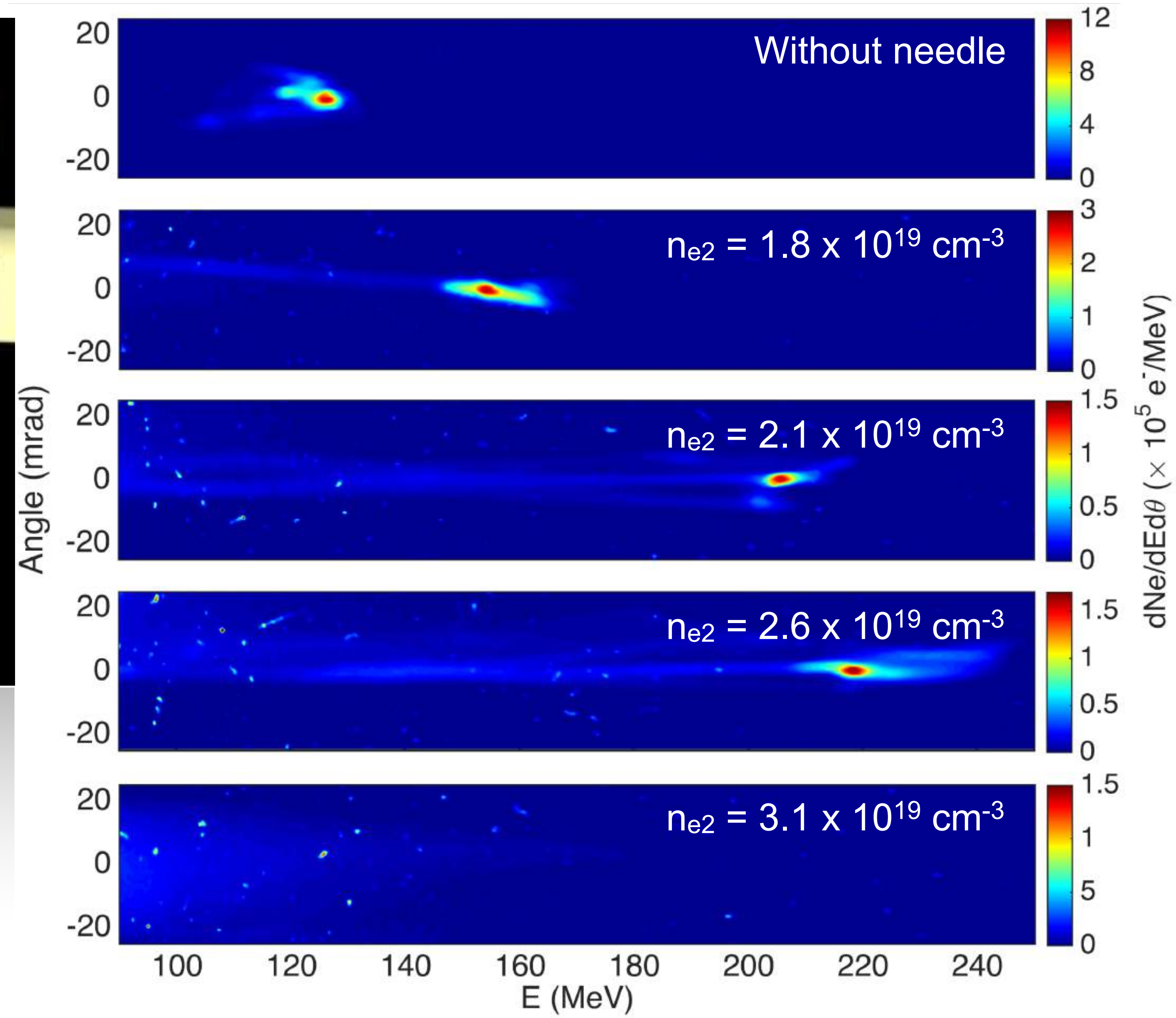




Energy boost of a mono-energetic e-beam



boosting a monoenergetic electron beam



E. Guillaume et al., PRL **115** (2015)

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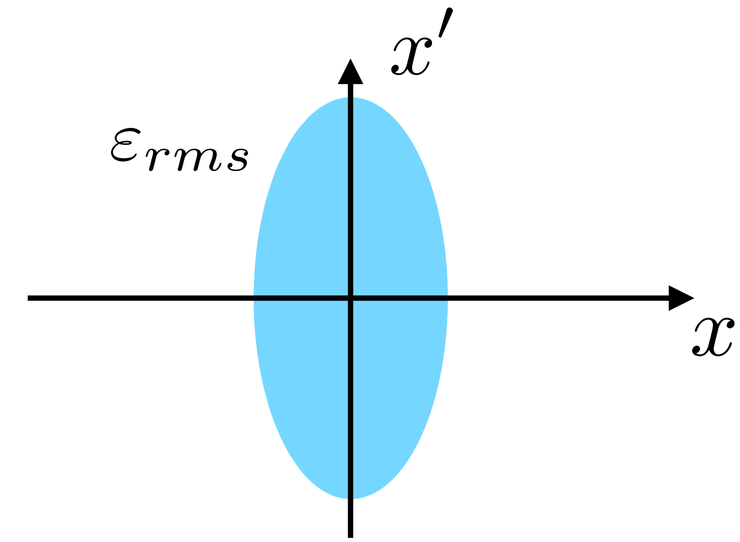
Manipulating the p⊥ momentum : emittance definition

electrons beam emittance :

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



typical transverse size of the e-beam **< 1 µm**

typical divergence of the e-beam : **~ 4 mrad**

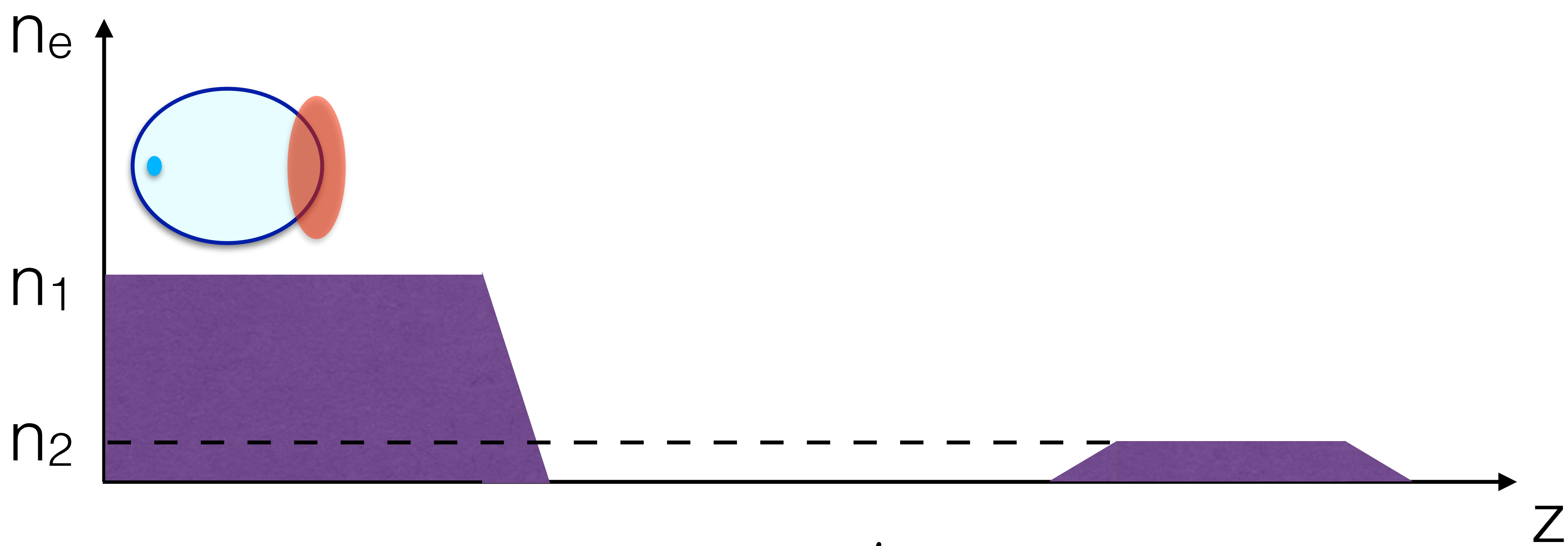
} emittance is dominated by the divergence

→ too large for example for some applications (FEL, …)

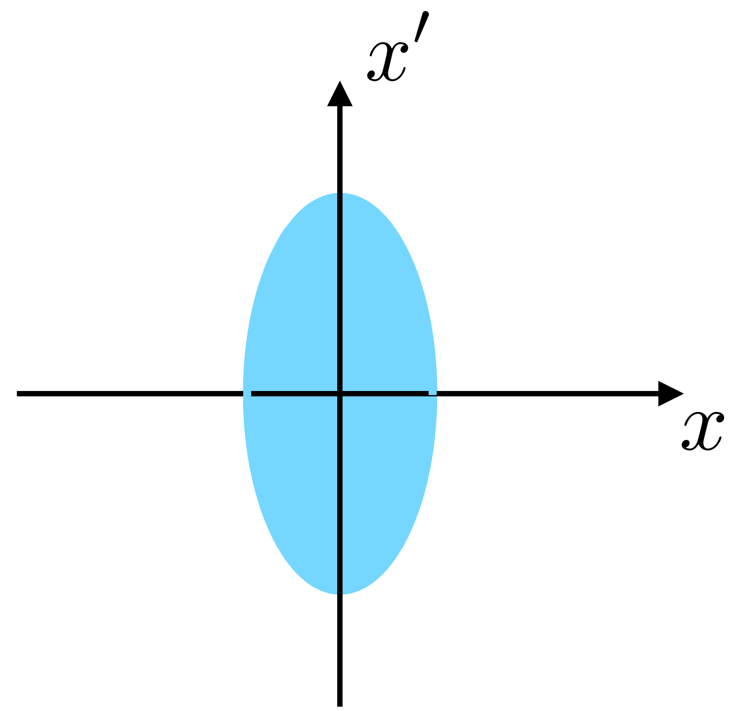
Goal :

reduce the divergence of the beam by manipulating the transverse phase space

Manipulating the p⊥ momentum : principle



Acceleration &
betatron oscillation



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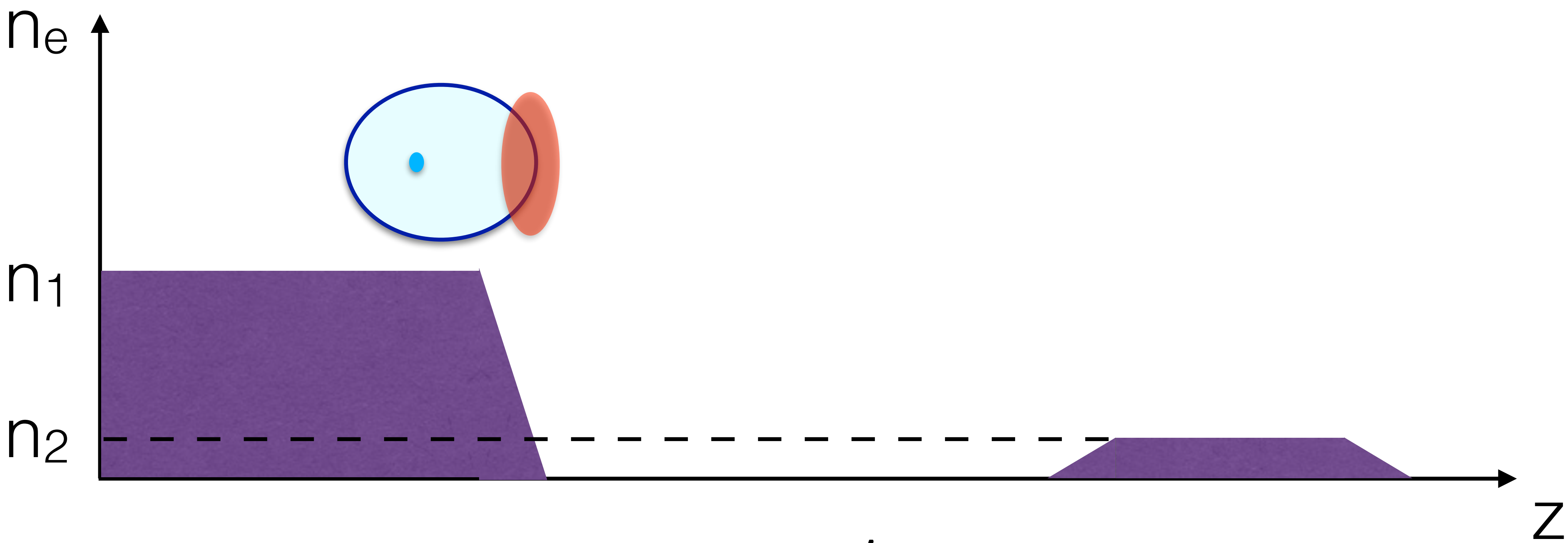

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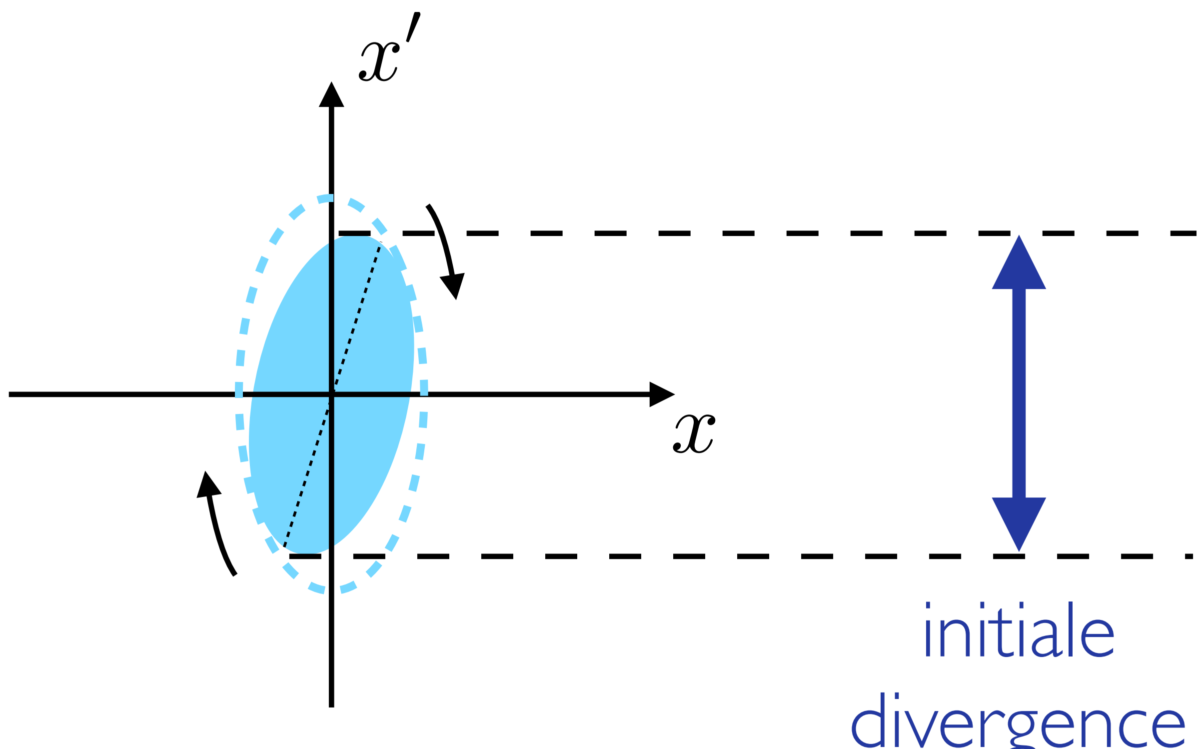

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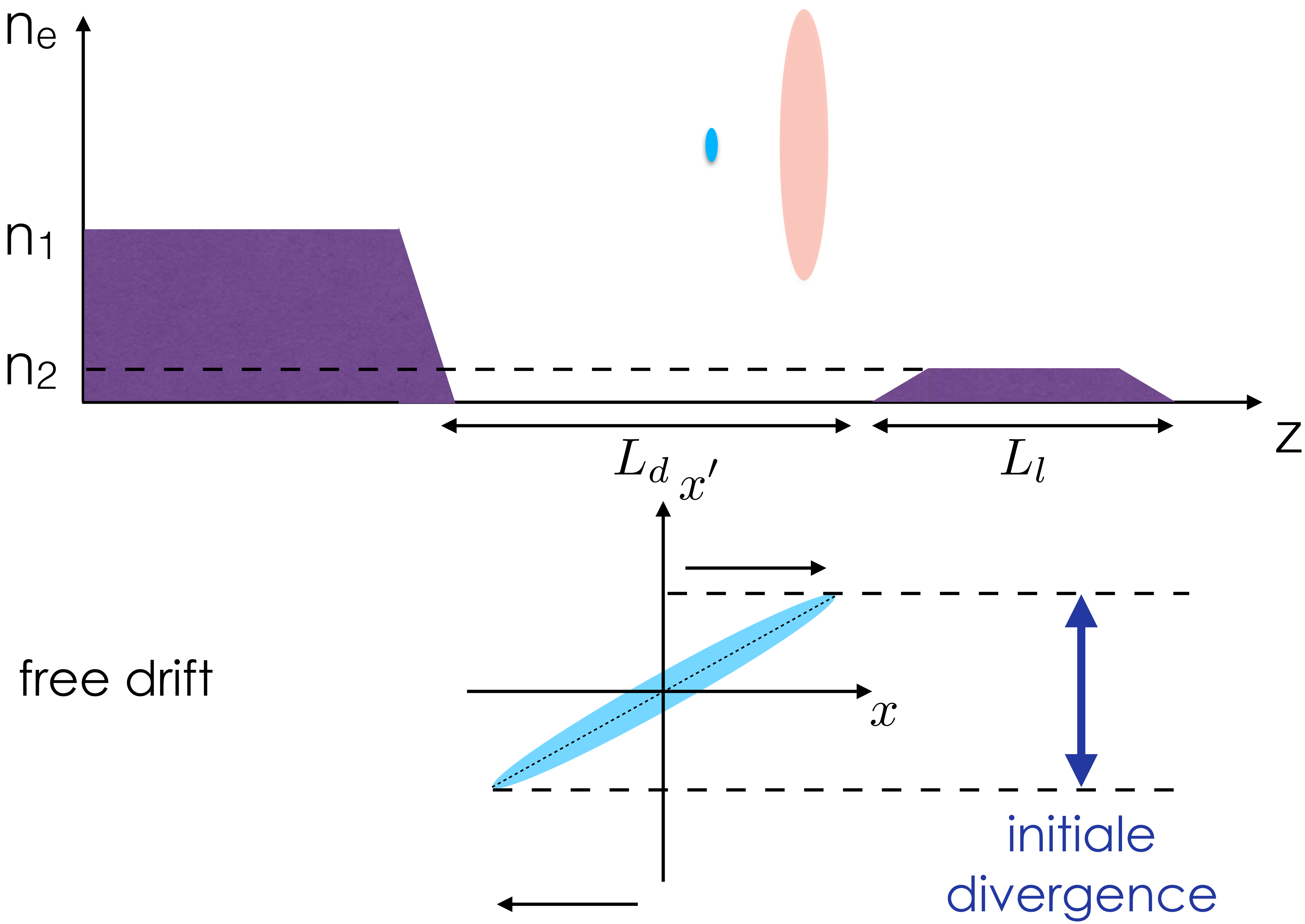

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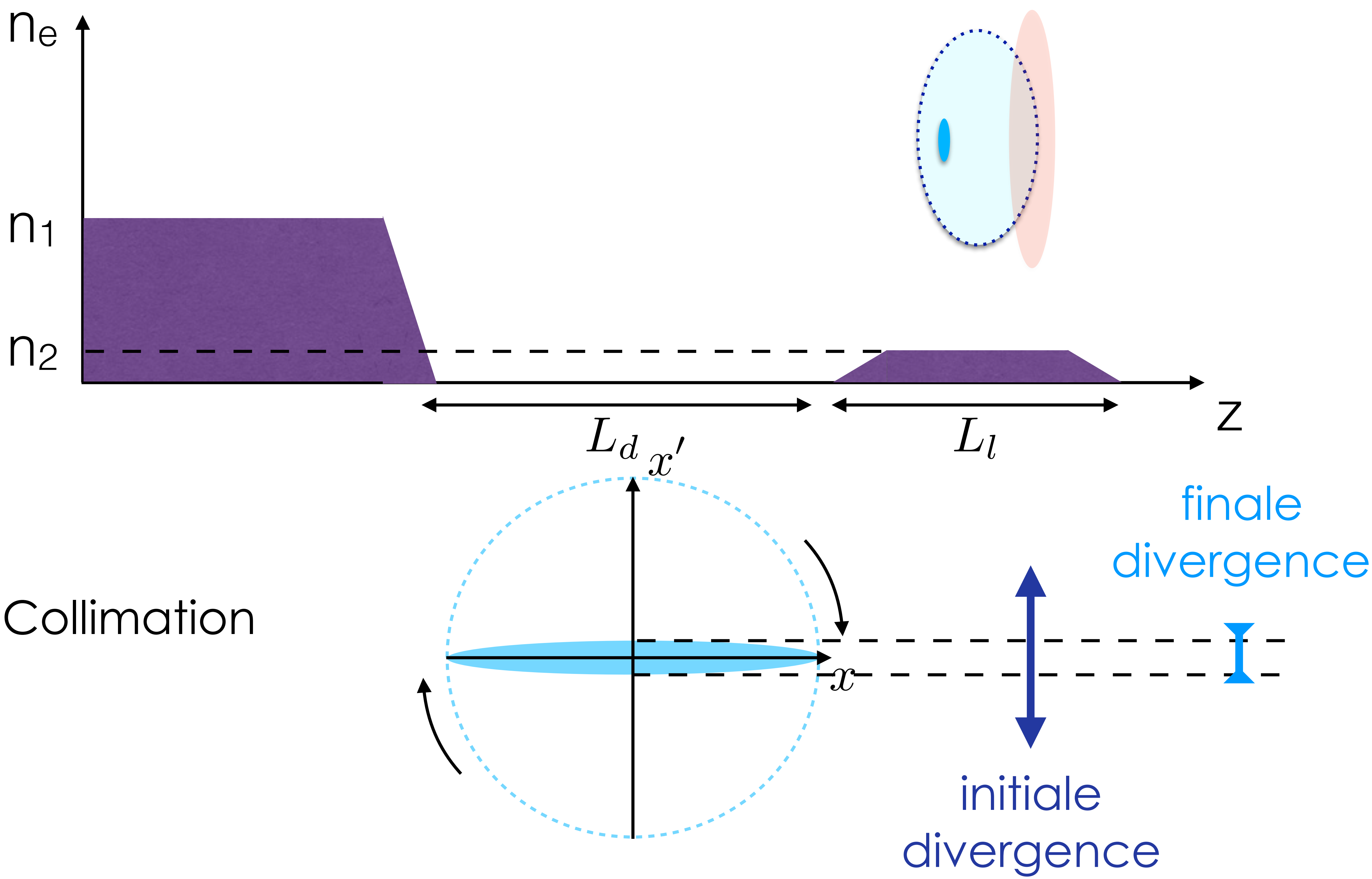


Collimation

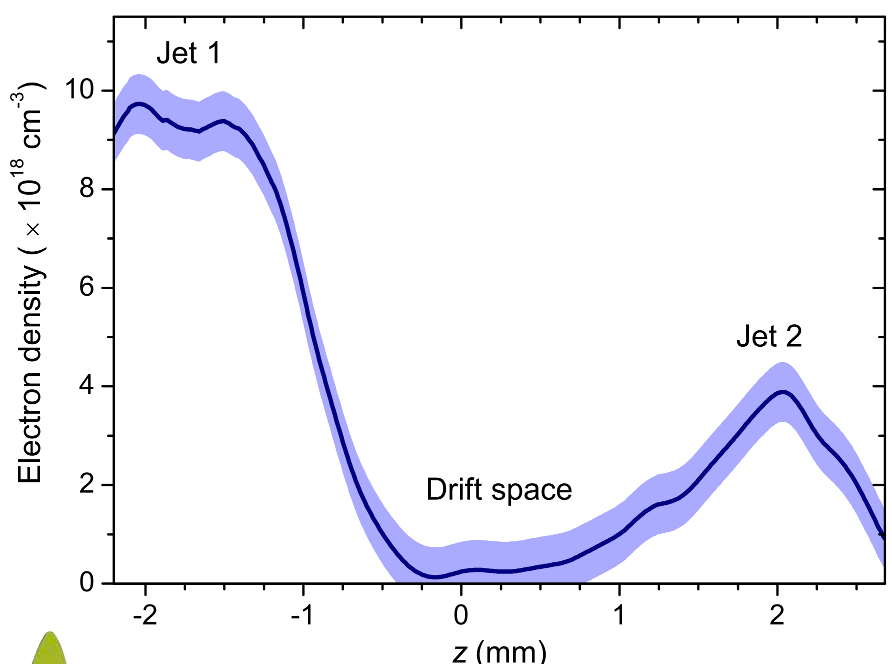
Manipulating the p⊥ momentum : experimental set-up

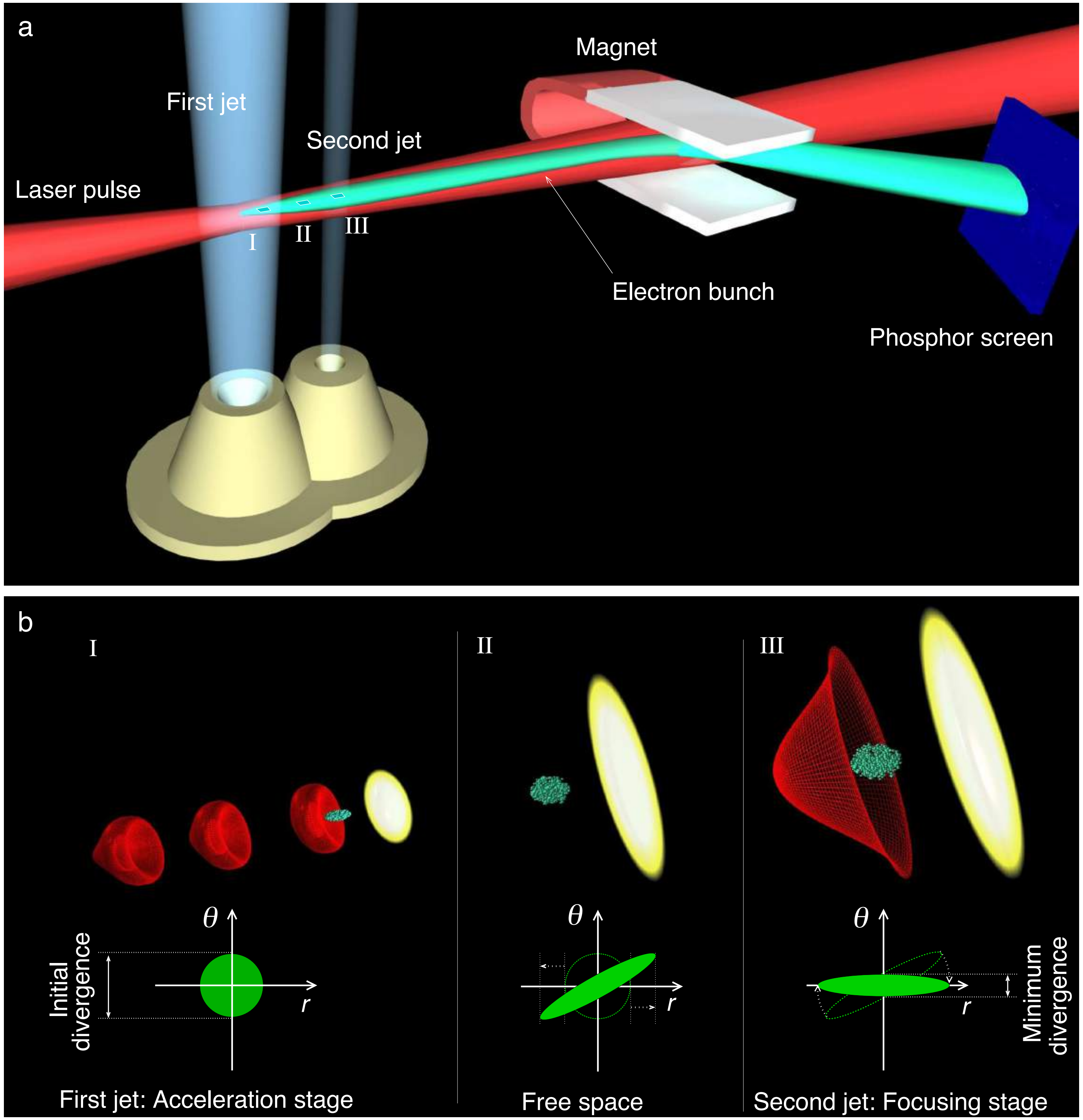
Acceleration stage

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

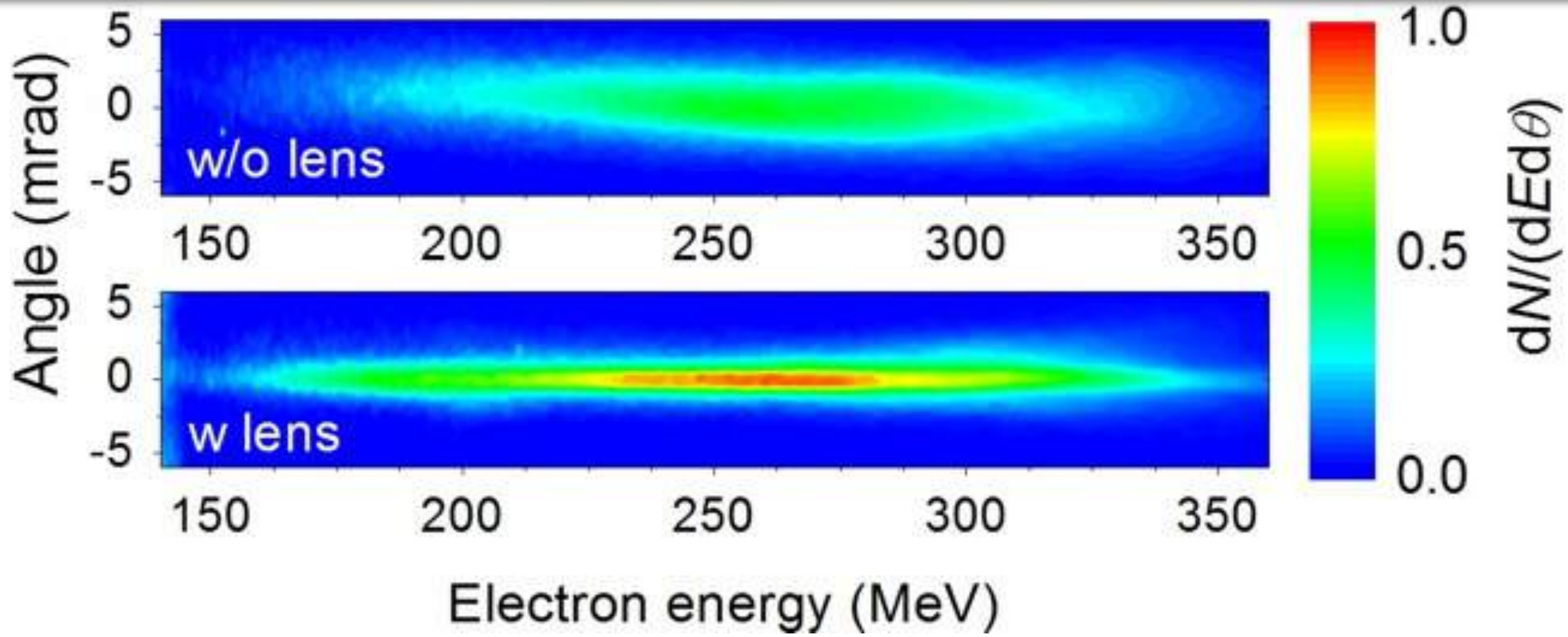
Focusing stage

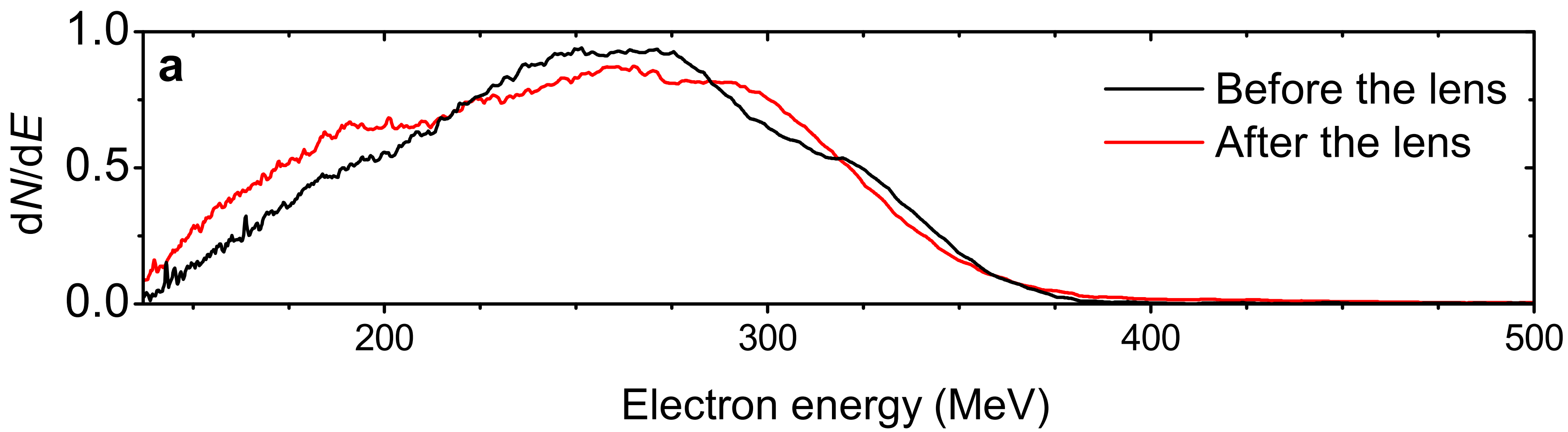
1 mm nozzle with variable n_2
Variable L_d





Manipulating the p⊥ momentum : demonstration of the laser plasma lens





Focusing stage parameters :

L_d = 1.8 mm

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

Divergence after the lens (FWHM)

σ_θ = 1. 6± 0.2 mrad

Divergence reduction ~ 2.6 ± 0. 7

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

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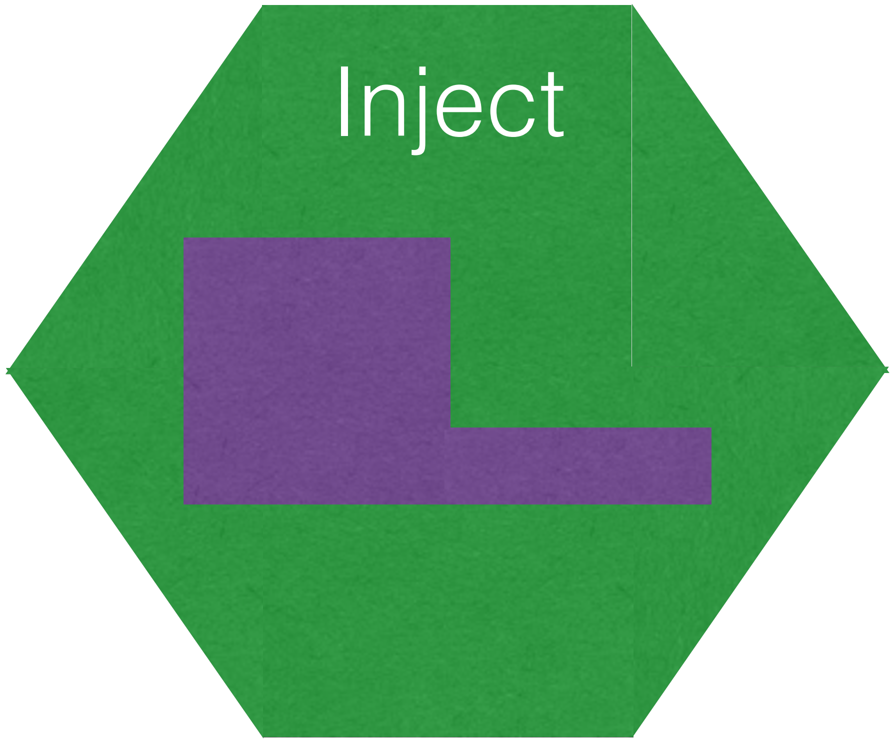
Simple plasma devices produced with a single laser pulse



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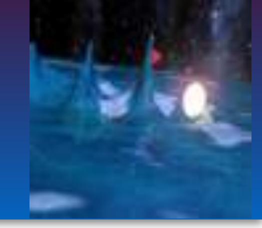

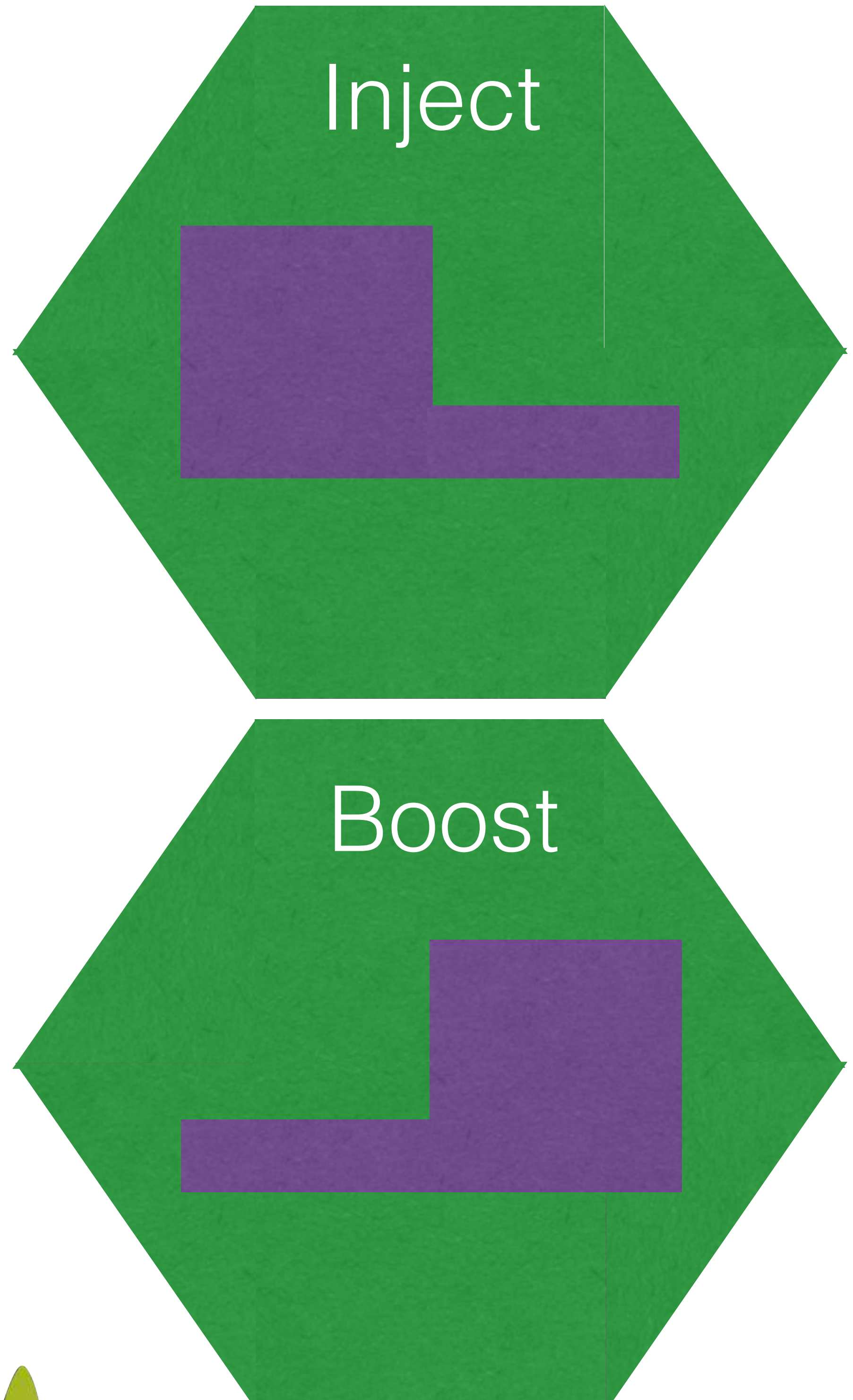

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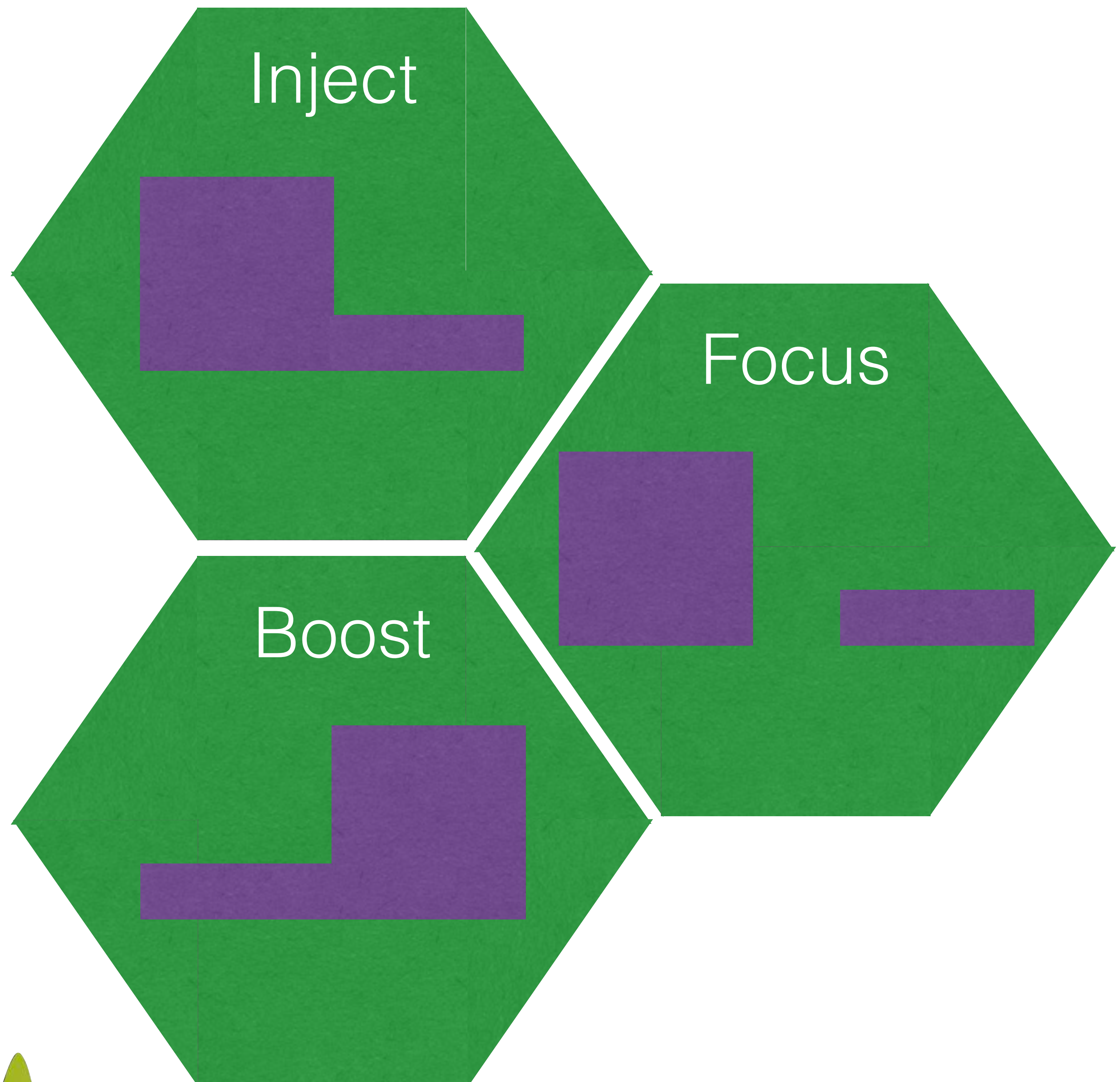

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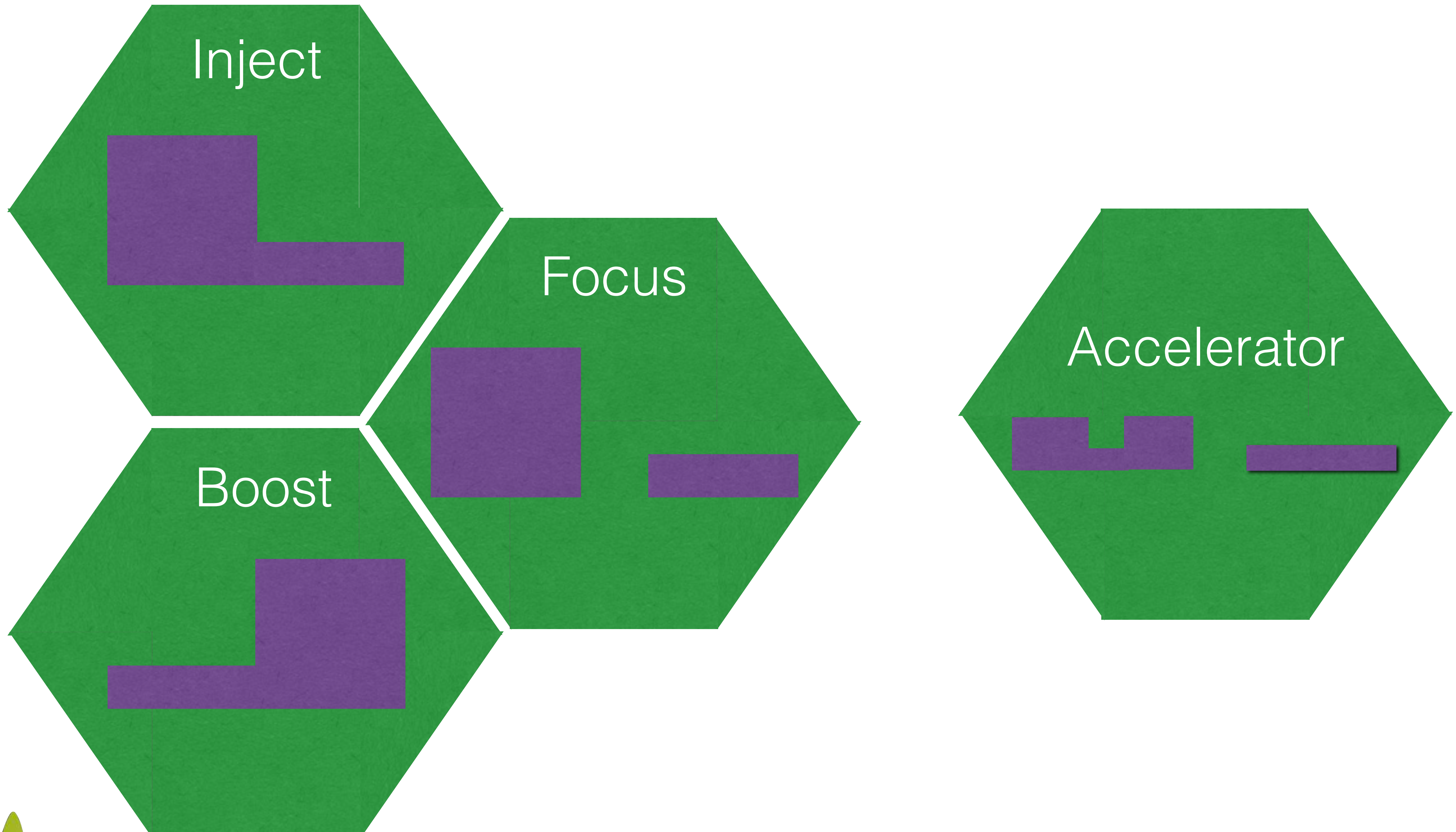

Conclusion & perspectives

By improving the control of the electron motion with intense lasers one can shape the electric field and manipulate the beam properties in the phase space.

Laser Plasma Accelerators have made significant progresses delivering stable, reliable high quality and high current e-beams.

Applications in medicine (radiotherapy, cancer imaging, security) are almost here.

V. Malka *et al.*, Nature Physics **4** (2008), V. Malka Phys. of Plasma 19, 055501 (2012)
E. Esarey et al. , Rev. Mod. Phys. **81** (2009), S. Corde et al., Rev. Mod. Phys. **85** (2013)

Acknowledgements

Emilien Guillaume[1], Sebastien Corde[1], Remi Lehe[1], Kim Ta Phuoc[1], Cédric Thaury[1], Agustin Lifschitz[1], Igor Andriyash[1], Antoine Rousse[1], Stephane Sebban[1], Lazlo Veisz[2], S. W. Chou[2], Martin Hansson[3], Olle Lundh[3],

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