Manipulating Relativistic Electrons with Intense Lasers*

Victor Malka[1,2]

[1]LOA, Laboratoire d'Optique Appliquée, ENSTA ParisTech, CNRS, Ecole polytechnique, Université Paris-Saclay, France
[2]Weizmann Institute of Science, Rehovot, Israel

*EPL, **115**, 54001 (2016)

www.youtube.com/watch?v=qVO65x2IGbk

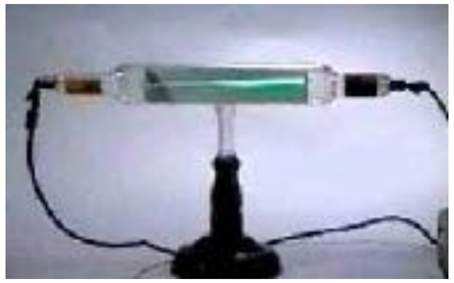
Laser Plasma Accelerators : Outline

- Introduction : context and motivations
- Injection in a density gradient
- Manipulating the longitudinal momentum
- Manipulating the transverse momentum
- Applications
- Conclusion and perspectives

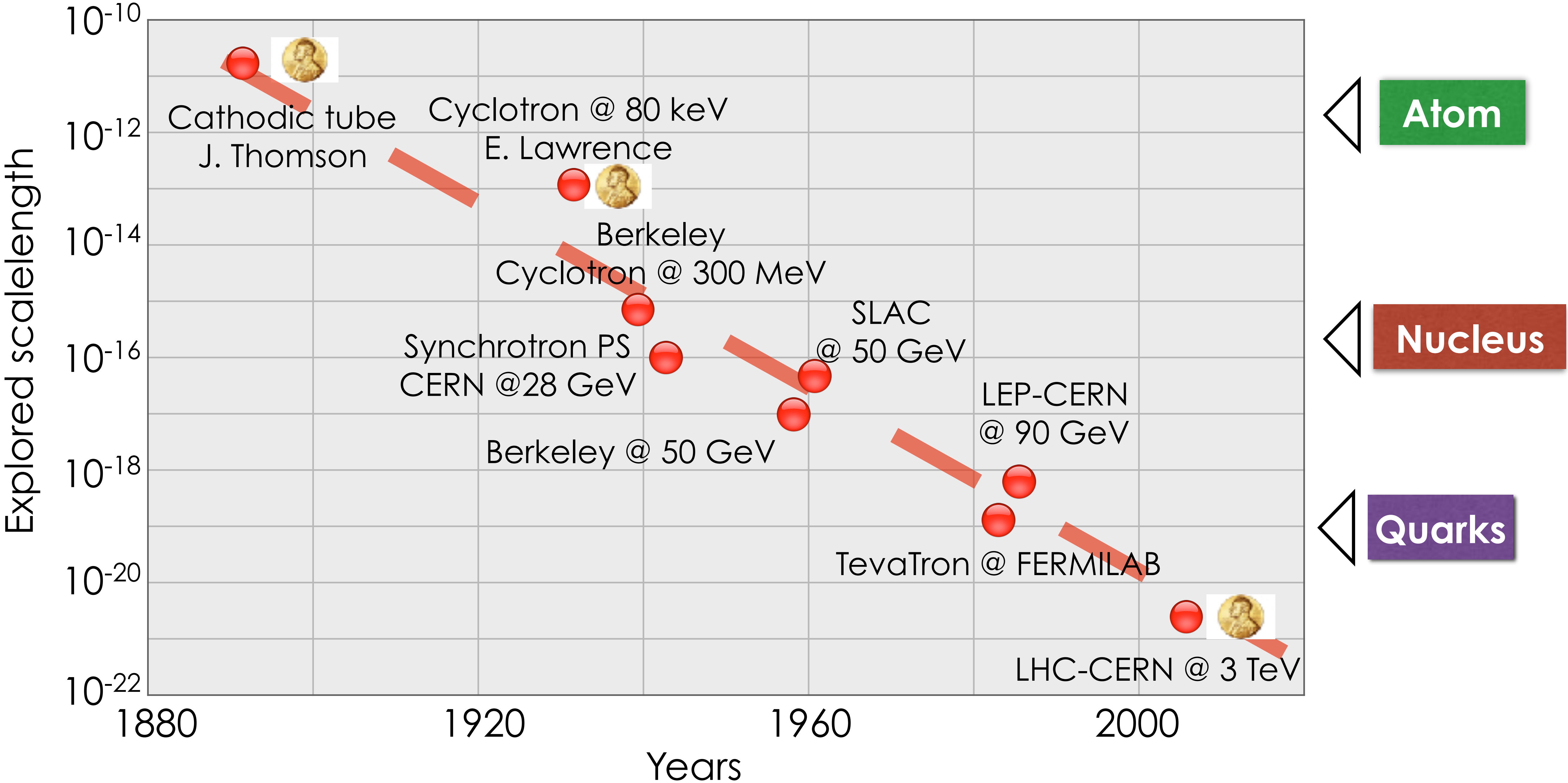
Laser Plasma Accelerators : Outline

- Introduction : context and motivations
- Injection in a density gradient
- Manipulating the longitudinal momentum
- Manipulating the transverse momentum
- Applications
- Conclusion and perspectives

Accelerators: One century of exploration of the infinitively small







Industrial Market for Accelerators

The development of state of the art accelerators for HEP has lead to :
research in other field of science (light source, spallation neutron sources…)
industrial accelerators (cancer therapy, ion implant., electron cutting&welding…)

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**	

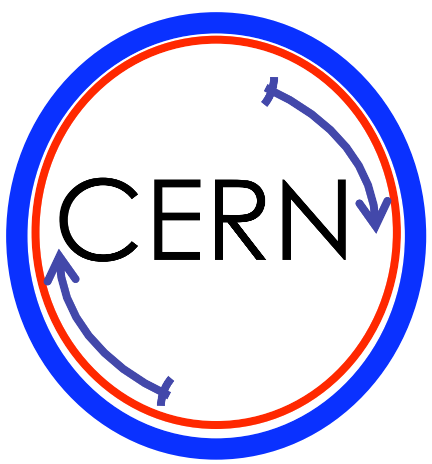
Plasma Accelerators : motivations

E-field $_{max}$ ≈ few 10 MeV /meter (Breakdown)

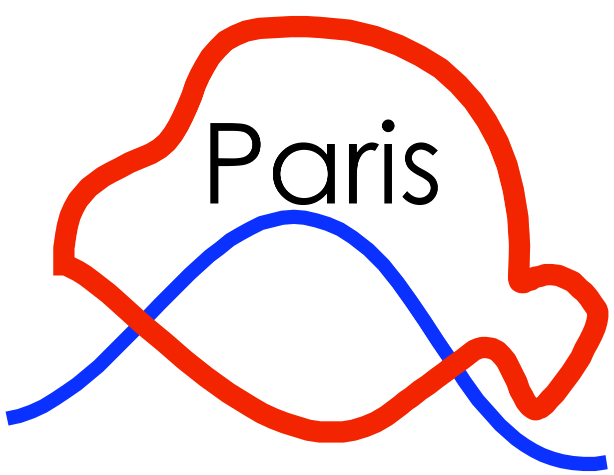
R>R$_{min}$ Synchrotron radiation

→ Energy ↗ → Length ↗ → Cost ↗

LHC
27 km



≈

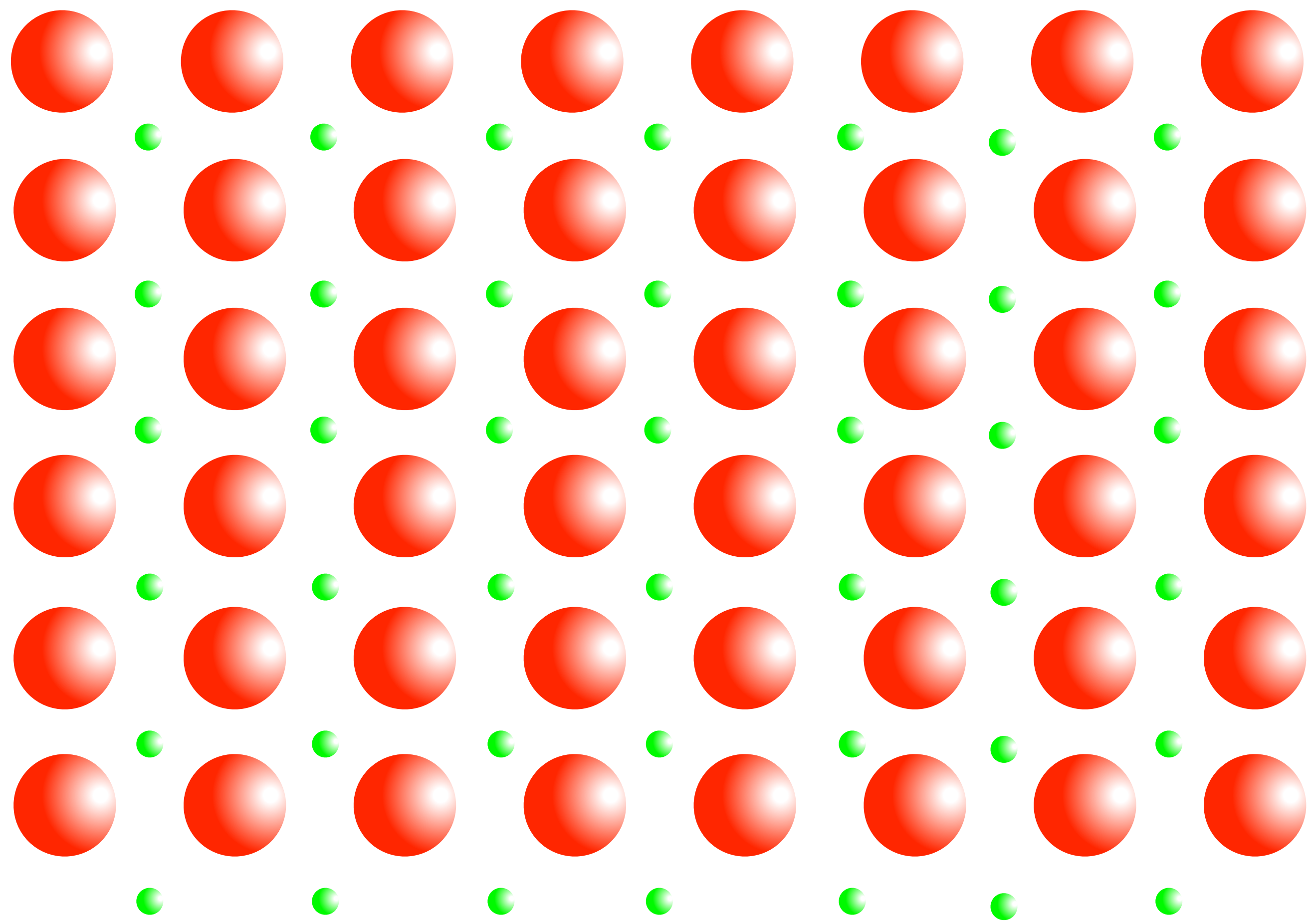


Circle road
31 km

➡ New medium : the plasma

Why is a plasma useful ?

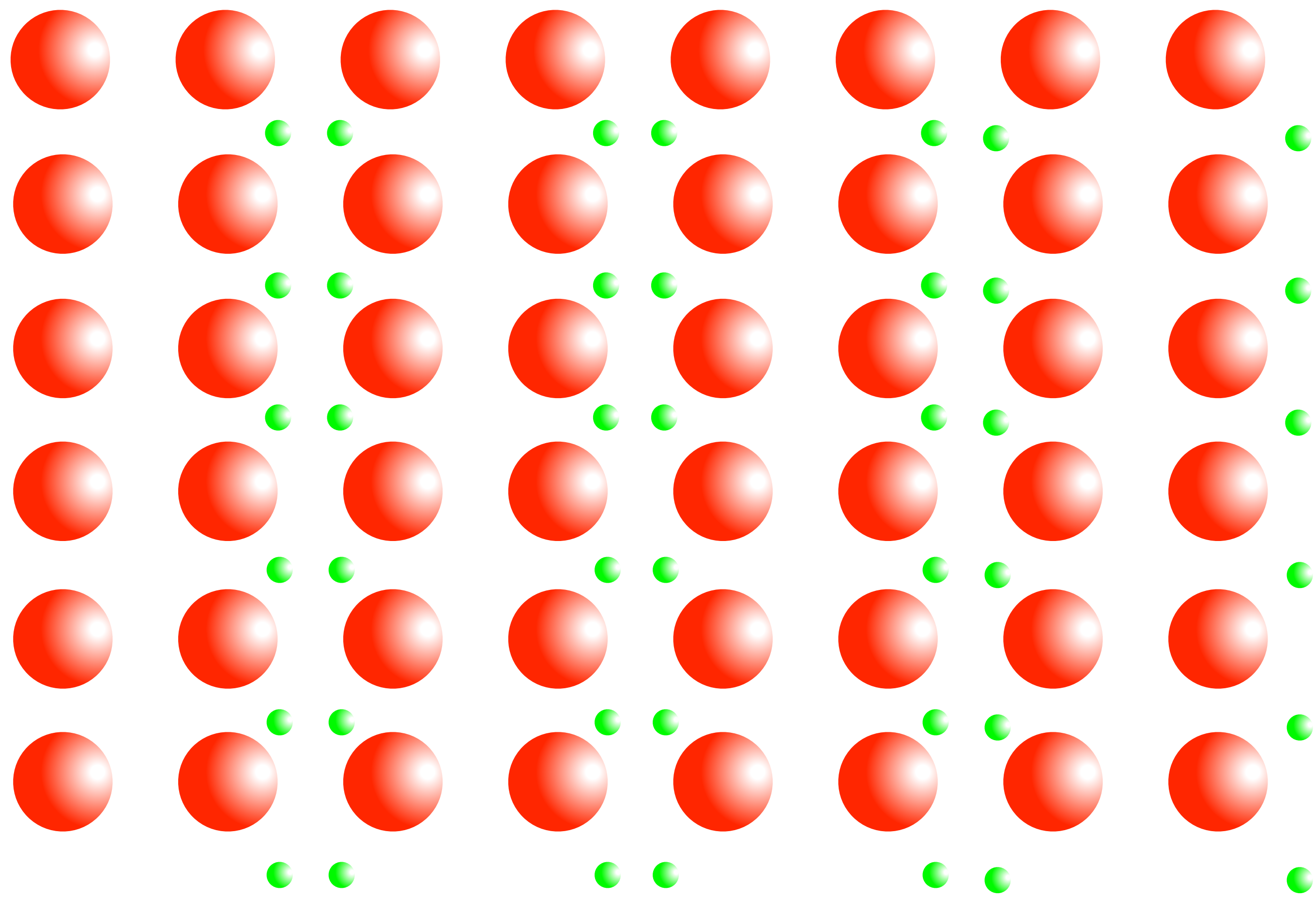
Plasma is an Ionized Medium => High Electric Fields



electrons plasma oscillation

Why is a plasma useful ?

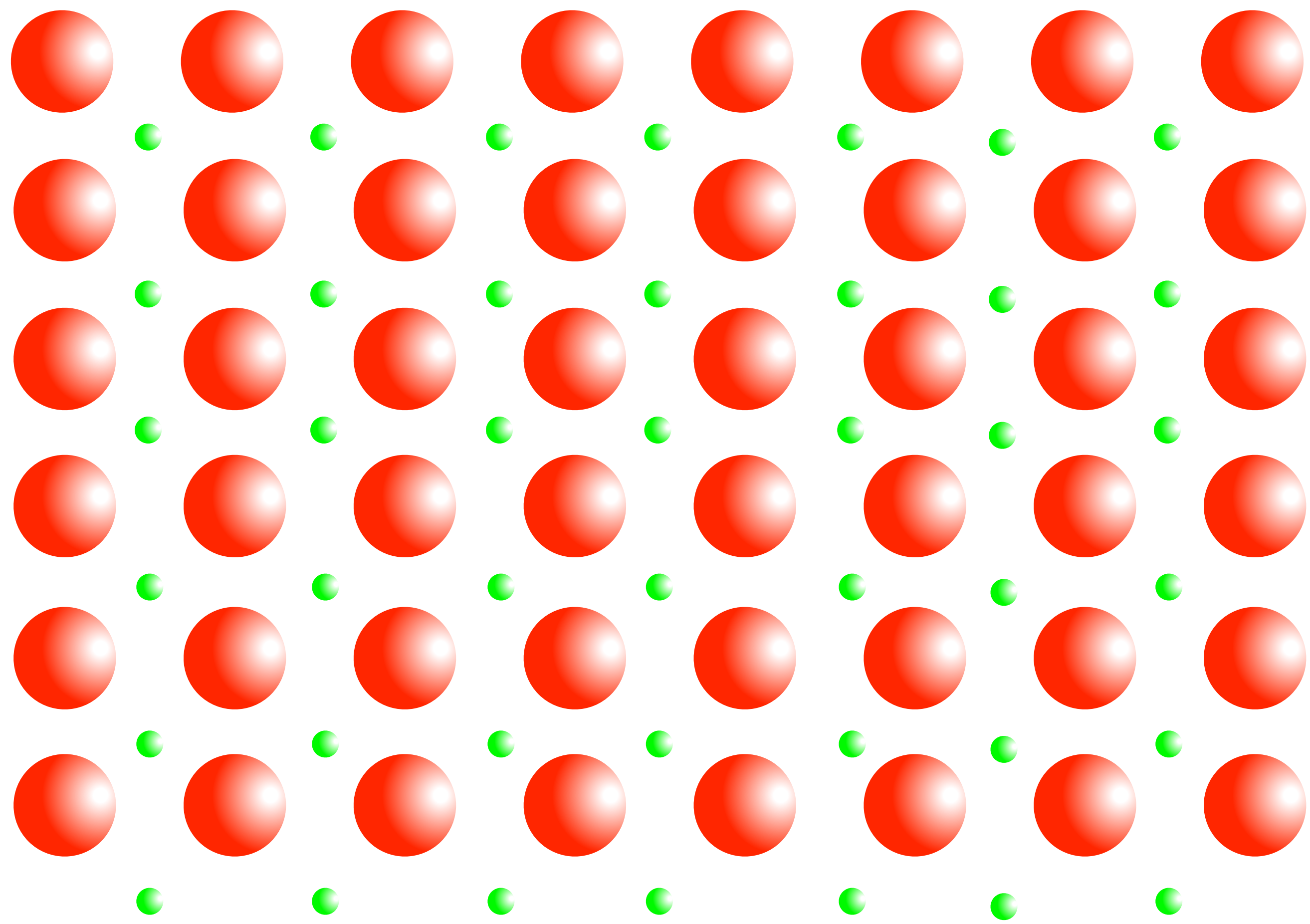
Plasma is an Ionized Medium => High Electric Fields



electrons plasma oscillation

Why is a plasma useful ?

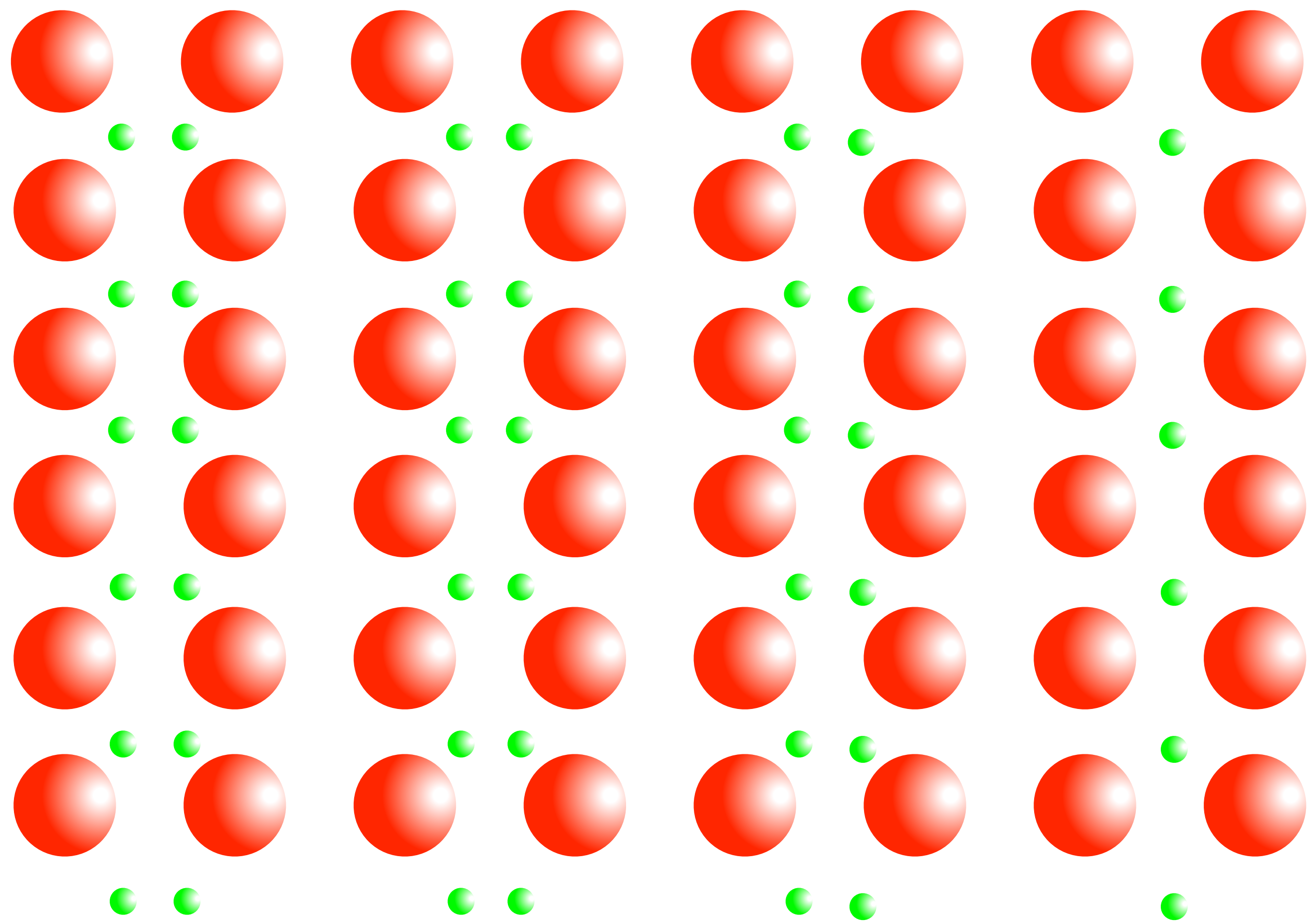
Plasma is an Ionized Medium => High Electric Fields



electrons plasma oscillation

Why is a plasma useful ?

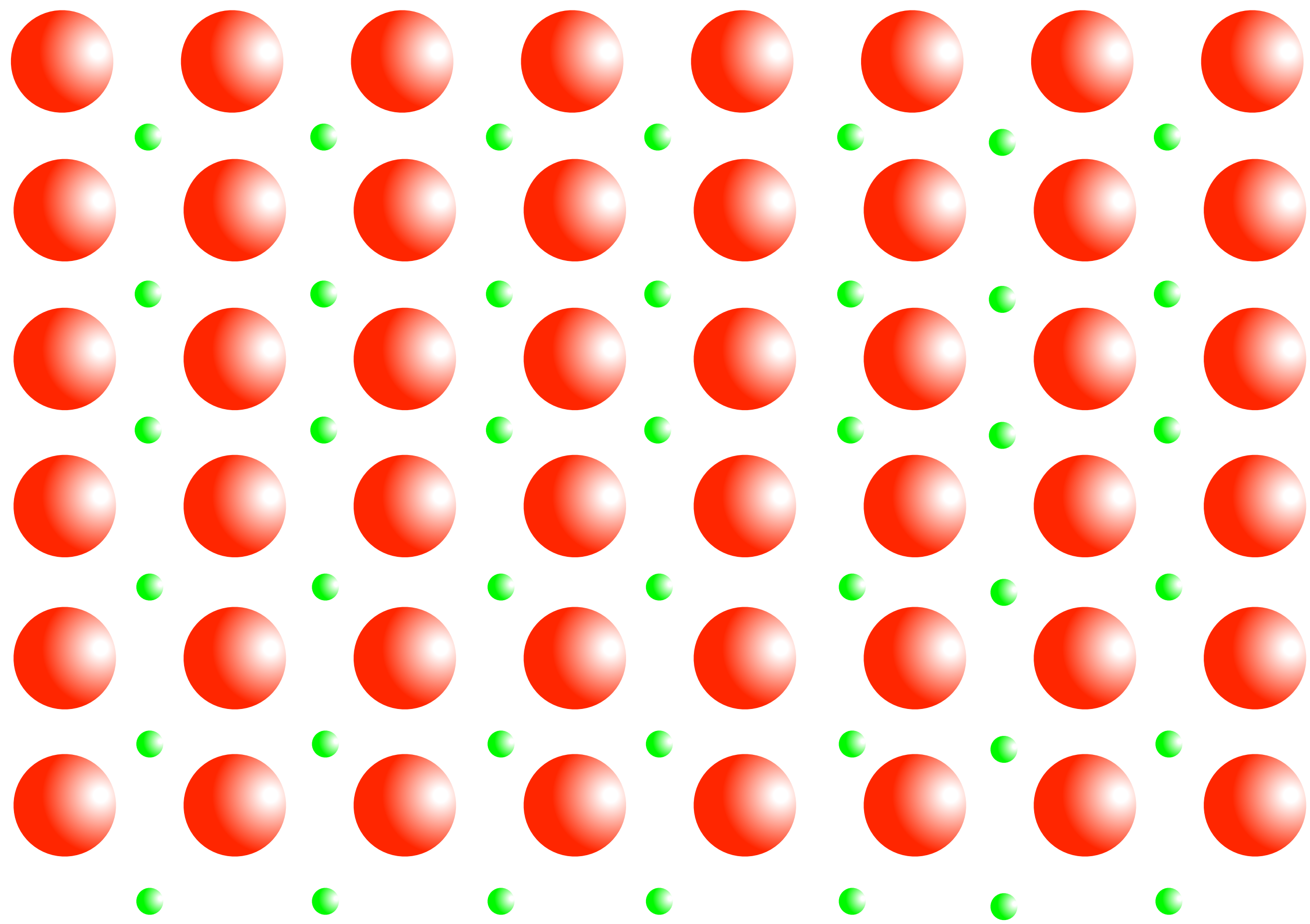
Plasma is an Ionized Medium => High Electric Fields



electrons plasma oscillation

Why is a plasma useful ?

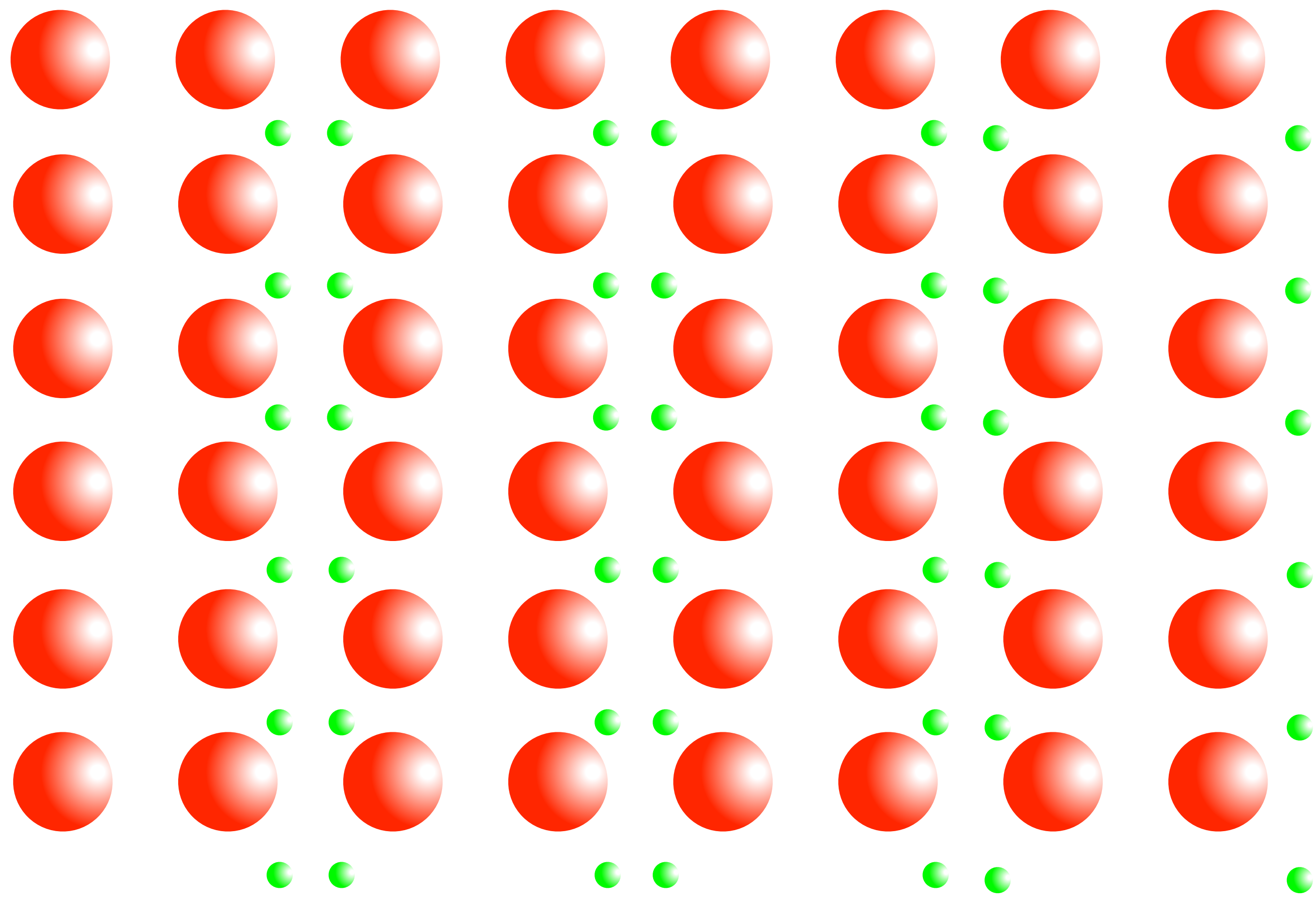
Plasma is an Ionized Medium => High Electric Fields



electrons plasma oscillation

Why is a plasma useful ?

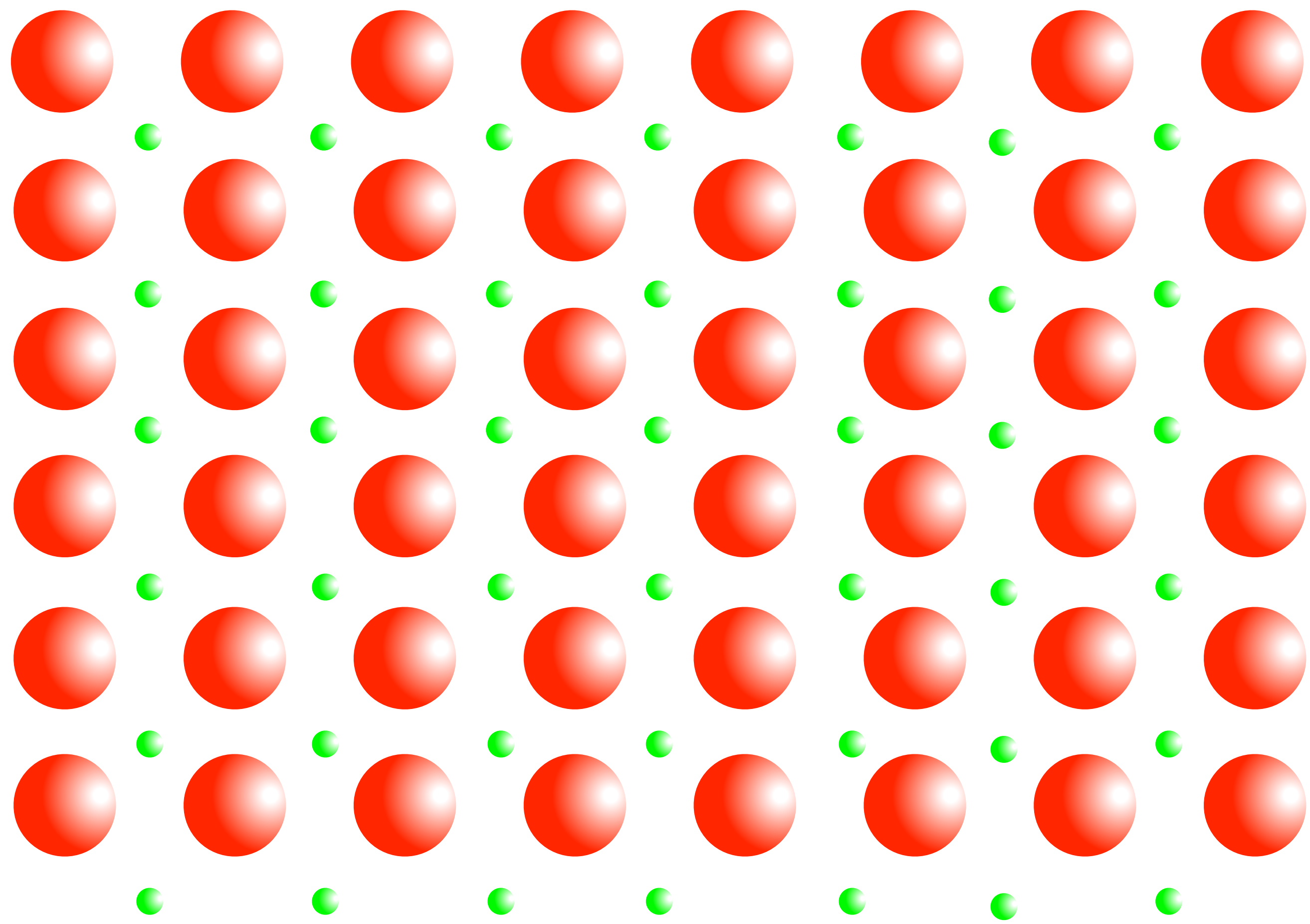
Plasma is an Ionized Medium => High Electric Fields



electrons plasma oscillation

Why is a plasma useful ?

Plasma is an Ionized Medium => High Electric Fields



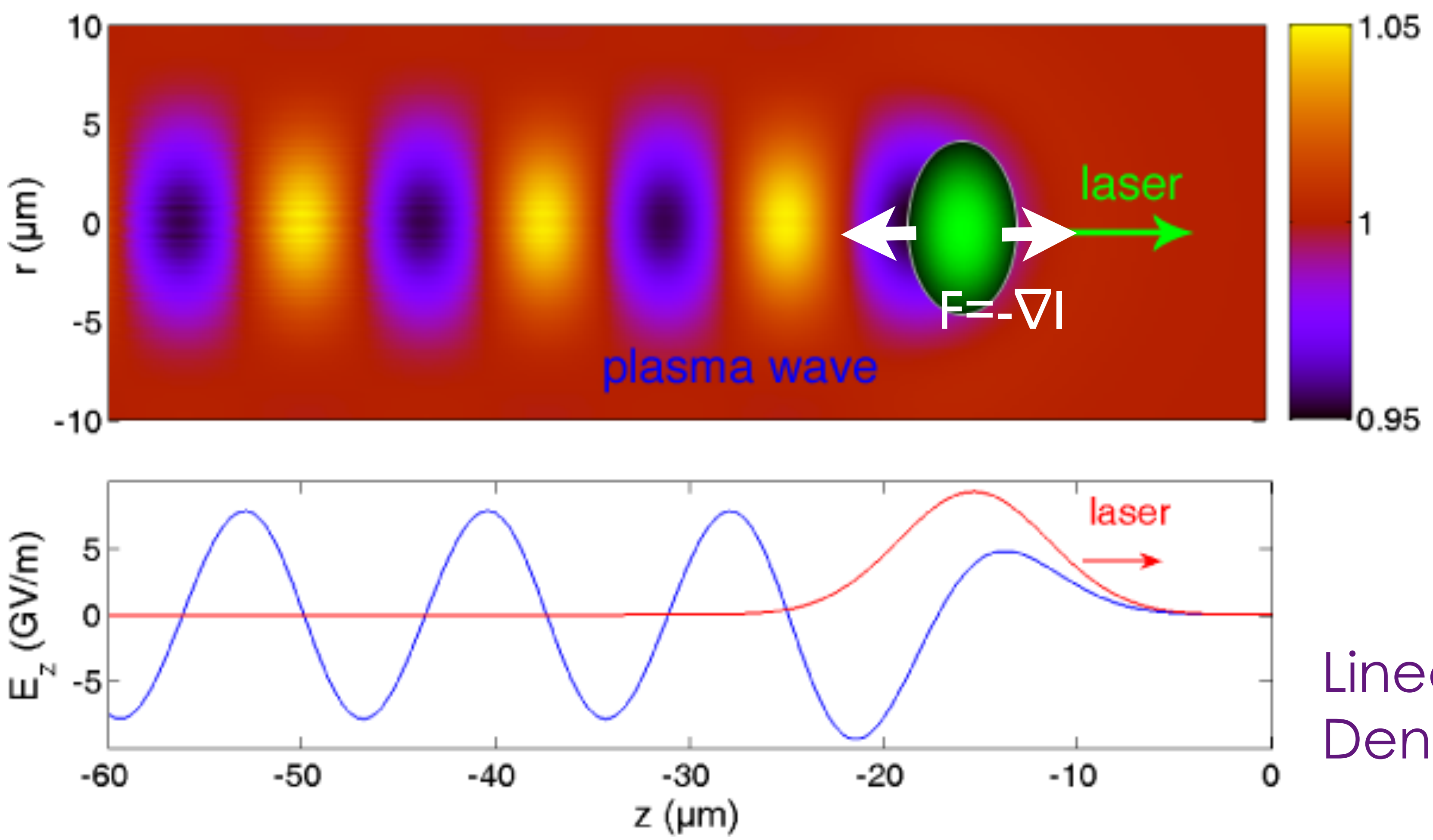
electrons plasma oscillation

The linear wakefield regime: GV/m electric field

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



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

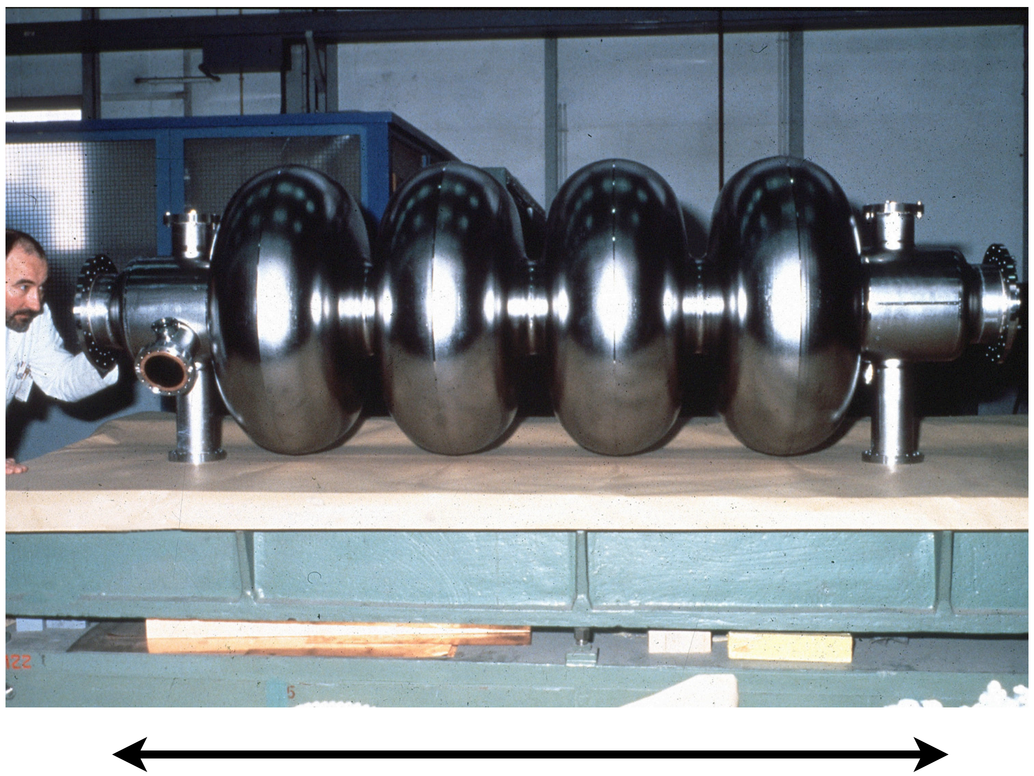
wave in the wake of a boat

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

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

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

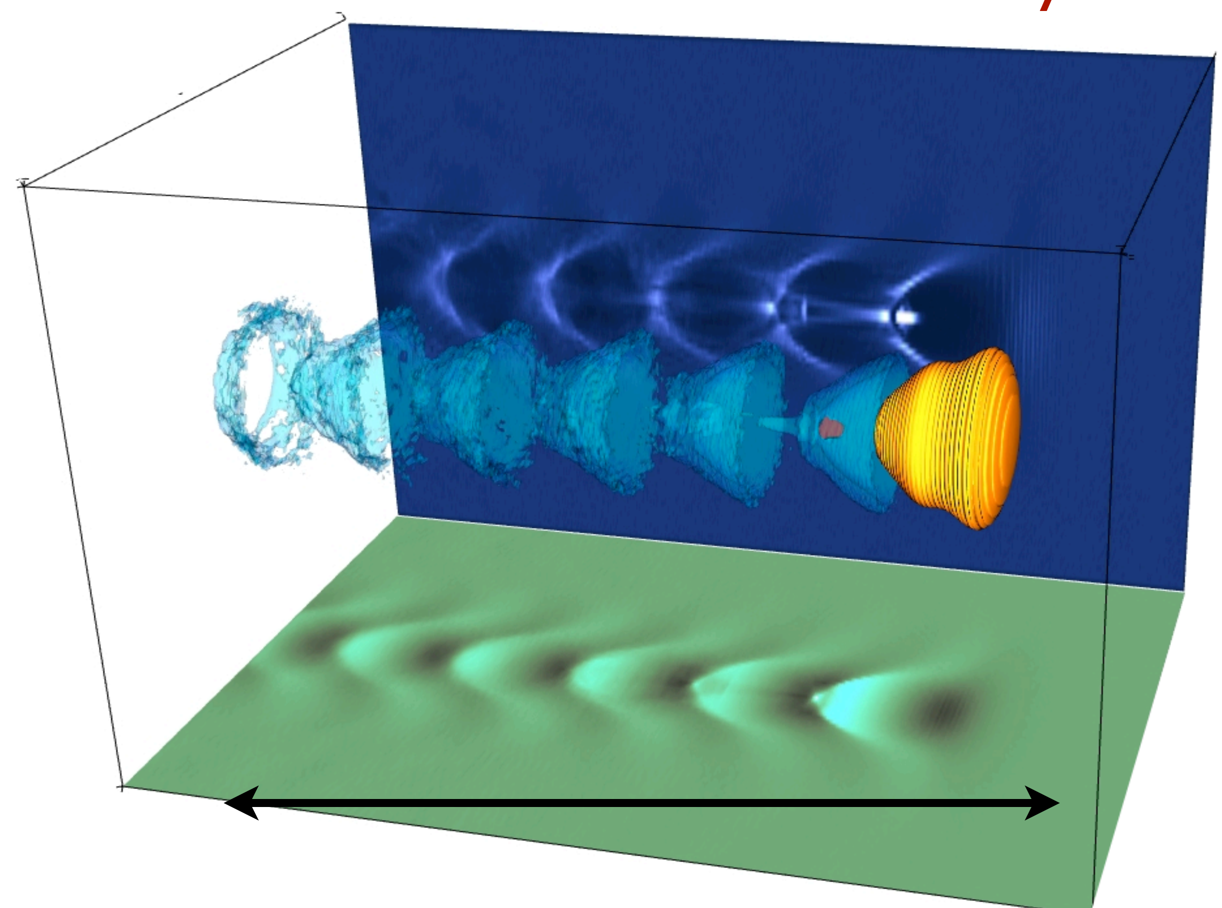
RF Cavity



1 m => 100 MeV Gain

Electric field < 100 MV/m

Plasma Cavity

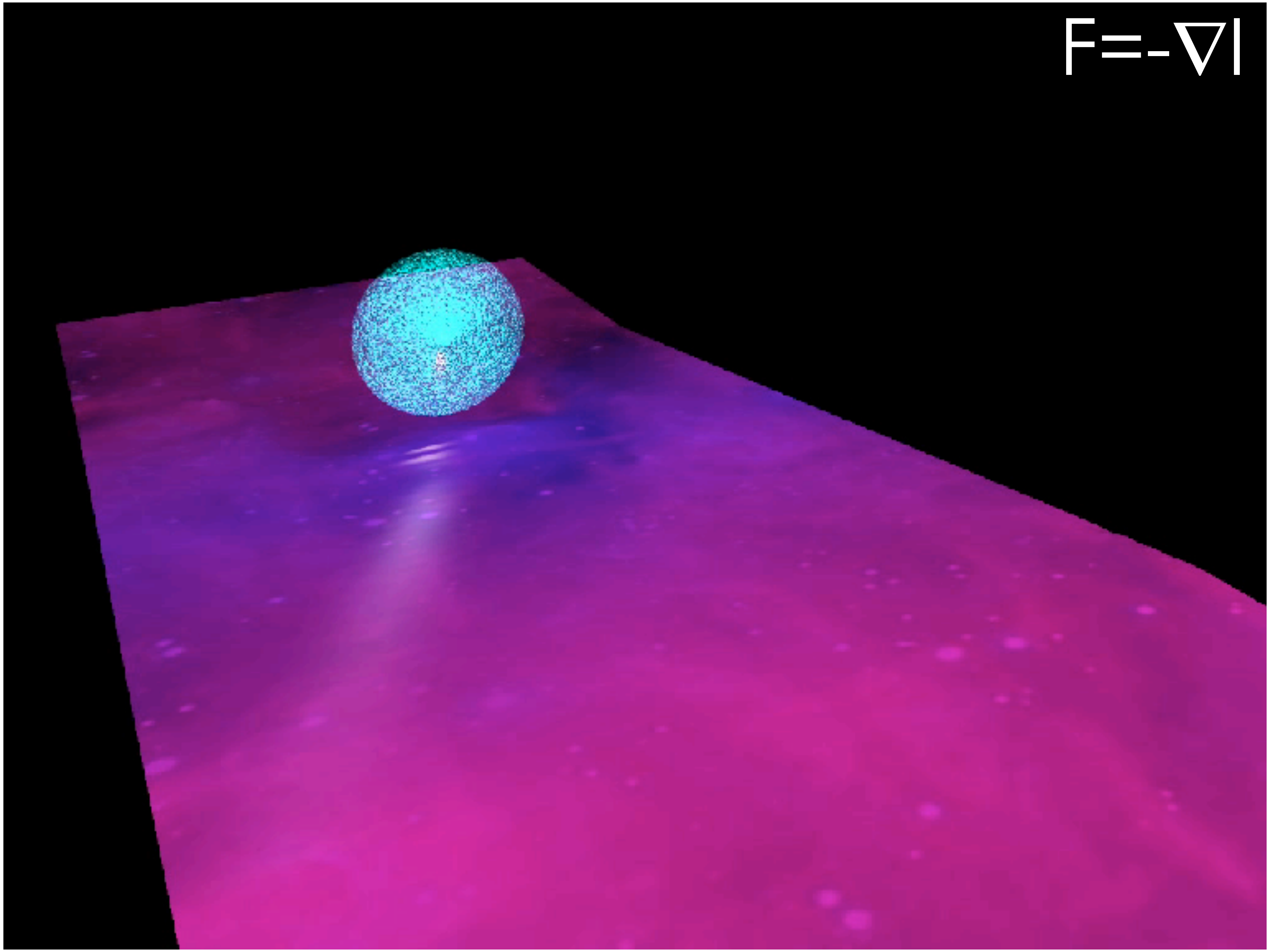


1mm => 100 MeV

Electric field > 100 GV/m

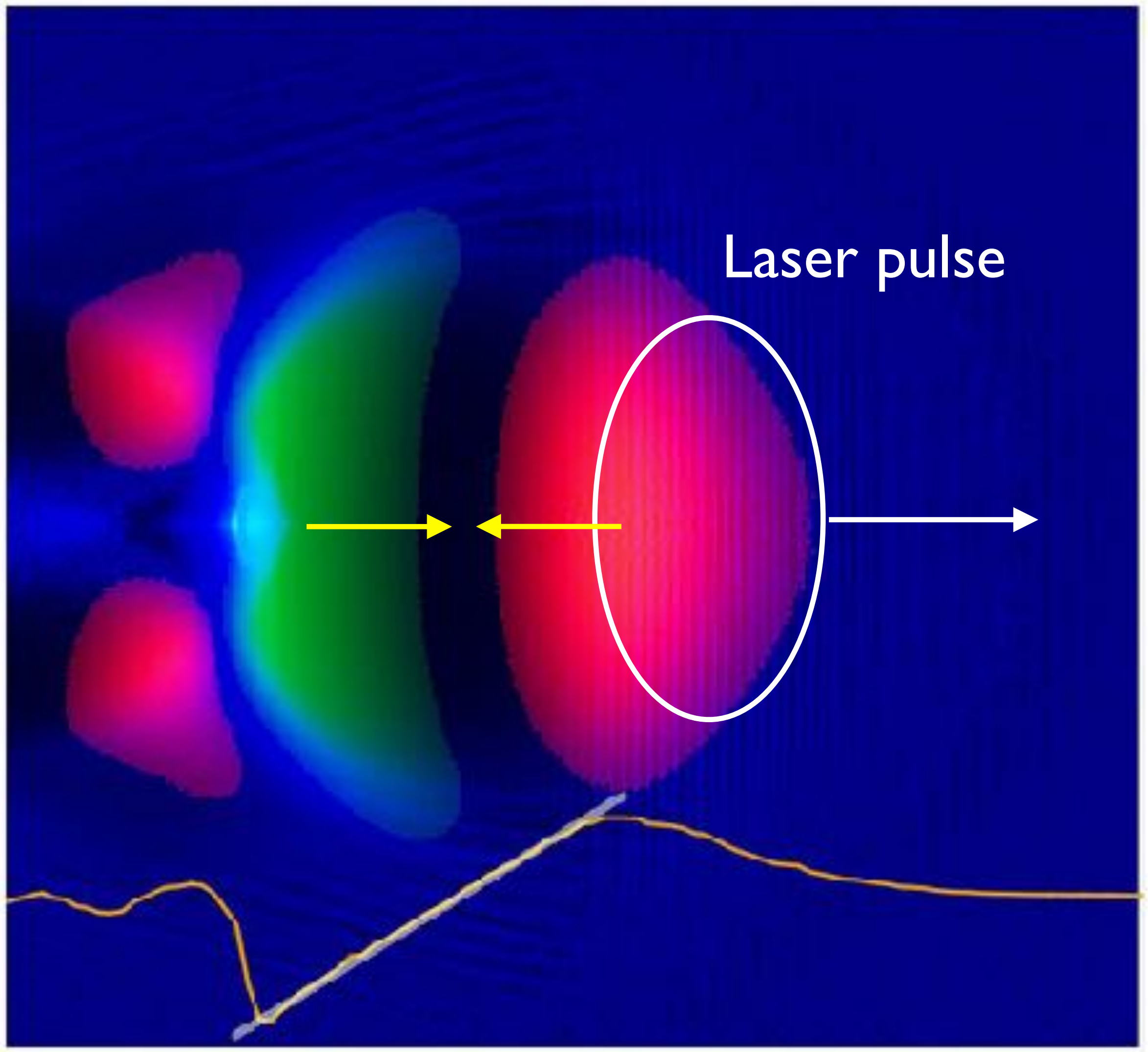
Non Linear Wakefield
V. Malka *et al.*, Science **298**, 1596 (2002)

The Non Linear Regime

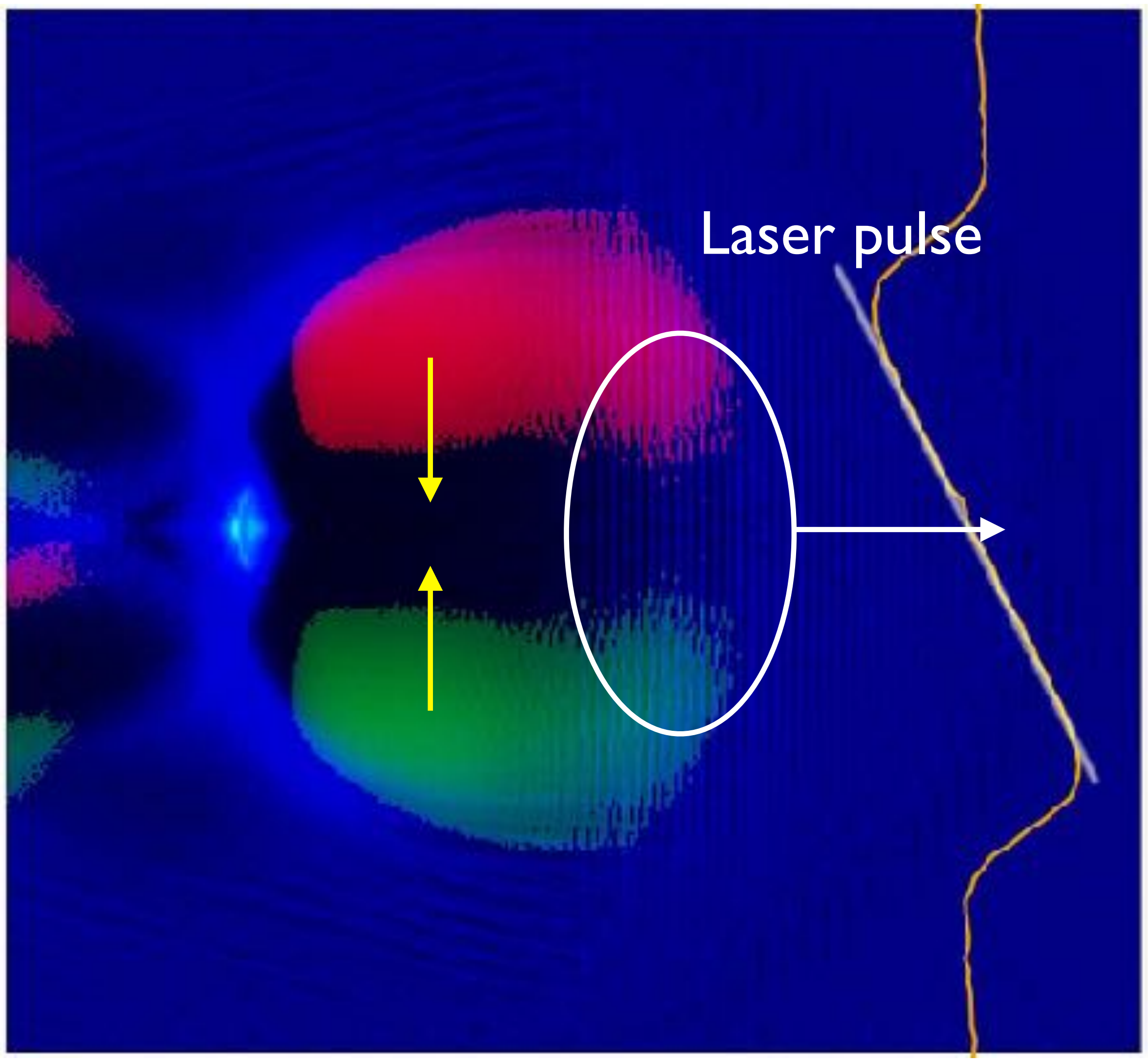


Laser Plasma Accelerator: Non linear regime

Electric field components : Longitudinal and Transverse



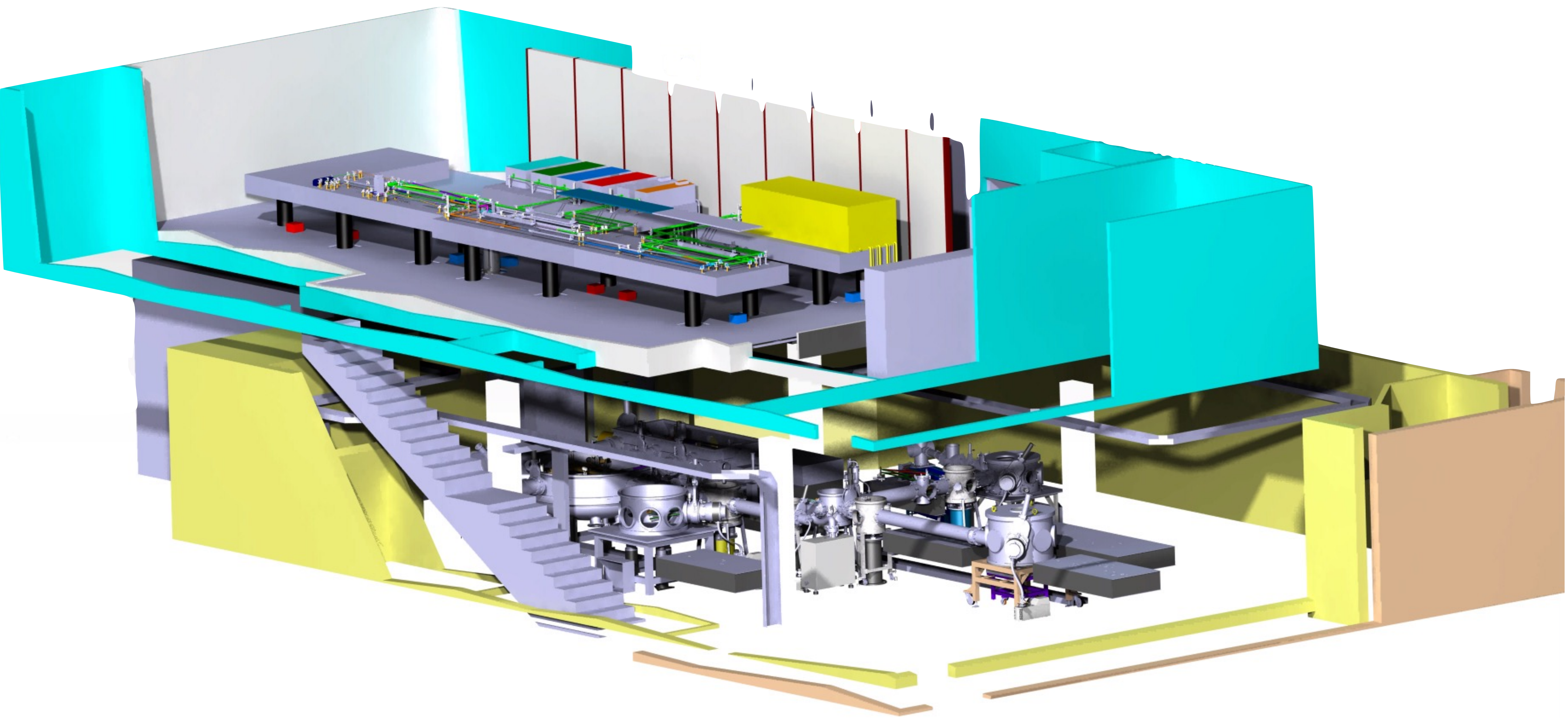
Linear accelerating gradient



Linear Focusing gradient

« Salle Jaune Laser » : Home made laser

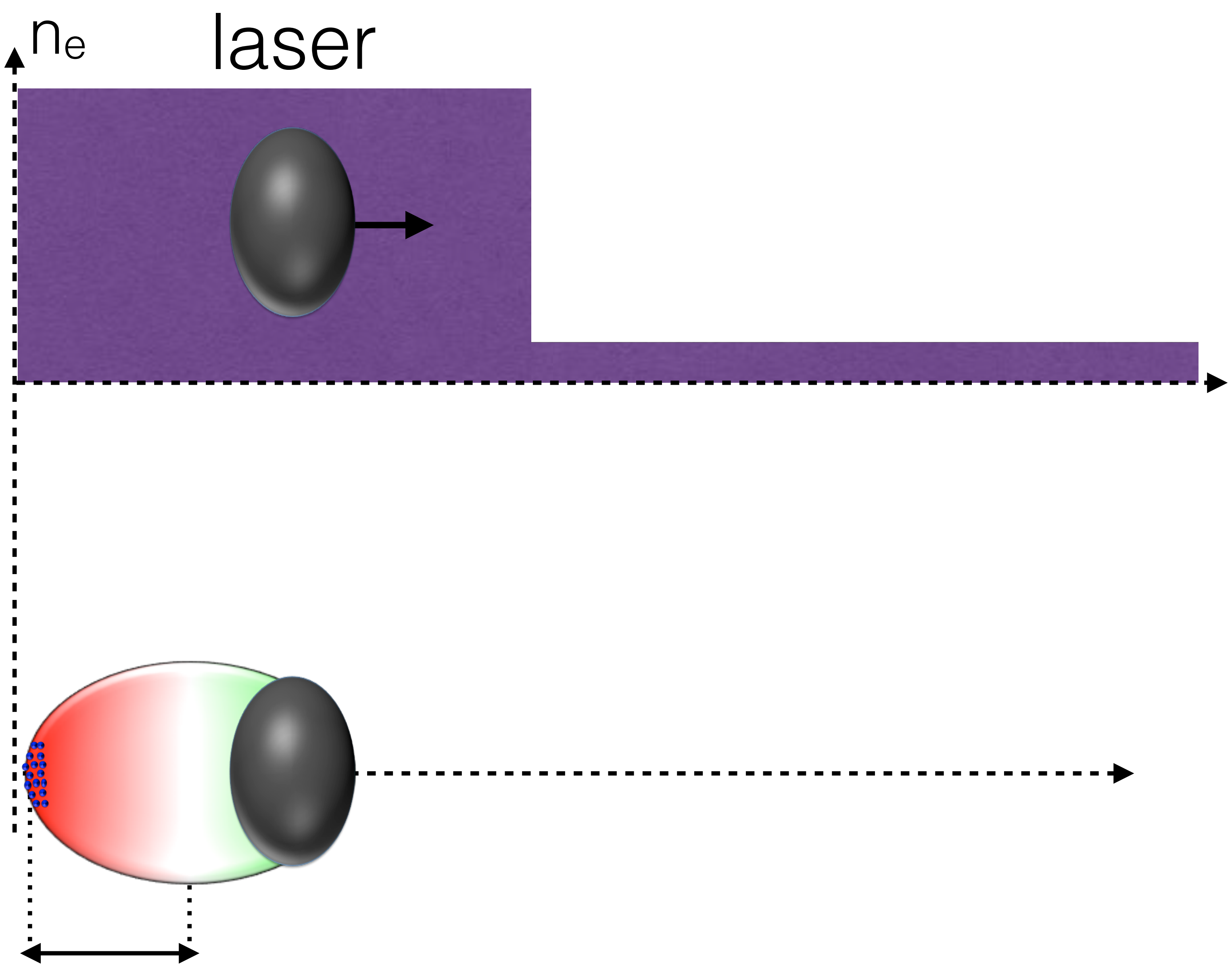
2 Joules in 2 laser beams of 30 fs duration delivered at 1 Hz



Laser Plasma Accelerators : Outline

- Introduction : context and motivations
- Injection in a density gradient
- Manipulating the longitudinal momentum
- Manipulating the transverse momentum
- Applications
- Conclusion and perspectives

Injection in a sharp density gradient



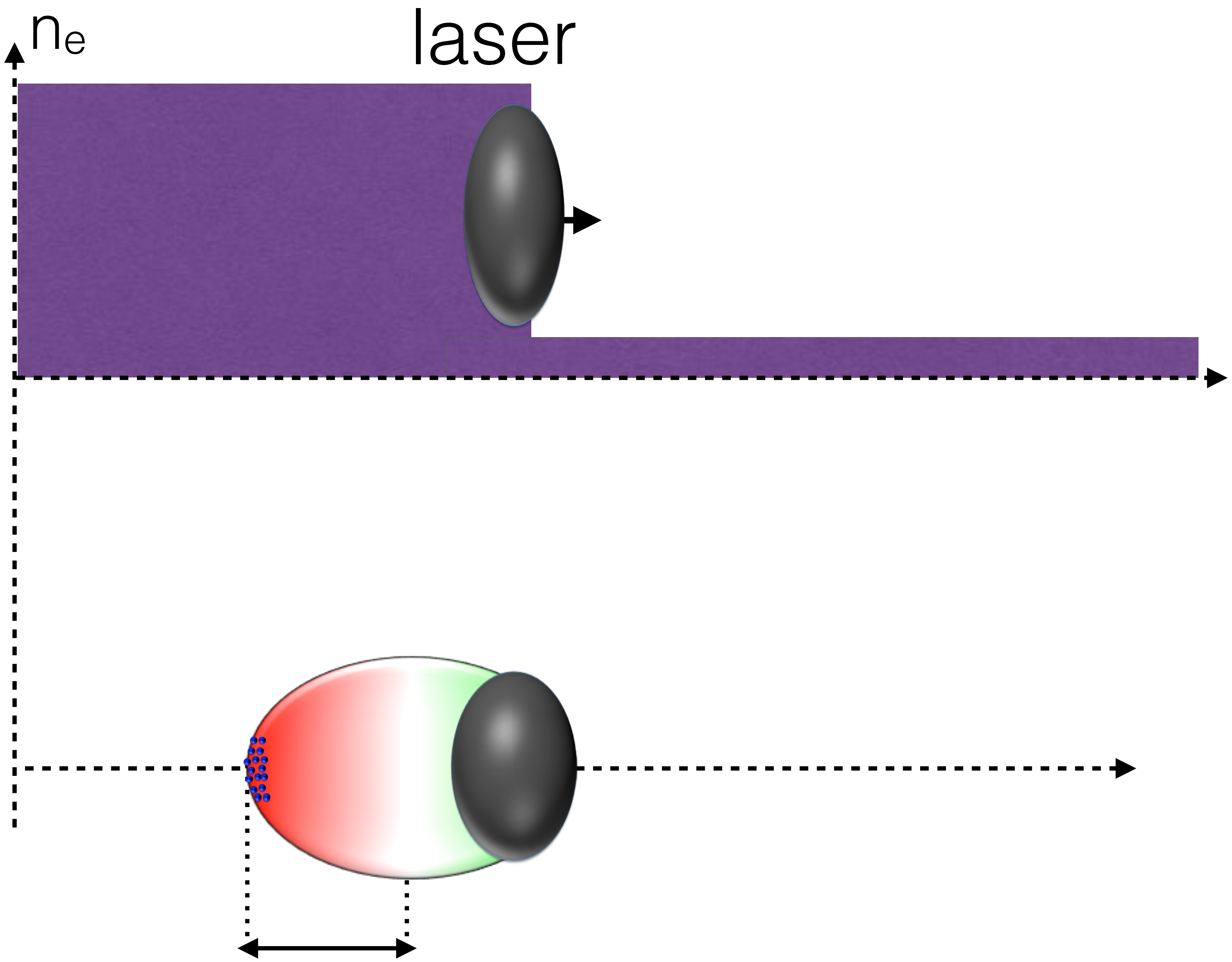
Density drop => increase of the cavity lenght

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

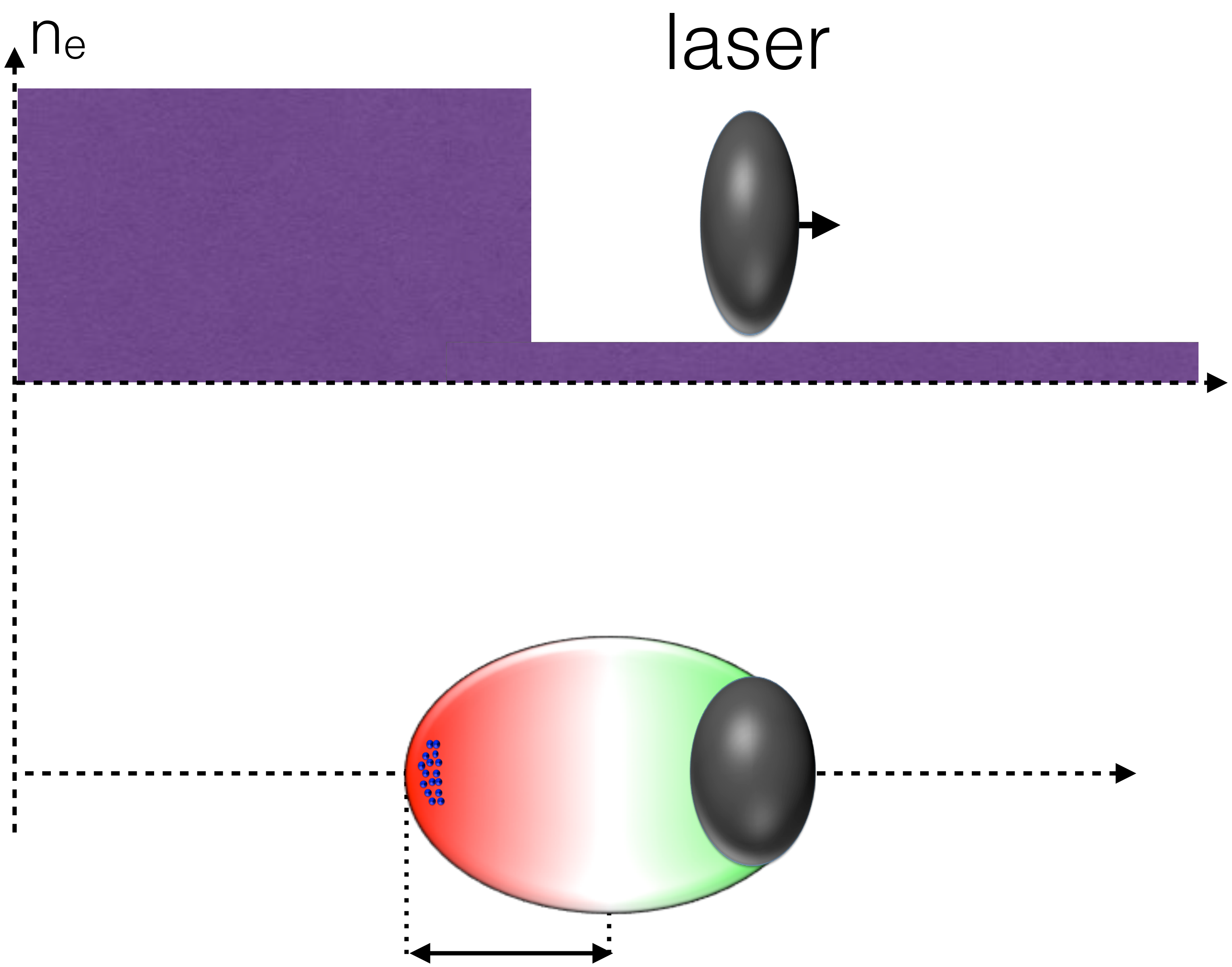


Density drop => increase of the cavity lenght

the bubble expansion allows electrons injection and energy gain.

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

Injection in a sharp density gradient

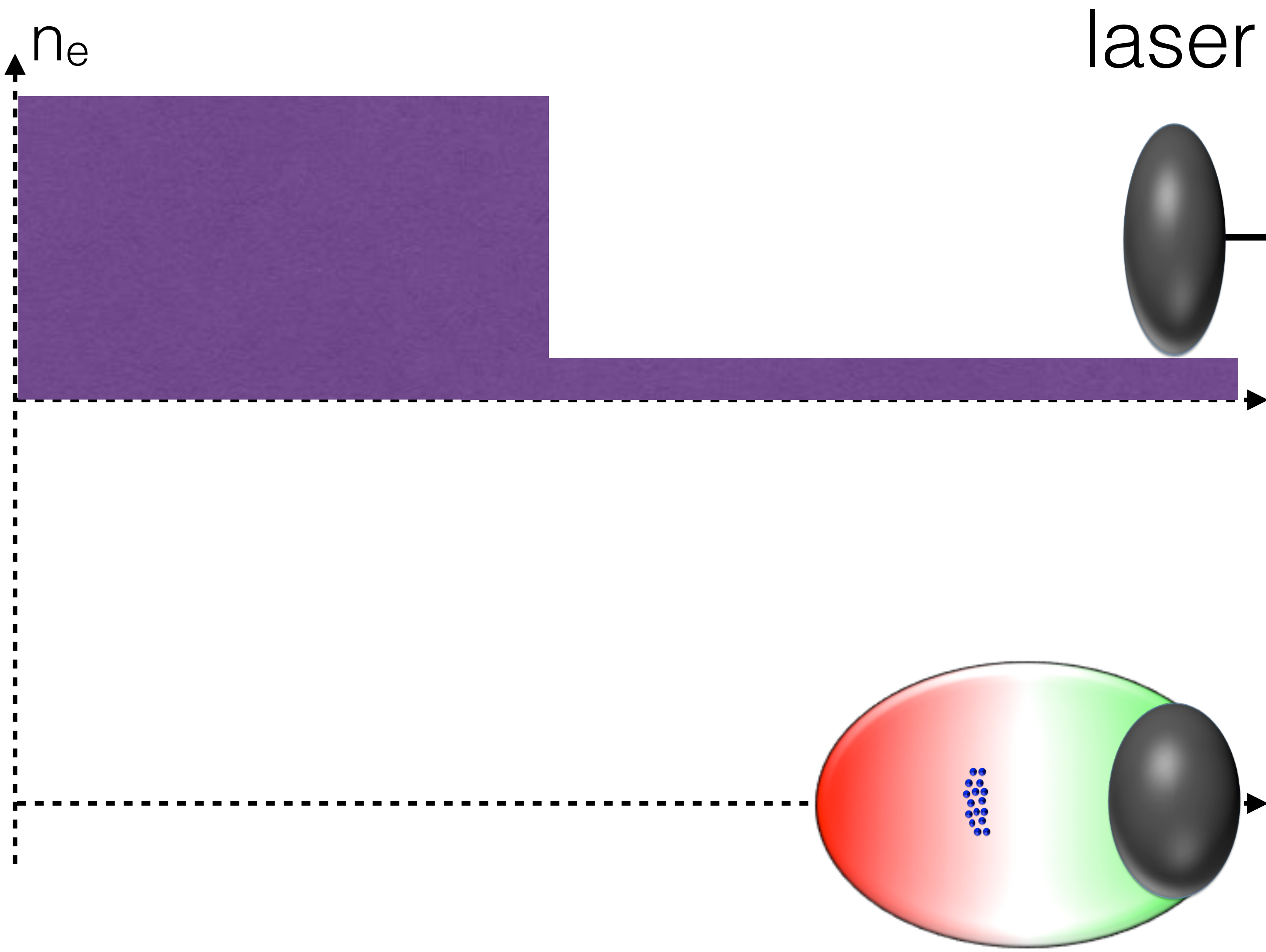


Density drop => increase of the cavity lenght

the bubble expansion allows electrons injection and energy gain.

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

Injection in a sharp density gradient



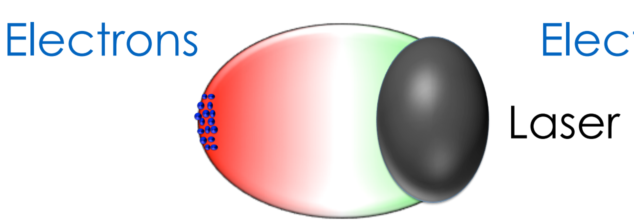
Density drop => increase of the cavity lenght

the bubble expansion allows electrons injection and energy gain.

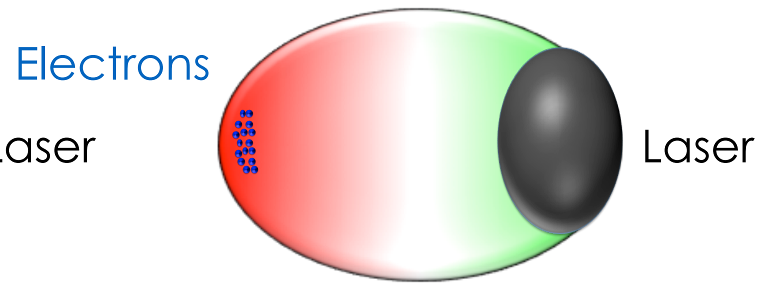
Sharp density ramp is requires to localize the injection and reduce the energy spread !

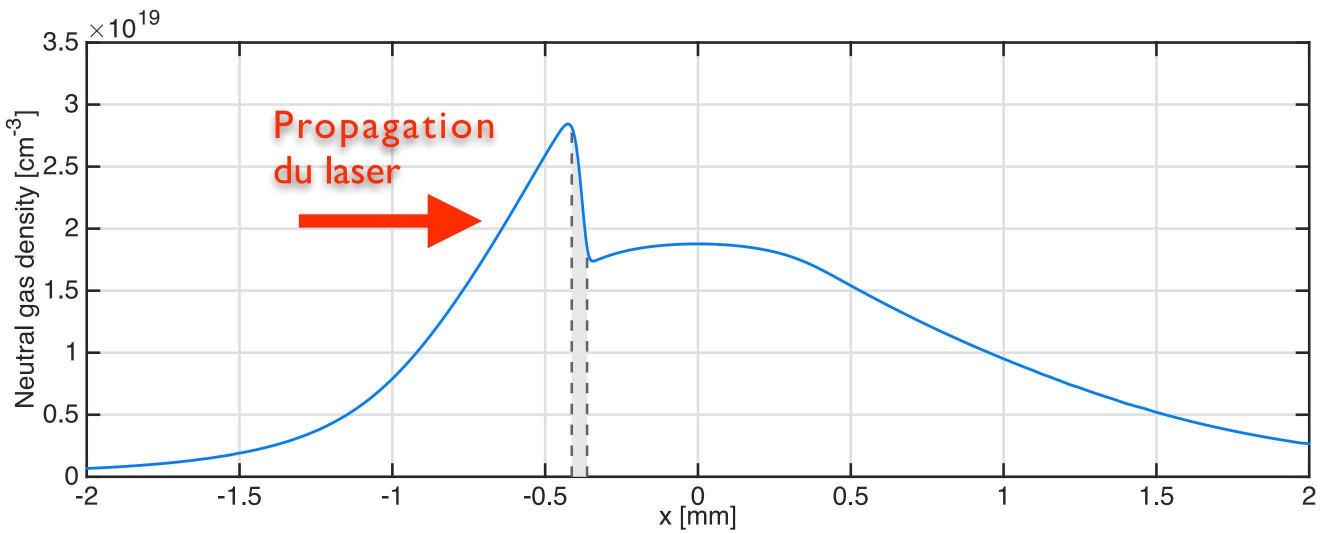
Injection in a shock front : principle

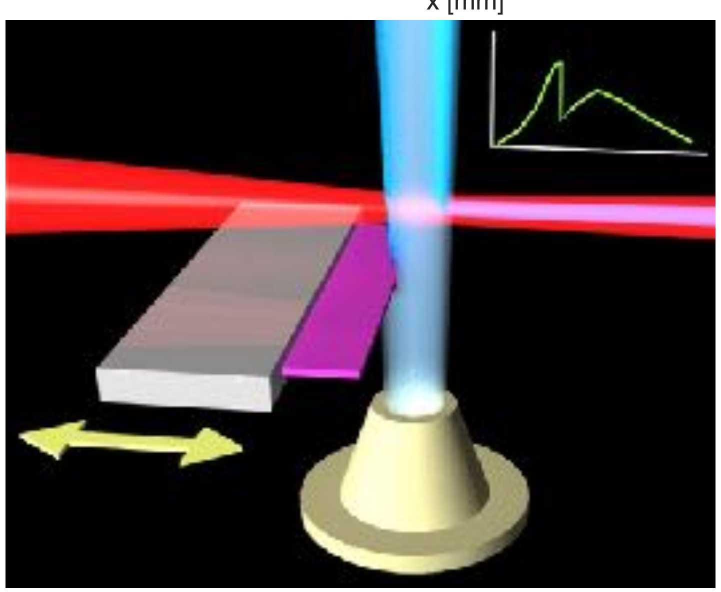
Plasma cavity before the shock front



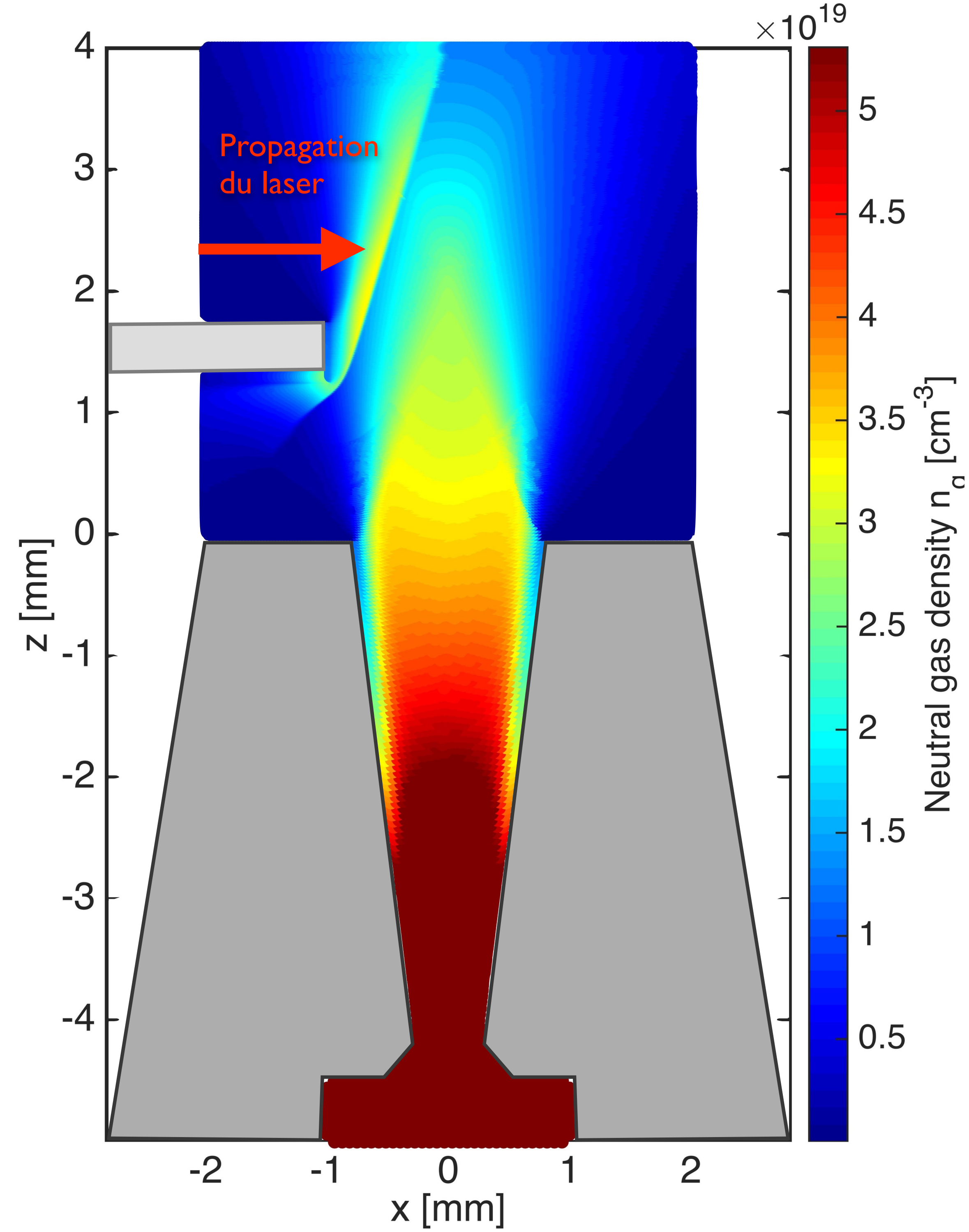
Plasma cavity after the shock front



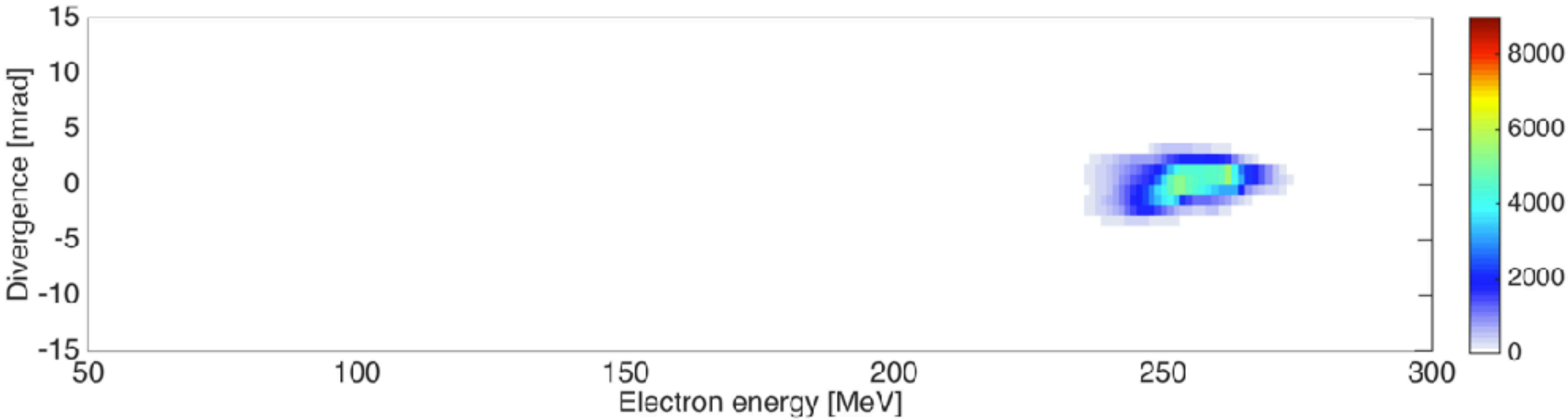




Simulations ANSYS Fluent



Injection in a shock front : pur helium gas



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

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

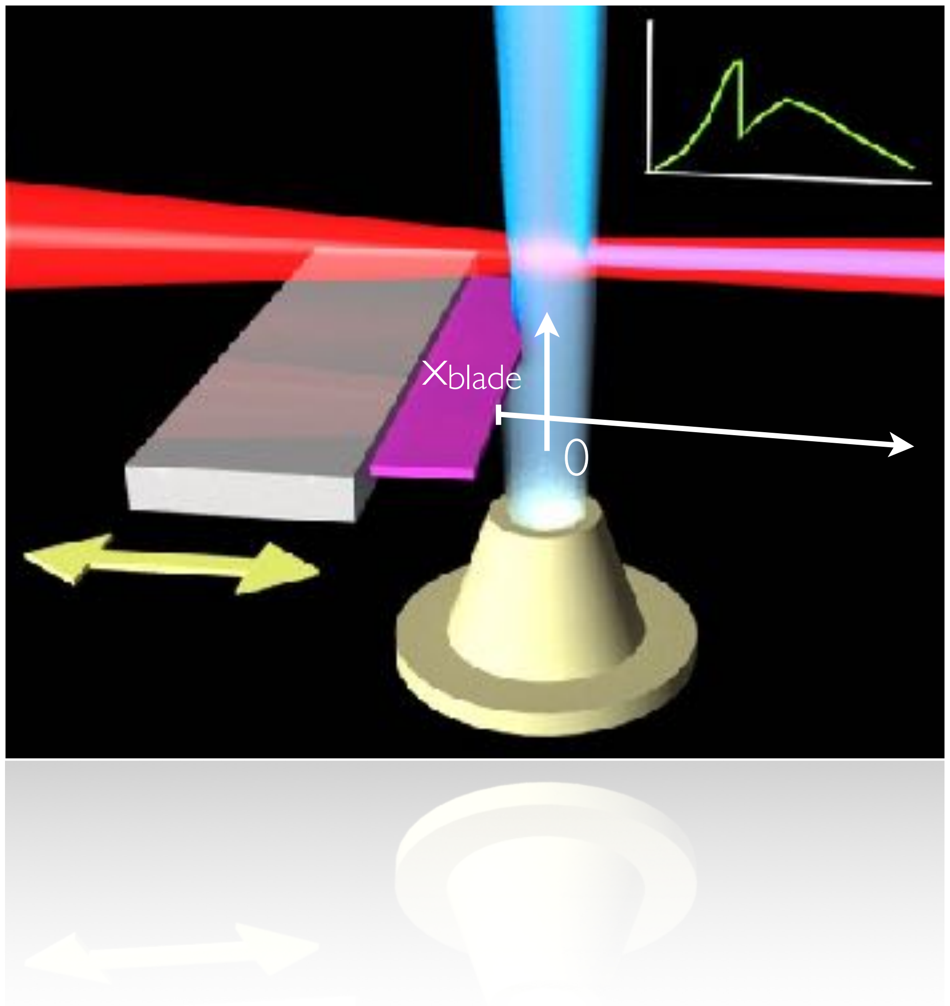
$$\Delta E = 15.5 \pm 2 \text{ MeV}$$

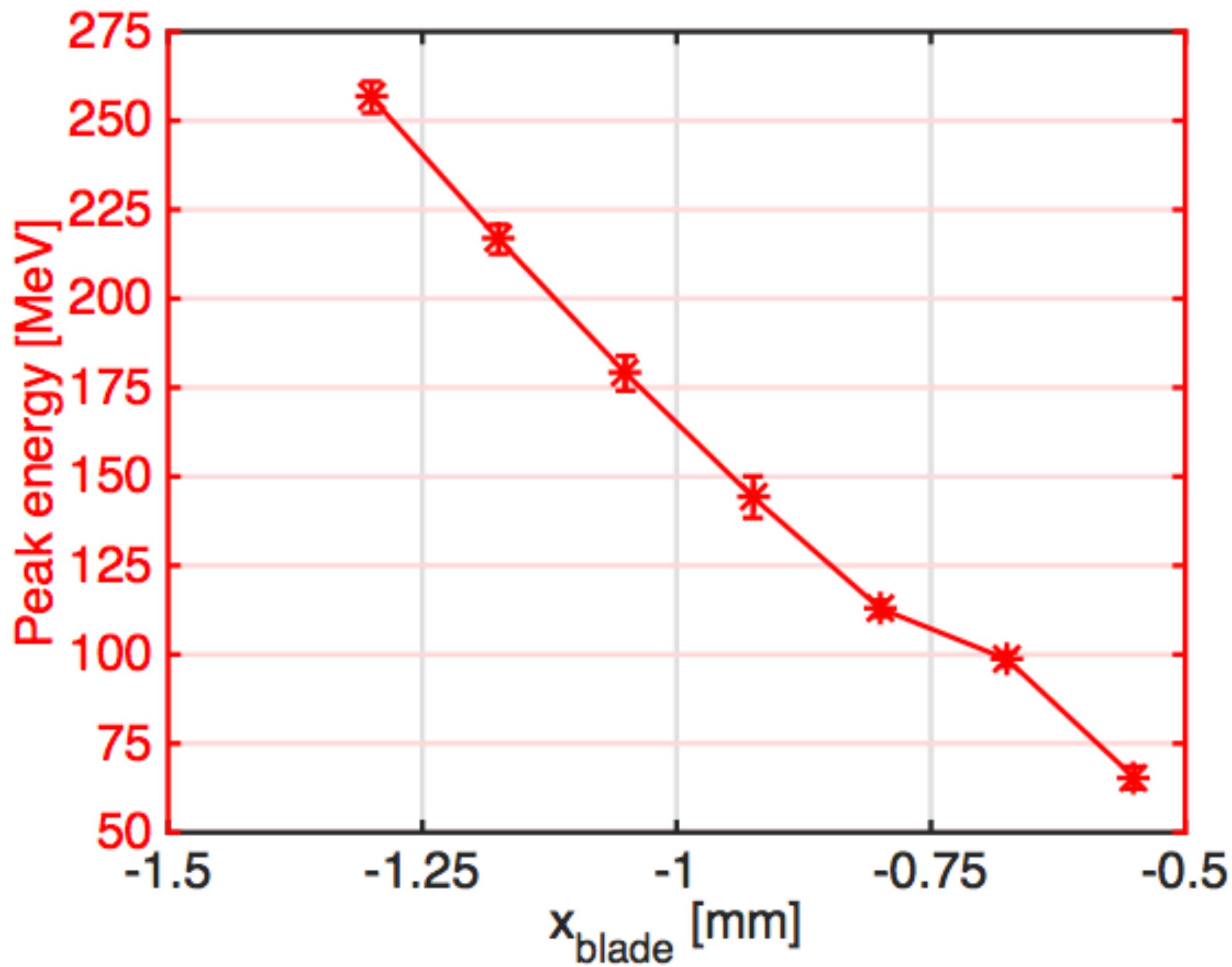
$$\Delta E / E = 6 \pm 1\%$$

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

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

Injection in a shock front : pur helium gas

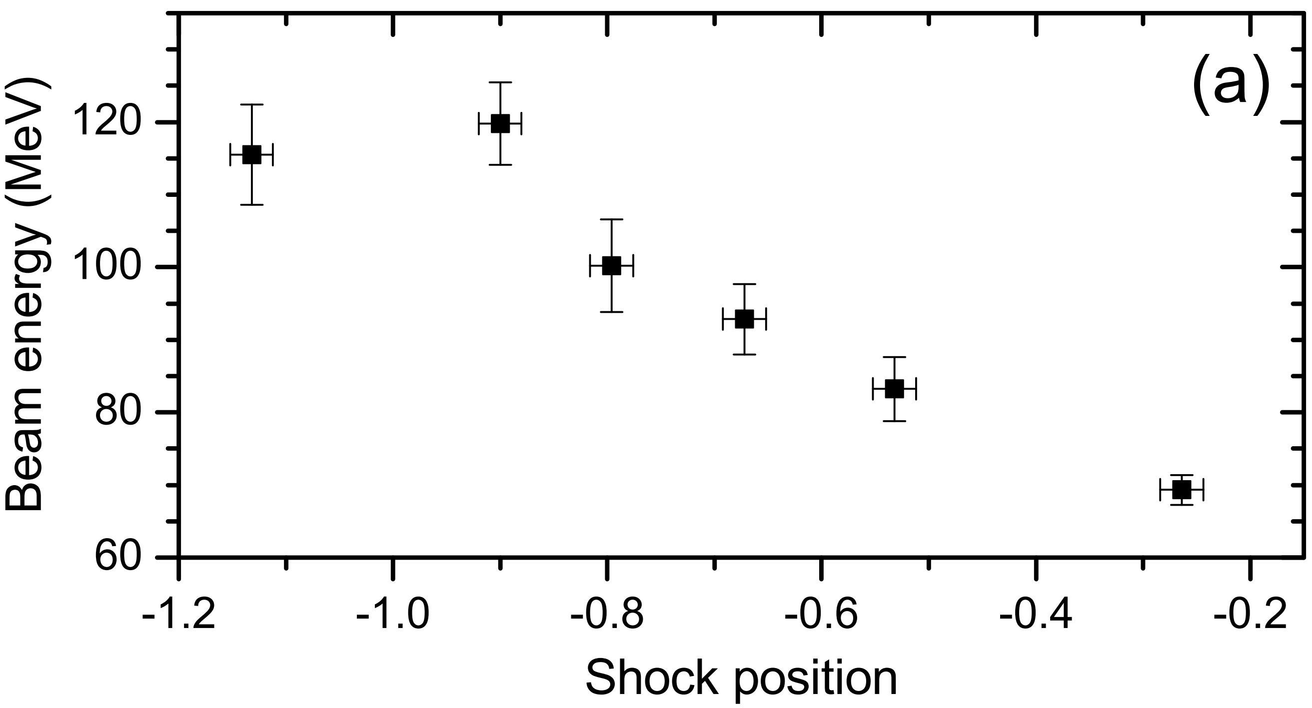


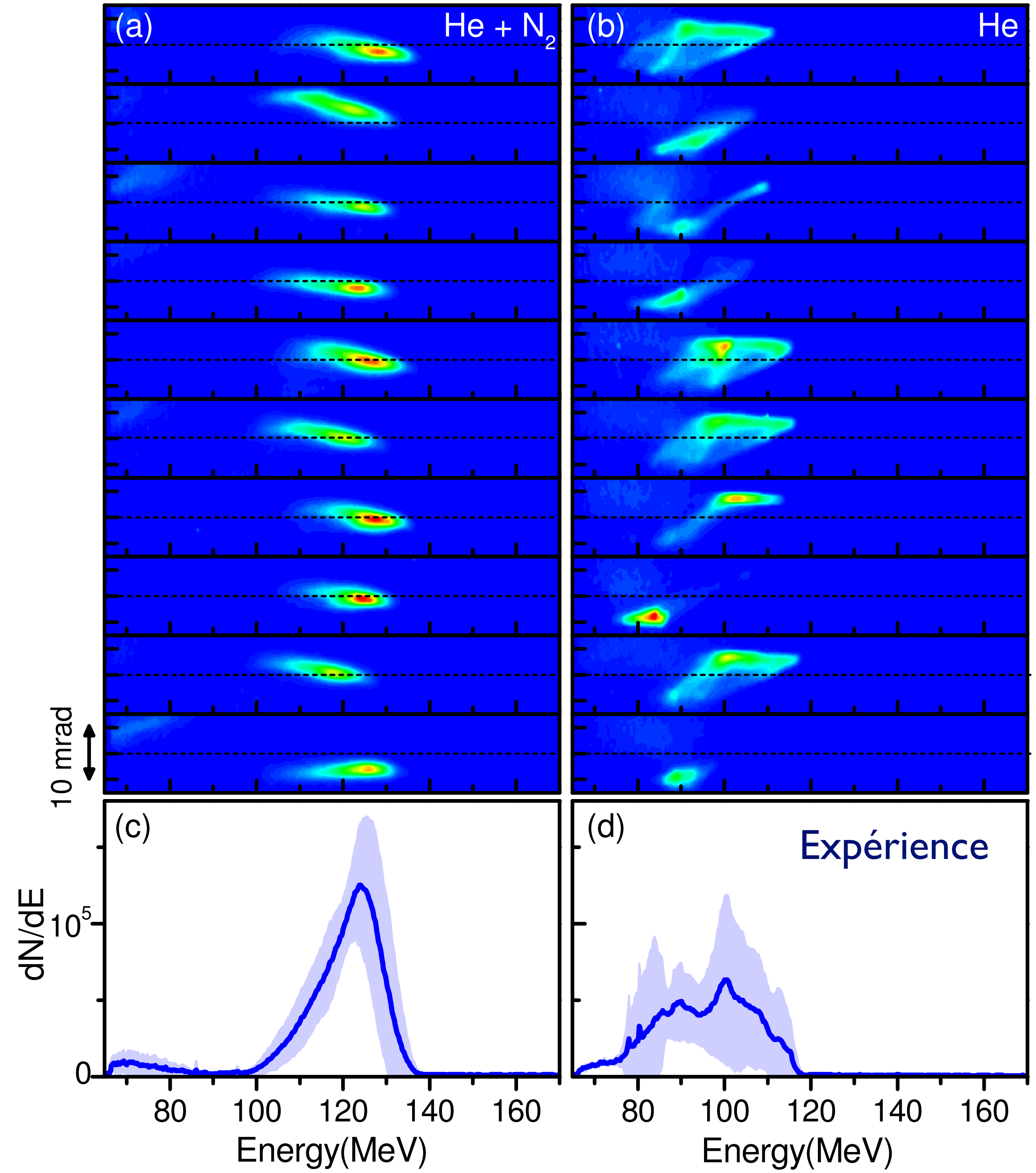


Electron energies is controlled by the position of the blade

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)

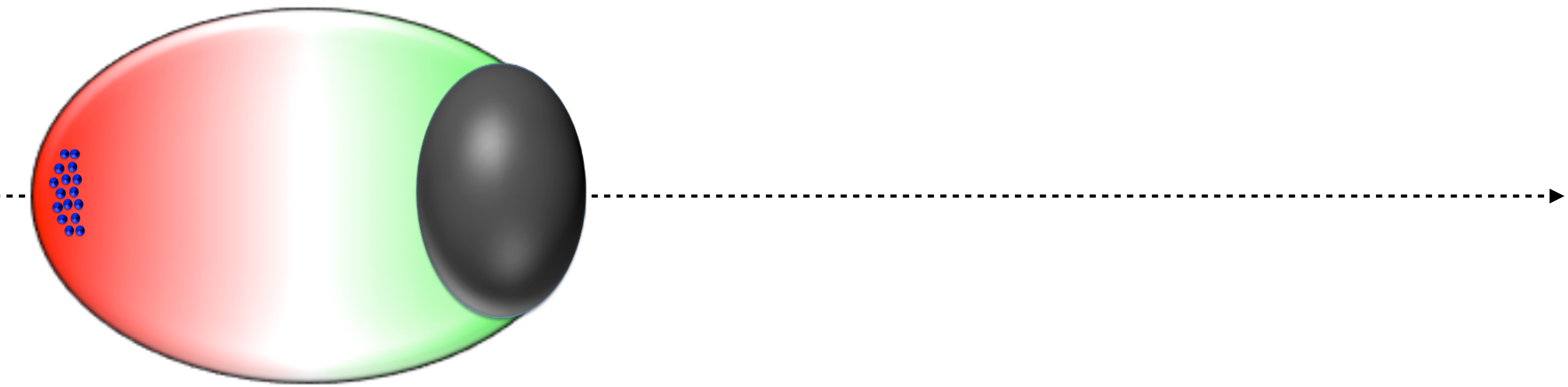
Laser Plasma Accelerators : Outline

- Introduction : context and motivations
- Injection in a density gradient
- Manipulating the longitudinal momentum
- Manipulating the transverse momentum
- Applications
- Conclusion and perspectives

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

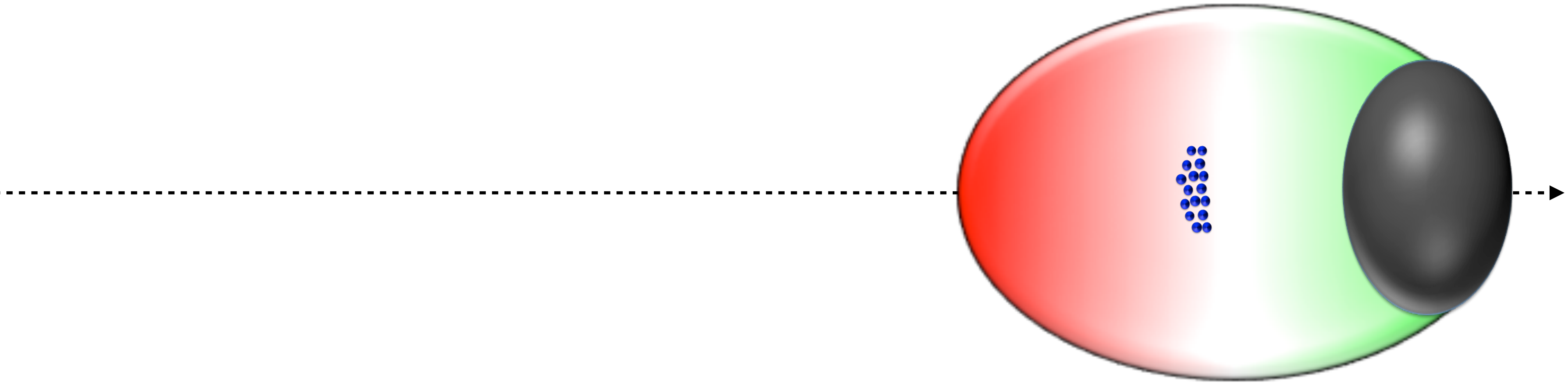


R. Lehe

Overcoming the dephasing limit

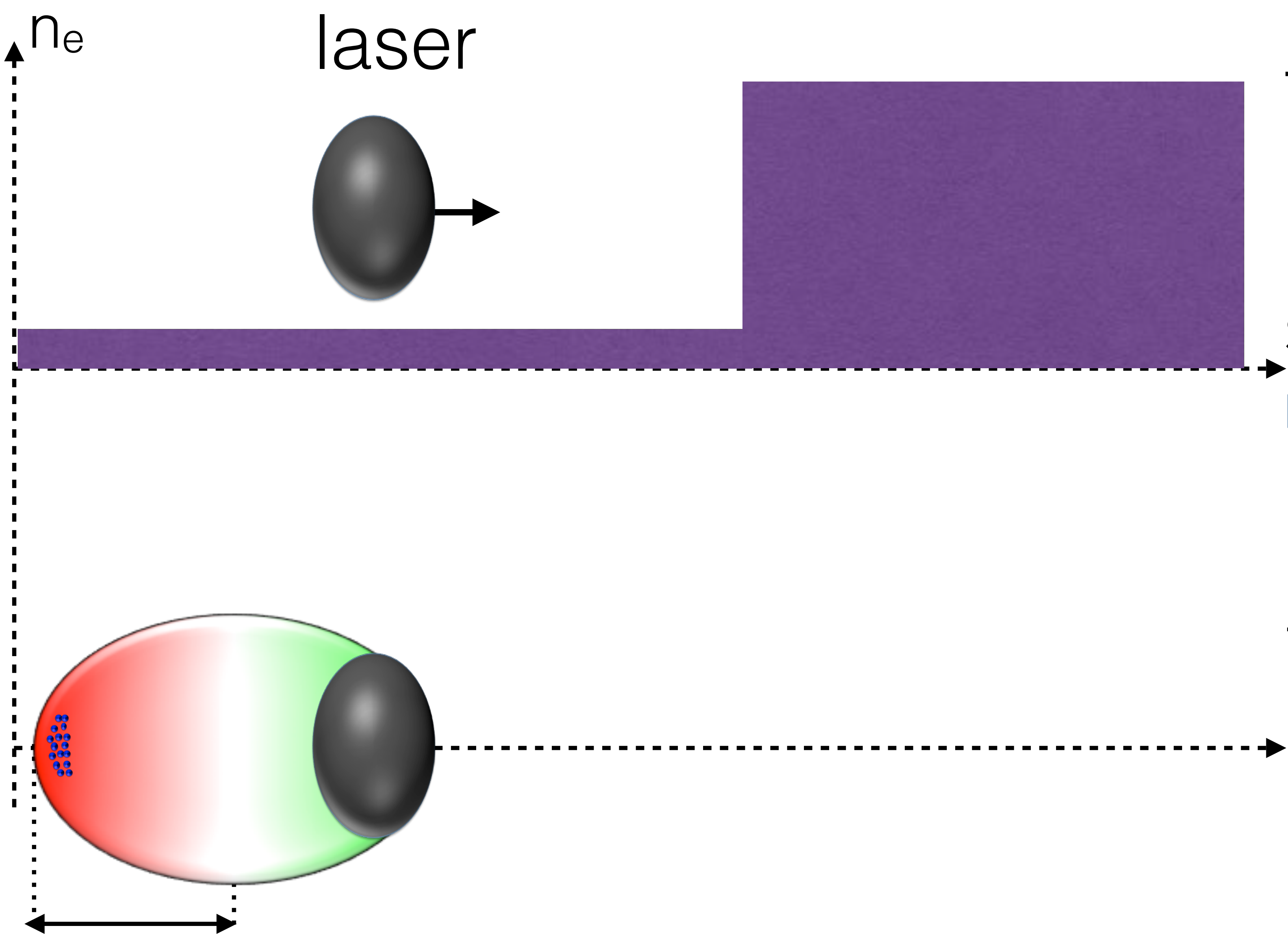
since the laser group velocity is < c, when electrons energy is getting ~c they dephase

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



R. Lehe

Overcoming the dephasing limit

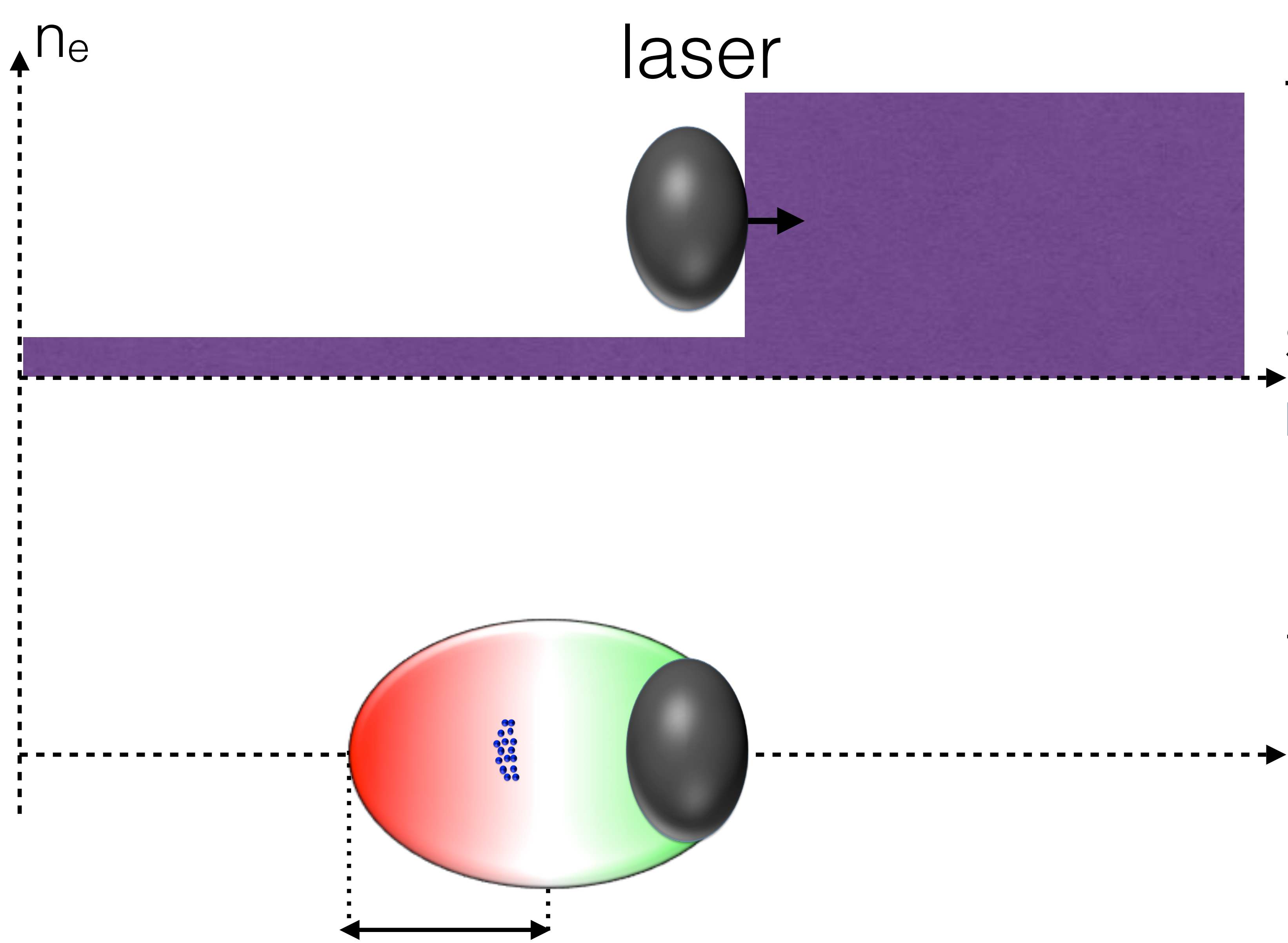


The reduction of the bubble size at the right position by increasing suddently the density resets the electrons phase.
Electrons can start again to gain energy.

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

R. Lehe

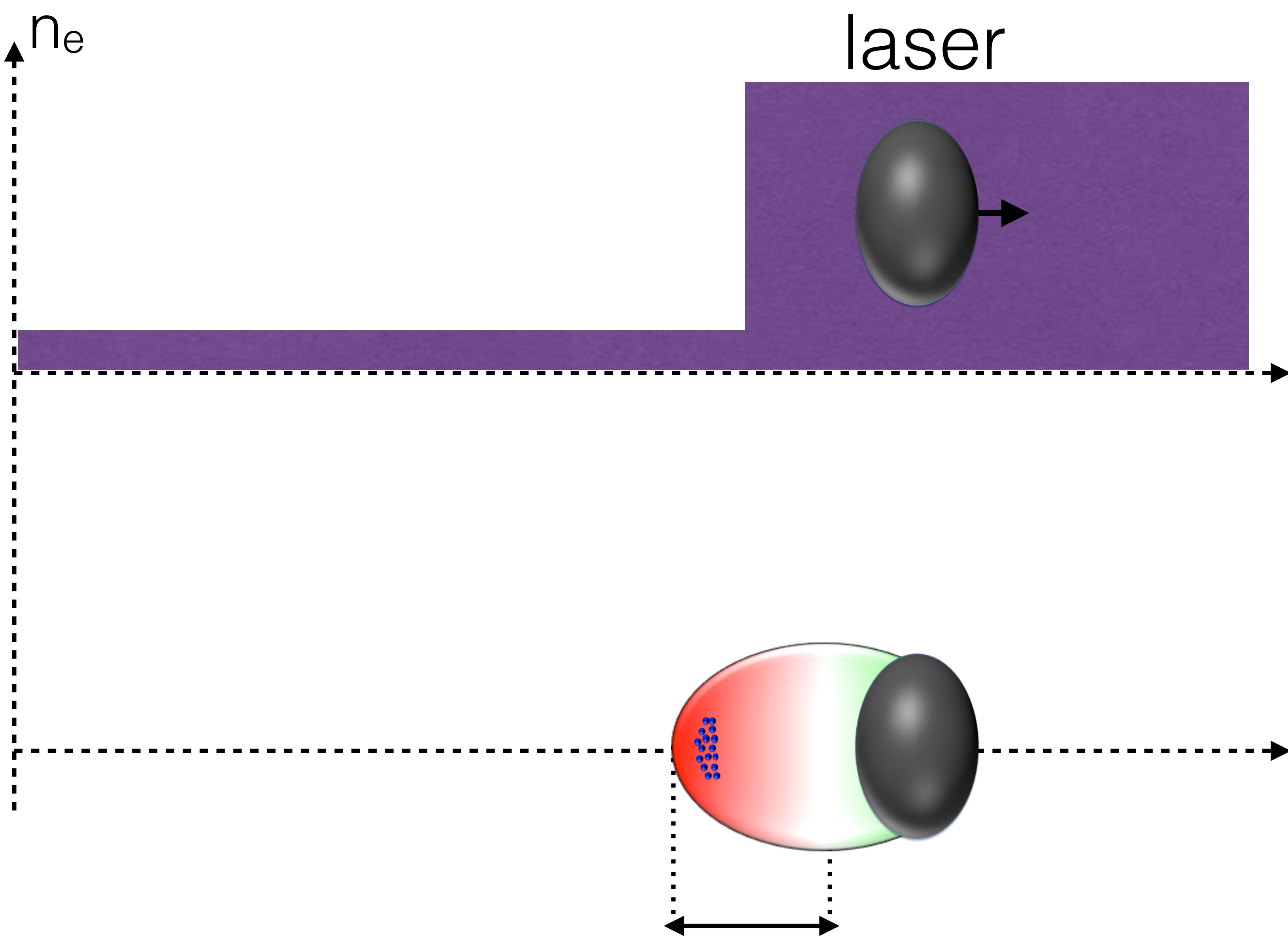
Overcoming the dephasing limit



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.

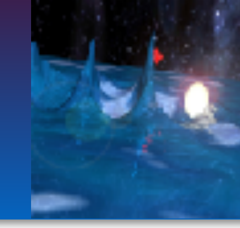
Overcoming the dephasing limit

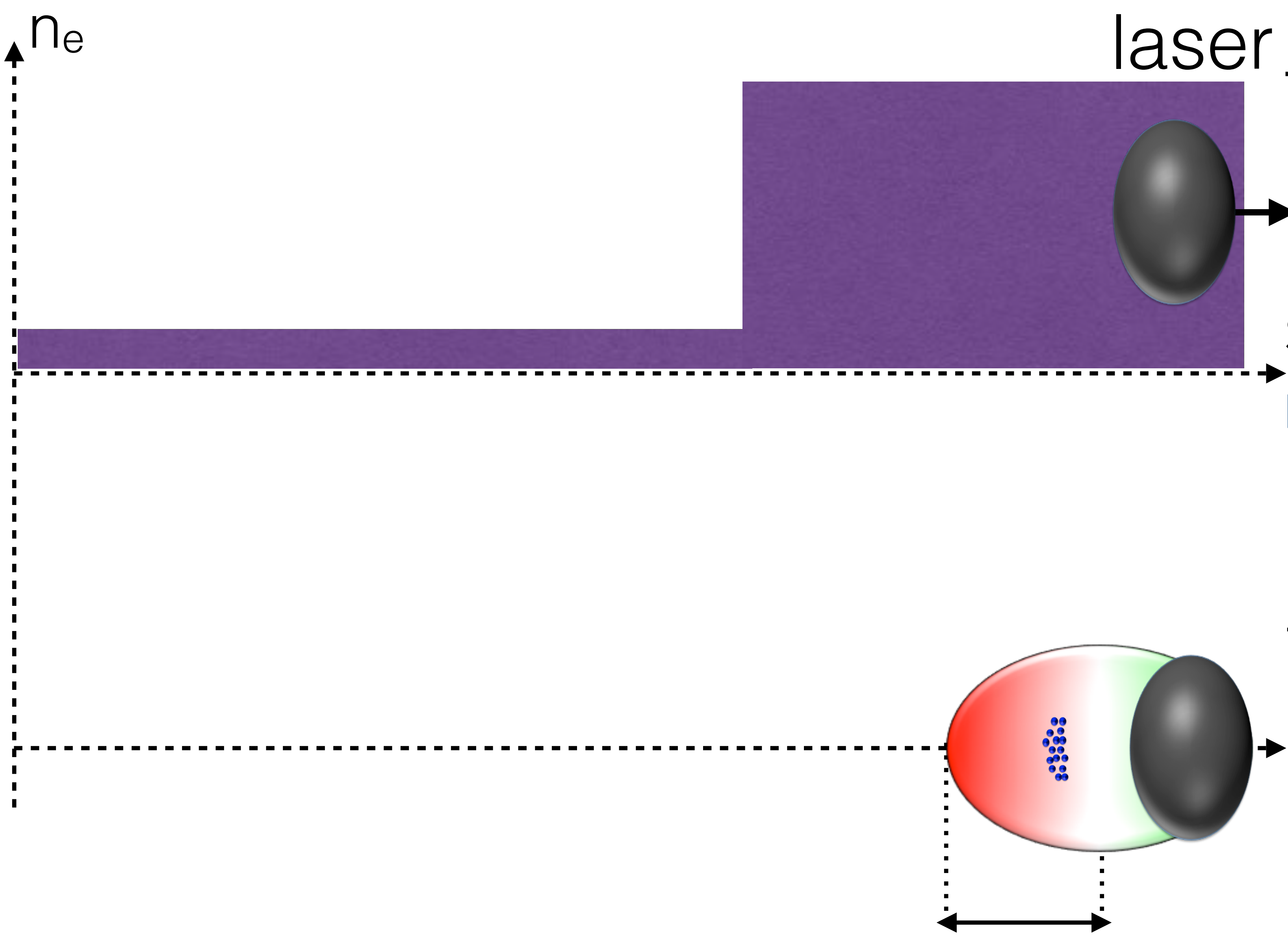


The reduction of the bubble size at the right position by increasing suddently the density resets the electrons phase.
Electrons can start again to gain energy.

R. Lehe

Overcoming the dephasing limit

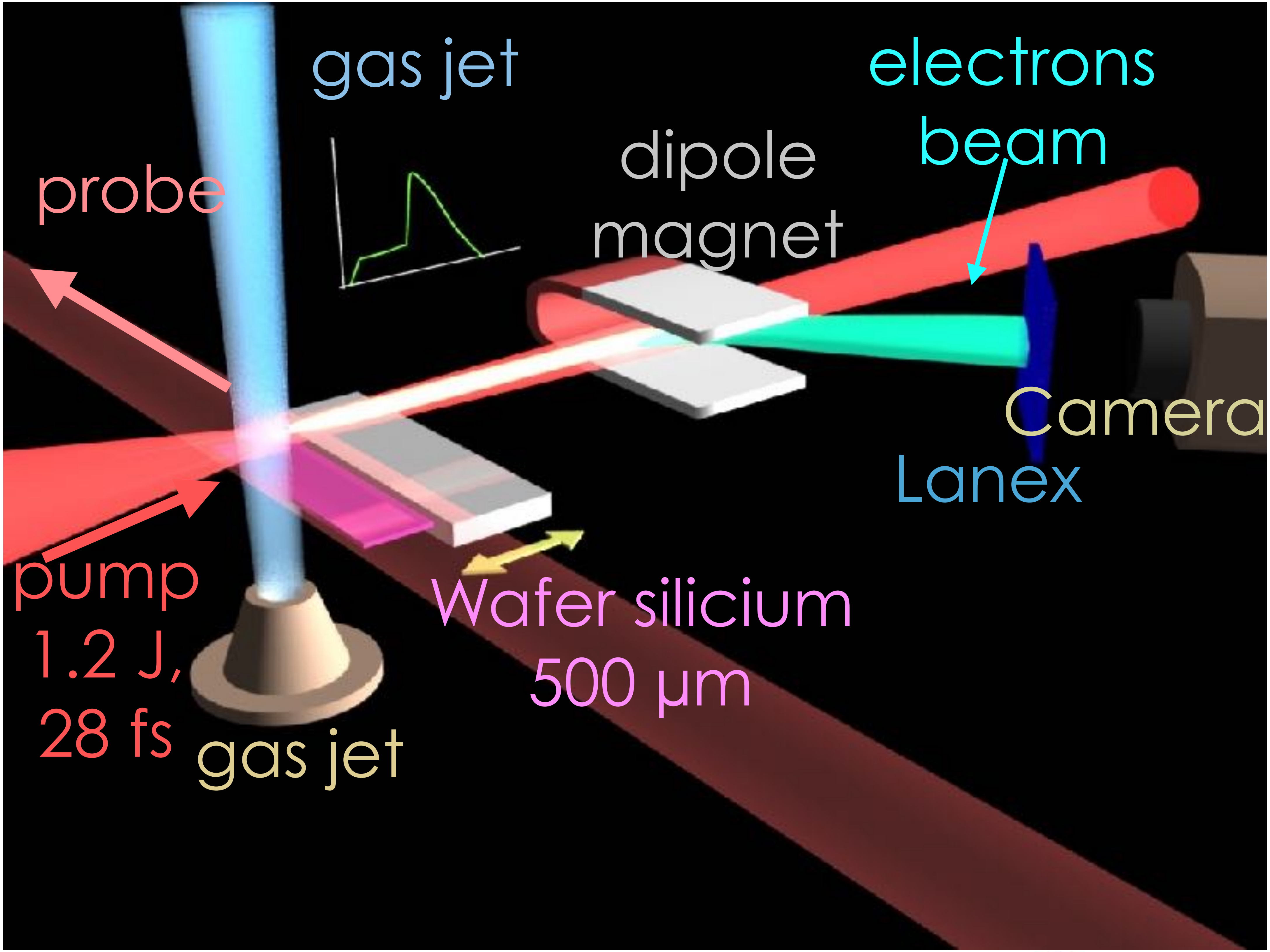




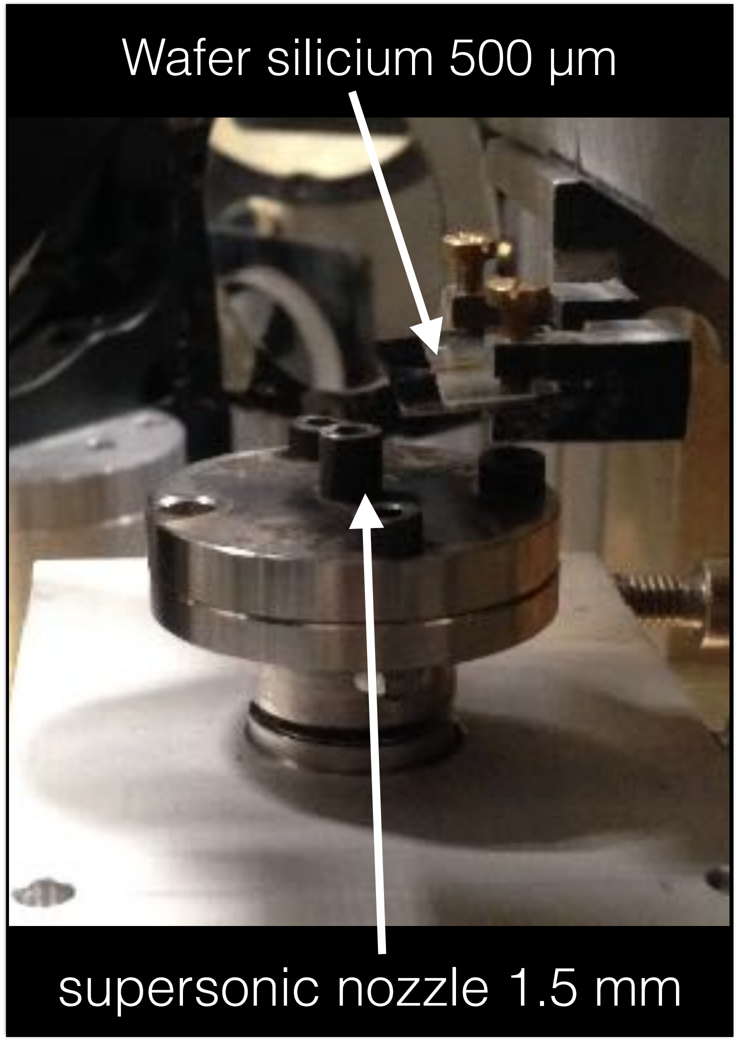
The reduction of the bubble size at the right position by increasing suddently the density resets the electrons phase.

Electrons can start again to gain energy.

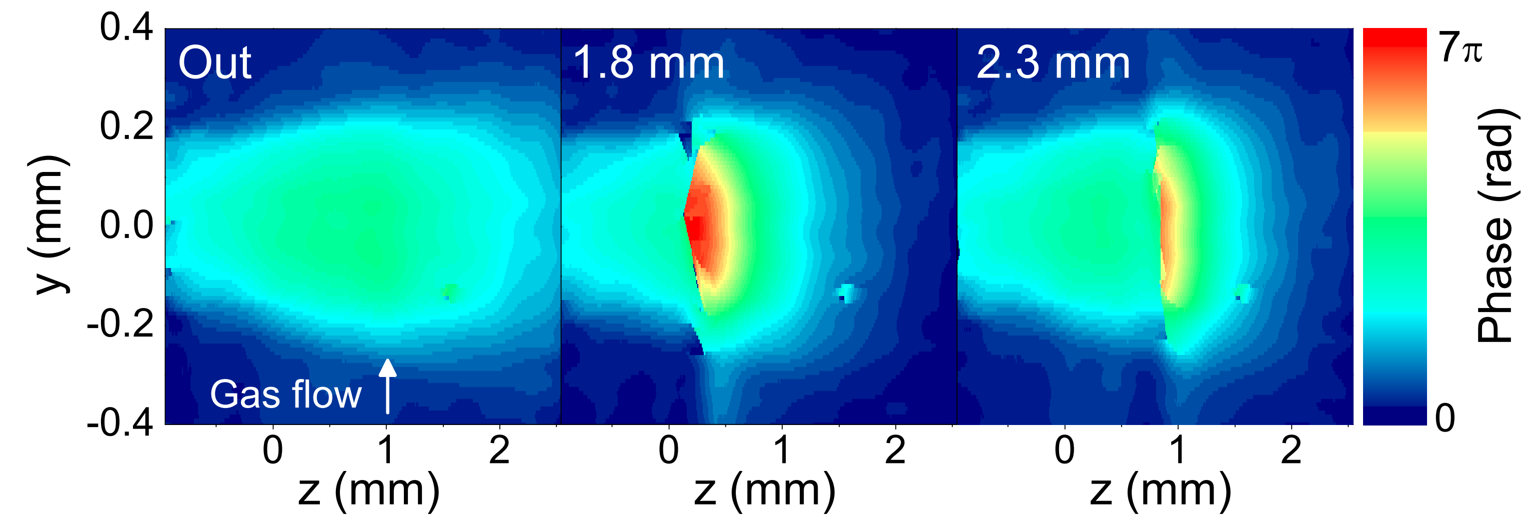
Overcoming the dephasing limit: experimental set-up

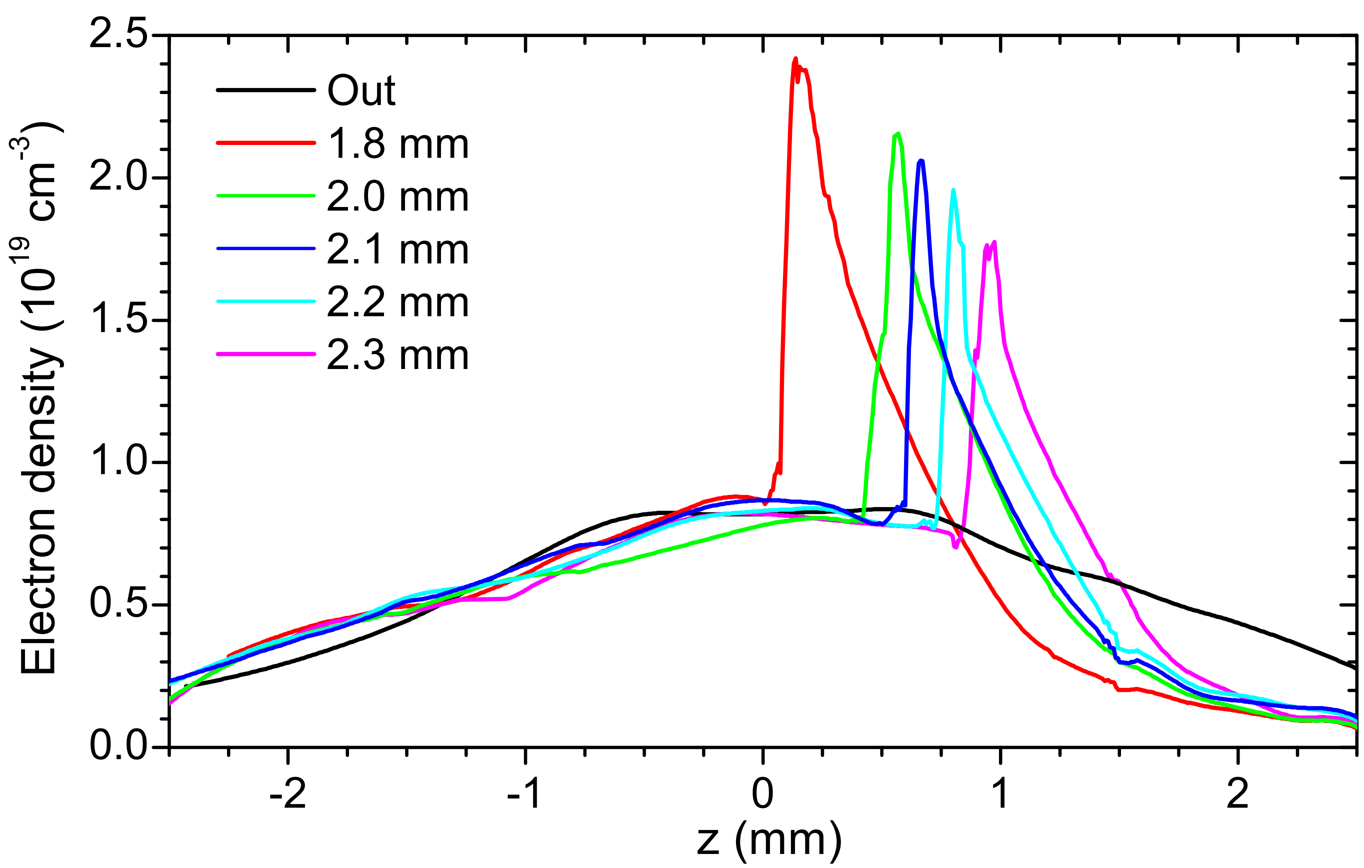


Overcoming the dephasing limit: results

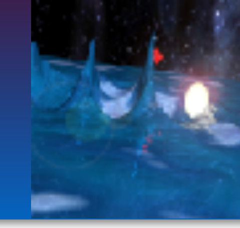


The density transition is controlled by changing the wafer position



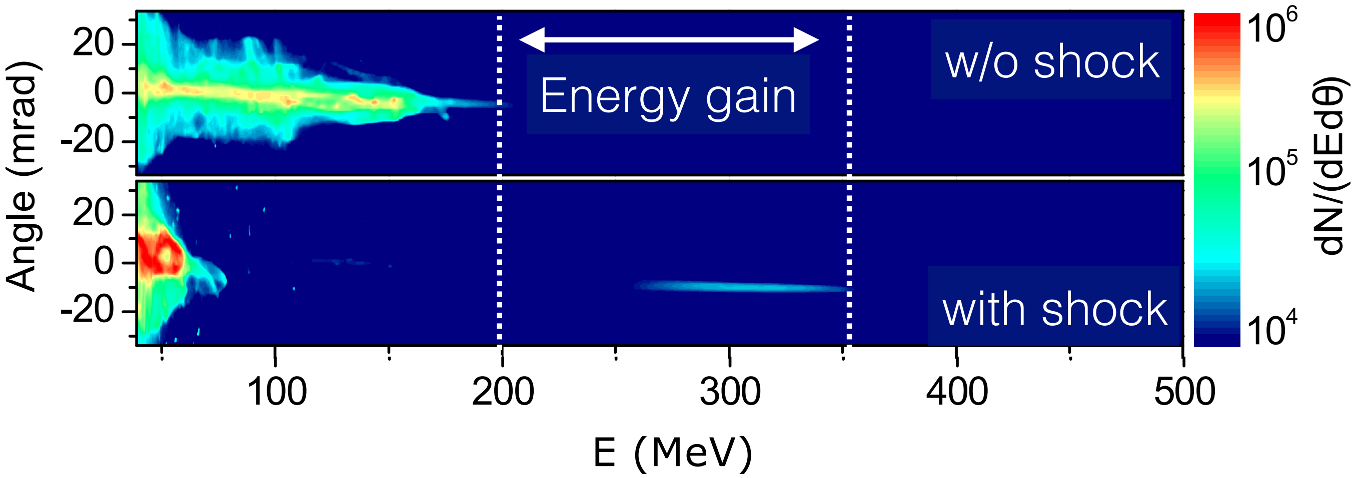


Overcoming the dephasing limit: experimental results & simulations

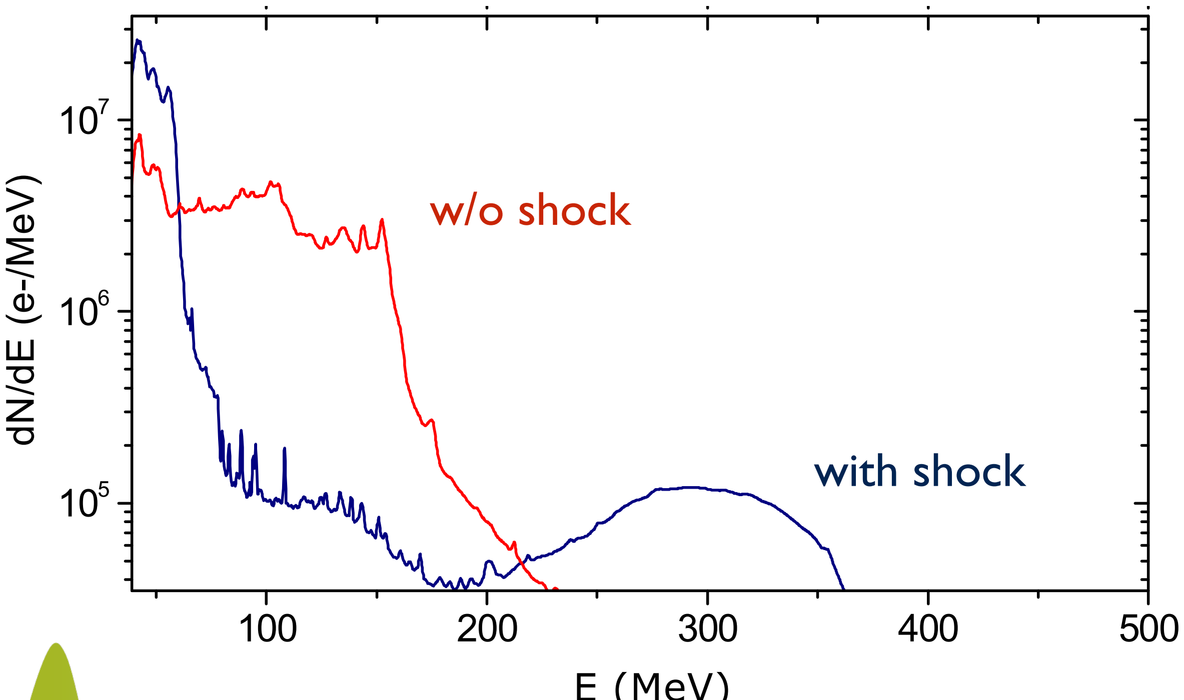


Experiment

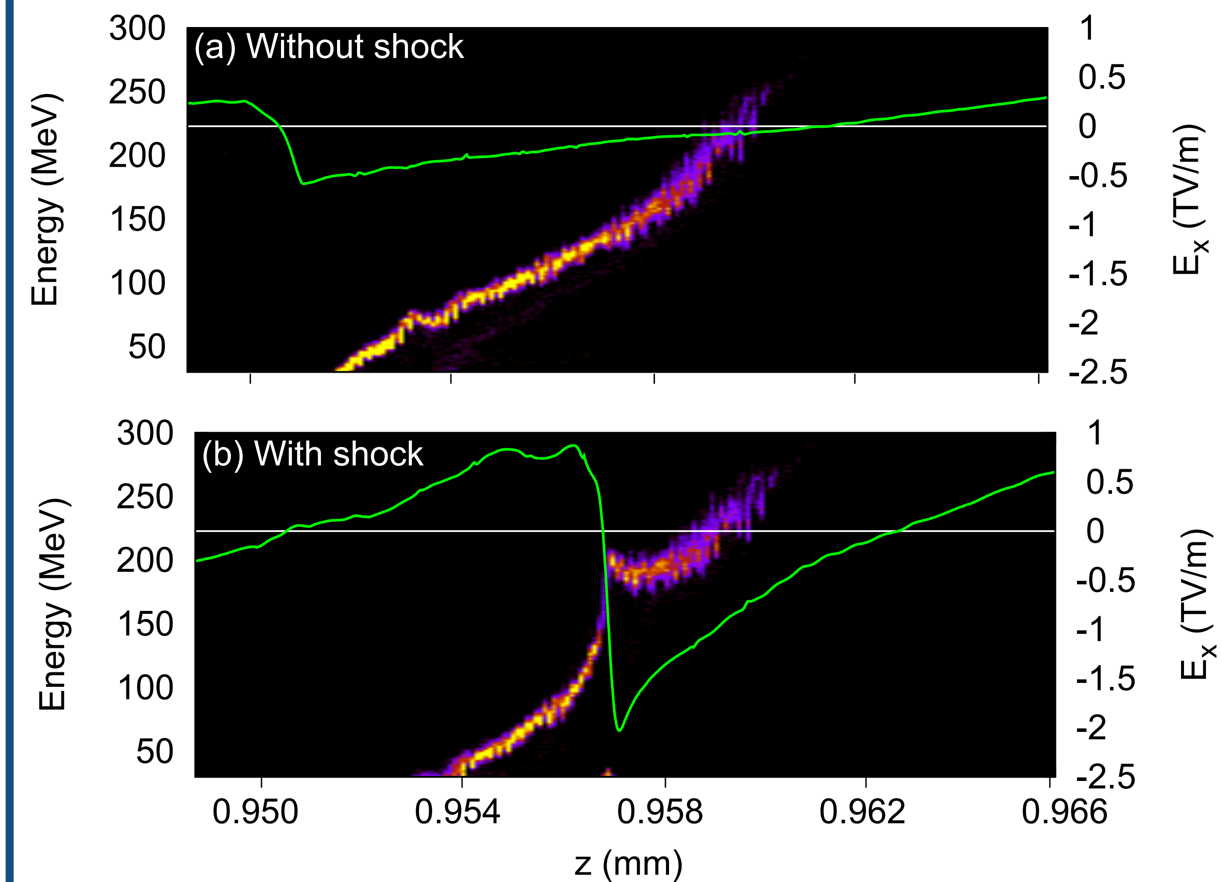
2D dispersion corrected spectra

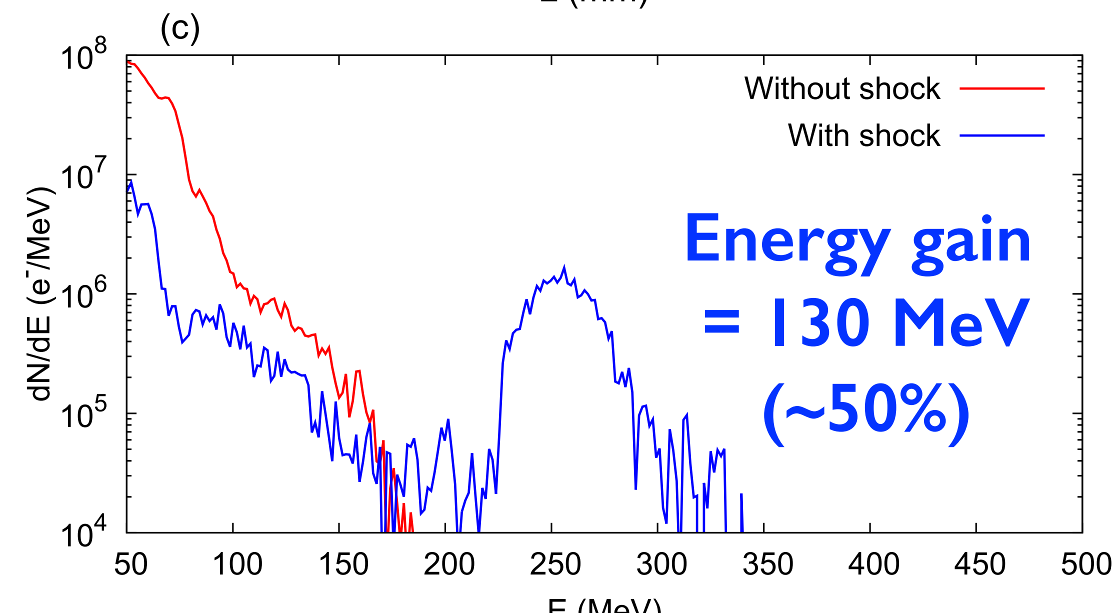


Angularly integrated spectra

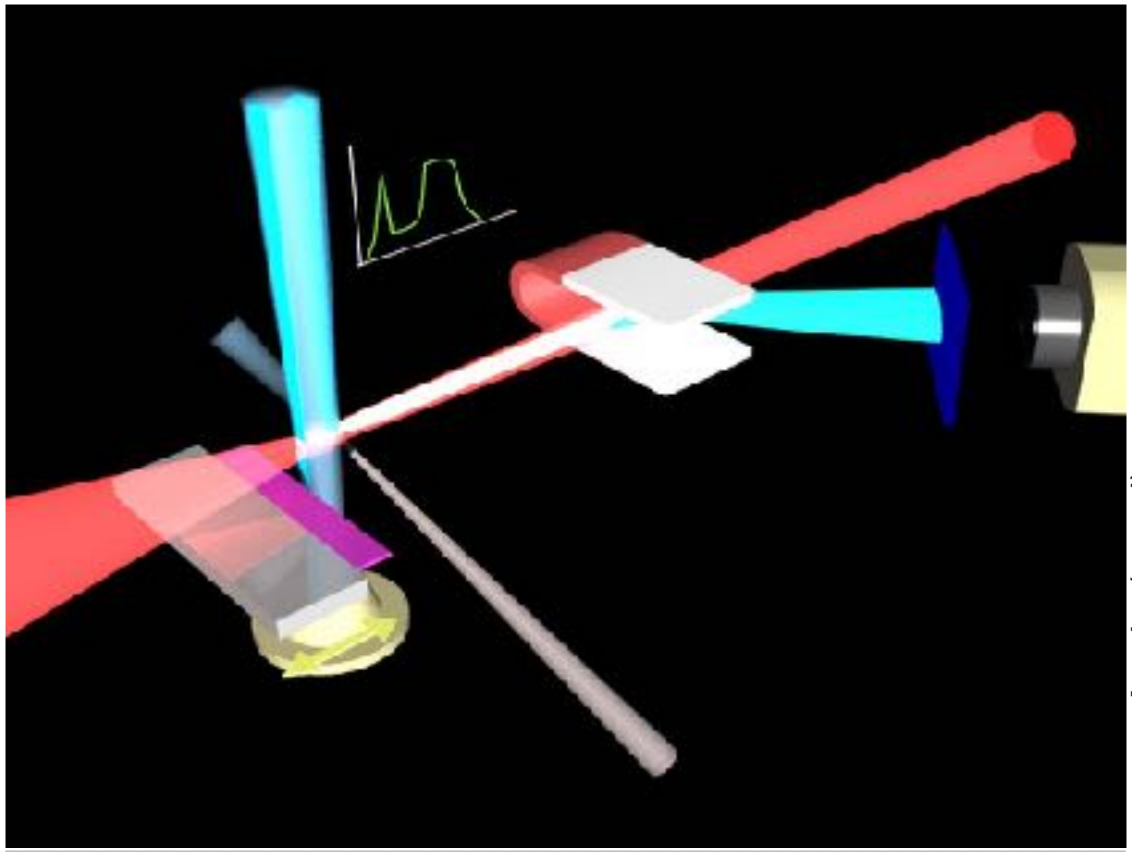


Calder-Circ PIC Simulations

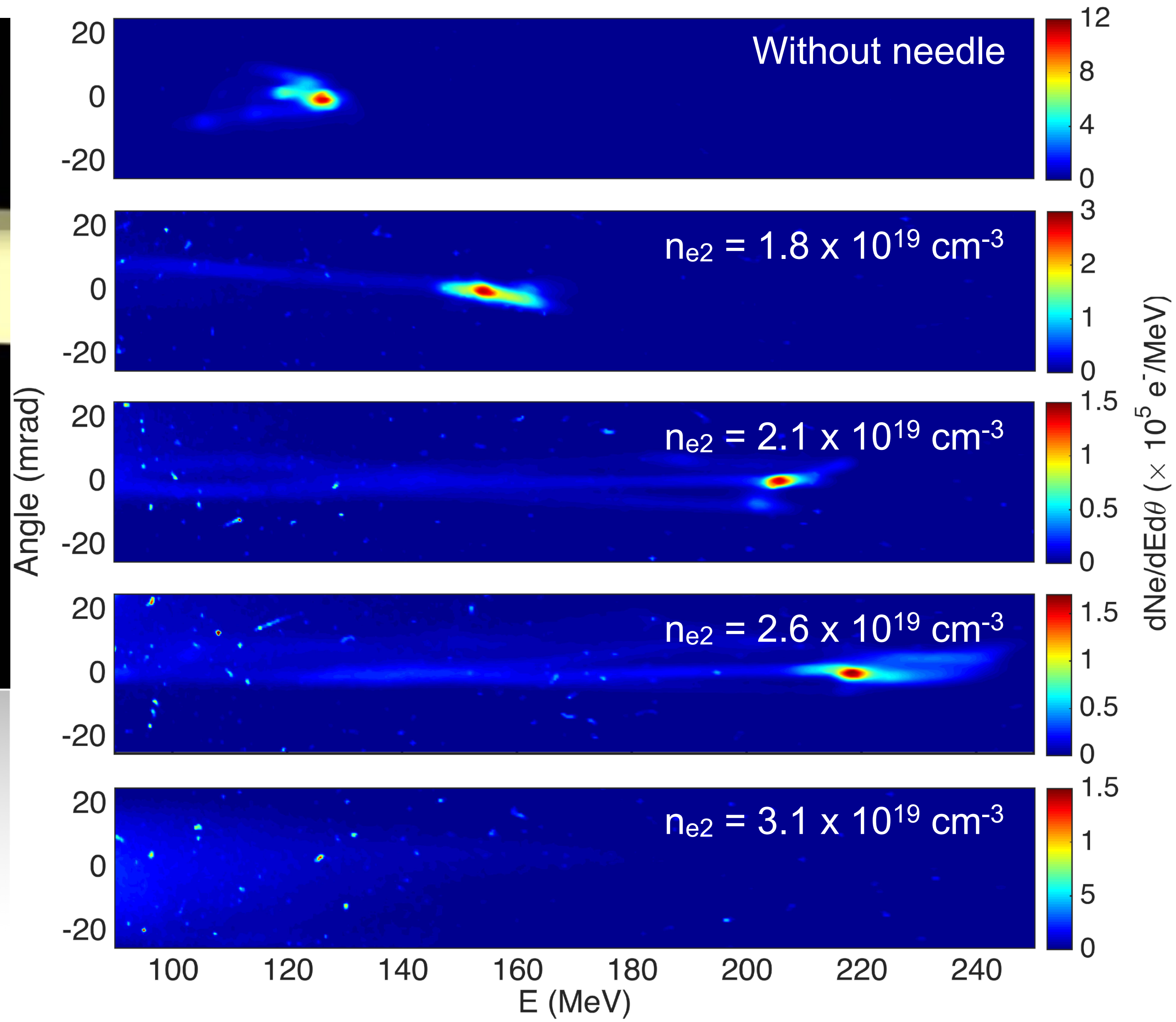




Energy boost of a mono-energetic e-beam



boosting a monoenergetic electron beam



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

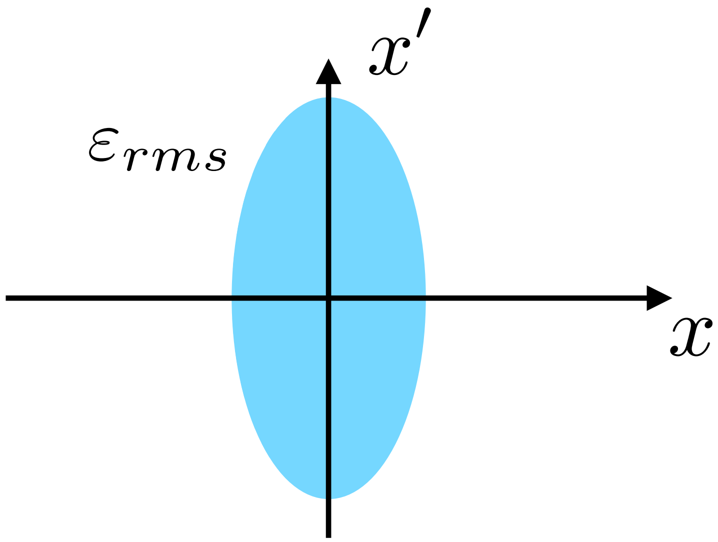
Laser Plasma Accelerators : Outline

- Introduction : context and motivations
- Injection in a density gradient
- Manipulating the longitudinal momentum
- Manipulating the transverse momentum
- Applications
- Conclusion and perspectives

Manipulating the p⊥ momentum : emittance definition

electrons beam emittance :

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



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

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

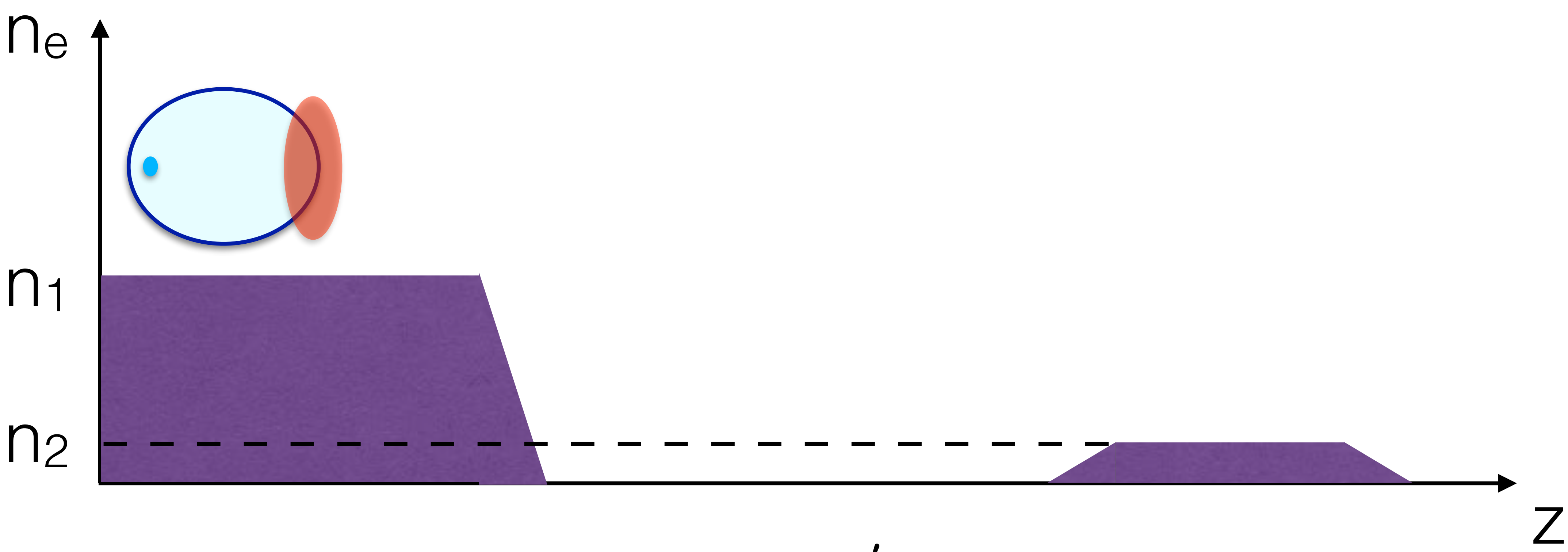
} emittance is dominated by the divergence

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

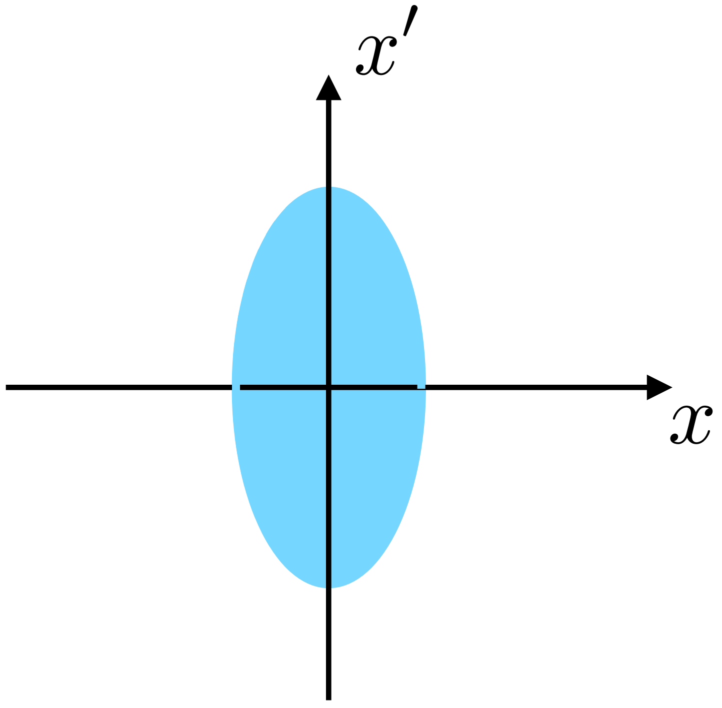
Goal :

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

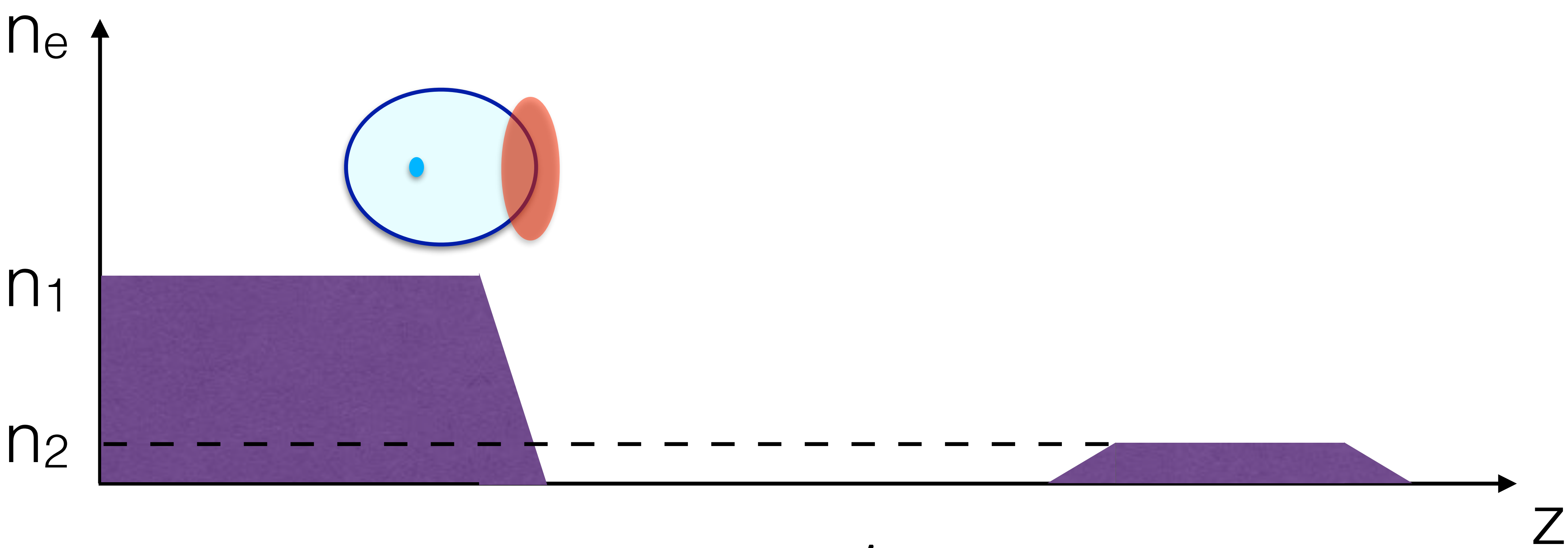
Manipulating the p⊥ momentum : principle



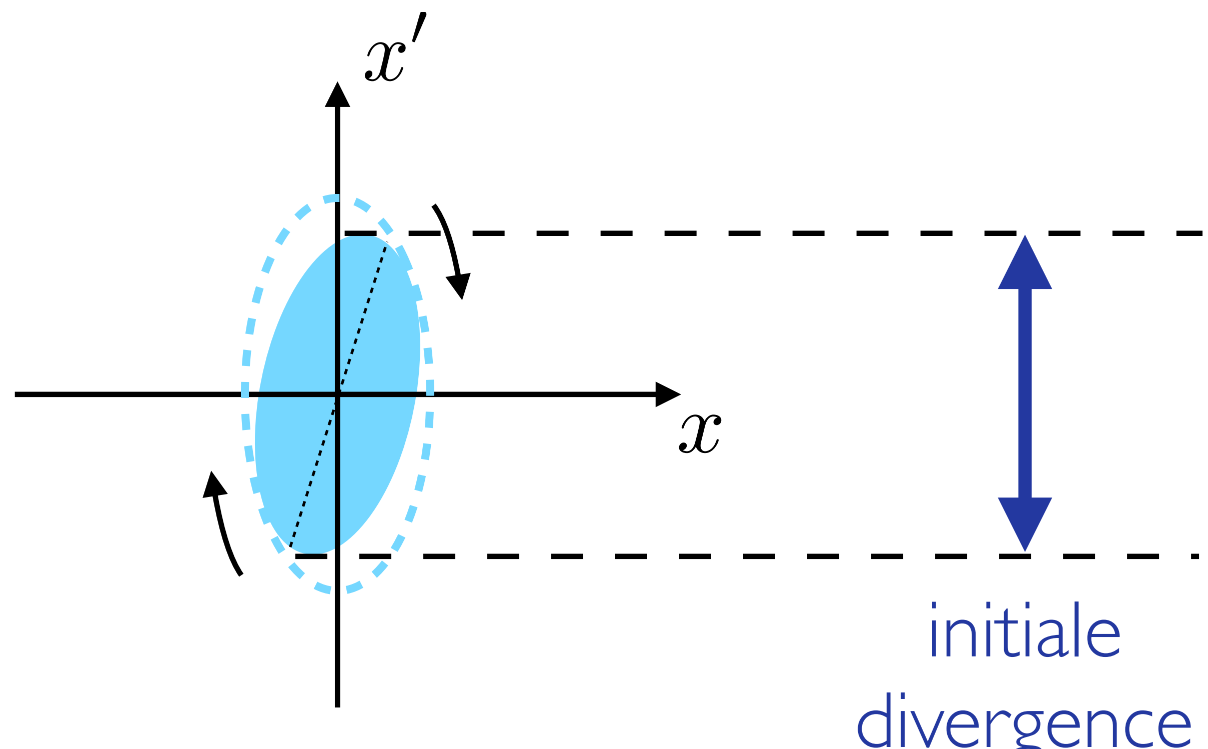
Acceleration &
betatron oscillation



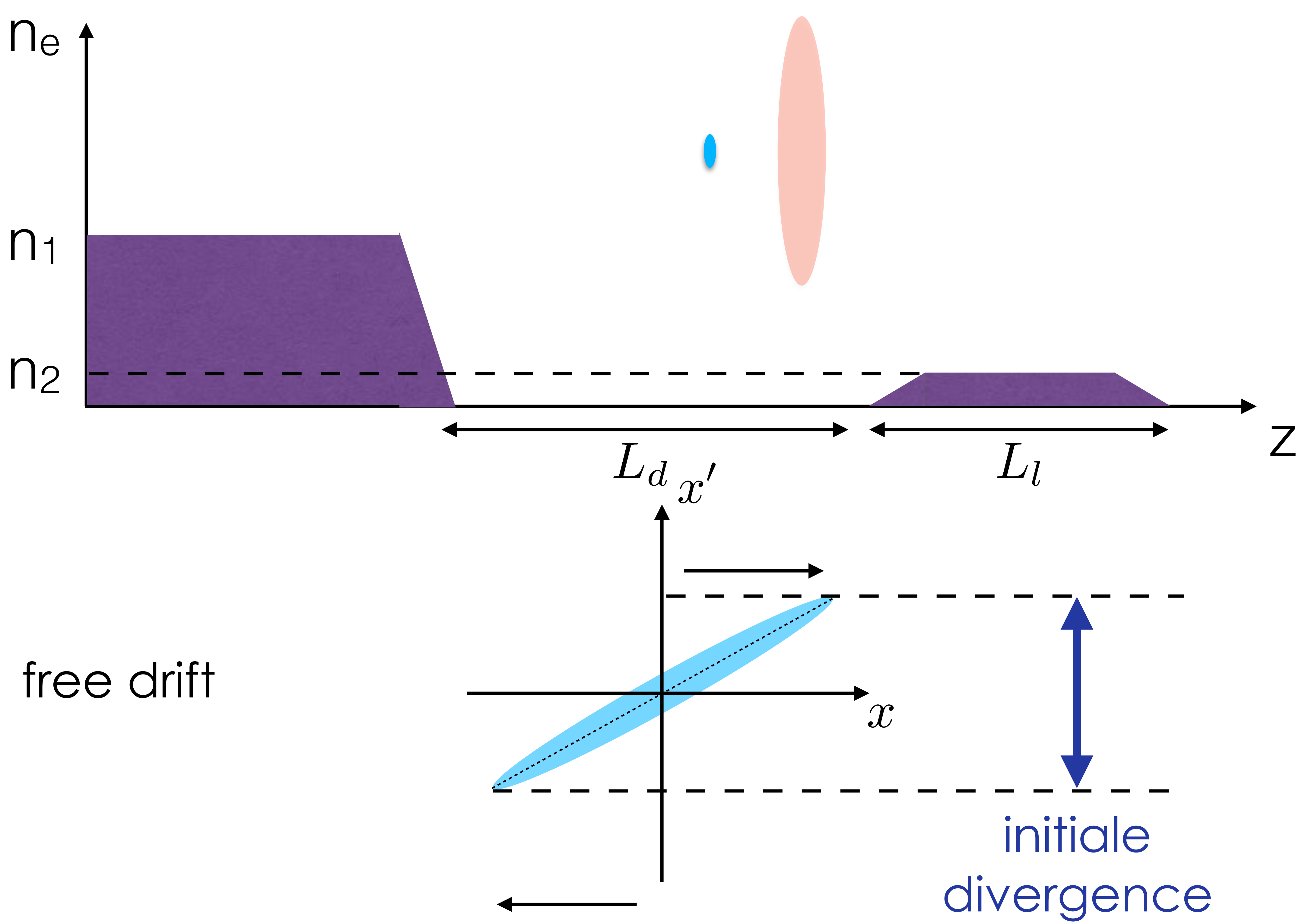
Manipulating the $p_\perp$ momentum : principle



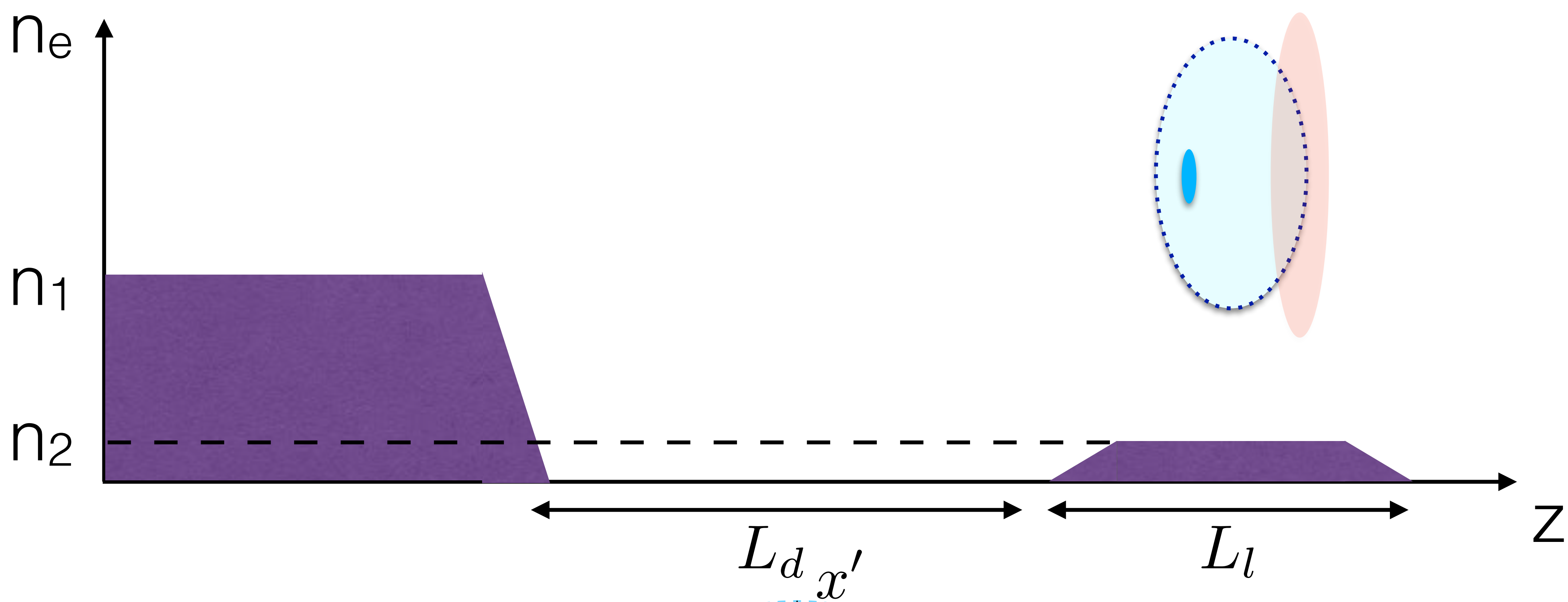
Acceleration & betatron oscillation



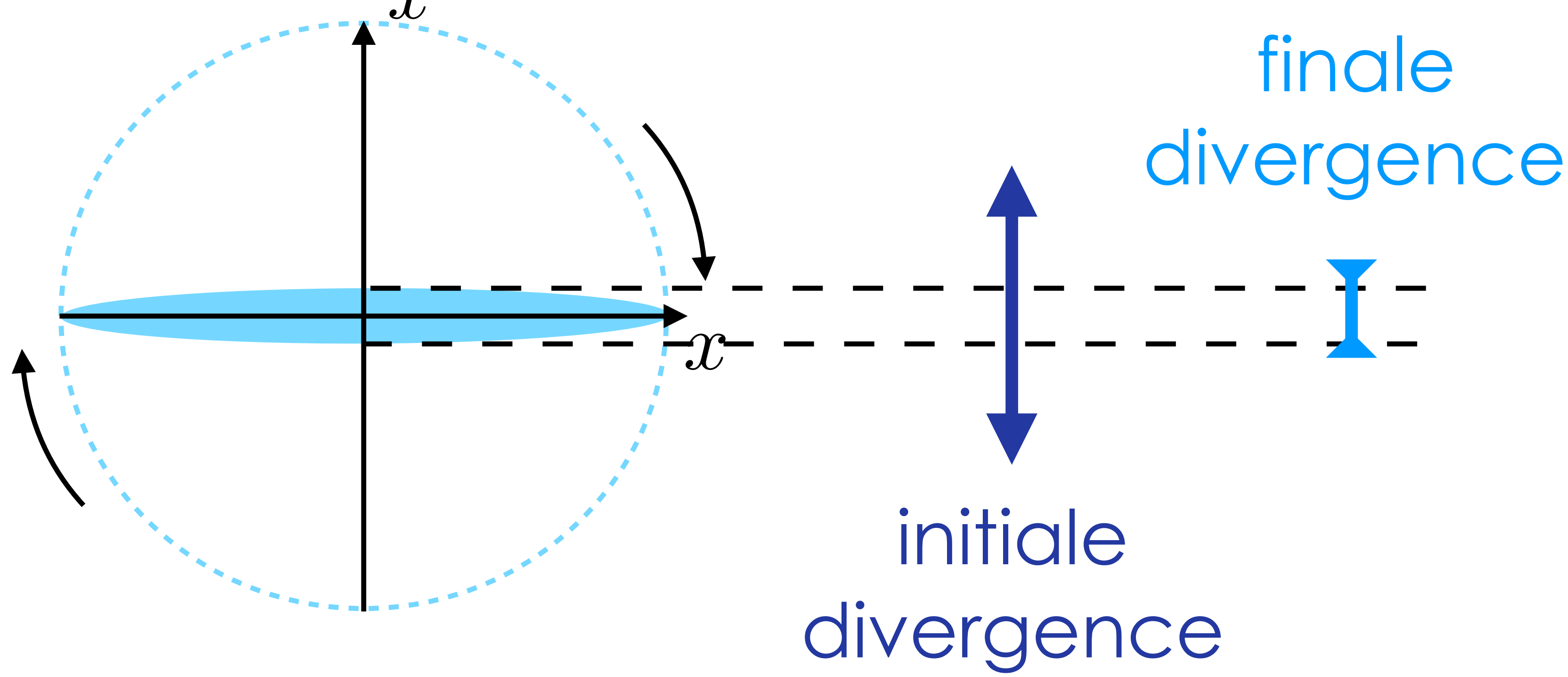
Manipulating the p⊥ momentum : principle



Manipulating the p⊥ momentum : principle



Collimation



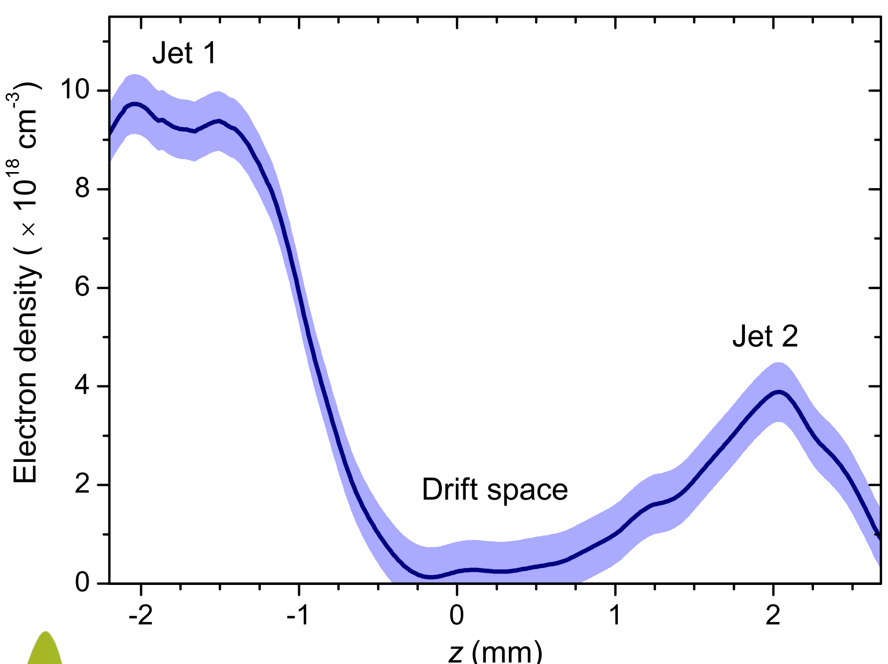
Manipulating the $p_\perp$ momentum : experimental set-up

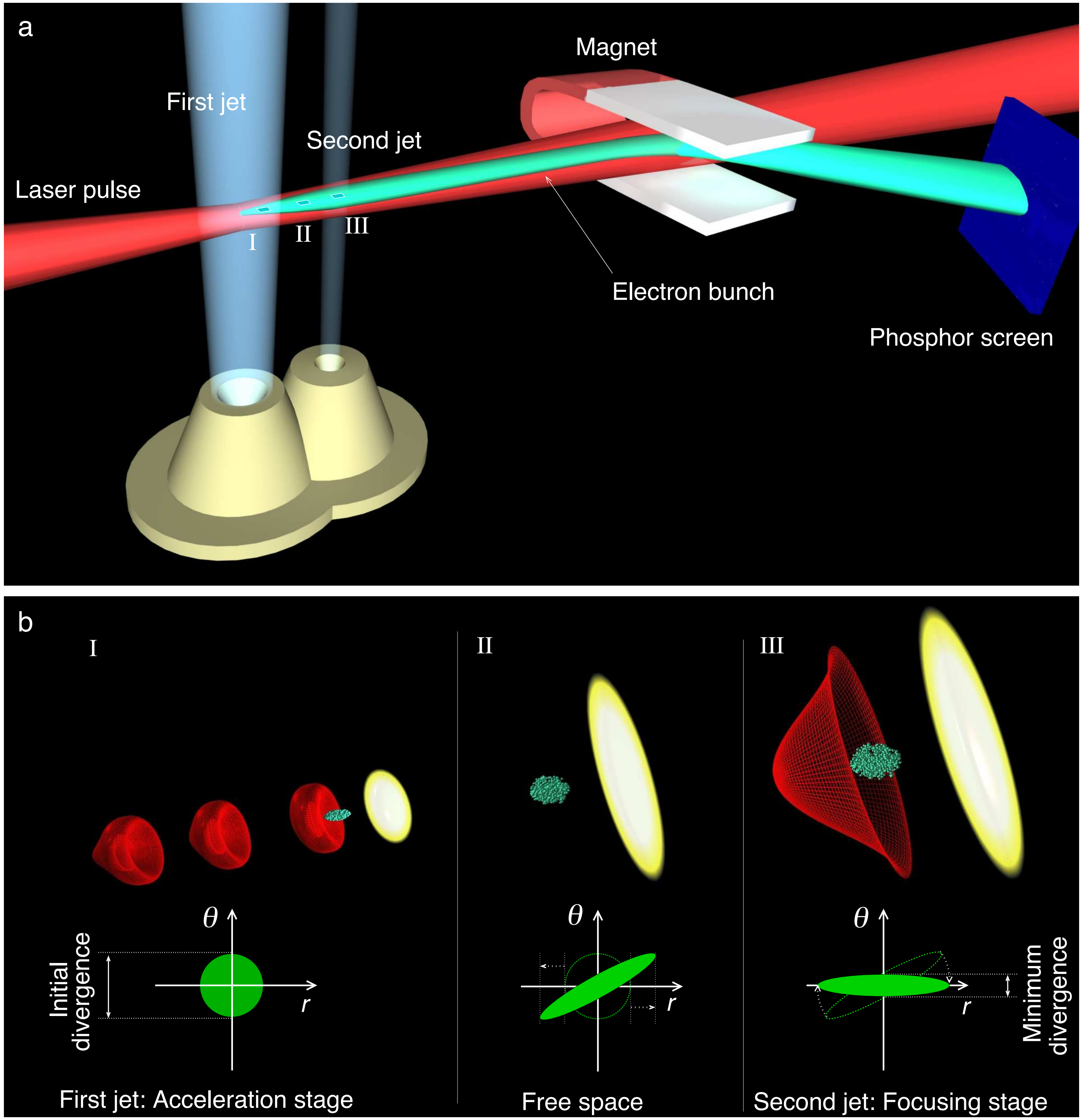
Acceleration stage

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
$n_1=9.2\times10^{18}cm^{-3}$

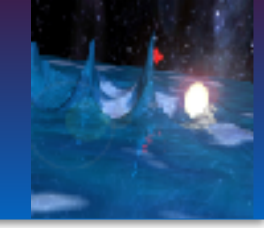
Focusing stage

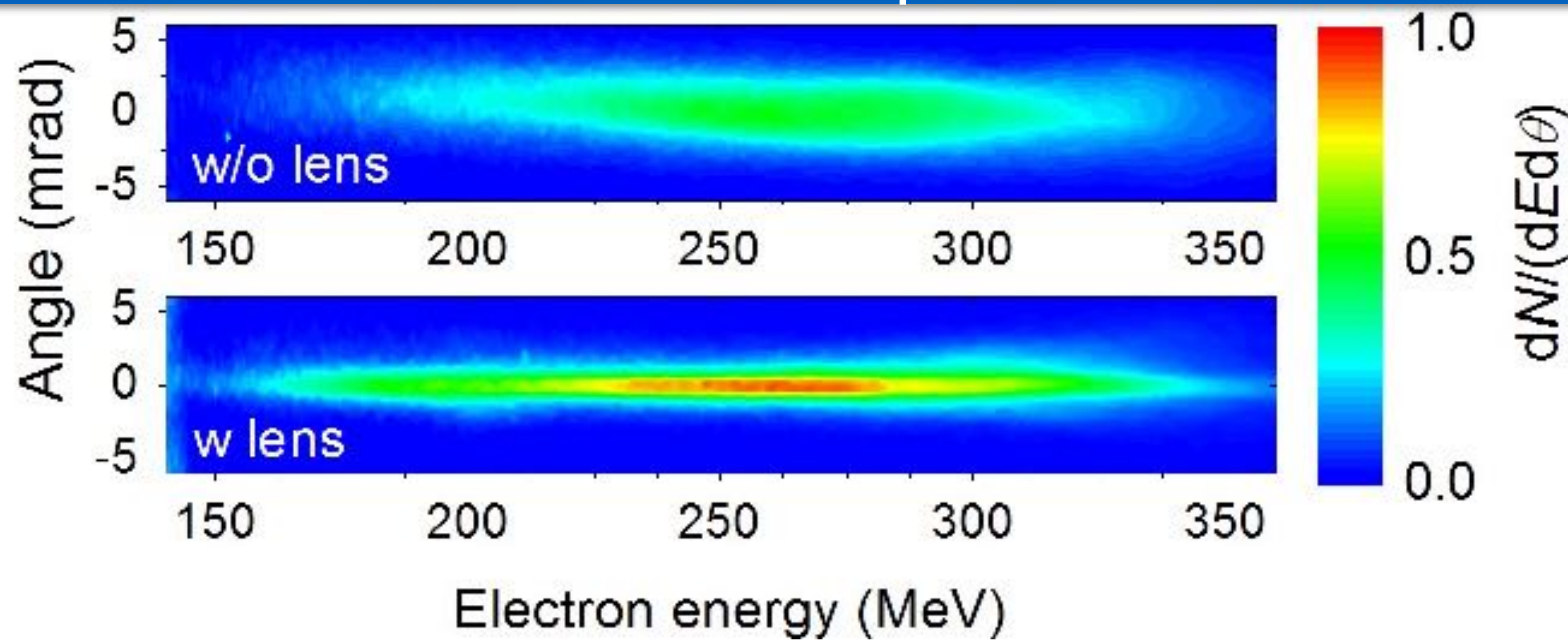
1 mm nozzle with variable n_2
Variable L_d

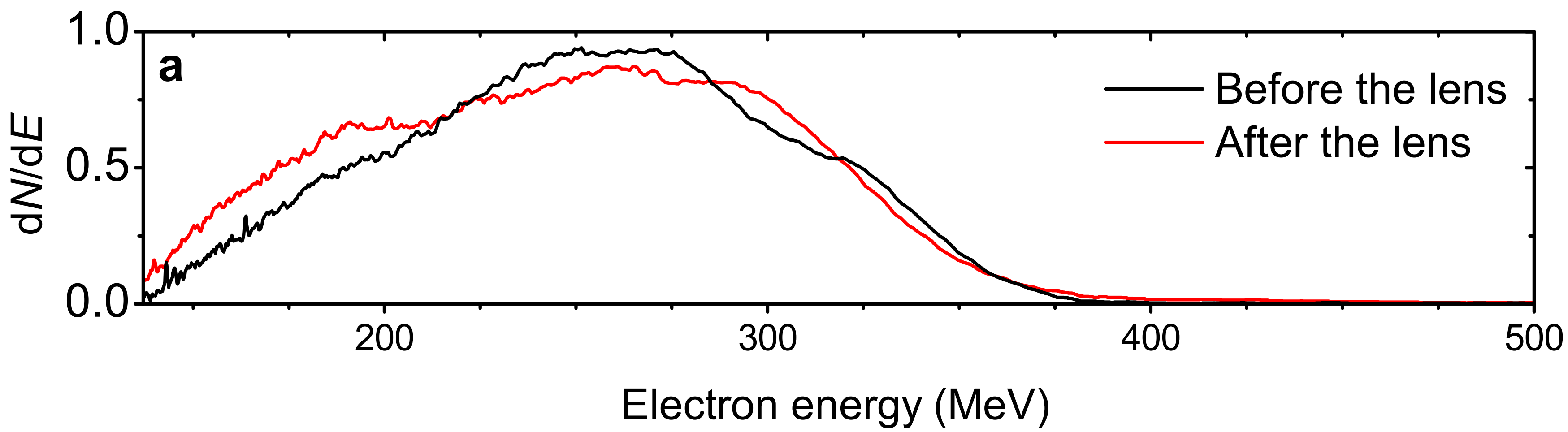




Manipulating the p⊥ momentum : demonstration of the laser plasma lens







Focusing stage parameters :

L_d = 1.8 mm

$n_2 = 3.9 \times 10^{18}$ 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)

Laser Plasma Accelerators : Outline

- Introduction : context and motivations
- Injection in a density gradient
- Manipulating the longitudinal momentum
- Manipulating the transverse momentum
- Applications
- Conclusion and perspectives

X rays source with Laser Plasma accelerators

Nonlinear Thomson 2003
Betatron radiation 2004
Compton scattering 2011
Bremsstrahlung 2010

1 keV | **10 keV** | **100 keV** | **1 MeV** | **10 MeV**

Xuv | **X** | **ɣ**

Common features: Collimated beams (mrad)
Femtosecond duration (few fs)
Micron source size
High peak brightness (>10^{20} ph/s/mm^2/$mrad^2$)

- naturally synchronized (ideal for pump-probe experiments)
- compacts and useful for small scale laboratories

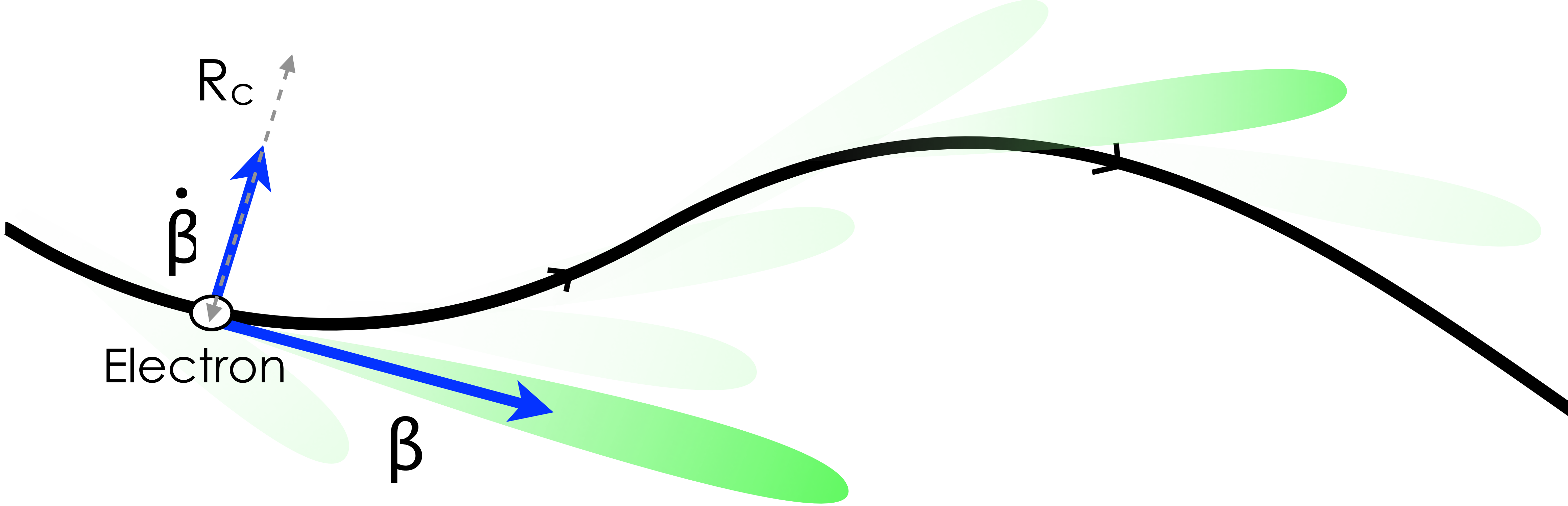
Moving charge radiation

Velocity *Acceleration*

$$\frac{d^2 I}{d\omega d\Omega} = \frac{e^2}{4\pi^2 c} \left| \int_{-\infty}^{+\infty} e^{i\omega[t - \vec{n}.\vec{r}(t)/c]} \frac{\vec{n} \times [(\vec{n} - \vec{\beta}) \times \dot{\vec{\beta}}]}{(1 - \vec{\beta}\,.\,\vec{n})^2} dt \right|^2$$

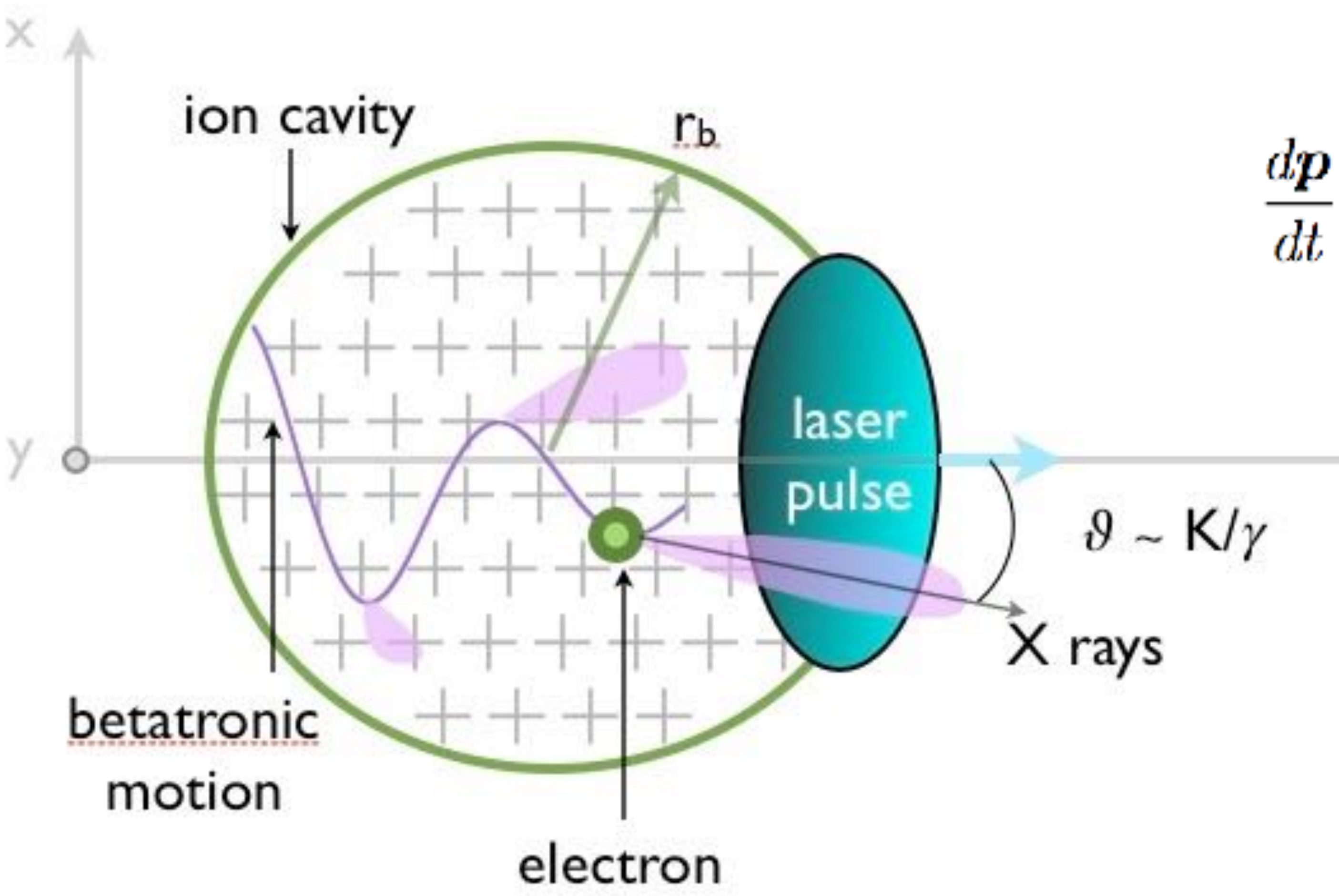
Radiated energy

n *unit vector in the observation direction*



To efficiently produce X-ray radiation we need relativistic electrons undergoing oscillations (synchrotron radiation)

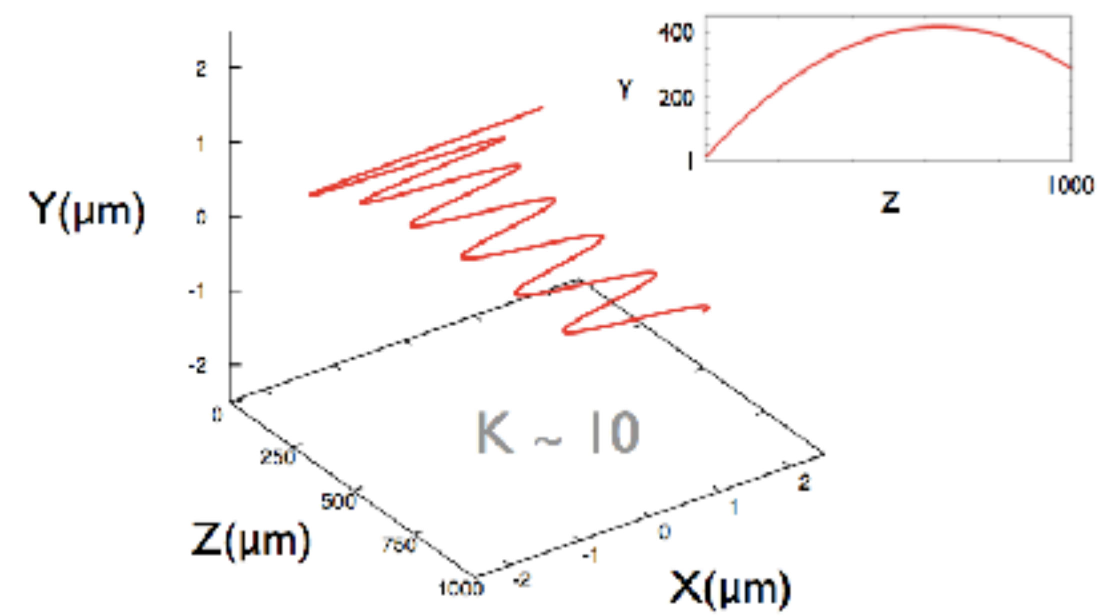
Betatron radiation properties



Transverse force

$$\frac{d\boldsymbol{p}}{dt} = \boldsymbol{F}_{\parallel} + \boldsymbol{F}_{\perp} = -\frac{m\omega_p^2}{2}\zeta\hat{\boldsymbol{z}} - \frac{m\omega_p^2}{2}(x\hat{\boldsymbol{x}} + y\hat{\boldsymbol{y}})$$

Longitudinal Force



Betatron oscillation properties:

$$\lambda_u = \sqrt{2\gamma}\lambda_p$$
$$K = r_\beta k_p \sqrt{\gamma/2}$$

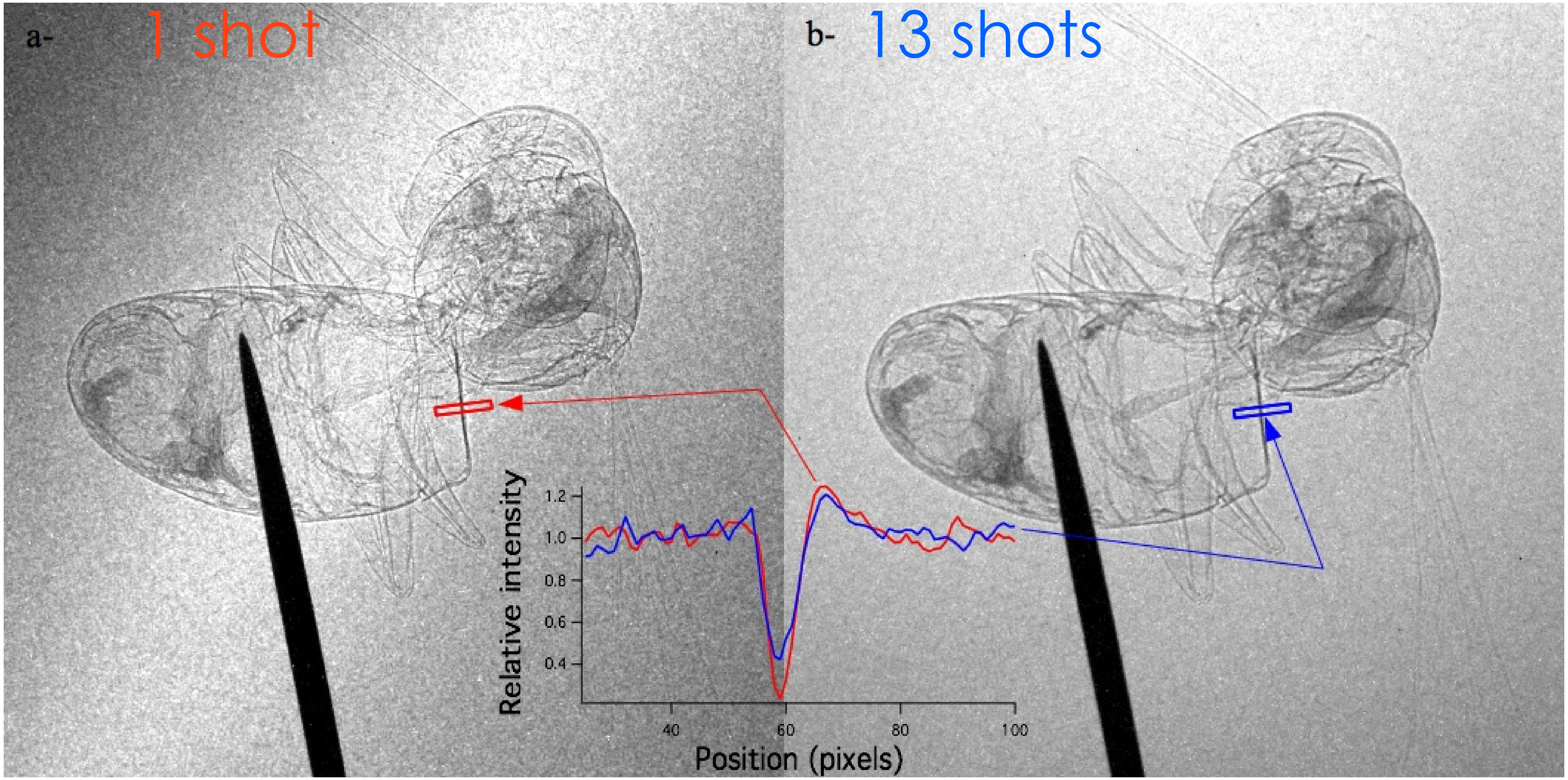
$$\xrightarrow[r_\beta \sim 1\ \mu\text{m}]{\sim 100\ \text{MeV}}$$
$$n_e \sim 10^{19}\ \text{cm}^{-3}$$

$$\lambda_u \sim 200\ \mu\text{m}$$
$$K \sim 5$$

Phase contrast imaging : results

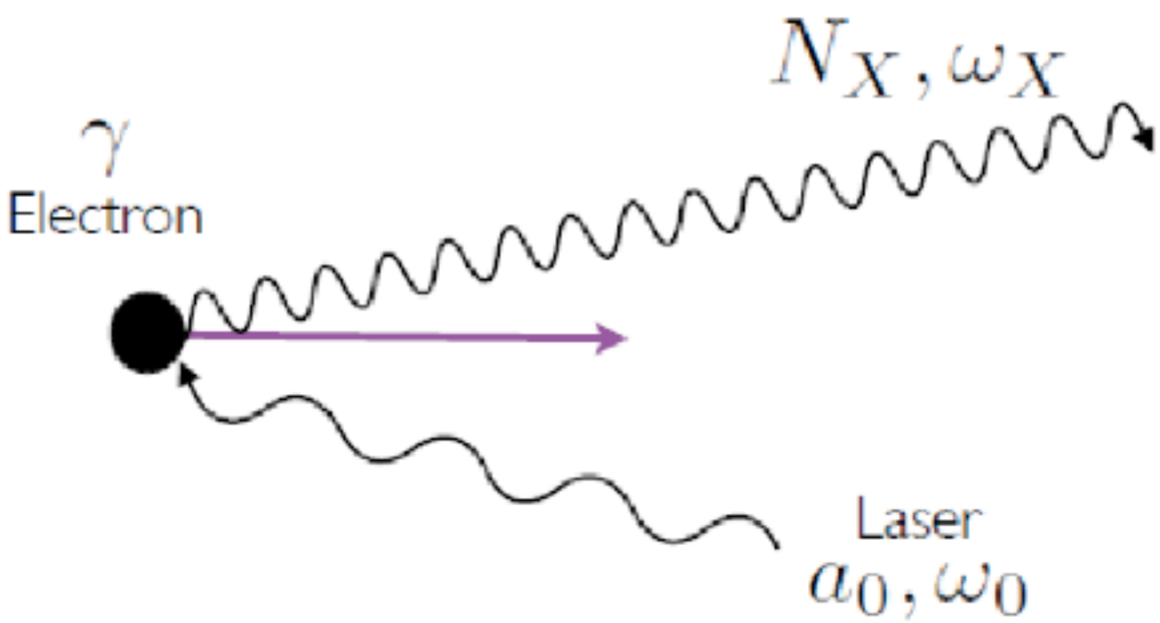
Bee contrast image :

- Contrast of 0.68 in single shot.
- Very tiny details can be observed in single shot that disappear in multi shots.



S. Fourmaux *et al.*, Opt. Lett. **36**, 2426 (2011)

Inverse Compton Scattering



Doppler upshift : high energy photons with modest electrons energy :

$\omega_x = 4\gamma^2\omega_0$

For example :

20 MeV electrons can produce 10 keV photons

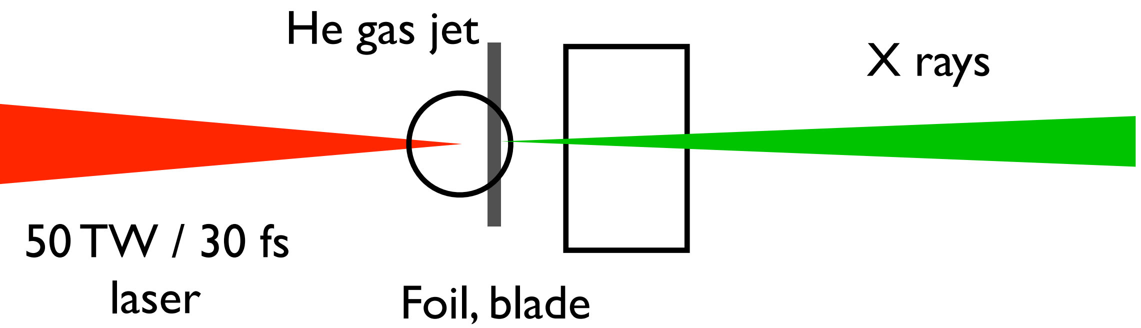
200 MeV electrons can produce 1 MeV photons

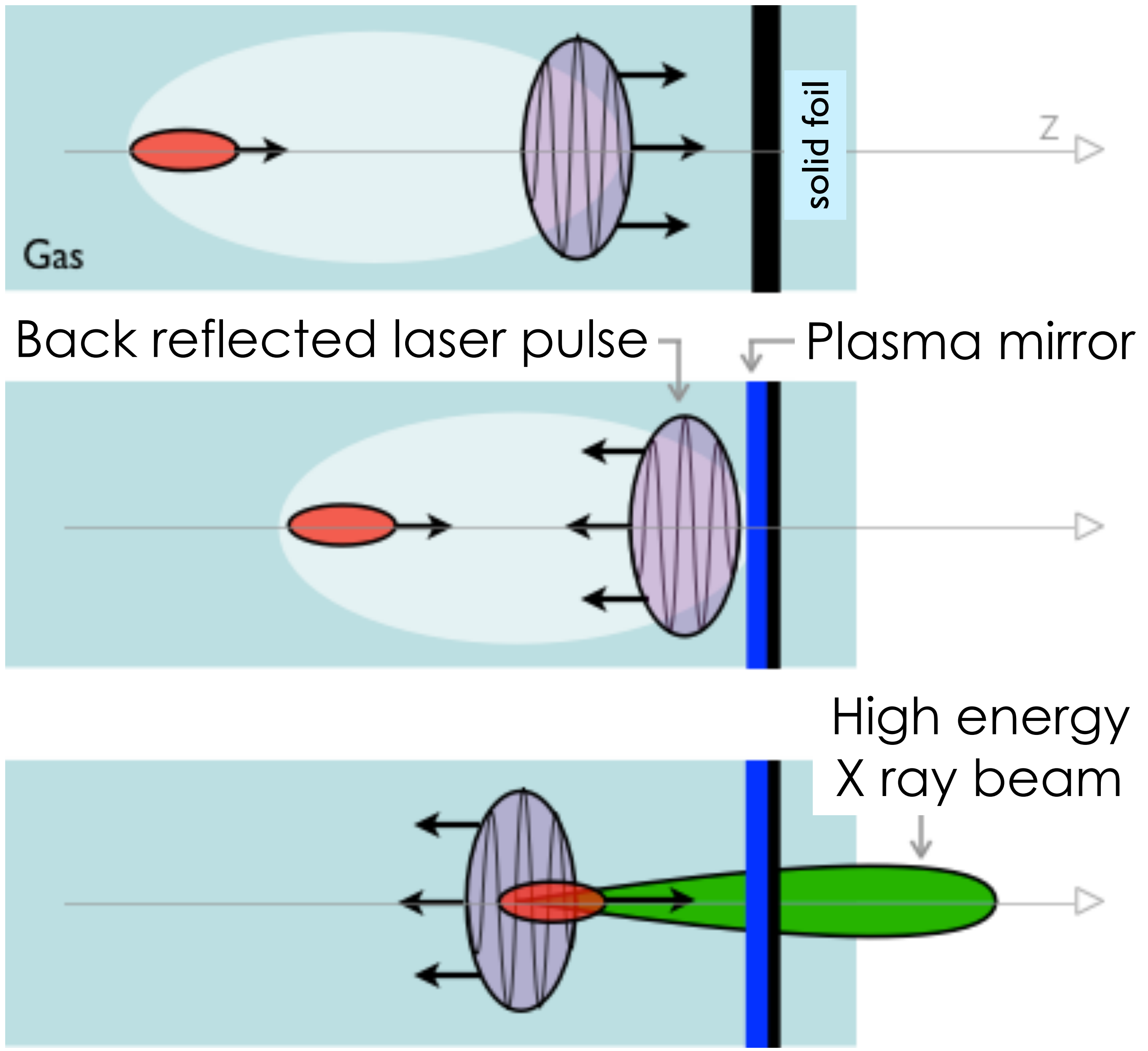
The number of photons depends on the electron charge N_e and a_0^2 : $N_x \propto a_0^2 \times N_e$

Duration (fs), source size (μm) = electron bunch length and electron beam size

Spectral bandwidth : $\Delta E/E \propto 2\Delta\gamma/\gamma, \gamma^2\Delta\theta^2$

Inverse Compton Scattering : New scheme





A single laser pulse

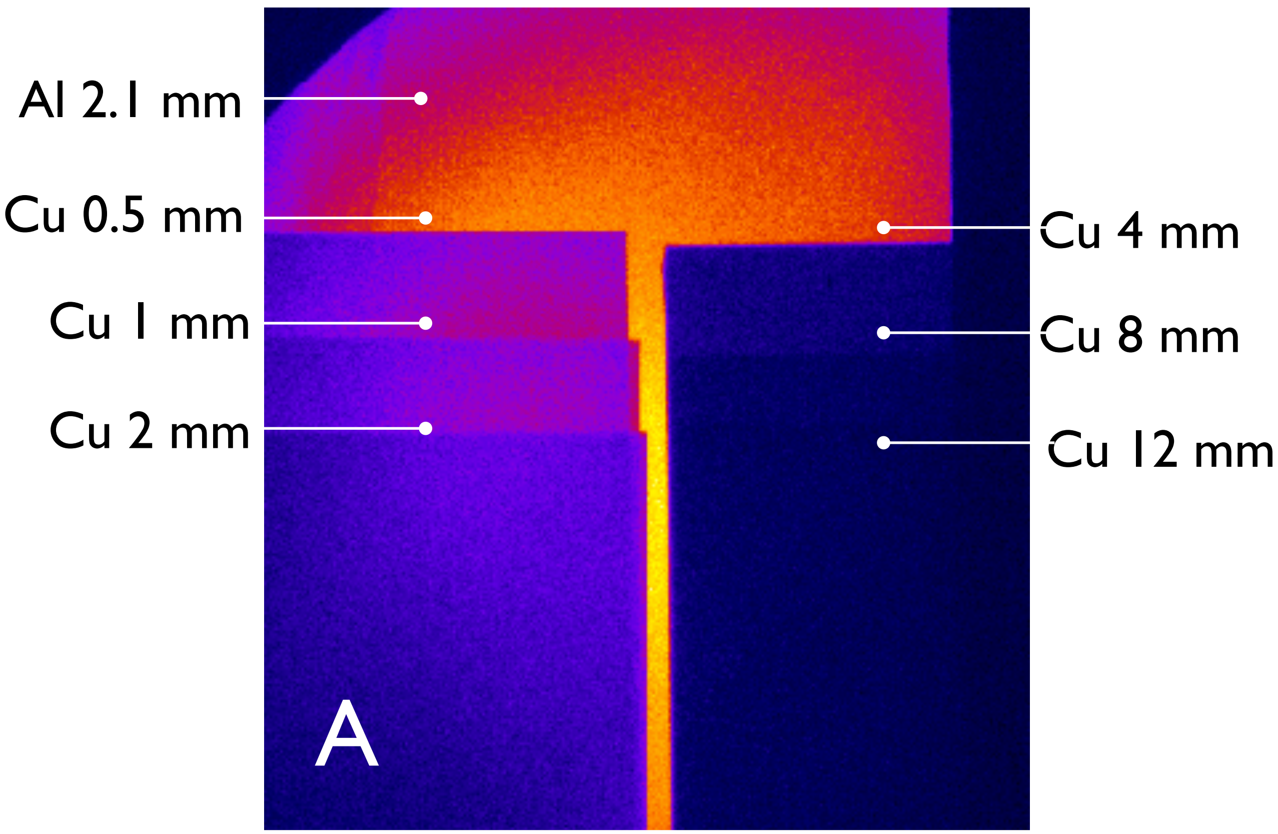
A plasma mirror reflects the laser beam

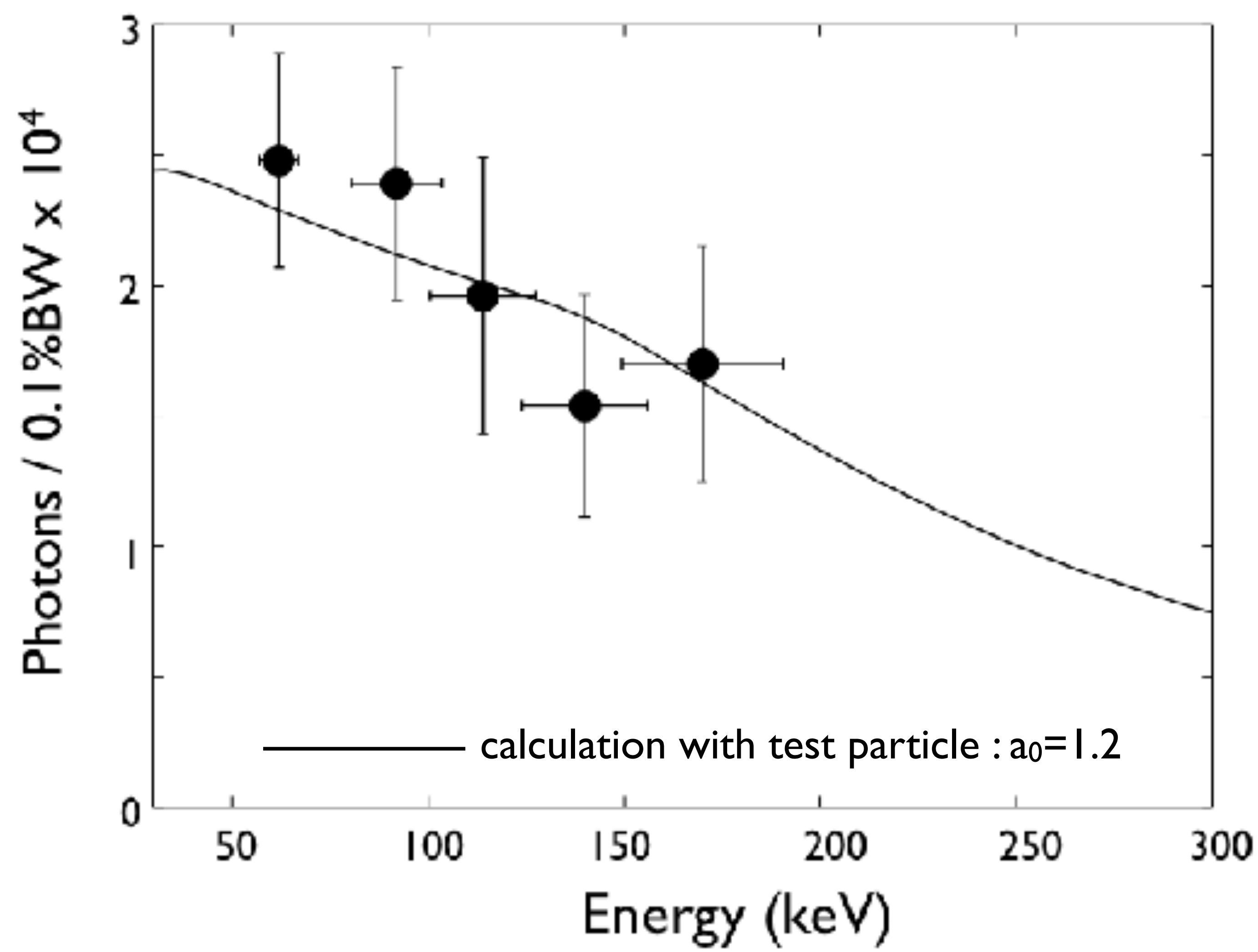
The back reflected laser collides with the accelerated electrons

No alignement : the laser and the electron
beams naturally overlap

Save the laser energy !

Inverse Compton Scattering : Compton Spectra

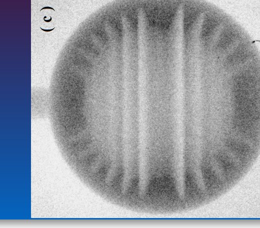




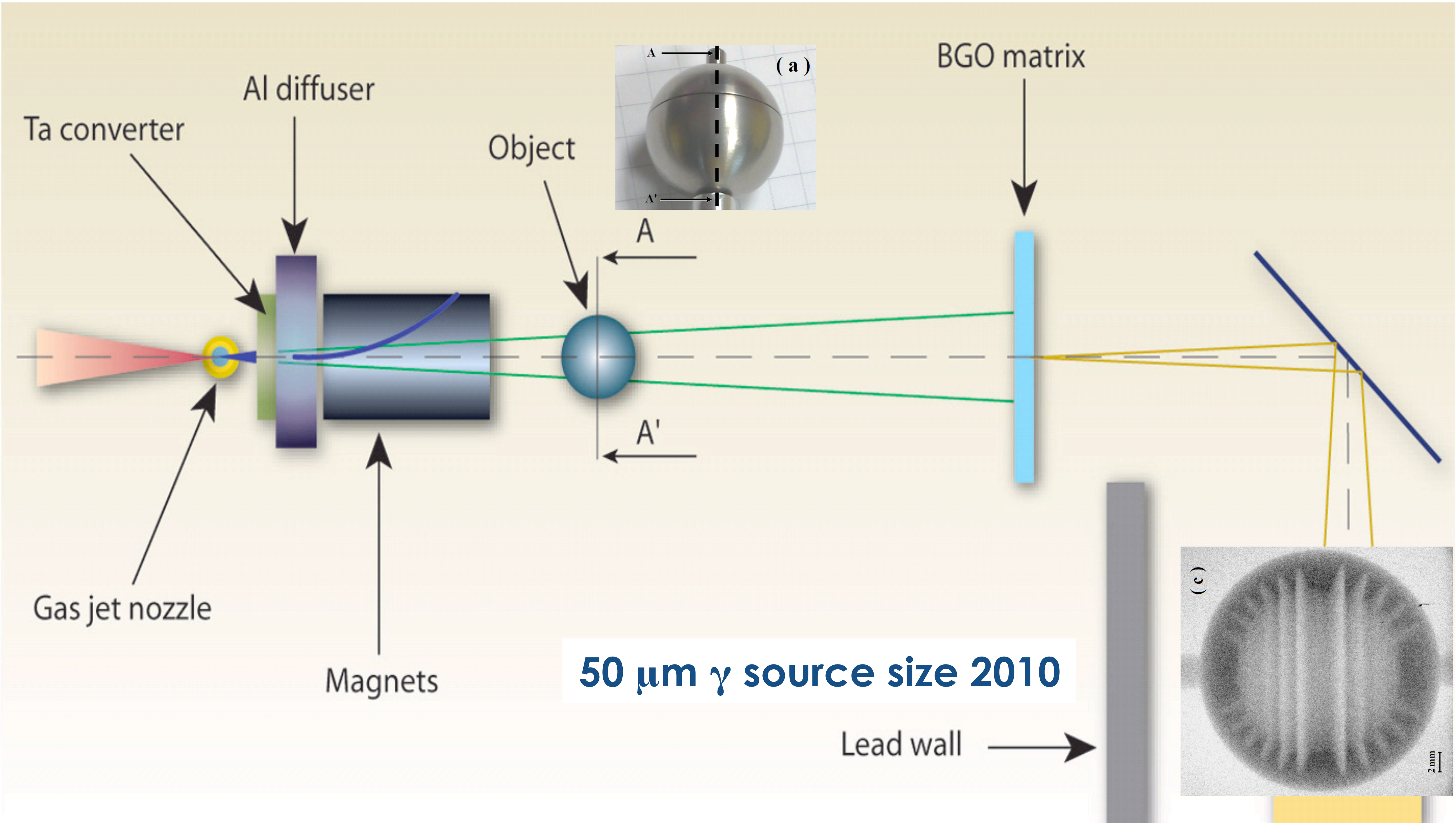
- About 10^8 ph/shot, a few 10^4 ph/shot/0.1%BW@100 keV
- Source size less of 1.5 um
- Brigthness: 10^{21} ph/s/mm^2/mrad^2/0.1%BW @100 keV

K. Ta Phuoc *et al.*, Nature Photonics, May 2012

Some examples of applications : radiography for non destructive inspection

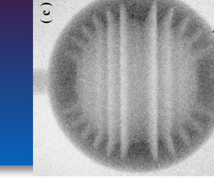


High resolution radiography of dense object with a low divergence, point-like electron source



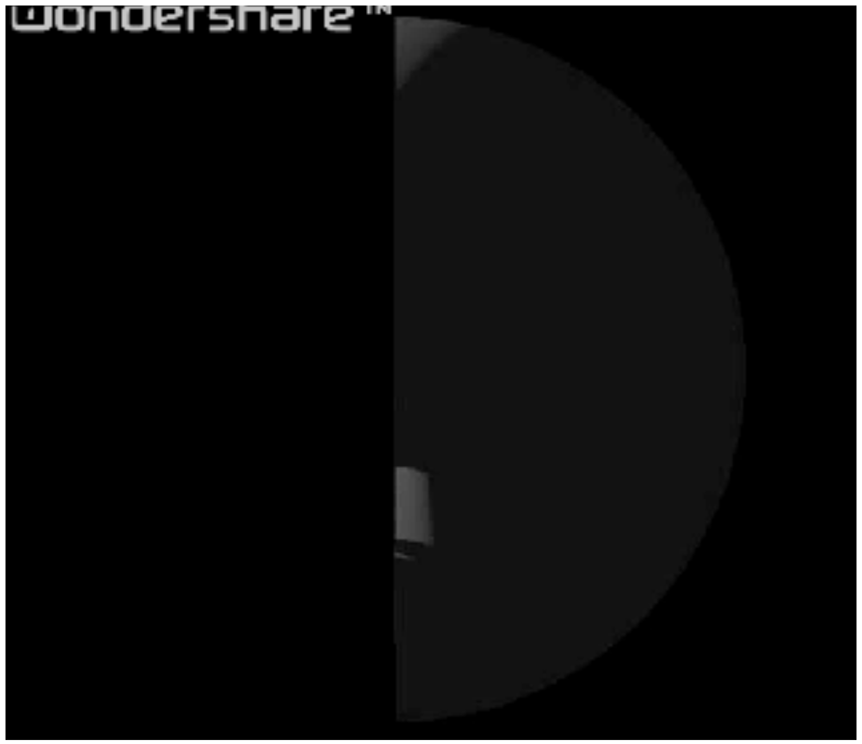
Y. Glinec *et al.*, PRL **94**, 025003 (2005) A. King *et al.*, Mrs Bulletin **94**, 8 (2006)
A. Ben-Ismail *et al.*, NIM A **629** (2010), App. Phys. Lett. **98**, 264101 (2011)

Some examples of applications : radiography



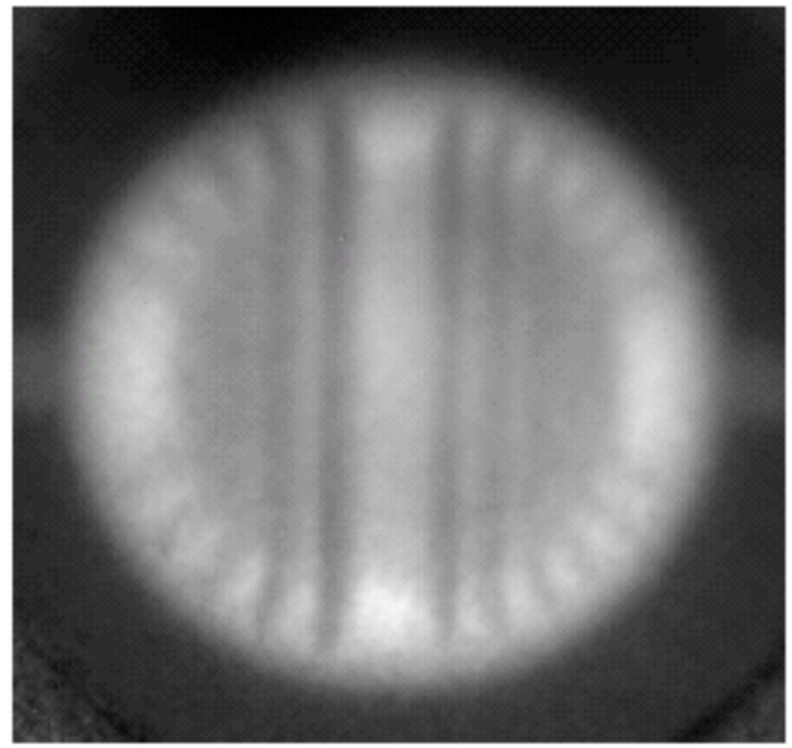
Non destructive dense matter inspection

High resolution radiography of dense object with a low divergence, point-like electron source

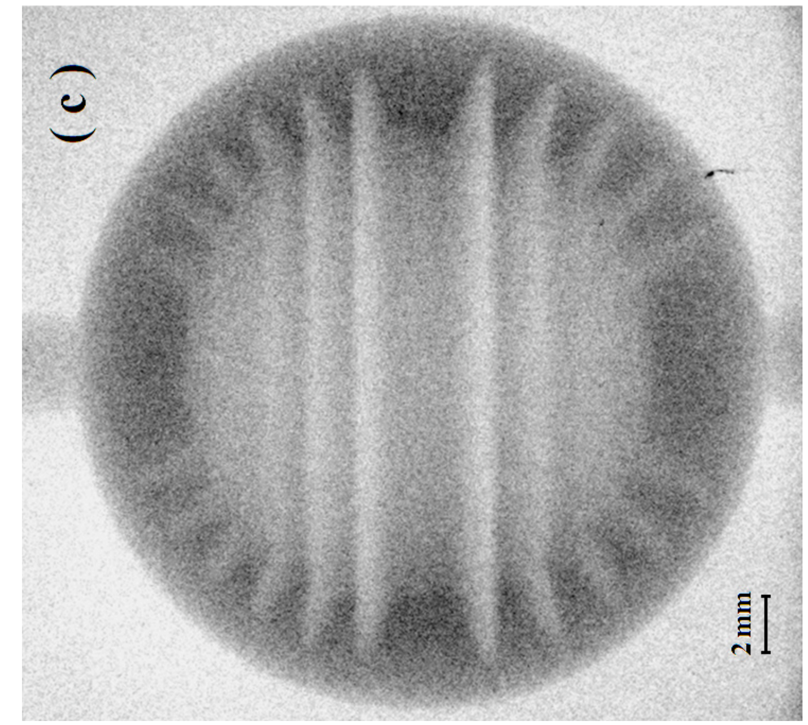


Cut of the object in 3D

Spherical hollow object in tungsten with sinusoidal structures etched on the inner part.



400 µm γ source size
2005

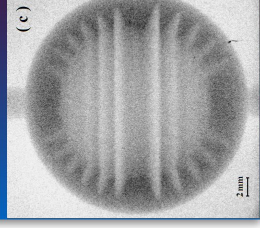


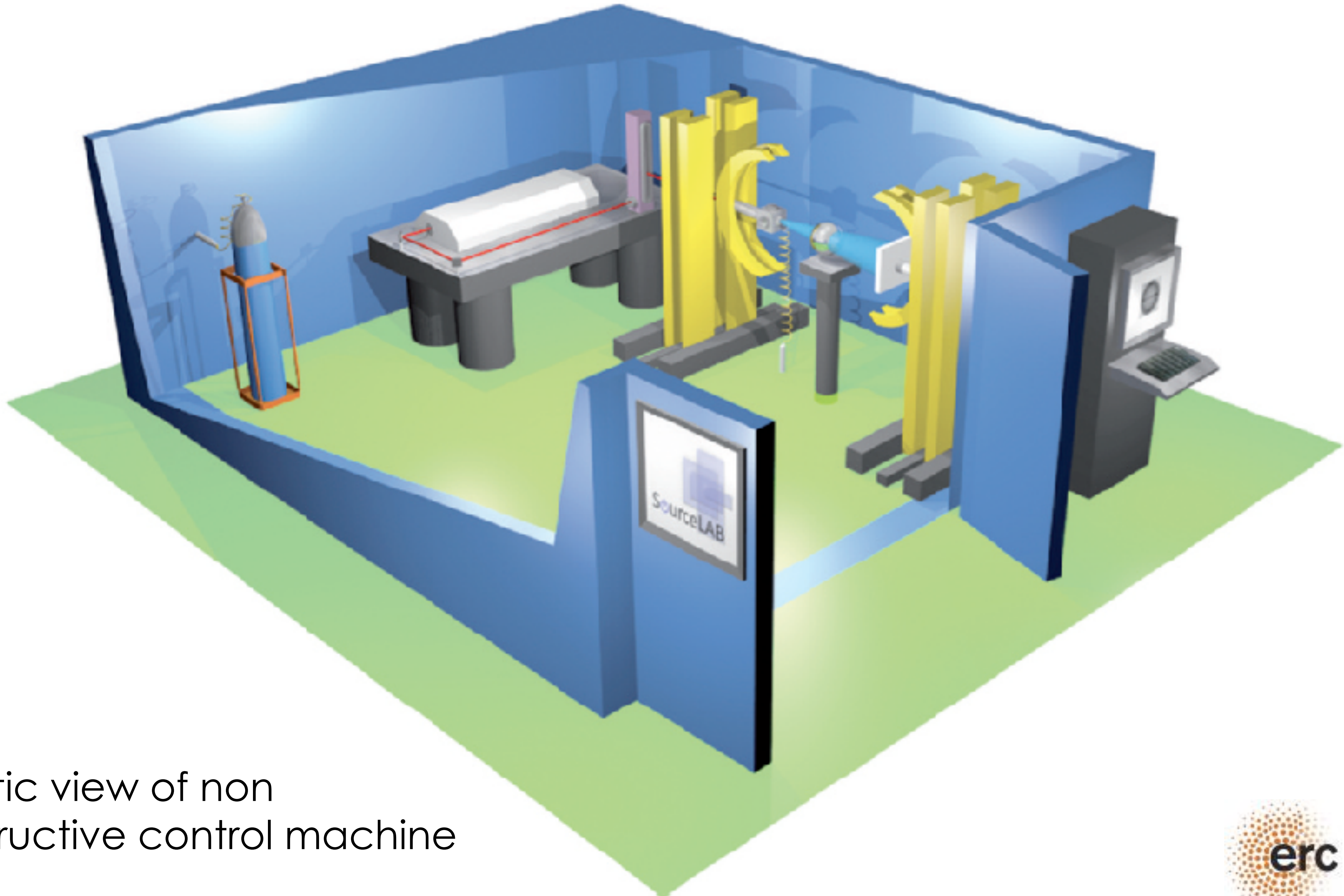
50 µm γ source size
2010

Y. Glinec *et al.*, PRL **94**, 025003 (2005) A. King *et al.*, Mrs Bulletin **94**, 8 (2006)

A. Ben-Ismail *et al.*, NIM A **629** (2010), App. Phys. Lett. **98**, 264101 (2011)

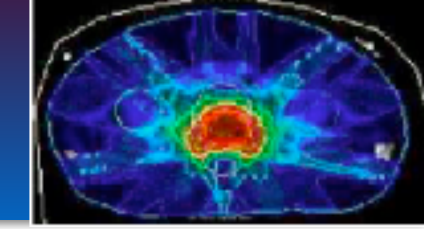
Some examples of applications : radiography for non destructive inspection

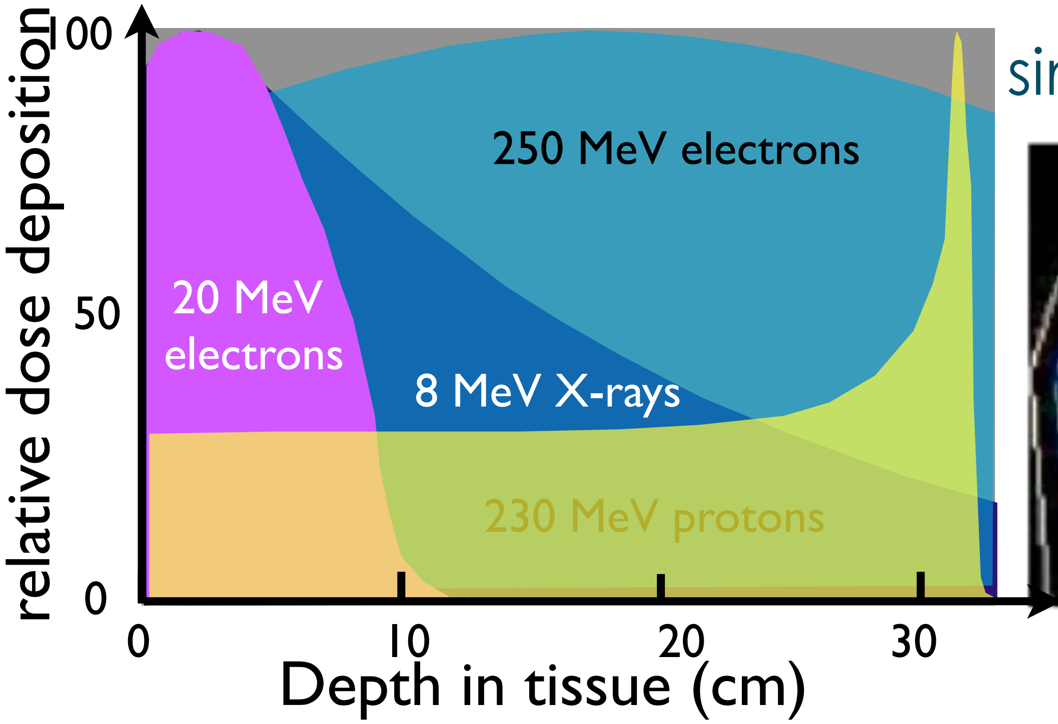




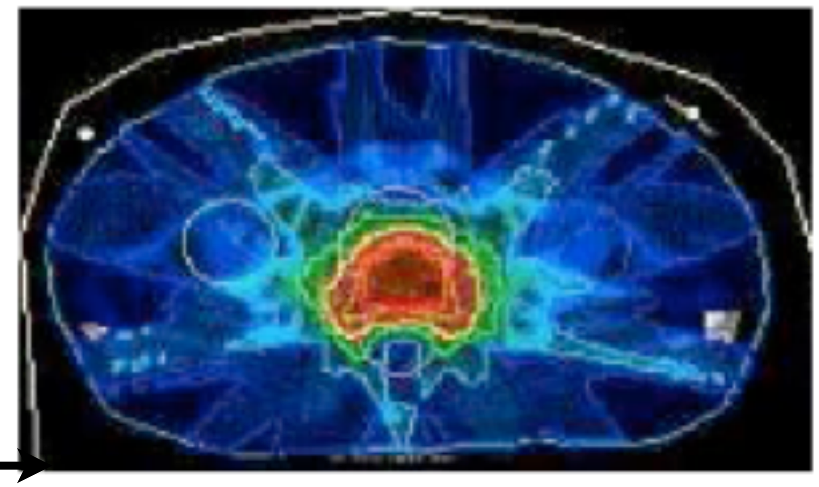
Artistic view of non destructive control machine

Some examples of applications : radiotherapy

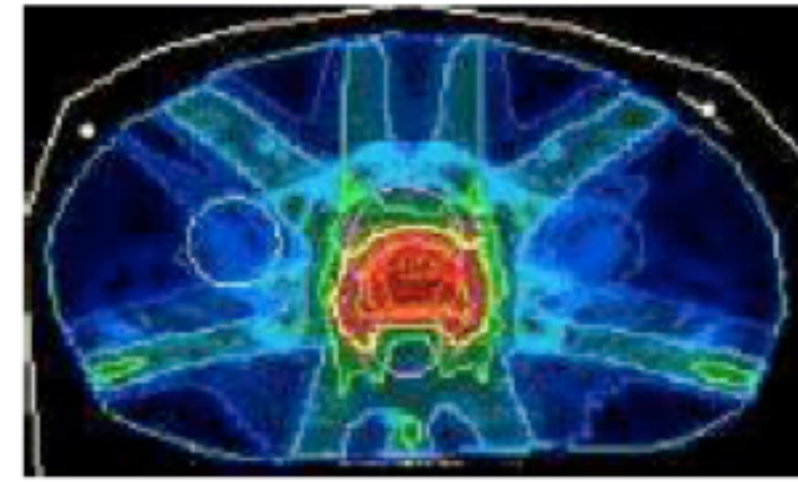




simulations of prostate cancer with 7 irradiation beams



250 MeV electrons



X rays IMRT

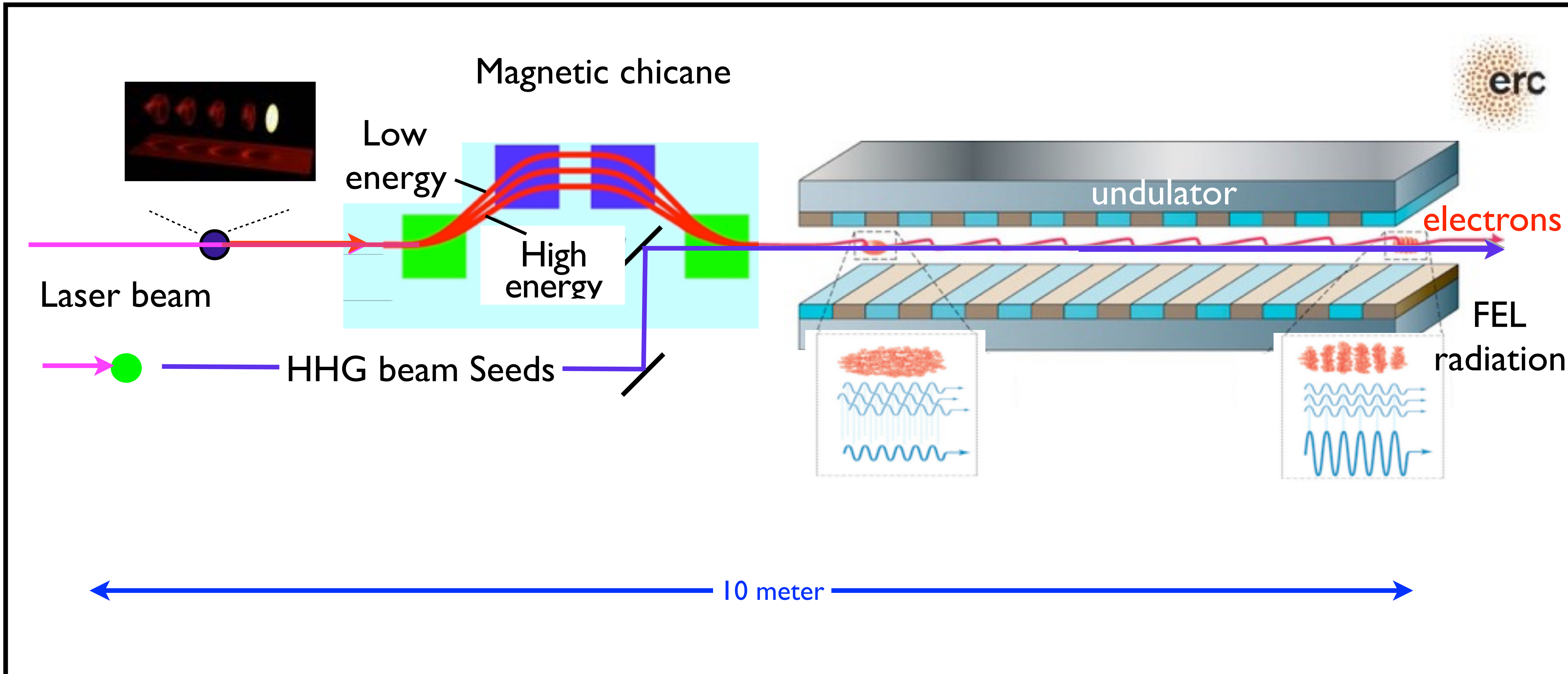
A comparison of dose deposition with 6 MeV X ray an improvement of the quality of a clinically approved prostate treatment plan. While the target coverage is the same or even slightly better for 250 MeV electrons compared to photons the dose sparing of sensitive structures is improved (up to 19%).

T. Fuchs *et al.* Phys. Med. Biol. **54**, 3315-3328 (2009), in coll. with DKFZ

Y. Glinec *et al.* Med. Phys. **33**, 1, 155-162 (2006)

O. Lundh *et al.*, Medical Physics **39**, 6 (2012)

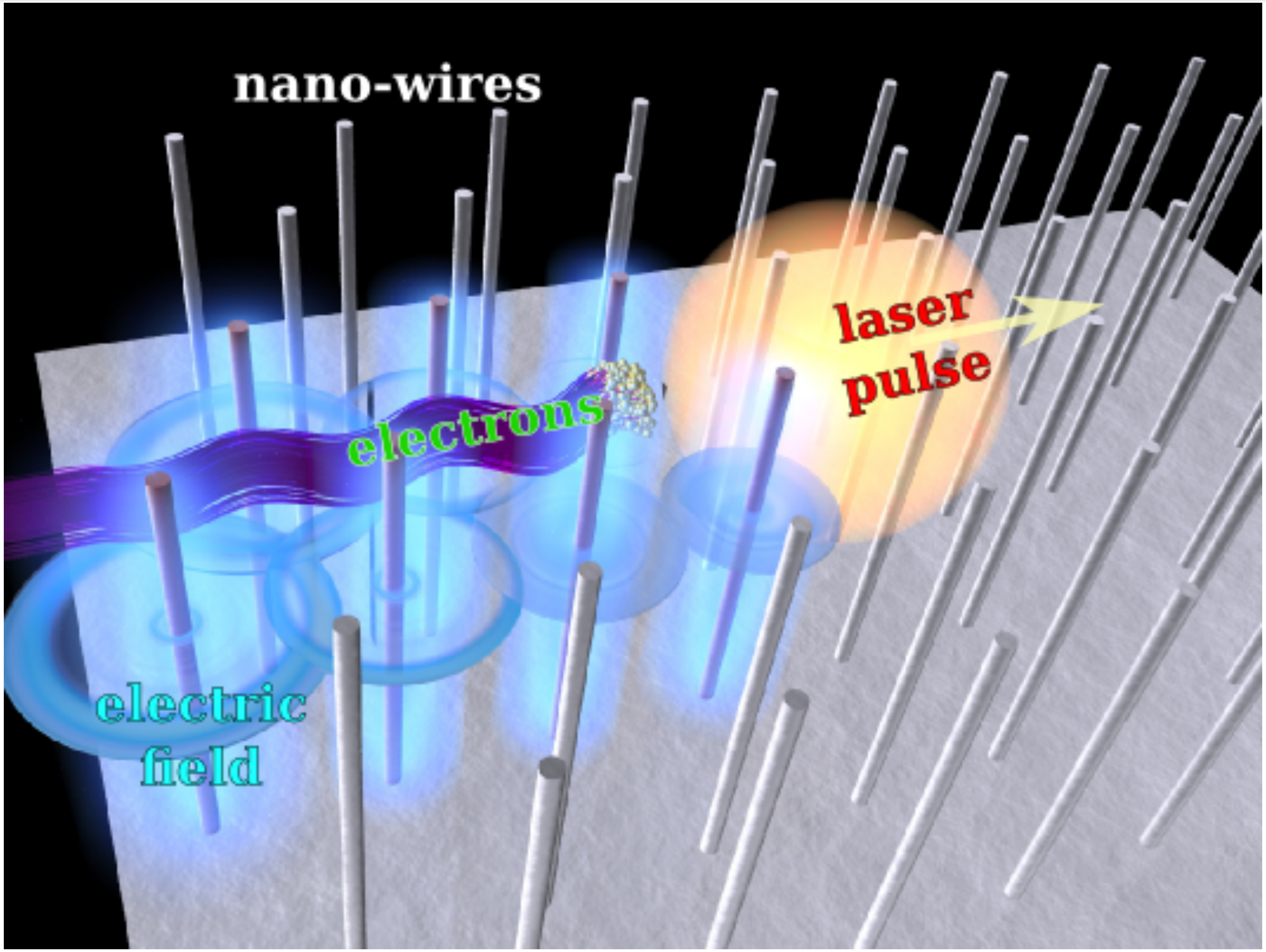
FEL experiment on Seeding mode with LPA



in collaboration with M.-E. Couprie from Soleil

M. E. Couprie *et al.*, Journal of Physics B : At. Mol. Opt. Phys. **47** 234001 (2014)
A. Loulergues *et al.*, NJP-102026 (2015)

Advanced concept for ultra compact X rays beam



I. Andriyash *et al.*, Nat. Communications, 5736 (2014)

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

Advanced concept for ultra compact X rays beam: plasma undulator

Varying electron energy

Energy 200 / 400 / 600 MeV

Undulator emission

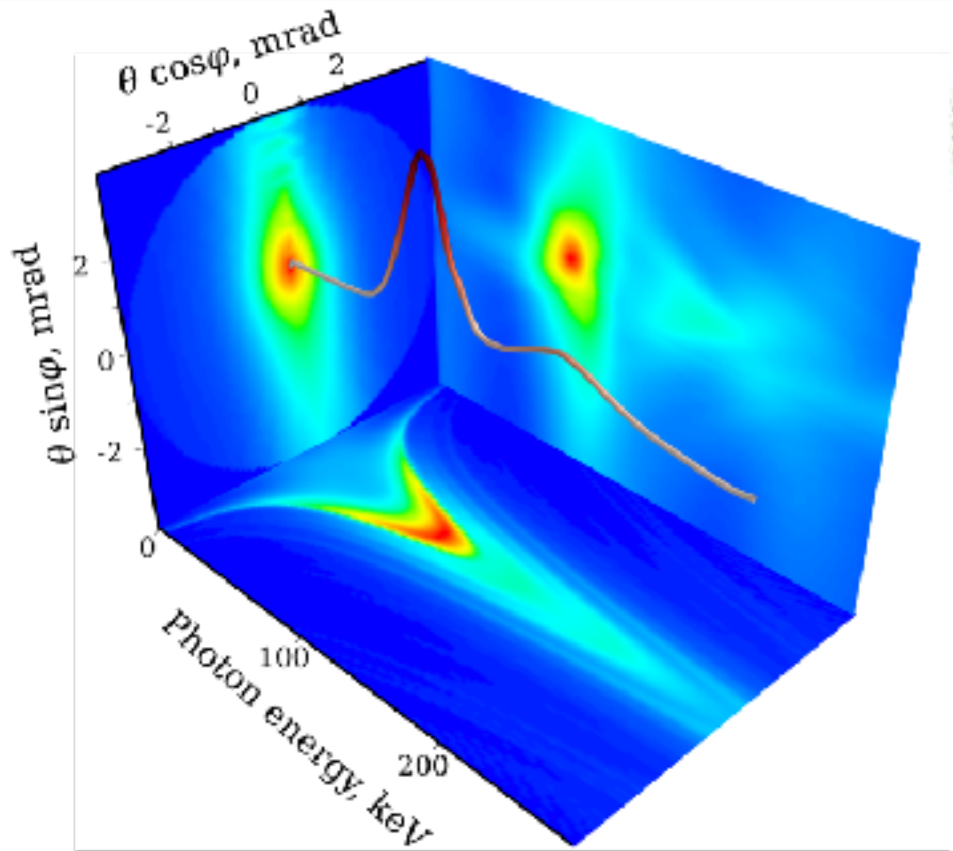
Photon energy 12 / 47 / 106 keV

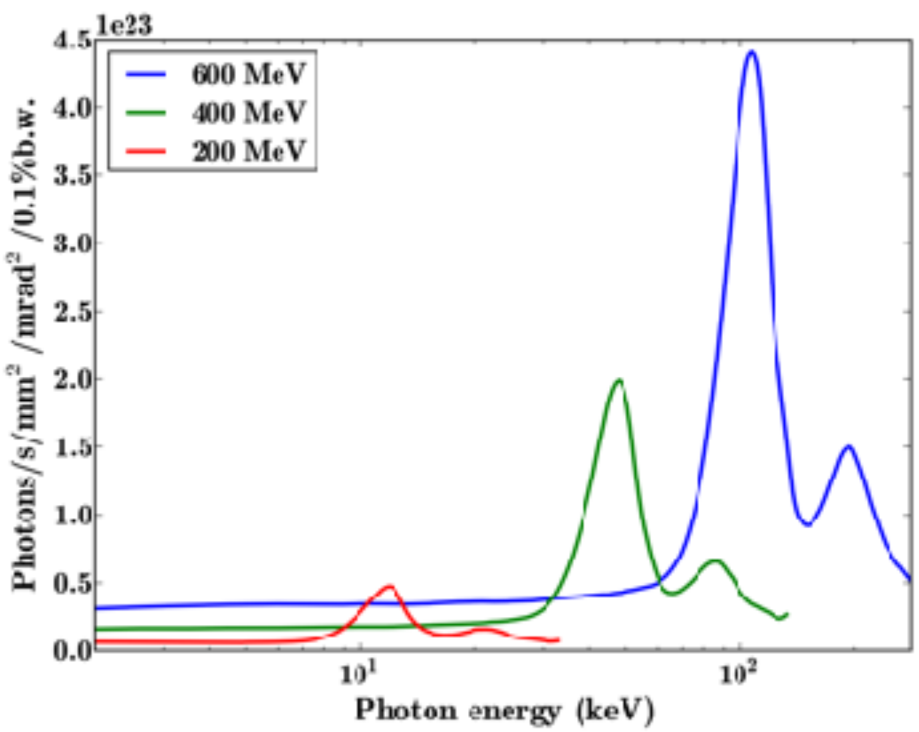
Brightness 0.5 / 2 / 4.5×10^{23}s.u.

Angular sizes 0.85×1.7 mrad

Laser plasma nanostructured SR source

- Quasi-monoenergetic collimated spectrum
- Tunability λ_u, ε_e
- Brightness ~ γ_b^2
- Source brightness level 10^{23} s.u.
- Interaction length ≲ 1 mm

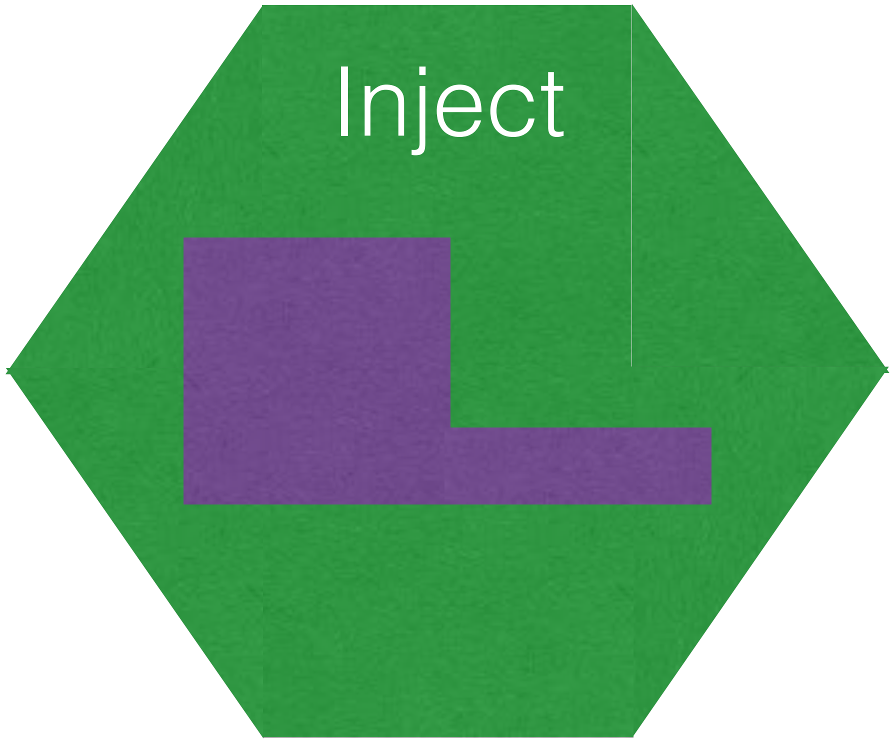




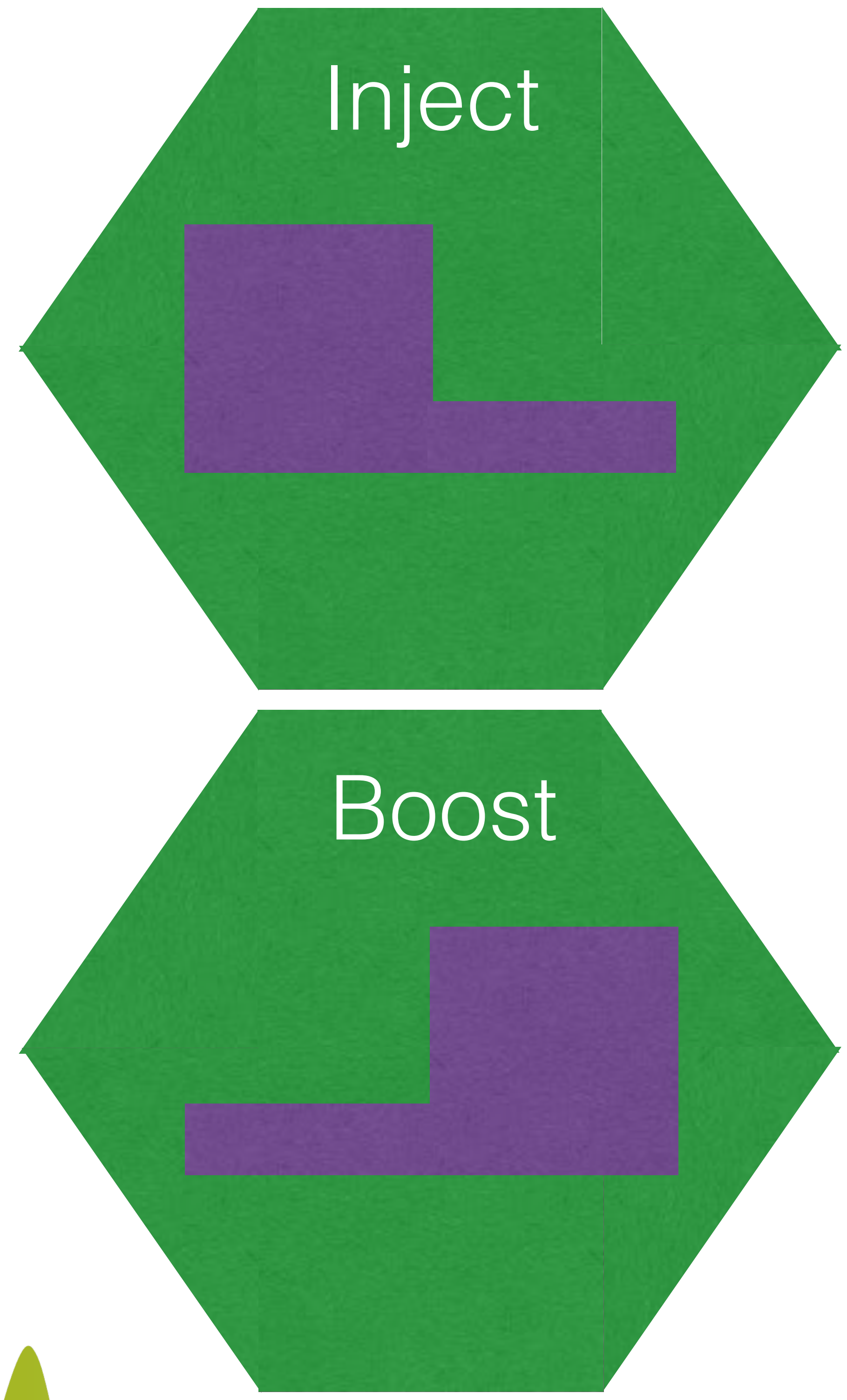
Laser Plasma Accelerators : Outline

- Introduction : context and motivations
- Injection in a density gradient
- Manipulating the longitudinal momentum
- Manipulating the transverse momentum
- Applications
- Conclusion and perspectives

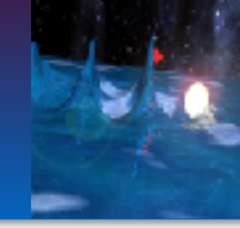
Simple plasma devices produced with a single laser pulse

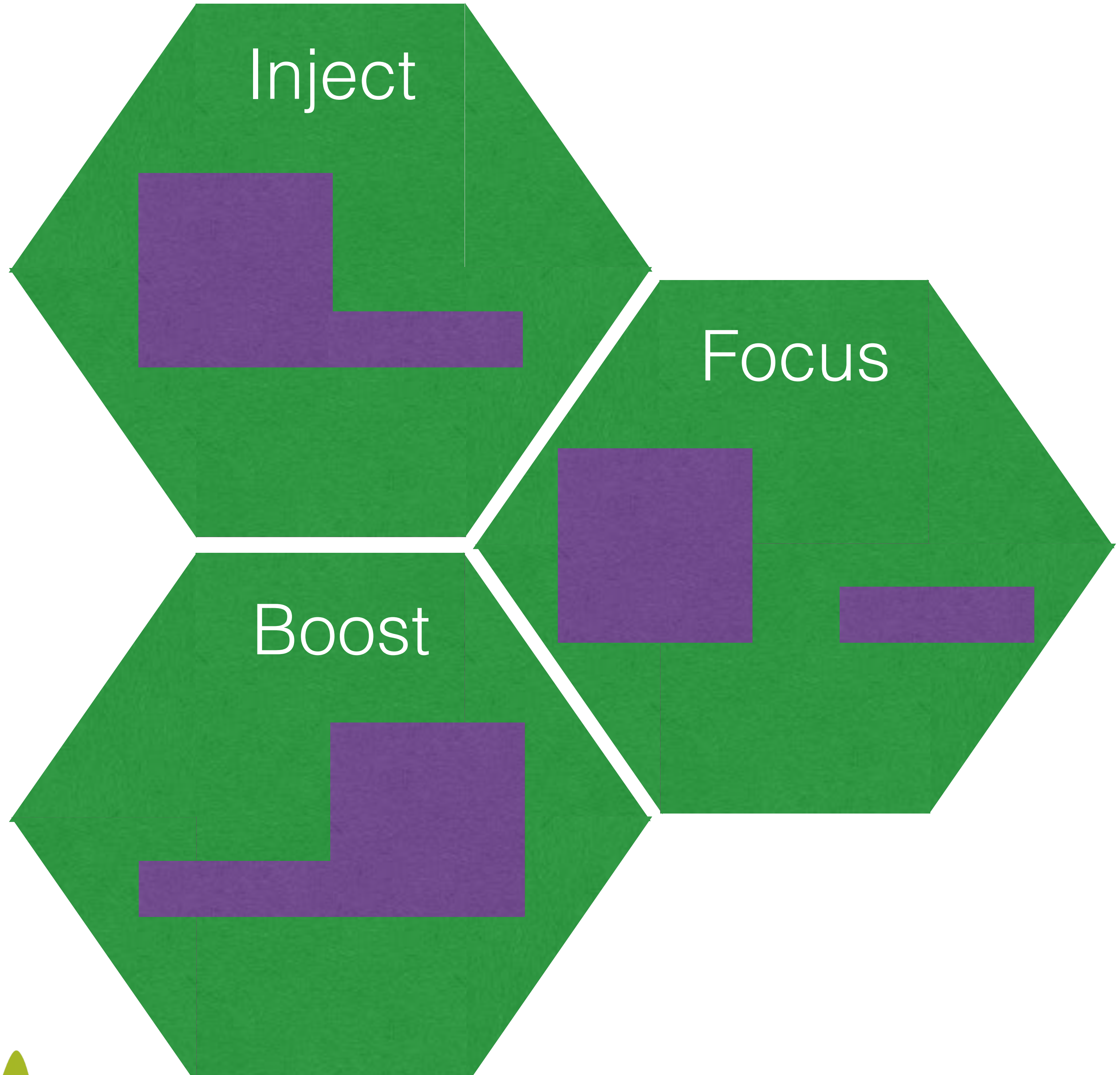


Simple plasma devices produced with a single laser pulse

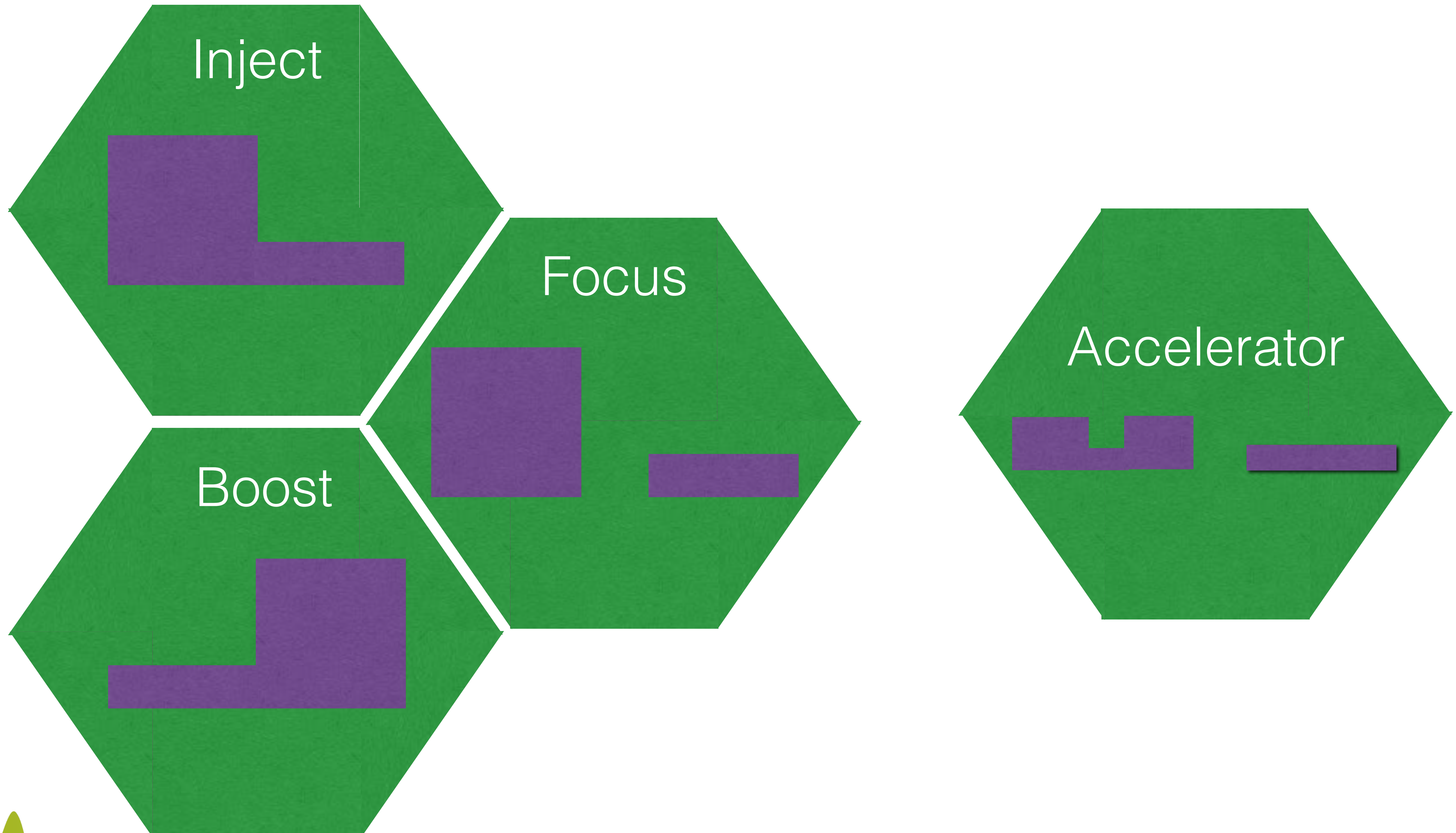


Simple plasma devices produced with a single laser pulse





Simple plasma devices produced with a single laser pulse



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.

As a consequence, 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.

Compact FEL based on LWFA is one very important challenge that has been identified by the community.

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], Andreas Dopp[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],

[1]LOA, Laboratoire d'Optique Appliquée, ENSTA ParisTech, CNRS, Ecole polytechnique, Université Paris-Saclay, France
[2]MPQ, Garching, Germany
[3]Lund Laser Center, Lund University, Lund, Sweden

Open positions for laser engineer and laser technician and for post-doc

ERC (Paris & X-five & XMED & VERSATILE),
Charpac/Laserlab3, CARE & ANAC2/Eucard1-2