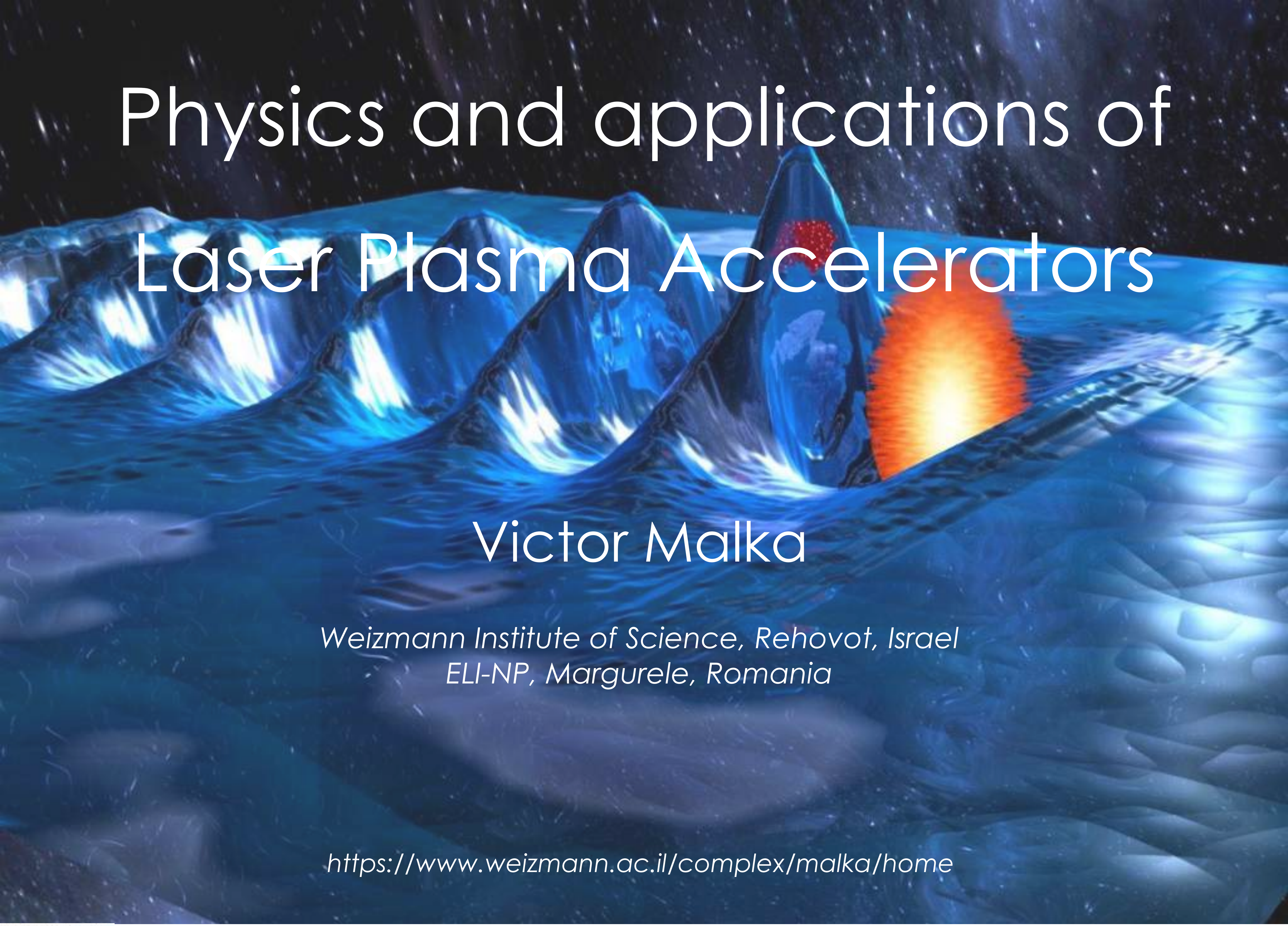

Physics and applications of Laser Plasma Accelerators

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https://www.weizmann.ac.il/complex/malka/home

Outline

- Part I : Motivation, basis and principle

- Part II : External and Self-Injection in Laser Wakefield

- Part III : High quality electron beams in LPA with the colliding pulses scheme

- Part IV : Applications, conclusion and perspectives

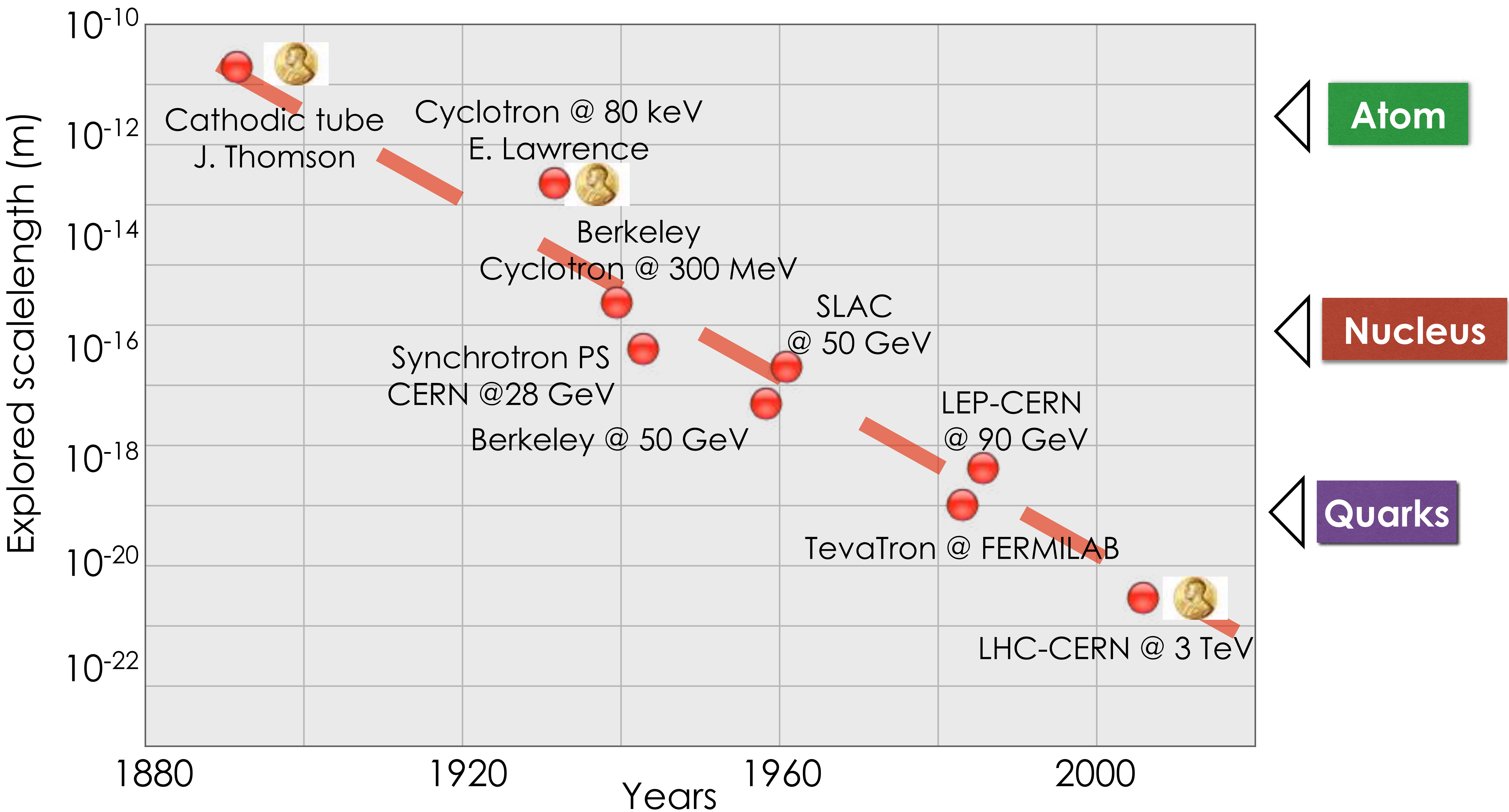
Part I : Motivation, basis and principle

- Introduction : context and motivations
- Electron in a laser field
- Laser driven plasma wave : theory
- Trapping Conditions

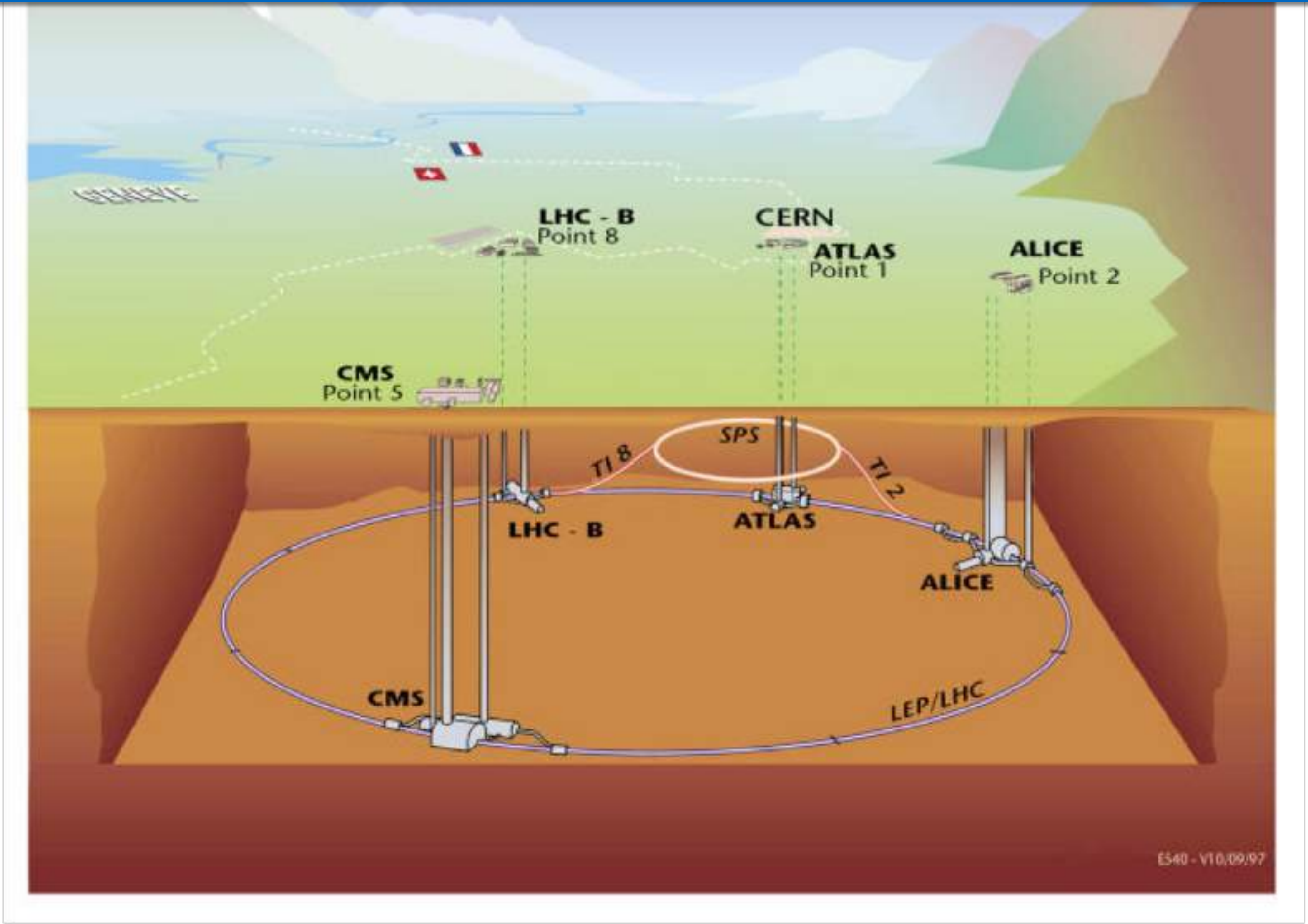
Accelerators: One century of exploration of the infinitively small







Overall view of LHC



9 km

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**	

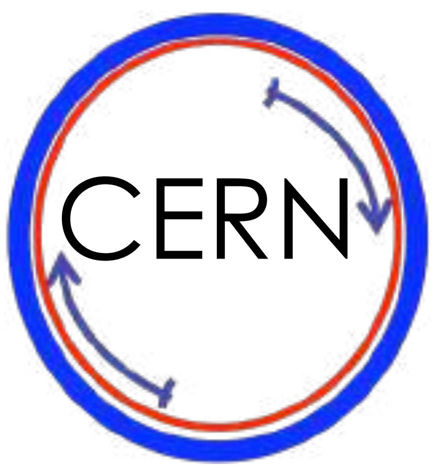
Plasma Accelerators : motivations

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

$R>R_{min}$ Synchrotron radiation

→ Energy ↗ → Length ↗ → Cost ↗

LHC
27 km



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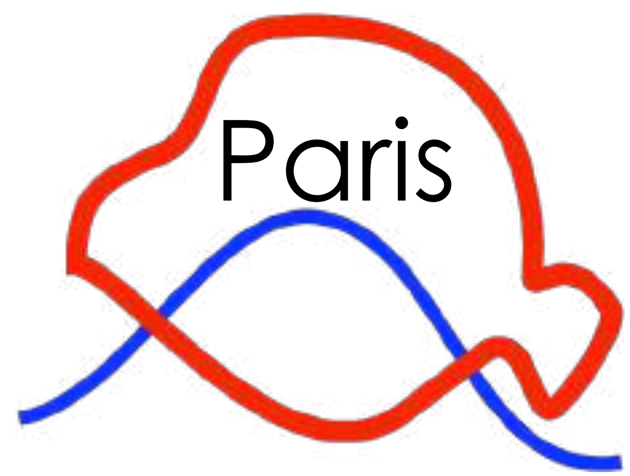


Circle road
34 km

→ New medium : the plasma

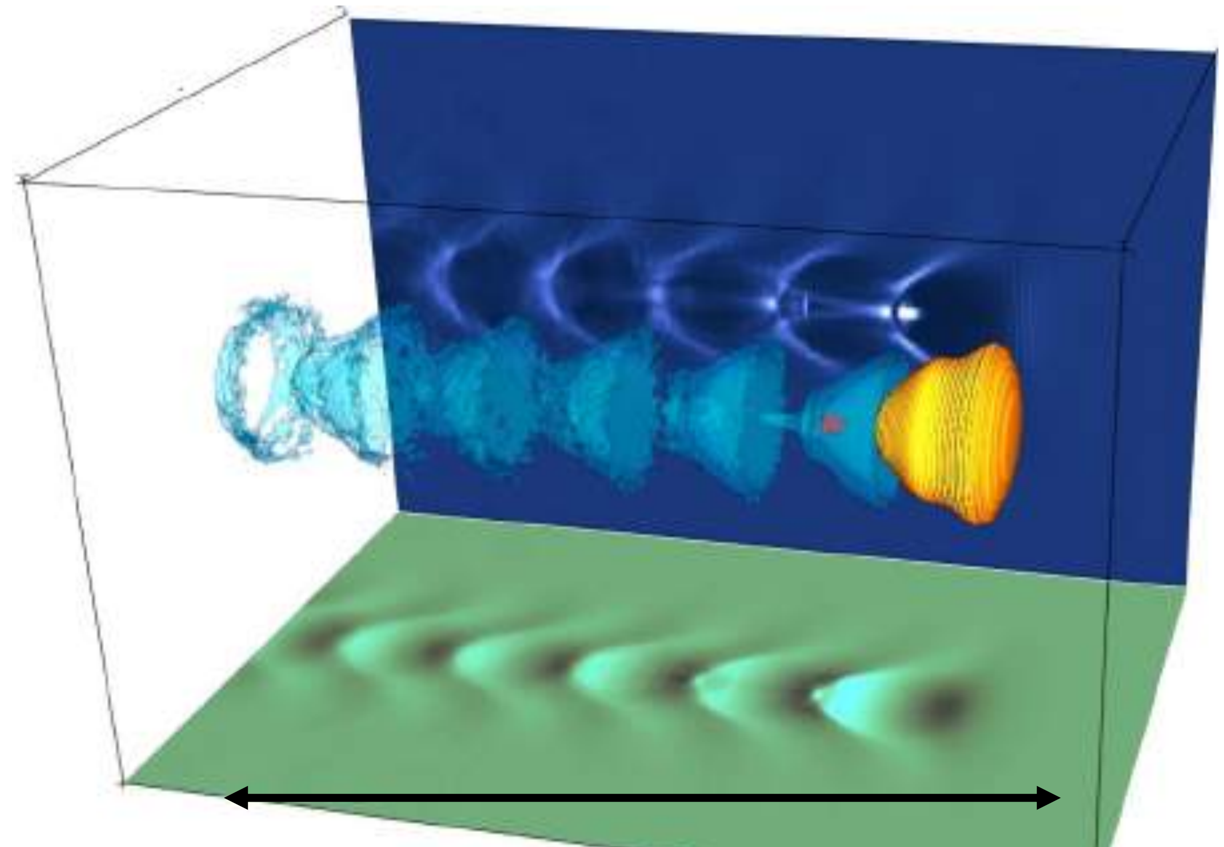
Compactness of Laser Plasma Accelerators

RF Cavity

1 m => 50 MeV Gain

Electric field < 100 MV/m

Plasma Cavity



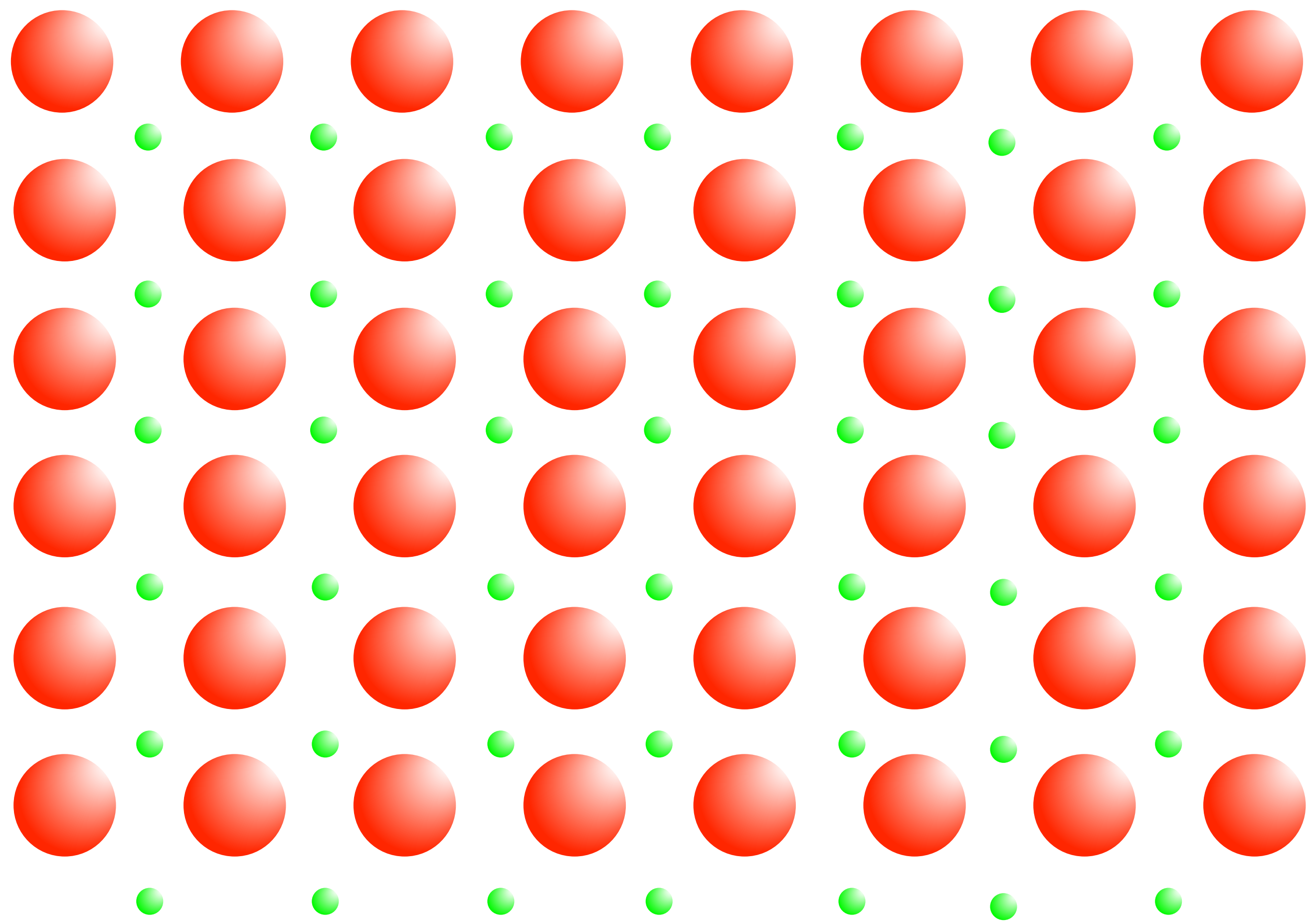
1mm => 100 MeV

Electric field > 100 GV/m

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

Why is a plasma useful ?

Plasma is an Ionized Medium => High Electric Fields



electrons plasma oscillation

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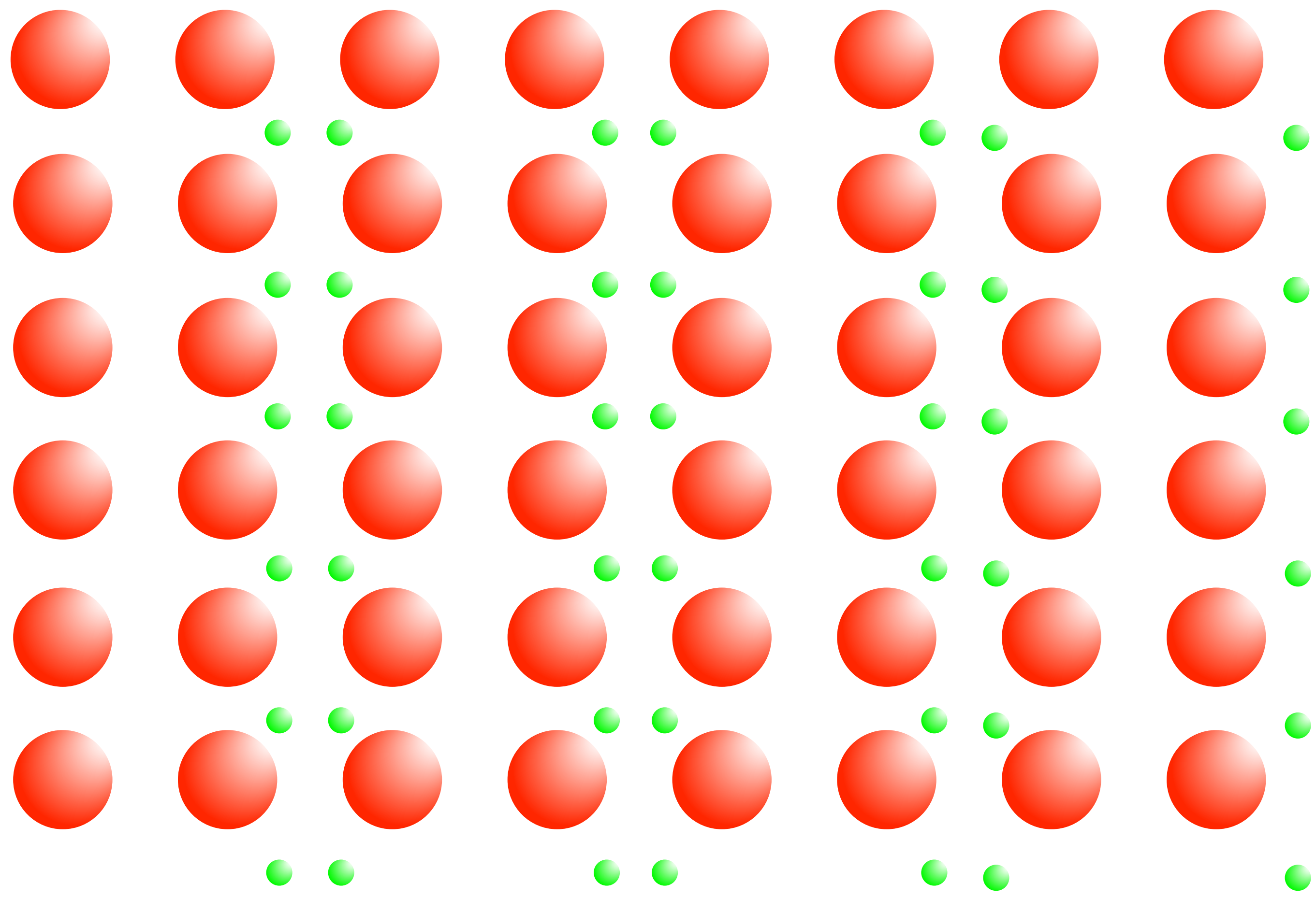
Plasma is an Ionized Medium => High Electric Fields



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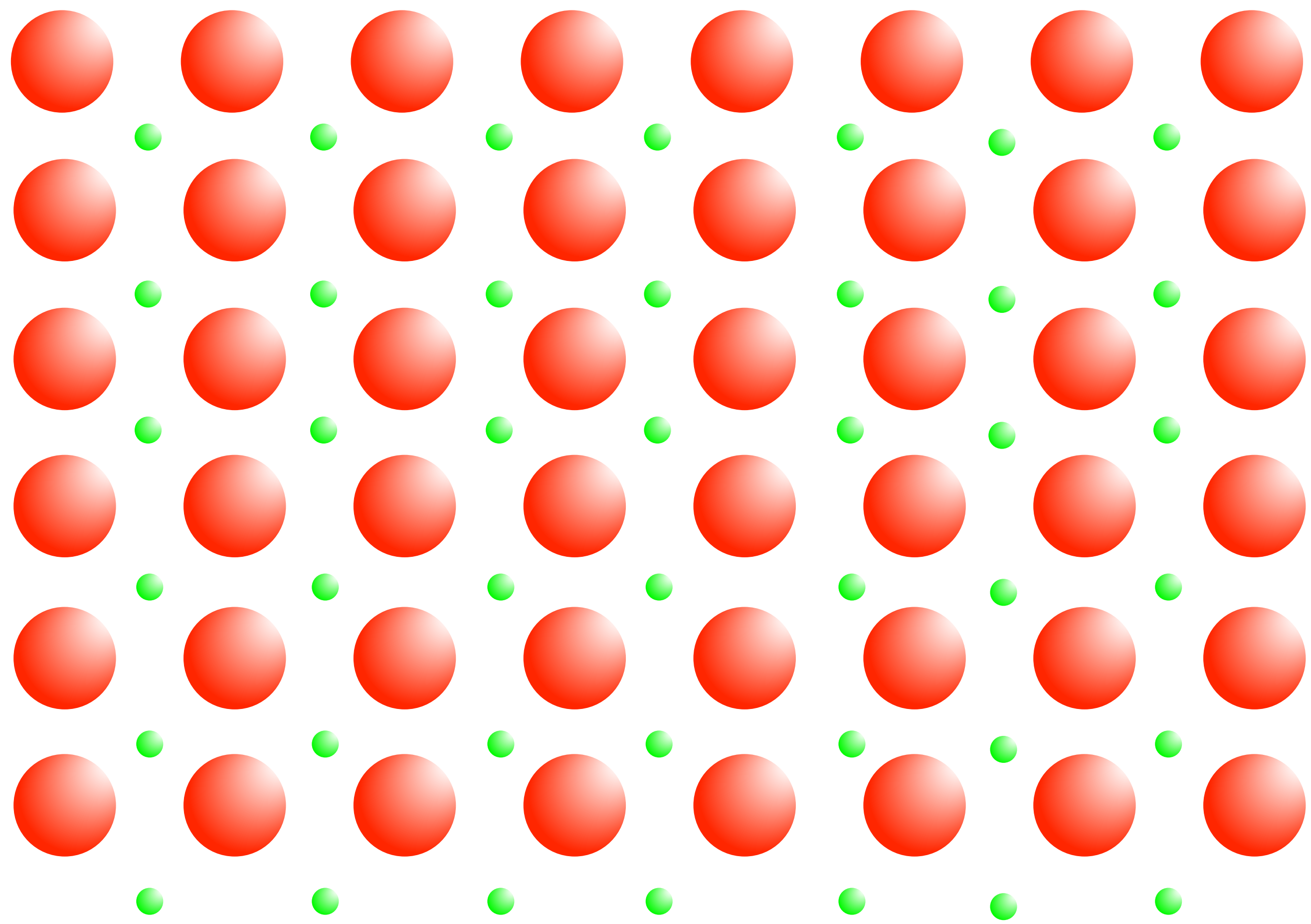

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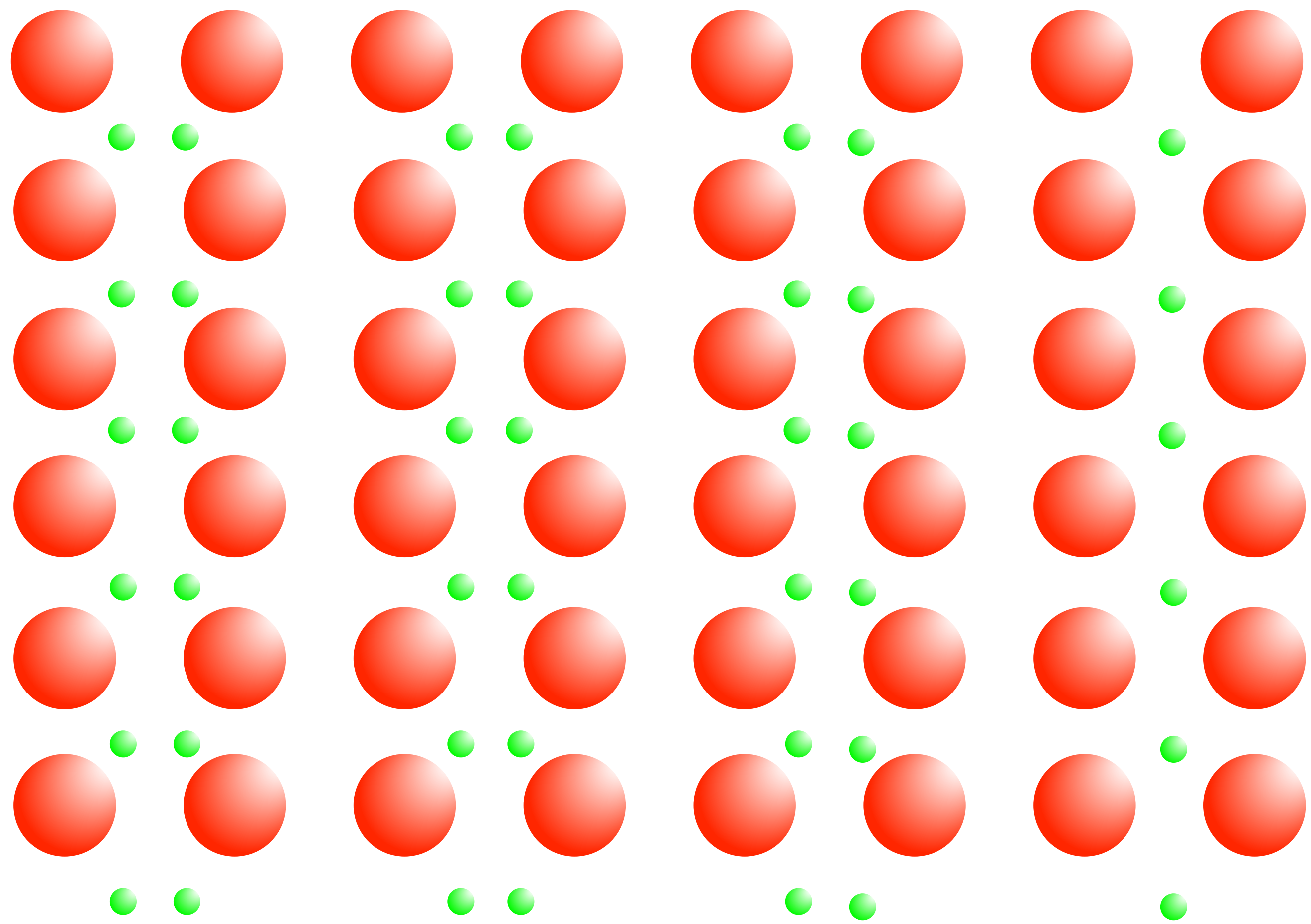

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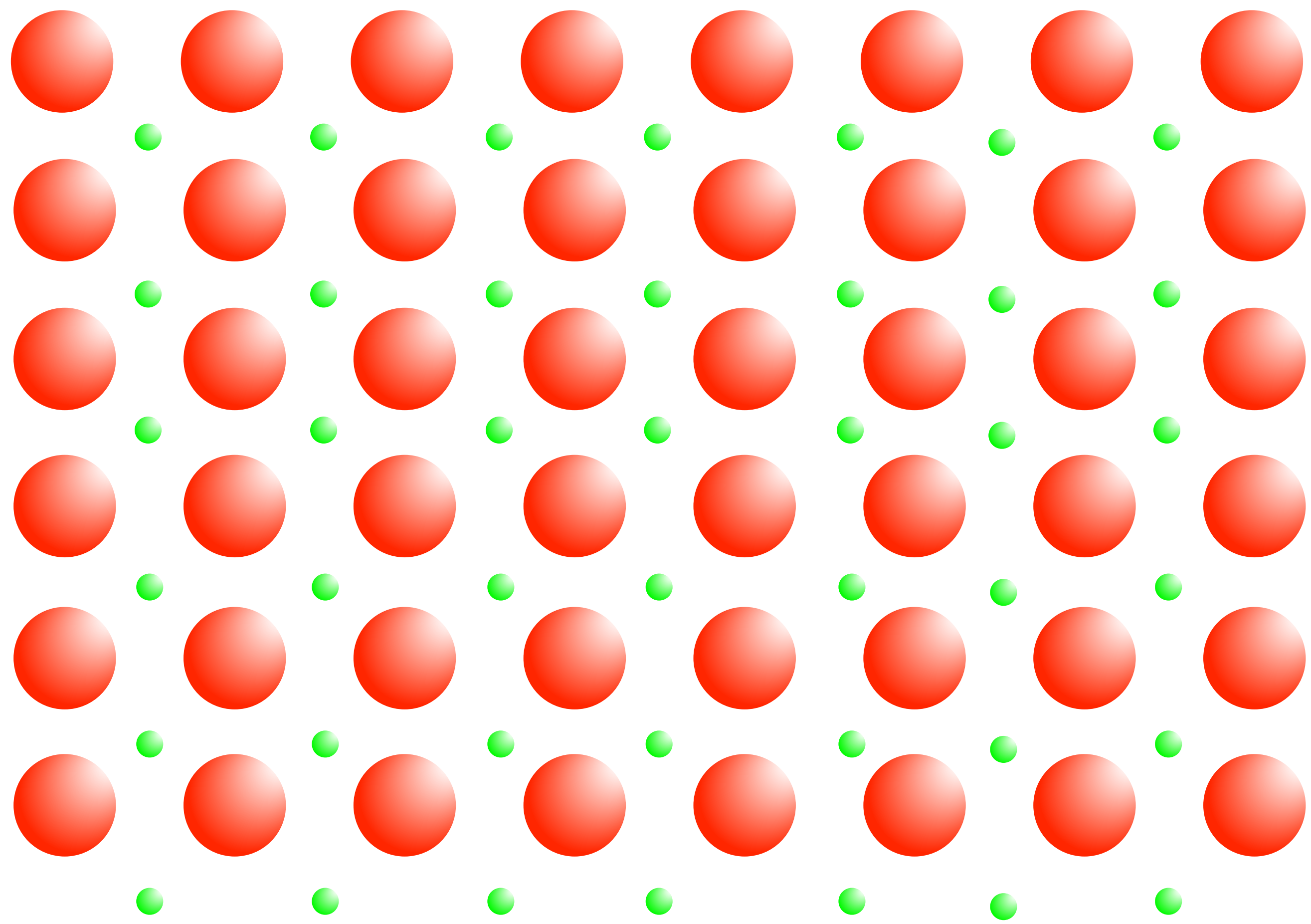

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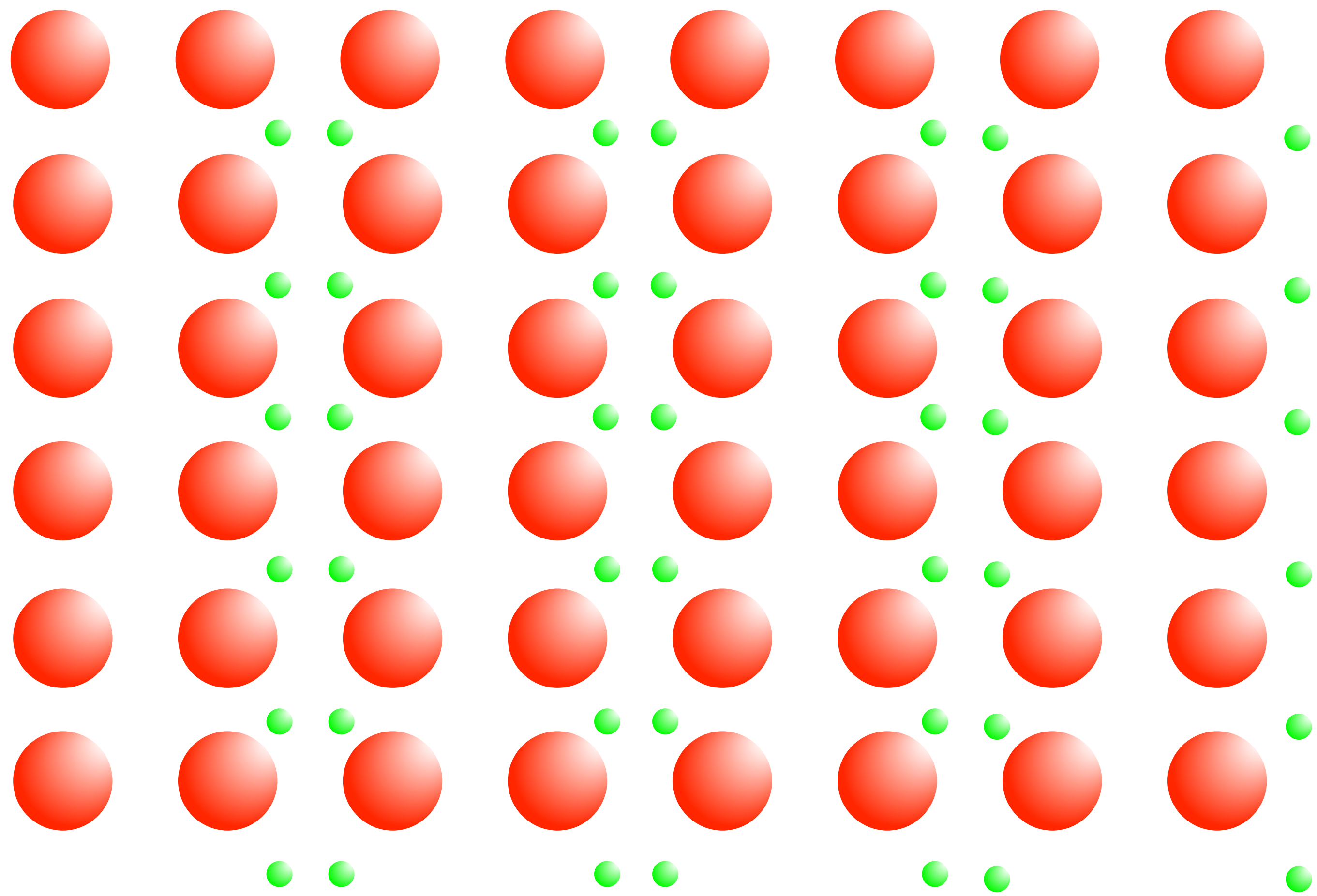

electrons plasma oscillation

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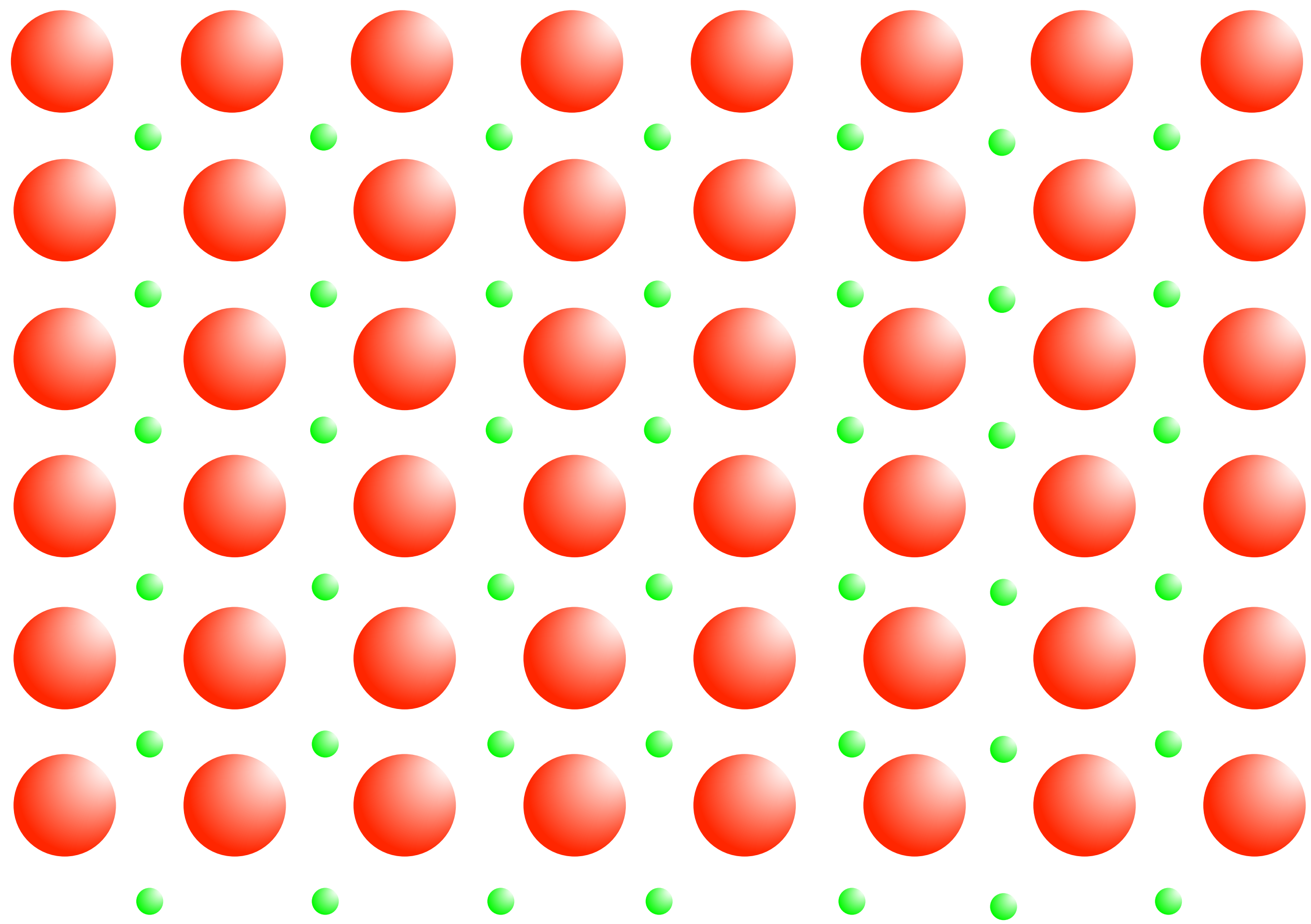
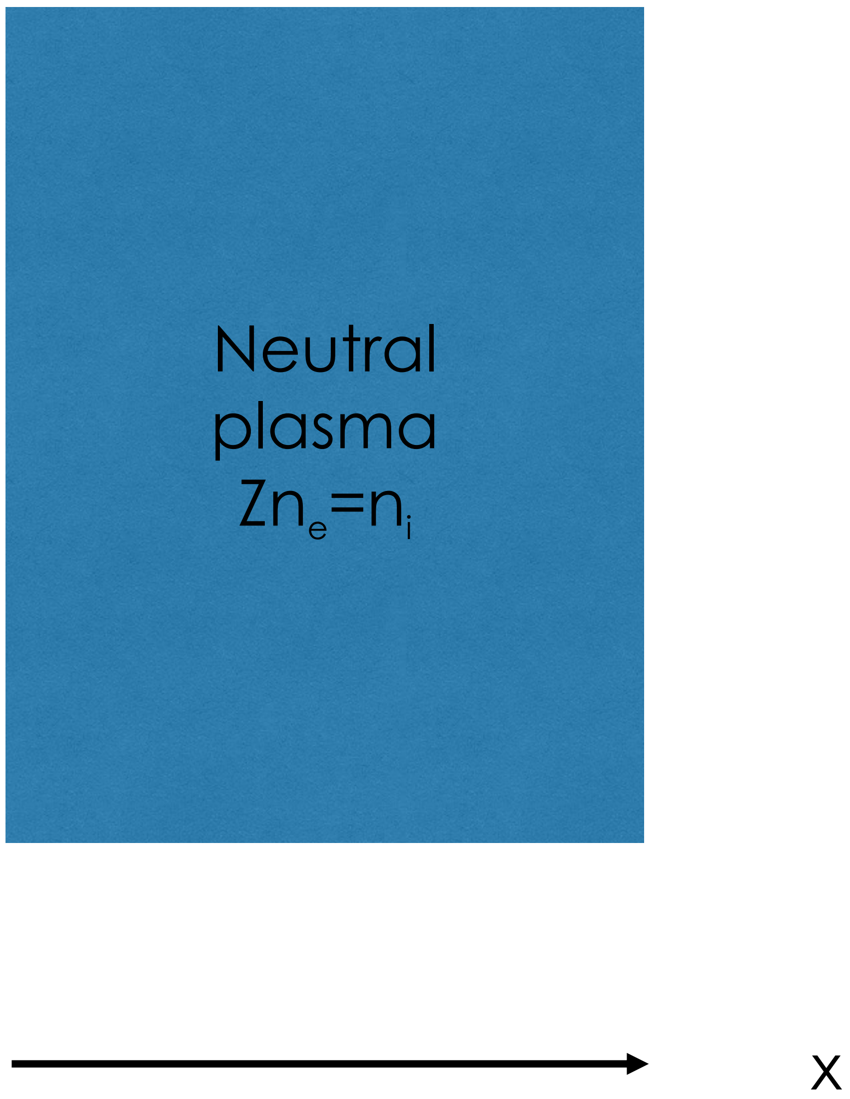
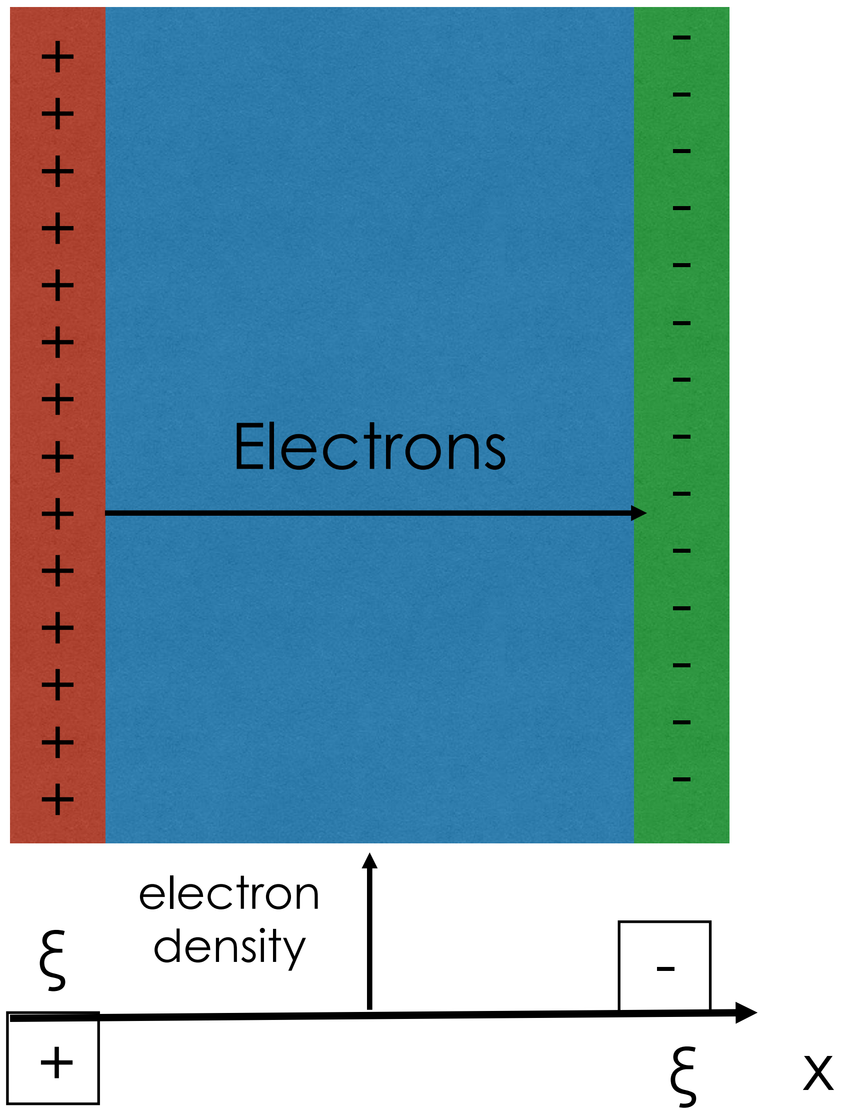


electrons plasma oscillation

The electron plasma frequency : ω_p



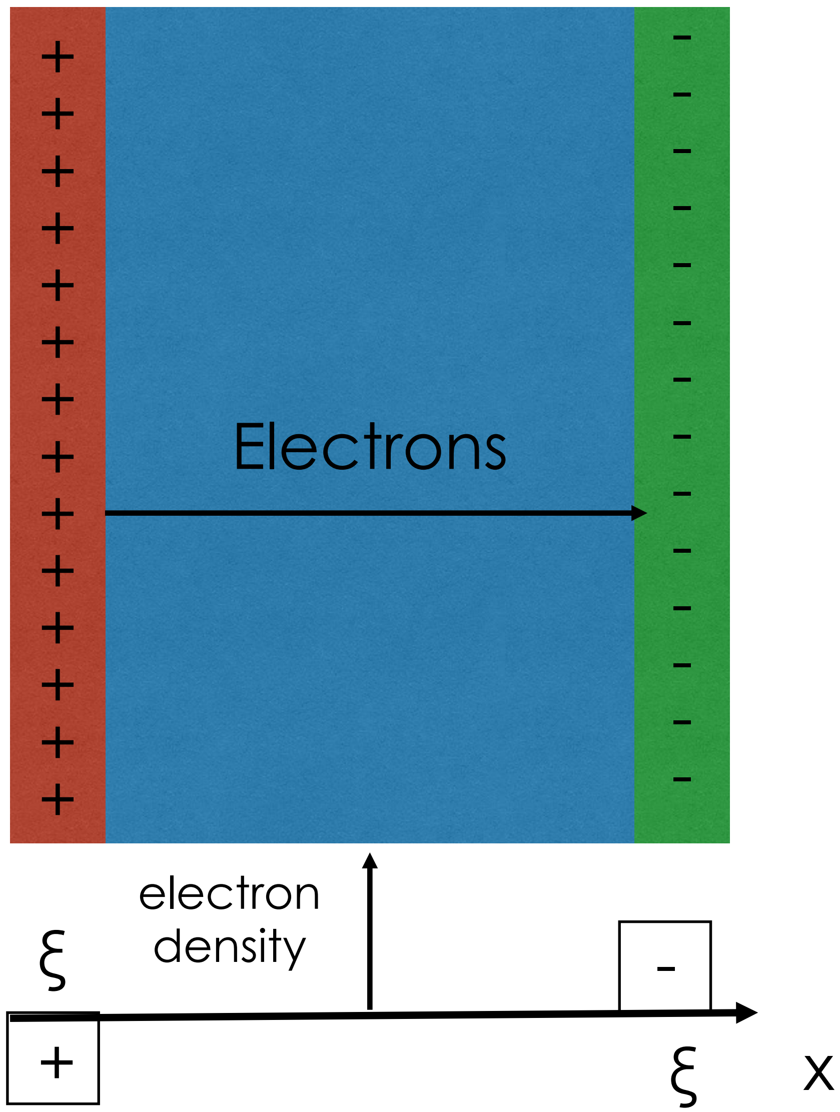
The electron plasma frequency : ω_p



$$E = \sigma/\varepsilon_0 = n_e \xi e/\varepsilon_0$$

$$F = qE$$

The electron plasma frequency : ω_p



$$E = \sigma/\varepsilon_0 = n_e \xi e/\varepsilon_0$$

$$F=qE$$

$$m_e d\xi^2/dt^2 = -eE$$

$$d\xi^2/dt^2 + (n_e e^2/m_e \varepsilon_0)\xi = 0$$

$$\omega_p = (n_e e^2/m_e \varepsilon_0)^{1/2}$$

V. I. Veksler, “Coherent Principle of Acceleration of Charged Particles.” *Proceedings of the CERN Symposium on High Energy Accelerators and Pion Physics*, vol. 1. Geneva, 1956. Pages 80–83.

1979 Relativistic plasma waves with Laser pulse

VOLUME 43, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 1979

Laser Electron Accelerator

T. Tajima and J. M. Dawson
Department of Physics, University of California, Los Angeles, California 90024
(Received 9 March 1979)

An intense electromagnetic pulse can create a weak of plasma oscillations through the action of the nonlinear ponderomotive force. Electrons trapped in the wake can be accelerated to high energy. Existing glass lasers of power density 10^{18}W/cm^2 shone on plasmas of densities 10^{18} cm^{-3} can yield gigaelectronvolts of electron energy per centimeter of acceleration distance. This acceleration mechanism is demonstrated through computer simulation. Applications to accelerators and pulsers are examined.

Such a wake is most effectively generated if the length of the electromagnetic wave packet is half the wavelength of the plasma waves in the wake:

$$L_t = \lambda_w/2 = \pi c/\omega_p \,. \tag{2}$$

=> Laser wakefield

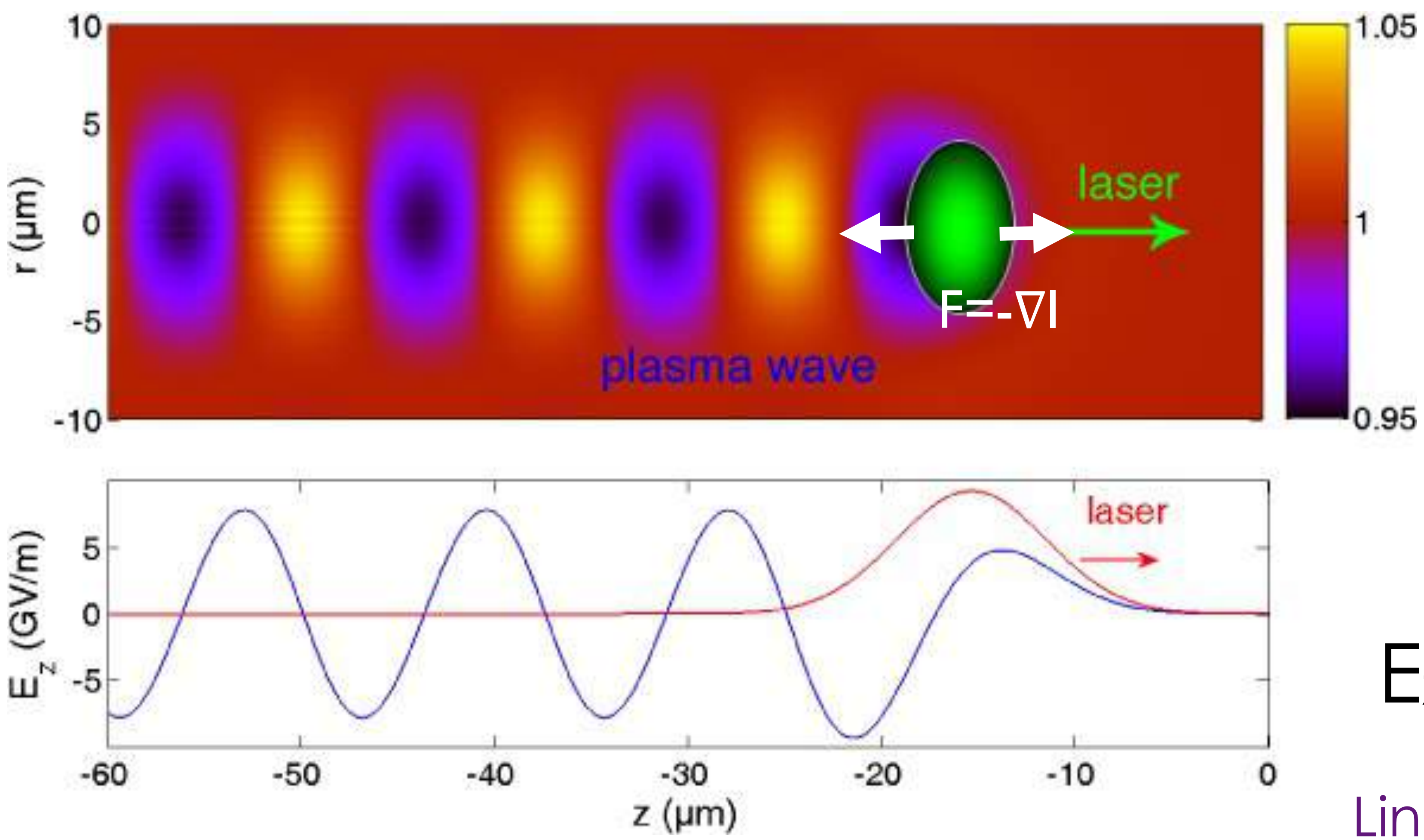
An alternative way of exciting the plasmon is to inject two laser beams with slightly different frequencies (with frequency difference $\Delta\omega \sim \omega_p$) so that the beat distance of the packet becomes $2\pi c/\omega_p$. The mechanism for generating the wakes

=> Laser beatwave

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

E_z (GV/m) ≈ $\delta n/n \times \sqrt{n}$

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)

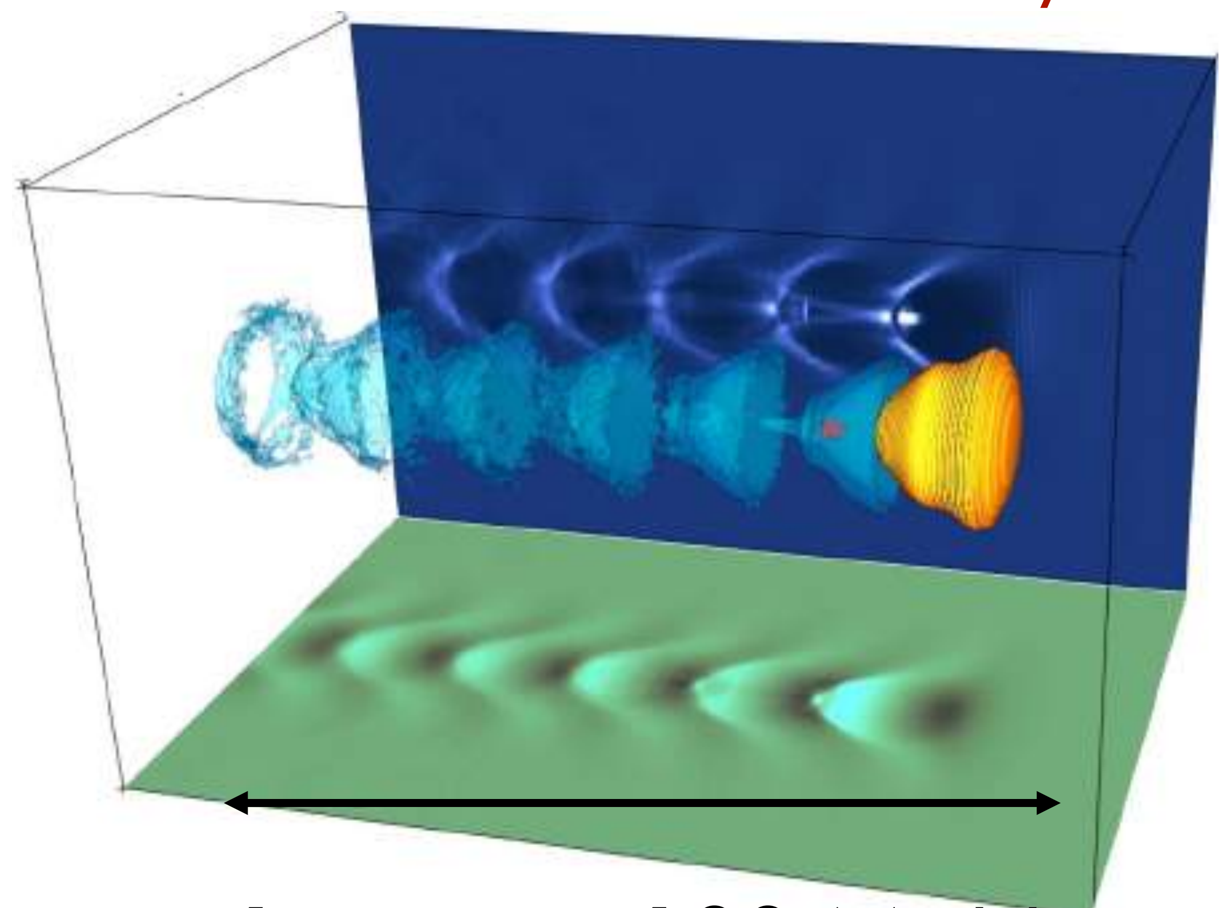
The non-linear wakefield regime : 100’s GV/m electric field

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)

Part I : Motivation, basis and principle

- Introduction : context and motivations
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Laser intensity: definition

The laser electromagnetic wave is given by :

$$\mathbf{E_L}(z,t) = E_0/2.exp[-i(k_0 z - w_0 t)]\mathbf{e_x} + c.c.$$

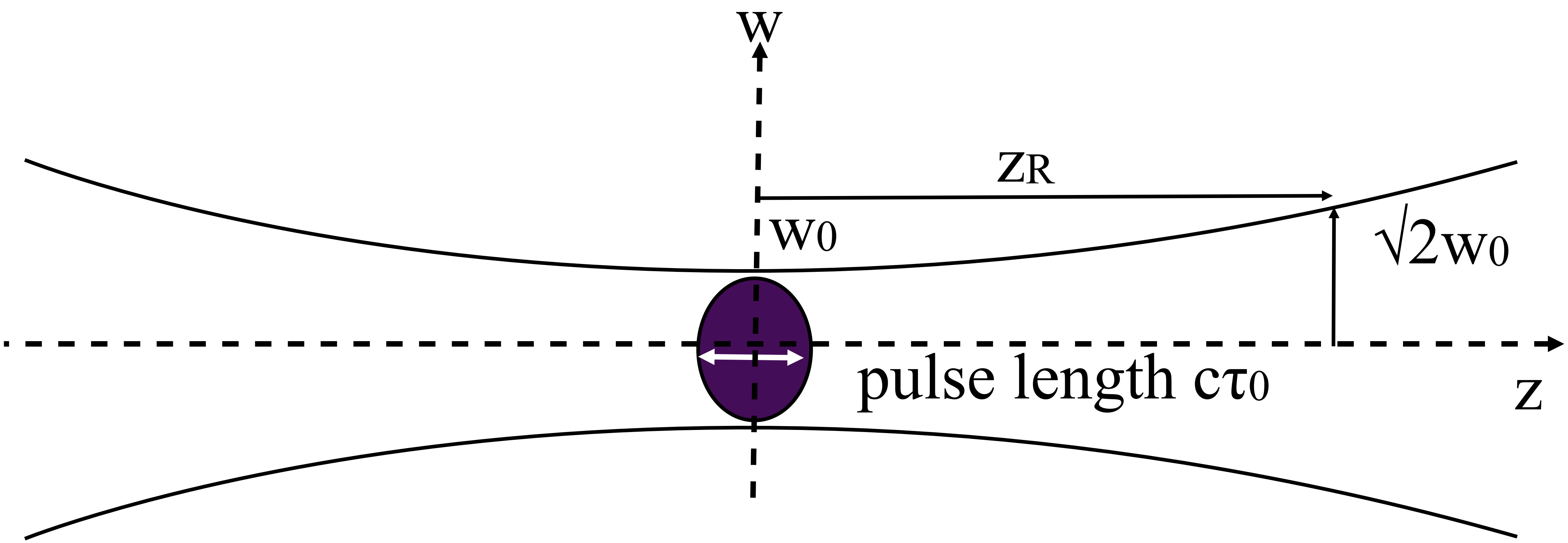
where k_0 is the laser wave vector and ω_0 the laser pulsation

Peak intensity: $$I_0 = \frac{1}{\mu_0}\langle \mathbf{E} \wedge \mathbf{B} \rangle = \frac{c\epsilon_0 E_0^2}{2}$$

For a gaussian beam at focus: $$I(r,t) = I_0 exp[-\frac{2r^2}{w_0^2}]exp[-\frac{4ln2t^2}{\tau_0^2}]$$

With peak intensity : $$I_0 = \frac{2E}{\pi w_0^2 \tau_0}$$

Propagation of gaussian beam



Rayleigh length for which I_0 changes to $I_0/2$: $z_R = \pi w_0^2/\lambda_0$

example : $\lambda_0 = 1\mu m$, $w_0 = 20\mu m$ => $z_R = 1.2$ mm

Relativistic quantities & equation of motion

Lorentz factor : $\gamma = (1 - \frac{v^2}{c^2})^{-1/2}$

$$\gamma = \sqrt{1 + \frac{p^2}{m^2c^2}}$$

Momentum : $\mathbf{p} = m\gamma\mathbf{v}$

Energy : $E = \gamma m_e c^2$ Kinetic energy : $E_{kin} = mc^2(\gamma - 1)$

Equation of motion : $\frac{d\mathbf{p}}{dt} = -e(\mathbf{E}_L + \mathbf{v} \wedge \mathbf{B_L})$

For $v \ll c$ $$\frac{dv_{osc}}{dt} = -e\frac{E_L}{m_e} = \frac{e}{m_e}\frac{\partial A}{\partial t}$$

$$\frac{v_{osc}}{c} = a$$

$$a_0 = 0.85[I_{18}(W/cm^2)\lambda(\mu m)^2]^{1/2}$$

$mc^2 = 0.511MeV$ for electrons

The ponderomotive force :

First, linearize the equation of motion $\frac{d\mathbf{p}}{dt} = -e(\mathbf{E_L} + \mathbf{v} \wedge \mathbf{B_L})$

$\mathbf{v} = \mathbf{v_l} + \mathbf{v_{nl}}$ with $\mathbf{v_{nl}} << \mathbf{v_l}$ $\quad \nabla \wedge \mathbf{E_L} = -\frac{\partial \mathbf{B_L}}{\partial t}$

The second order gives $\frac{\partial \mathbf{v_{nl}}}{\partial t} = -(\mathbf{v_l}\nabla)\mathbf{v_l} - \frac{e}{m_e}(\mathbf{v_l} \wedge \mathbf{B_L})$

by averaging over an optical cycle, one obtains : $m_e \frac{\partial < \mathbf{v_{nl}} >_t}{\partial t} = -\frac{\nabla I}{2cn_c} = \mathbf{F_p}$

$\mathbf{F_p}$ is called the ponderomotive force. This force repels charged particles from regions where the laser intensity gradient is large (whatever the sign of the charge). This ponderomotive force derives from a ponderomotive potential which is written as follow:

$$\phi_p = \frac{I_L}{2cn_c} = \frac{e^2 E_L^2}{4m_e\omega_0^2}$$

$$(\mathbf{v}.\nabla)\mathbf{v} + \mathbf{v} \wedge (\nabla \wedge \mathbf{v}) = \frac{\nabla v^2}{2}$$

For an intensity of $10^{19} W/cm^2$ @1micron, the ponderomotive potential is 1 MeV

Relativistic quantities & equation of motion

Equation of motion : $\dfrac{d\mathbf{p}}{dt} = -e(\mathbf{E}_L + \mathbf{v} \wedge \mathbf{B_L})$

Maxwell's equation $\mathbf{B} = \nabla \wedge \mathbf{A} \qquad \mathbf{E} = -\dfrac{\partial A}{\partial t}$

Equation of motion : $\dfrac{d(\mathbf{p} - e\mathbf{A})}{dt} = -e(\nabla \mathbf{A}).\mathbf{v}$

Direction of propagation of the e.m. wave along x, $\mathbf{A}$ is normal to x

$$\frac{d(\mathbf{p}_\perp - e\mathbf{A})}{dt} = 0 \qquad \text{and} \qquad \frac{dp_x}{dt} = -e\mathbf{v}_\perp . \frac{\partial \mathbf{A}}{\partial x}$$

$$\frac{d\gamma mc^2}{dt} = \frac{e^2}{2m\gamma}\frac{\partial A^2}{\partial t} \quad \textit{(1)} \qquad \text{and} \qquad \frac{dp_x}{dt} = -\frac{e^2}{2m\gamma}\frac{\partial A^2}{\partial x} \quad \textit{(2)}$$

(1) - c(2) =>* $\gamma = 1 + \dfrac{p_x}{mc}$

$\mathbf{v} \wedge (\nabla \wedge \mathbf{A}) = (\nabla \mathbf{A}).\mathbf{v} - (\mathbf{v}.\nabla)\mathbf{A}$ $(\nabla \mathbf{A}).\mathbf{v}$ being the sommation on the same index of $v_j(\partial_i A^j)\mathbf{e}_i$

Relativistic quantities & equation of motion

$$\frac{p_x}{mc} = \frac{1}{2}(\frac{e\mathbf{A}}{mc})^2$$

$$\gamma = 1 + \frac{1}{2}(\frac{e\mathbf{A}}{mc})^2$$

$$a_0 = \frac{e|\mathbf{A}|}{mc} = \frac{eE_0}{mc\omega_0} \qquad a_0 = (\frac{e^2}{2\pi^2\epsilon_0 m^2 c^5} I_0 \lambda^2)^{1/2} = 0.85(I_{18}\lambda^2_{\mu m})^{1/2}$$

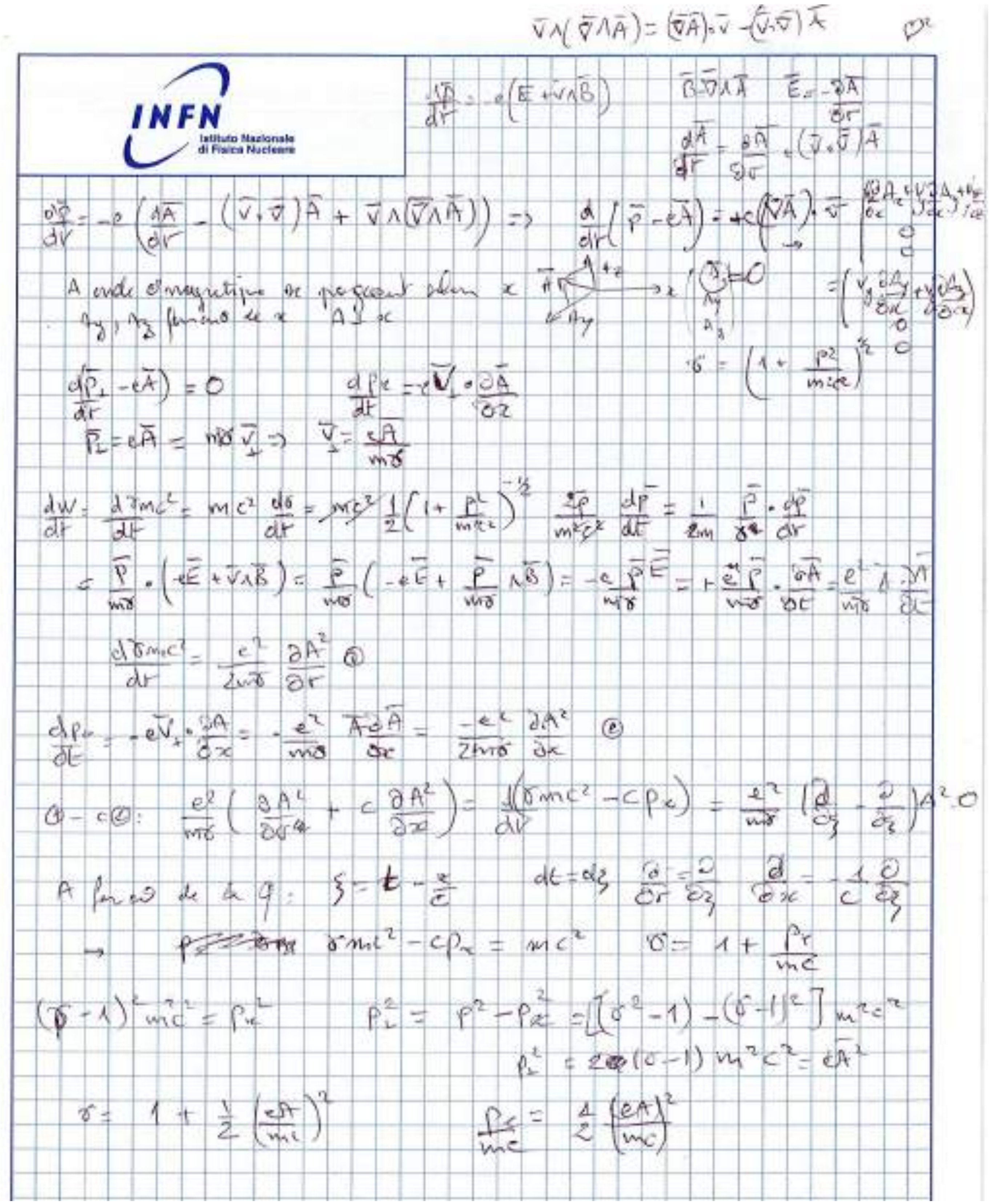
$$\theta = \arctan(\frac{p_\perp}{p_x}) = \arctan(2/a) = \arctan(\sqrt{\frac{2}{\gamma - 1}})$$

Classical regime, $a << 1$, then $p_x << p_\perp << 1$, non relativistic transversale motion

Relativistic regime, $a > 1$, electron motion has a longitudinal component, that originales from the Lorentz force

Ultra-relativistic regime, $a >> 1, p_x >> p_\perp >> 1$, motion mainly longitudinal

Relativistic quantities & equation of motion



$$\vec{v}\wedge(\vec{\nabla}\wedge\vec{A}) = (\vec{\nabla}\vec{A})\cdot\vec{v} - (\vec{v}\cdot\vec{\nabla})\vec{A}$$

INFN Istituto Nazionale di Fisica Nucleare

$$\frac{d\vec{p}}{dt} = -e(\vec{E} + \vec{v}\wedge\vec{B}) \qquad \vec{B} = \vec{\nabla}\wedge\vec{A} \qquad \vec{E} = -\frac{\partial\vec{A}}{\partial t}$$

$$\frac{d\vec{A}}{dt} = \frac{\partial\vec{A}}{\partial t} + (\vec{v}\cdot\vec{\nabla})\vec{A}$$

$$\frac{d\vec{p}}{dt} = -e\left(\frac{d\vec{A}}{dt} - (\vec{v}\cdot\vec{\nabla})\vec{A} + \vec{v}\wedge(\vec{\nabla}\wedge\vec{A})\right) \Rightarrow \frac{d}{dt}(\vec{p} - e\vec{A}) = +e(\vec{\nabla}\vec{A})\cdot\vec{v}$$

A onde électromagnétique se propageant selon x; A_y, A_z fonction de x; $A \perp x$

$$\vec{A} = \begin{pmatrix} 0 \\ A_y \\ A_z \end{pmatrix} \qquad = \left(v_y\frac{\partial A_y}{\partial x} + v_z\frac{\partial A_z}{\partial x}\right), 0, 0$$

$$\gamma = \left(1 + \frac{p^2}{m^2c^2}\right)^{1/2}$$

$$\frac{d}{dt}(\vec{p}_\perp - e\vec{A}) = 0 \qquad \frac{dp_x}{dt} = -e\vec{v}_\perp\cdot\frac{\partial\vec{A}}{\partial x}$$

$$\vec{p}_\perp = e\vec{A} = m\gamma\vec{v}_\perp \Rightarrow \vec{v}_\perp = \frac{e\vec{A}}{m\gamma}$$

$$\frac{dW}{dt} = \frac{d\gamma mc^2}{dt} = mc^2\frac{d\gamma}{dt} = mc^2\frac{1}{2}\left(1 + \frac{p^2}{m^2c^2}\right)^{-1/2}\frac{2\vec{p}}{m^2c^2}\frac{d\vec{p}}{dt} = \frac{1}{m}\frac{\vec{p}}{\gamma}\cdot\frac{d\vec{p}}{dt}$$

$$= \frac{\vec{p}}{m\gamma}\cdot(-e\vec{E} + \vec{v}\wedge\vec{B}) = \frac{\vec{p}}{m\gamma}\left(-e\vec{E} + \frac{\vec{p}}{m\gamma}\wedge\vec{B}\right) = -\frac{e}{m\gamma}\vec{p}\,\vec{E} = +\frac{e\vec{p}}{m\gamma}\cdot\frac{\partial\vec{A}}{\partial t} = \frac{e^2}{m\gamma}\vec{A}\cdot\frac{\partial\vec{A}}{\partial t}$$

$$\frac{d\gamma mc^2}{dt} = \frac{e^2}{2m\gamma}\frac{\partial A^2}{\partial t} \quad (a)$$

$$\frac{dp_x}{dt} = -e\vec{v}_\perp\cdot\frac{\partial\vec{A}}{\partial x} = -\frac{e^2}{m\gamma}\vec{A}\cdot\frac{\partial\vec{A}}{\partial x} = \frac{-e^2}{2m\gamma}\frac{\partial A^2}{\partial x} \quad (b)$$

$$(a) - c(b): \quad \frac{e^2}{m\gamma}\left(\frac{\partial A^2}{\partial t} + c\frac{\partial A^2}{\partial x}\right) = \frac{d}{dt}(\gamma mc^2 - cp_x) = \frac{e^2}{m\gamma}\left(\frac{\partial}{\partial\xi} - \frac{\partial}{\partial\xi}\right)A^2 = 0$$

A fonction de la φ: $\xi = t - \frac{x}{c}$ $\quad dt = d\xi \quad \frac{\partial}{\partial t} = \frac{\partial}{\partial\xi} \quad \frac{\partial}{\partial x} = -\frac{1}{c}\frac{\partial}{\partial\xi}$

$$\rightarrow \gamma mc^2 - cp_x = mc^2 \qquad \gamma = 1 + \frac{p_x}{mc}$$

$$(\gamma - 1)^2 m^2c^2 = p_x^2 \qquad p_\perp^2 = p^2 - p_x^2 = [(\gamma^2 - 1) - (\gamma - 1)^2]\,m^2c^2$$

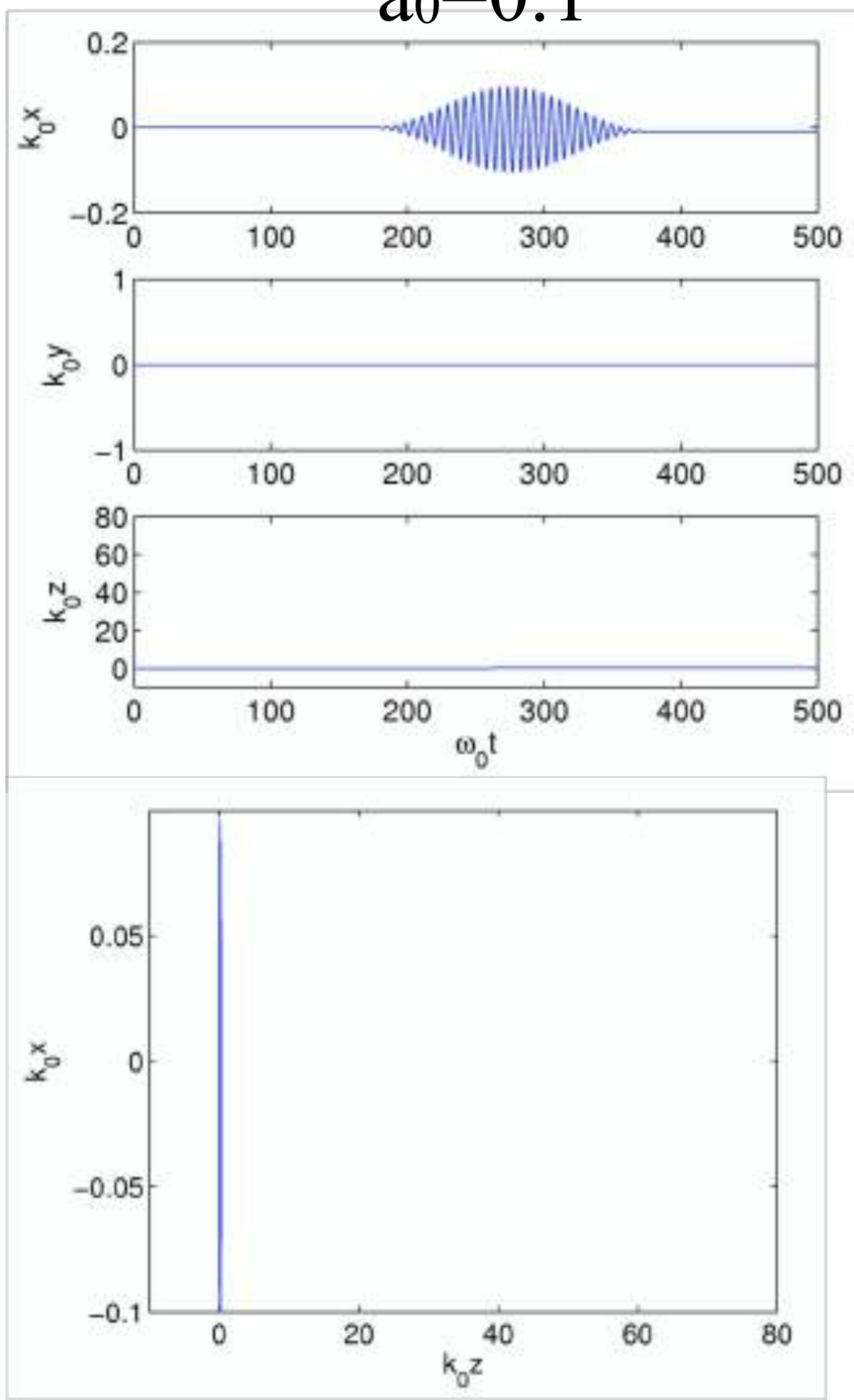
$$p_\perp^2 = 2(\gamma - 1)\,m^2c^2 = e\vec{A}^2$$

$$\gamma = 1 + \frac{1}{2}\left(\frac{eA}{mc}\right)^2 \qquad \frac{p_x}{mc} = \frac{1}{2}\left(\frac{eA}{mc}\right)^2$$

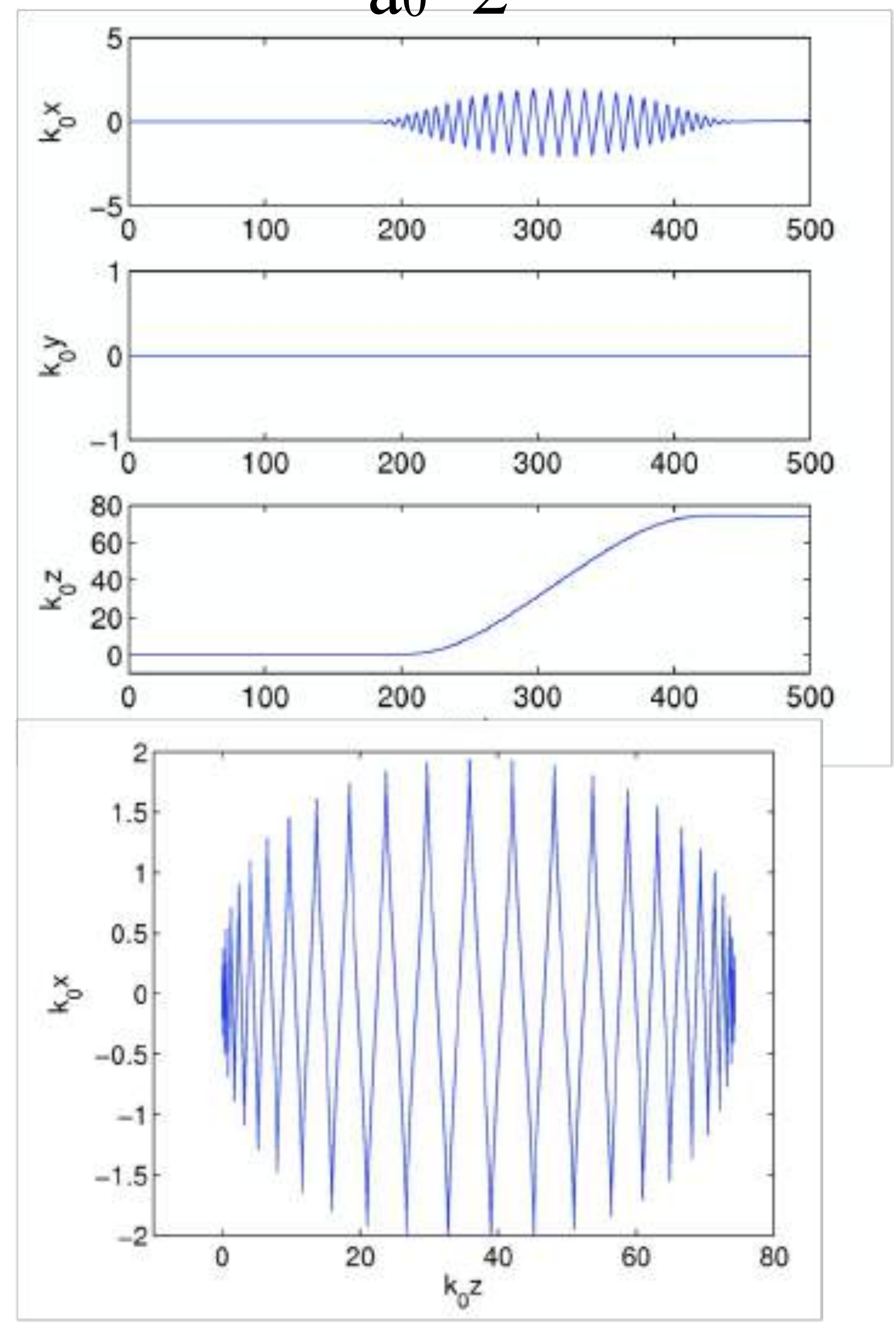
Electron motion in intense fields :

Laser linear polarization along x and propagating along z : $\frac{d\mathbf{p}}{dt} = -e(\mathbf{E}_L + \mathbf{v} \wedge \mathbf{B_L})$

$a_0=0.1$



$a_0=2$



Part I : Motivation, basis and principle

- Introduction : context and motivations
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Fluid model : hypothesis & beams definitions

- Ions are immobile : $\tau_{laser} << 1/\omega_{pi}$
- Plasma is a fluid of electrons : n(**r**,t), v(**r**,t)
- Plasma is cold : $v_{osc} >> v_{th}$
- Plasma is underdense : $\omega_p << \omega_0$
- Laser field : $\mathbf{a} = a(r,z,t)cos(k_0 z - \omega_0 t)\mathbf{e_x}$
- Envelop : $a^2(r,\zeta) = a_0^2 exp(-\zeta^2/L_0^2)$ with $\zeta = z - v_g t$
- Particle beam : $n_b(r,\zeta') = n_{b0} exp(-\zeta'^2/L_0^2) exp(-r^2/\sigma_b^2)$

  with $\zeta' = z - v_b t$

Poisson's equation : general case

$$\nabla.\mathbf{E} = \frac{\rho}{\epsilon_0} \qquad \rho = -e(n - n_0) + qn_b \text{ with q=-1 for an electron beam}$$

In addition, this fields can be written in terms of potentials :

$$\mathbf{E} = -\nabla\Phi - \frac{\partial \mathbf{A}}{\partial t} \qquad \mathbf{B} = \nabla \wedge \mathbf{A}$$

Coulomb gauge so that $\nabla.\mathbf{A} = 0$

$$\nabla^2\Phi = \frac{e}{\epsilon_0}(n + n_b - n_0)$$

Finally, one obtains the general Poisson's equation :

$$\nabla^2\Phi = \frac{en_0}{\epsilon_0}(\frac{\delta n}{n_0} + \frac{n_b}{n_0})$$

Fluid equation :

Conservation equation

$$\frac{\partial n}{\partial t} + \nabla . n\mathbf{v} = 0$$

Equation of motion for fluid electrons

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v}.\nabla)\mathbf{v} = -\frac{e}{m_e}(\mathbf{E} + \mathbf{v} \wedge \mathbf{B})$$

Which can be rewritten with « **L** » laser - high frequency :

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v}.\nabla)\mathbf{v} = -\frac{e}{m_e}(\mathbf{E_L} + \mathbf{v} \wedge \mathbf{B_L} - \nabla\Phi)$$

Fluid equation : general case

We now linearize the conservation equation in order to have the system of equations:

$$\frac{\partial \delta n}{\partial t} + n_0 \nabla.\mathbf{v} = 0$$

Equation of motion for fluid electrons

$$\frac{\partial \mathbf{v}}{\partial t} = -c^2 \nabla \frac{a^2}{4} + \frac{e}{m_e} \nabla \Phi \qquad \nabla^2 \Phi = \frac{e n_0}{\epsilon_0} (\frac{\delta n}{n_0} + \frac{n_b}{n_0})$$

Which gives :

$$(\frac{\partial^2}{\partial t^2} + \omega_p^2) \frac{\delta n}{n_0} = c^2 \nabla^2 \frac{a^2}{4} - \omega_p^2 \frac{n_b}{n_0}$$

Fluid equation : general case

General equation :

$$(\frac{\partial^2}{\partial t^2}+\omega_p^2)\frac{\delta n}{n_0}=c^2\nabla^2\frac{a^2}{4}-\omega_p^2\frac{n_b}{n_0}$$

The potential is given by :

$$\phi = e\Phi/m_e c^2 \qquad \nabla^2\phi = k_p^2\delta n/n_0$$

Which gives for laser only : $$(\frac{\partial^2}{\partial t^2}+\omega_p^2)\phi=\omega_p^2\frac{a^2}{4}$$

Flowing window : in the laser frame

The laser driver moves at the velocity of light (a is a function of $\zeta = z - v_g t$), so it is practical to change variables in order to follow the laser pulse according to : $\tau = t$ and $\zeta = z - v_g t$.

$$\frac{\partial}{\partial t} = \frac{\partial}{\partial \tau} - v_g \frac{\partial}{\partial \zeta}$$

$$\frac{\partial}{\partial z} = \frac{\partial}{\partial \zeta}$$

$$\frac{\partial^2}{\partial t^2} = \frac{\partial^2}{\partial \tau^2} + v_g^2 \frac{\partial^2}{\partial \zeta^2} - 2v_g \frac{\partial^2}{\partial \zeta \partial \tau}$$

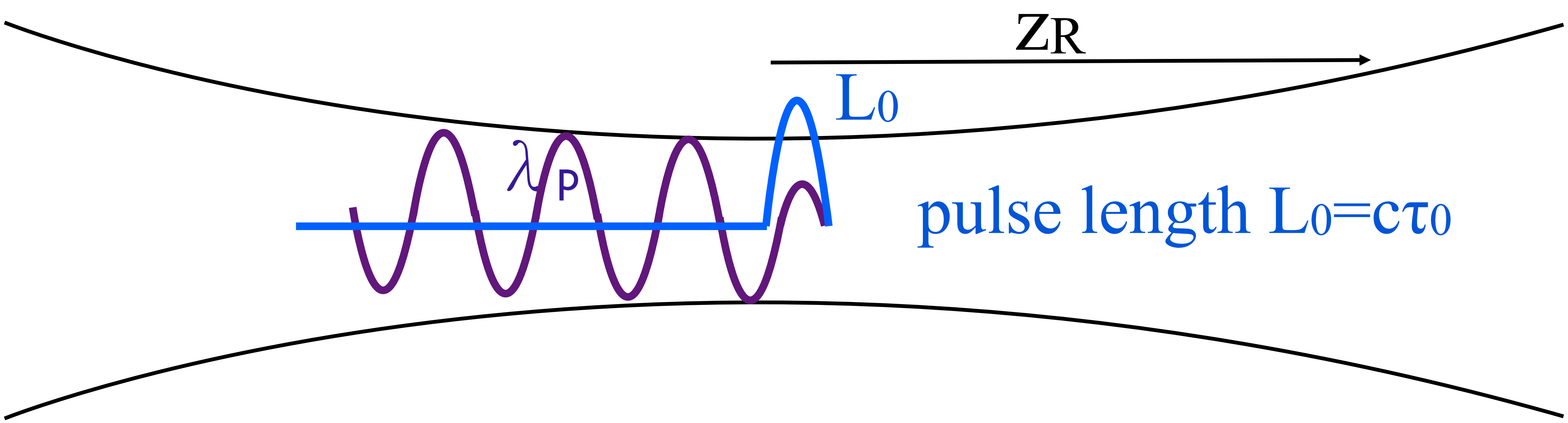
$$\frac{\partial^2}{\partial z^2} = \frac{\partial^2}{\partial \zeta^2}$$

$$\left(\frac{\partial^2}{\partial \tau^2} + v_g^2 \frac{\partial^2}{\partial \zeta^2} - 2v_g \frac{\partial^2}{\partial \zeta \partial \tau} + \omega_p^2\right)\phi = \omega_p^2 \frac{a^2}{4}$$

Quasi static approximation

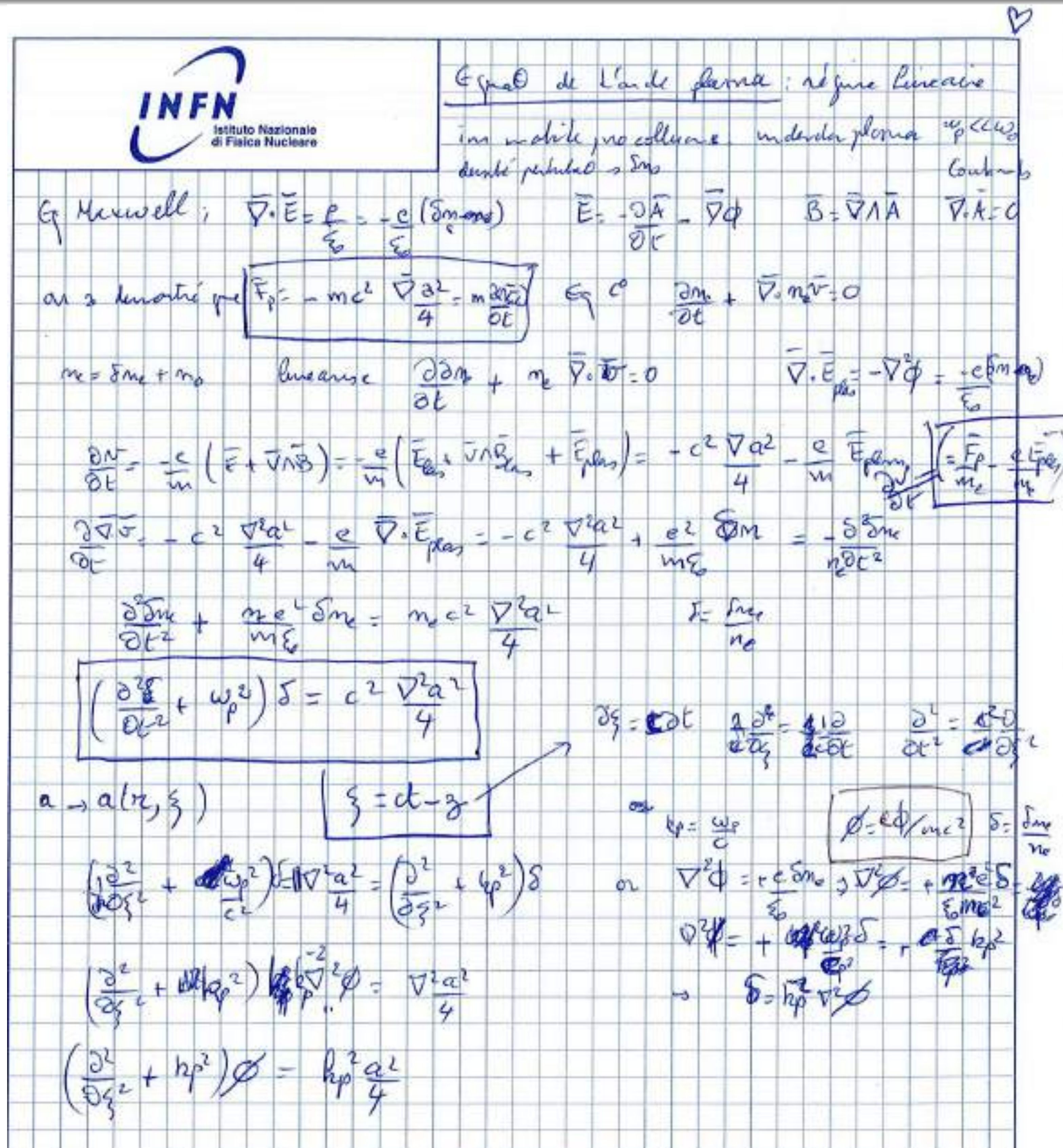
Neglect the derivatives in τ versus ζ one

Physics meaning : adiabatic response of the laser due to the slow evolution of the laser



$$\left(\frac{\partial^2}{\partial\zeta^2}+k_p^2\right)\phi = k_p^2\frac{a^2}{4}$$

Some notes



Quasi static approximation

$$\left(\frac{\partial^2}{\partial\zeta^2}+k_p^2\right)\phi=k_p^2\frac{a^2}{4}$$

Solution of the equation =0 for $\zeta=+\infty$
(no perturbation before the laser pulse)

$$\longrightarrow\quad \phi(r,\zeta)=-\frac{k_p}{4}\int_{\zeta}^{+\infty}a^2(\zeta')\sin(k_p(\zeta-\zeta'))d\zeta'$$

At $\zeta=-\infty, a^2=0$ $\longrightarrow$ $\phi(r,\zeta)=-\frac{k_p}{4}\int_{-\infty}^{+\infty}a^2(\zeta')\sin(k_p(\zeta'-\zeta')d\zeta'$

$$\phi(r,\zeta)=-\frac{k_p}{4}(sin(k_p\zeta)\int_{-\infty}^{+\infty}a^2(\zeta')\cos(k_p\zeta')d\zeta'+cos(k_p\zeta)\int_{-\infty}^{+\infty}a^2(\zeta')\sin(k_p(\zeta'))d\zeta')$$

Since a^2 is an even function, the second term is nul, then:

$$\phi(r,\zeta)=-\frac{k_p}{4}\sin(k_p\zeta)\mathrm{TF}(a^2)$$

For a gaussian beam, $a(r,\zeta)=a_0\exp(-\frac{r^2}{w_0^2})\exp(-2\ln(2)\frac{\zeta^2}{c^2\tau^2})$

$$f(x)=e^{-\alpha\frac{x^2}{2}}\rightarrow\hat{f}(p)=\frac{1}{\sqrt{\alpha}}e^{-\frac{p^2}{2\alpha}}$$

Solution of the envelop equation

Solution (after the gaussian laser pulse have gone):

Potential: $\phi = -\sqrt{\pi} a_0^2 \frac{k_p L_0}{4} e^{-k_p^2 L_0^2/4} e^{-r^2/\sigma^2} sin(k_p \zeta)$

Electric field: $\frac{\mathbf{E}}{E_0} = -\frac{1}{k_p} \nabla \phi = -\frac{1}{k_p} (\mathbf{e_z} \frac{\partial}{\partial \zeta} + \mathbf{e_r} \frac{\partial}{\partial r}) \phi$

Longitudinal E: $\frac{E_z}{E_0} = \sqrt{\pi} a_0^2 \frac{k_p L_0}{4} e^{-k_p^2 L_0^2/4} e^{-r^2/\sigma^2} cos(k_p \zeta)$

Transversal E: $\frac{E_r}{E_0} = -\sqrt{\pi} a_0^2 \frac{L_0 r}{\sigma^2} e^{-k_p^2 L_0^2/4} e^{-r^2/\sigma^2} sin(k_p \zeta)$

E_0 Wave breaking E field: $E_0 = \frac{m_e c \omega_p}{e} \sim n^{1/2}$

$$L_0 = \frac{c\tau_0}{2\sqrt{\log 2}}$$

Solution for the density perturbation

From the Poisson's equation, one then obtains

Longitudinal density perturbation :

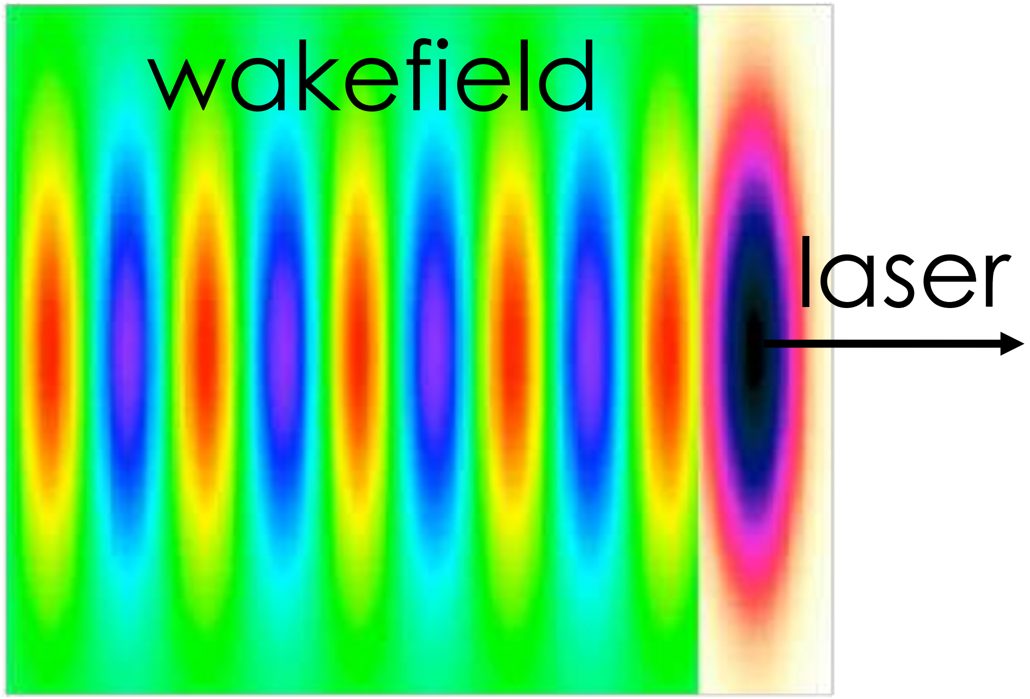
$$\frac{\delta n_z}{n_0} = \sqrt{\pi} a_0^2 \frac{k_p L_0}{4} e^{-k_p^2 L_0^2/4} e^{-r^2/\sigma^2} sin(k_p \zeta)$$

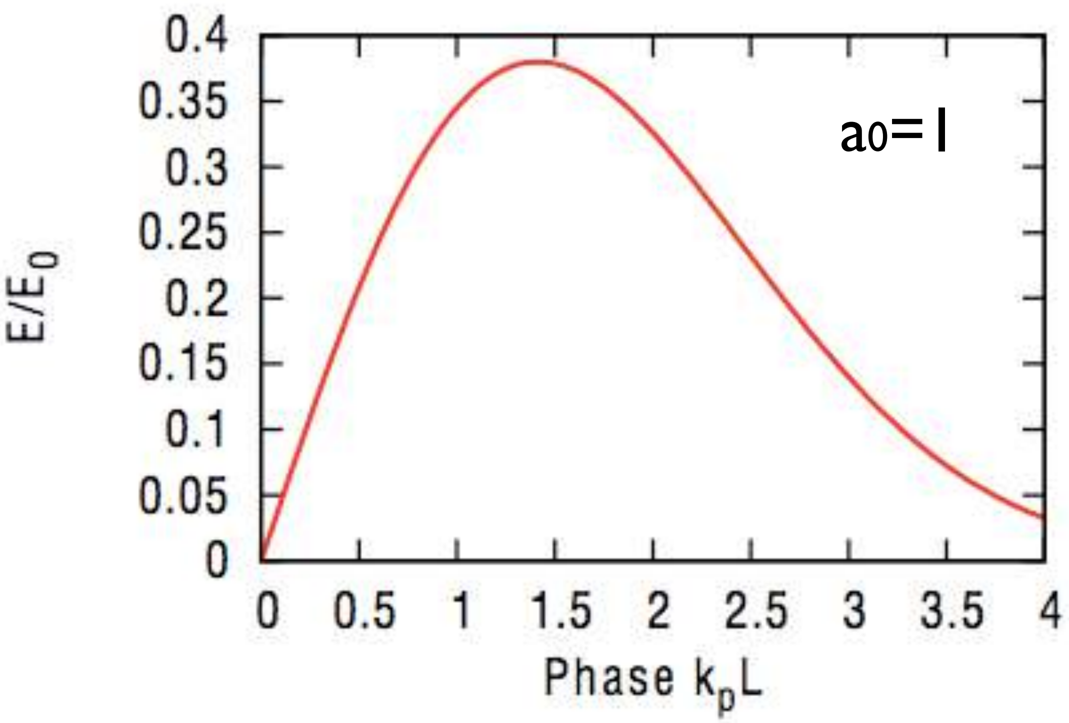
Radial density perturbation :

$$\frac{\delta n_r}{n_0} = \frac{\delta n_z}{n_0} \frac{4}{k_p^2 \sigma^2} (1 - \frac{r^2}{\sigma^2})$$

$$\phi = \sqrt{\pi} a_0^2 \frac{k_p L_0}{4} e^{-k_p^2 L_0^2/4}$$

Resonance condition for Laser Wakefield





Optimum potential: $\frac{\partial \phi}{\partial L_0} = 0$ which gives $k_p L_0 = \sqrt{2}$

$$(\delta n_z / n_0)_{max} \approx 0.4 a_0^2$$

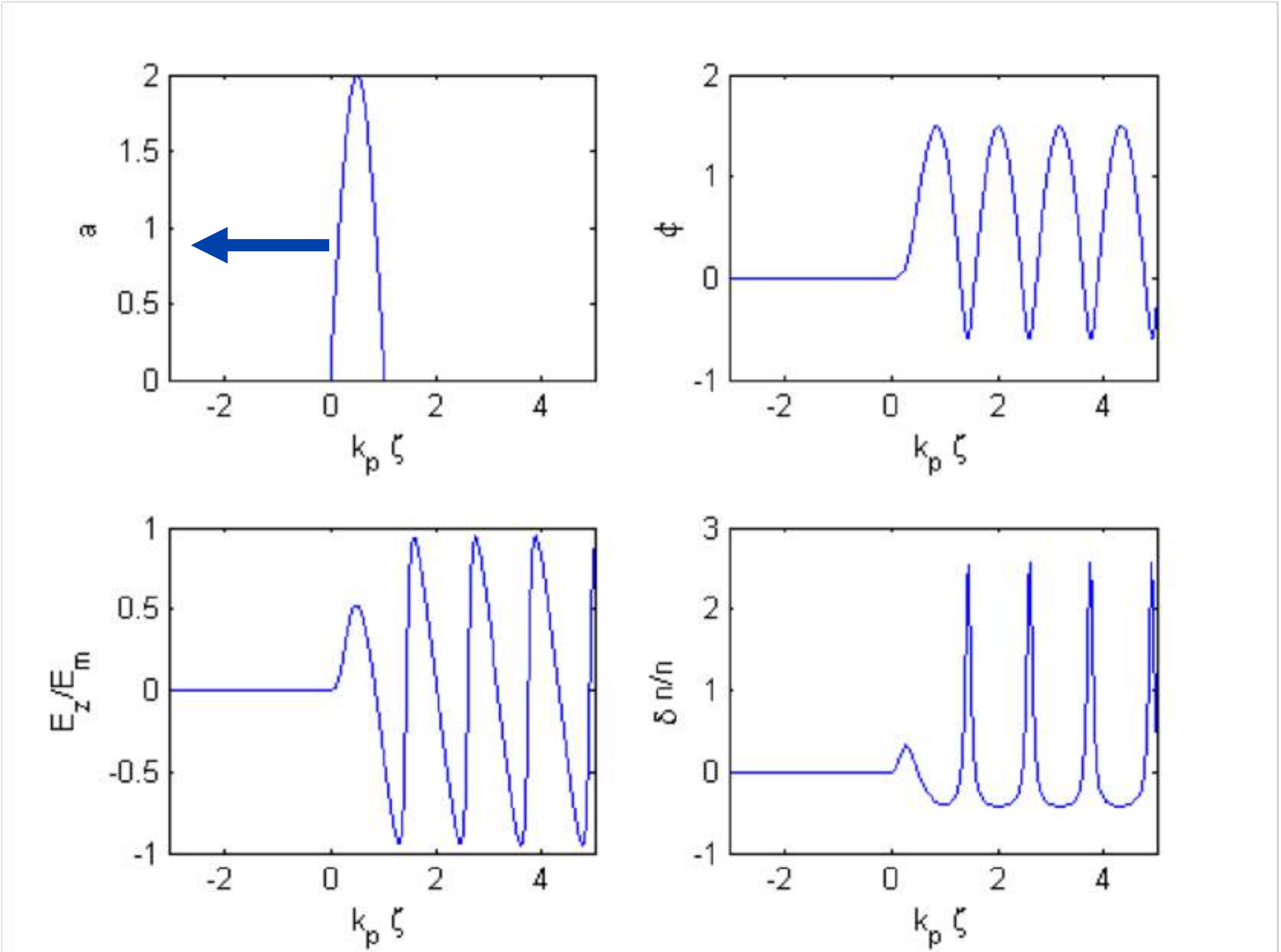
In the laser wakefield the resonance is very broad

$$n_e(cm^{-3}) = \frac{1.7 \times 10^{21}}{\tau_{FWHM}^2 (fs)}$$ => 30 fs @ $1.9\text{x}10^{18}\text{cm}^{-3}$

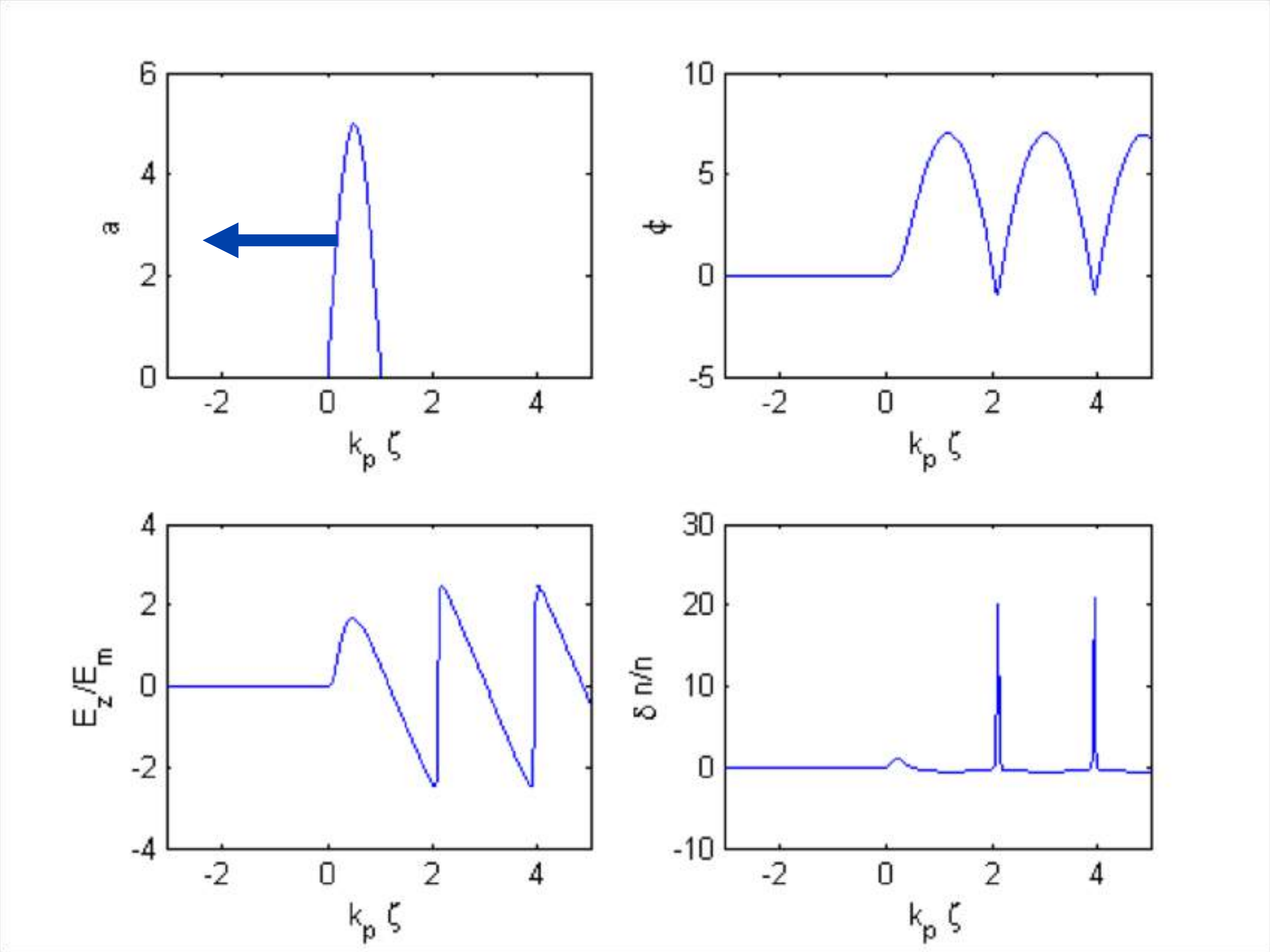
Gorbunov et al. Sov. Phys. JETP 66 (87)

Twist movie: the resonance

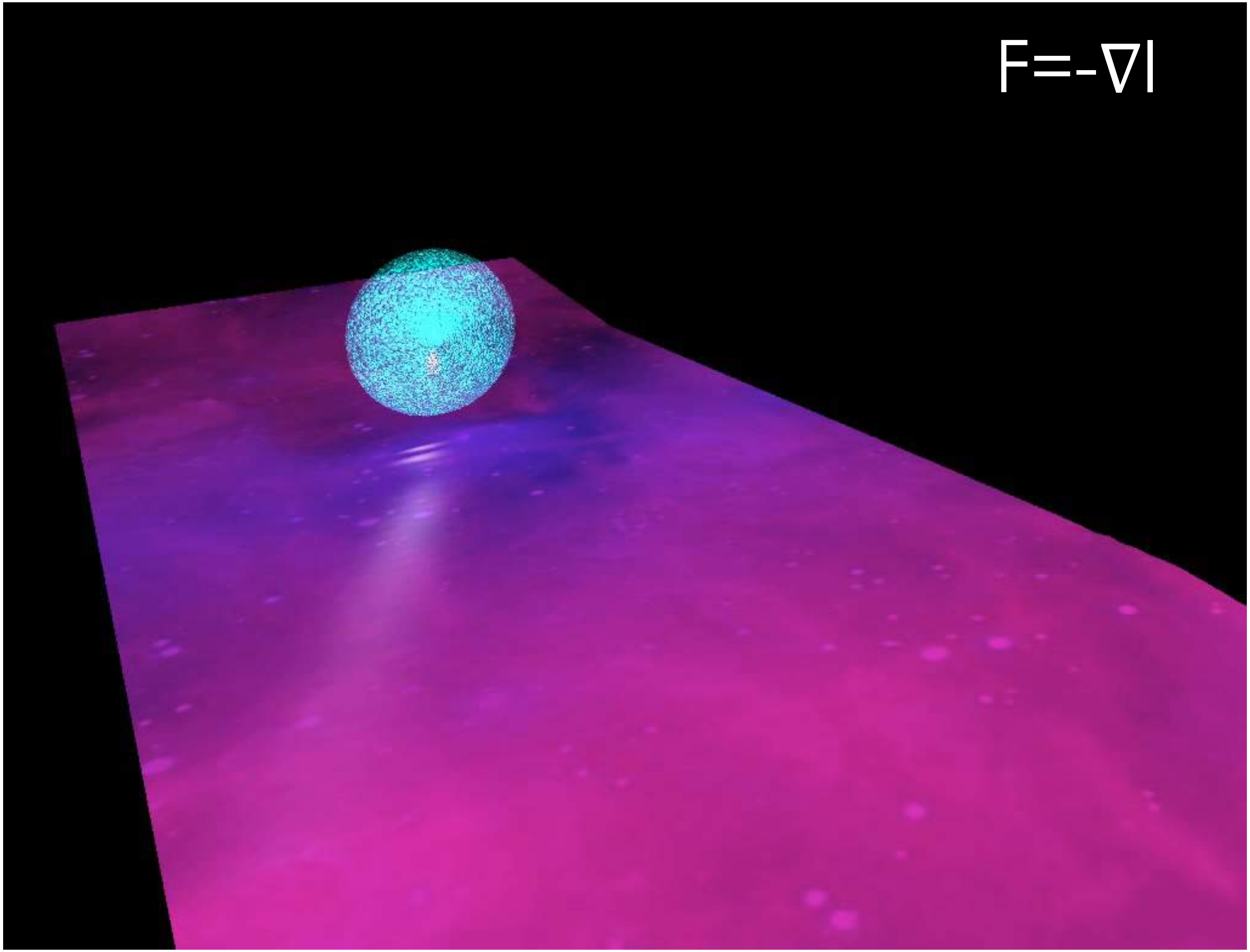
Non Linear Plasma waves 1D : a_0=2 (30fs)



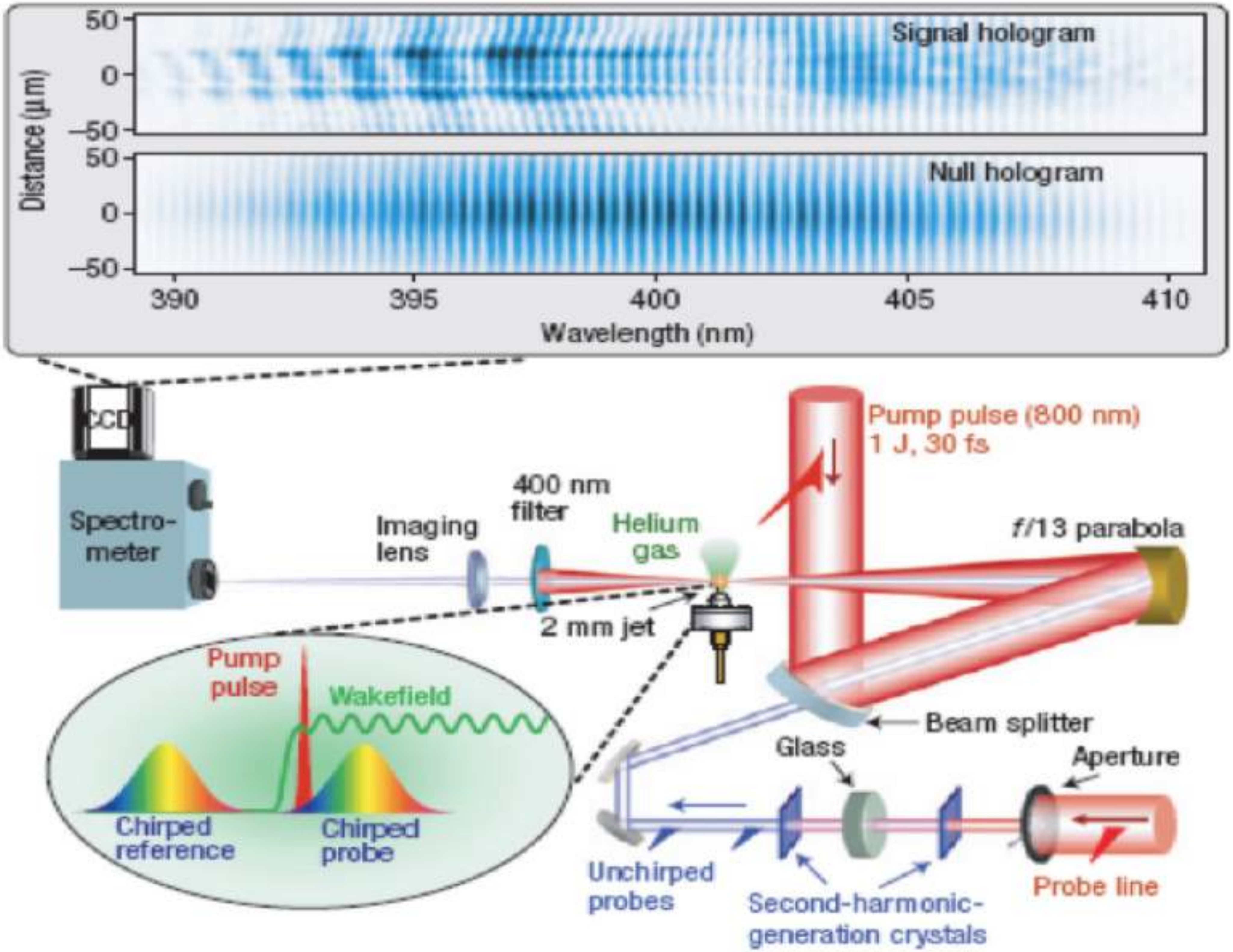
Non Linear Plasma waves 1D : a_0=5 (30fs)



The Forced laser wakefield

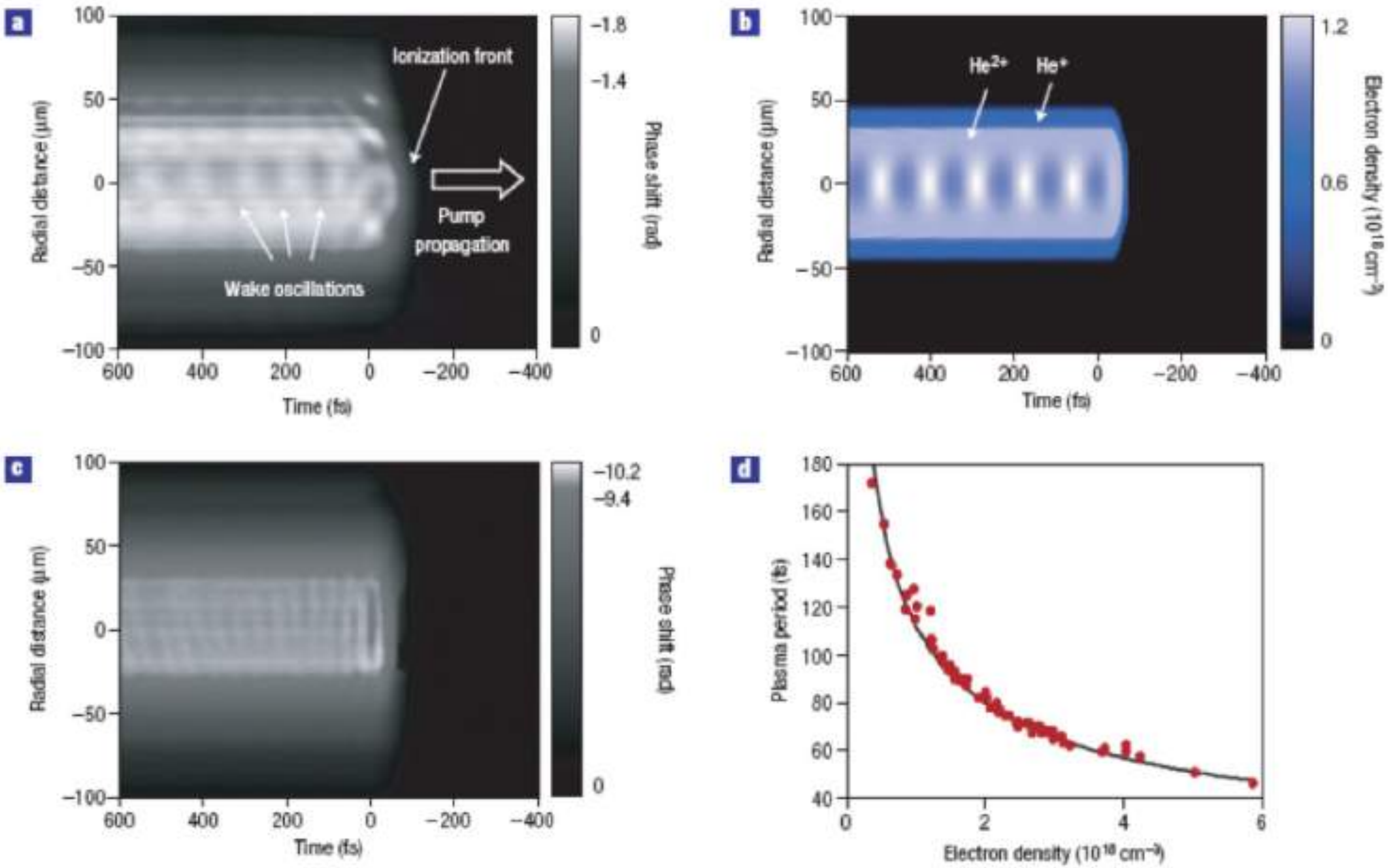


Snapshots of laser wakefield



N. H. Matlis *et al.* , Nature Physics 2006

Snapshots of laser wakefield

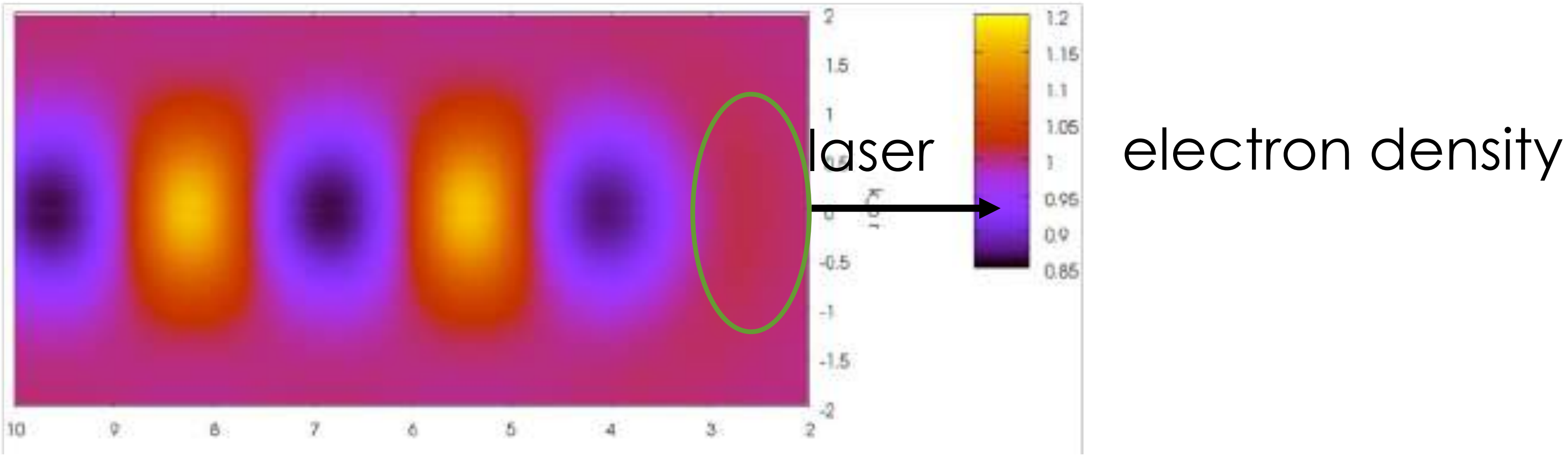


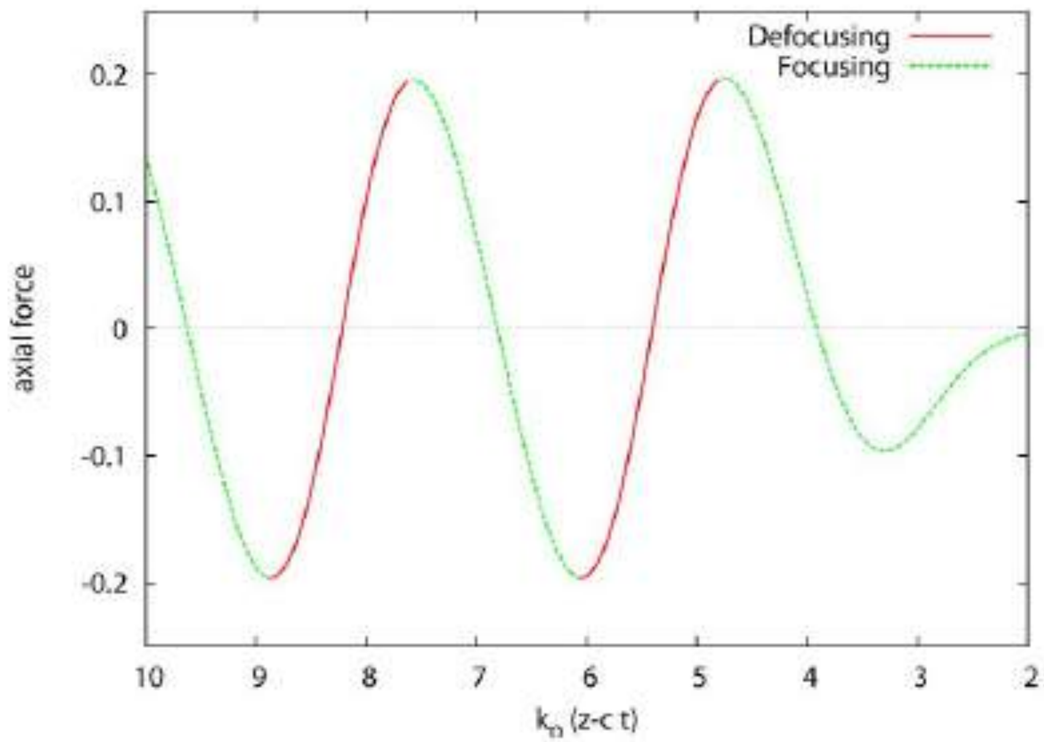
Small amplitude wakes with flats wavefronts. a) probe phase shift 10TW, 30 fs at $0.95\text{x}10^{19}\text{cm}^{-3}$. b) Simulated wake density profile. c) same than a) at $5.9\text{x}10^{19}\text{cm}^{-3}$. d) wake period versus n_e.

N. H. Matlis *et al.* , Nature Physics 2006

Accel./decel.-focusing/defocusing fields: Linear case

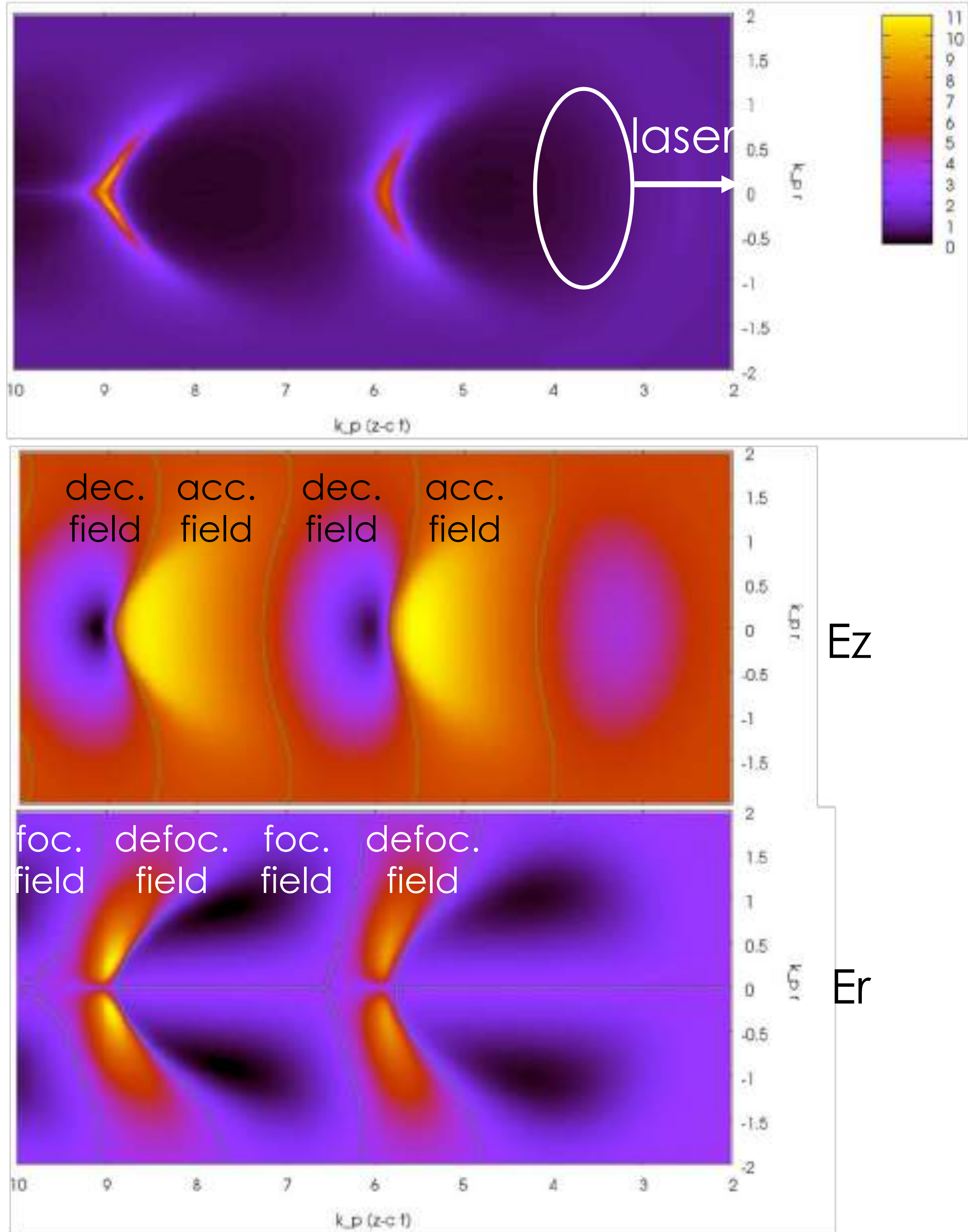
a_0=0.5





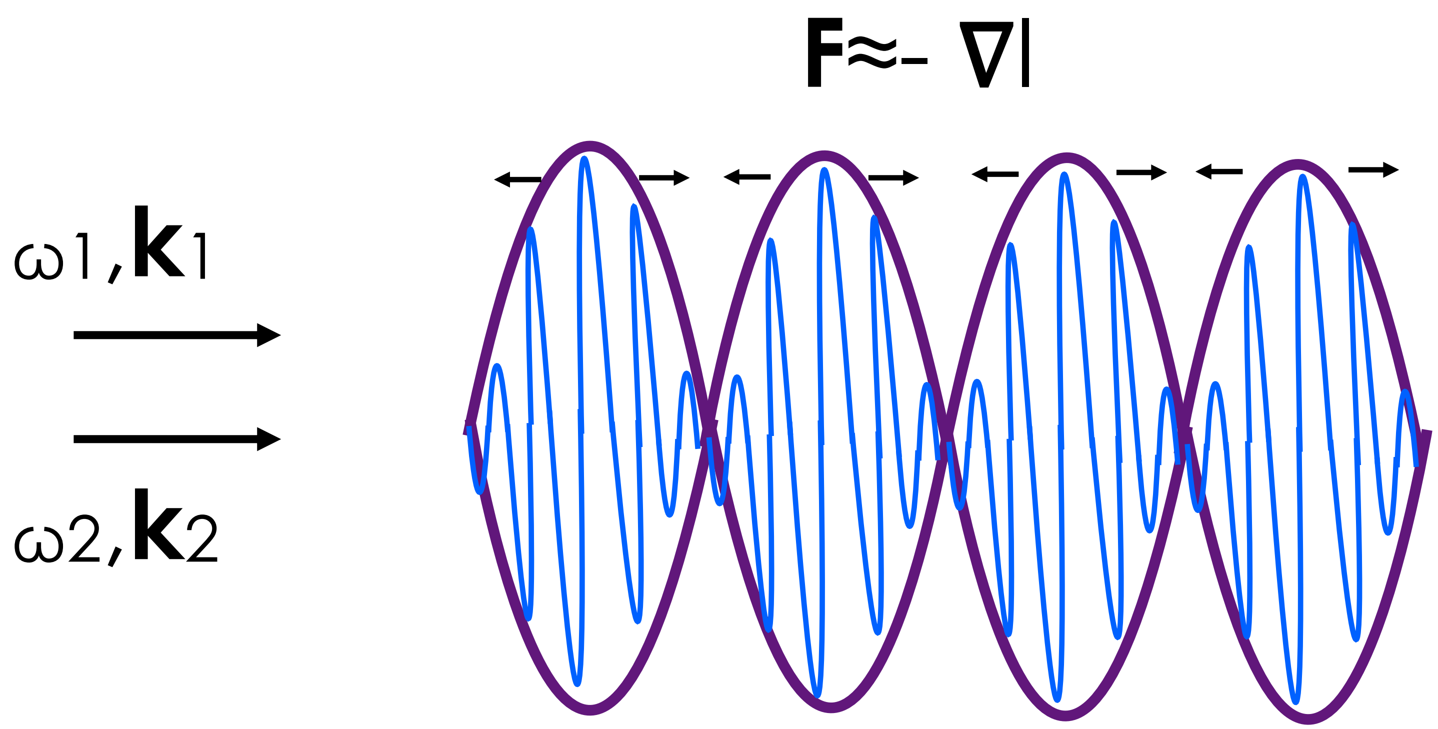
Accel./decel.-focusing/defocusing fields: Non-Linear case

$a_0=2$



1985-1995 How to excite a plasma wave ? LBW

The laser beat waves : $\tau_L >> T_p$



$$$$!

$\omega_1 - \omega_2 = \omega_p$

linear growth rate $\delta(t) = 1/4$

$a_1 a_2 \omega_p t$

=> homogenous plasmas

saturation : relativistic, ion motion

Train of short resonant pulses

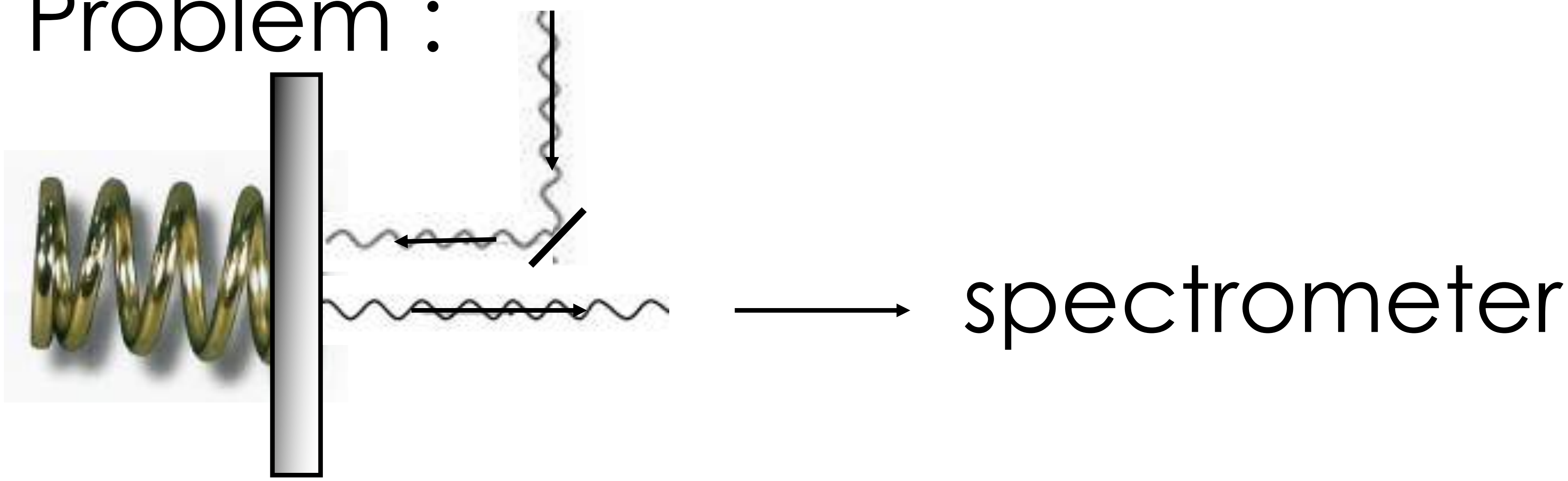
Optical demonstration by Thomson scattering :

Clayton *et al.* PRL 1985, Amiranoff *et al.* PRL 1992, Dangor *et al.* Phys. Scrypta 1990

Chen, Introduction to plasma physics and controlled fusion, 2nd Edition, Vol.1, (1984)

Analogy : oscillating mirror's problem

Problem :



Part I : Motivation, basis and principle

- Introduction : context and motivations
- Electron in a laser field
- Laser driven plasma wave : theory
- Trapping Conditions

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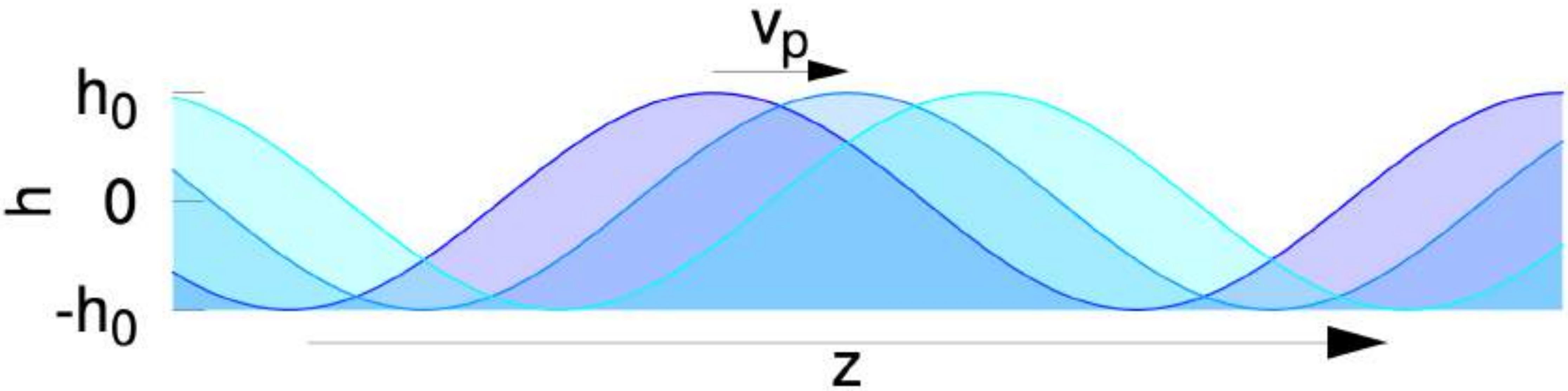
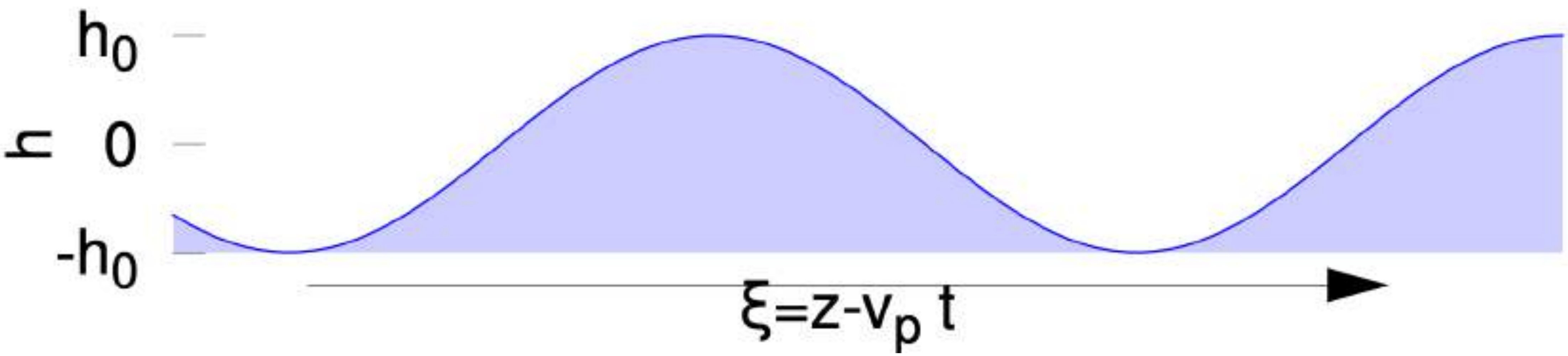
Injection criteria : the surfer

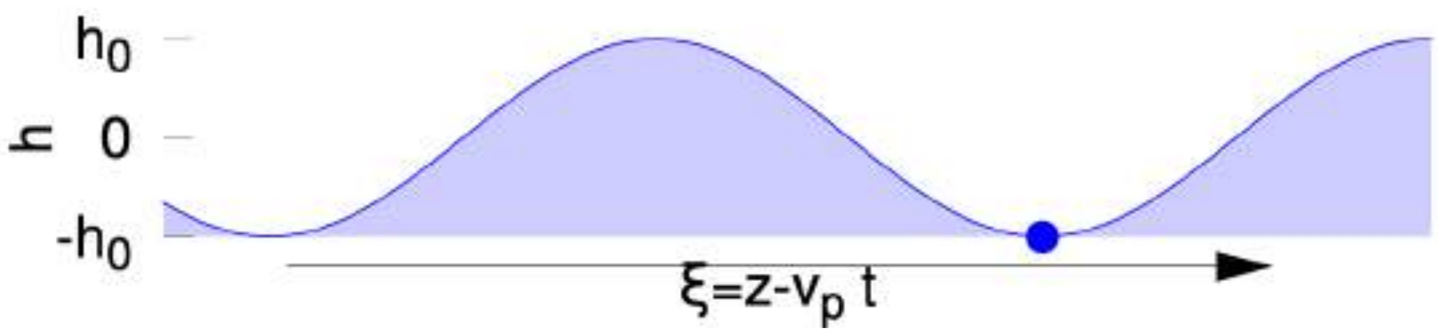


in the terrestrial reference frame $h = h_0 \cos(z - v_p t)$

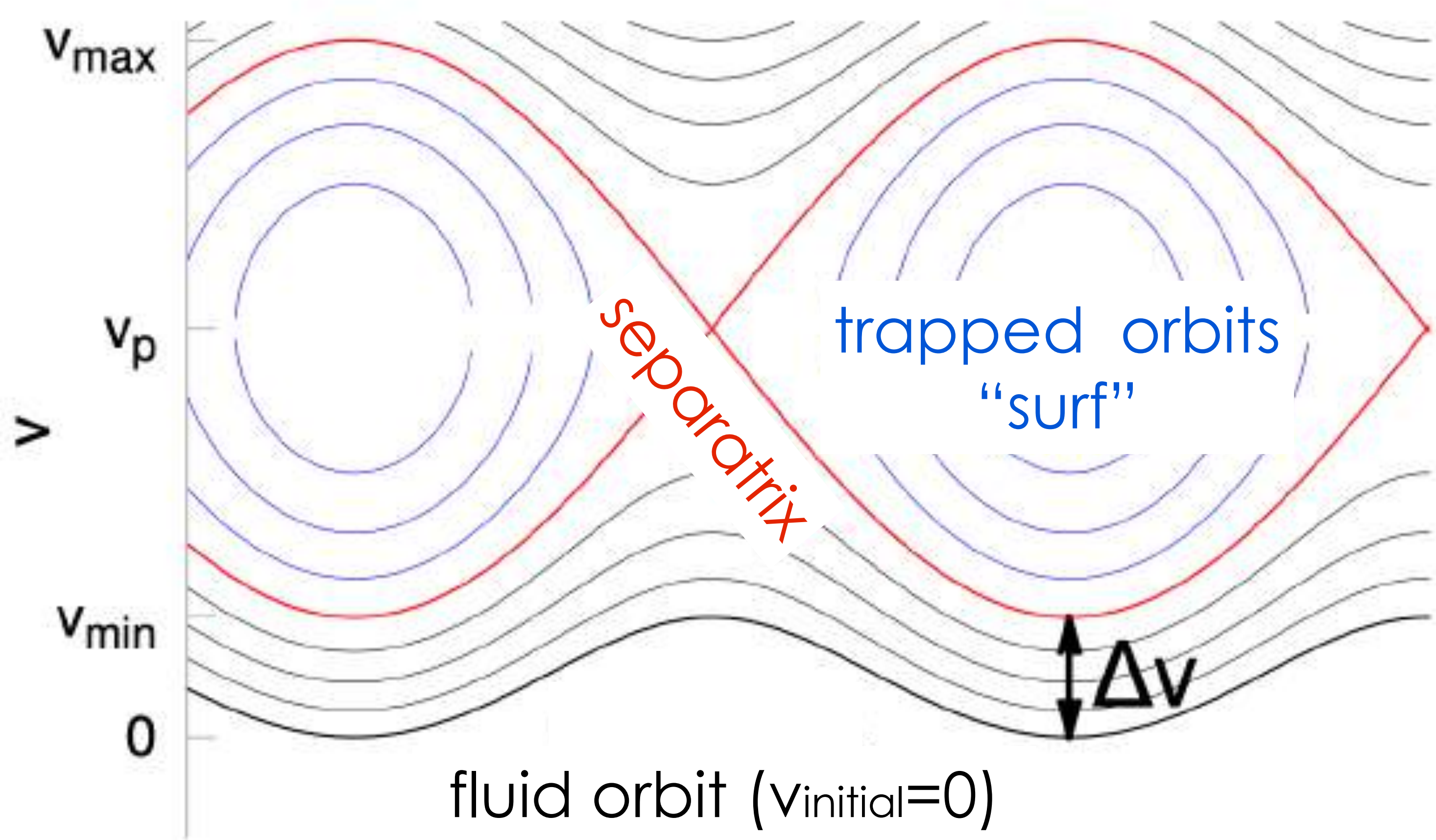


in the wawe reference frame $h = h_0 \cos(\xi)$

Injection criteria : the surfer experiences



phases space (ξ , $v-v_p$)

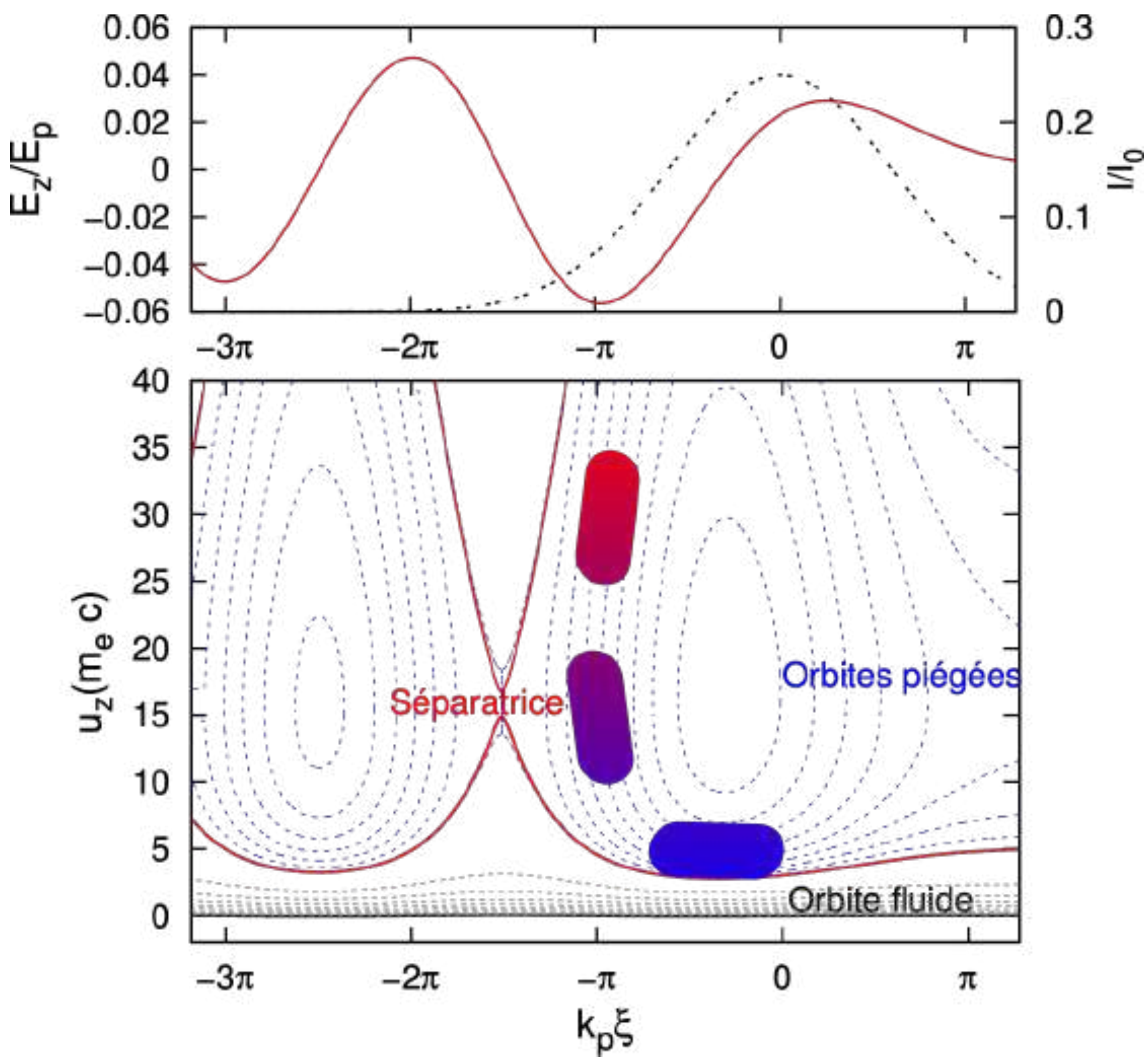


fluid orbit ($v_{initial}=0$)

conclusions :

- Trapped orbits allow higher energy gain
- One needs to transmit enough velocity ΔV

1 D maximum energy gain : Wmax: eEpLdeph



In plasma wave :

- E field is not homogenous
- Volume is phase space is conserved
- very small initial volume

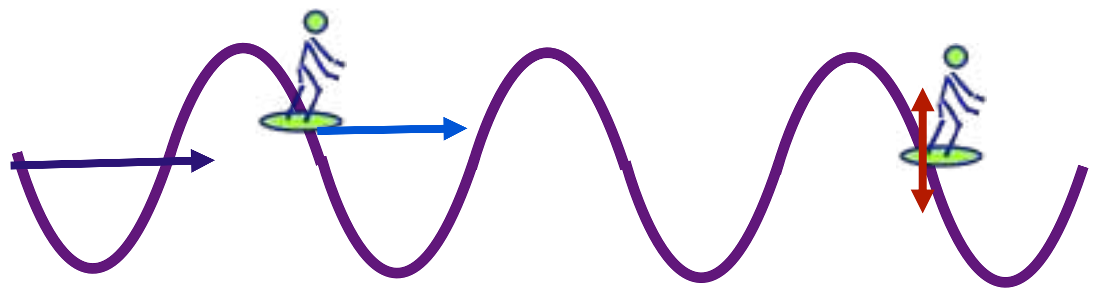
external injection :

- Size≈ µm
- Length≈ µm (fs)
- Synchronization ≈ fs
- Controle ?

=> very challenging wit conventional accelerator

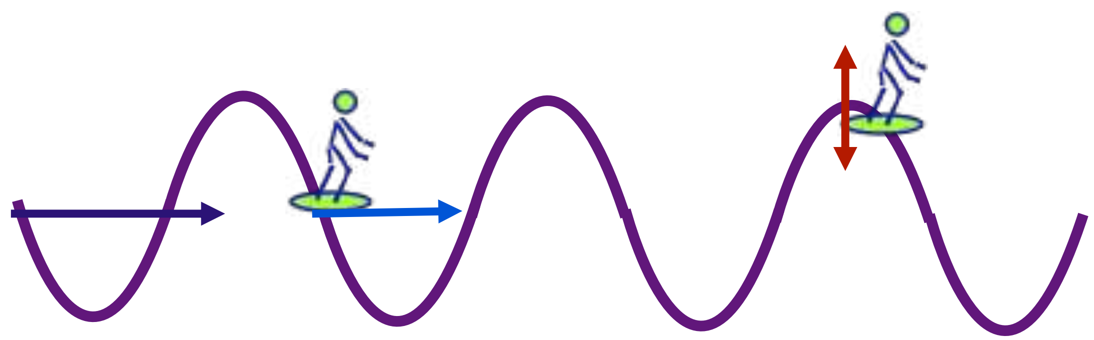
Trapping energy : analogy electron/surfer

surfer with enough initial velocity



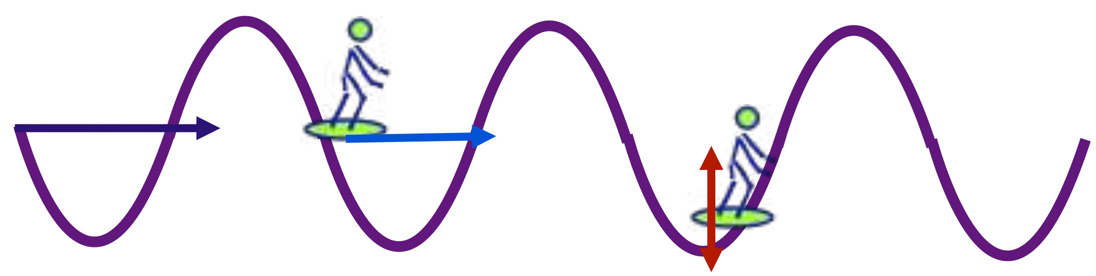
surfer initially at rest

surfer with enough initial velocity



surfer initially at rest

surfer with enough initial velocity



surfer initially at rest

Trapping energy : analogy electron/surfer

Single electron dynamic in a plasma wave:

For a sinusoidal plasma wave, plasma wave, $\delta n = \delta n_e \sin(k_p z - \omega_p t)$ where ω_p and k_p are the angular frequency and the wave number of the plasma wave.

This density perturbation leads to a perturbation of the electric field $\delta\vec{E}$ via the Poisson equation

$$\vec{\nabla}.\delta\vec{E} = -\frac{\delta n\ e}{\varepsilon_0}$$

This gives

$$\delta\vec{E}(z,t) = \frac{\delta n_e\ e}{k_p \varepsilon_0}\cos(k_p z - \omega_p t)\vec{e_z}$$

Because we want to describe the electron acceleration to relativistic energies by a plasma wave, we consider now a plasma wave with a phase velocity is close to the speed of light $v_p = \omega_p/k_p \sim c$. Let $E_0 = m_e c\omega_{pe}/e$. The electric field becomes :

$$\delta\vec{E}(z,t) = E_0 \frac{\delta n_e}{n_e}\cos(k_p z - \omega_p t)\vec{e_z}$$

One notice that the electric field is dephased by $-\pi/4$ with respect to the electron density.

Single electron dynamic in a plasma wave:

Let's now describe the evolution of an electron placed in the electric field.
The goal is to obtain the required conditions for trapping to occur.
The following variables are introduced to describe the electron in the laboratory frame : z the position, t the associated time, β the velocity normalized to c, $\gamma = 1/\sqrt{1-\beta^2}$ the associated Lorentz's factor.
In plasma wave frame z', t' ,β' and γ' represent the equivalent quantities.

The plasma wave frame is in uniform constant translation at speed $v_p = \beta_p c$.
One writes γ_p the Lorentz's factor associated to this velocity.
The Lorentz's transform allows to switch from the laboratory frame to the wave frame :

$$z' = \gamma_p(z - v_p t)$$

$$ct' = \gamma_p(ct - x \times v_p/c)$$

$$\gamma' = \gamma\gamma_p(1 - \vec{\beta}.\vec{\beta_p})$$

In the new frame, the electric field remains unchanged $\delta\vec{E}'$

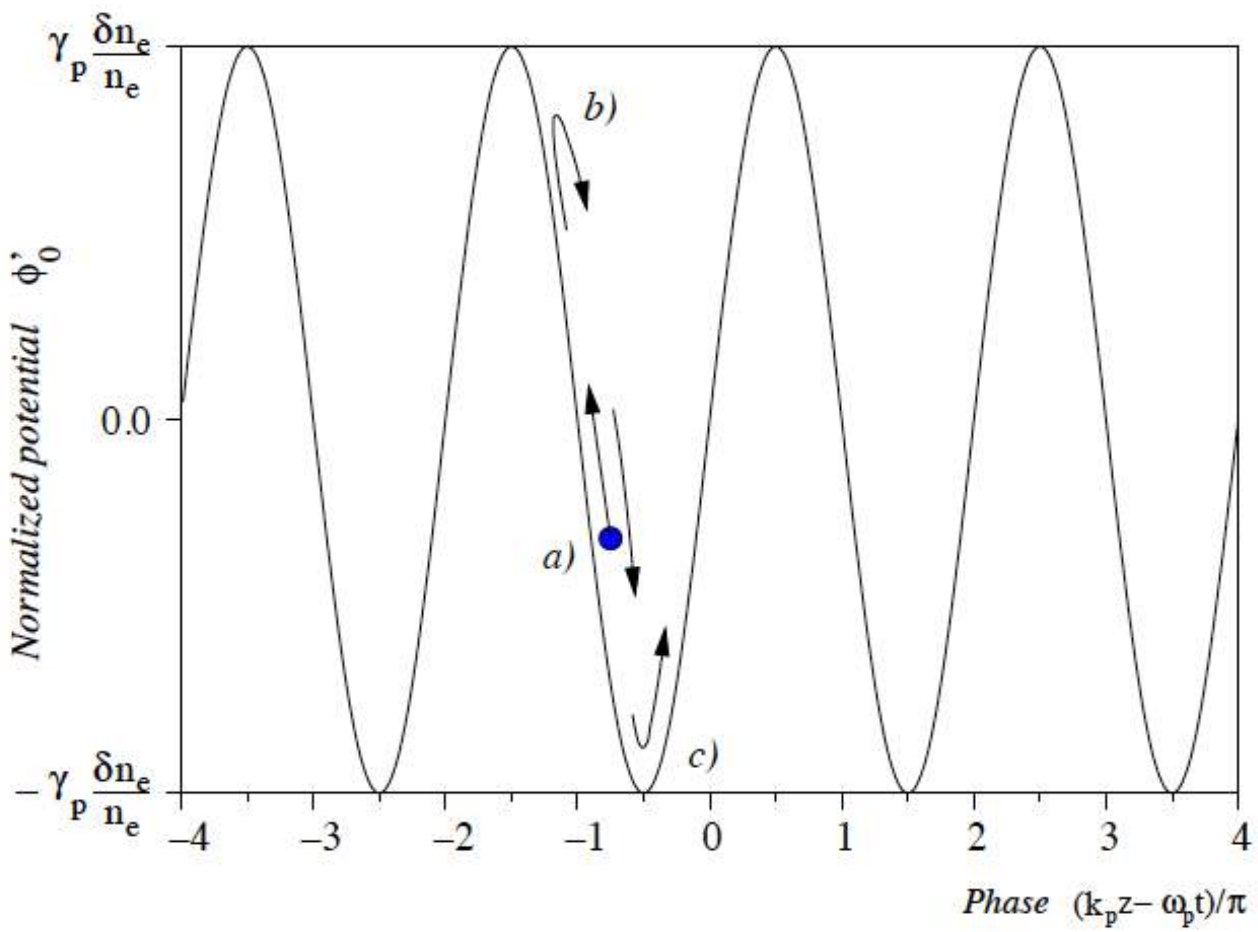
$$\delta\vec{E}'(z') = \delta\vec{E}(z,t) = E_0\frac{\delta n_e}{n_e}\cos(k_p z'/\gamma_p)\vec{e_z} \quad \text{and } \vec{F} = -e\delta\vec{E}' \equiv -\vec{\nabla}'\Phi'$$

Single electron dynamic in a plasma wave:

This leads to $\Phi'(z') = mc^2\gamma_p \frac{\delta n_e}{n_e}\sin(k_p z'/\gamma_p) \equiv mc^2\phi'(z')$

The total energy conservation for the particle in this frame compared to the initial energy at the injection time (labelled with subscript 0) gives:

$$\gamma'(z') + \phi'(z') = \gamma'(z'_0) + \phi'(z'_0)$$

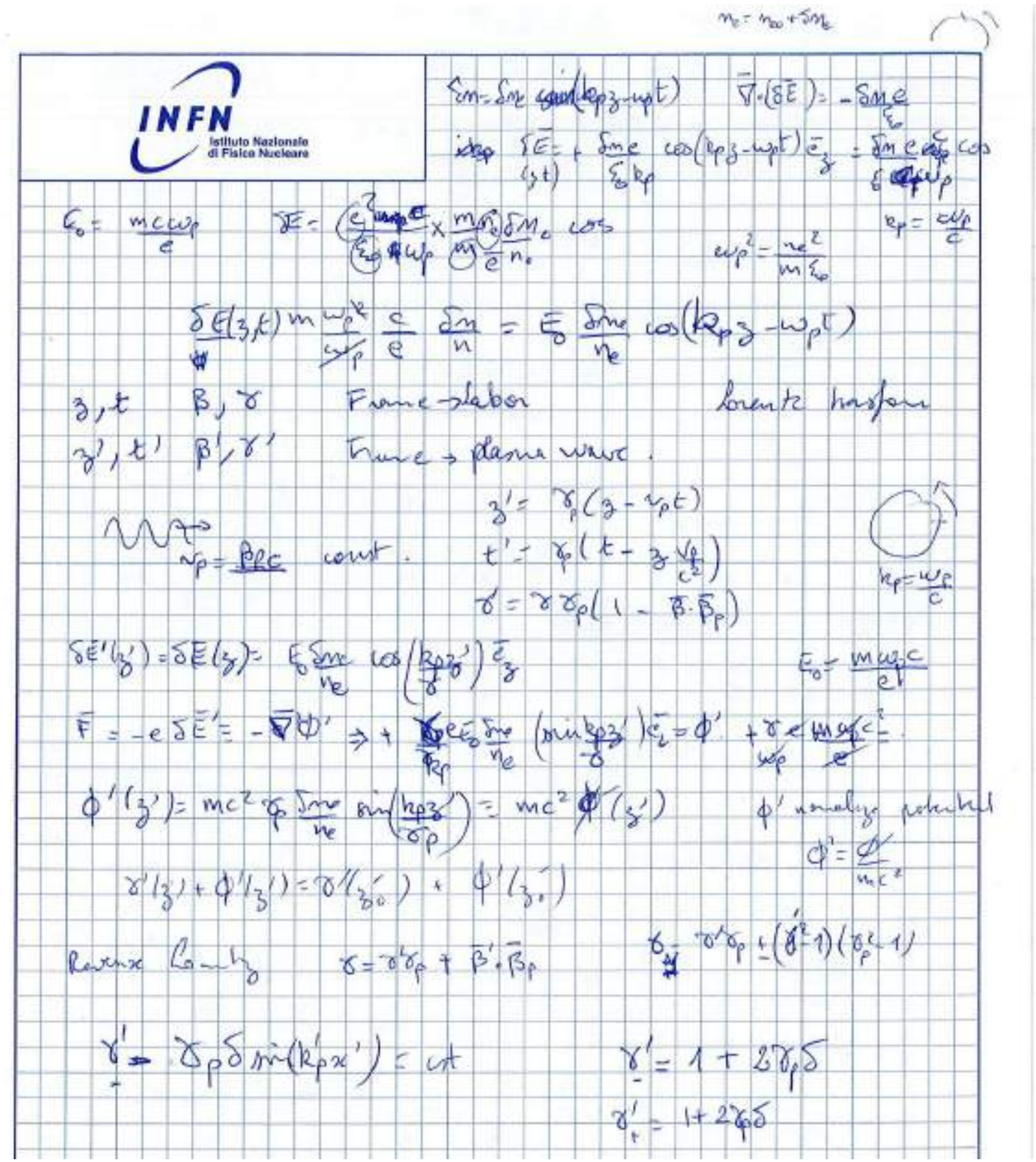


Trajectory of an electron injected in the potential of the plasma wave in the frame of the wave. The letters correspond to the instant when : a) the electron is injected in the wave, b) the electron travels at the speed of the plasma wave, c) the electron has the maximal velocity and enters the decelerating part of the wave.

Single electron dynamic in a plasma wave:

Conservation energy equation gives the relation between the electron energy and its position in the plasma wave. The previous figure illustrates the motion of an electron injected in this potential. Finally, we perform the reverse Lorentz's transform to give this energy in the laboratory frame.
For $\beta' > 0$, the scalar product $\vec{\beta}.\vec{\beta}_p$ is positive, then :
$$\gamma = \gamma'\gamma_p + \sqrt{\gamma'^2 - 1}\sqrt{\gamma_p^2 - 1}$$
For $\beta' < 0$, the scalar product $\vec{\beta}.\vec{\beta}_p$ is negative, then :
$$\gamma = \gamma'\gamma_p - \sqrt{\gamma'^2 - 1}\sqrt{\gamma_p^2 - 1}$$
This separatrix gives the minimum and maximum energies for trapped particles. This is comparable to the hydrodynamic case, where a surfer has to crawl to gain velocity and to catch the wave. In terms of relativistic factor, γ has to belong to the interval $[\gamma_{min}; \gamma_{max}]$ with :
$$\gamma_{min} = \gamma_p(1 + 2\gamma_p\delta) - \sqrt{\gamma_p^2 - 1}\sqrt{(1 + 2\gamma_p\delta)^2 - 1}$$
$$\gamma_{max} = \gamma_p(1 + 2\gamma_p\delta) + \sqrt{\gamma_p^2 - 1}\sqrt{(1 + 2\gamma_p\delta)^2 - 1}$$
where $\delta = \delta n_e/n_e$ is the relative amplitude of the density perturbation.

Single electron dynamic in a plasma wave:



$n_e = n_{e0} + \delta n_e$

$\delta n = \delta n_e \sin(k_p z - \omega_p t)$ $\quad \vec{\nabla}\cdot(\delta\vec{E}) = -\frac{\delta n_e e}{\epsilon_0}$

$\delta\vec{E}(z,t) = +\frac{\delta n_e e}{\epsilon_0 k_p}\cos(k_p z - \omega_p t)\,\vec{e}_z$

$E_0 = \frac{m c \omega_p}{e}$ $\quad \omega_p^2 = \frac{n e^2}{m \epsilon_0}$ $\quad k_p = \frac{\omega_p}{c}$

$\delta E(z,t) = E_0 \frac{\delta n_e}{n_e}\cos(k_p z - \omega_p t)$

z, t $\quad \beta, \gamma$ $\quad$ Frame → labor $\quad$ Lorentz transform

z', t' $\quad \beta', \gamma'$ $\quad$ Frame → plasma wave

$v_p = \beta_p c$ const.

$z' = \gamma_p(z - v_p t)$

$t' = \gamma_p\left(t - z\frac{v_p}{c^2}\right)$

$\gamma = \gamma\gamma_p(1 - \beta\cdot\beta_p)$

$\delta E'(z') = \delta E(z) = E_0\frac{\delta n_e}{n_e}\cos\left(\frac{k_p z'}{\gamma_p}\right)\vec{e}_z$ $\quad E_0 = \frac{m\omega_p c}{e}$

$\vec{F} = -e\,\delta\vec{E}' = -\vec{\nabla}\phi'$ ⇒ [illegible]

$\phi'(z') = mc^2\gamma_p\frac{\delta n_e}{n_e}\sin\left(\frac{k_p z'}{\gamma_p}\right) = mc^2\bar{\phi}'(z')$ $\quad \phi'$ normalized potential $\bar{\phi}' = \frac{\phi'}{mc^2}$

$\gamma'(z') + \bar{\phi}'(z') = \gamma'(z'_0) + \bar{\phi}'(z'_0)$

Return to lab $\quad \gamma = \gamma'\gamma_p + \beta'\cdot\beta_p$ $\quad \gamma = \gamma'\gamma_p \pm (\gamma'^2 - 1)(\gamma_p^2 - 1)$

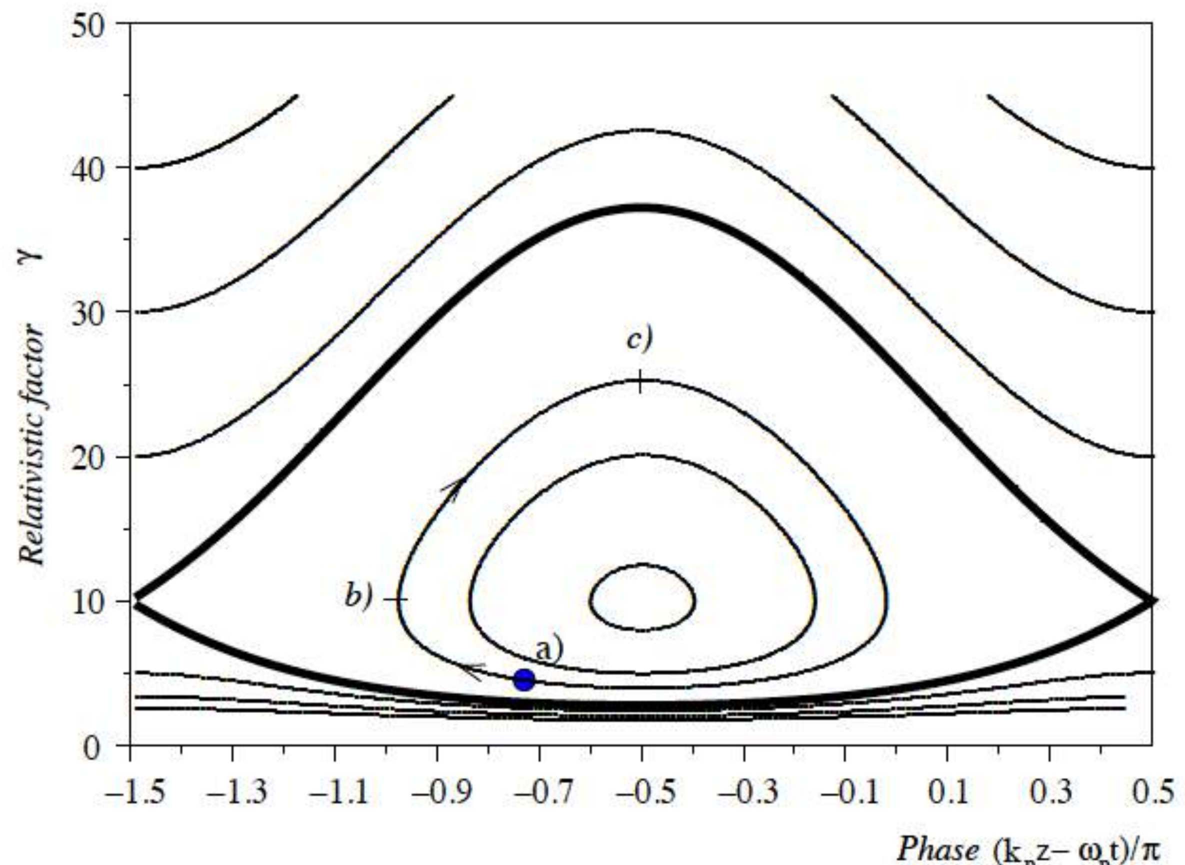
$\gamma' + \gamma_p\delta\sin(k'_p x') = \text{cst}$ $\quad \gamma'_- = 1 + 2\gamma_p\delta$

$\gamma'_+ = 1 + 2\gamma_p\delta$

Single electron dynamic in a plasma wave:

One deduces that the maximum energy gain ΔW_{max} for a trapped particle is reached for a closed orbit with maximum amplitude. This corresponds to the injection at γ_{min} on the separatrix and its extraction at γ_{max}. The maximum energy gain is then written $\Delta W_{max} = (\gamma_{max} - \gamma_{min})mc^2$

At low density $n_e \ll n_c$, one has $\gamma_p = \omega_0/\omega_p \gg 1$ and $\Delta W_{max} = 4\gamma_p^2 \frac{\delta n_e}{n_e} mc^2$



Electron trajectory in a plasma wave in the phase space $(k_p z - \omega_p t, \gamma)$ for $\gamma_p = 10$ and $\delta n_e / n_e = 0.05$. The thick line represents the separatrix. Closed orbits are trapped trajectories and open orbits are untrapped trajectories. The letters match the instants defined in caption of the previous figure

Outline

- Part I : Motivation, basis and principle
- Part II : External and Self-Injection in Laser Wakefield
- Part III : High quality electron beams in LPA with the colliding pulses scheme
- Part IV : Applications, conclusion and perspectives

Part II : External and Self-Injection in LWF

- External injection : Laser wakefield and Beatwave experiments
- Self-injection : Self-Modulated Laser and Forced Wakefield
- Bubble regime
- Ionisation Injection, Gradient and Longitudinal injection

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1979 Relativistic plasma waves with laser pulse

VOLUME 43, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 1979

Laser Electron Accelerator

T. Tajima and J. M. Dawson
Department of Physics, University of California, Los Angeles, California 90024
(Received 9 March 1979)

An intense electromagnetic pulse can create a weak of plasma oscillations through the action of the nonlinear ponderomotive force. Electrons trapped in the wake can be accelerated to high energy. Existing glass lasers of power density 10^{18}W/cm^2 shone on plasmas of densities 10^{18} cm^{-3} can yield gigaelectronvolts of electron energy per centimeter of acceleration distance. This acceleration mechanism is demonstrated through computer simulation. Applications to accelerators and pulsers are examined.

Such a wake is most effectively generated if the length of the electromagnetic wave packet is half the wavelength of the plasma waves in the wake:

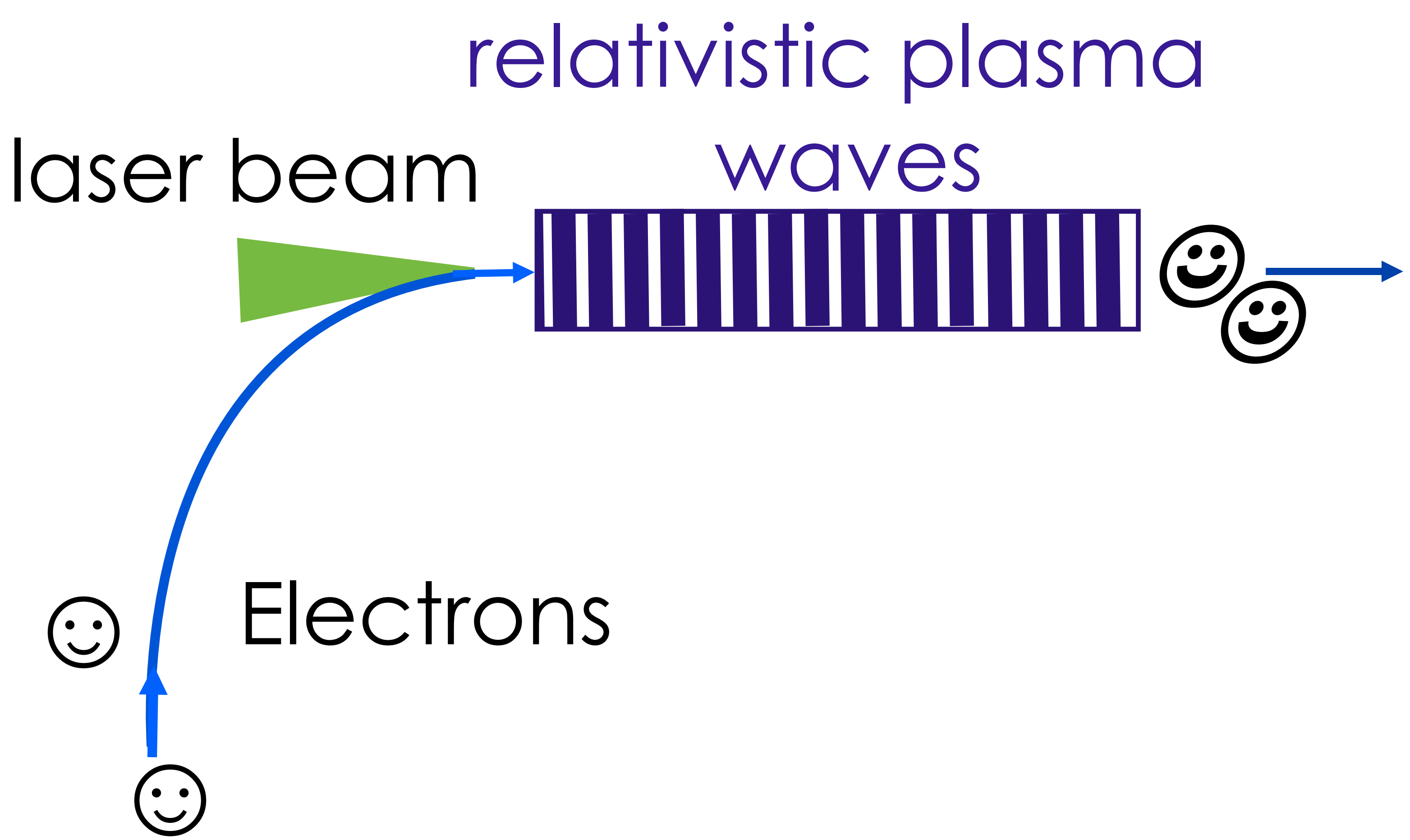
$$L_t = \lambda_w/2 = \pi c/\omega_p . \quad (2)$$

=> Laser wakefield

An alternative way of exciting the plasmon is to inject two laser beams with slightly different frequencies (with frequency difference $\Delta\omega \sim \omega_p$) so that the beat distance of the packet becomes $2\pi c/\omega_p$. The mechanism for generating the wakes

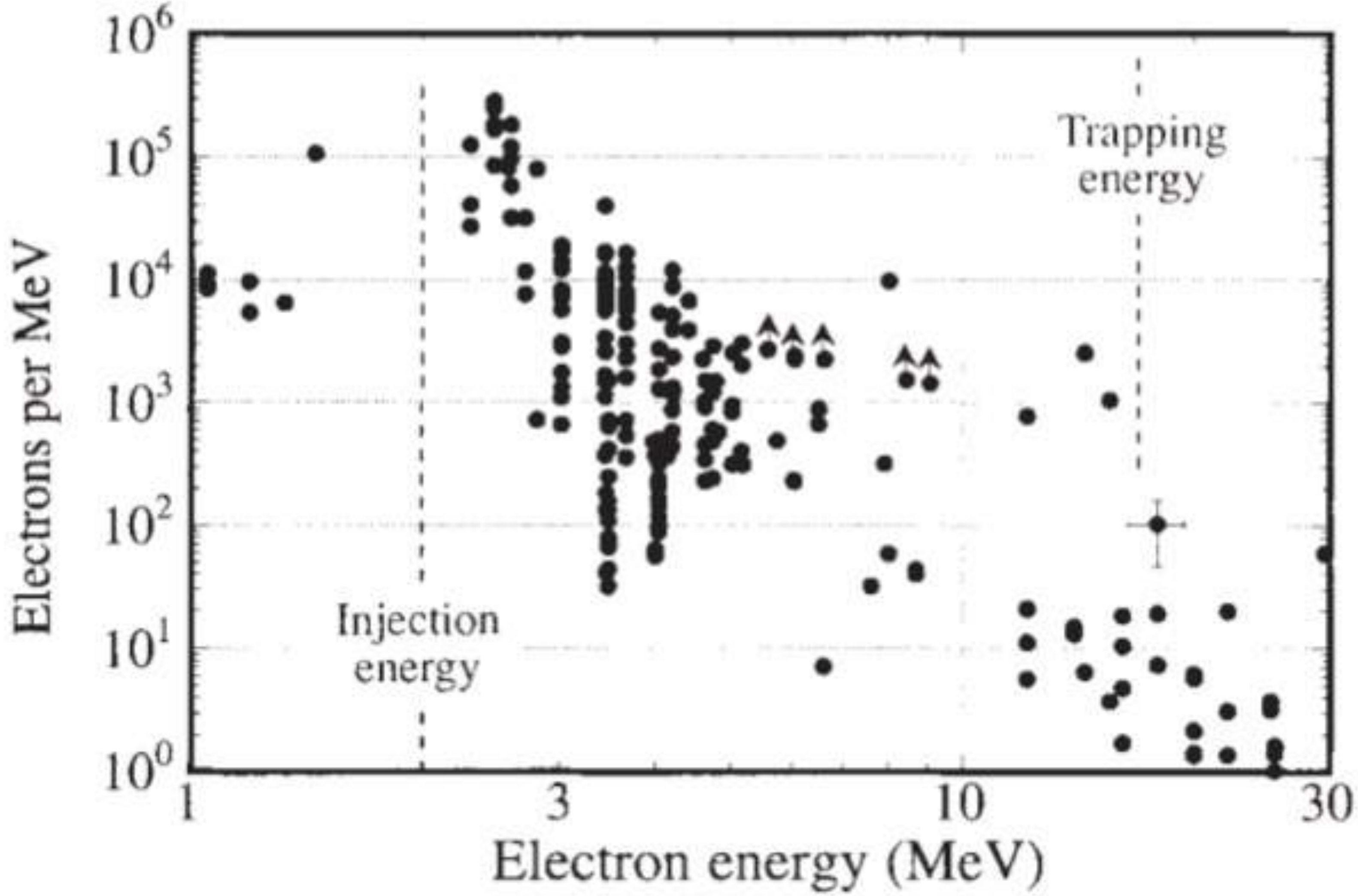
=> Laser beatwave

Scheme of principle of the first experiments : the laser Beat Wave (LBW)



1992-1994 Accelerated electrons in LBWF

The 2-MeV electrons are accelerated up to ≈ 28 MeV
Electron spectra indicate an E_{field} of ≈ 2.8 GV/m



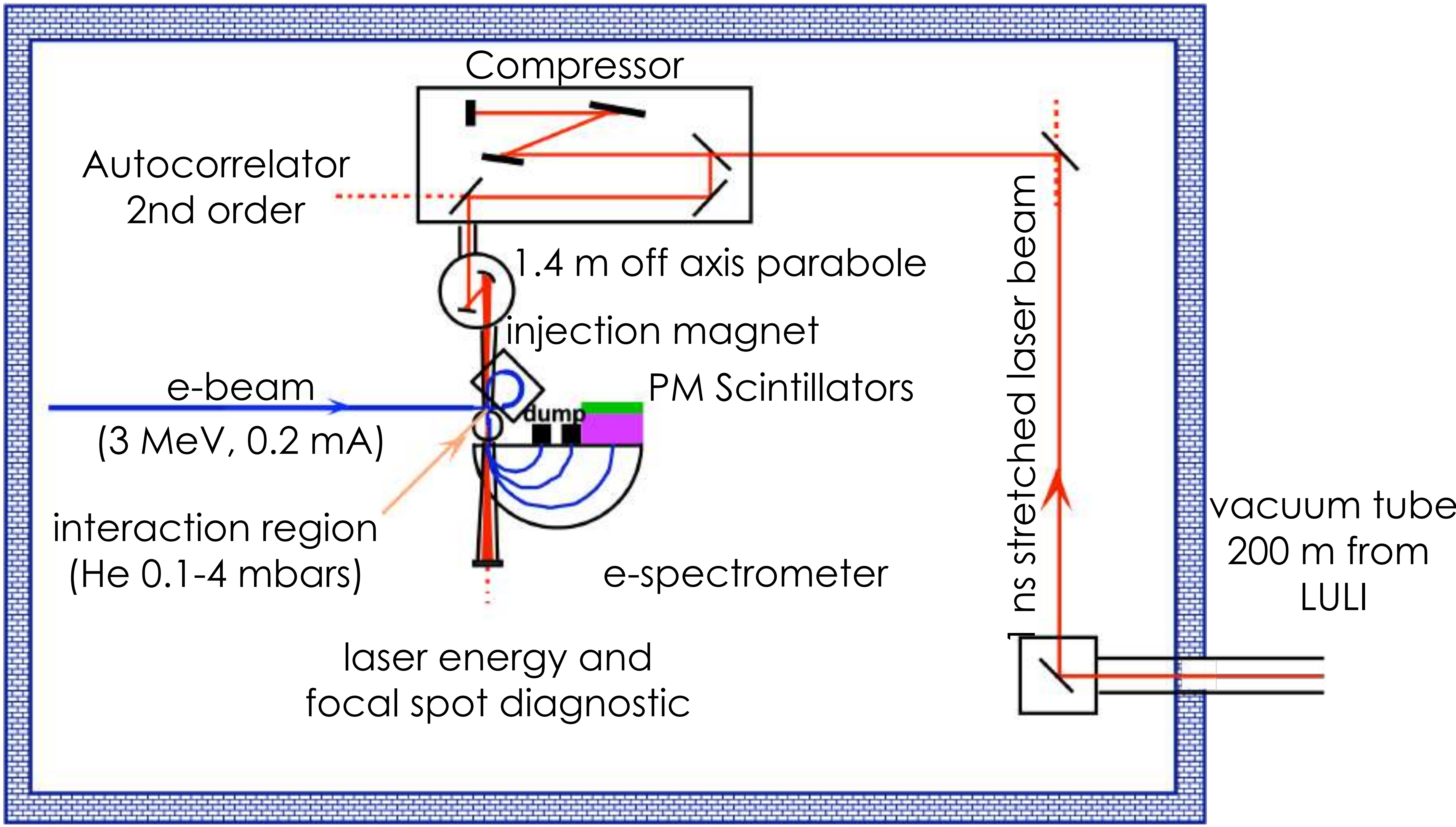
M. Everett *et al.*, Nature 1994

Electron gain demonstration Few MeV's:
Kitagawa *et al.* PRL 1992, Clayton *et al.* PRL 1993, N. A. Ebrahim *et al.*, J. Appl. Phys.1994, Amiranoff *et al.* PRL 1995

1998 Accelerated electrons in LWF

LULI/LPNHE/LSI/IC

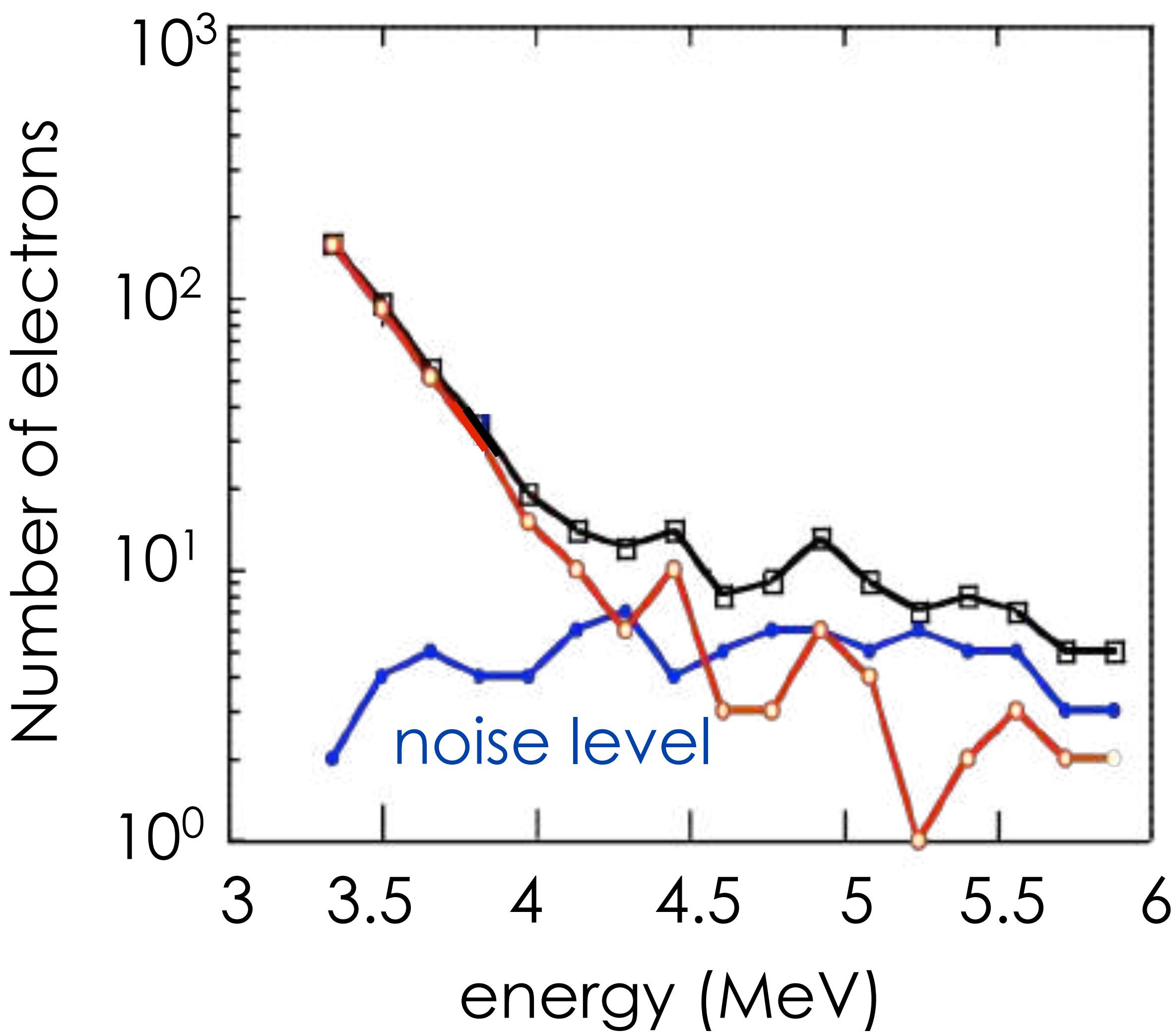
Electron spectra indicate an E_{field} of ≈ 1 GV/m



1998 Accelerated electrons in LWF

LULI/LPNHE/LSI/IC

The 3-MeV electrons are accelerated up to ≈ 4.5 MeV
Electron spectra indicate an E_{field} of ≈ 1.4 GV/m



2.5 J, 350 fs, 10^{17} W/cm^2, 0.5 mbar of He

F. Amiranoff *et al.*, PRL 1998

Part II : External and Self-Injection in LWF

- External injection : Laser wakefield and Beatwave experiments
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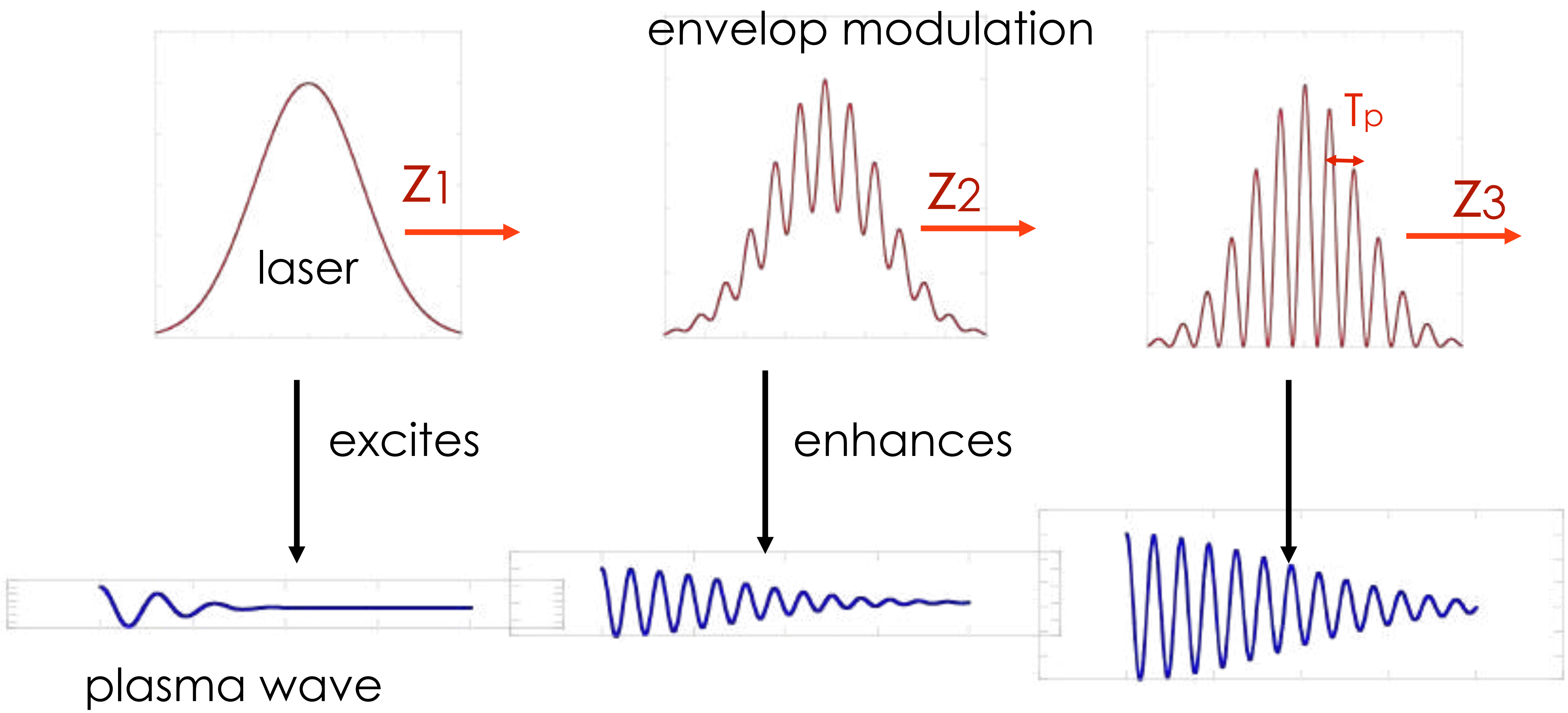
- Bubble regime
- Ionisation Injection, Gradient and Longitudinal injection

1992 How to excite a plasma wave: The SMLWF

Self modulated laser wakefield scheme : $c\tau_{laser} >> T_p$
(Andreev *et al.*, Antonsen *et al.*, Sprangle *et al.* 1992)



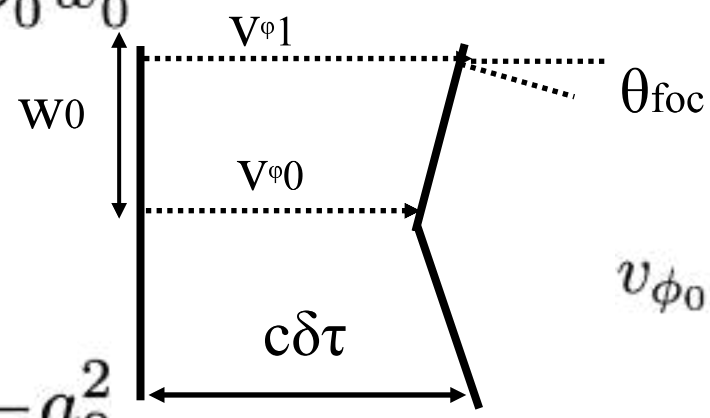
$P_L > P_c(GW) = 17\ n_c/n_e$ then wavebreaking can occur

The Relativistic self focusing

For a gaussian beam, in vacuum near the focus : $w = w_0(1 + t^2/t_R^2)^{1/2}$

Diffraction : $$\frac{d^2 w}{c^2 d\tau^2}|_{diff.} = \frac{w_0}{z_R^2} = \frac{4c^2}{\omega_0^2 w_0^3}$$

Relativistic self focusing :

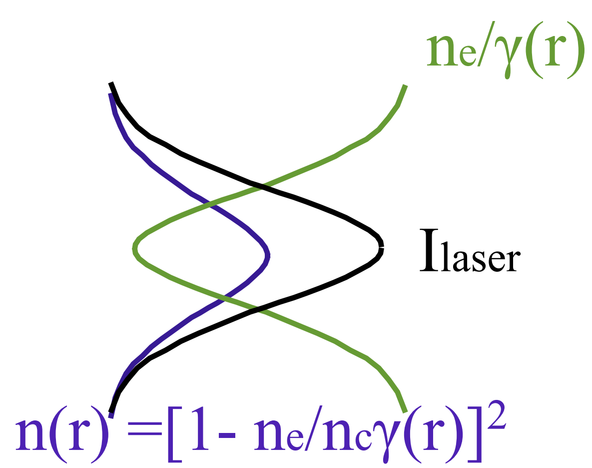


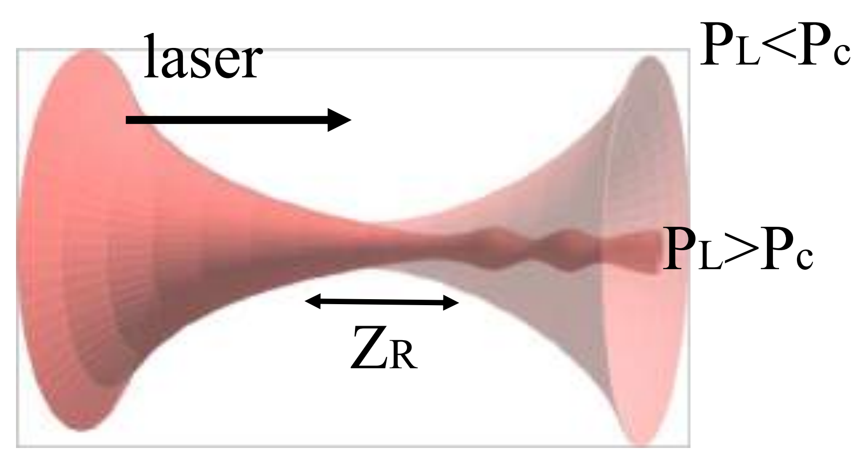
$$v_{\phi_1} = c(1 + \omega_p^2/2\omega_0^2)$$

$$v_{\phi_0} = c[1 + \omega_p^2/2\omega_0^2(1 - a_0^2/4)]$$

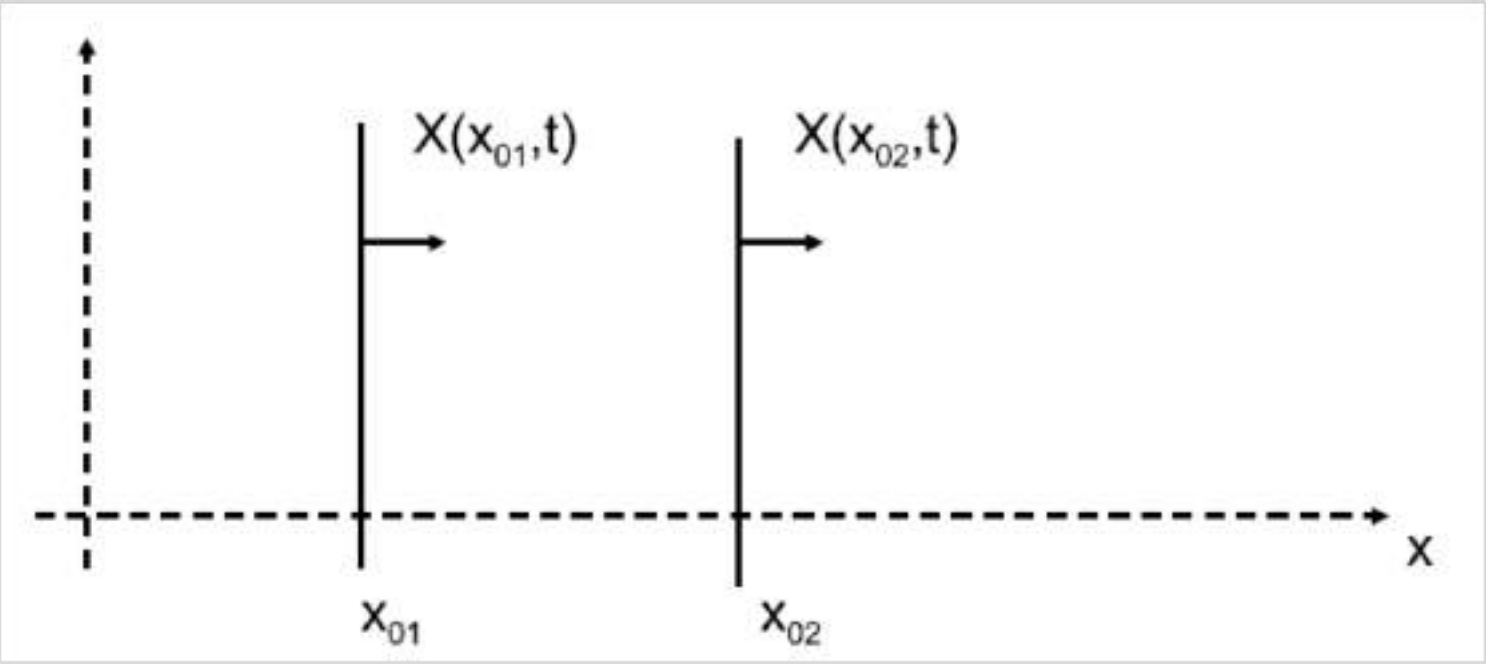
$$\frac{d^2 w}{c^2 d\tau^2}|_{foc.} = -\frac{v_{\phi_1} - v_{\phi_0}}{w_0} = \frac{\omega_p^2}{8\omega_0^2 w_0} a_0^2$$

$$\frac{\partial^2 (w/w_0)}{c^2 \partial\tau^2} = \frac{w_0^3}{z_R^2 w^3}(1 - \frac{P}{P_c}) \quad \text{with } P_c[GW] = 17\frac{\omega_0^2}{\omega_p^2}$$





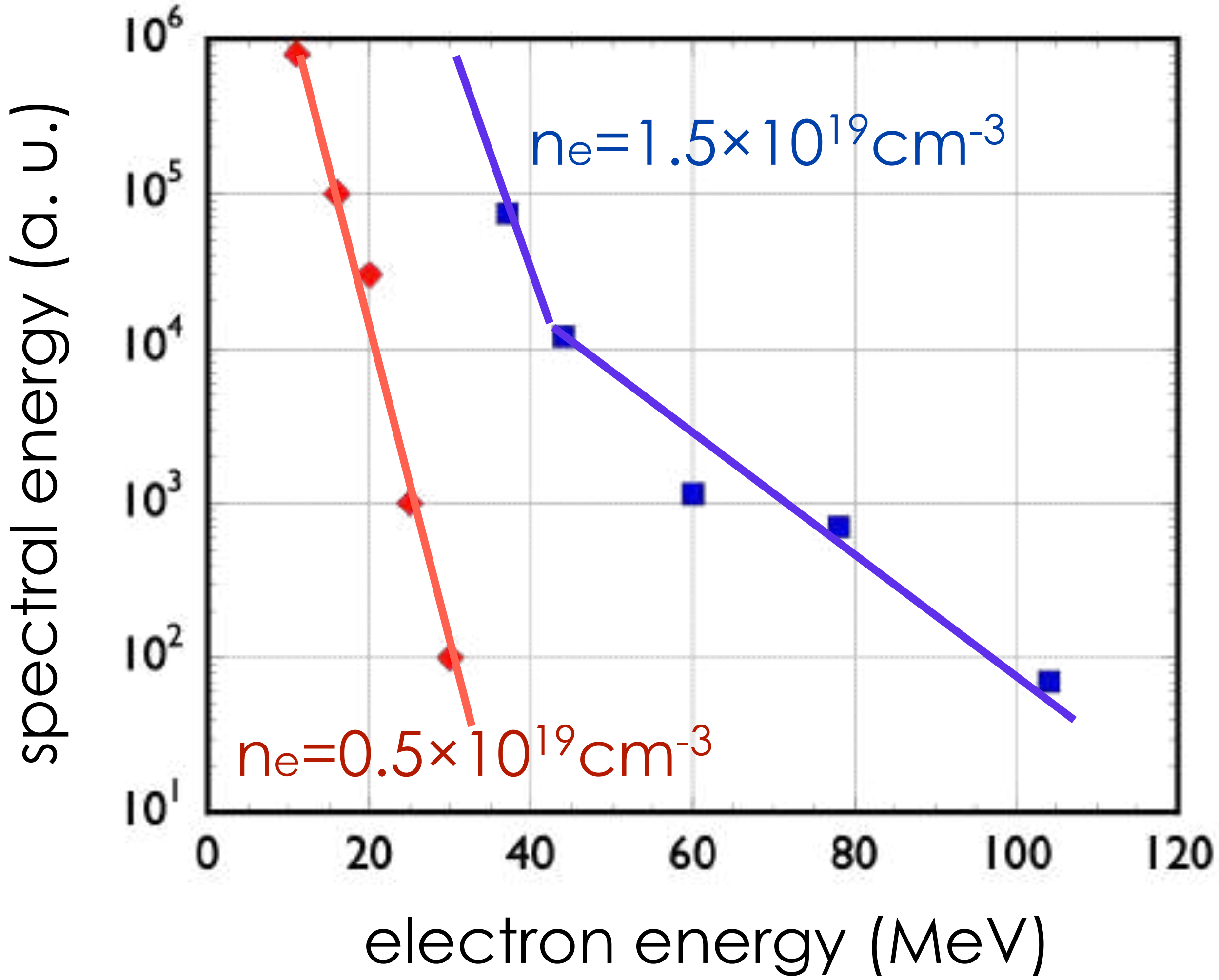
Wave breaking

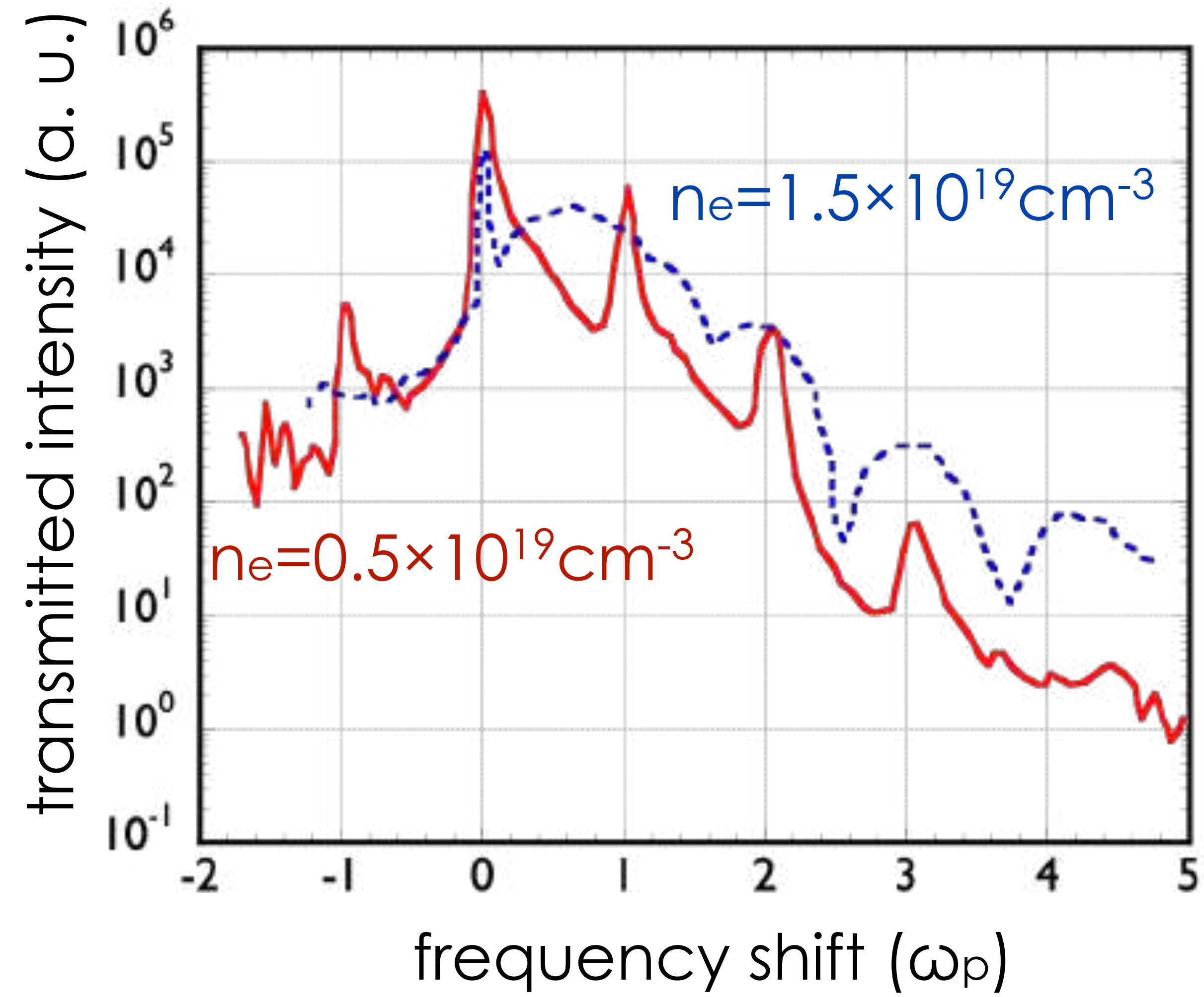


- 1D picture : slides of electrons oscillate at ω_p
- When the trajectories crossed each other: wavebreaking
- Which occurs when each slides displace by λ_p

Wave breaking

1995 Relativistic wave breaking(RAL/IC/UCLA/LULI)





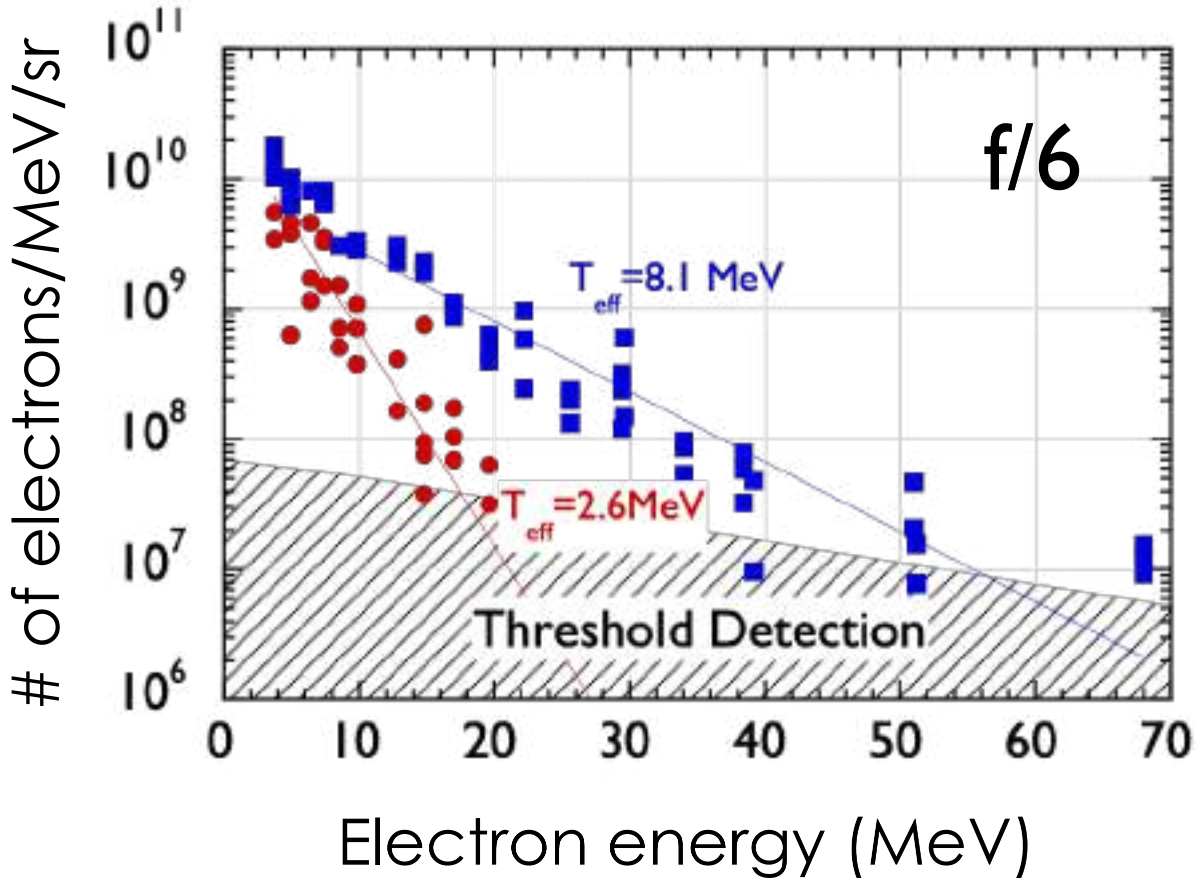
- Multiple satellites : high amplitude plasma waves
- Broadening at higher densities
- Loss of coherence of the relativistic plasma waves

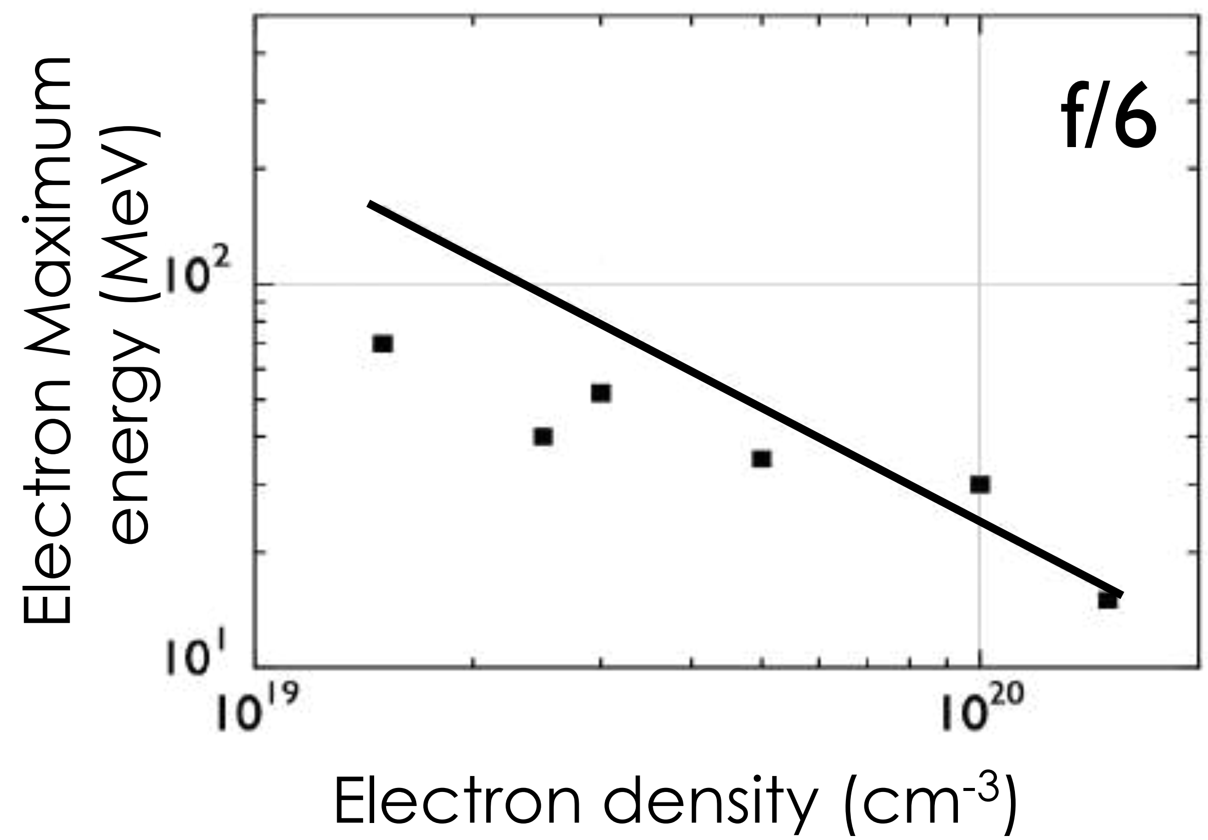
A. Modena *et al.*, Nature (1995)

2001 SMLWF with 10 Hz laser

Spectra : E_{max} increases when n_e decreases

Parameters: $n_e=5\times10^{19}cm^{-3}$ & $1.5\times10^{20}cm^{-3}$, $\tau_L=35fs$, $E=0.6J$, $I_L= 2\times10^{19}W/cm^2$

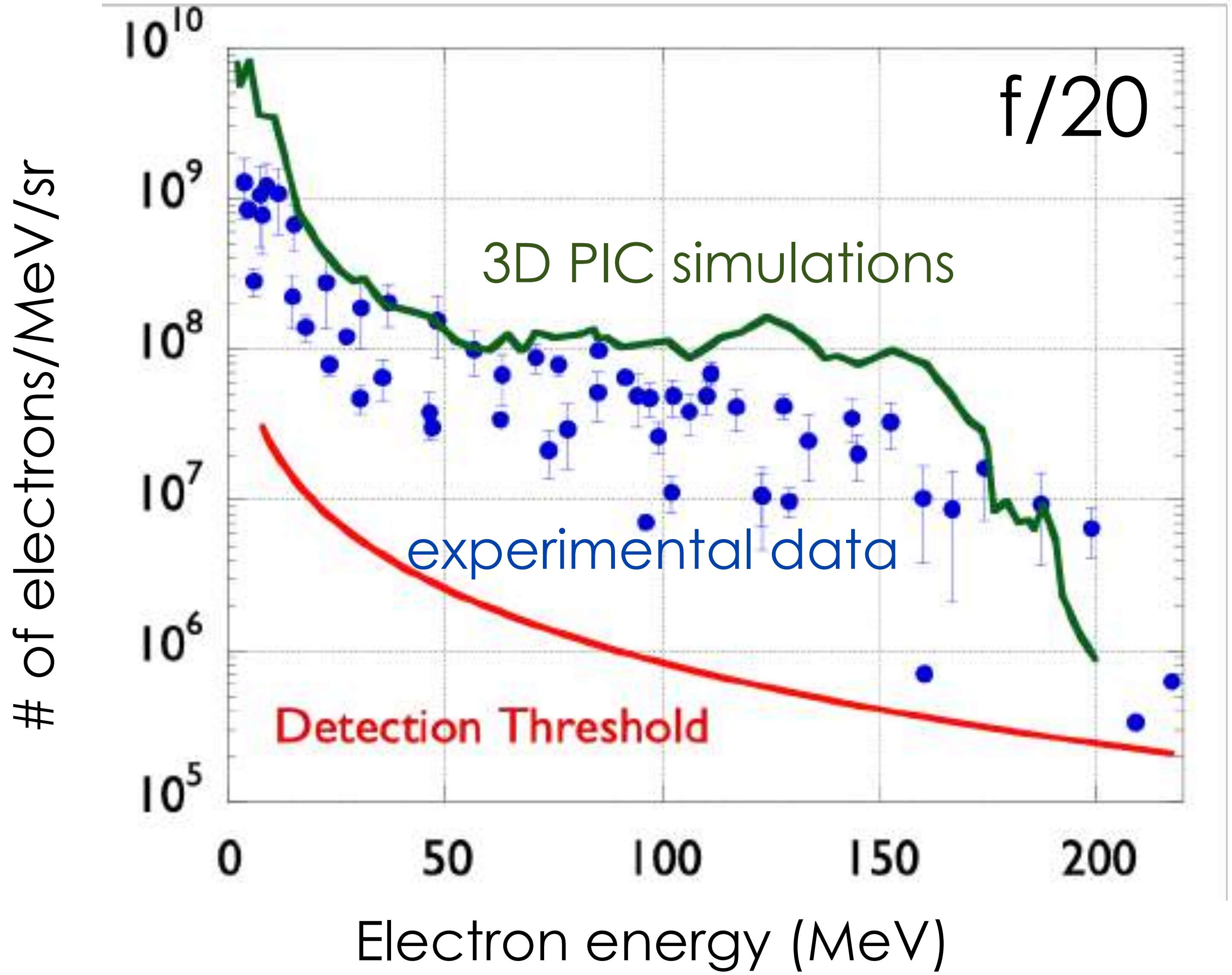




V. Malka et al., Phys. of Plasmas **8**, 6 (2001)

2002 The Forced Laser Wakefield: the NL regime

Parameters: $n_e=1.5\times10^{19}cm^{-3}$, $\tau_L=35fs$, E=0.6J, $I_L= 1\times10^{18}W/cm^2$ with $k_pw_0>1$

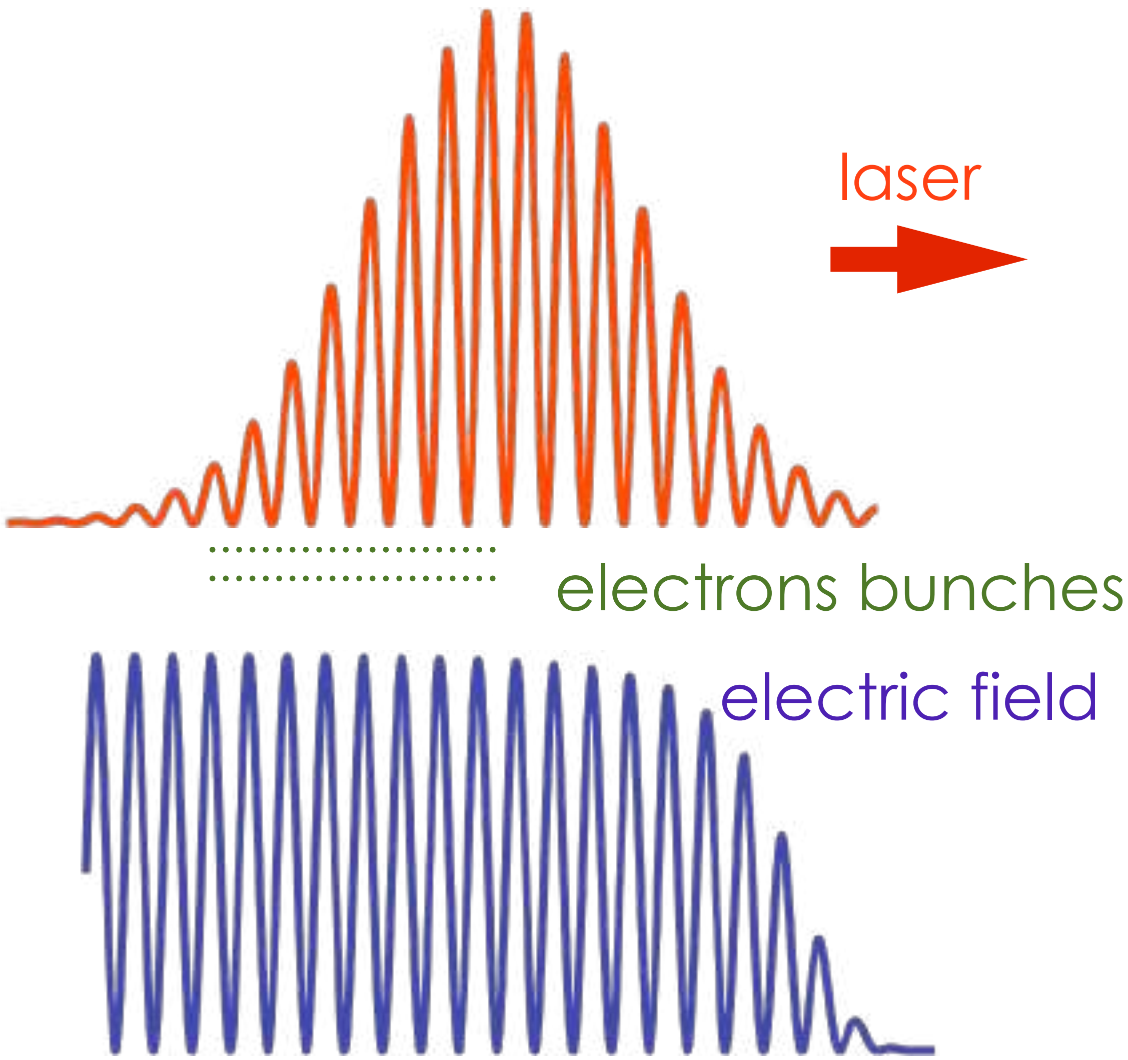


V. Malka *et al.*, Science **298**, 1596 (2002)

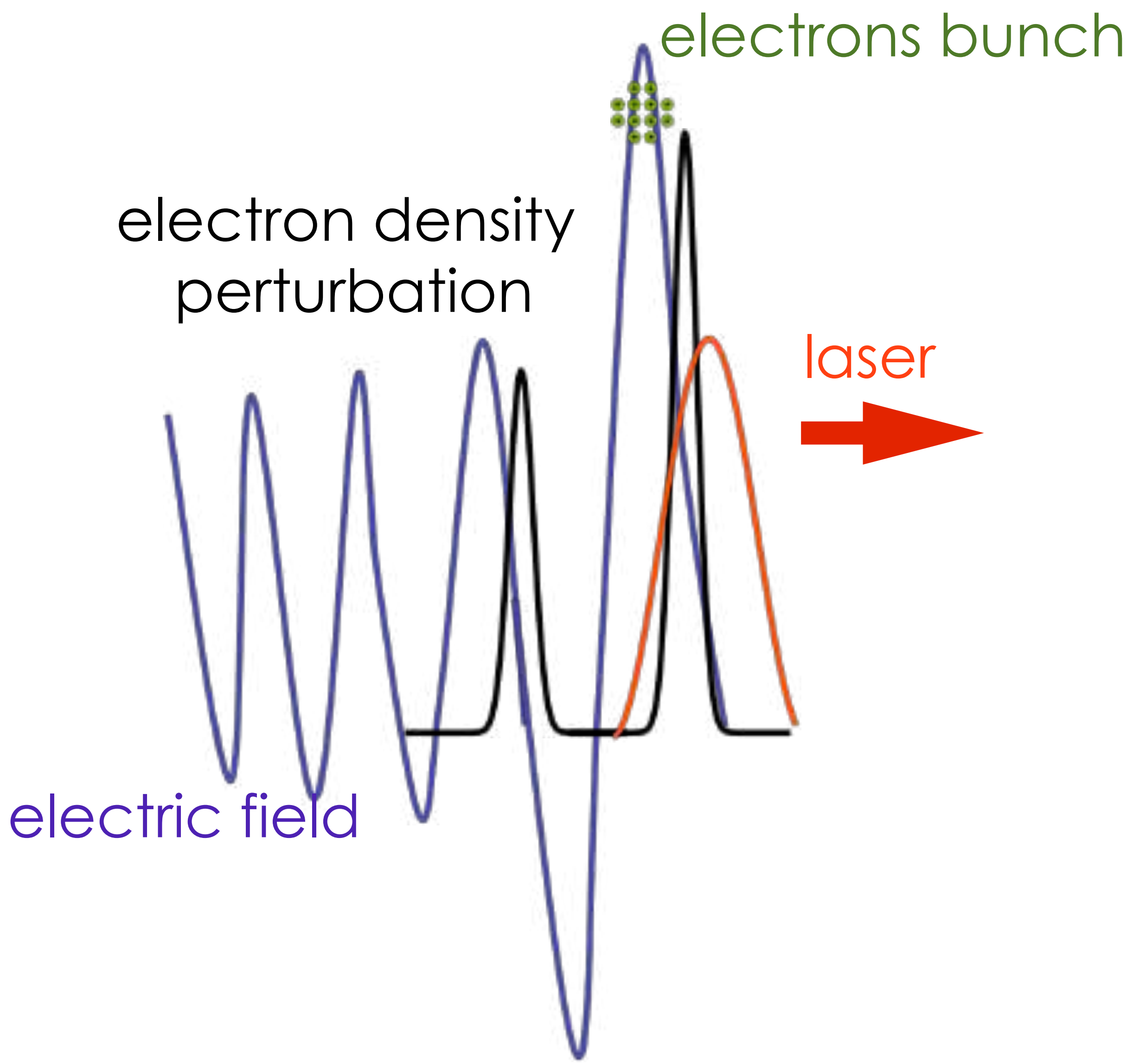
*CARE project

SMLWF / FLWF (ps/fs) :multiple/single bunch

SMLWF: $\omega_p\tau >> 1$



FLWF: $\omega_p\tau \approx 1$

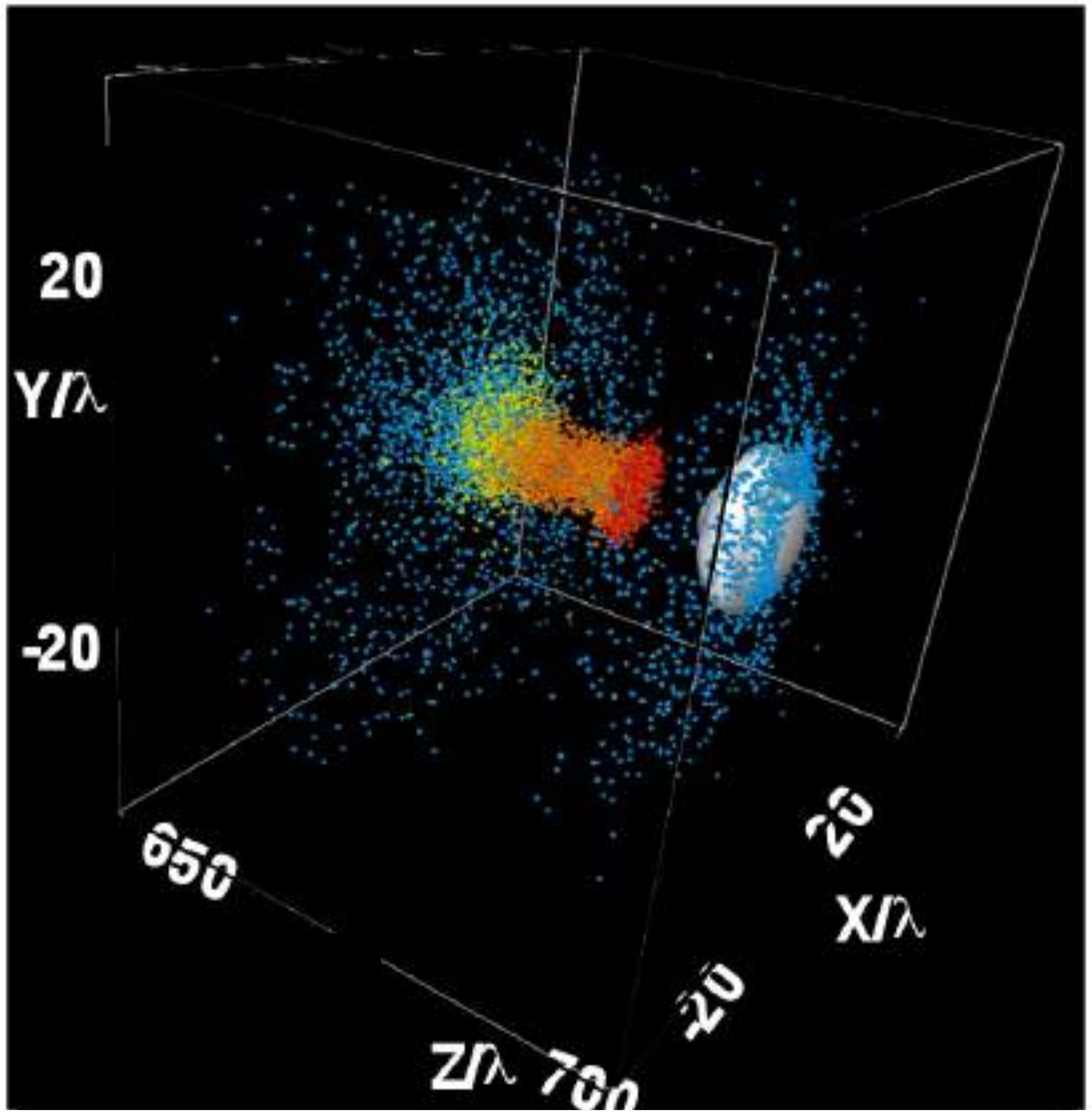


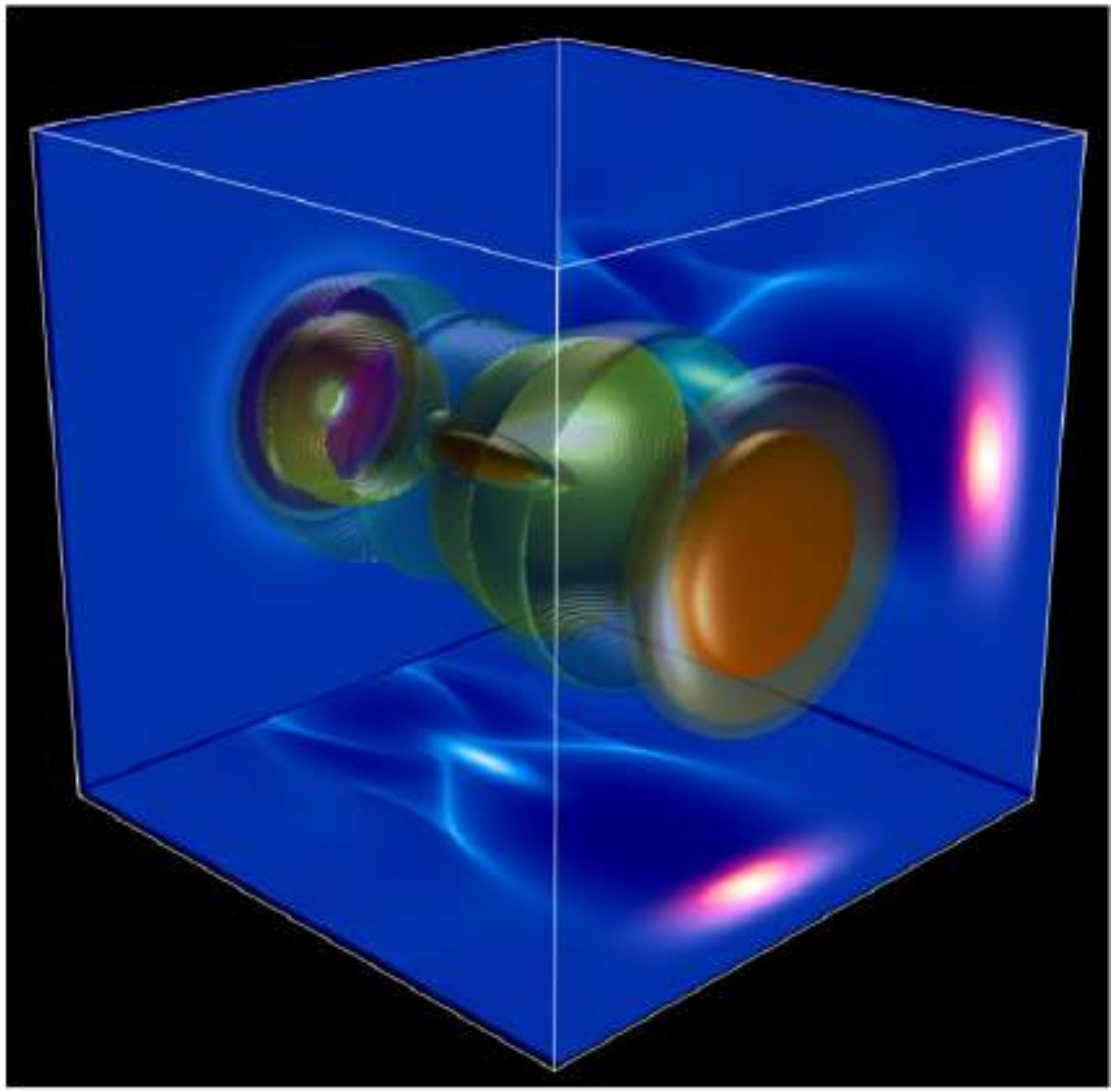
V. Malka, Europhysics News, April (2004)

Part II : External and Self-Injection in LWF

- External injection : Laser wakefield and Beatwave experiments
- Self-injection : Self-Modulated Laser and Forced Wakefield
- Bubble regime
- Ionisation Injection, Gradient and Longitudinal injection

2002 The Bubble regime





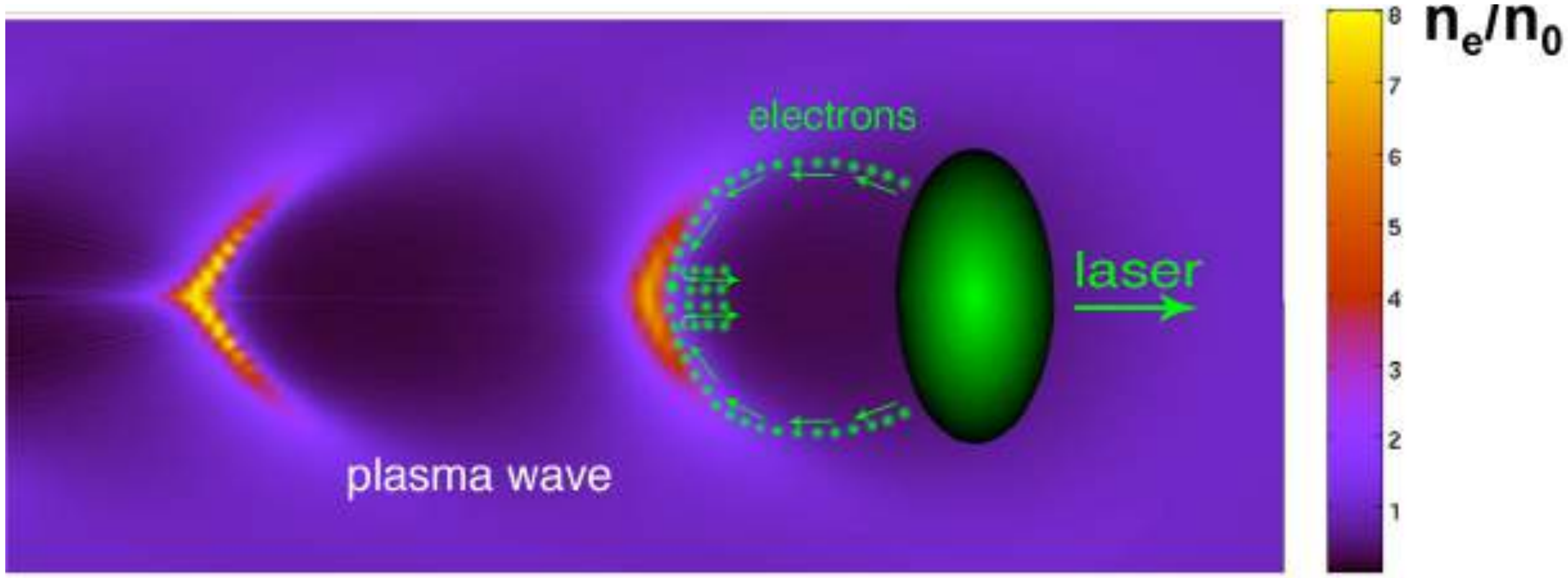
VLPL, courtesy of A. Pukhov

Golp, courtesy of L. Silva

A.Pukhov & J.Meyer-ter-Vehn, Appl. Phys. B, **74** (2002)

Bubble/blow-out regime : principle

Highly non-linear regime : self-injection

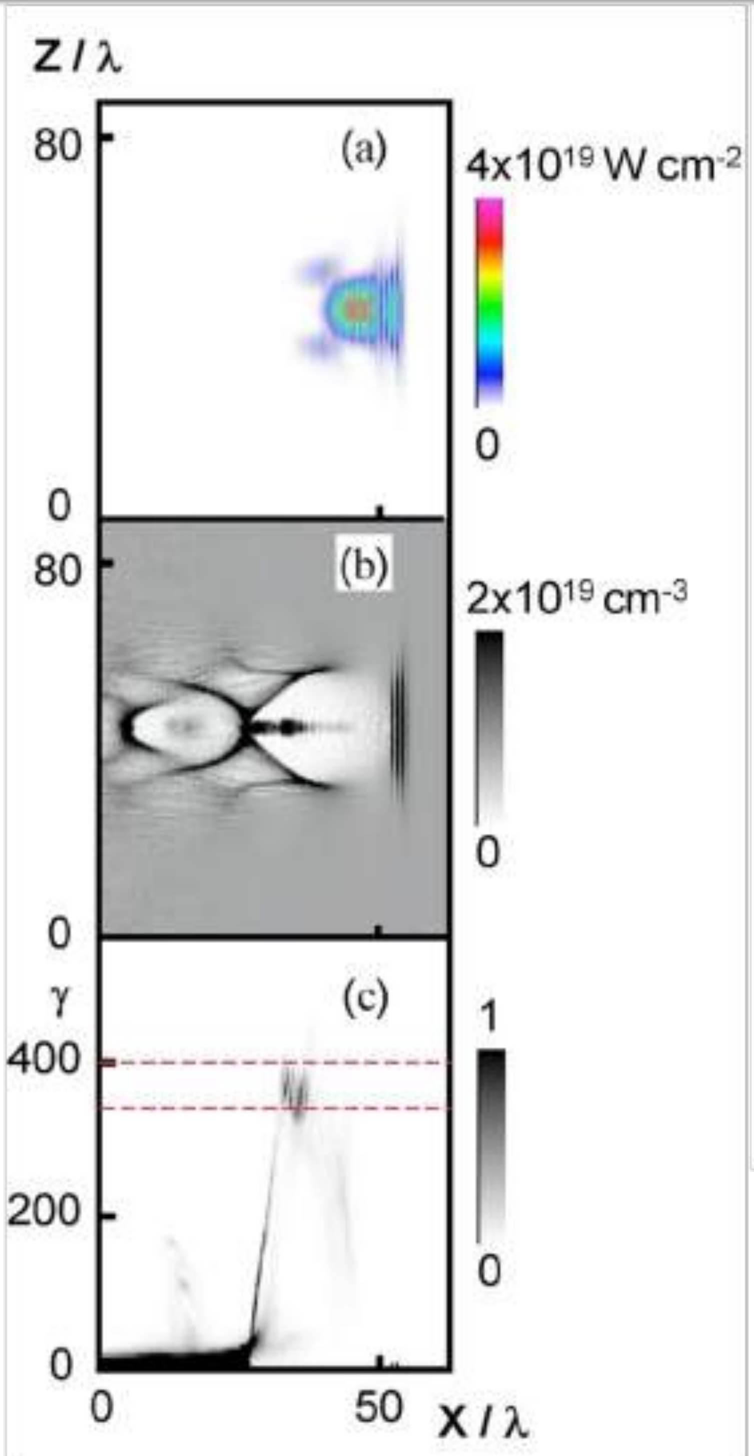


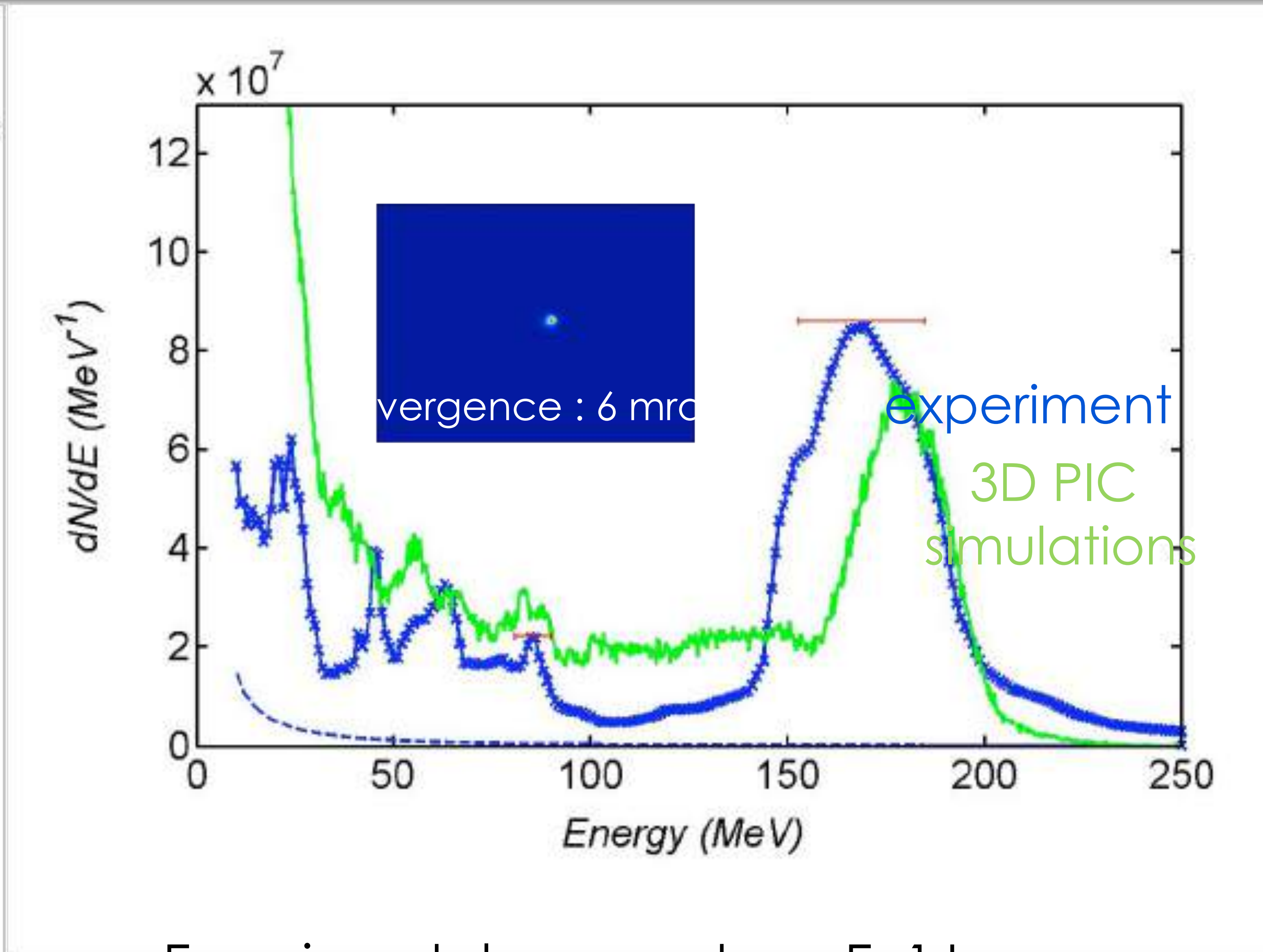
localized self injection in the bubble/blow-out regime

surfing behind a wake boat

A. Pukhov & J. Meyer-ter-Vehn, Appl. Phys. B **74**, 355-361 (2002),

2005 The Bubble regime : theory/experiments





Experimental parameters : E=1J,
τ_L=30fs, λ_L=0.8μm, $I_L=3.2\times10^{19}$W/cm^2,
$n_e=6\times10^{18}$cm^{-3}

J. Faure *et al.*, Nature **431**, 7008 (2004)

2004 The Dream Beam

Monoenergetic beams of relativistic electrons from intense laser–plasma interactions

S. P. D. Mangles[1], C. D. Murphy[1,2], Z. Najmudin[1], A. G. R. Thomas[1], J. L. Collier[2], A. E. Dangor[1], E. J. Divall[2], P. S. Foster[2], J. G. Gallacher[3], C. J. Hooker[2], D. A. Jaroszynski[3], A. J. Langley[2], W. B. Mori[4], P. A. Norreys[2], F. S. Tsung[4], R. Viskup[3], B. R. Walton[1] & K. Krushelnick[1]

[1]*The Blackett Laboratory, Imperial College London, London SW7 2AZ, UK*
[2]*Central Laser Facility, Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, UK*
[3]*Department of Physics, University of Strathclyde, Glasgow G4 0NG, UK*
[4]*Department of Physics and Astronomy, UCLA, Los Angeles, California 90095, USA*

High-quality electron beams from a laser wakefield accelerator using plasma-channel guiding

C. G. R. Geddes[1,2], Cs. Toth[1], J. van Tilborg[1,3], E. Esarey[1], C. B. Schroeder[1], D. Bruhwiler[4], C. Nieter[4], J. Cary[4,5] & W. P. Leemans[1]

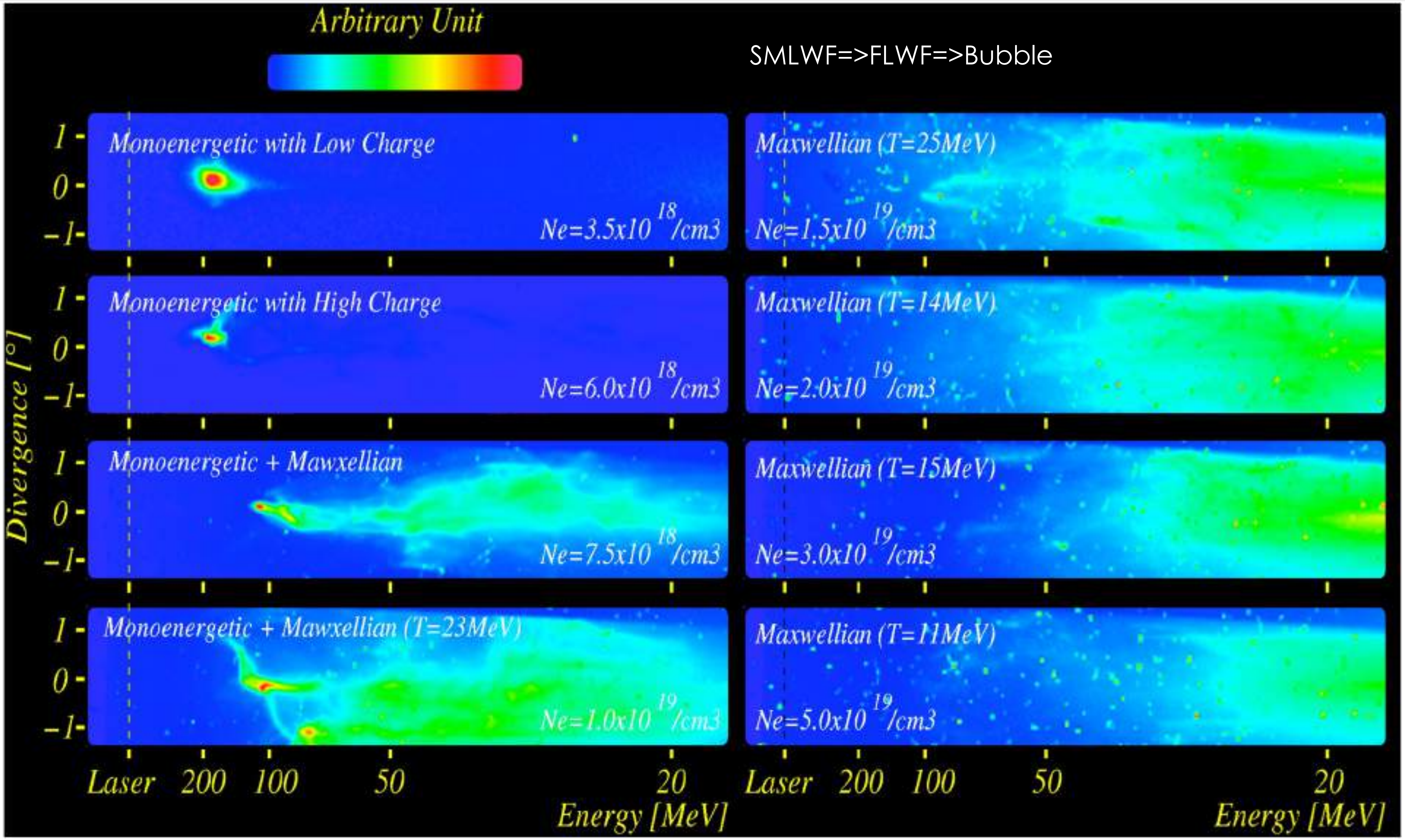
[1]*Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, California 94720, USA*
[2]*University of California, Berkeley, California 94720, USA*
[3]*Technische Universiteit Eindhoven, Postbus 513, 5600 MB Eindhoven, the Netherlands*
[4]*Tech-X Corporation, 5621 Arapahoe Ave. Suite A, Boulder, Colorado 80303, USA*
[5]*University of Colorado, Boulder, Colorado 80309, USA*

A laser–plasma accelerator producing monoenergetic electron beams

J. Faure[1], Y. Glinec[1], A. Pukhov[2], S. Kiselev[2], S. Gordienko[2], E. Lefebvre[3], J.-P. Rousseau[1], F. Burgy[1] & V. Malka[1]

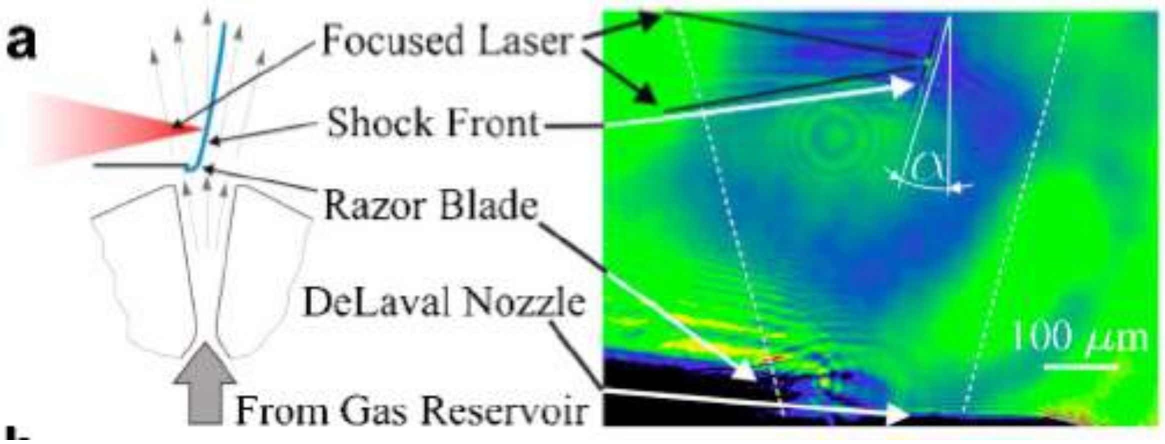
[1]*Laboratoire d'Optique Appliquée, Ecole Polytechnique, ENSTA, CNRS, UMR 7639, 91761 Palaiseau, France*
[2]*Institut fur Theoretische Physik, 1, Heinrich-Heine-Universitat Duesseldorf, 40225 Duesseldorf, Germany*
[3]*Département de Physique Théorique et Appliquée, CEA/DAM Ile-de-France, 91680 Bruyères-le-Châtel, France*

SMLWF => FLWF => Bubble regime

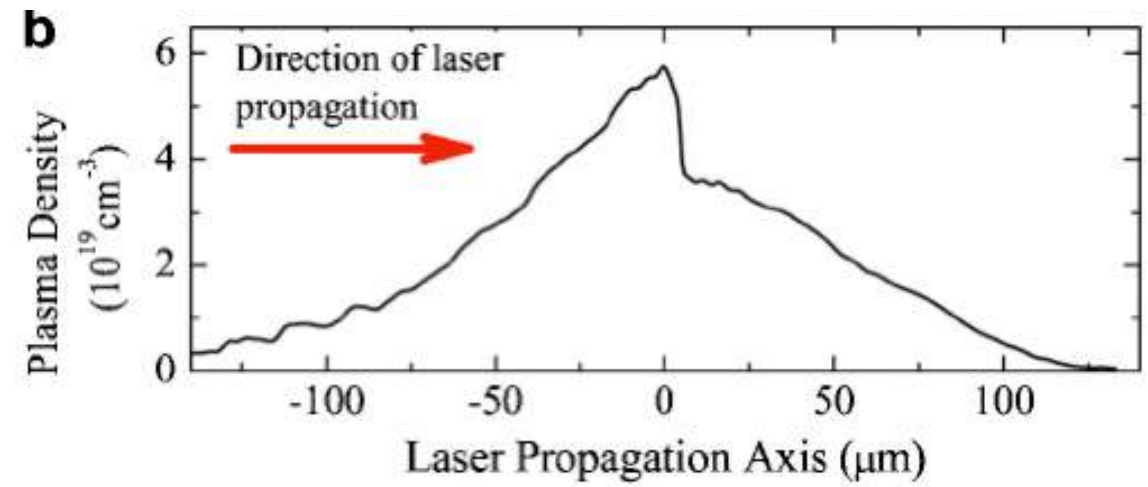


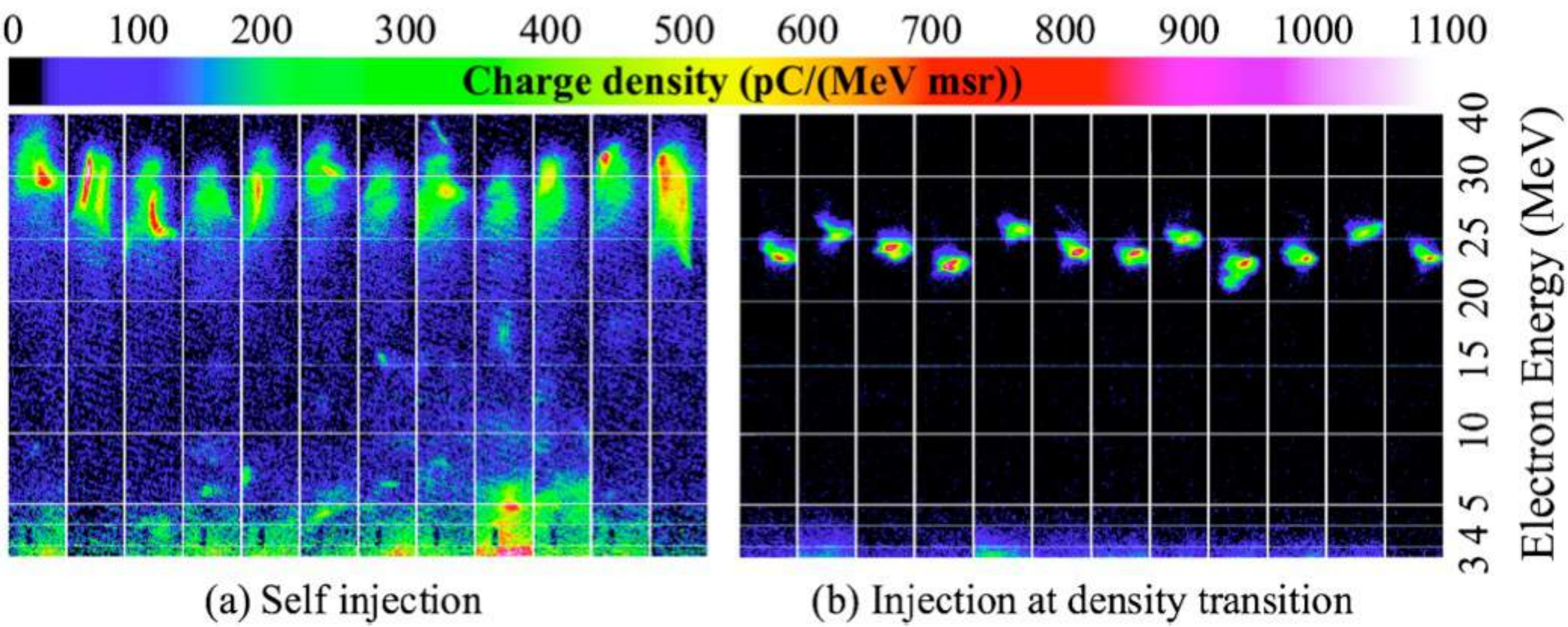
V. Malka *et al.*, Phys. of Plasmas **12**, 5 (2005)

2010 Sharp density ramp injection



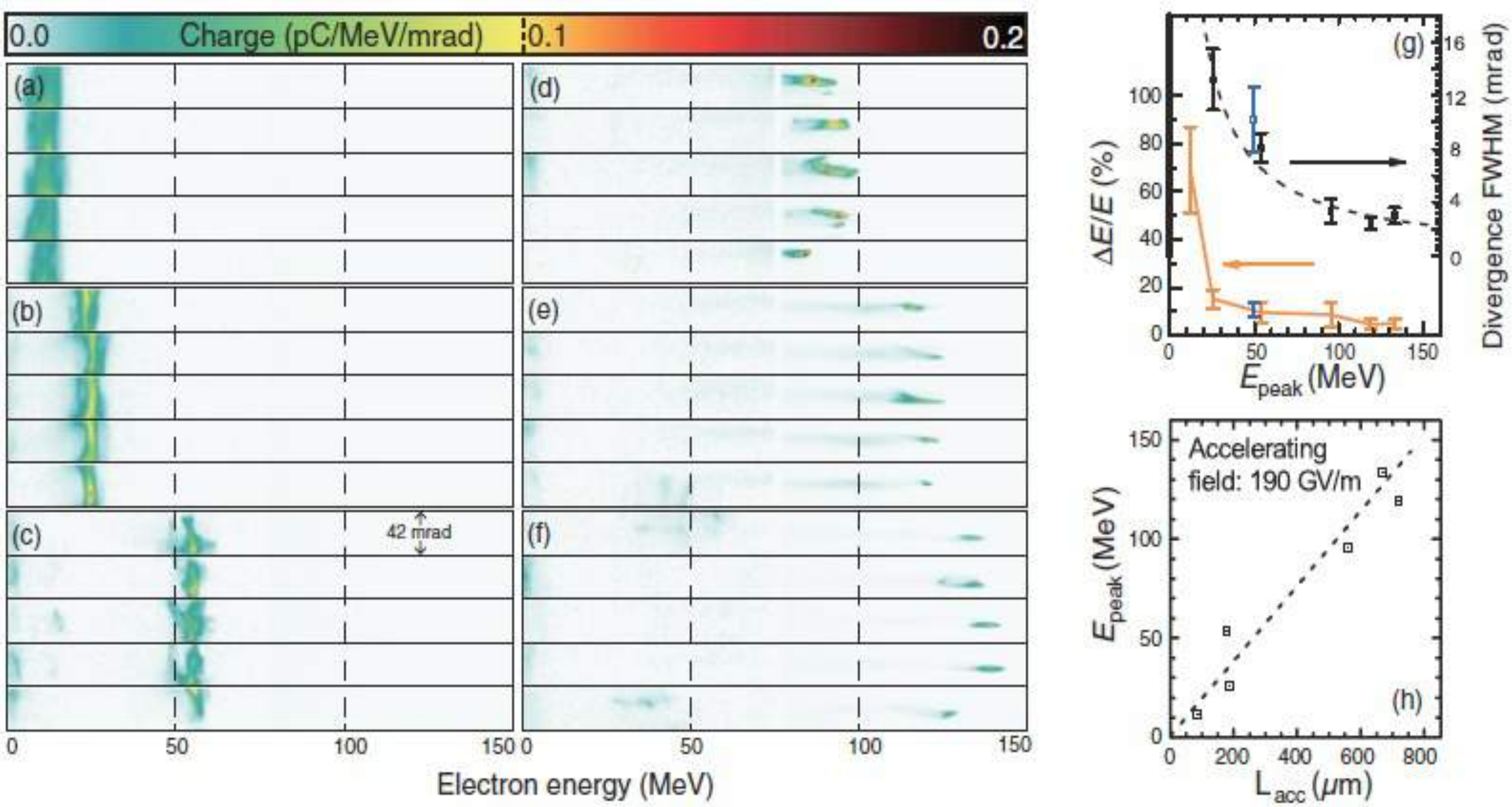
=>





K. Schmid et al., PRSTAB 13, 091301 (2010)

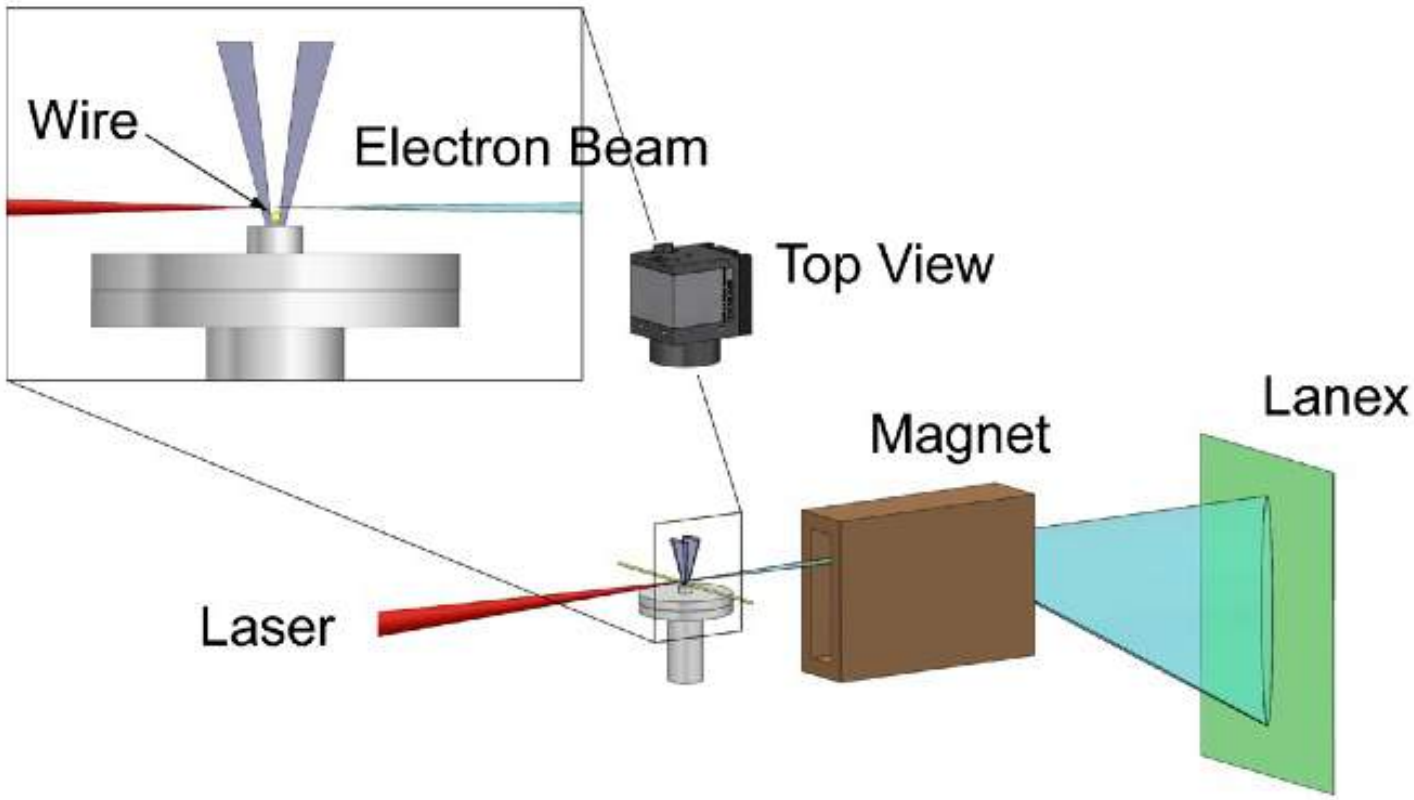
2013 Shock front injection

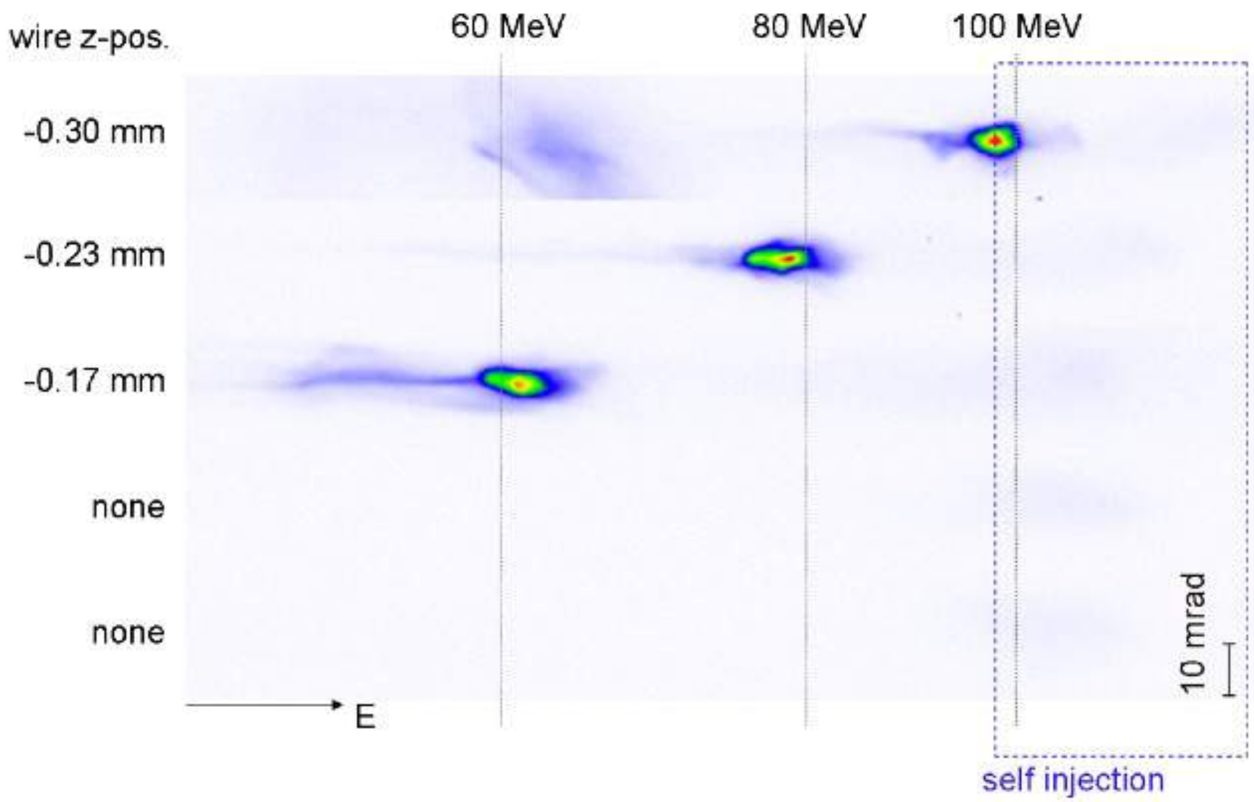


A. Buck *et al.*, PRSTAB 13, 091301 (2010)

2013 Shock front injection : LLC

Laser wakefield acceleration using wire produced double density ramps





M. Burza *et al.*, PRSTAB 16, 011301 (2013)

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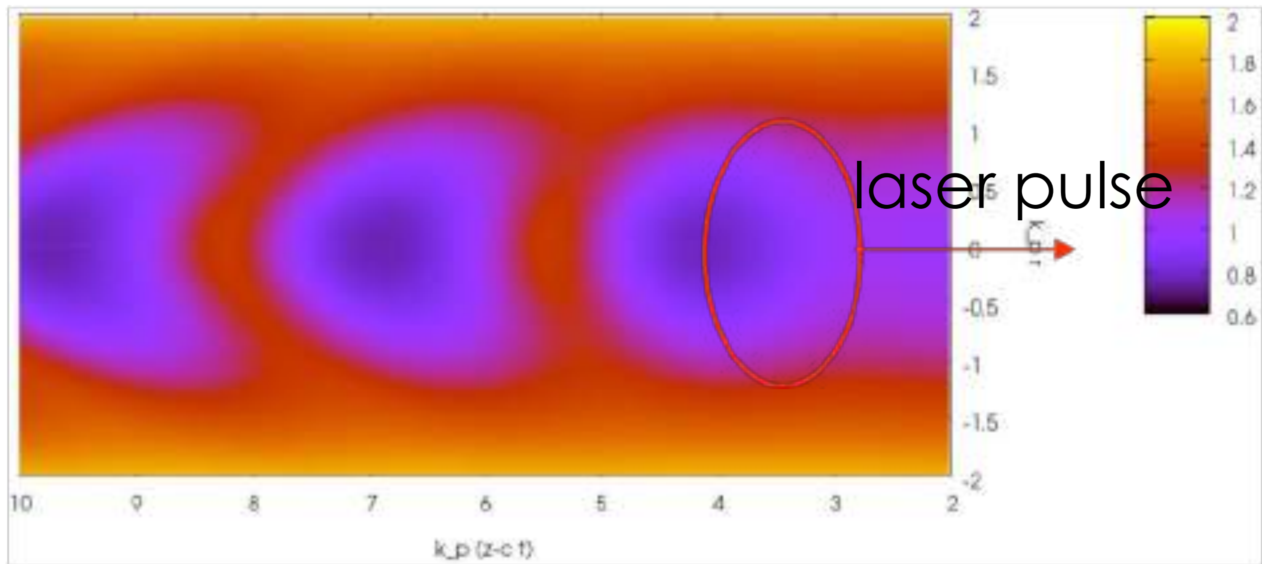
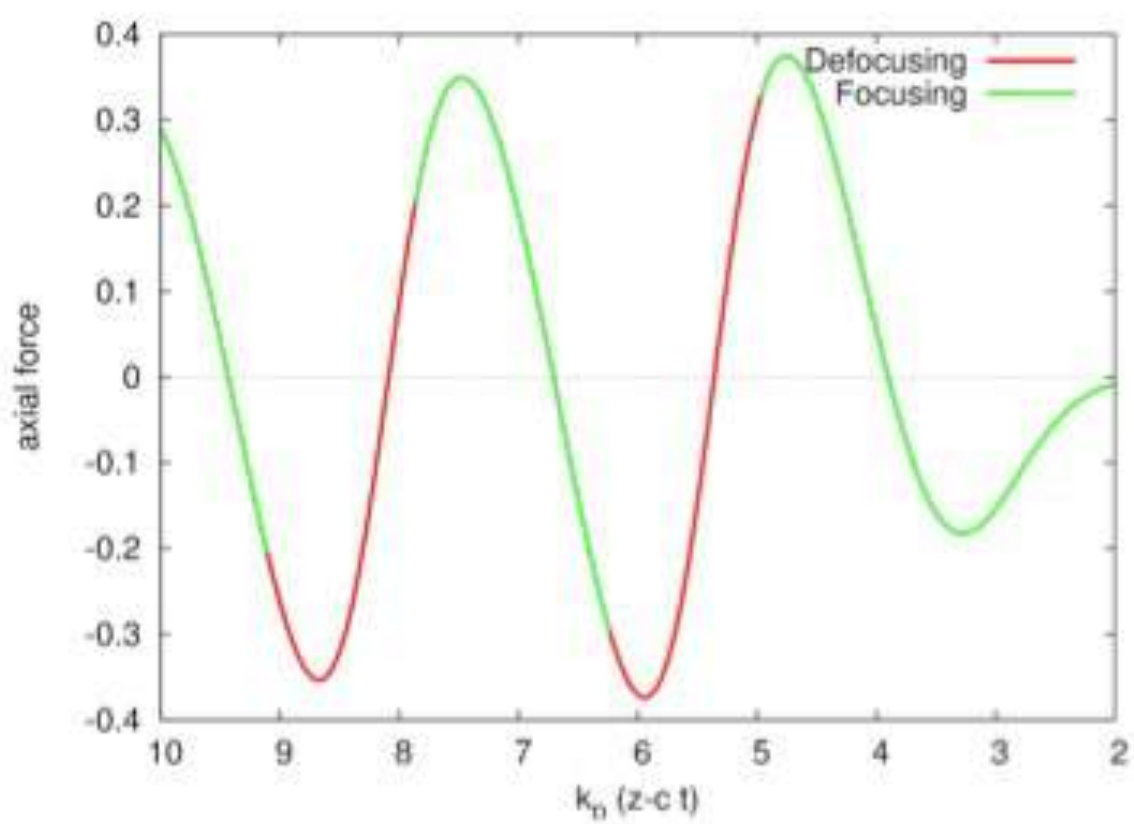
Towards a two stage plasma accelerator

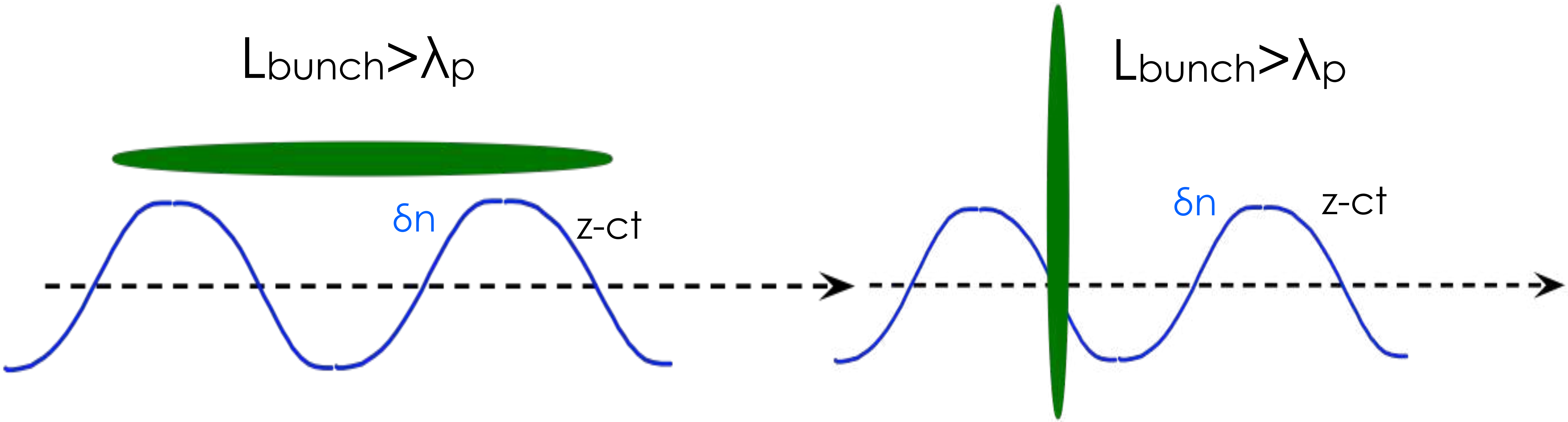
Small Laser amplitude a_0=0.5 & Parabolic plasma channel





V. Malka *et al.*, PRST-A **9**, 9 (2006)

Towards a two stage plasma accelerator



Different phases =>

Different E field =>

100 % energy spread

electrons "in phase" =>

same E field =>

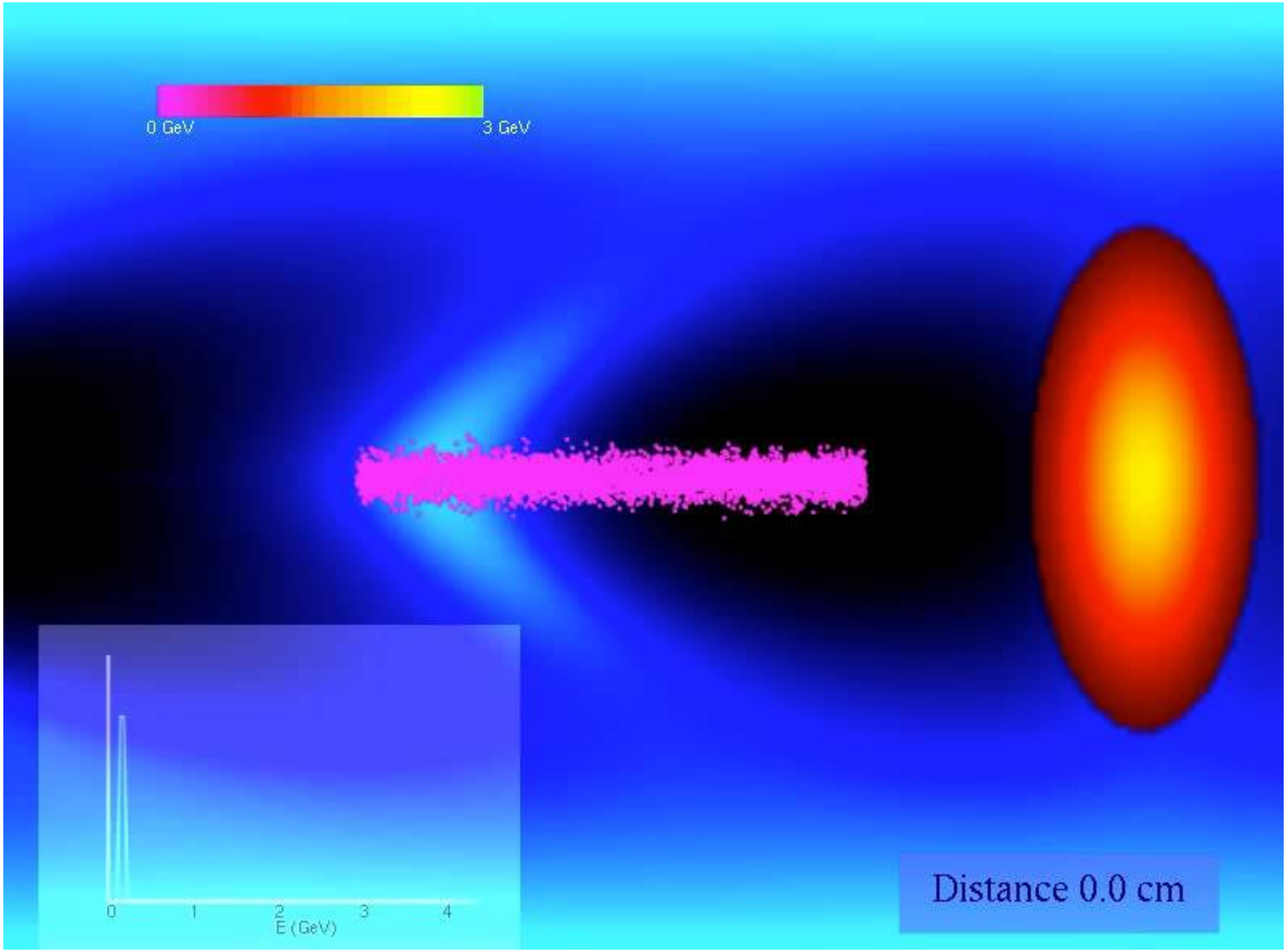
low energy spread

One needs L_{bunch} < 100 fs

Challenge for RF technology

Wake simulations of injected 100 fs electrons bunch

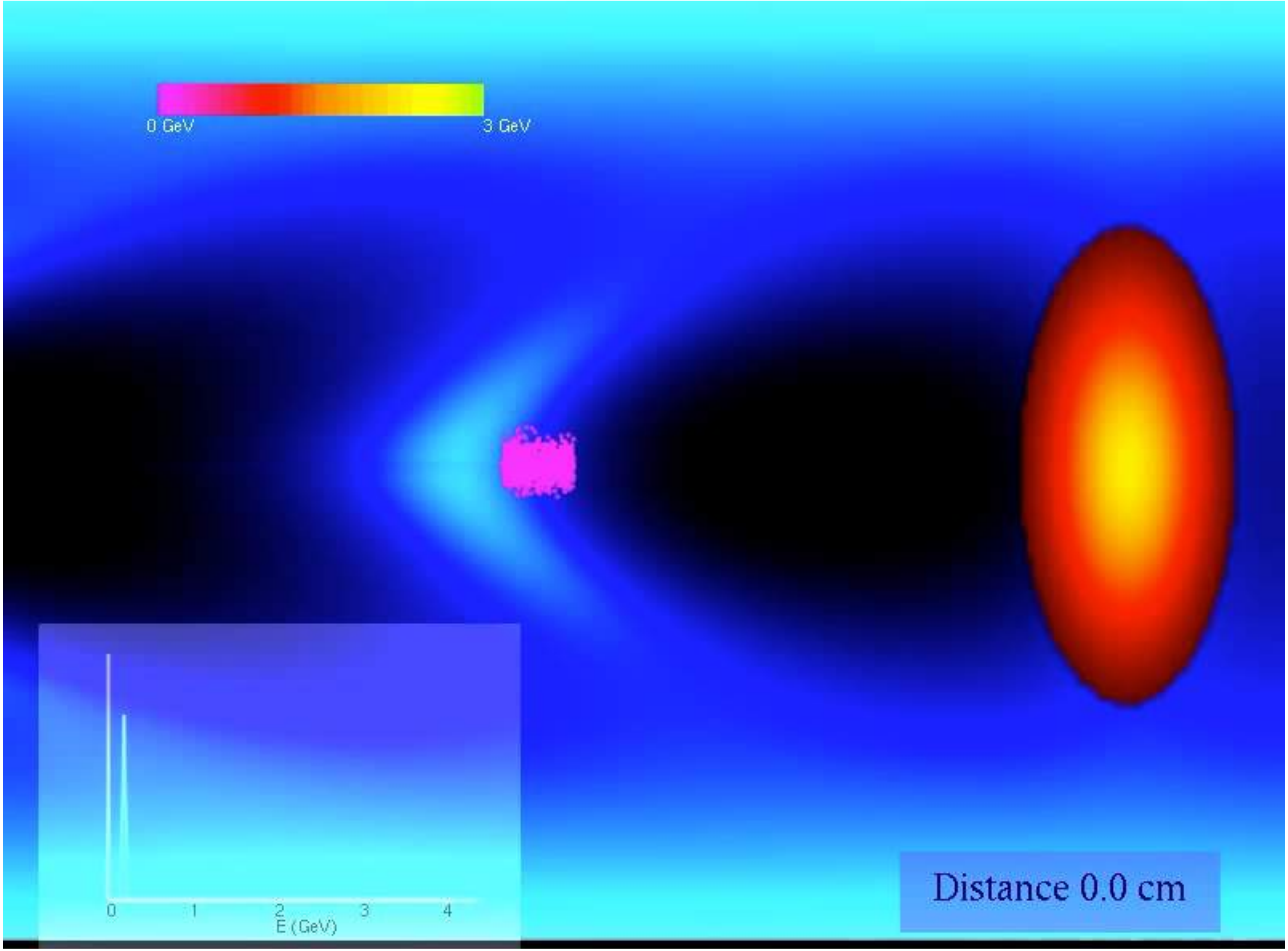
E=170 MeV, Laser : 9J, 150 TW, 60fs



V. Malka *et al.*, PRST-A **9**, 9 (2006)

Wake simulations of injected 30 fs electrons bunch

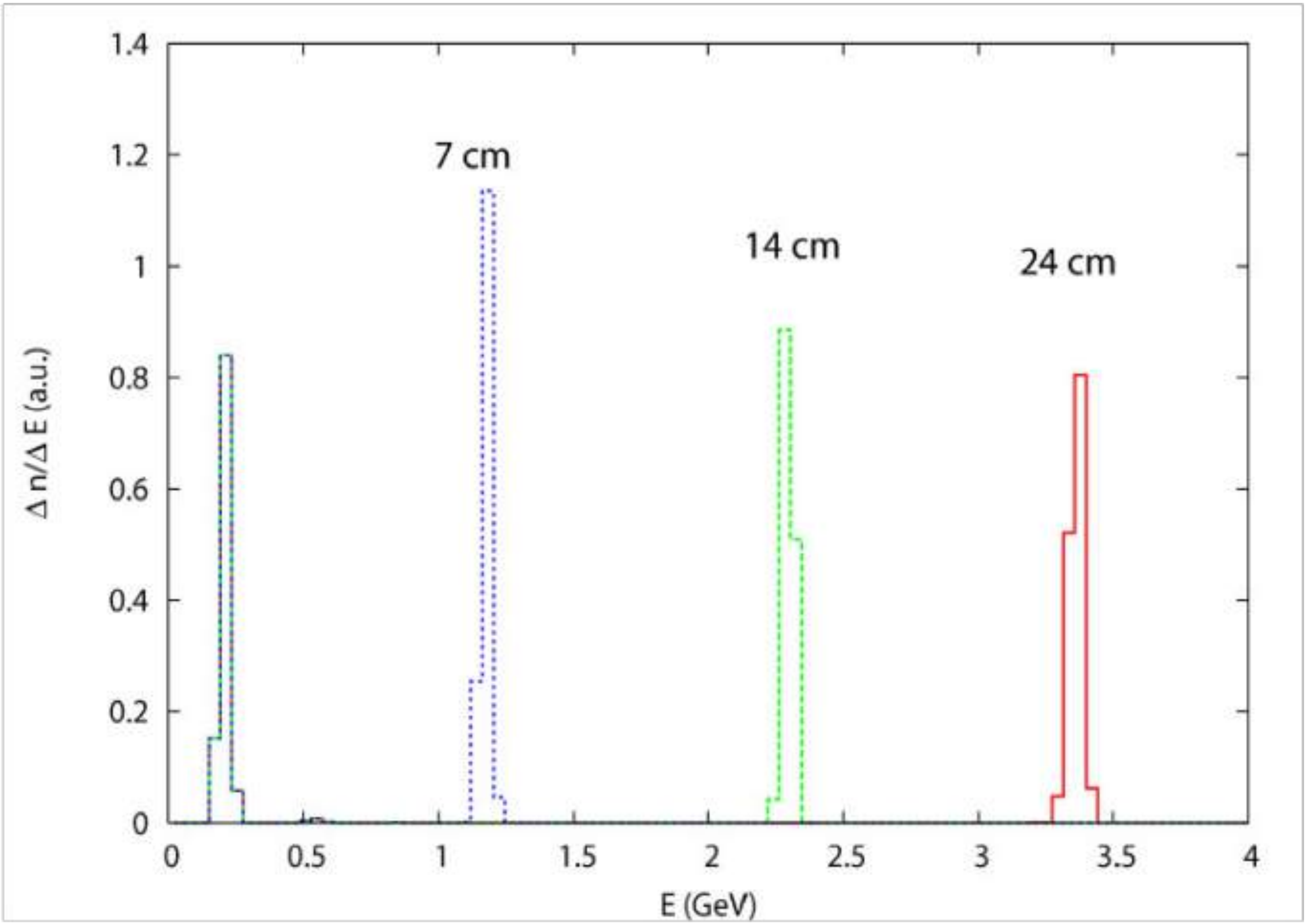
E=170 MeV, Laser : 9J, 150 TW, 60fs



V. Malka *et al.*, PRST-A **9**, 9 (2006)

Wake simulations of injected 30 fs electrons bunch

E=170 MeV, Laser : 9J, 150 TW, 60fs

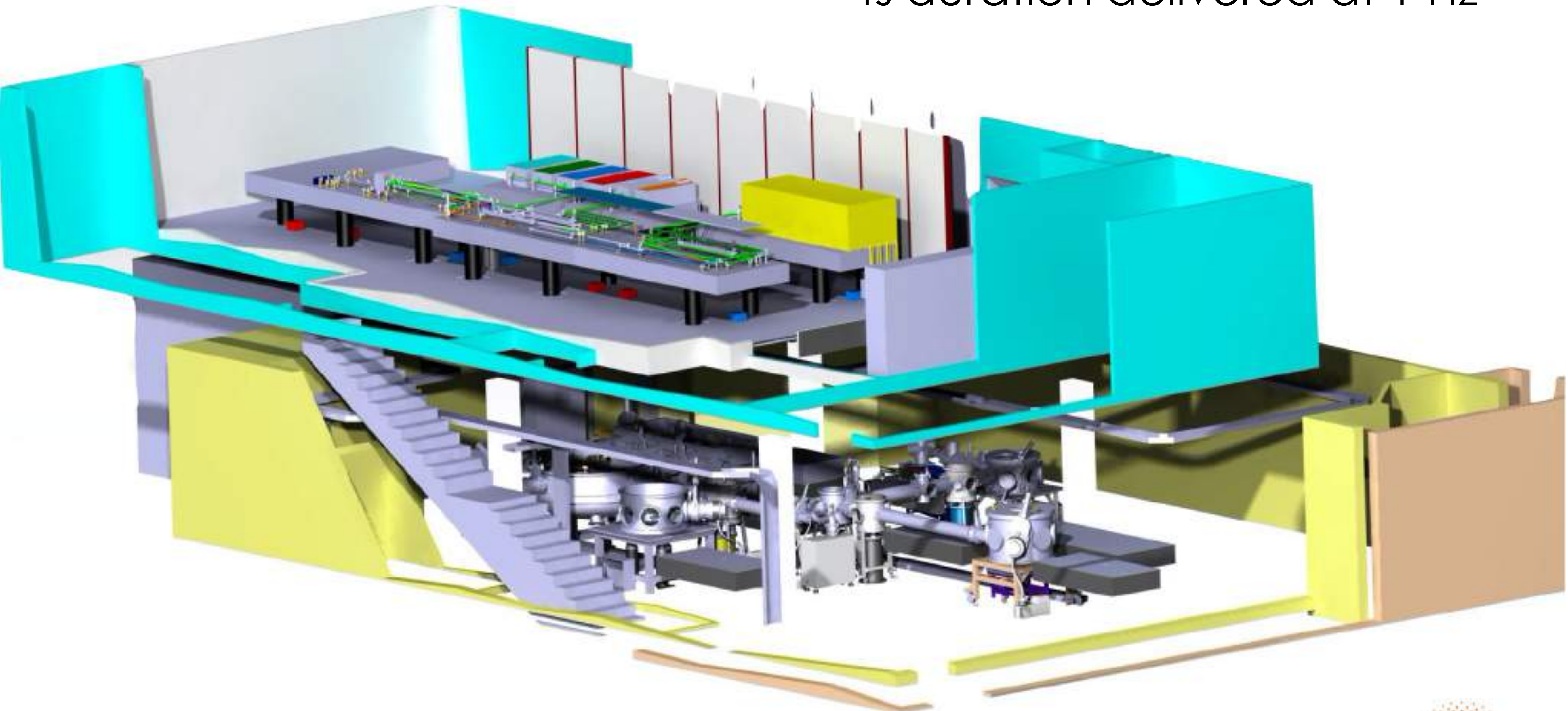


- E=9 J
- P= 0.15 PW
- a_0=1.5
- Parabolic channel:
- r_0=47 μm,
- $n(r)=n_0\ (1+0.585\ r/r_0)$
- $n_0 = 1.1\times10^{17}\ cm^{-3}$

3.5 GeV, with a relative energy spread FWHM of 1% and an un-normalized emittance of 0.006 mm

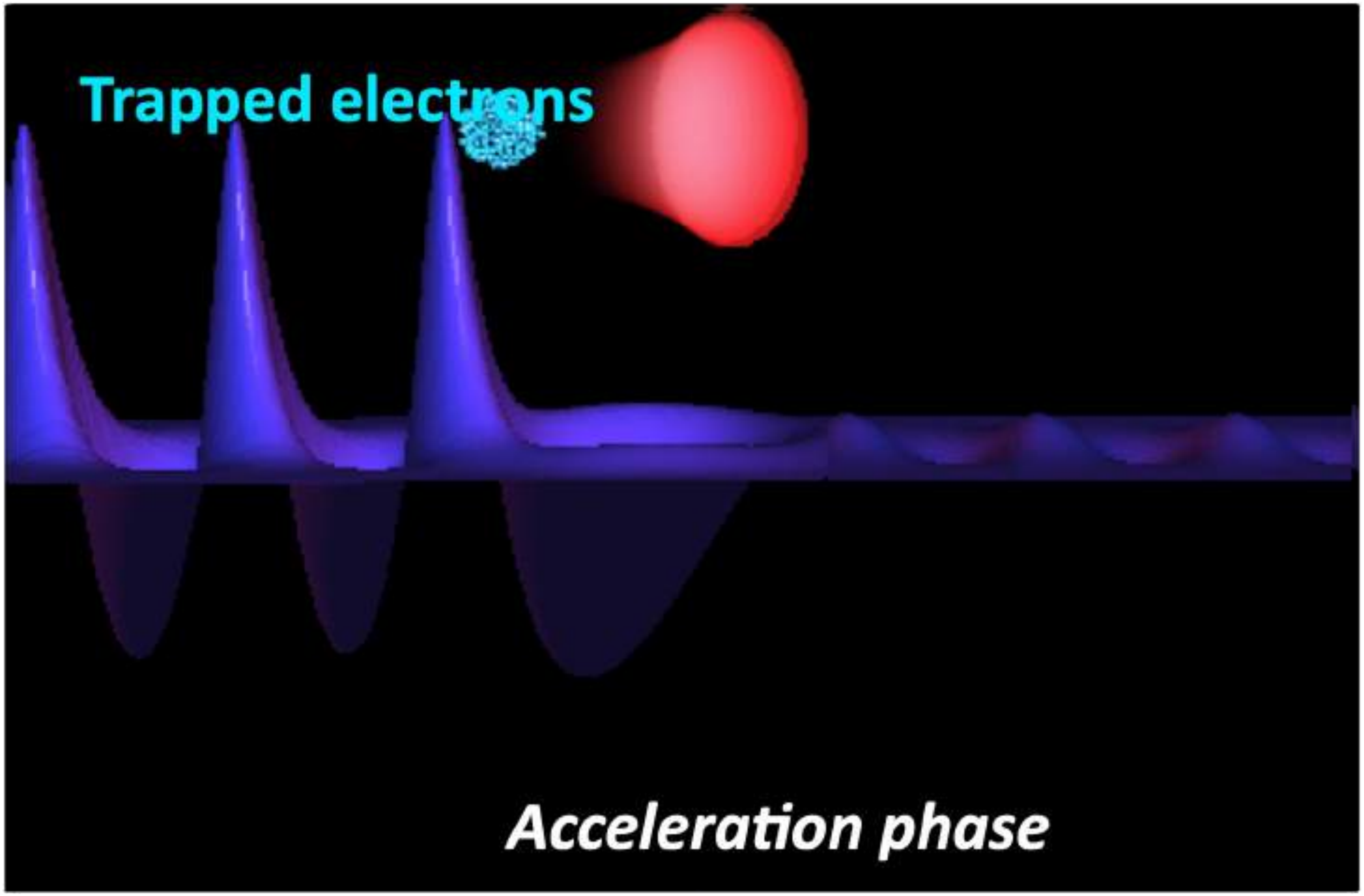
« Salle Jaune Laser » : Home made laser

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



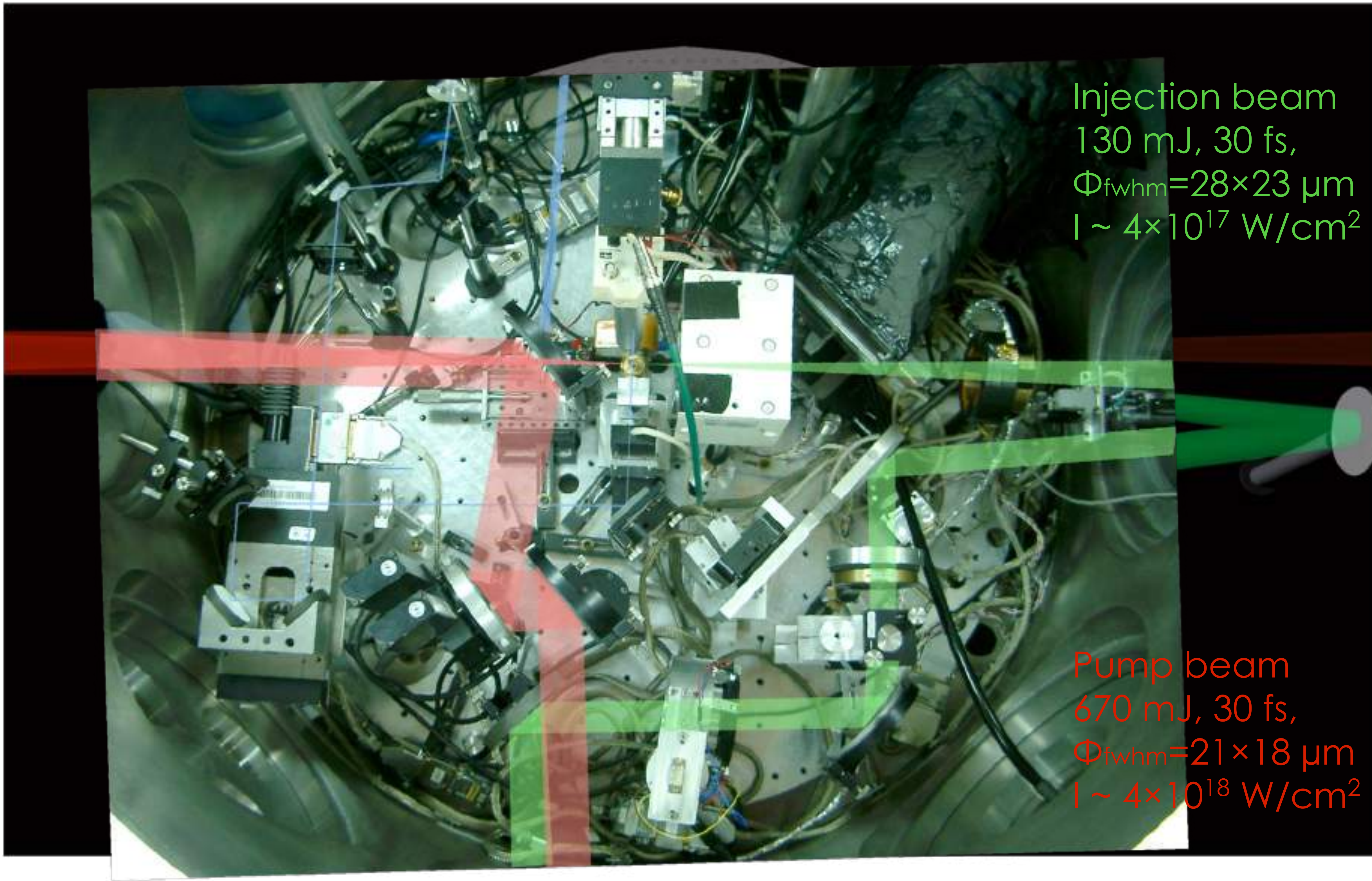
R. Lehe

Colliding Laser Pulses Scheme

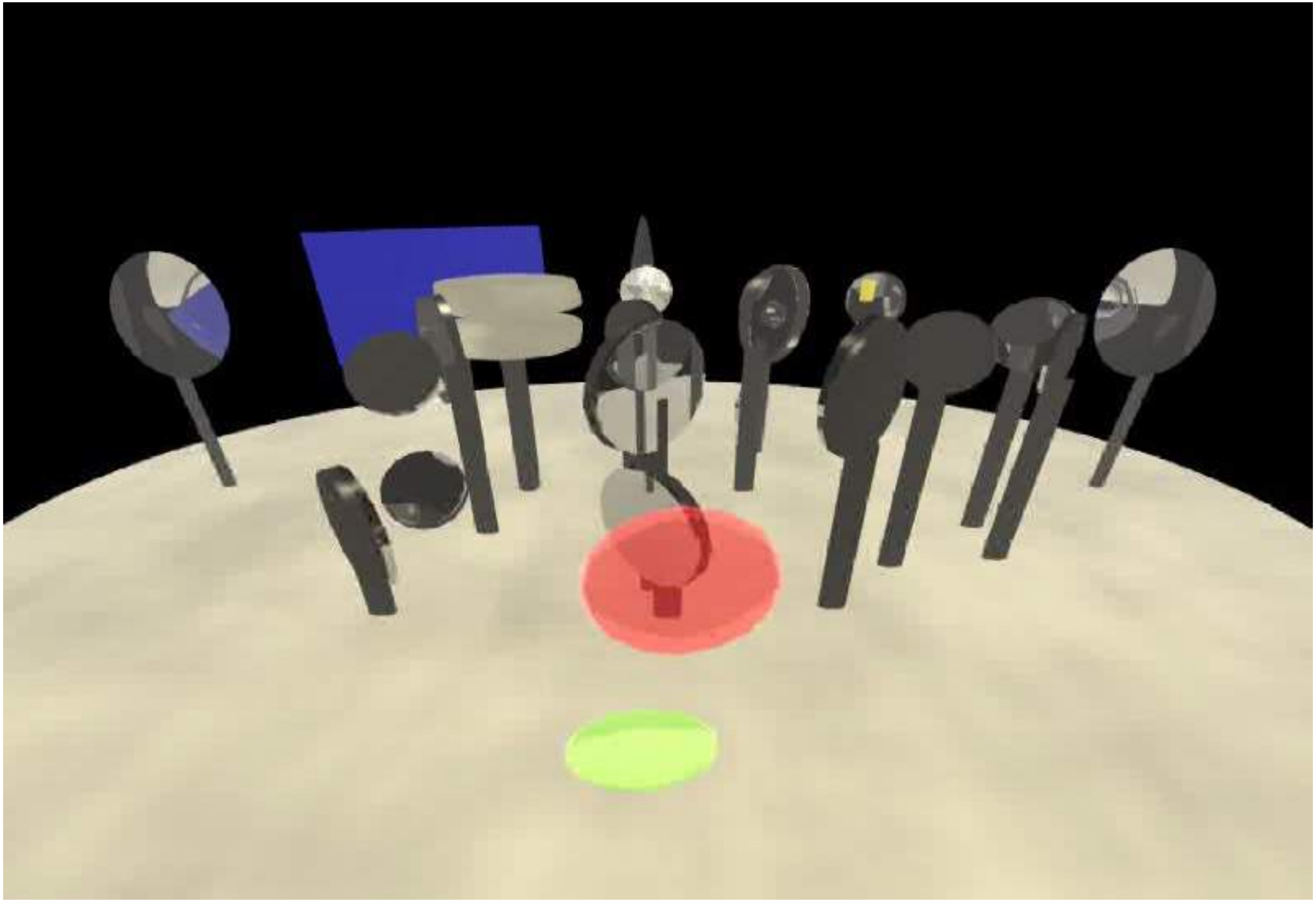


The first laser creates the accelerating structure
A second laser beam is used to heat electrons

Set-up for colliding pulses experiment

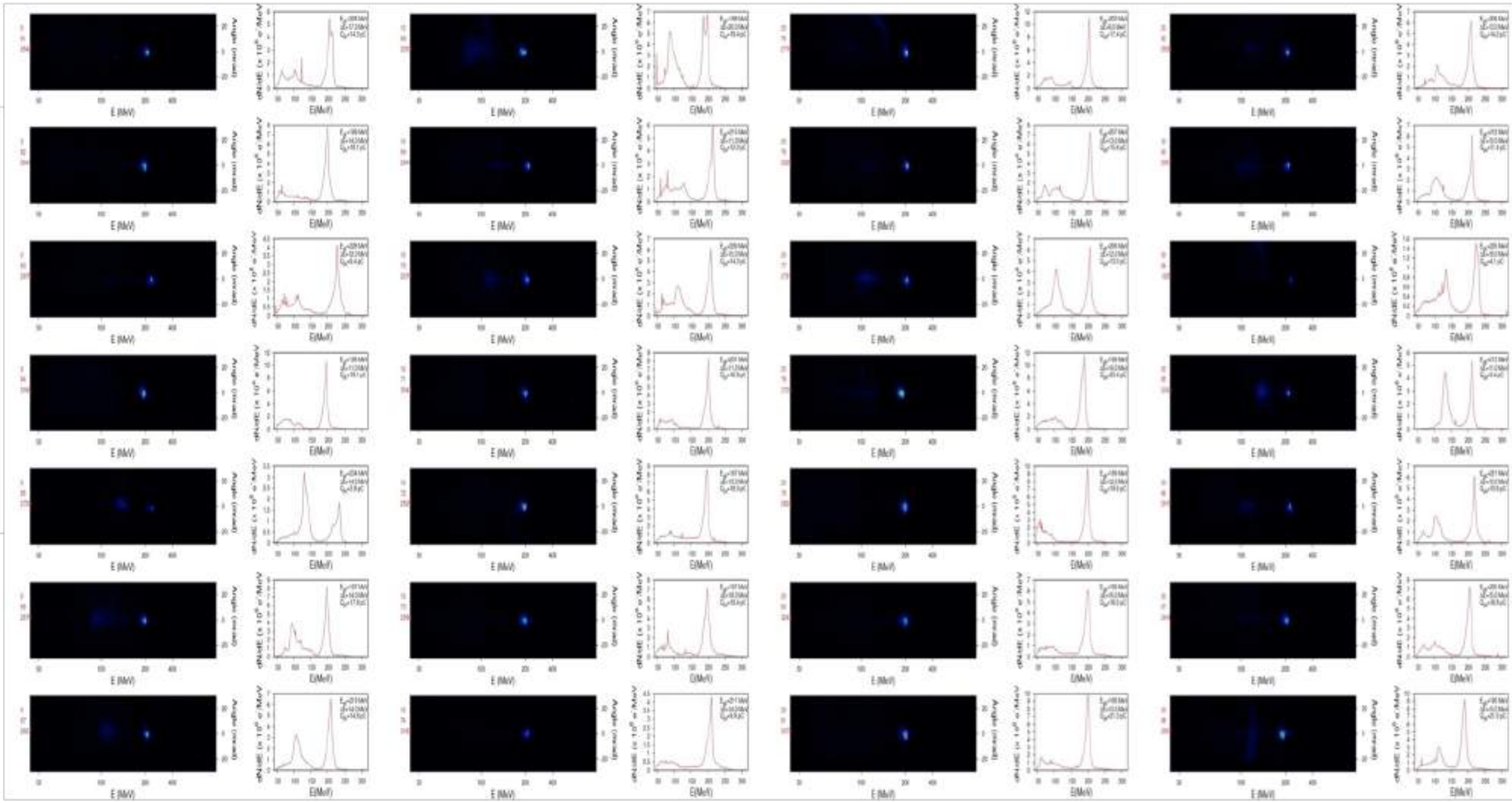


The colliding of two laser pulses scheme

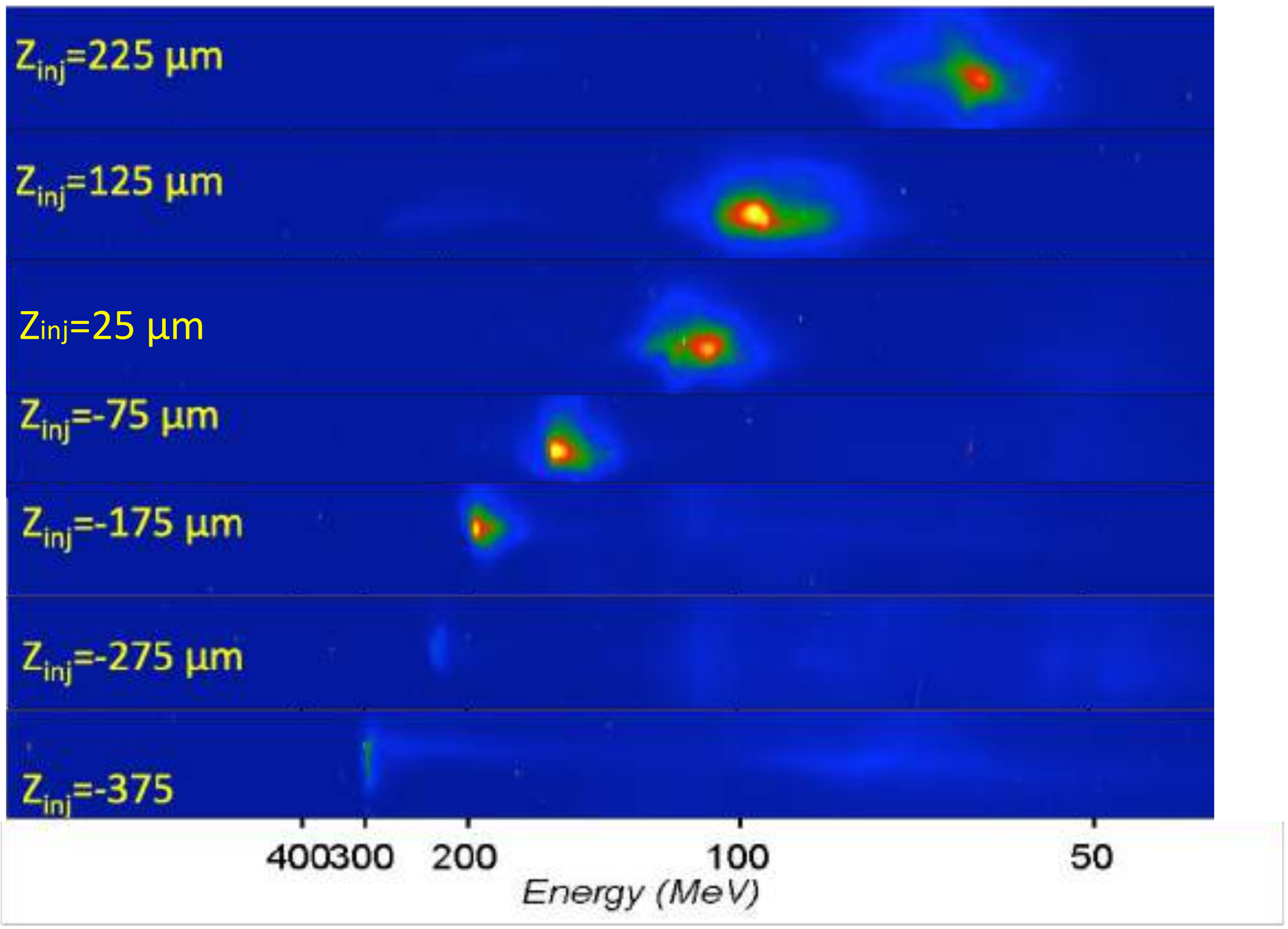


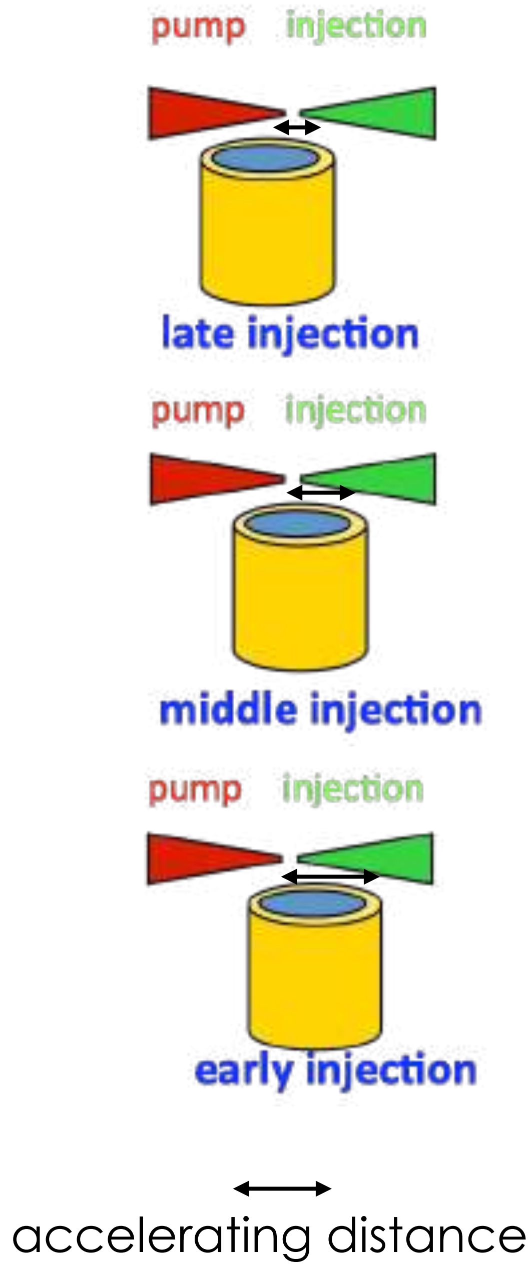
Towards a Stable Laser Plasma Accelerators

Series of 28 consecutive shots with : $a_0=1.5$, $a_1=0.4$, $n_e=5.7\times10^{18}cm^{-3}$



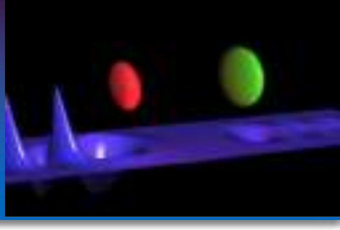
Tunability of the electrons energy

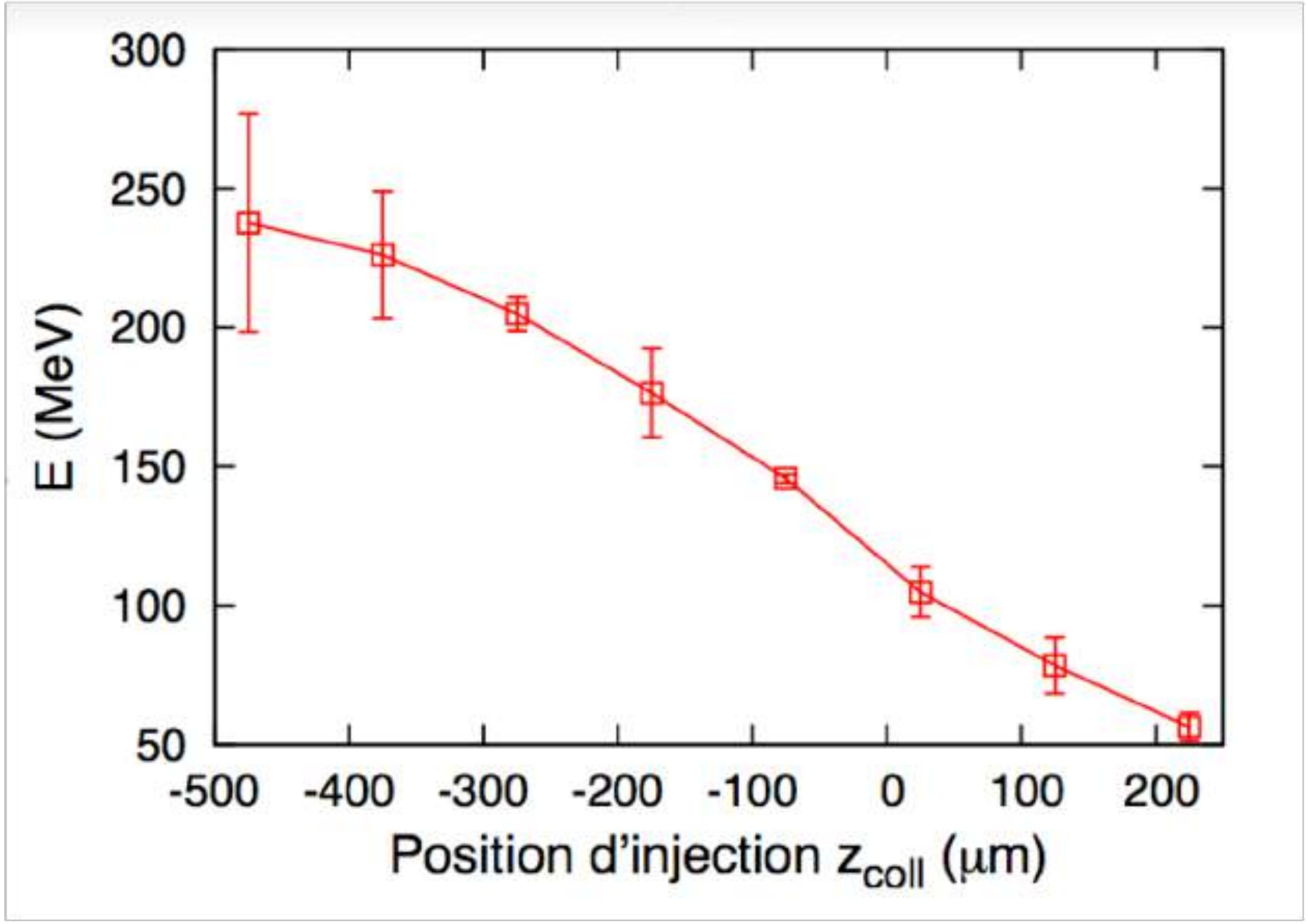




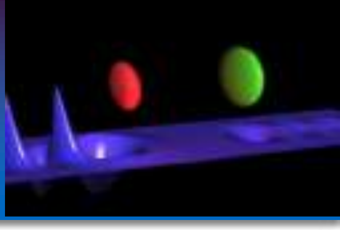
J. Faure *et al.*, Nature **444**, 737 (2006)

Tunability of the electrons energy



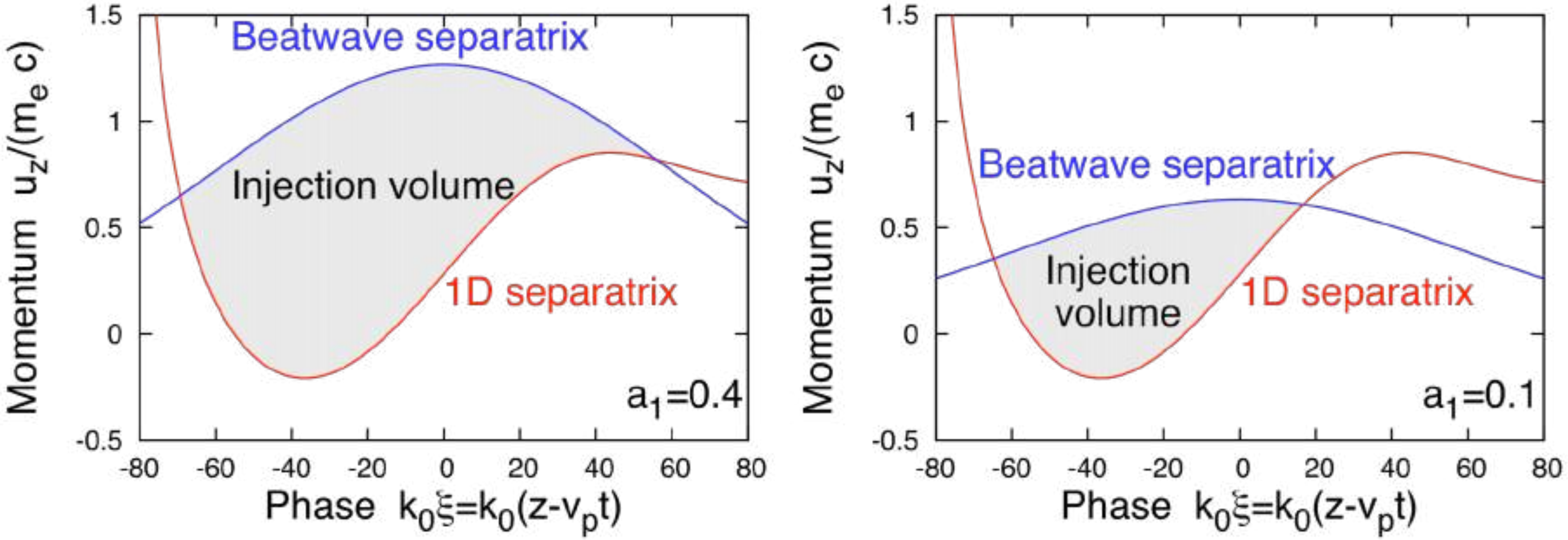


Tunability of charge & energy spread



Charge : controlling electrons heating processes => smaller $a_{inj.}$ means less heating and less trapping

Energy spread : Decreasing the phase space volume V_{trap} of trapped electrons by reducing $a_{inj.}$ or by reducing $c\tau/\lambda_p$ by changing n_e (i.e λ_p)

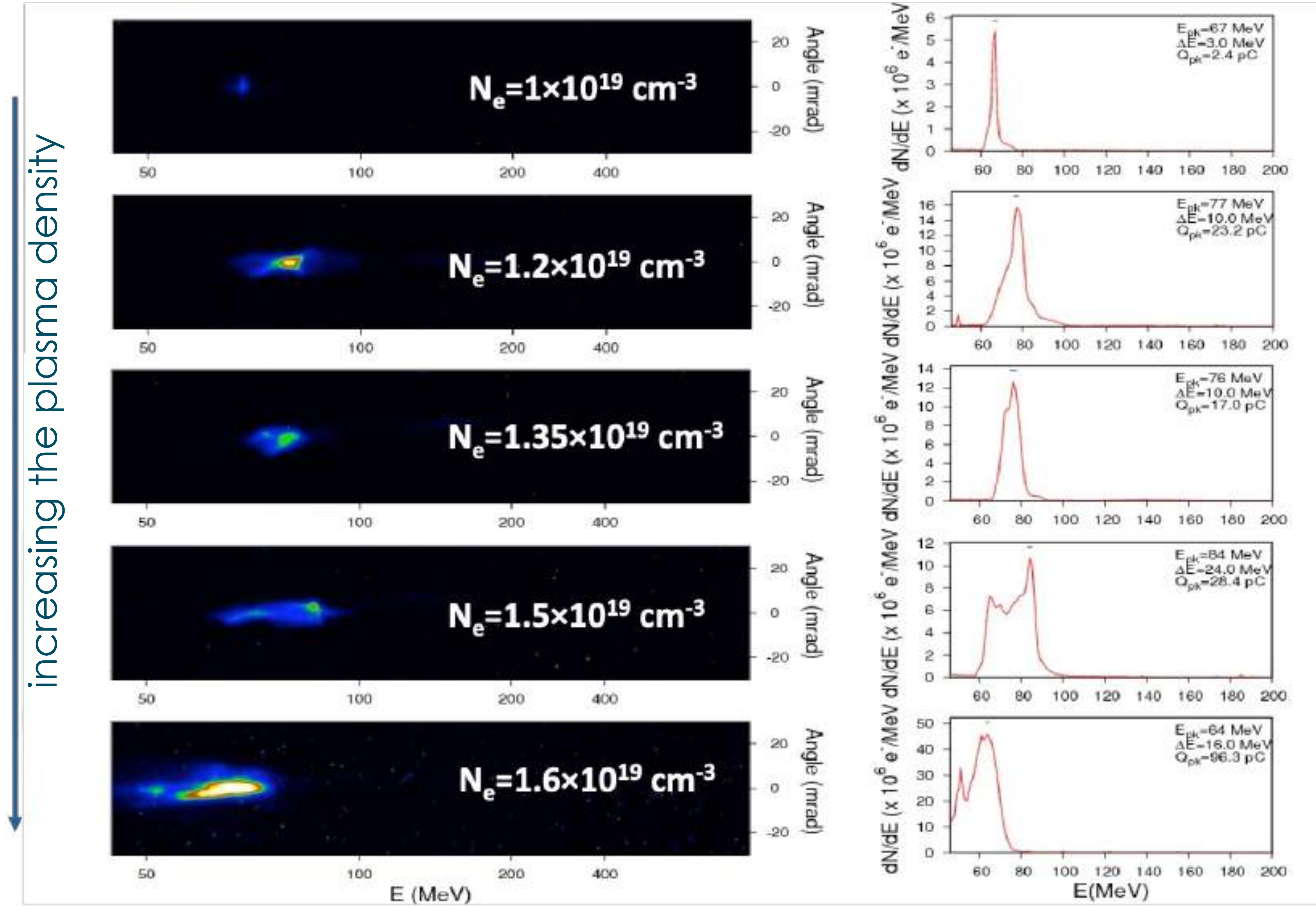


Evolution of injection volume with a_1 for $a_0 = 2$, $n_e = 7\times10^{18}cm^{-3}$.

Fields are computed for the 1D case and the beatwave separatrix corresponds to the circular polarization case.

In practice, energy spread and charge are correlated: Decreasing a_1 decreases the charge but also V_{trap}, and in consequence the energy spread

Tuning the charge & energy spread with the plasma density



E=67 MeV
ΔE=3 MeV
Q_{pk}=2.4pC

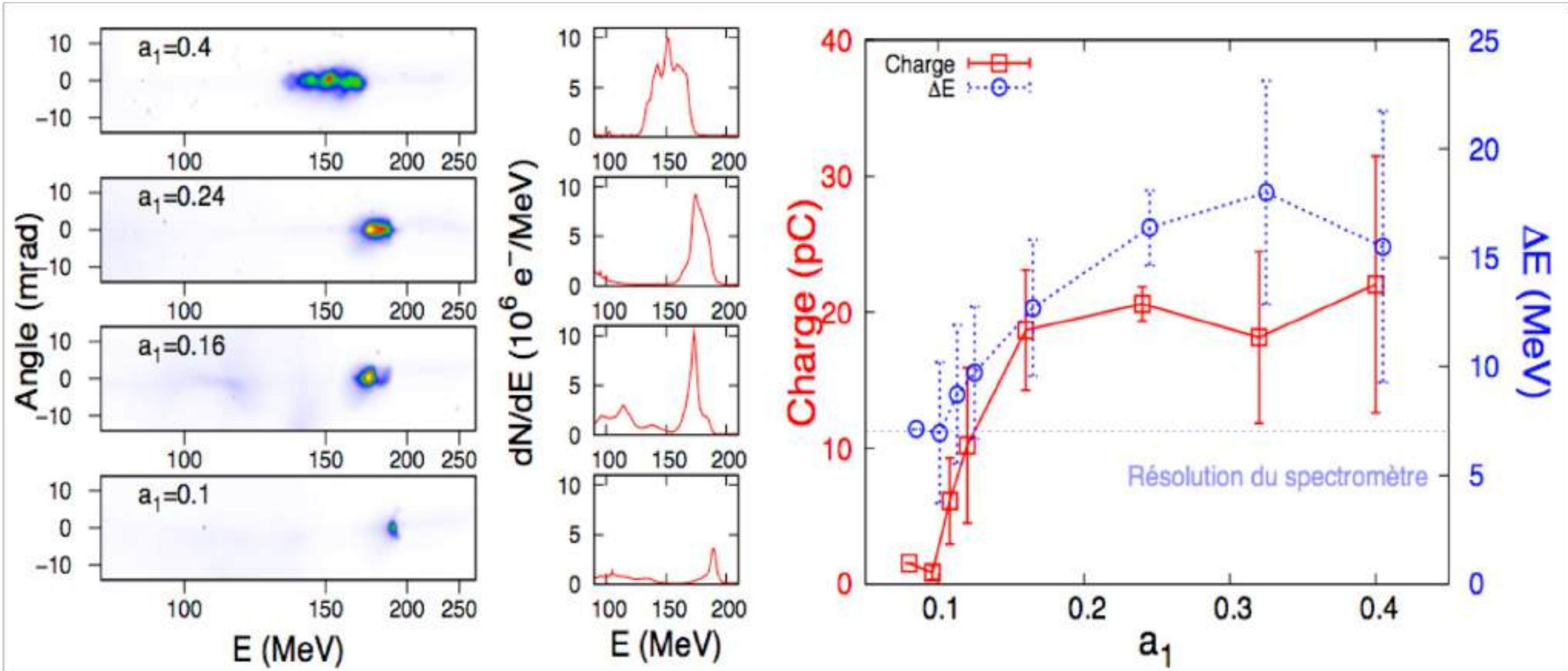
E=77 MeV
ΔE=10 MeV
Q_{pk}=23.2pC

E=76 MeV
ΔE=10.0 MeV
Q_{pk}=17pC

E=84 MeV
ΔE=24 MeV
Q_{pk}=25.4pC

E=64 MeV
ΔE=16 MeV
Q_{pk}=96pC

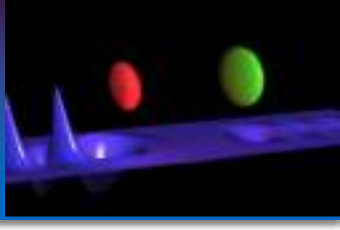
Tuning charge & energy spread with the inj. laser intensity



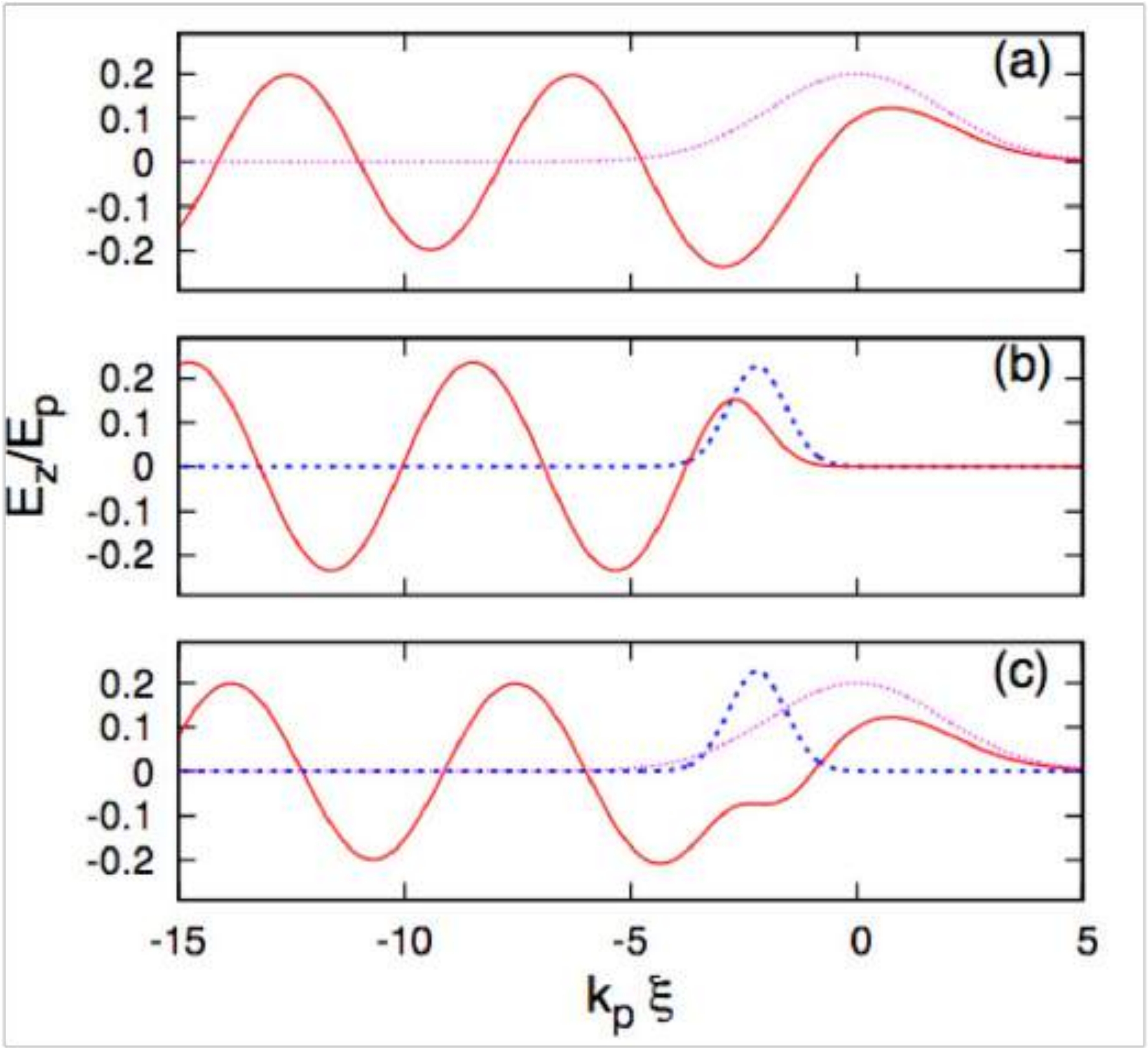
Charge from 60 pC to 5 pC, ΔE from 20 to 5 MeV

C. Rechatin *et al.*, Phys. Rev. Lett. **102**, 164801 (2009)

e- beam dynamics in plasma wave: beam loading



Parameters: n_e=1.5 10^{19}cm^{-3},τ =35fs, E=0.6J, I=2 10^{18} W/cm^2



Laser wakefield
n_e=7 10^{18}cm^{-3},τ = 30fs, a_0 = 0.5

E-beam wakefield
n_b/n_e=0.11, τ = 10fs, d_{FWHM}=4µm (Q=7pC)

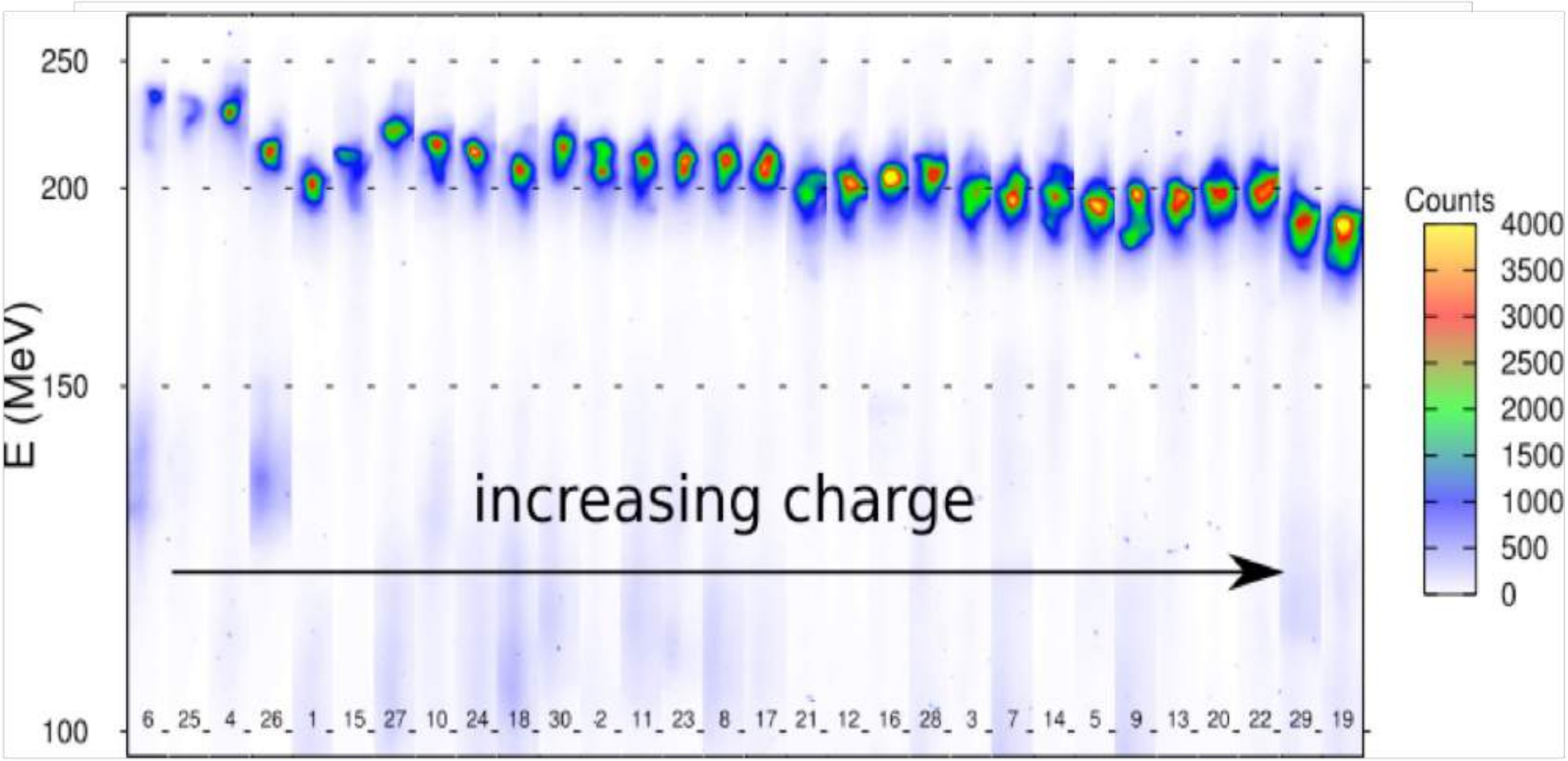
The end of the bunch experiments a modified wakefield

Limitation of the accelerated charge
Influence on energy and energy spread

Observables : correlation charge/energy spread/energy

T. Katsouleas *et al.*, (1987), M. Tzoufras *et al.*, Phys. Rev. Lett.,**101** (2008)

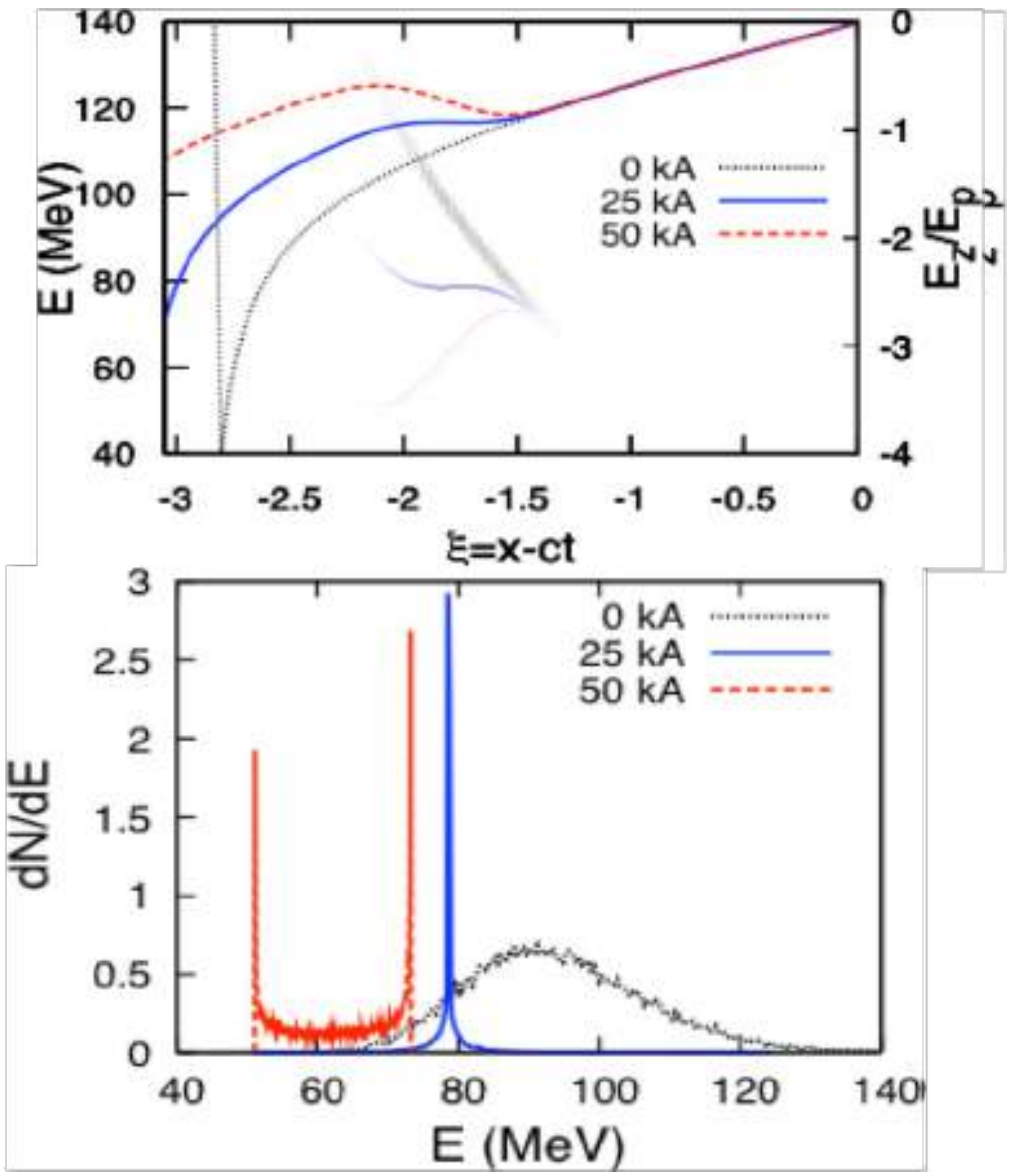
e⁻ beam dynamics in plasma waves: beam loading



Clear correlation !

Nb: very few electrons at low energy
δE/E=5% limited by the spectrometer

e- beam dynamics in plasma wave: beam loading



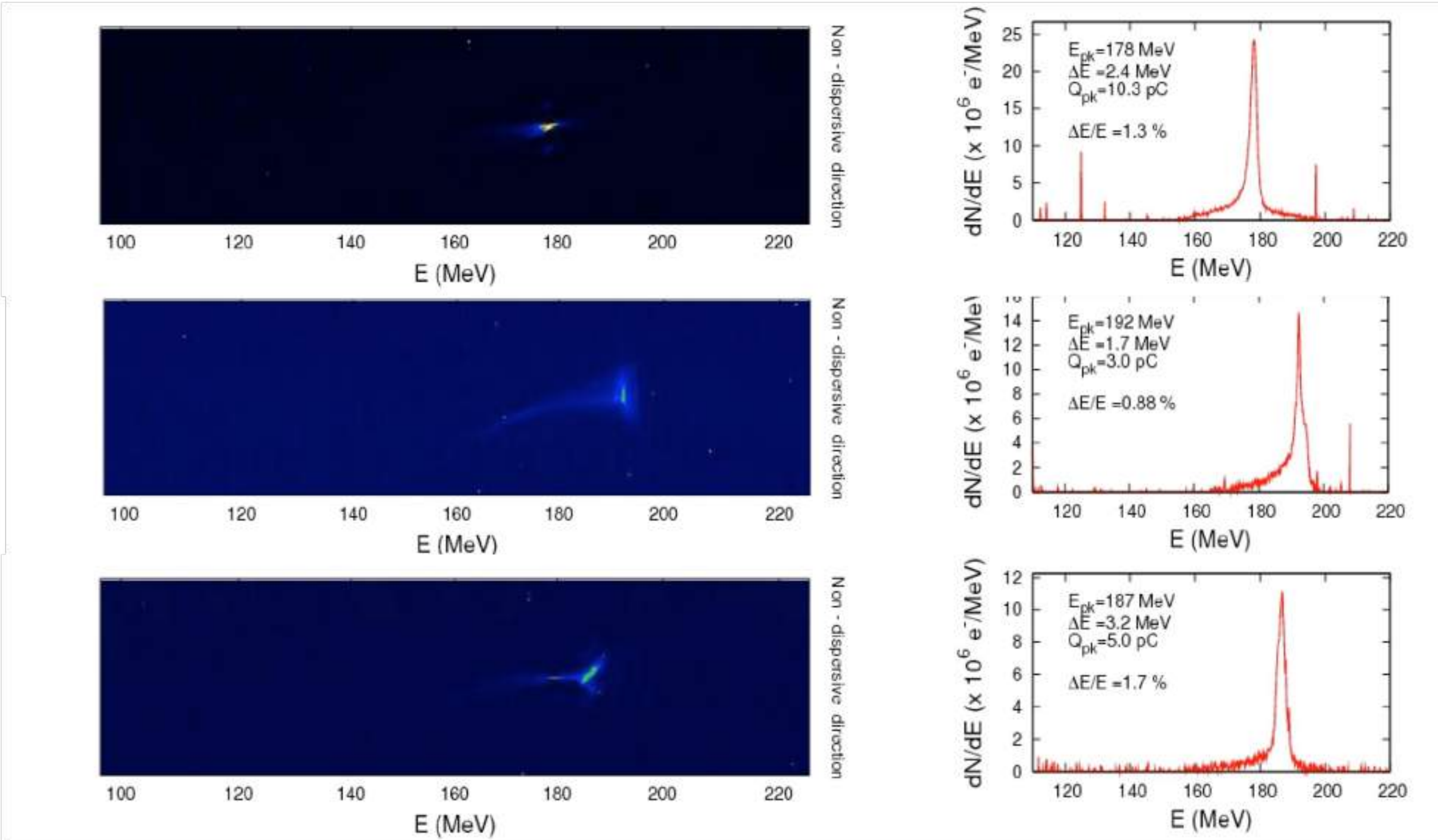
Low charge
=> large energy spread

Optimal charge
=> flat E field
=> low energy spread

High charge
=>End of the beam decelerated
=>high energy spread

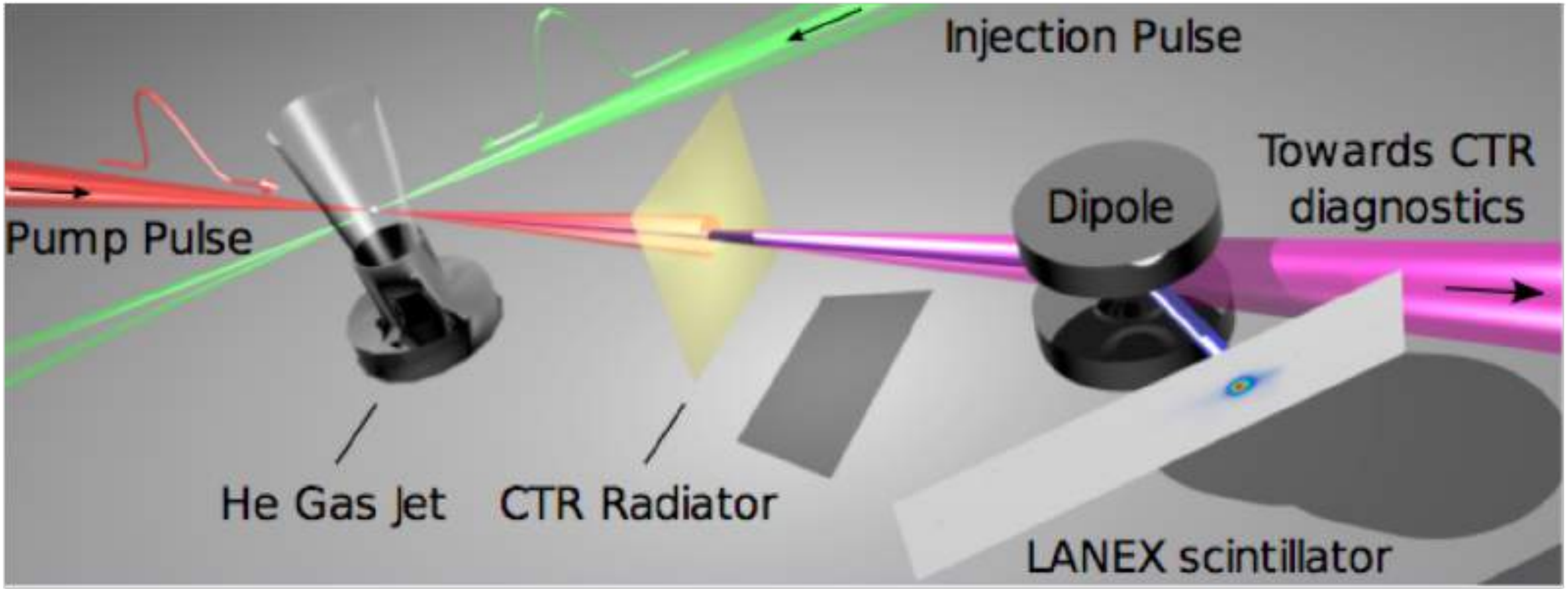
Observables : correlation charge/energy spread/energy

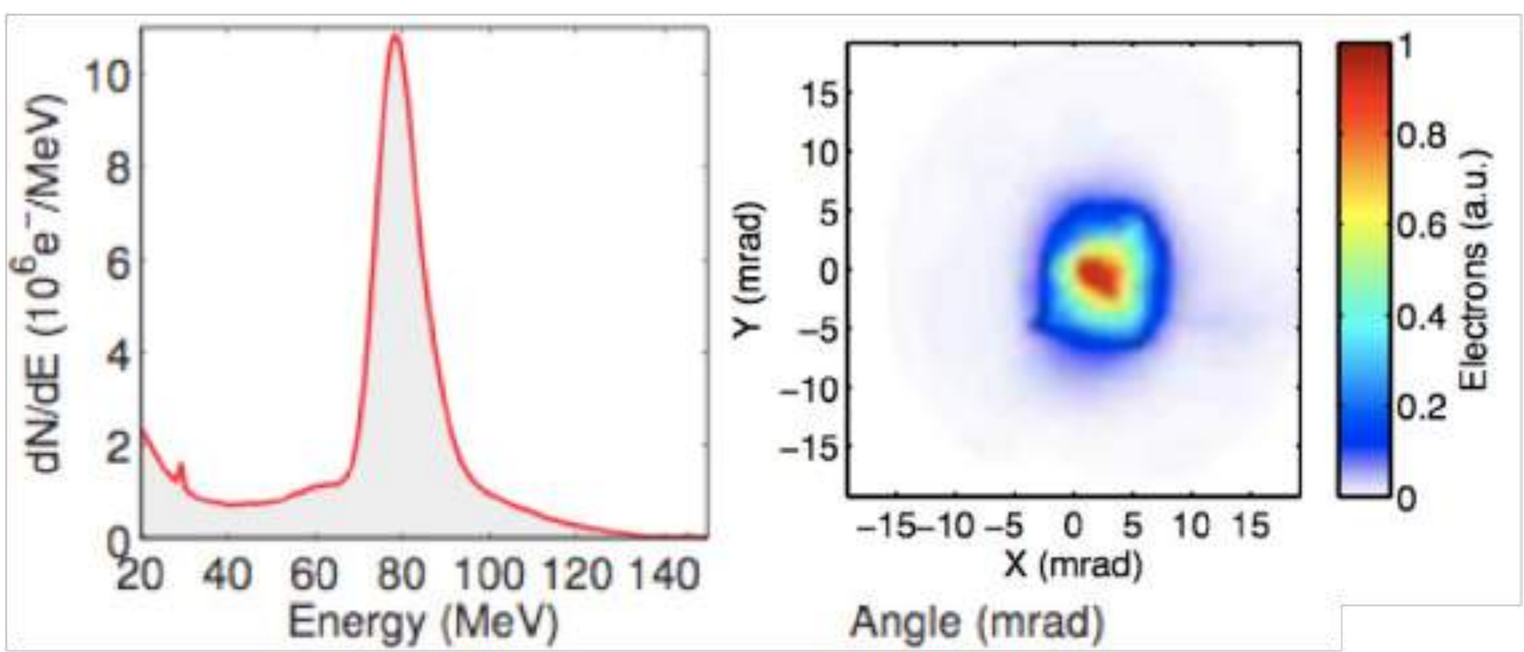
1% relative energy spread !



C. Rechatin *et al.*, Phys. Rev. Lett. **102**, 194804 (2009)

Bunch length measurement : CTR diagnostic

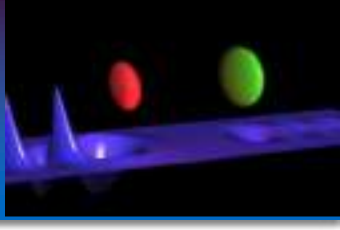


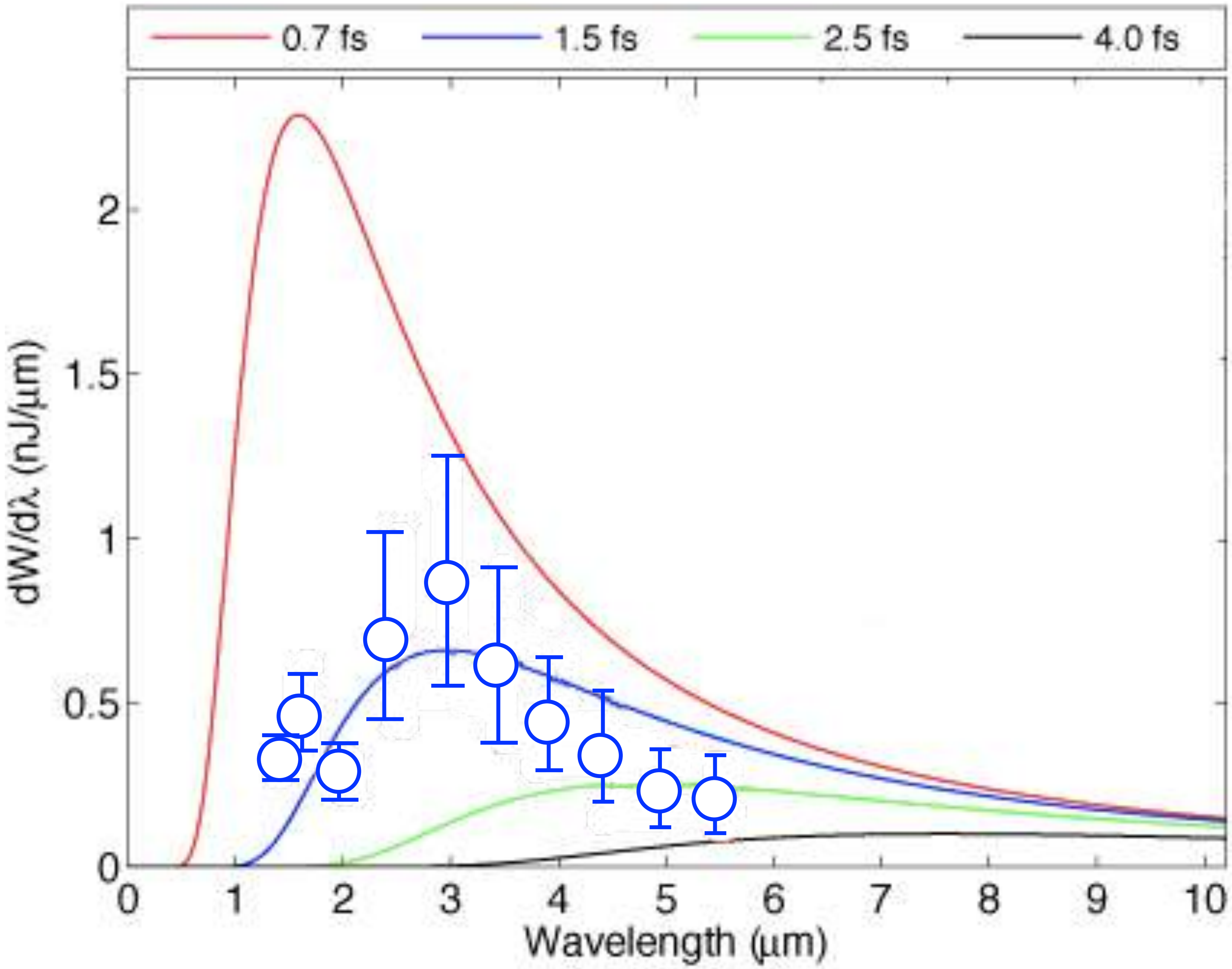


E=84 (±21) MeV, ΔE^*=20(±17) MeV
*after the foil

Q=15(±7) pC and $\Delta\theta$=6 (±1.6) mrad

1.5 fs RMS duration : Peak current of 4 kA





Analytic CTR model
Gaussian pulse shape
Measured e-beam :
- Charge
- Energy
- Divergence

Bunch duration
Peak wavelength
Peak intensity

Spectral features
Peak at 3 µm
Coherent

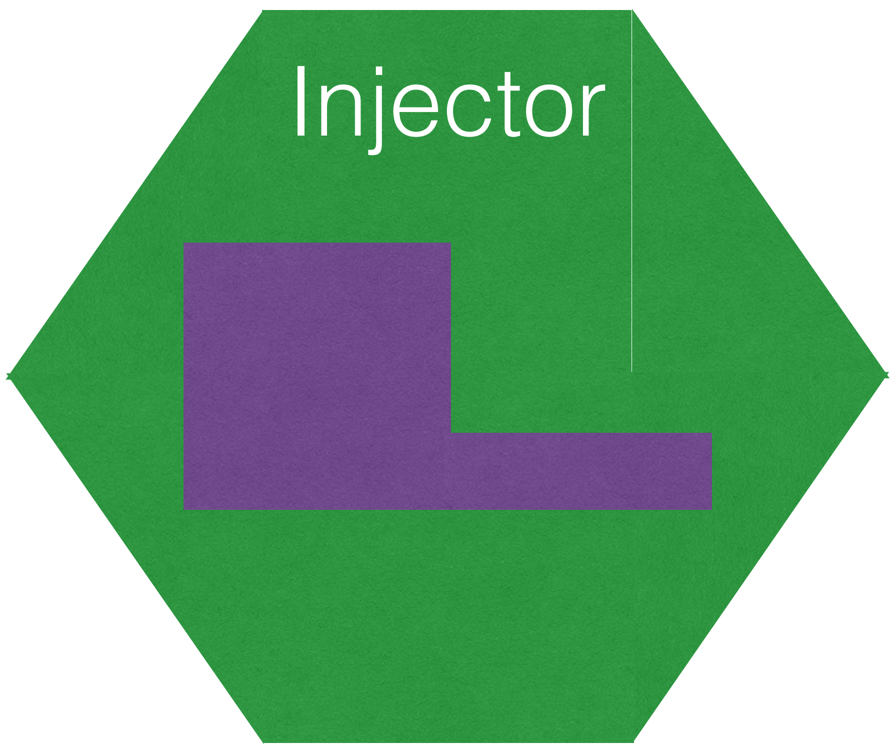
1.5 fs RMS duration : Peak current of 4 kA

O. Lundh et al., Nature Physics, **7** (2011)

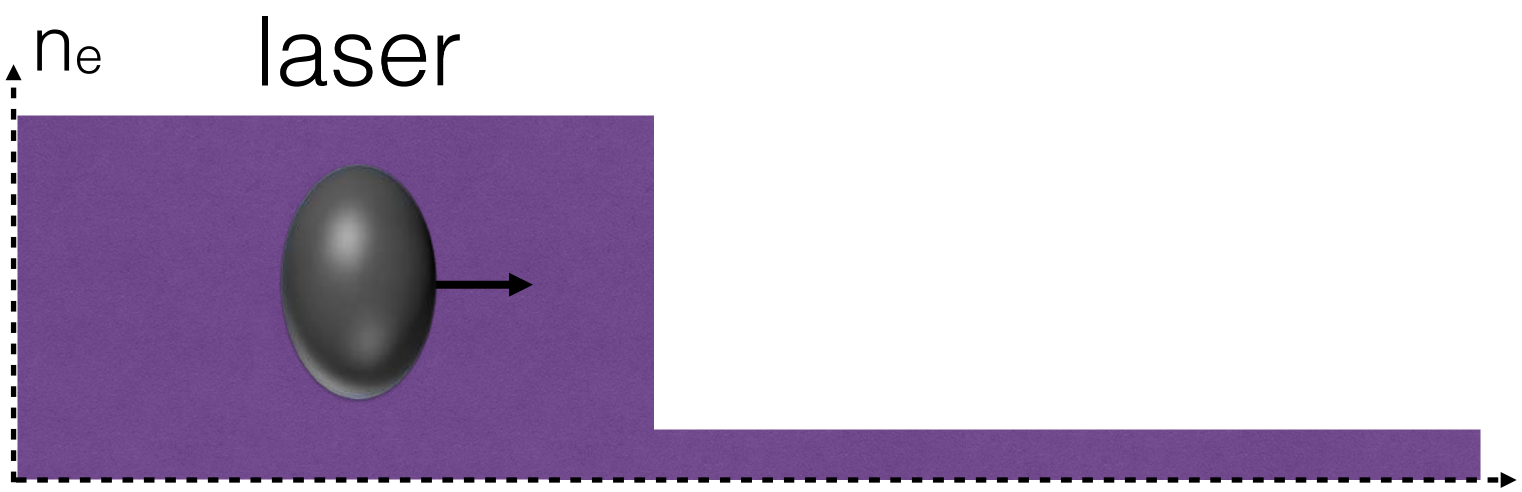
Laser Plasma Accelerators : Outline

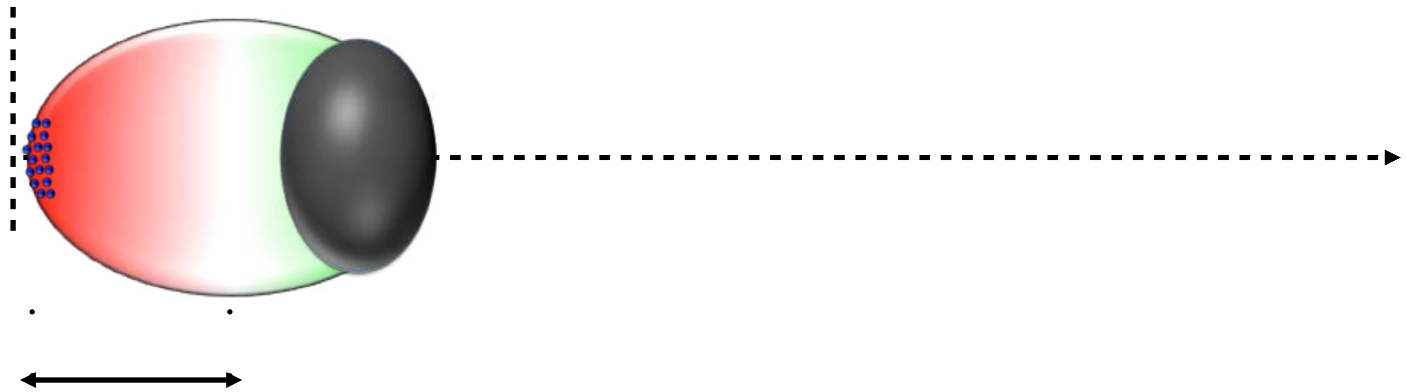
- Introduction : context and motivations
- Colliding laser pulses scheme
- Injection in a density gradient
- Manipulating the longitudinal momentum
- Manipulating the transverse momentum
- Applications
- Conclusion and perspectives

Injector



Injection in a sharp density gradient





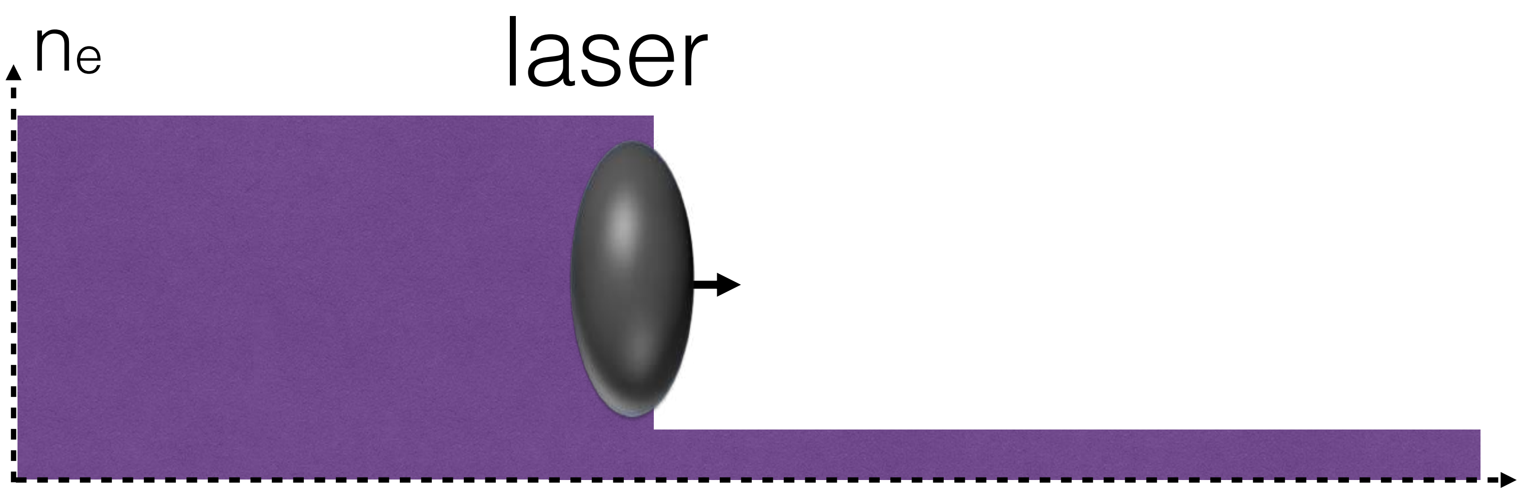
Density drop => increase of the cavity lenght

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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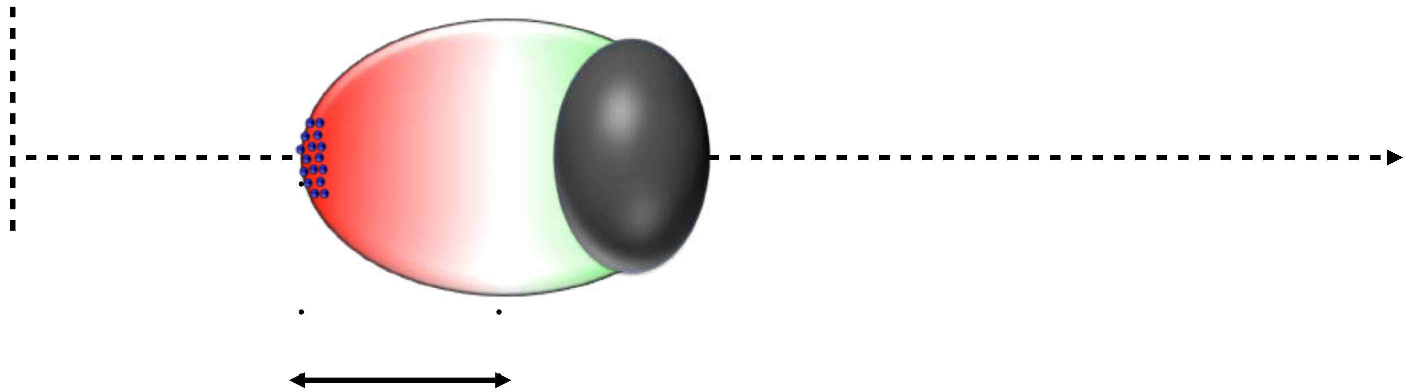

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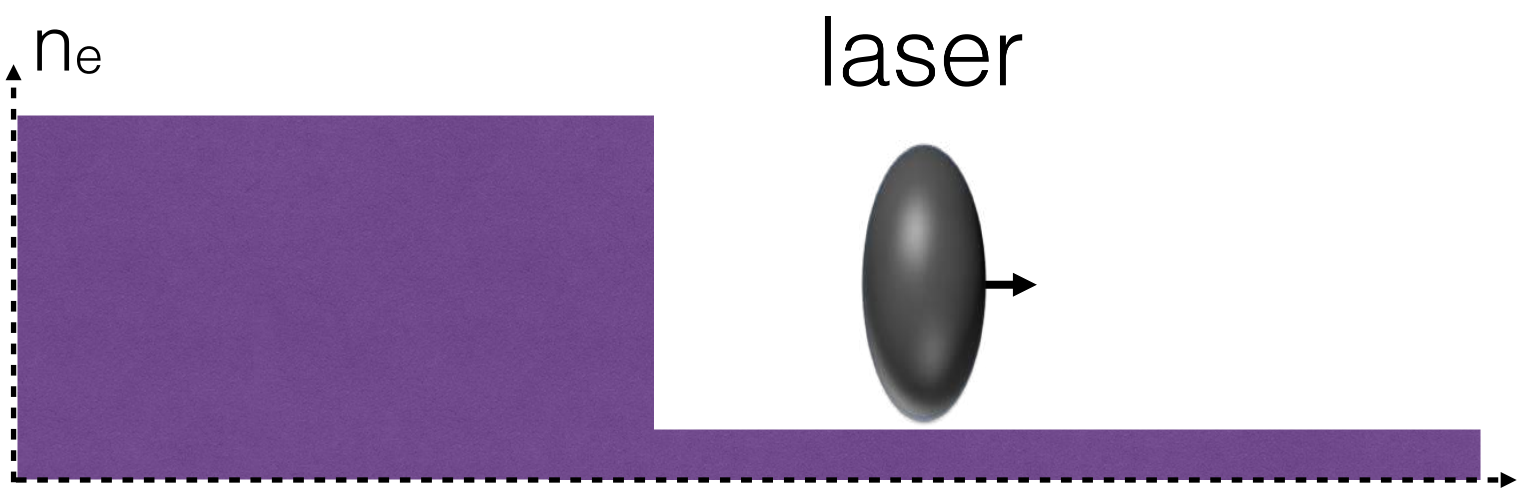

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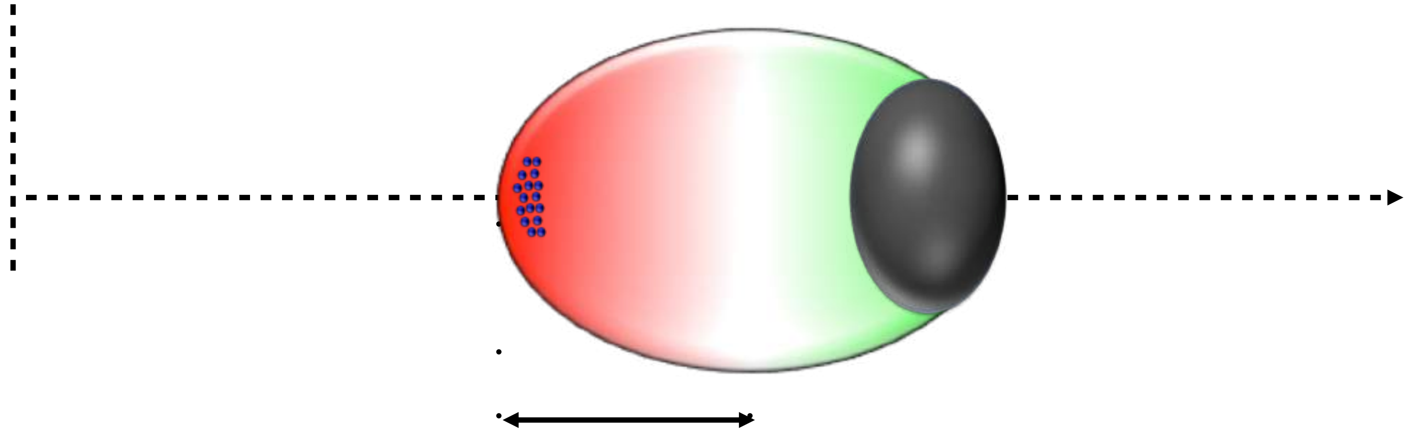

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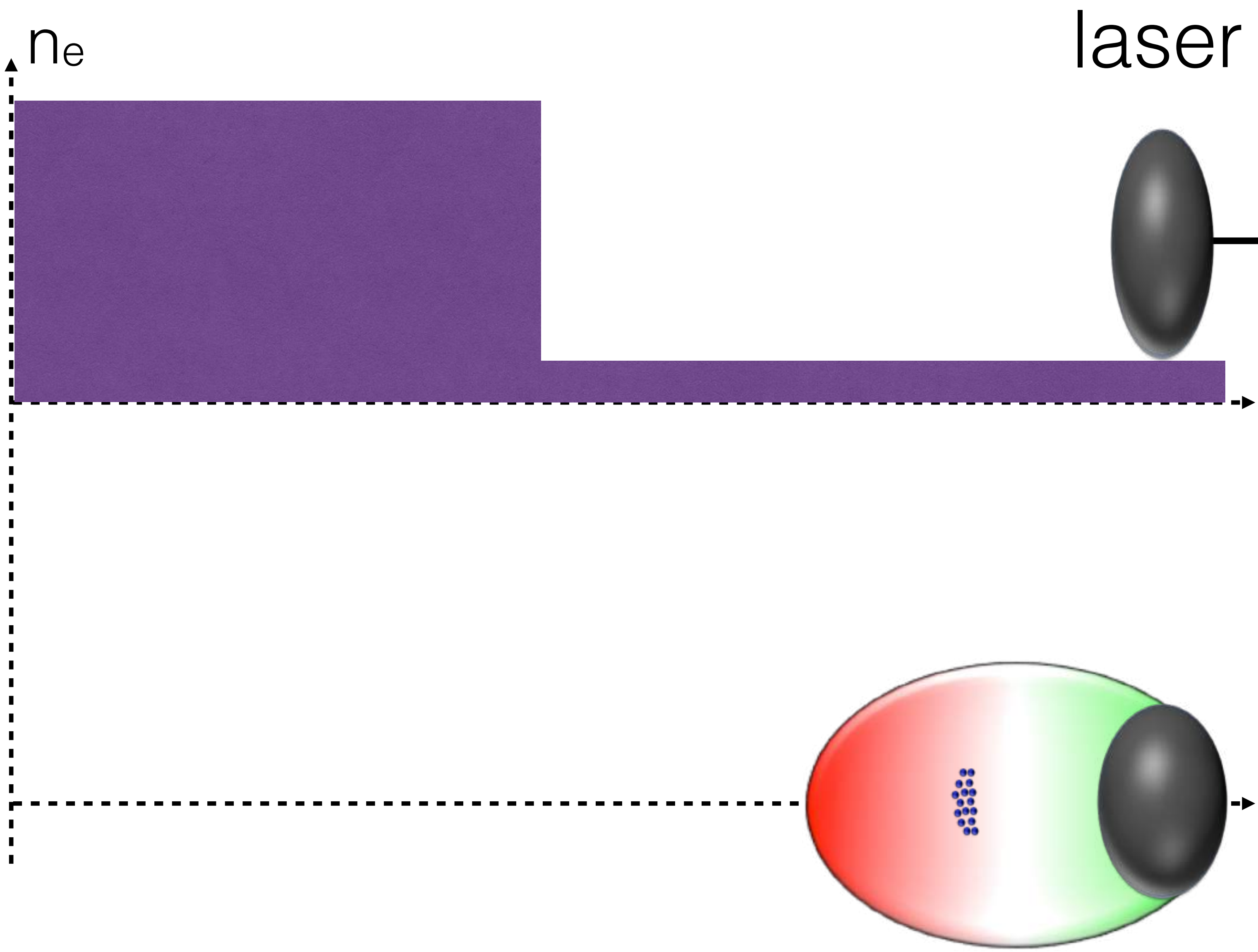
Injection in a sharp density gradient



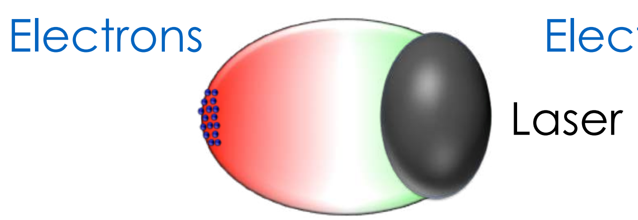
Density drop => increase of the cavity lenght

the bubble expansion allows electrons injection and energy gain.

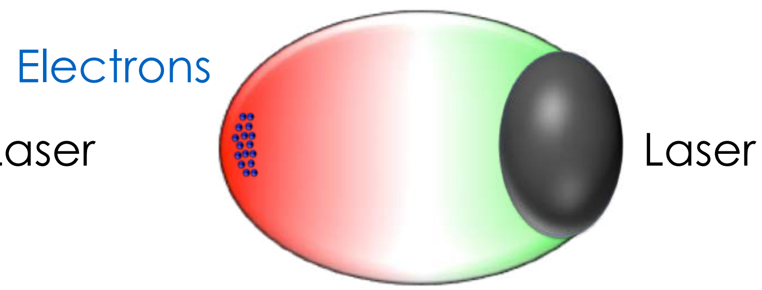
Sharp density ramp is requires to localize the injection and reduce the energy spread !

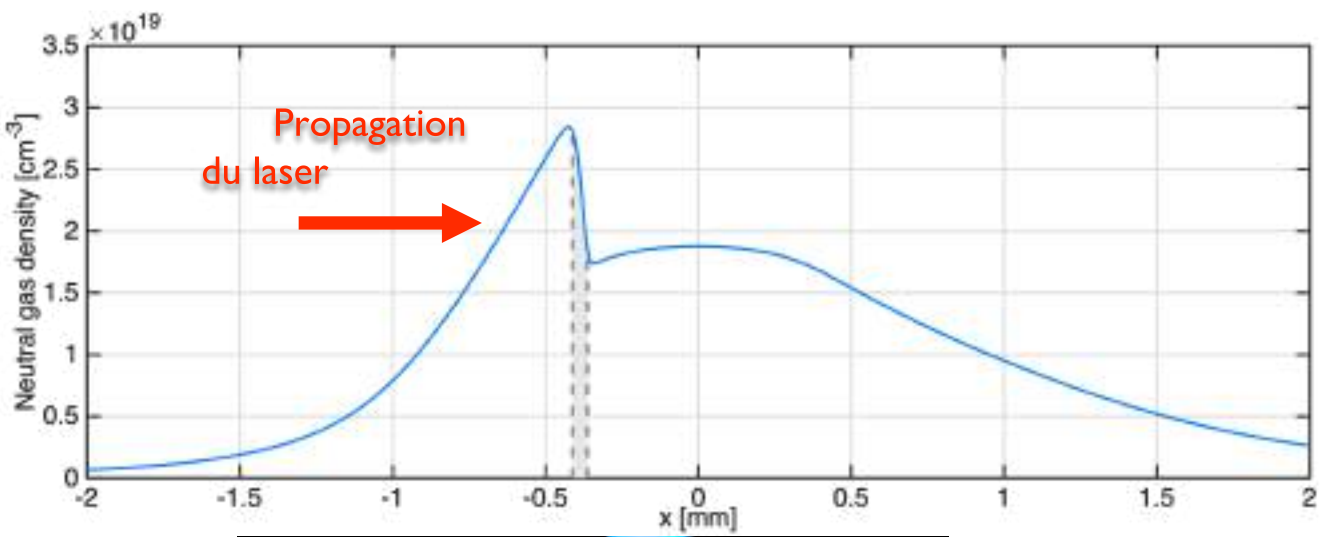
Injection in a shock front : principle

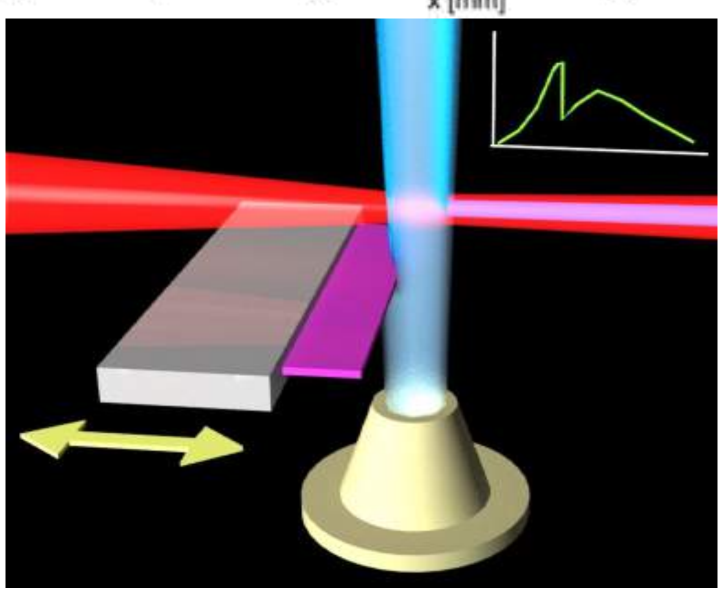
Plasma cavity before the shock front



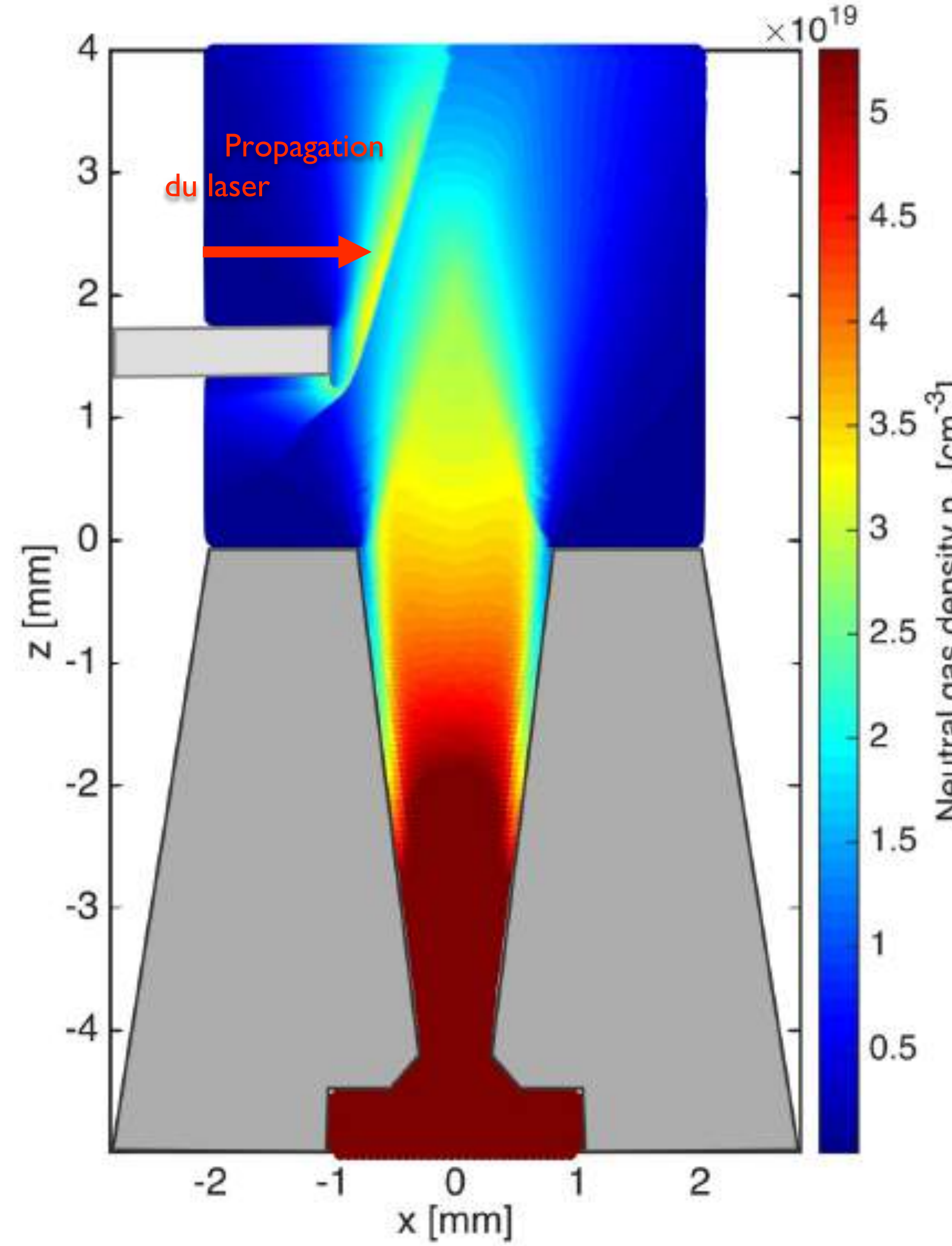
Plasma cavity after the shock front



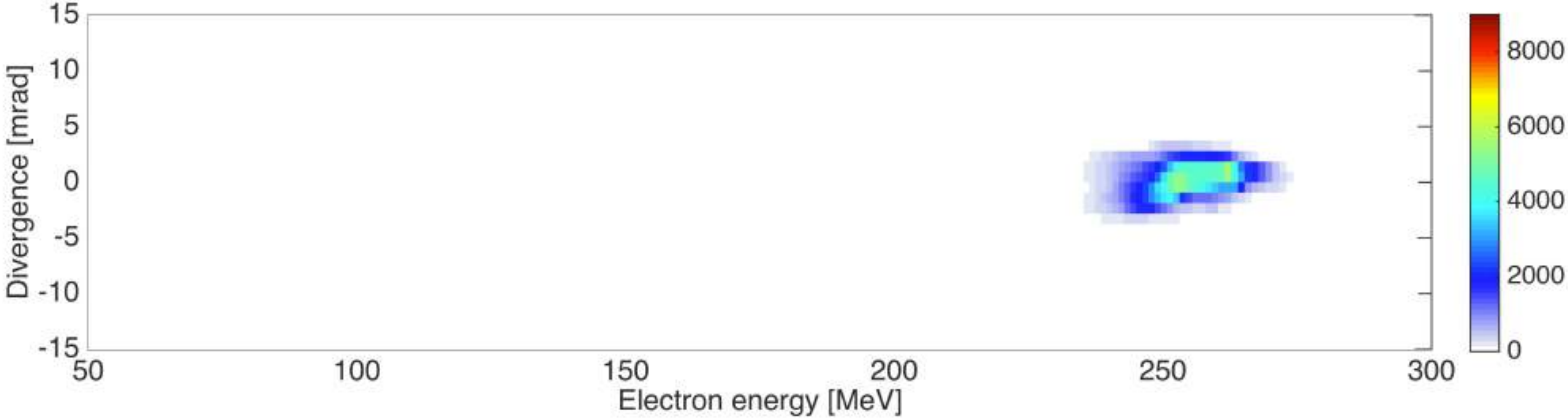




Simulations ANSYS Fluent



Injection in a shock front : pur helium gas

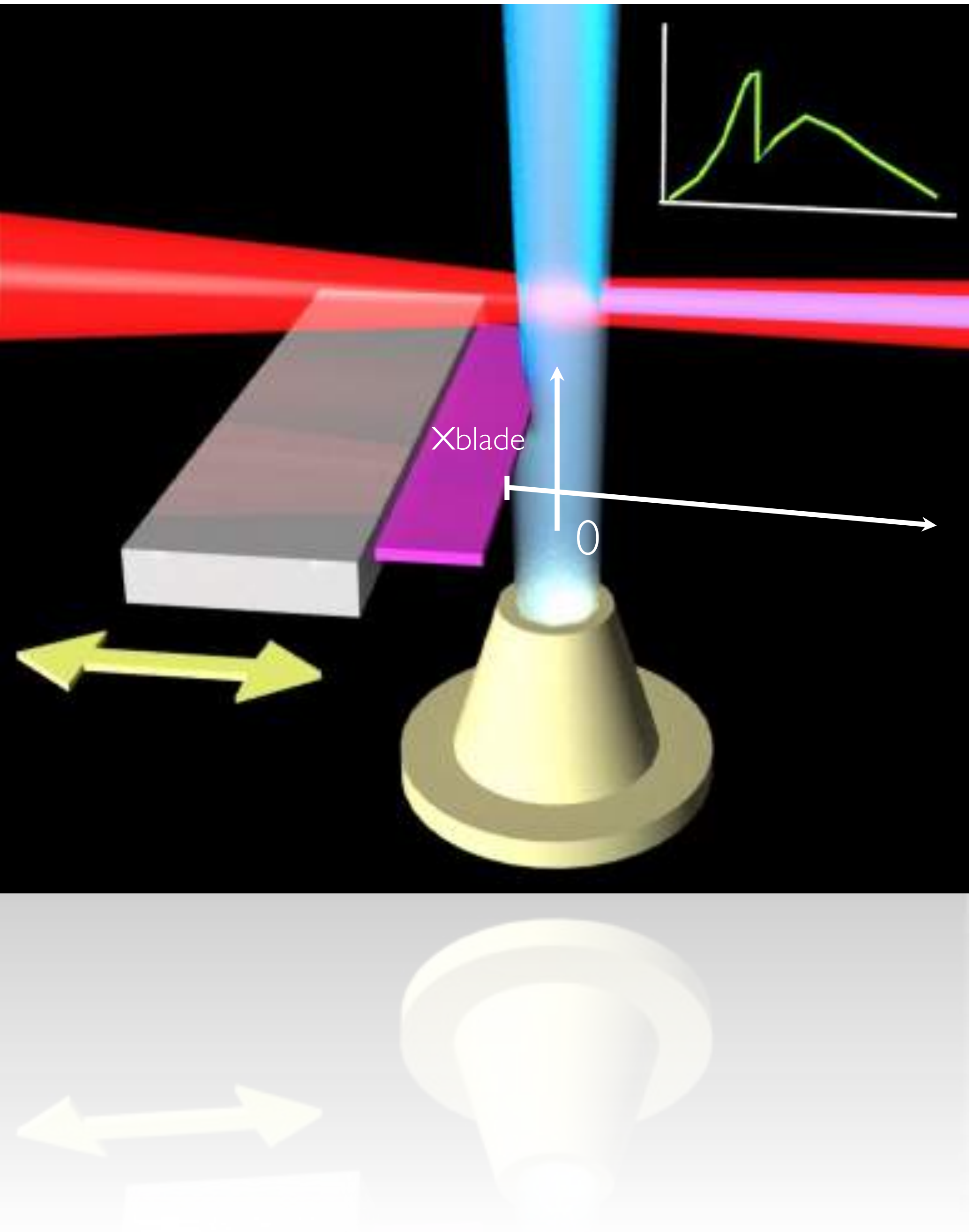


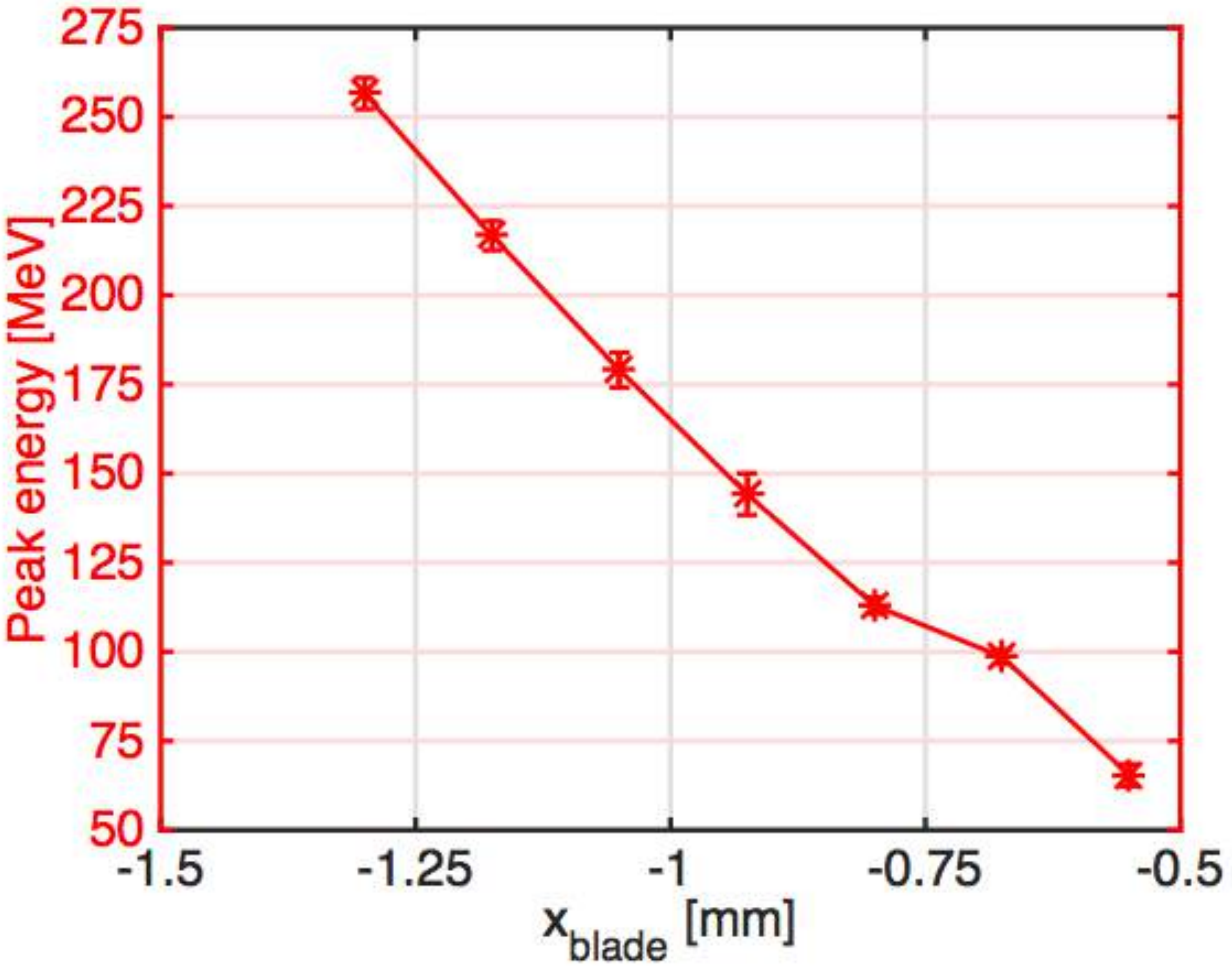
Generation of a stable e-beam ($n_2 = 7.5 \times 10^{18}$ cm^{-3}) :

$$E_{peak} = 256.5 \pm 4 \text{ MeV}$$
$$\Delta E = 15.5 \pm 2 \text{ MeV}$$
$$\Delta E/E = 6 \pm 1\%$$
$$Q_{peak} = 3.2 \pm 0.4 \text{ pC}$$
$$\text{Divergence} = 2.0 \pm 0.3 \text{ mrad}$$

R. Lehe

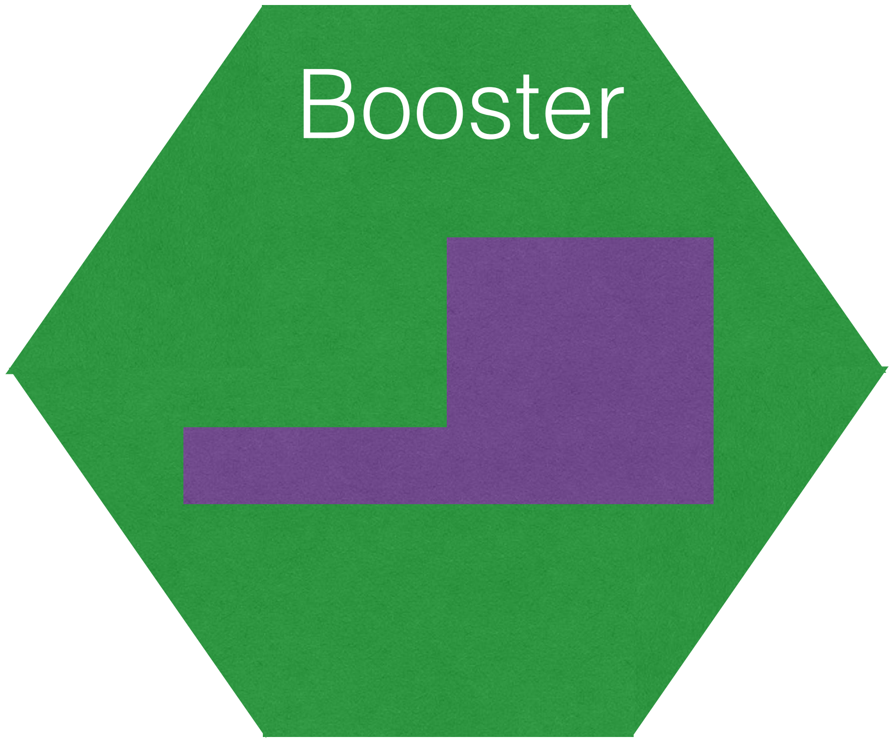
Injection in a shock front : pur helium gas





Electron energies is controlled by the position of the blade

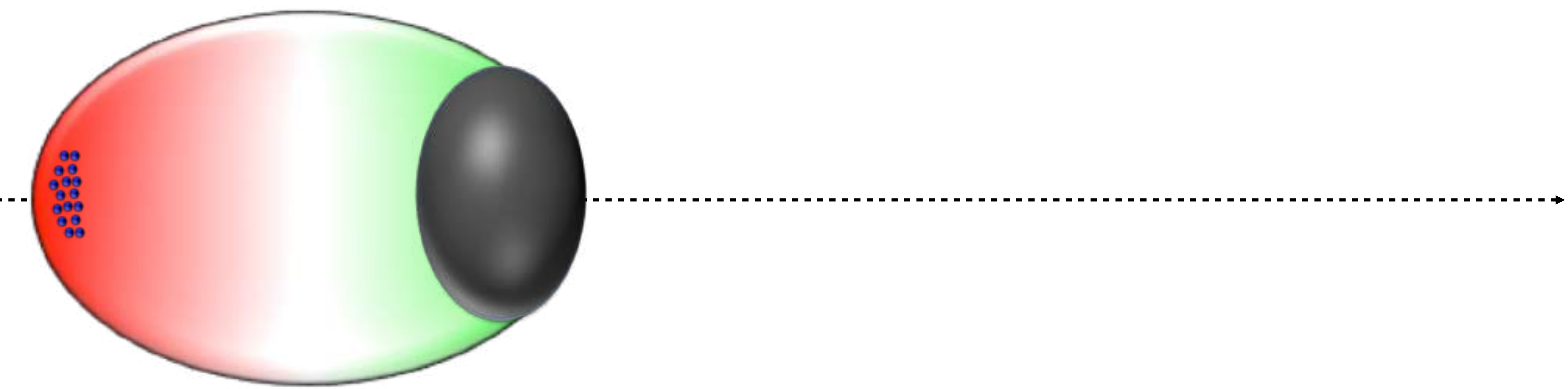
Booster



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

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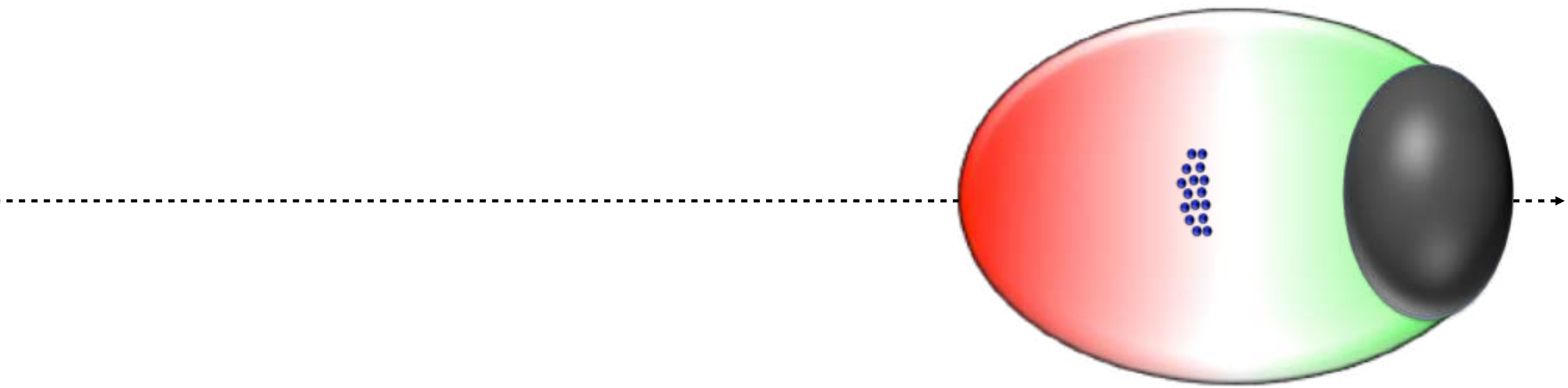
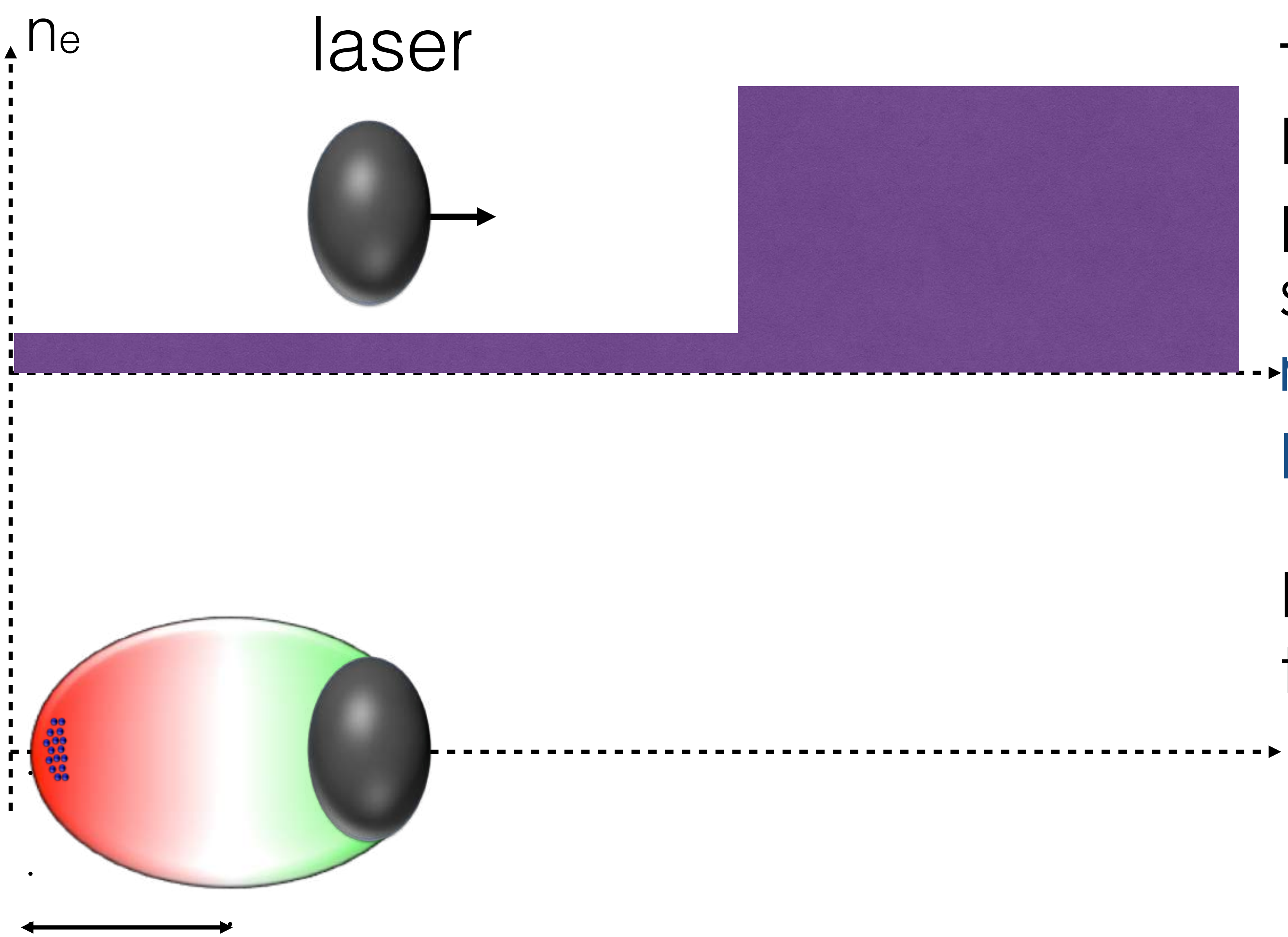


R. Lehe

Overcoming the dephasing limit



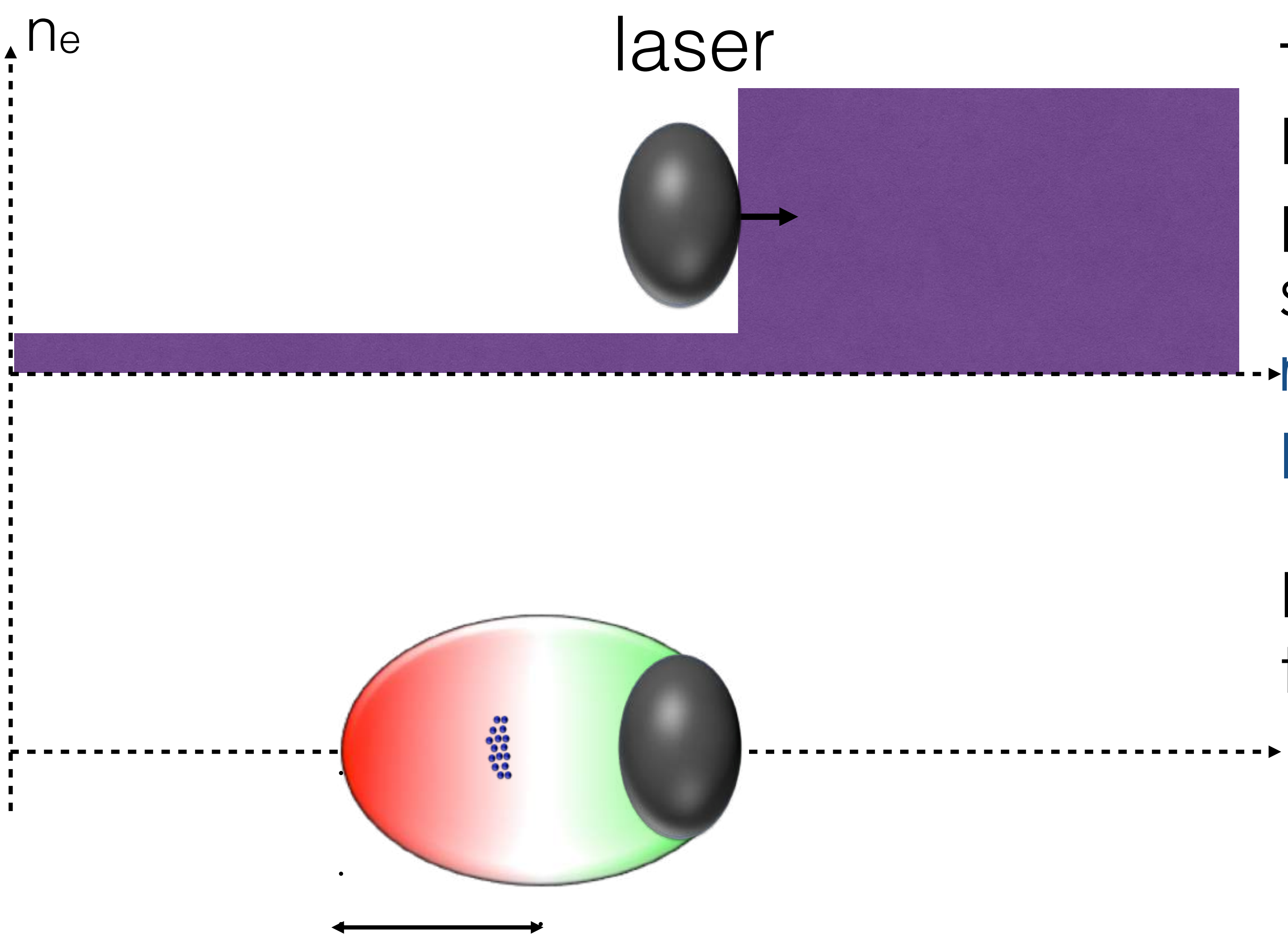
The reduction of the bubble size at the right position by increasing suddenly the density resets the electrons phase.

Electrons can start again to gain energy.

R. Lehe

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

Overcoming the dephasing limit



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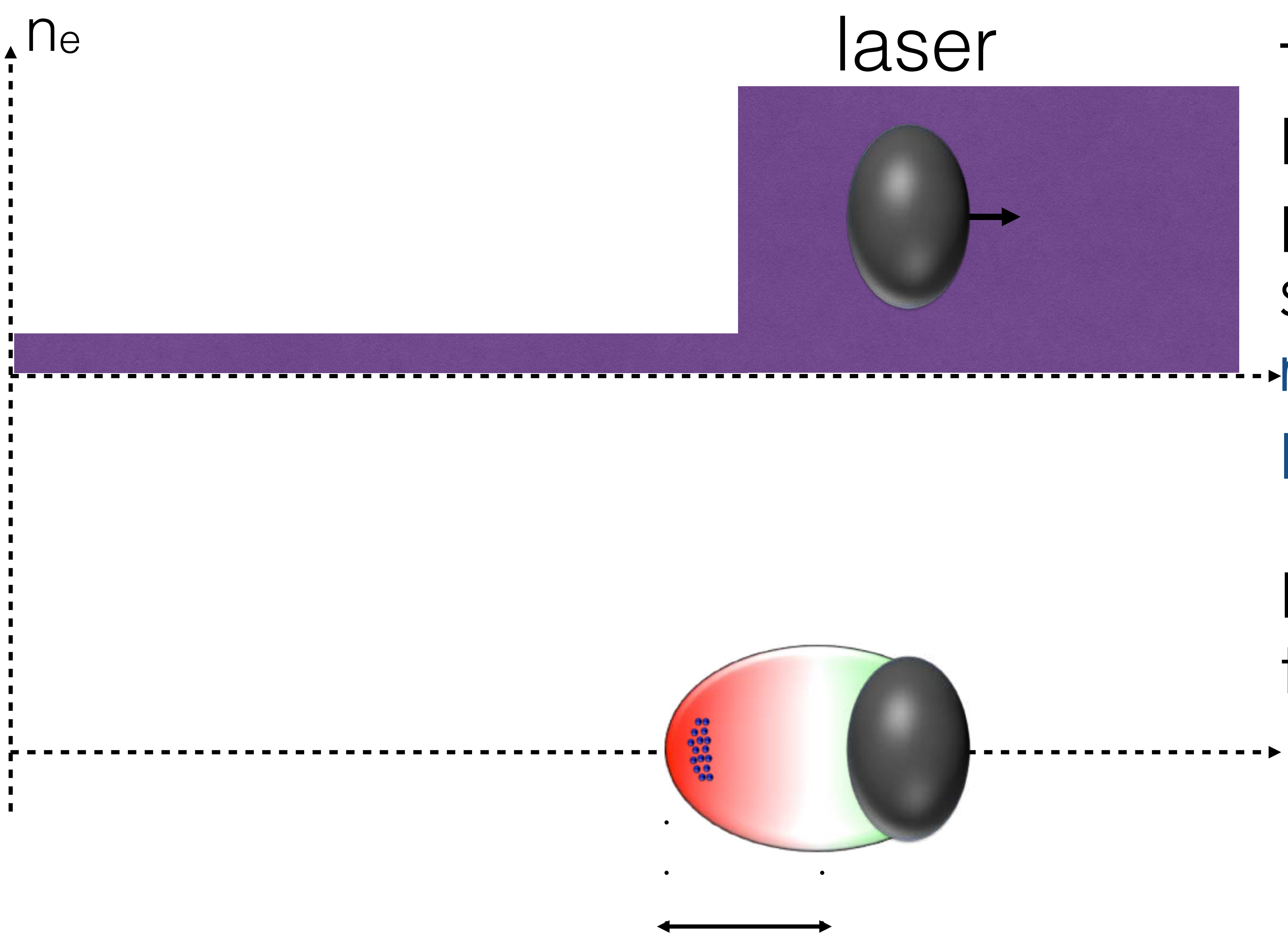

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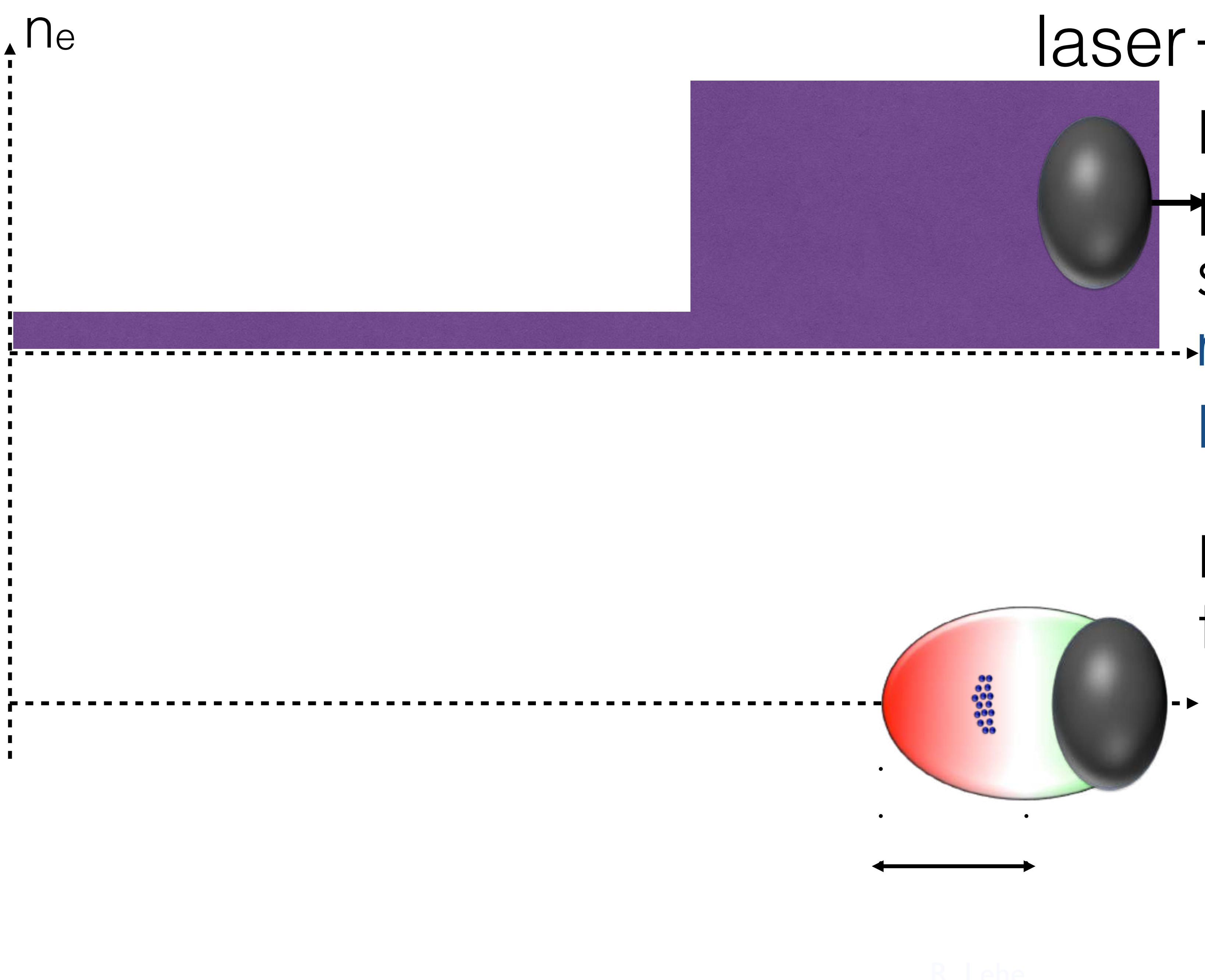

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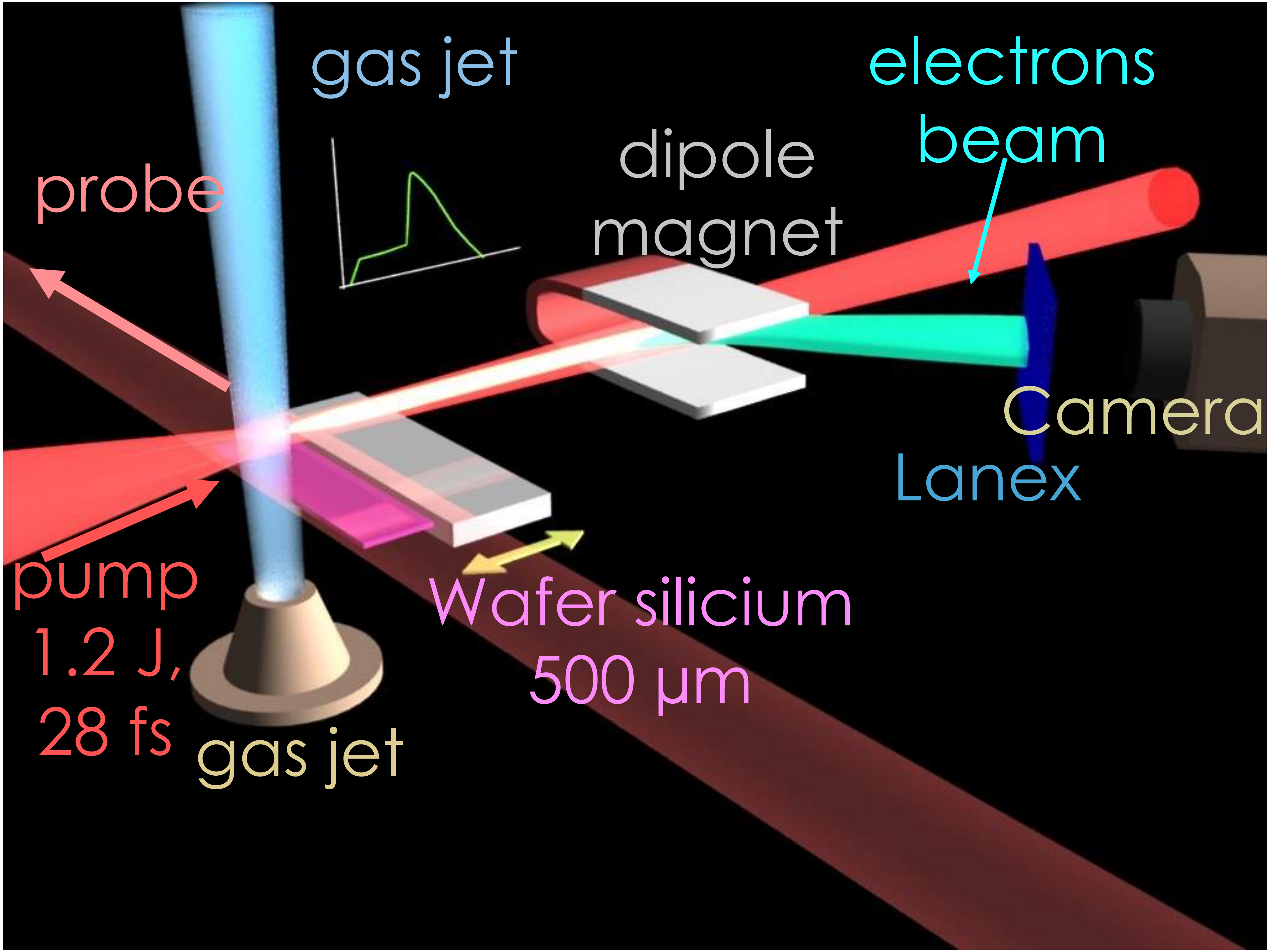
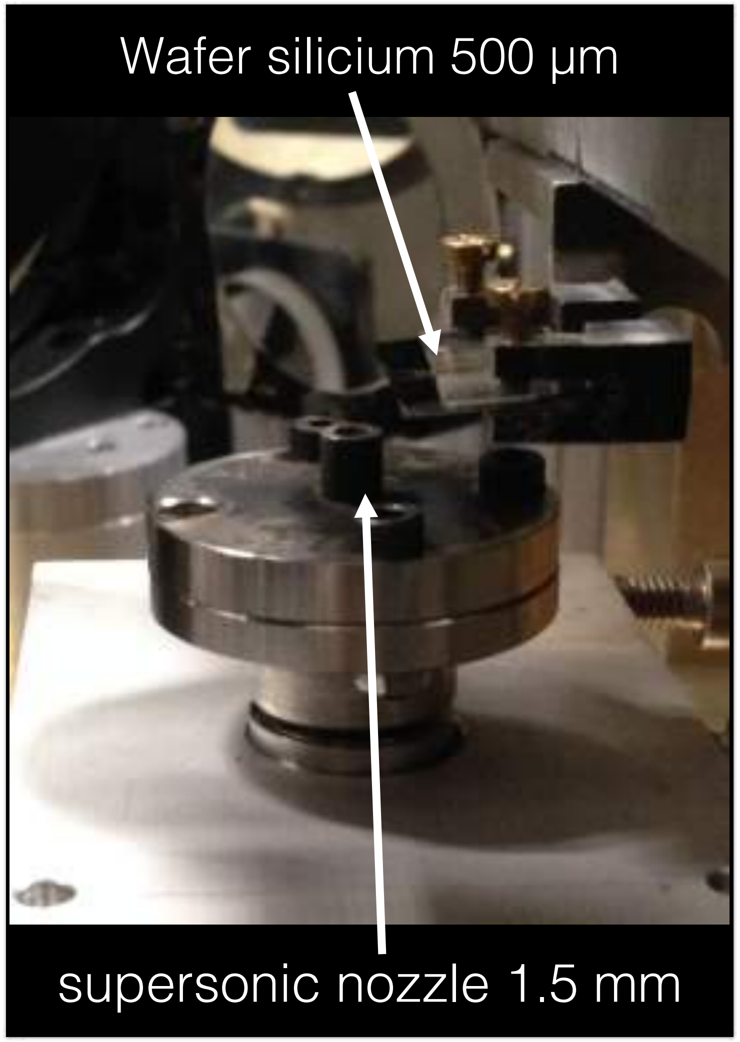
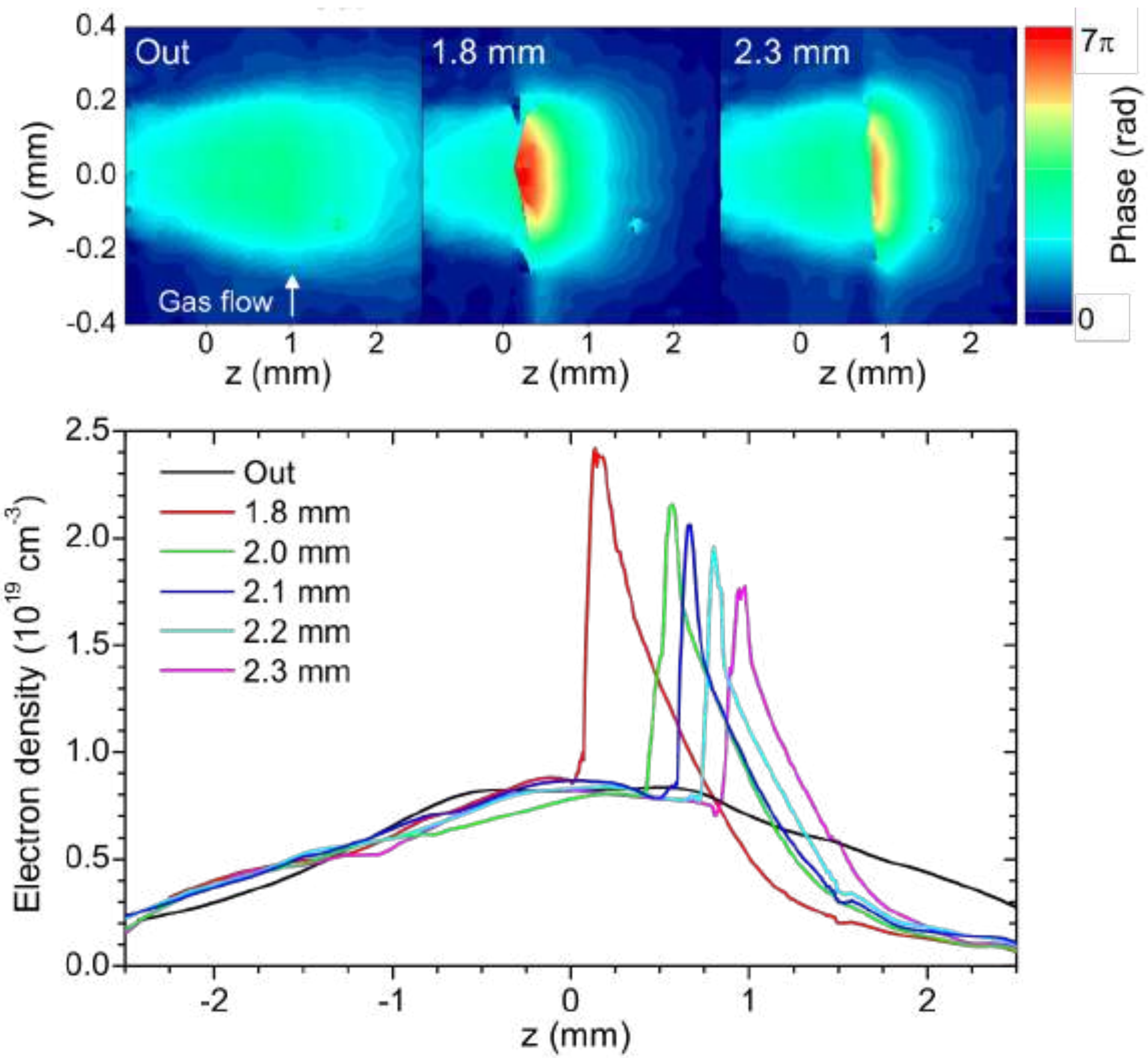
Overcoming the dephasing limit: experiments



Overcoming the dephasing limit: results



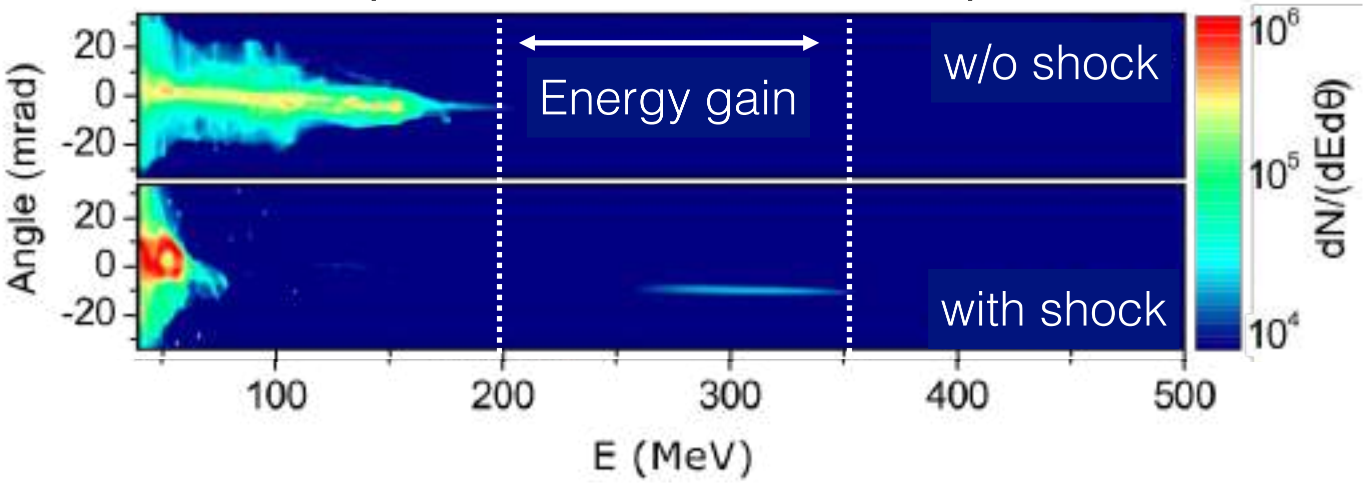
The density transition is controlled by changing the wafer position



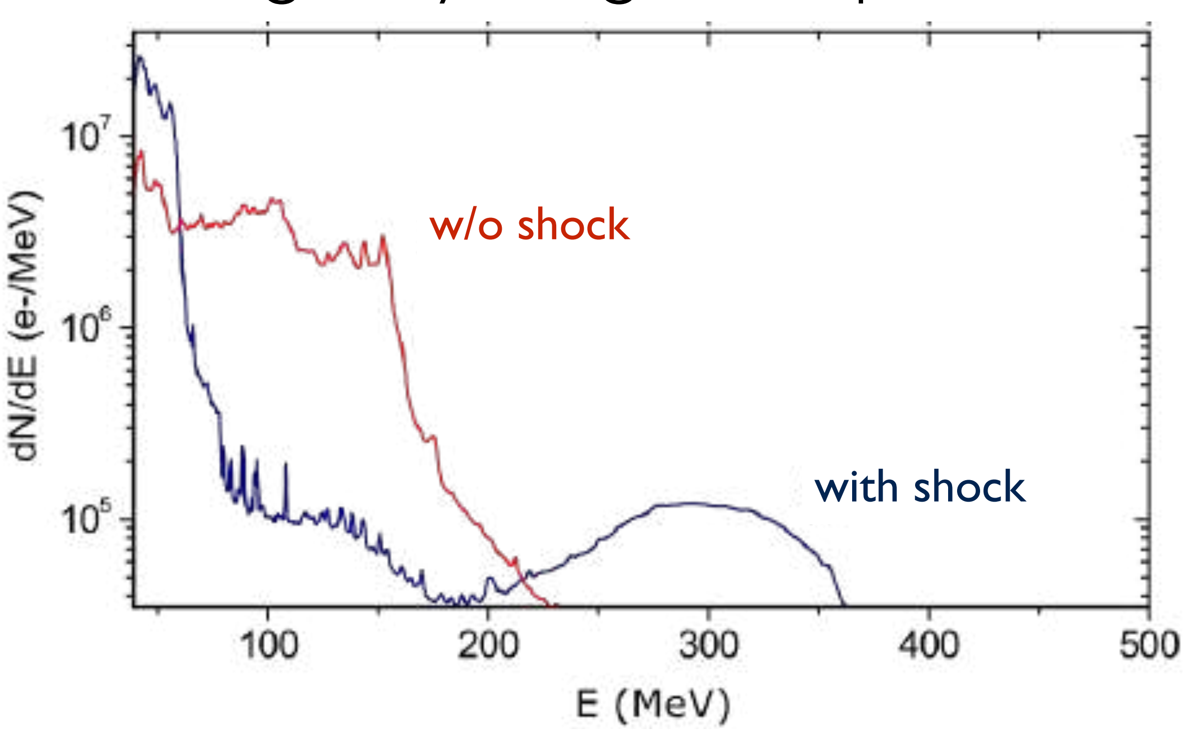
Overcoming the dephasing limit: experimental results & simulations

Experiment

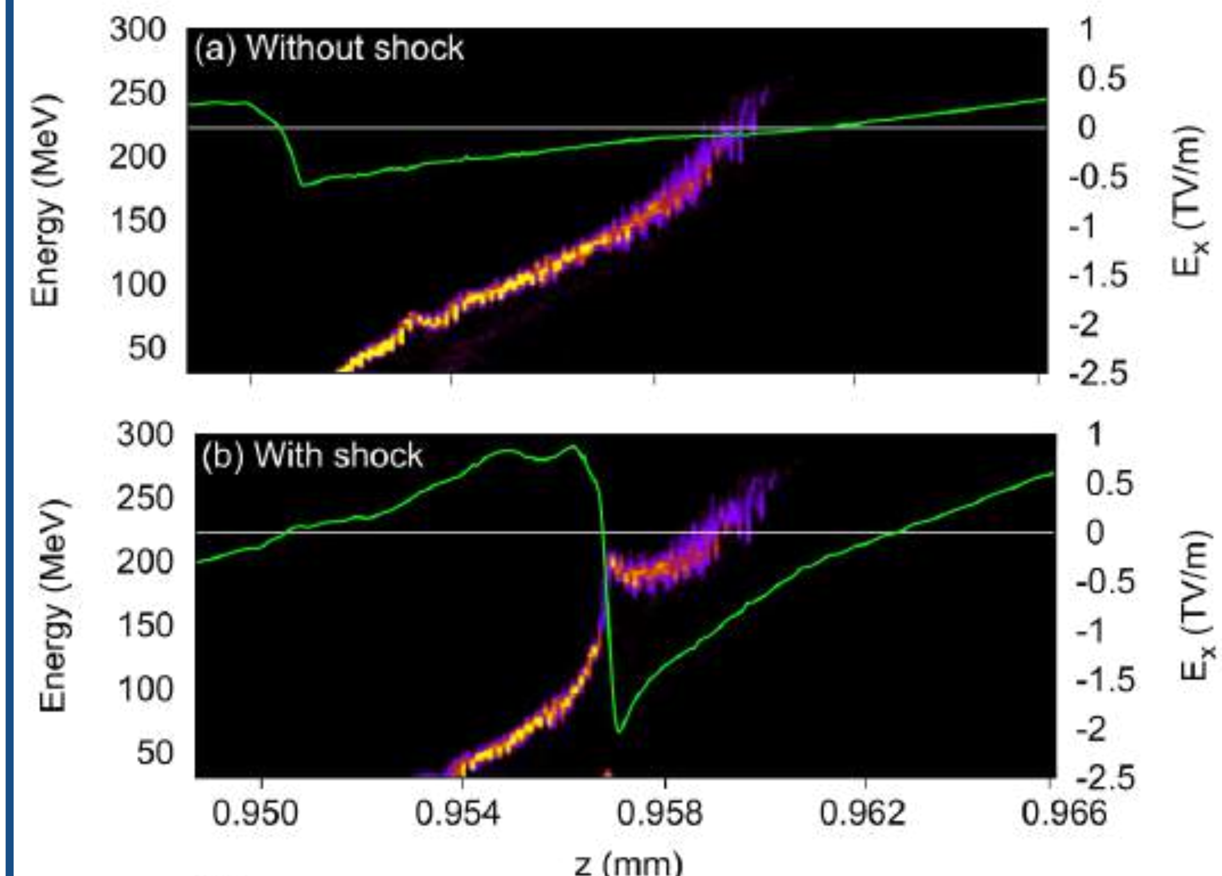
2D dispersion corrected spectra

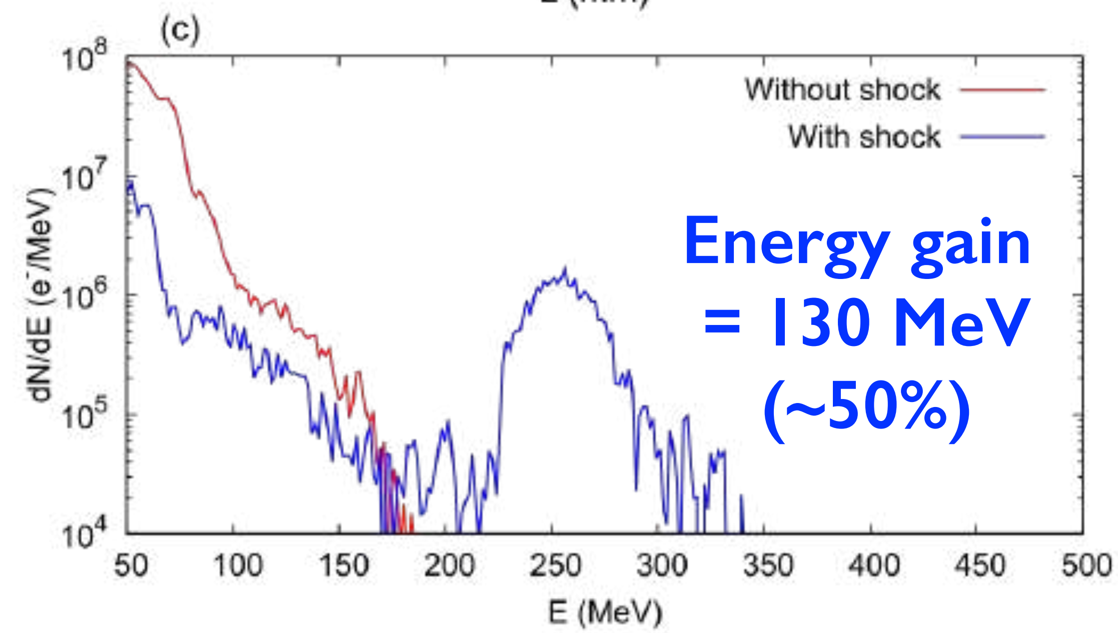


Angularly integrated spectra

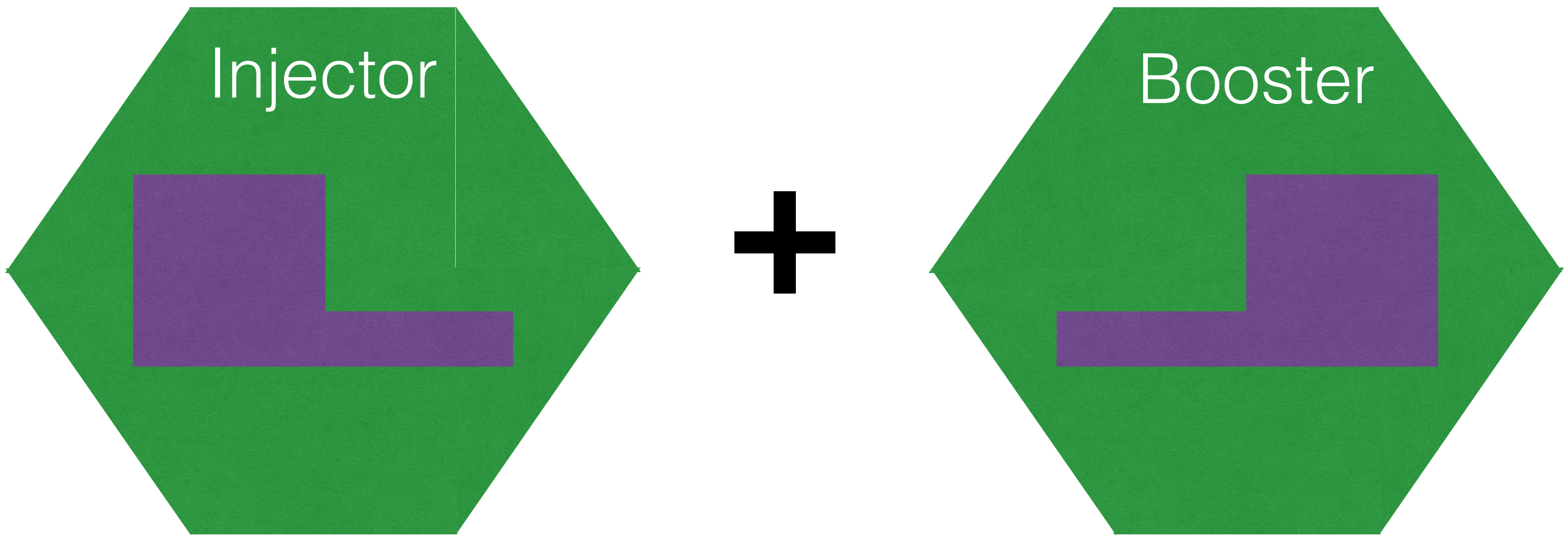


Calder-Circ PIC Simulations





Combining Injector and Booster



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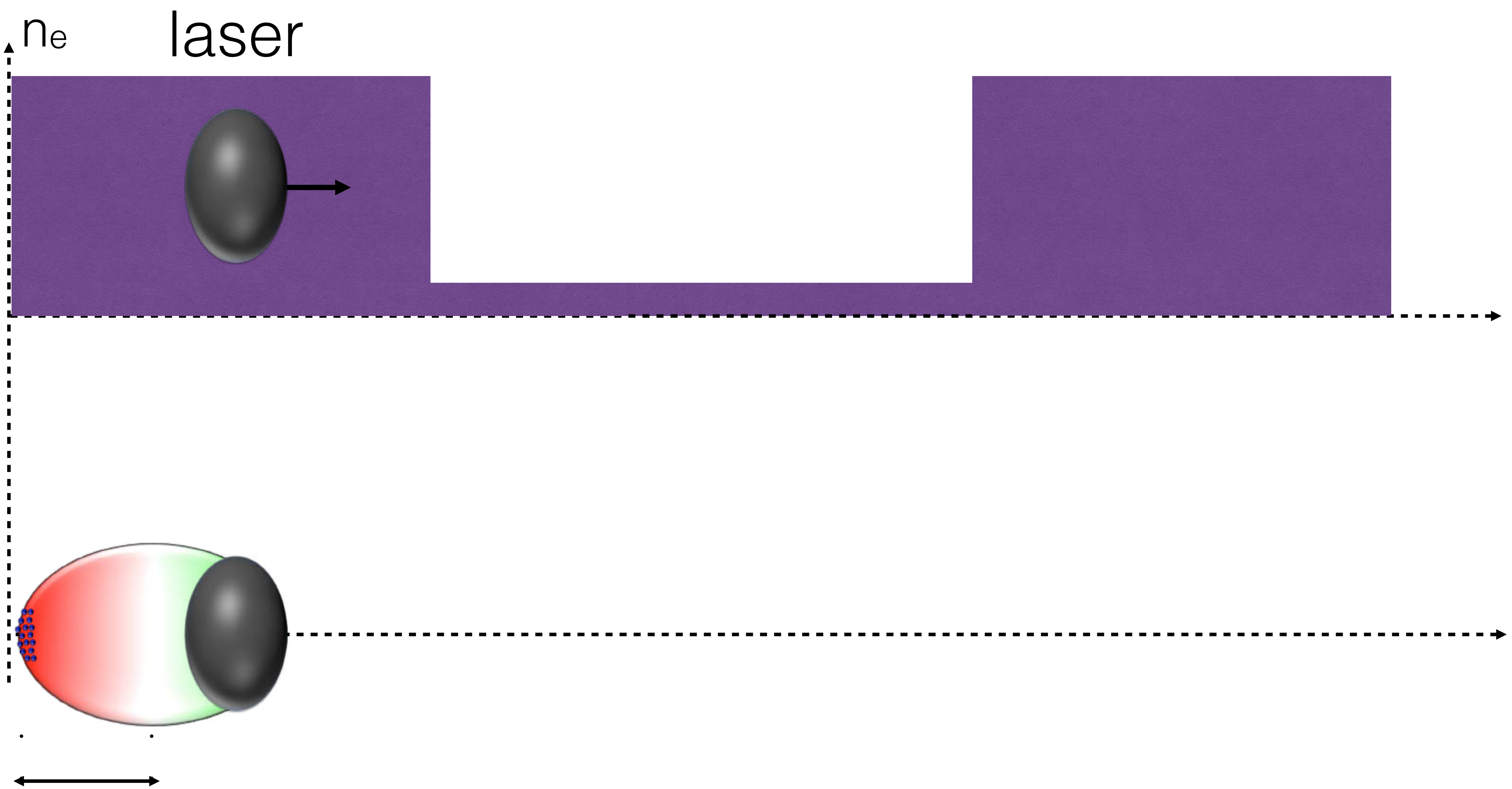

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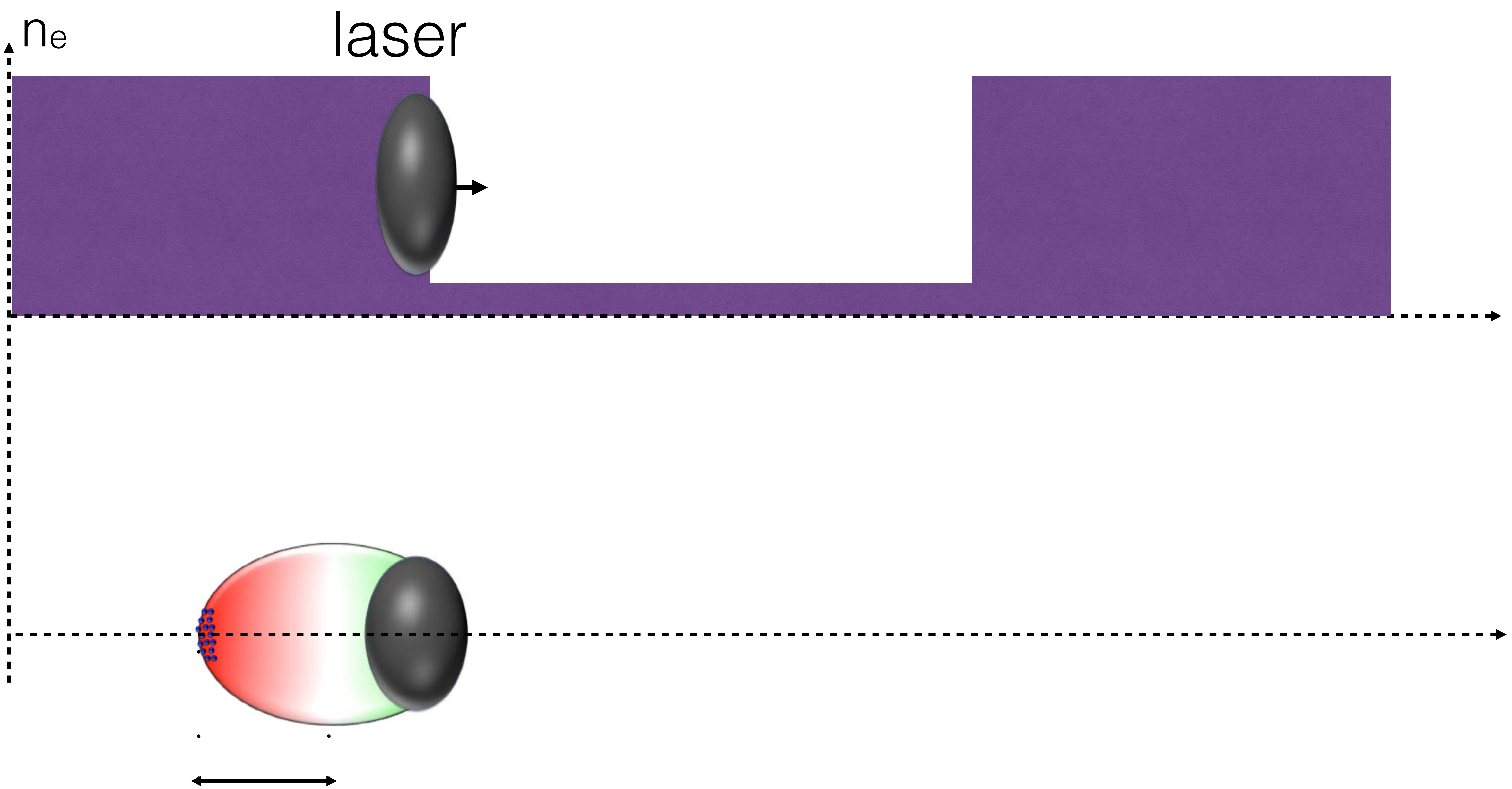

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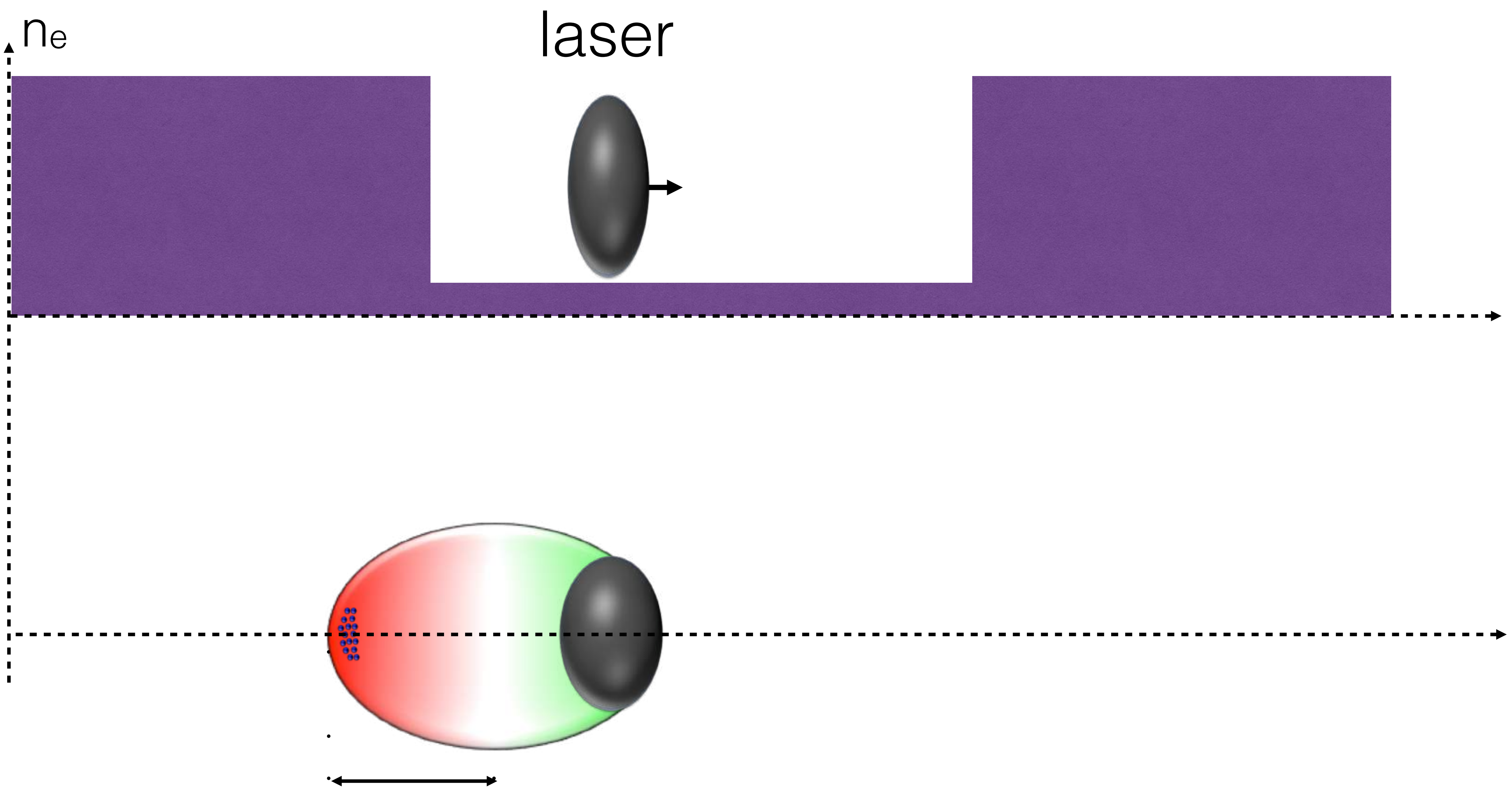

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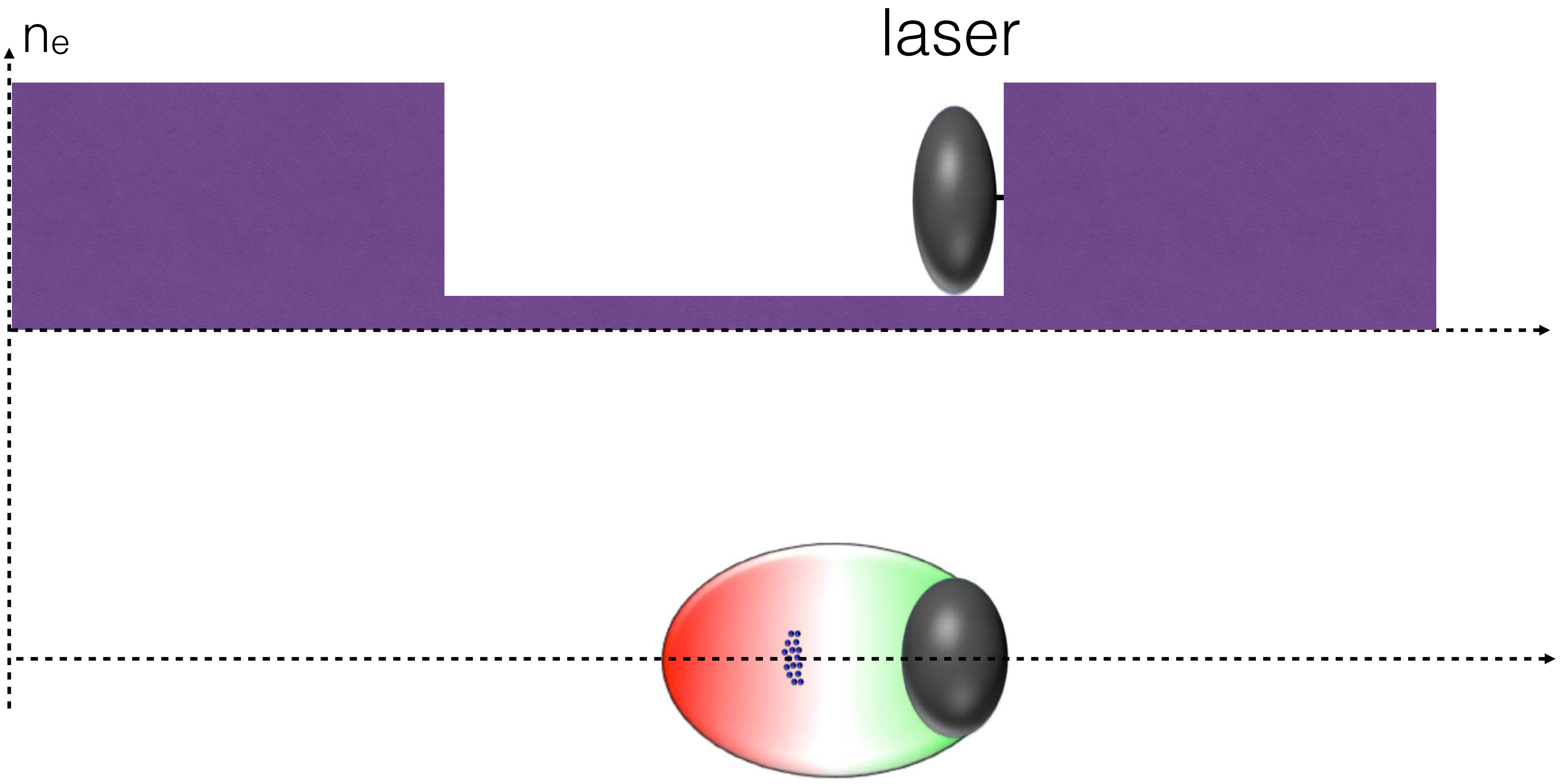

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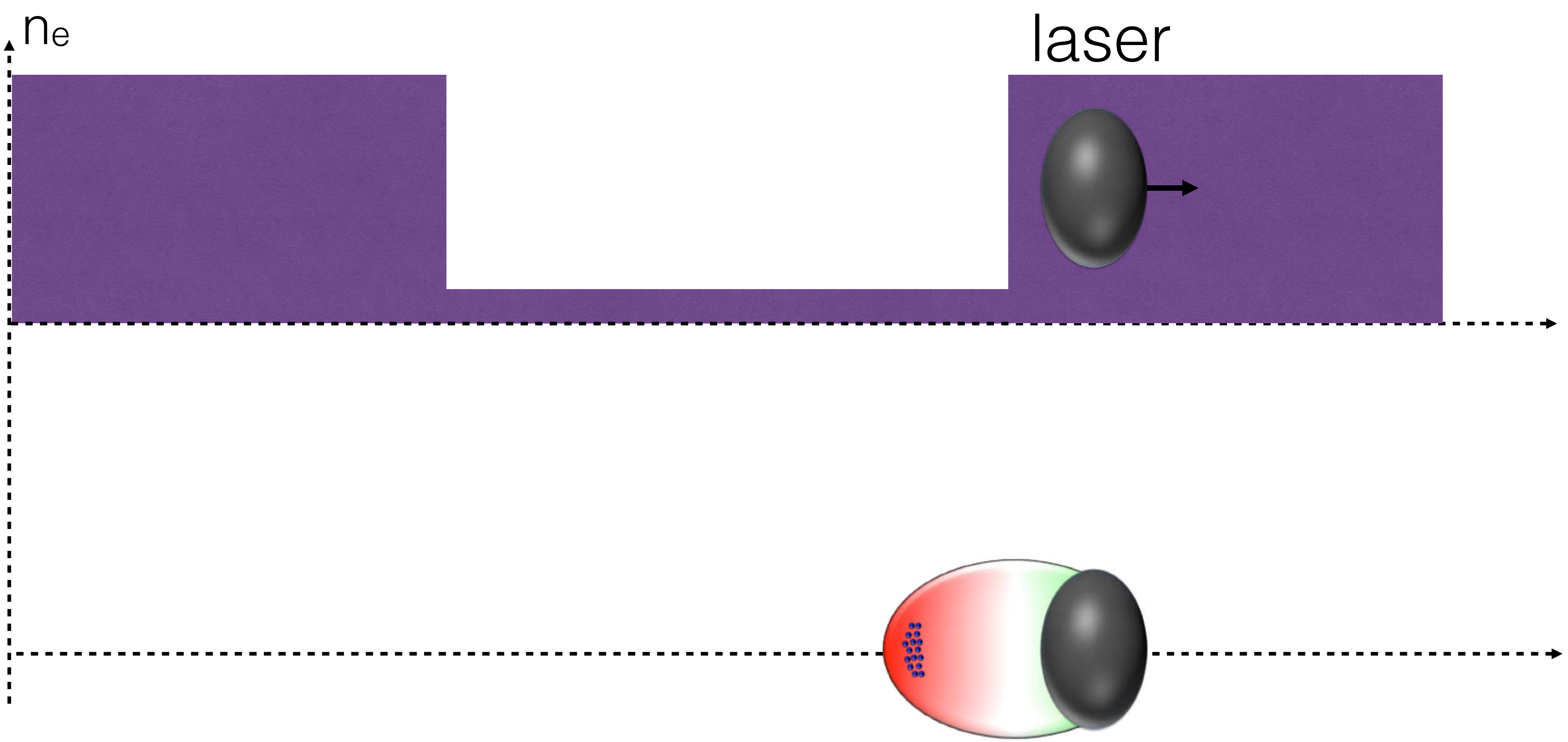

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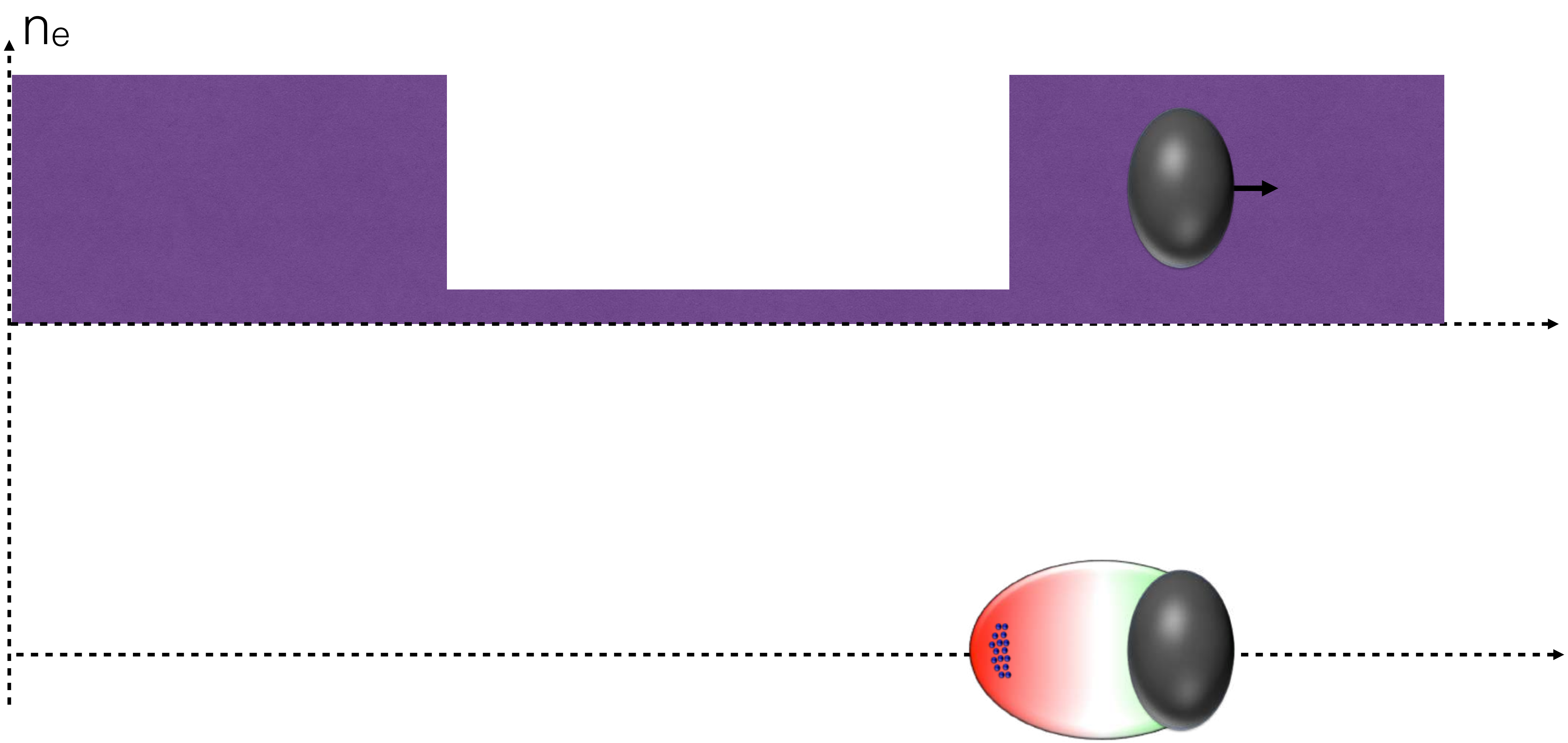

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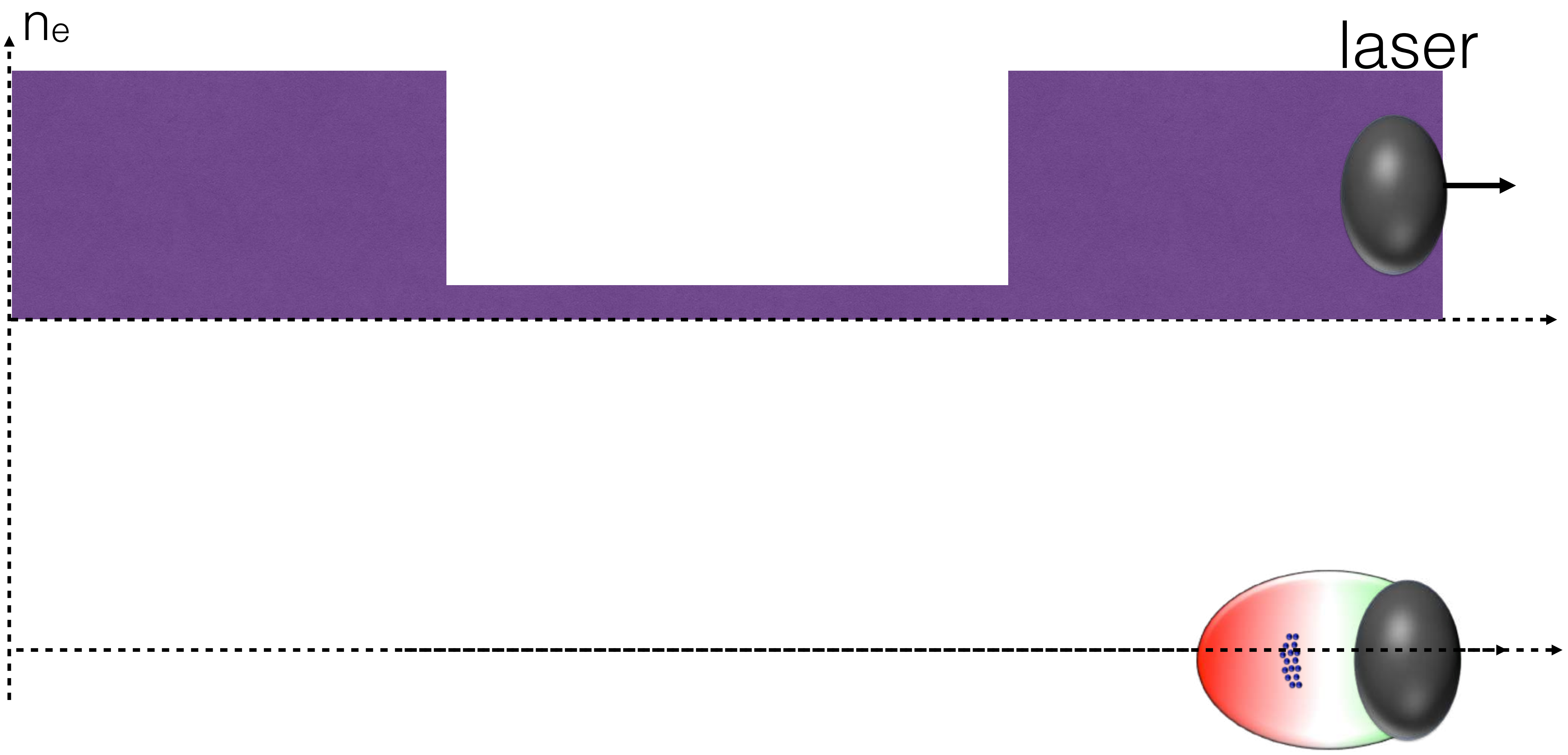
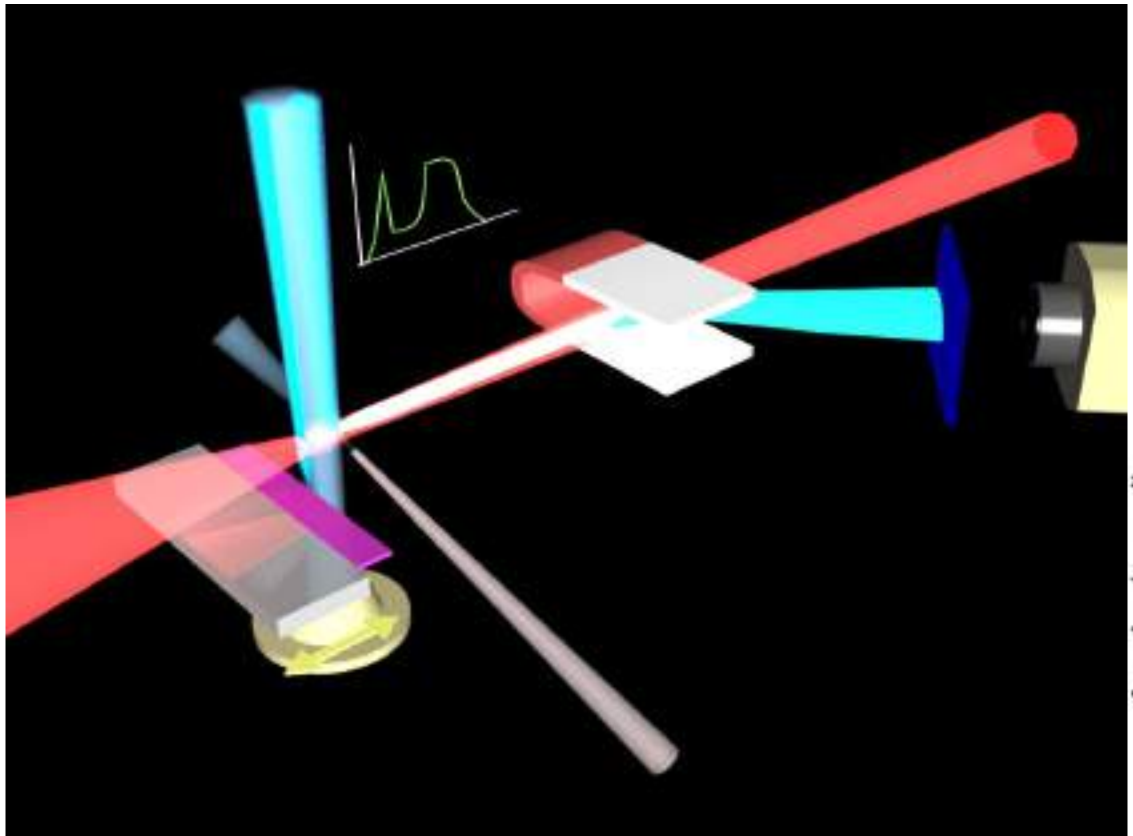
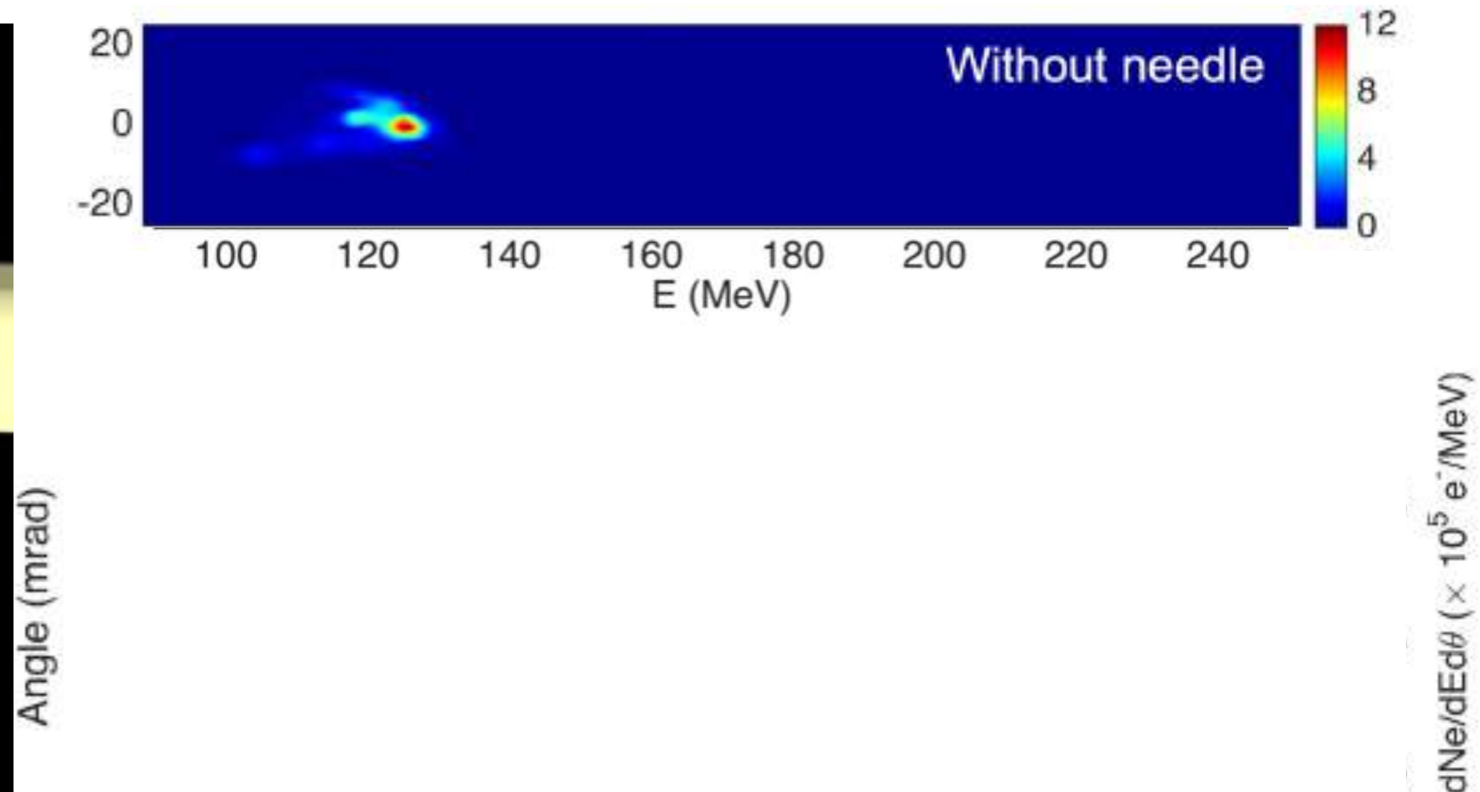


Energy boost of a mono-energetic e-beam



boosting a monoenergetic electron beam



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

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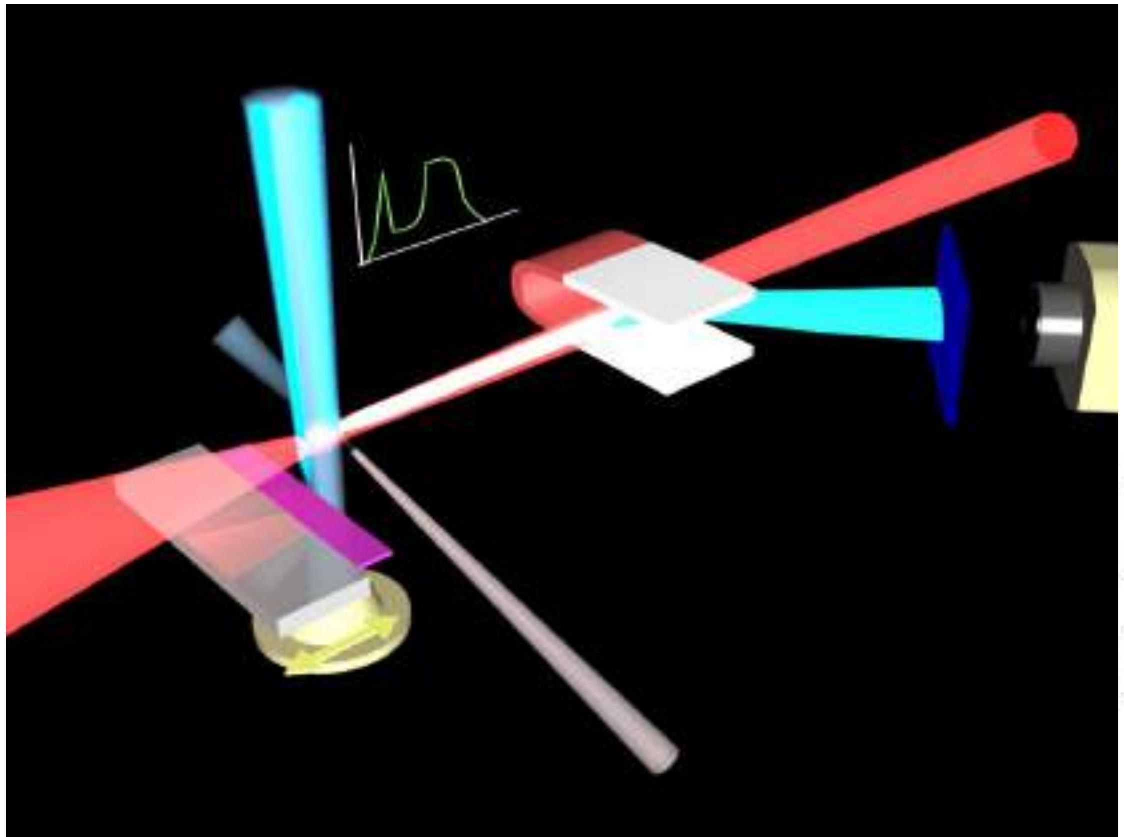

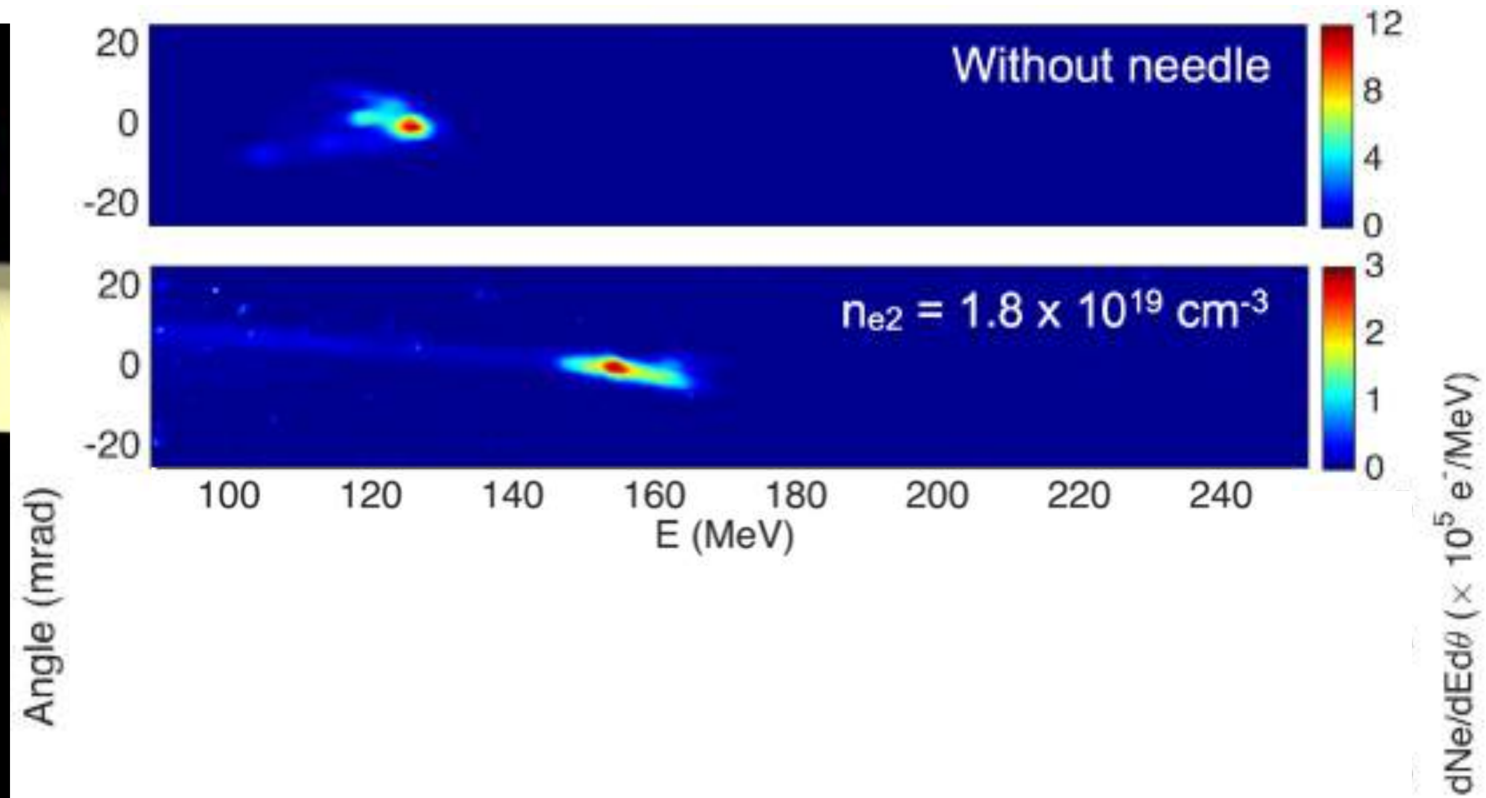

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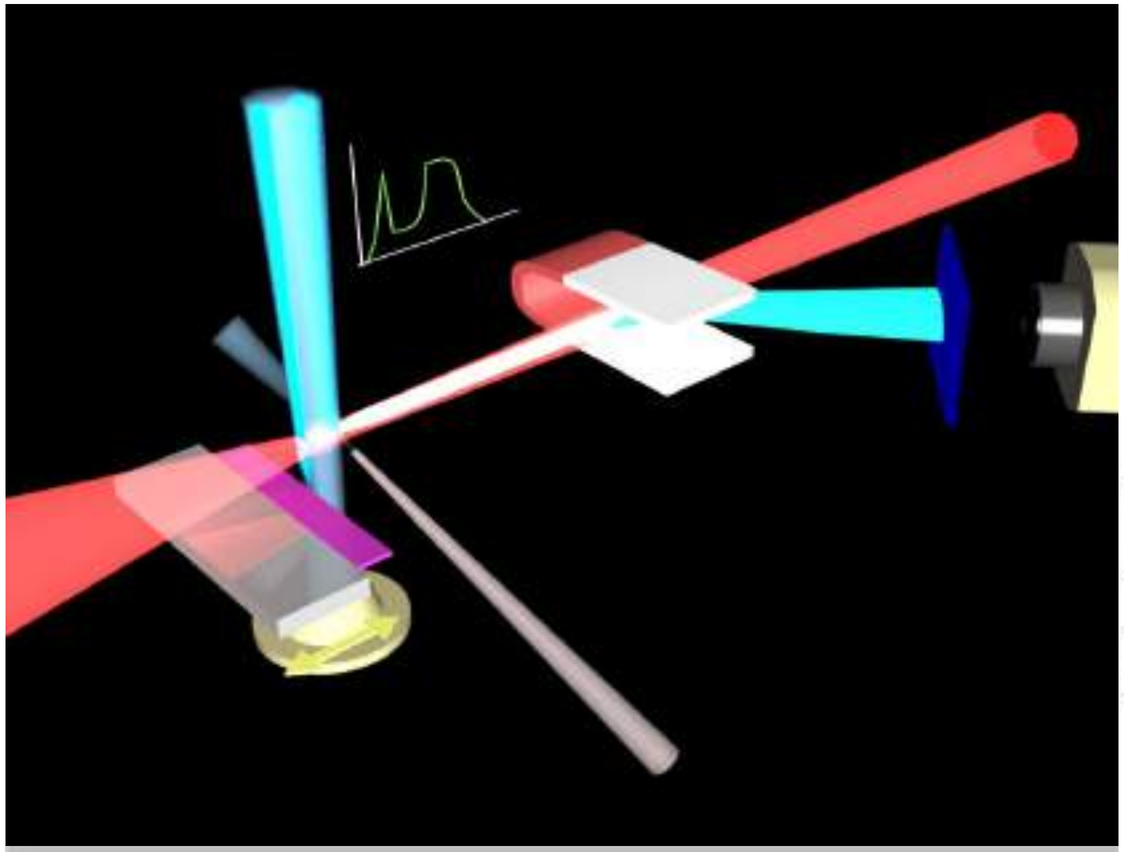

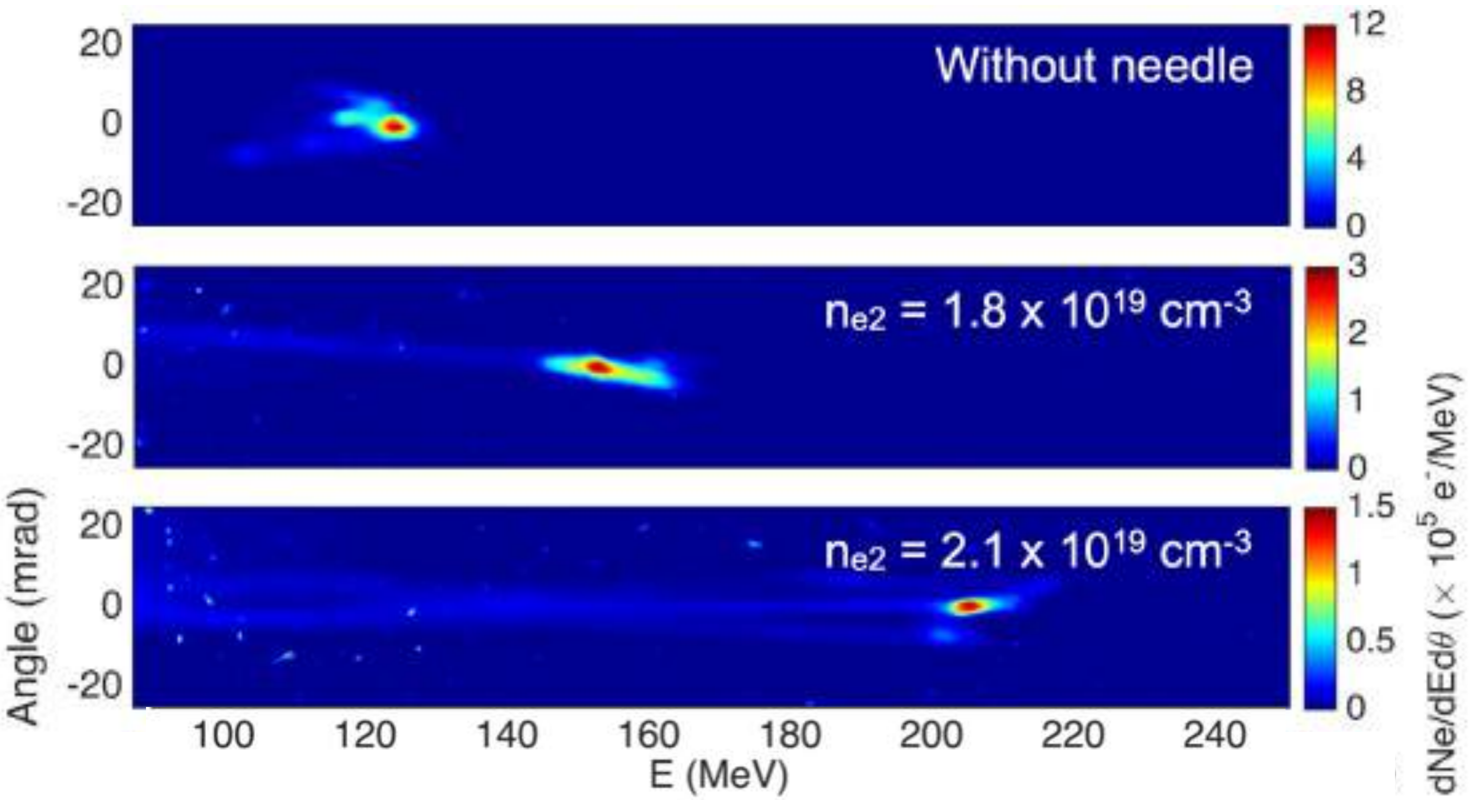

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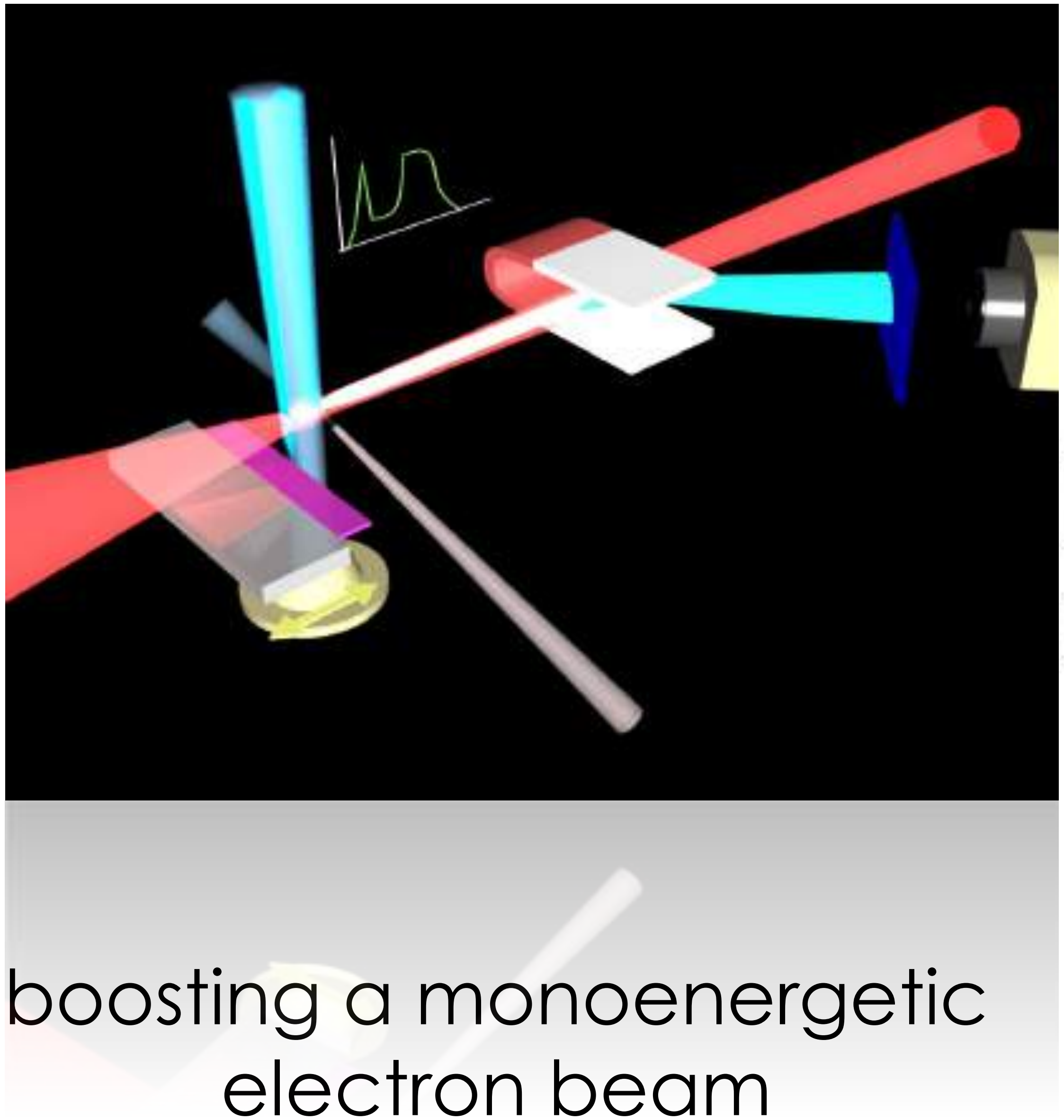
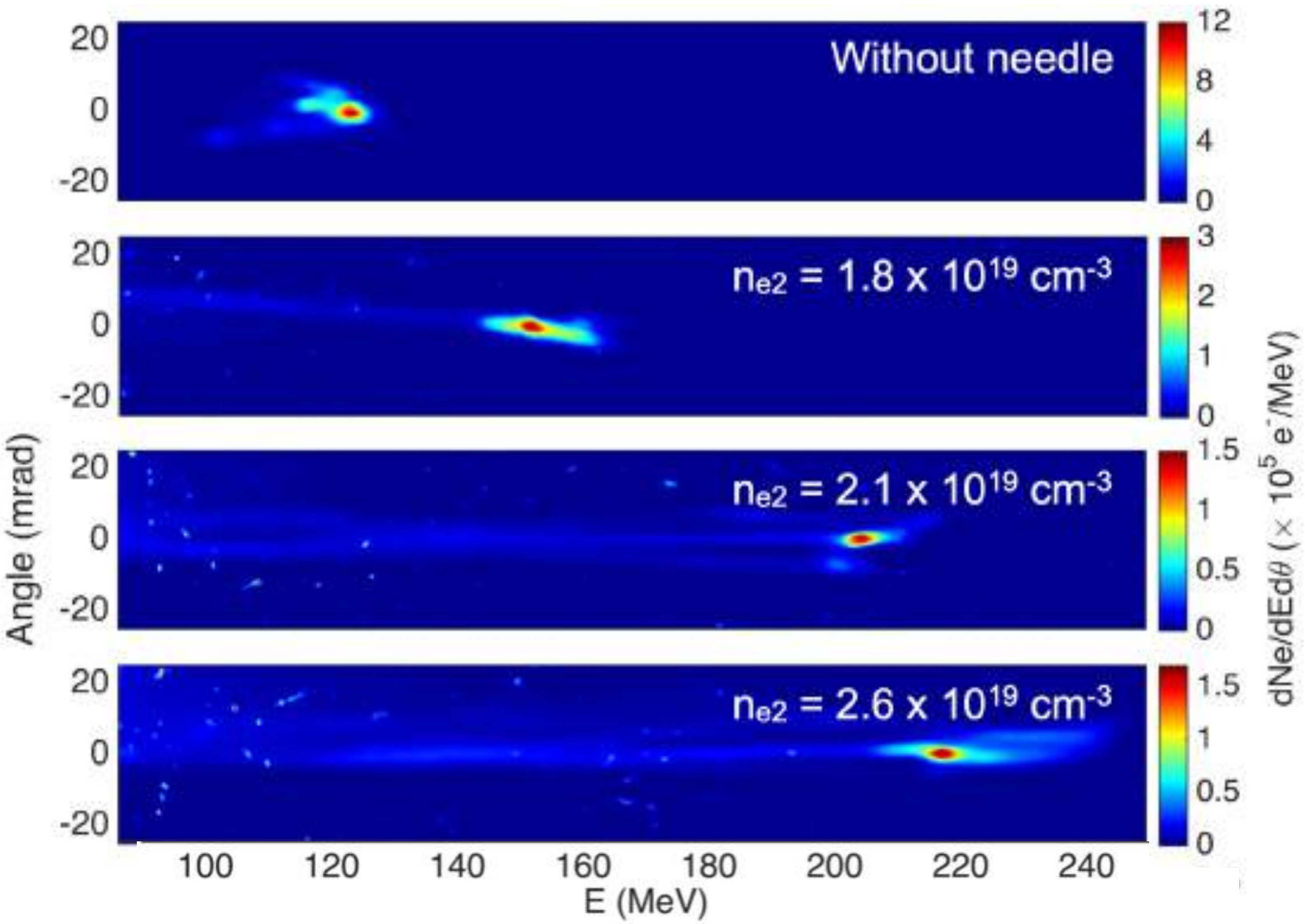
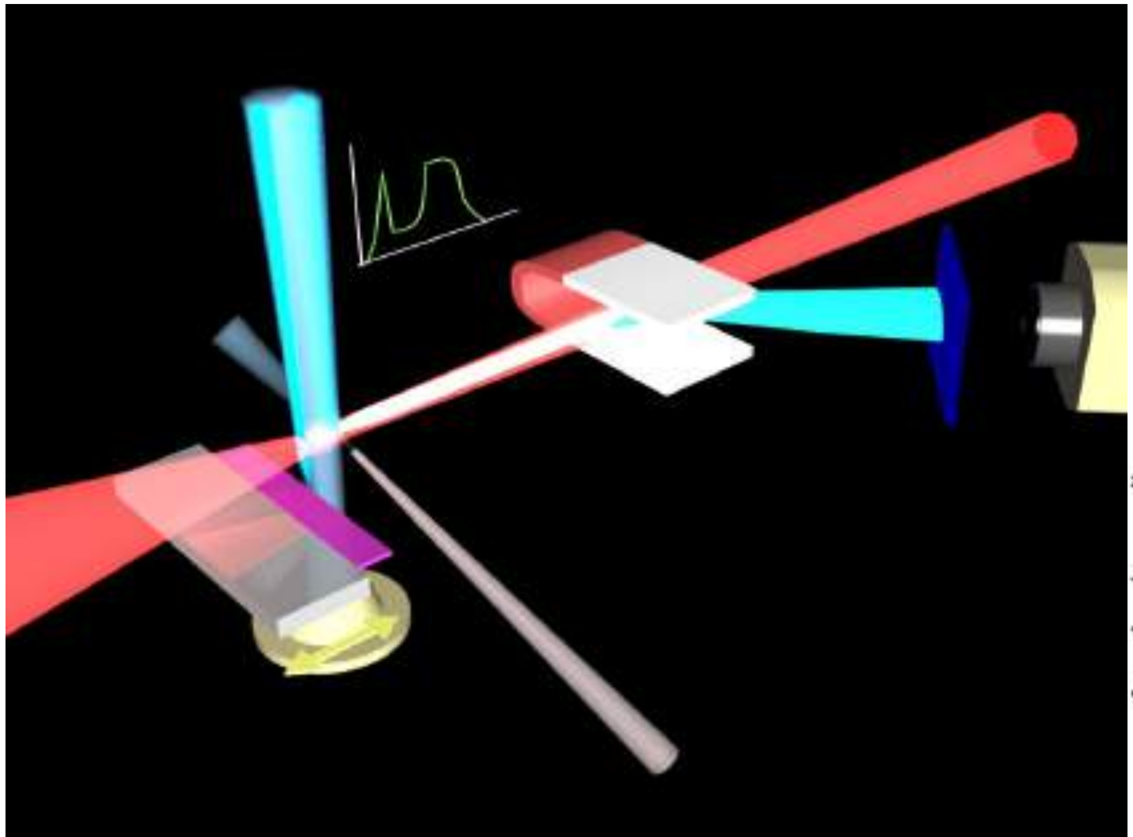




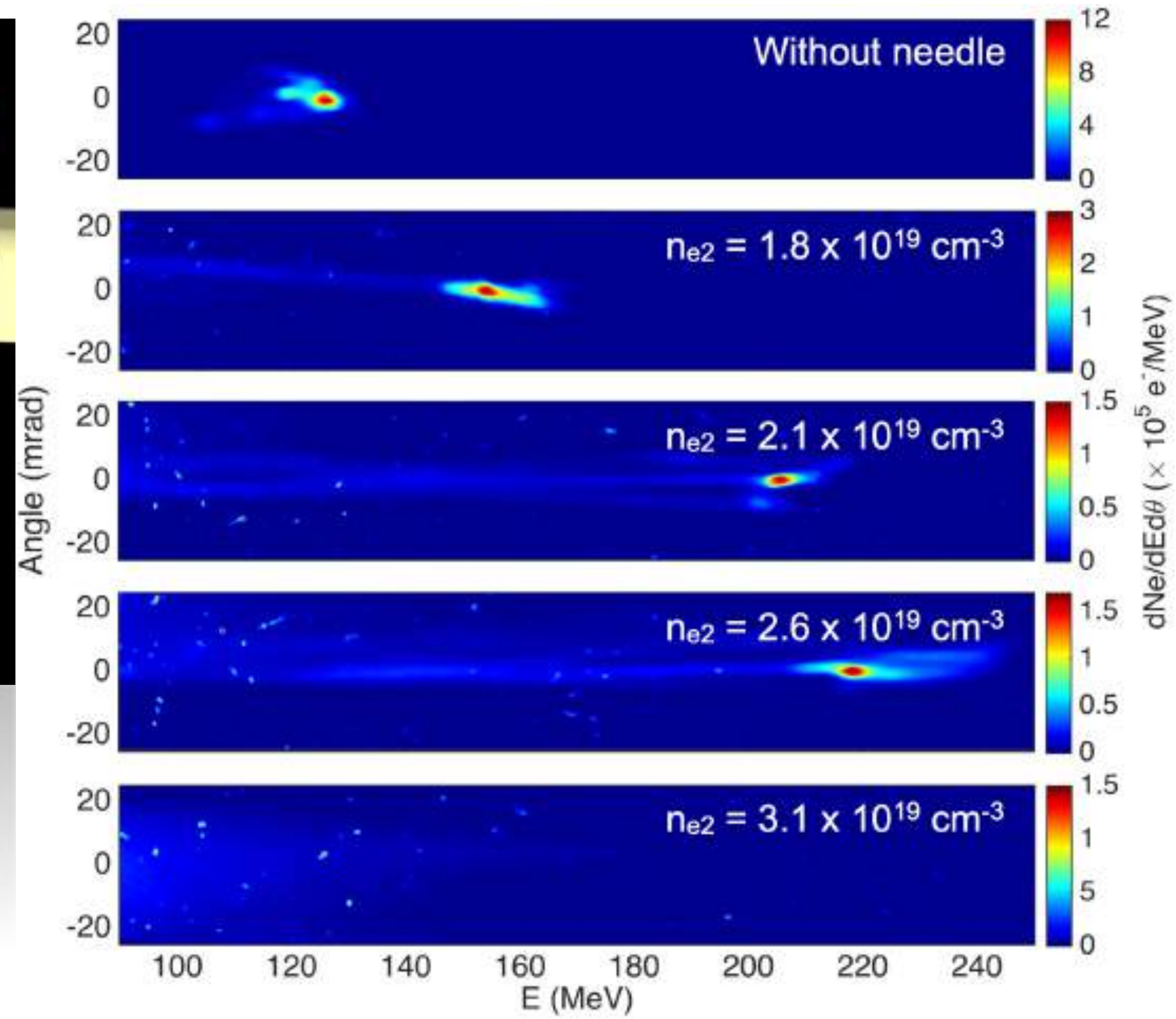
boosting a monoenergetic electron beam

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

Energy boost of a mono-energetic e-beam



boosting a monoenergetic electron beam

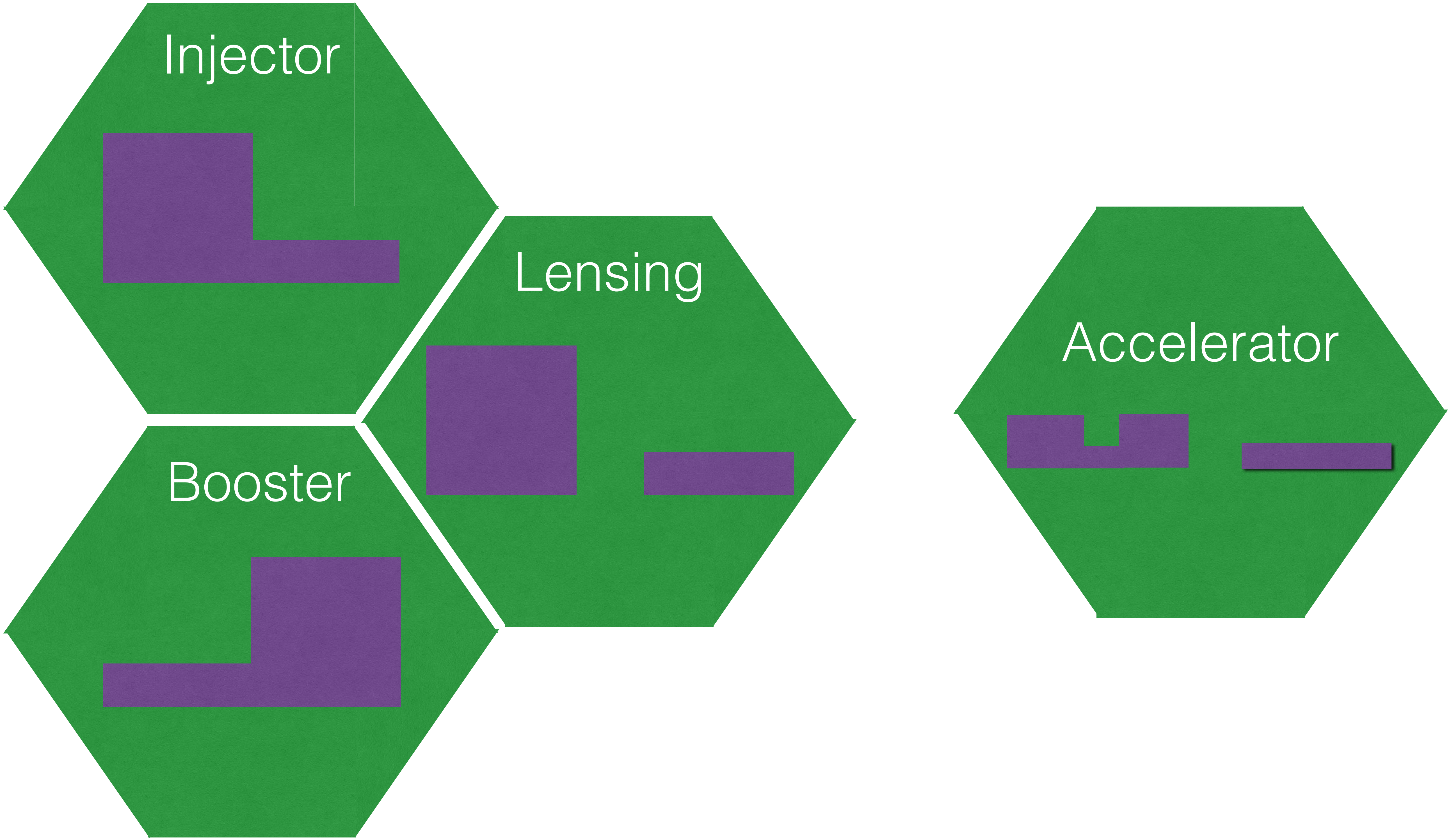


E. Guillaume et al., PRL **115** (2015)

Laser Plasma Accelerators : Outline

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

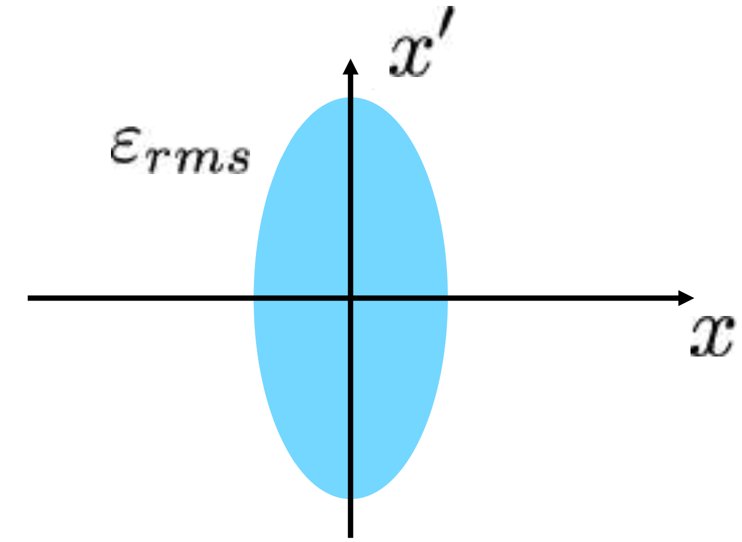
Simple plasma devices produced with a single laser pulse



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**

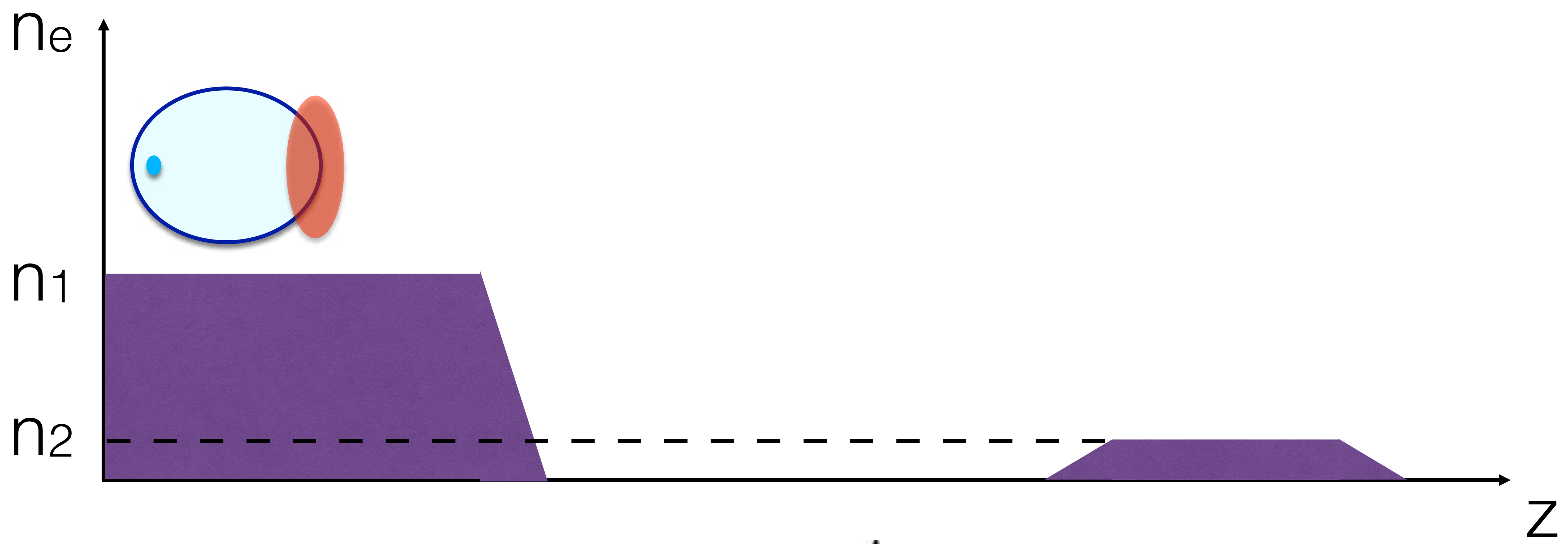
} emittance is dominated by the divergence

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

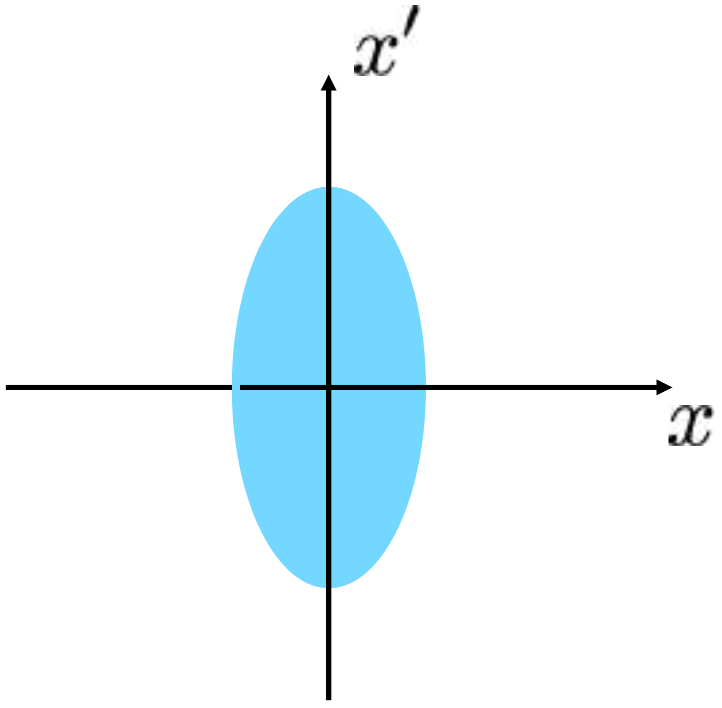
Goal :

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

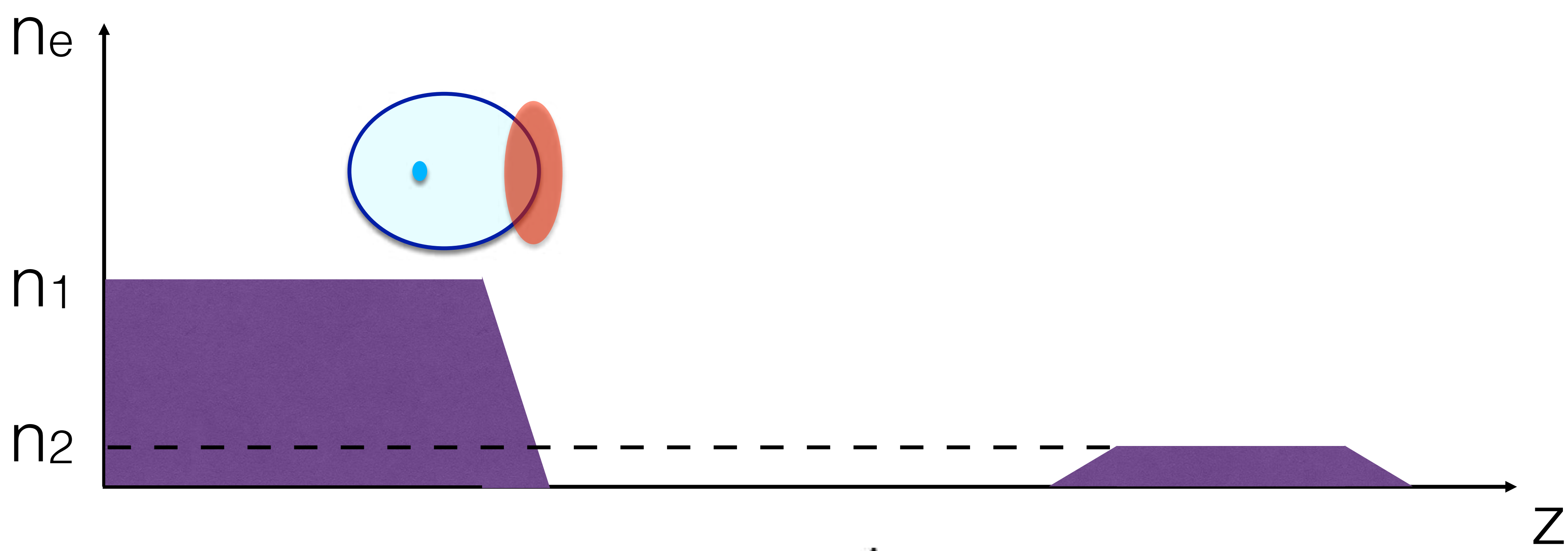
Manipulating the p⊥ momentum : principle

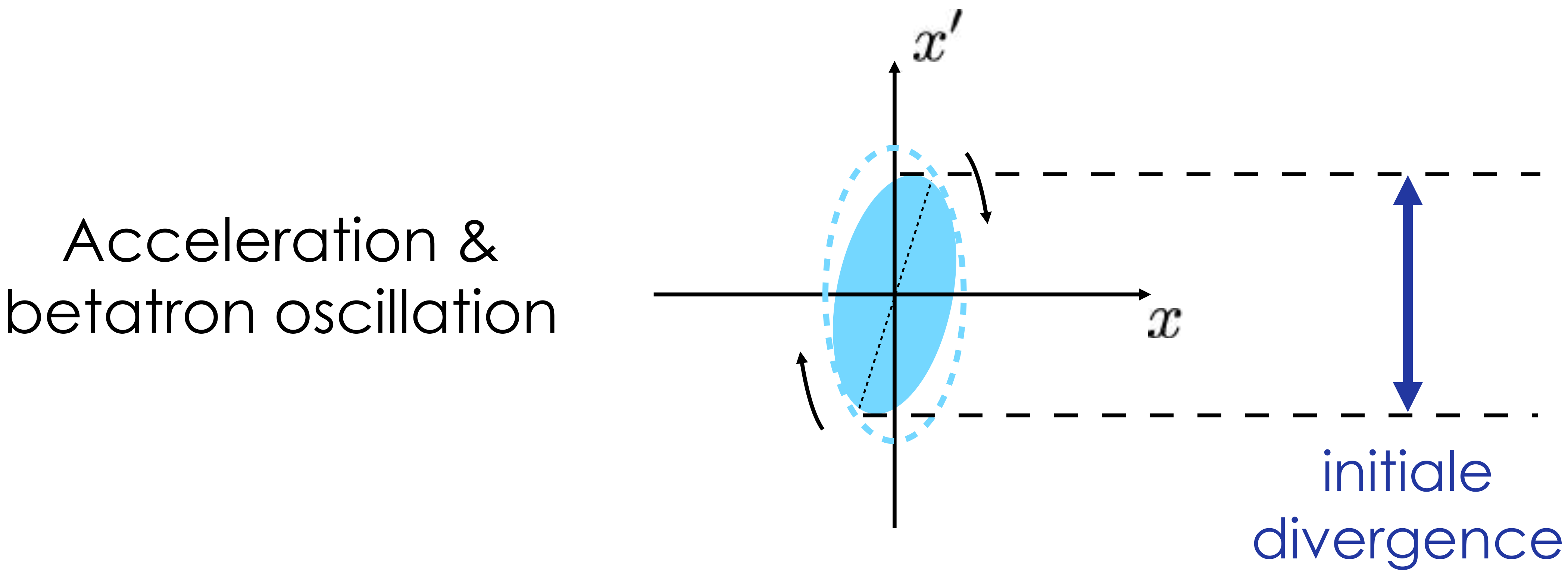


Acceleration &
betatron oscillation

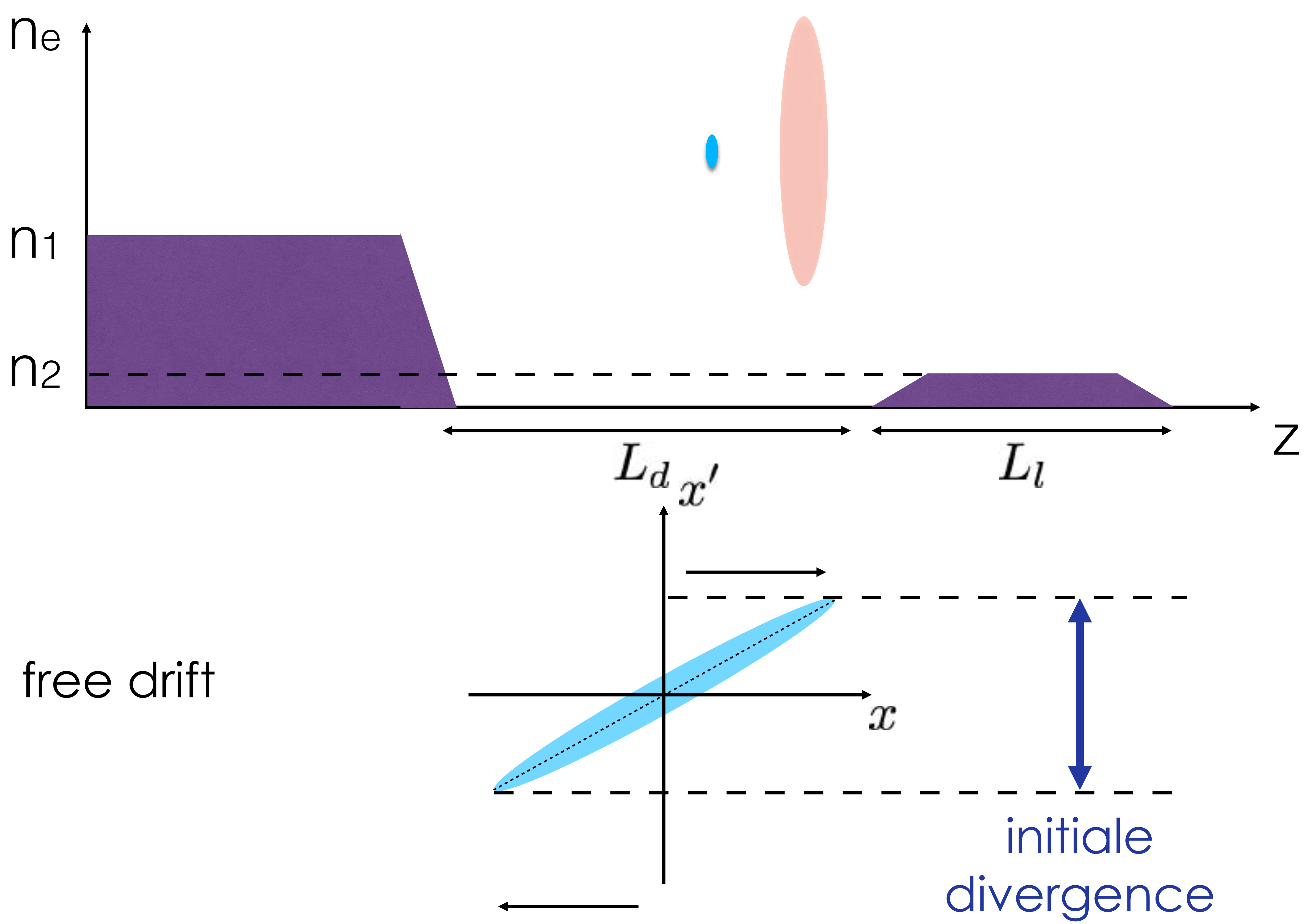


Manipulating the p⊥ momentum : principle

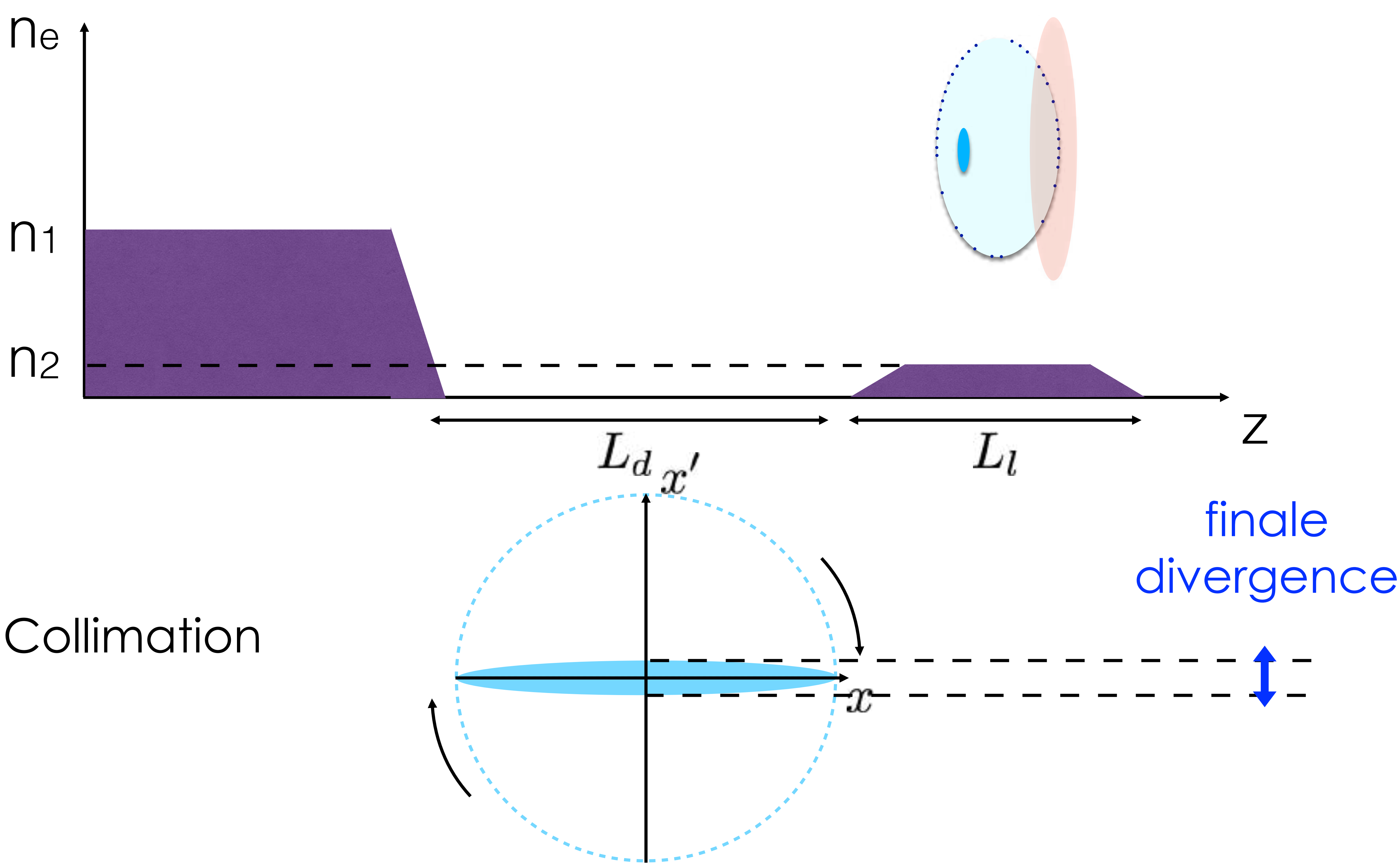




Manipulating the p⊥ momentum : principle



Manipulating the p⊥ momentum : principle



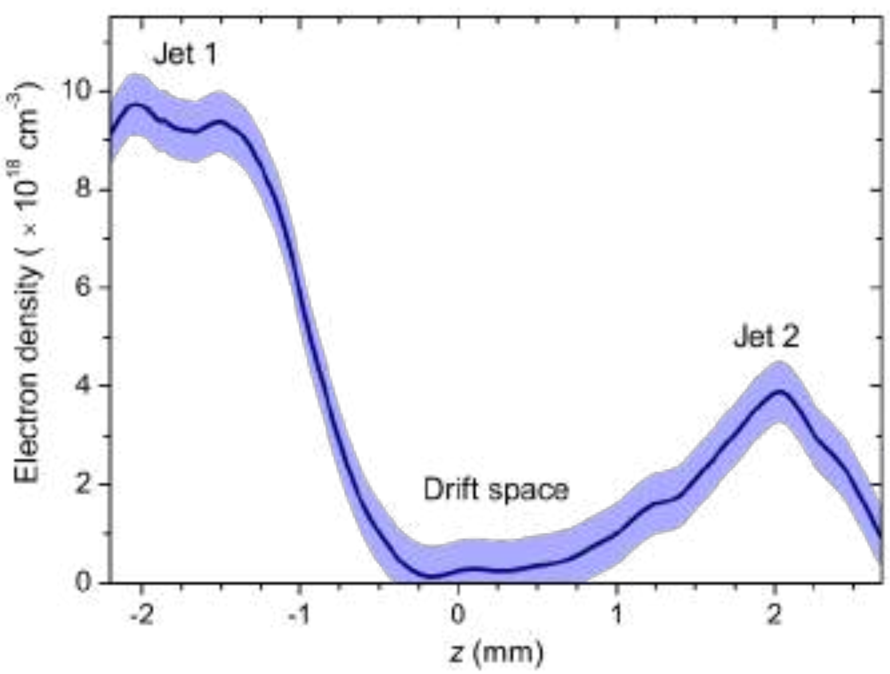
Manipulating the p⊥ momentum : experimental set-up

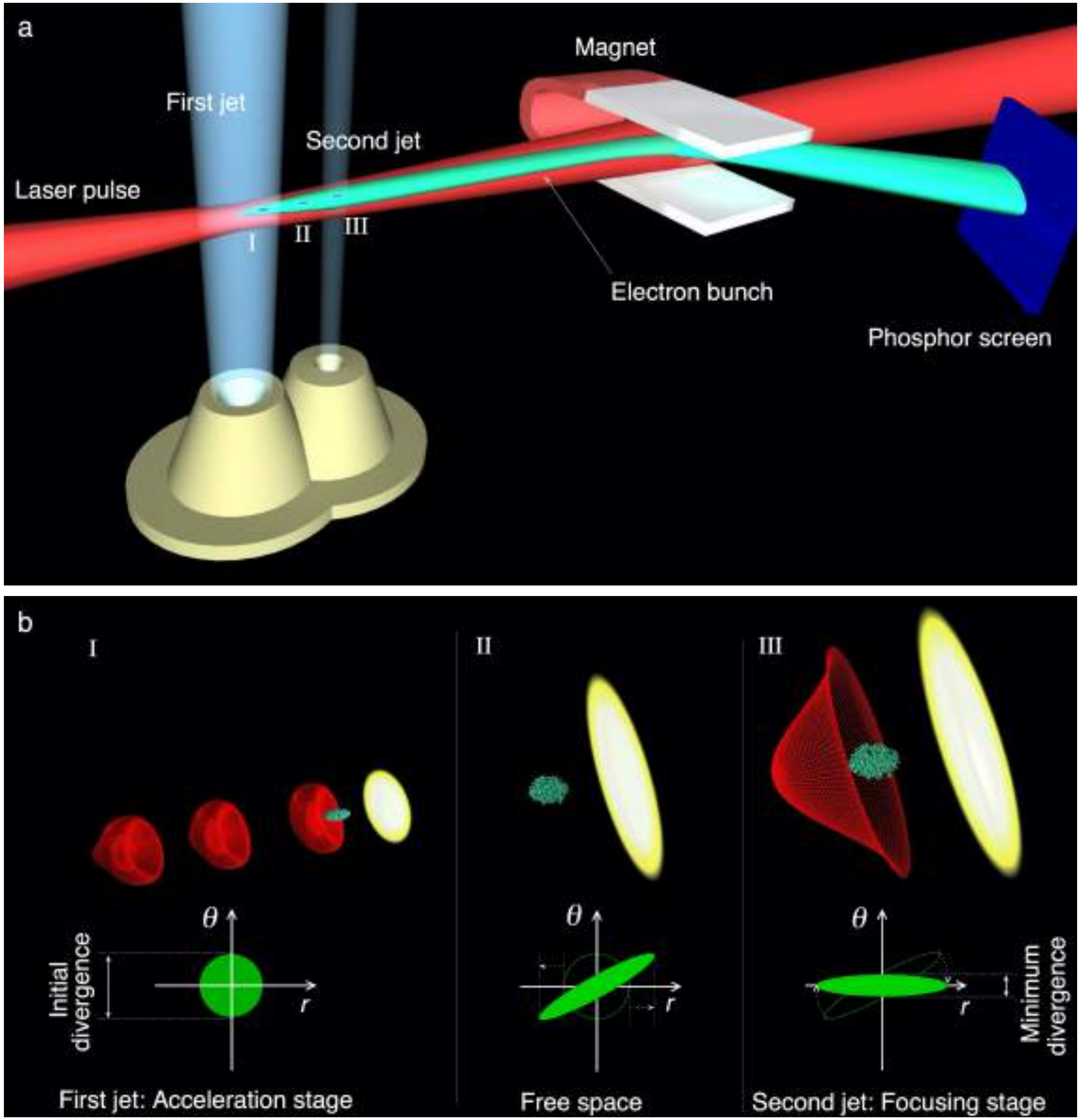
Acceleration stage

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

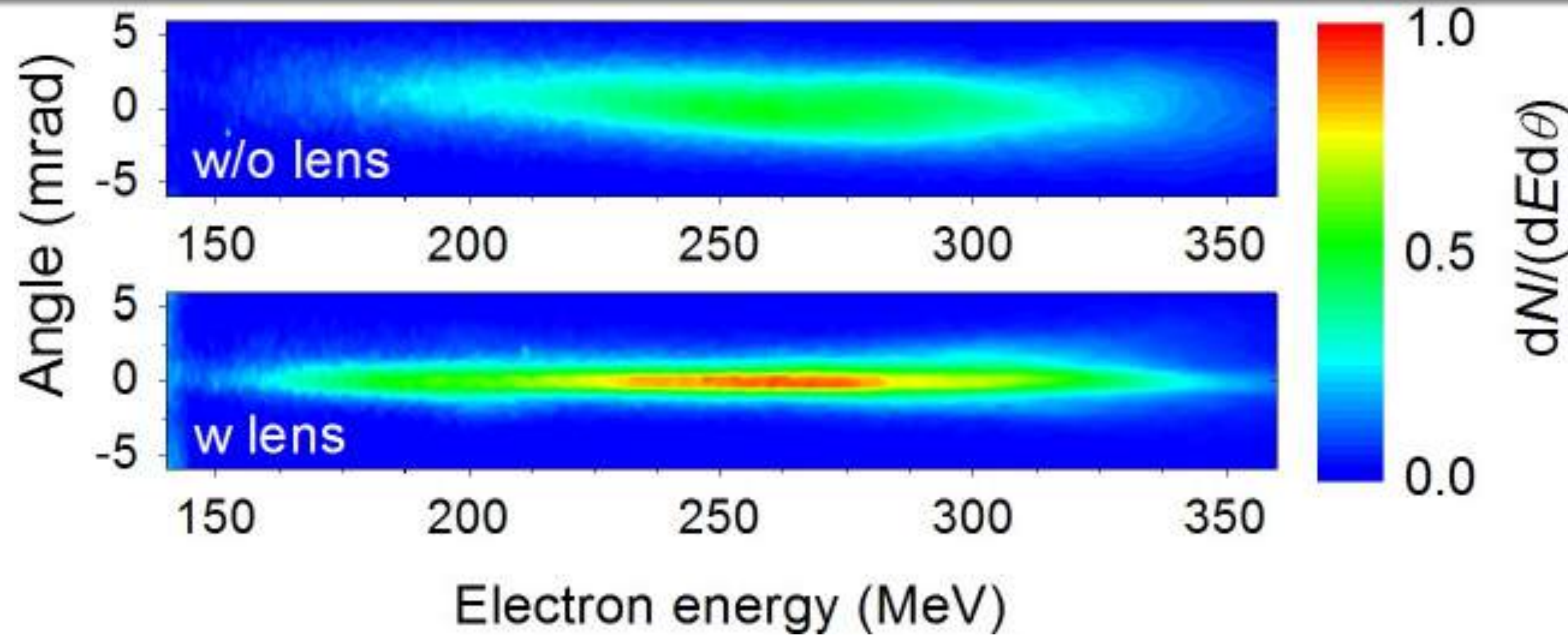
Focusing stage

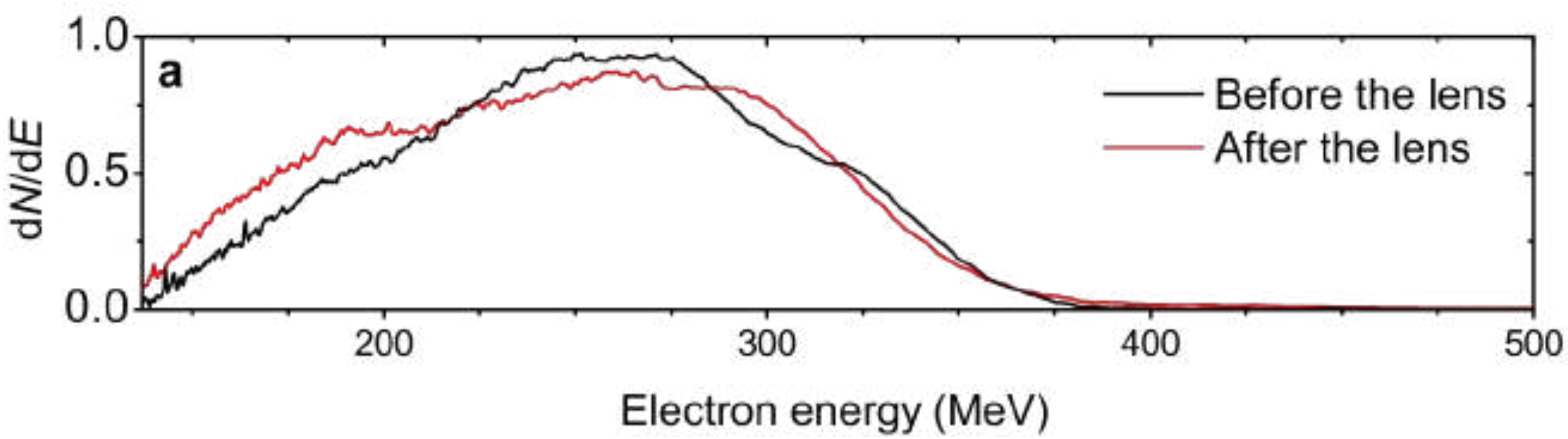
1 mm nozzle with variable n_2
Variable L_d





Manipulating the $p_{\perp}$ 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

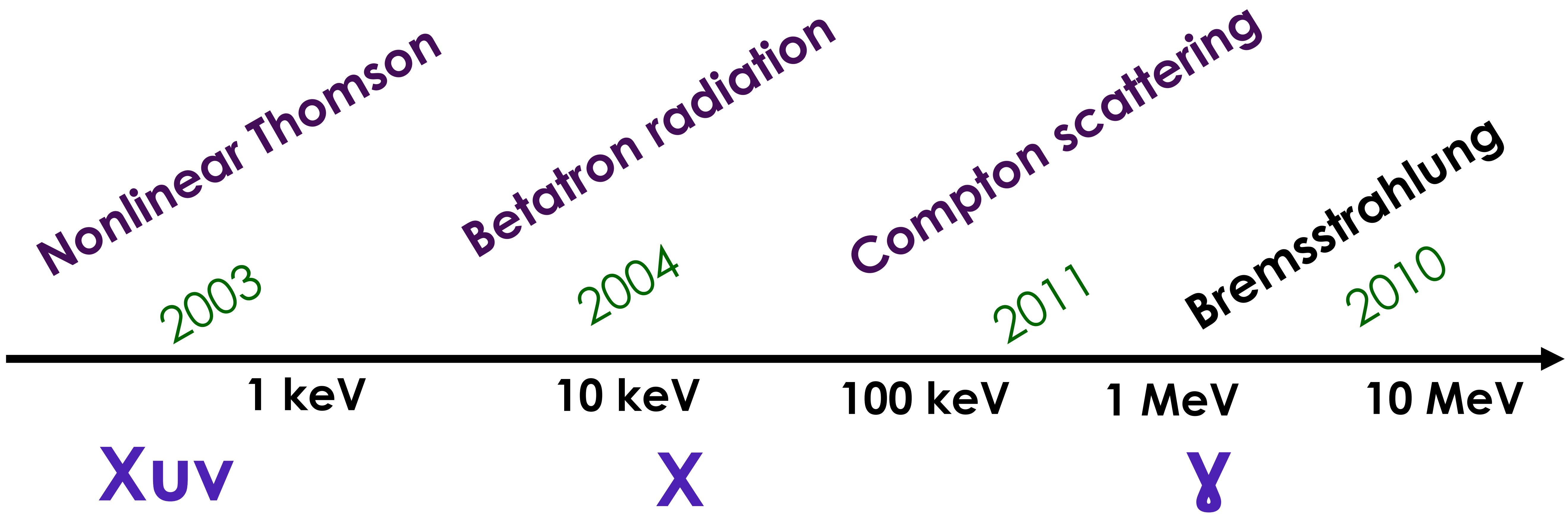
Divergence reduction ~ 2.6 ± 0. 7

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

Laser Plasma Accelerators : Outline

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

X rays source with Laser Plasma accelerators



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

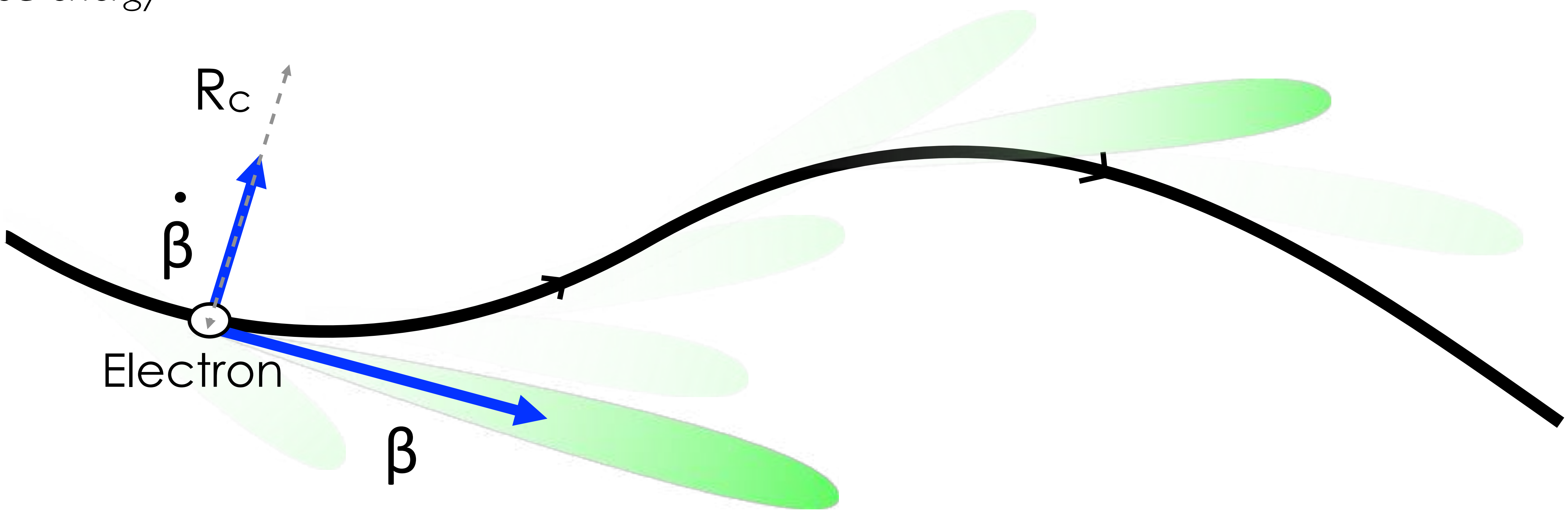
Moving charge radiation

Velocity — Acceleration

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

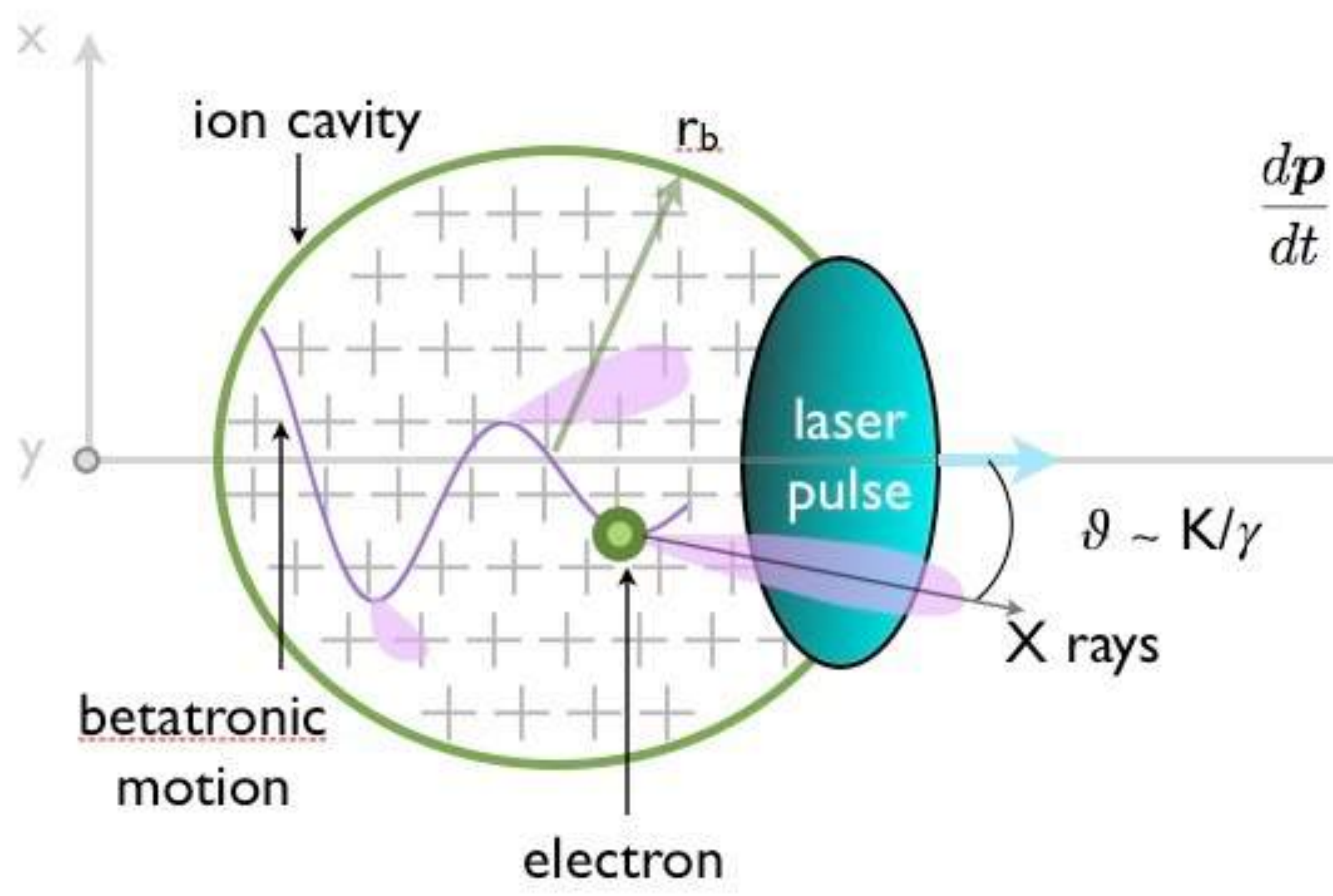
Radiated energy

***n** unit vector in the observation direction*



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

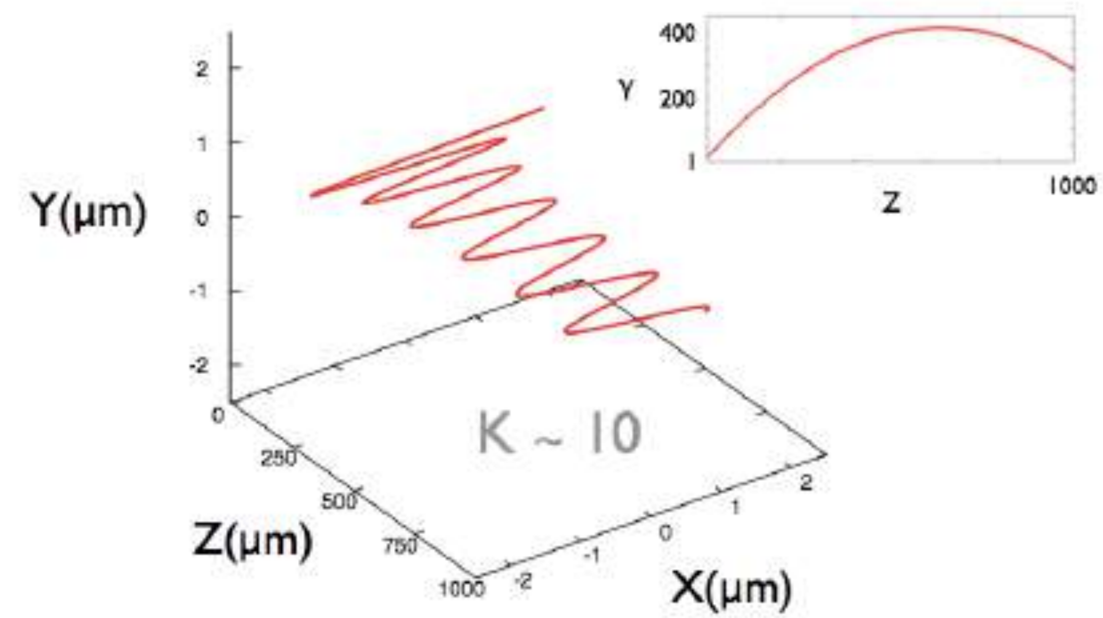
Betatron radiation properties



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



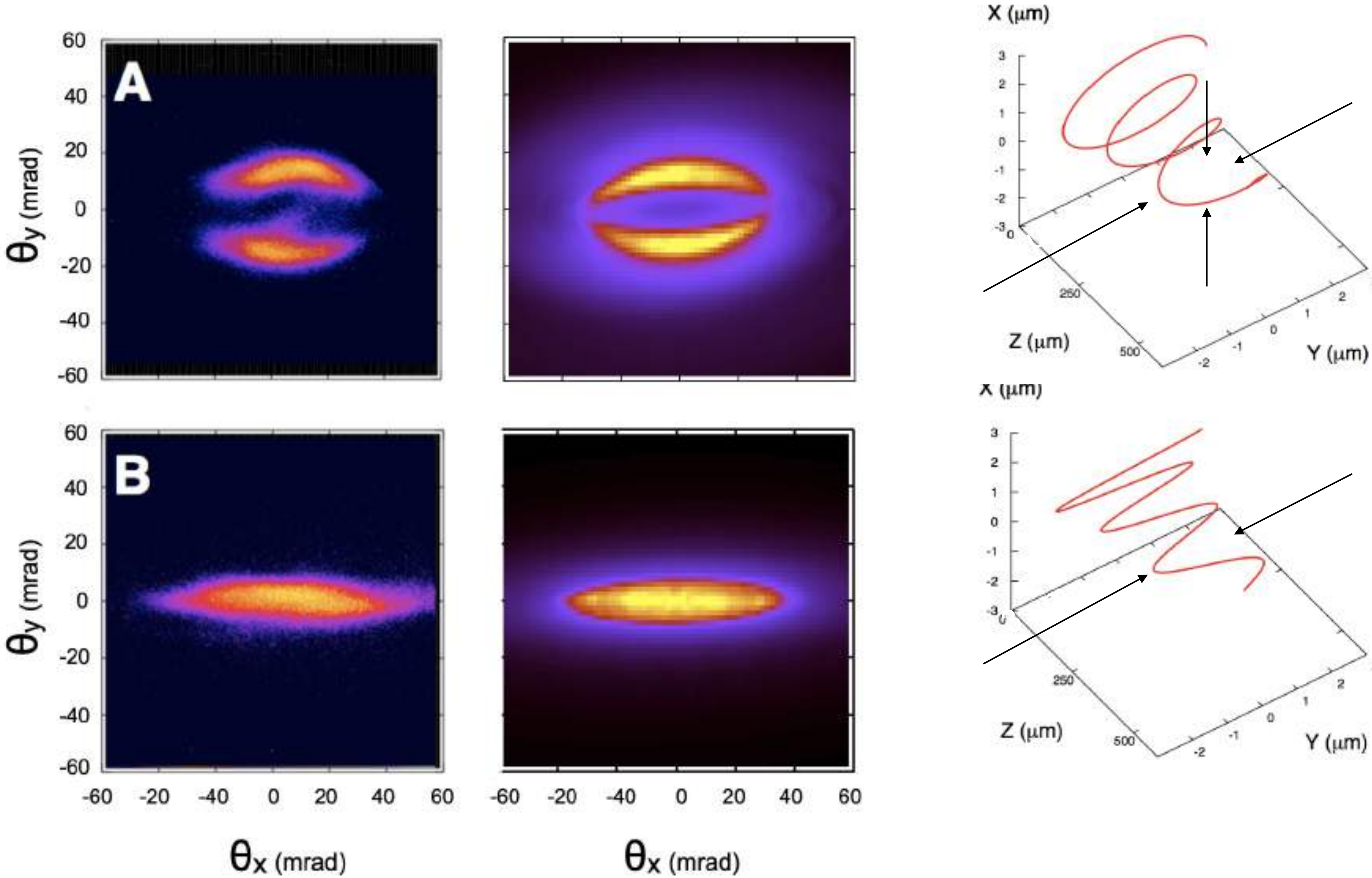
Betatron oscillation properties:

$$\lambda_u = \sqrt{2\gamma}\lambda_p$$

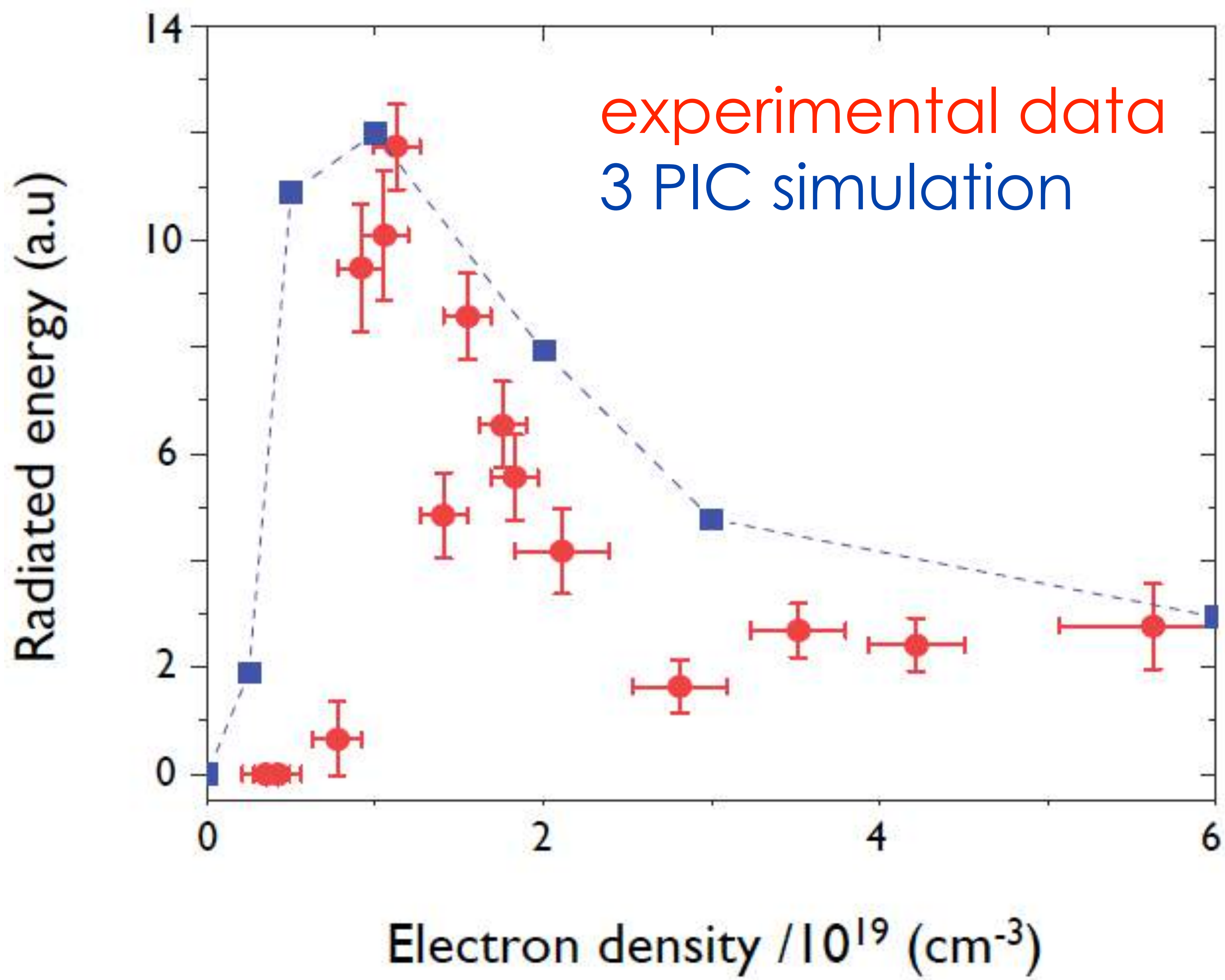
$$K = r_\beta k_p \sqrt{\gamma/2}$$

~ 100 MeV, $r_\beta \sim 1\ \mu$m, $n_e \sim 10^{19}$ cm^{-3} → $\lambda_u \sim 200\ \mu$m, $K \sim 5$

Betatron radiation properties

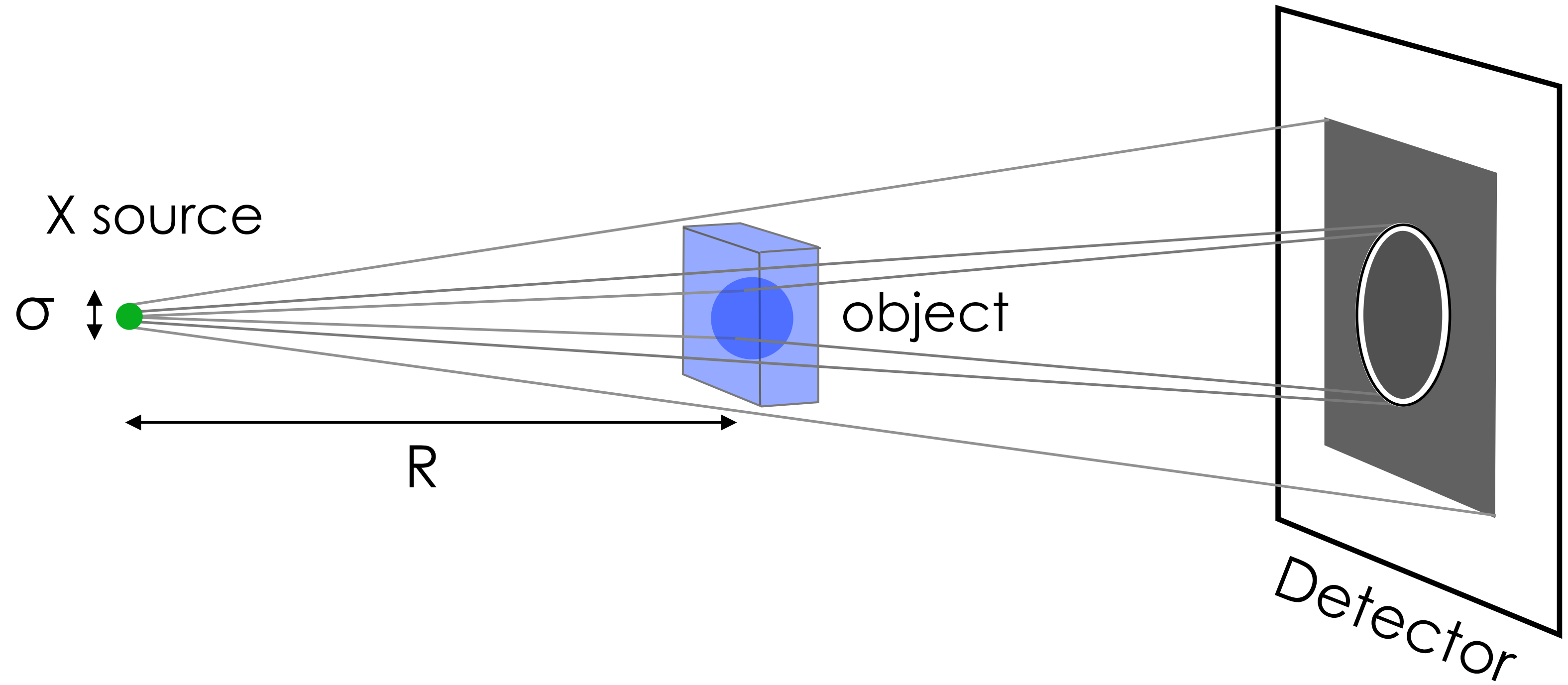


Betatron signal variation with density



A. Rousse *et al.*, Phys. Rev. Lett., 93, 135005 (2004)

X ray Phase Contrast Radiography



- Absorption contrast

Contrast is due to the absorption difference in the object

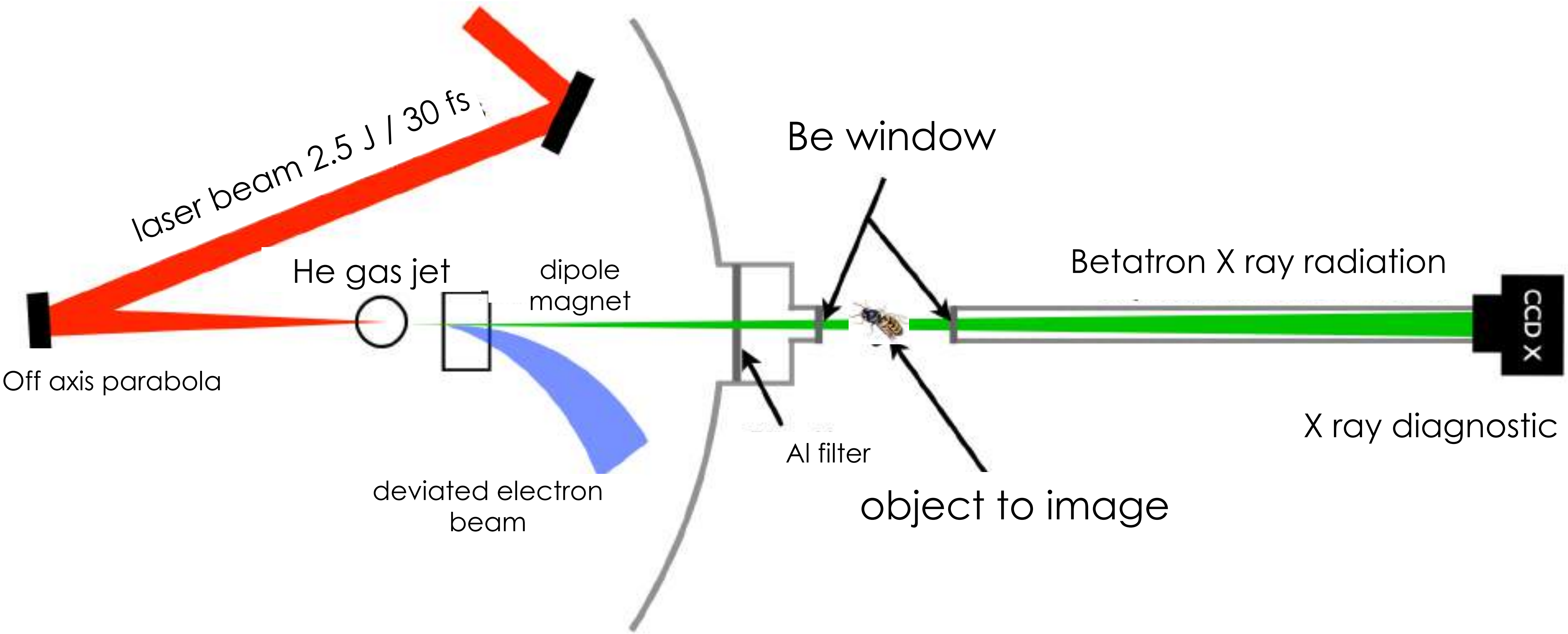
It works only with object with important absorption difference

- Phase contrast

Interferences can reveal object interfaces
Biological objects have phase contrast 1000 times higher than absorption contrast
It requires a very high spatial coherence (10's microns) :

$d = \lambda R / 2\pi\sigma$

X ray Phase Contrast Radiography: Experiments



Parameters of the source :

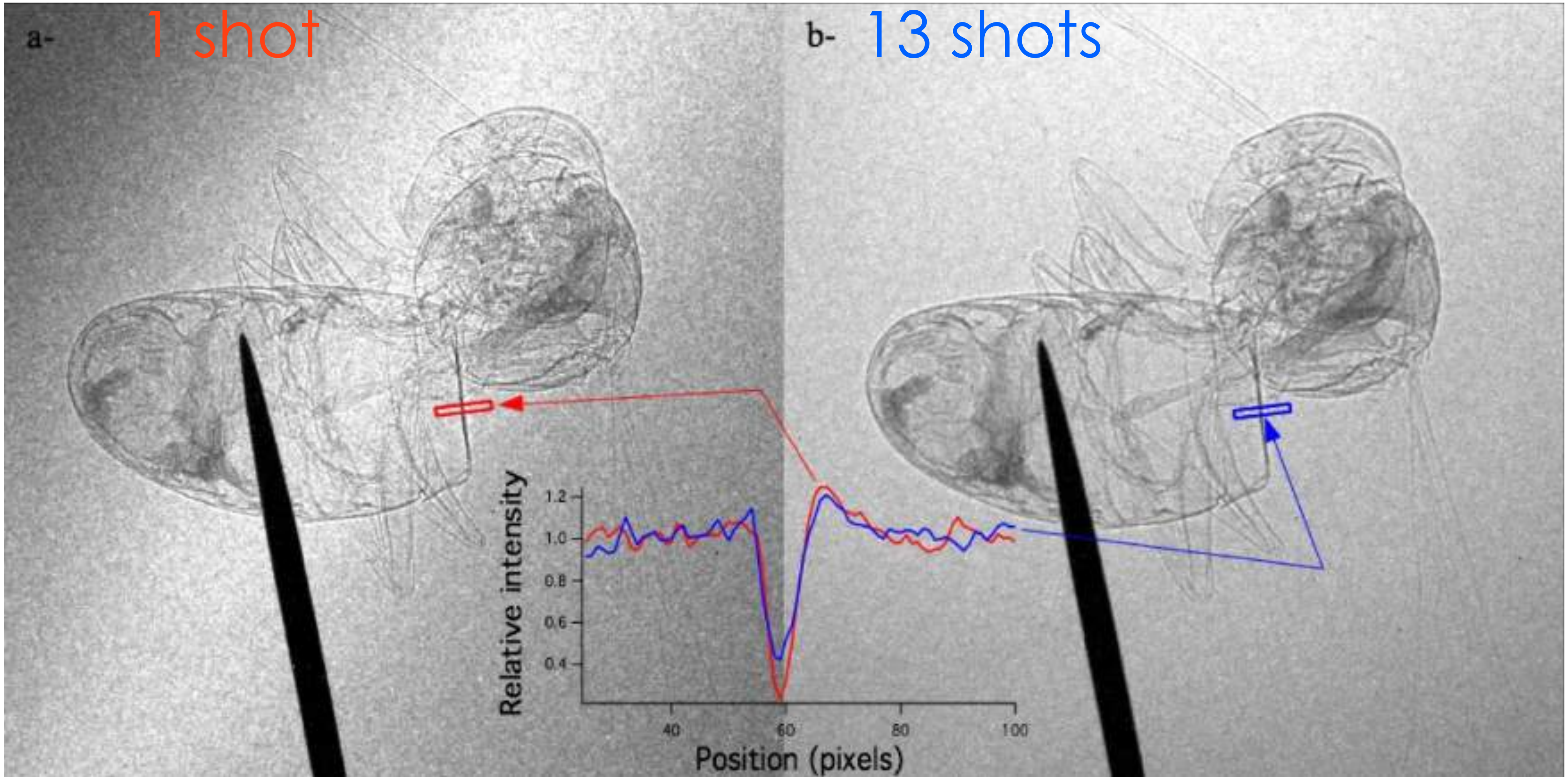
- E_C = 12.3 keV
- 2.2×10^8 photons/0.1%BW/sr/shot at 10 keV
- N = 10^9 photons in 28 mrad (FWHM) divergence beam

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

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)

X Contrast Phase Imaging

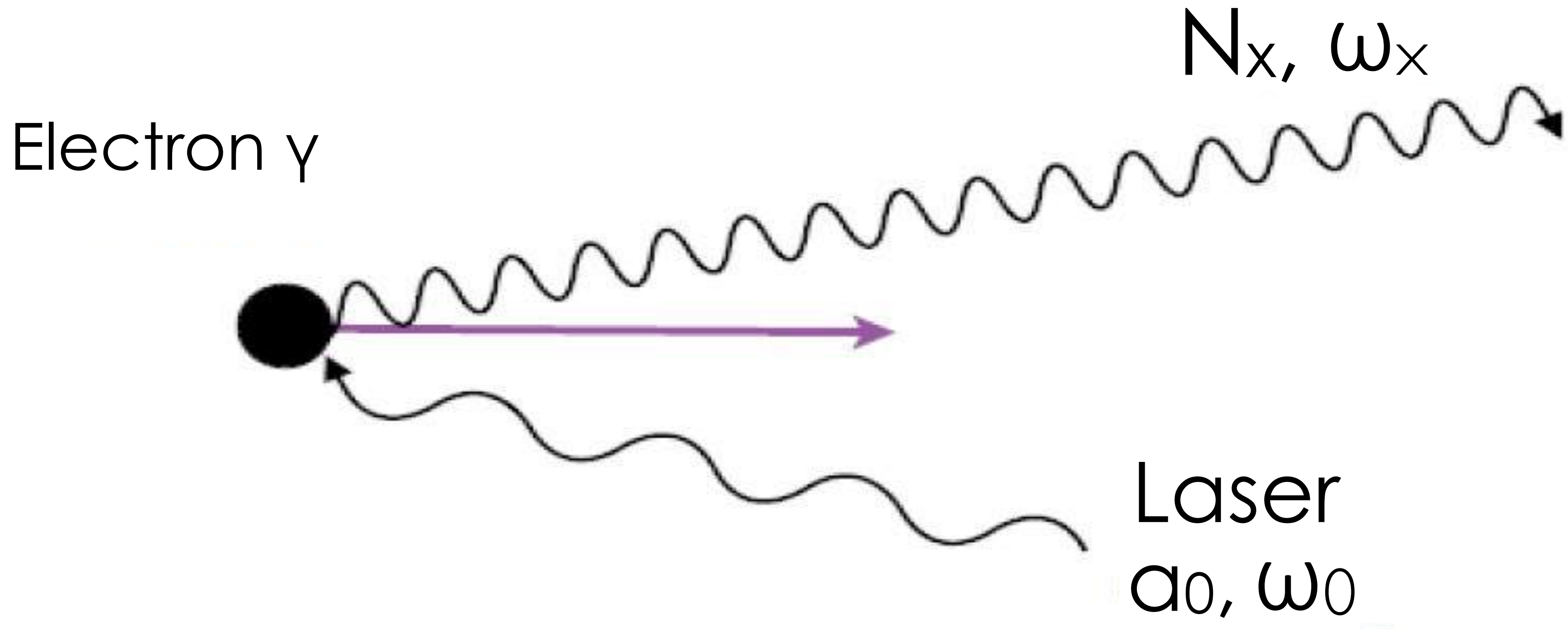
Early detection of tumour with an 10 micrometers resolution

X ray Absorption Imaging

X ray Contrast Phase Imaging

M. Bech *et al.*, Scientific reports (2013)

Inverse Compton Scattering



Doppler upshift : high energy photons with modest e^- energy : $\omega_X = 4\gamma^2\omega_0$

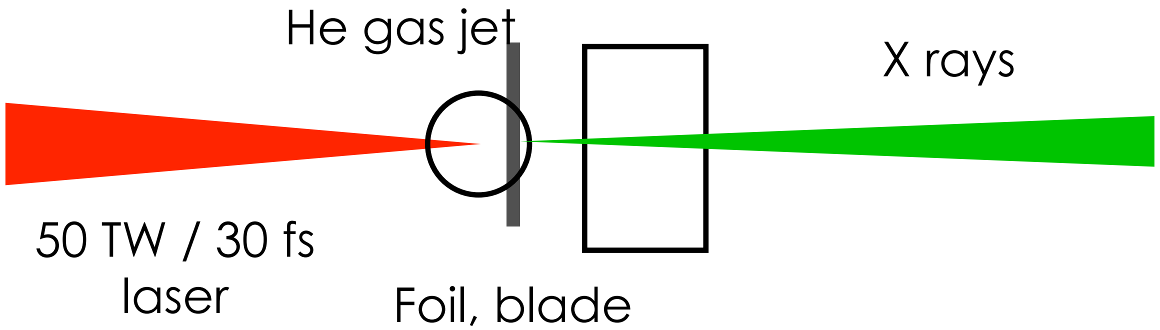
For example : 20 MeV electrons can produce 10 keV photons
200 MeV electrons can produce 1 MeV photons

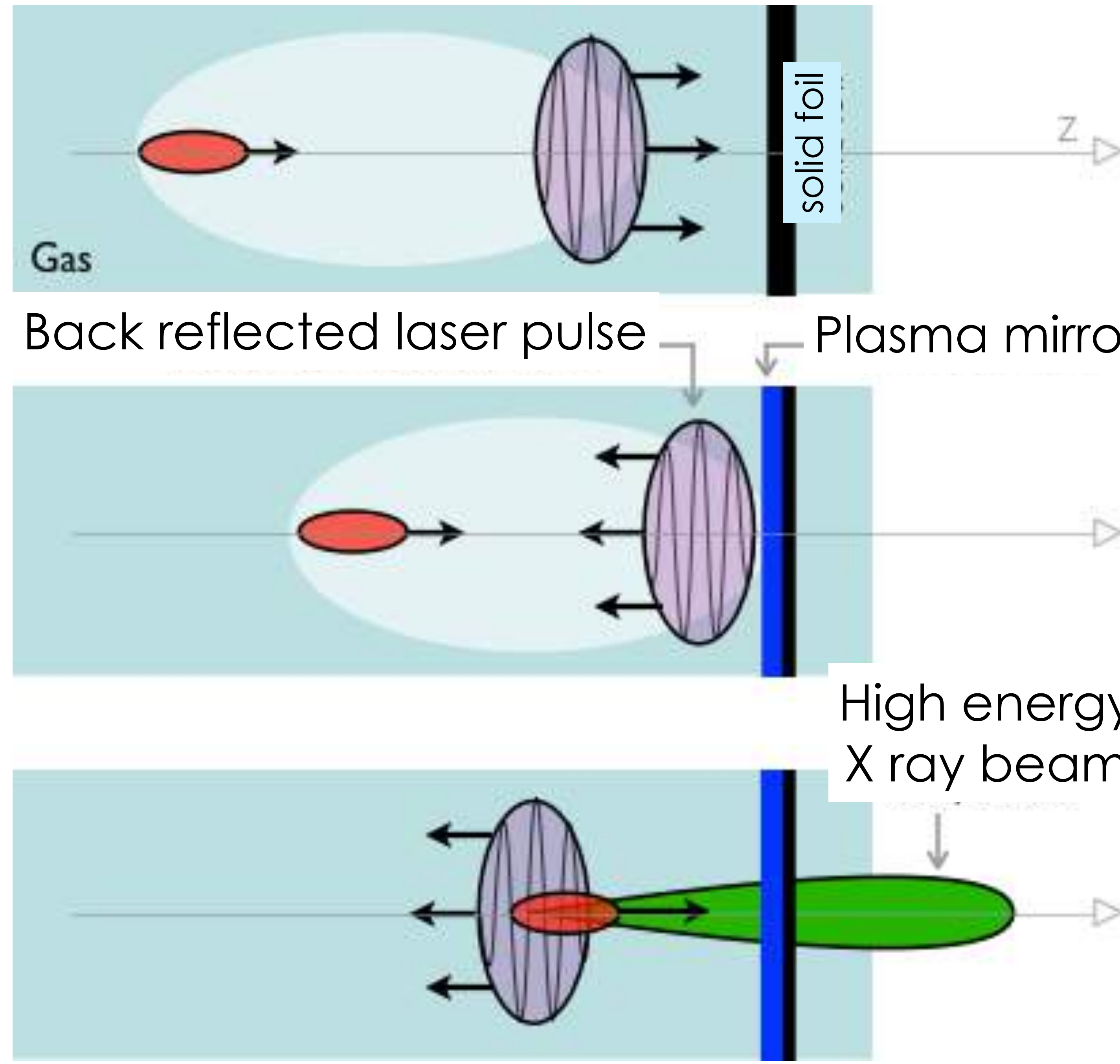
The number of photons depends on the n_e and a_0^2 : $n_X \propto a_0^2 \times n_e$

Duration (fs), source size (µm) = e^- 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

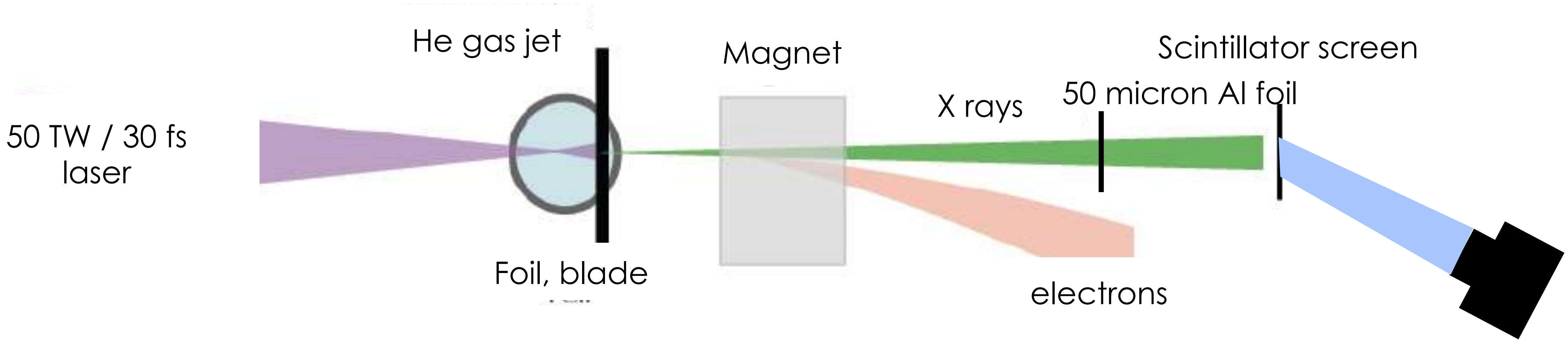
A plasma mirror reflects the laser beam

The back reflected laser collides with the accelerated electrons

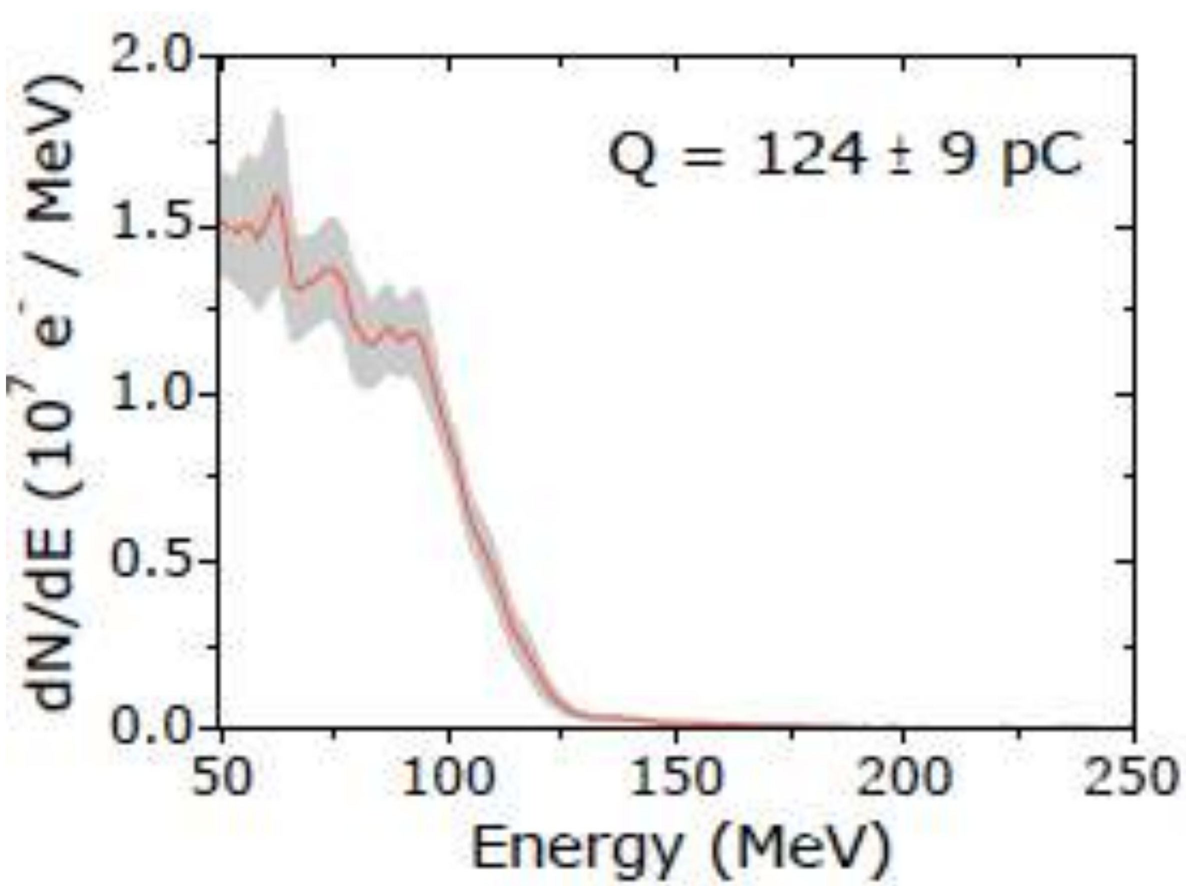
No alignment : the laser and the electron beams naturally overlap

Save the laser energy !

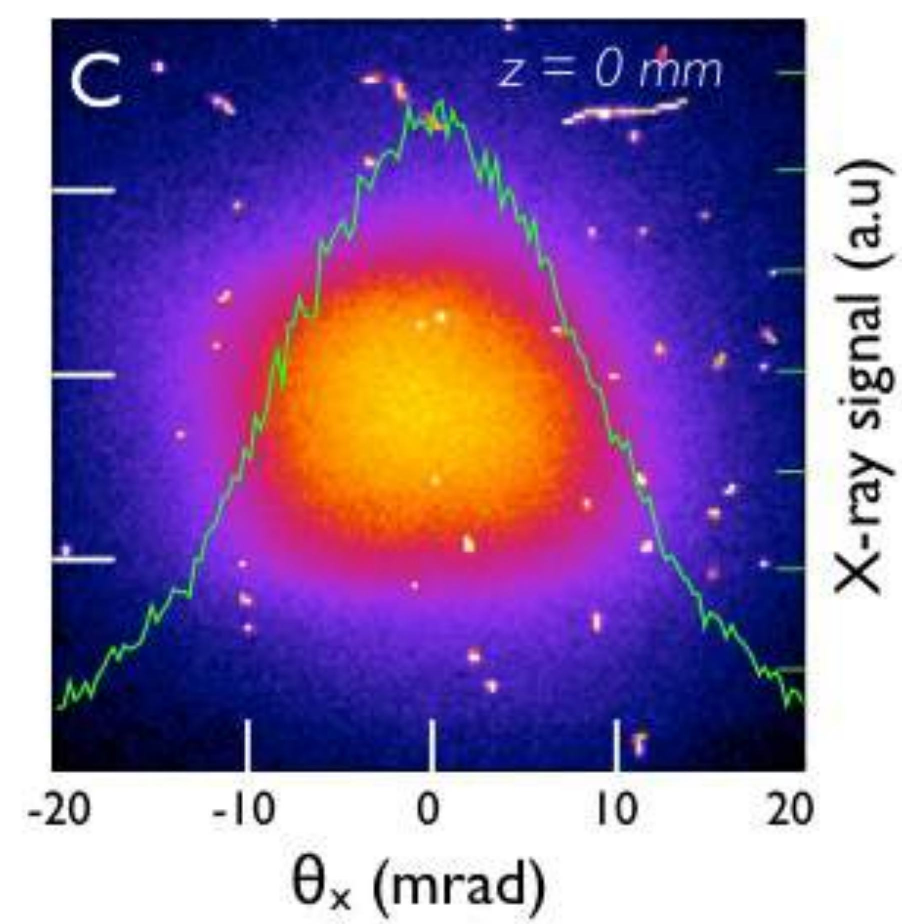
Inverse Compton Scattering : Exp. set-up



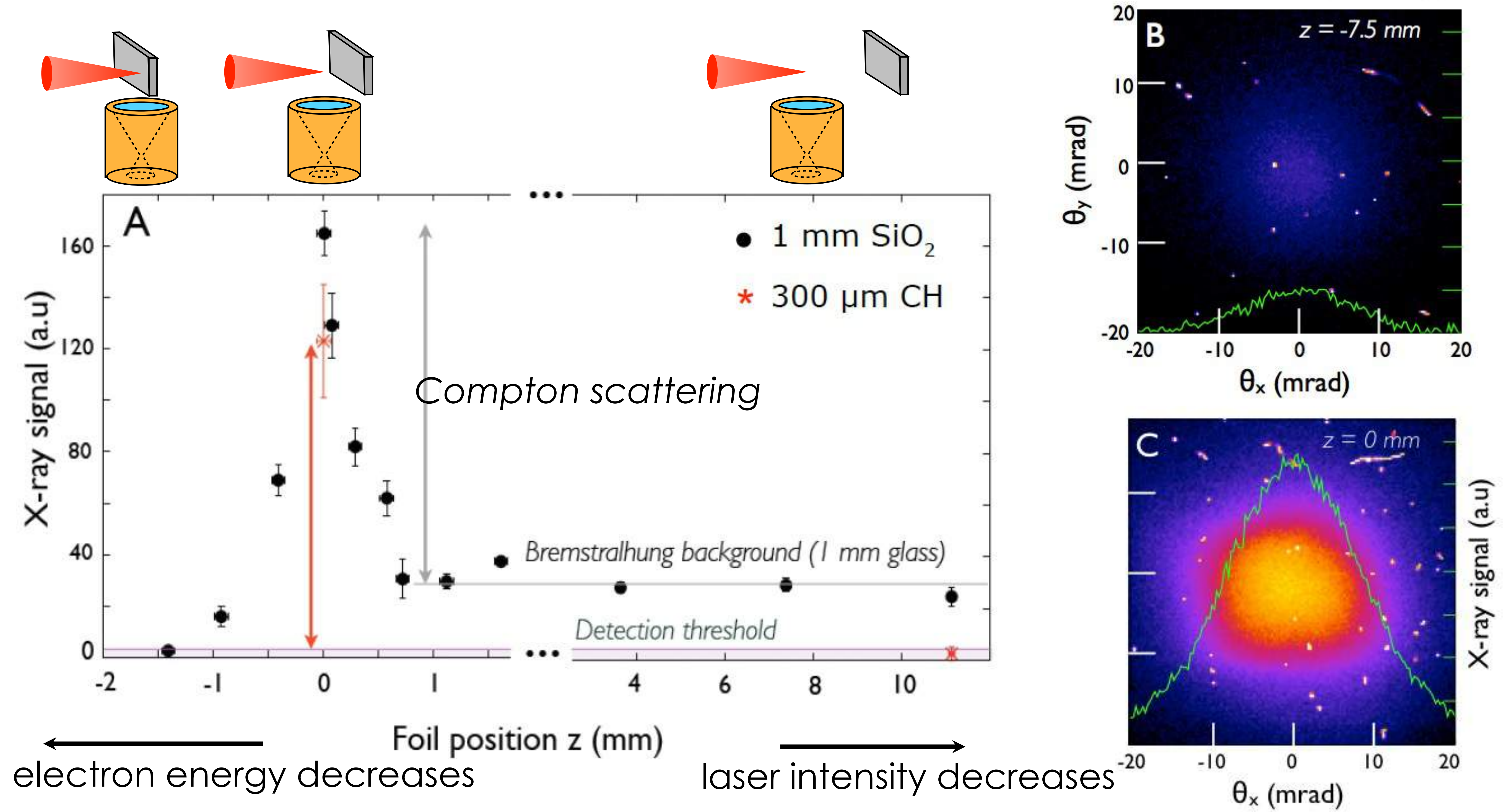
Electron spectra



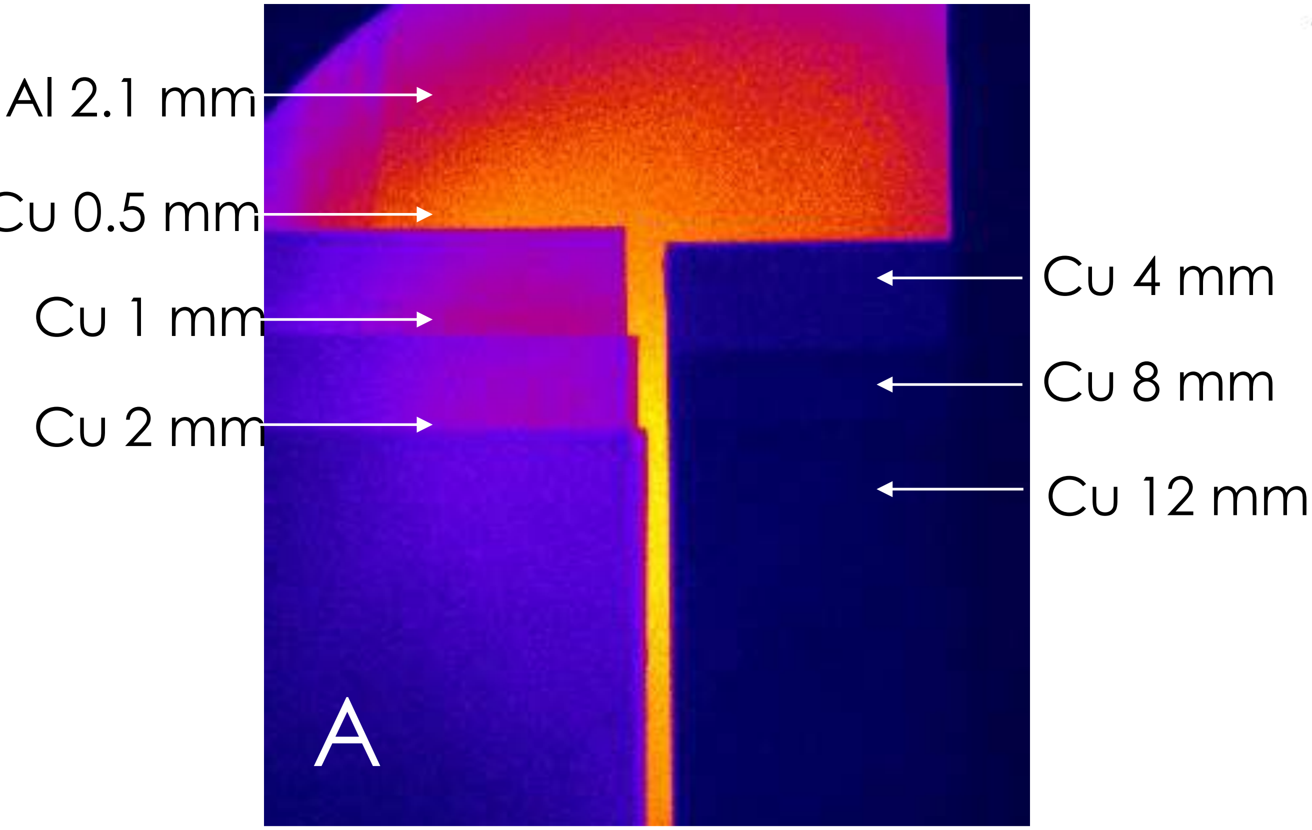
X ray beam profile

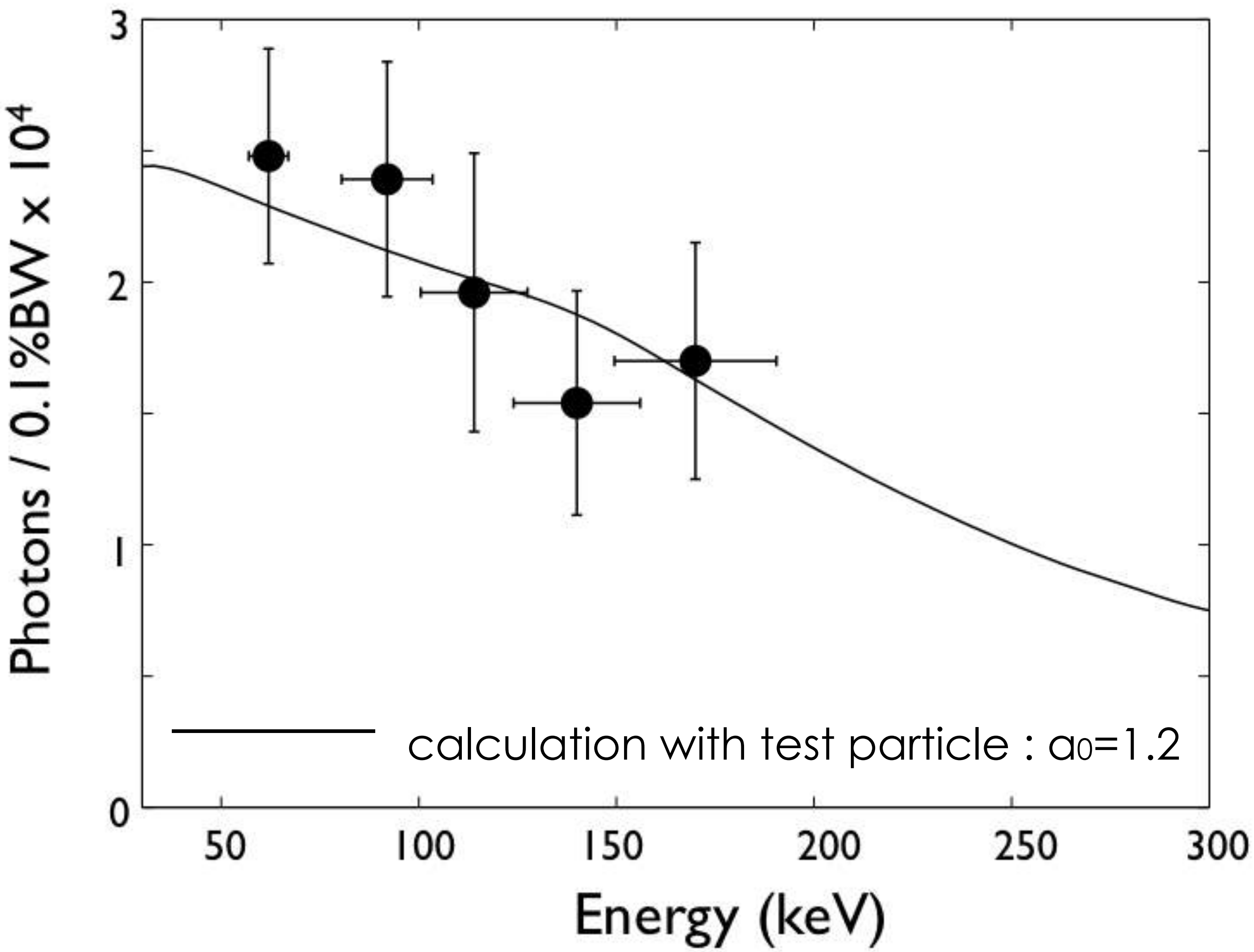


Inverse Compton Scattering : Exp. results



- The foil must be placed at the right to maximize a_0 and the electrons energy

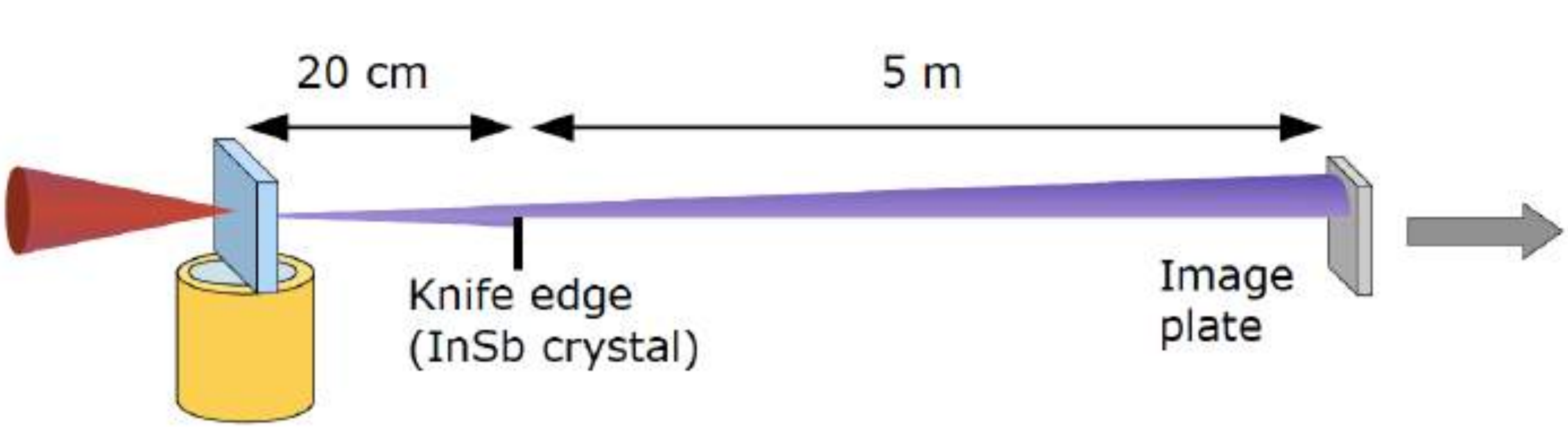


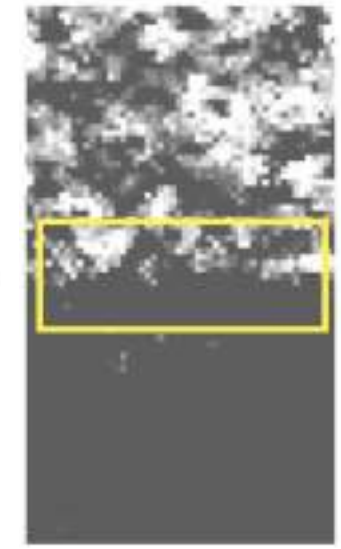


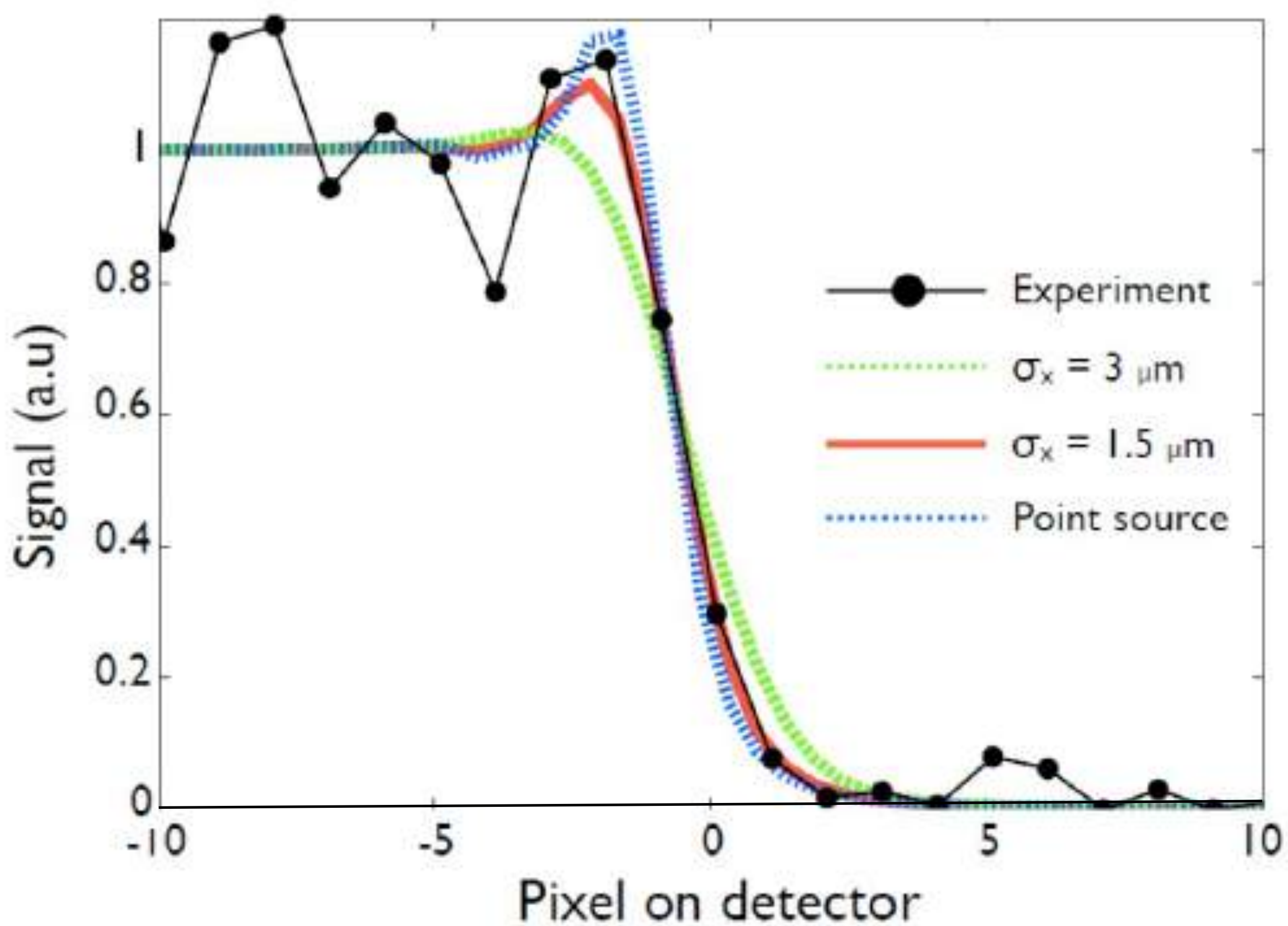
- About 10^8 ph/shot, a few 10^4 ph/shot/0.1%BW@100 keV
- Broad electron spectrum => broad X ray spectra
- Brightness: 10^{21} ph/s/mm^2/mrad^2/0.1%BW @100 keV

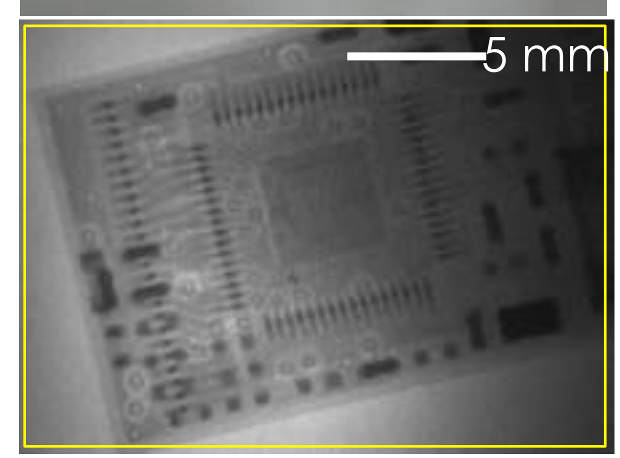
K. Ta Phuoc *et al.*, Nature Photonics (2012)

Inverse Compton Scattering : Source size



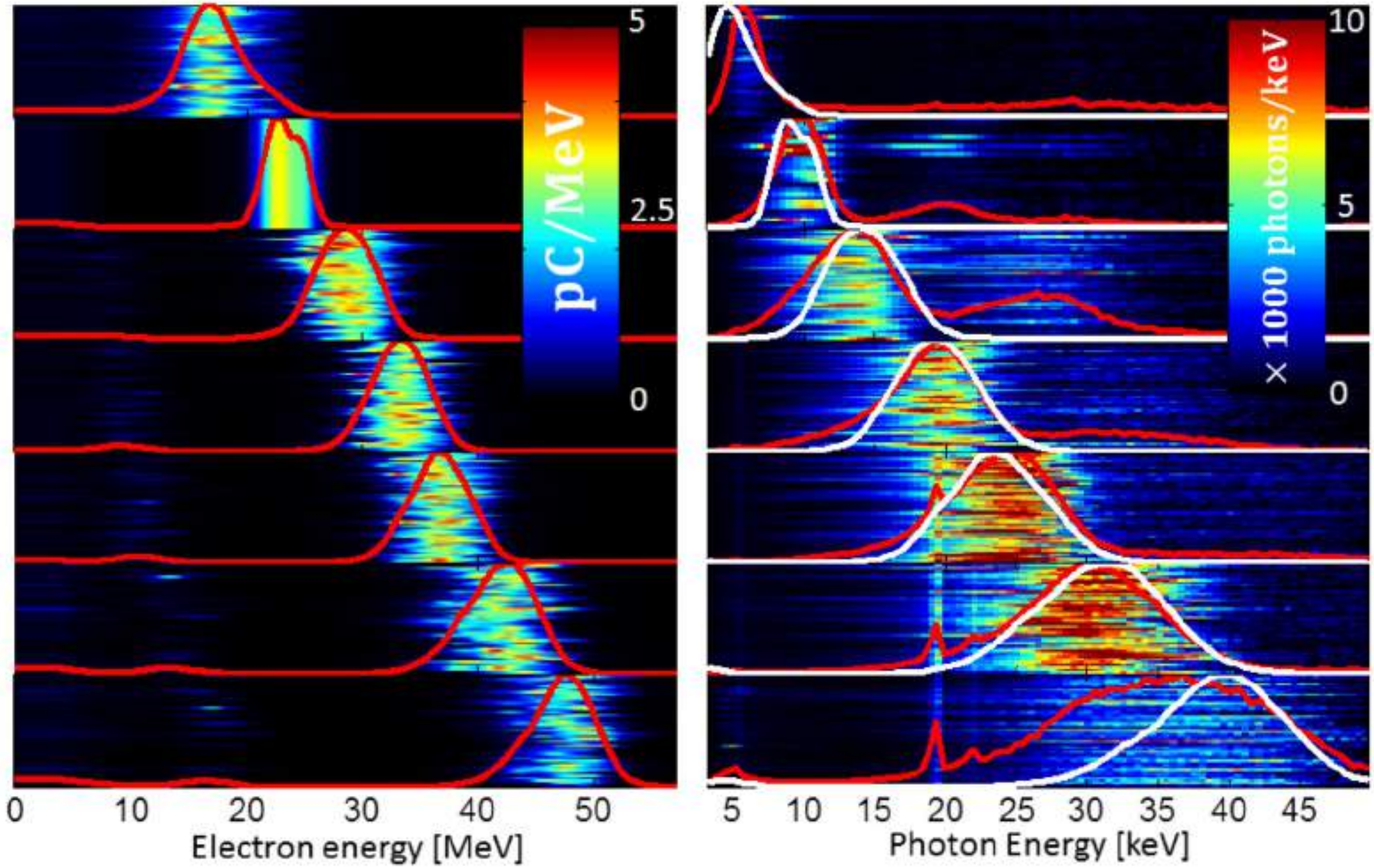






- In this image the resolution is limited by the detector and the small magnification

Inverse Compton Scattering : Compton Spectra

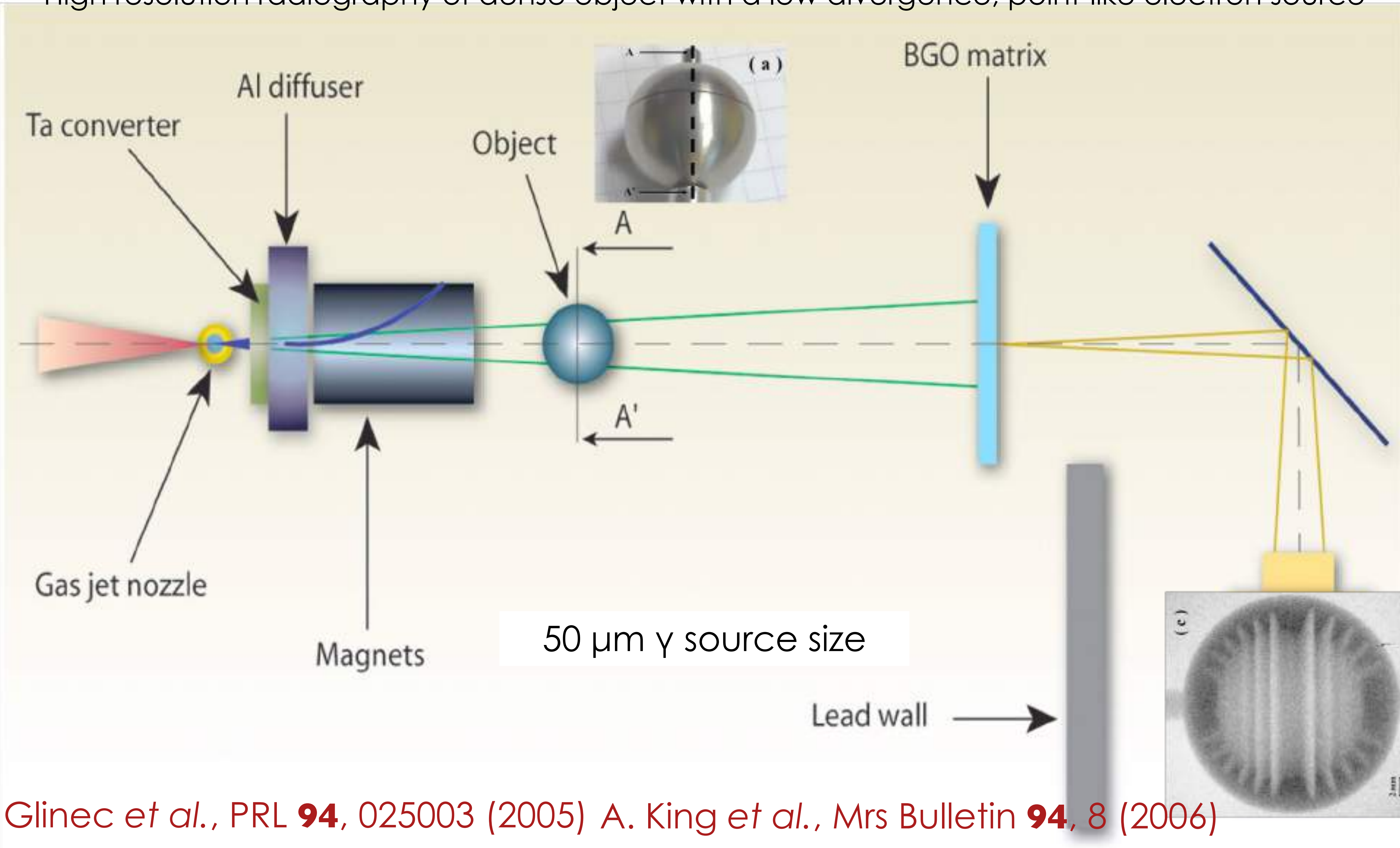


Courtesy of S. Karsh

Some examples of applications : radiography

Non destructive dense matter inspection

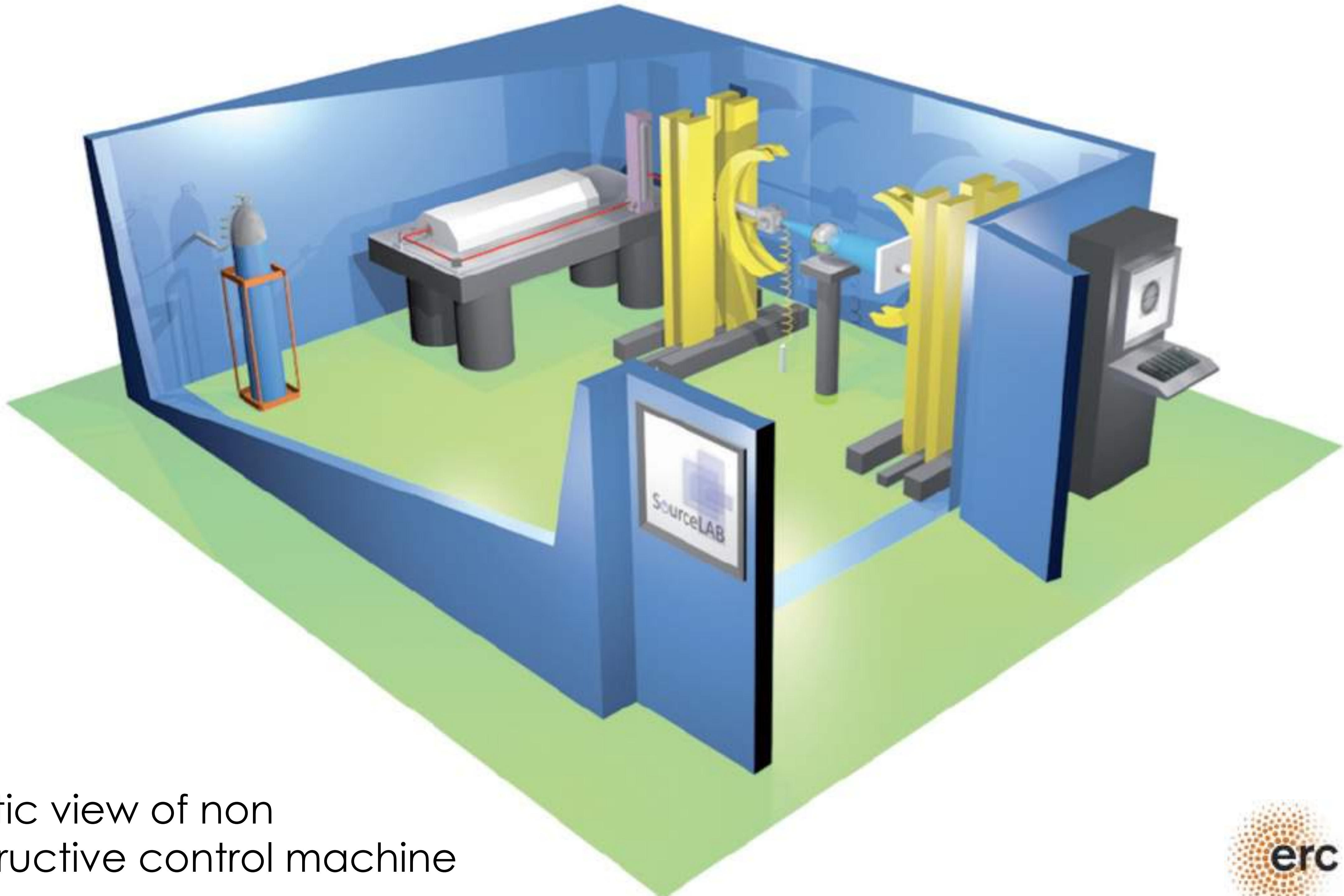
High resolution radiography of dense object with a low divergence, point-like electron source



50 µm γ source size

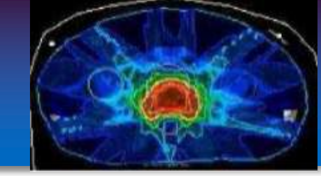
Y. Glinec *et al.*, PRL **94**, 025003 (2005) A. King *et al.*, Mrs Bulletin **94**, 8 (2006)
A. Ben-Ismail *et al.*, Nucl. Instr. and Meth. A **629** (2010), App. Phys. Lett. **98**, 264101 (2011)

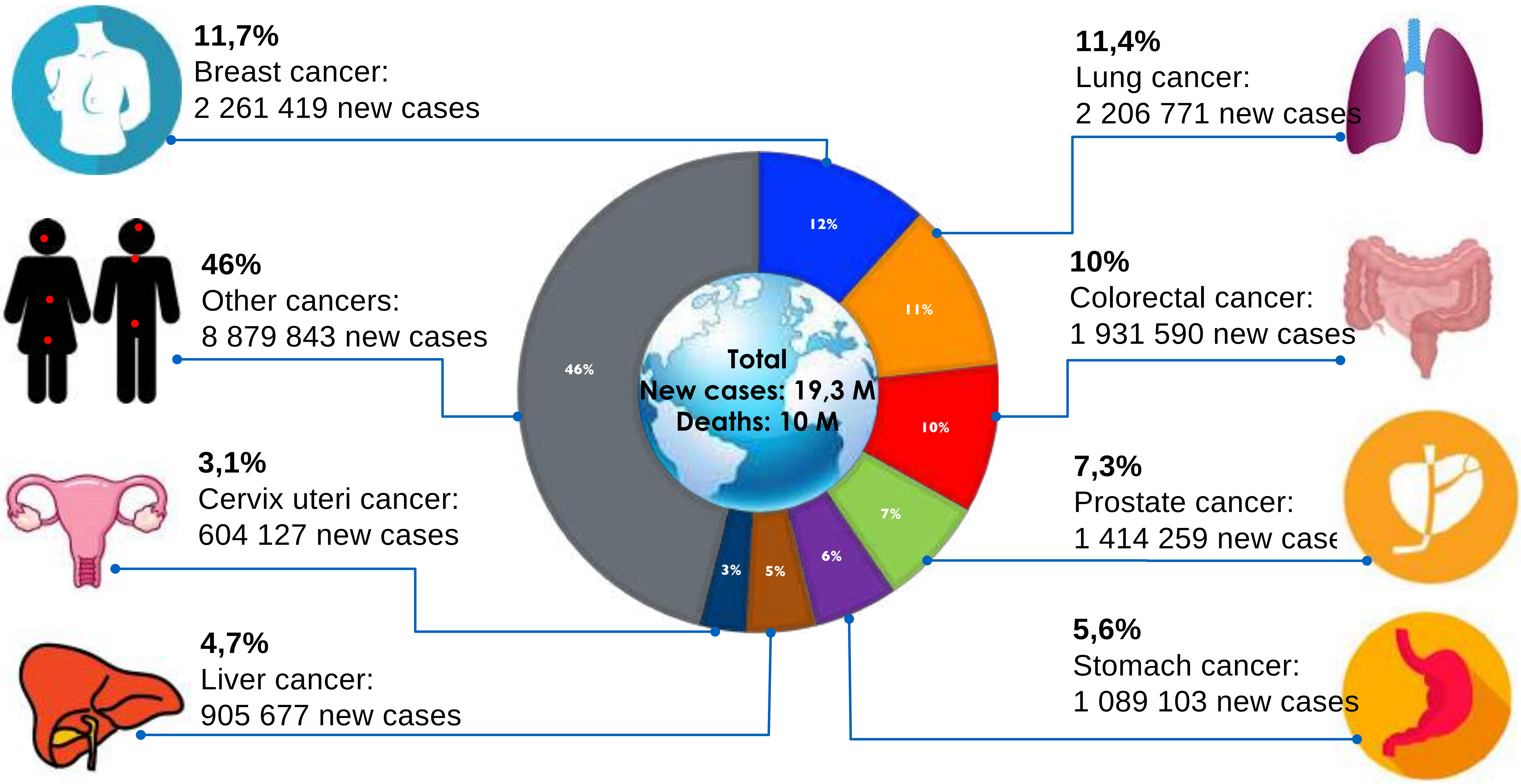
Applications: Non Destructive Control



Artistic view of non destructive control machine

Cancer : facts and numbers

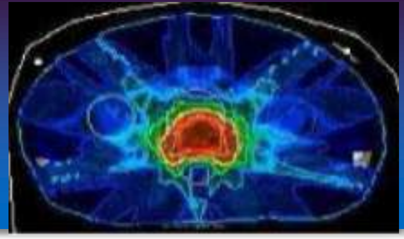


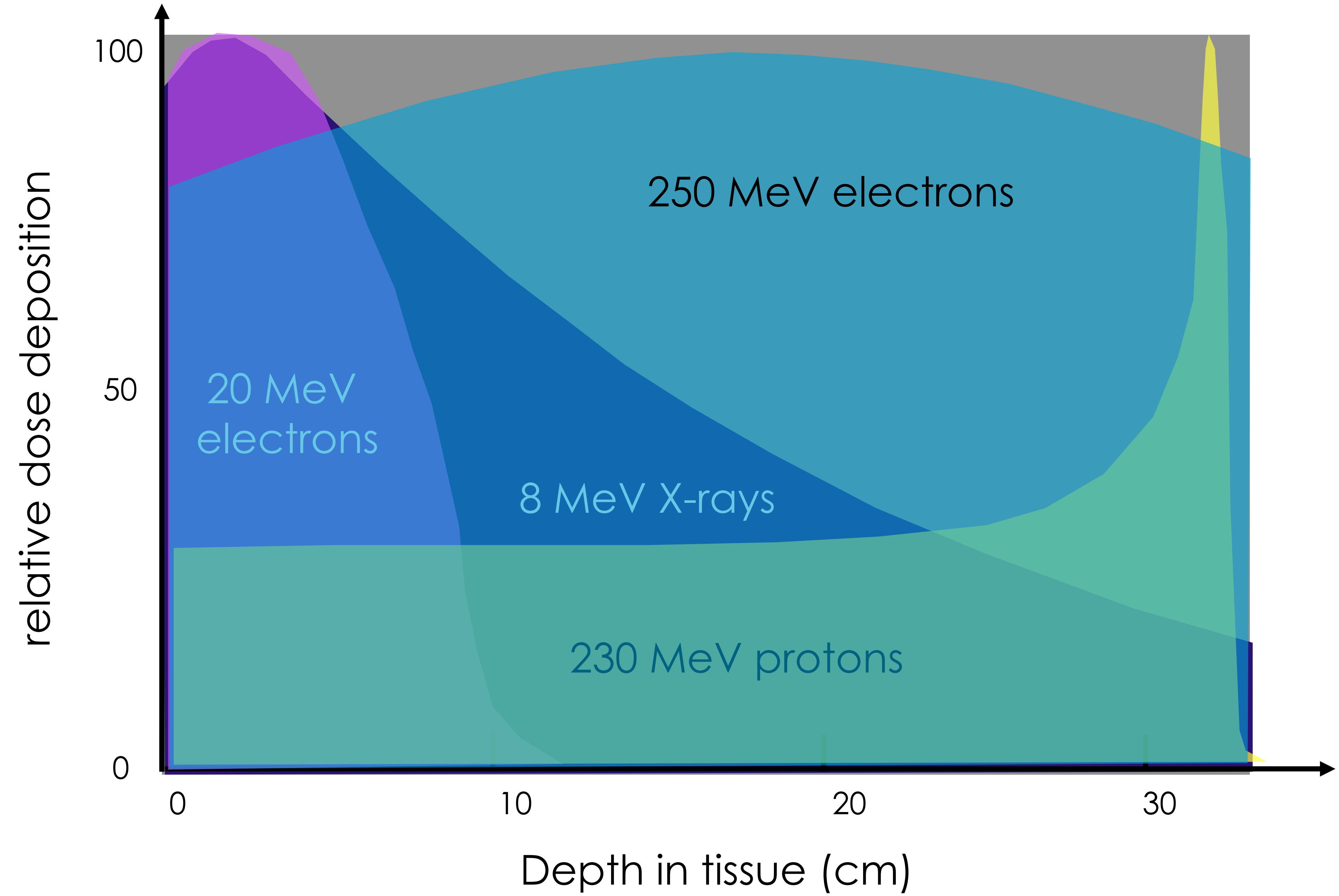


Estimated number of new cases in 2020, all cancers, both sexes, all ages*

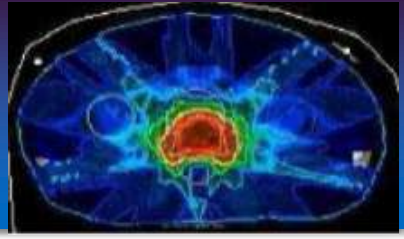
*World Health Organization: press release No 238 (2020)

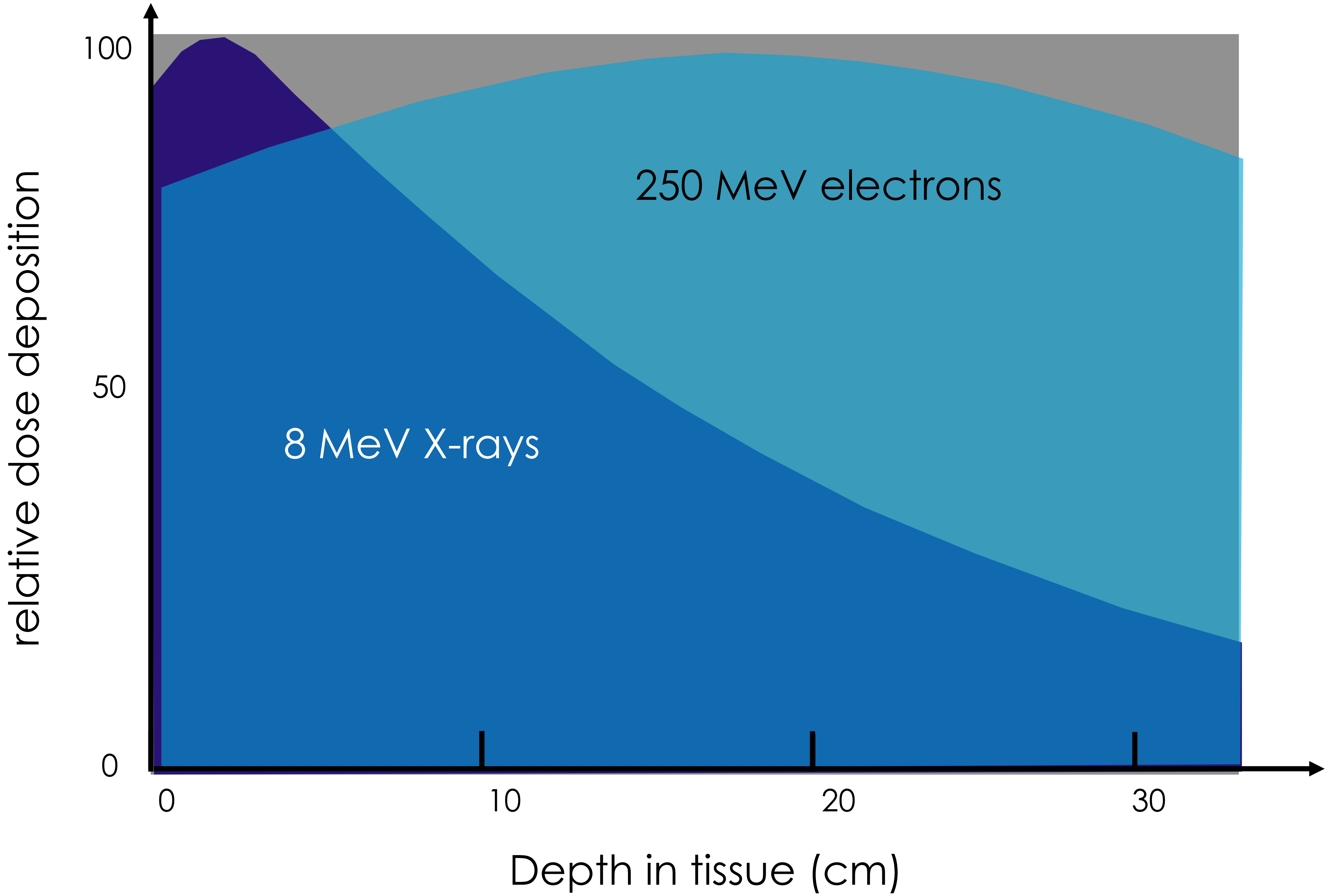
Particles @ radiation for therapy



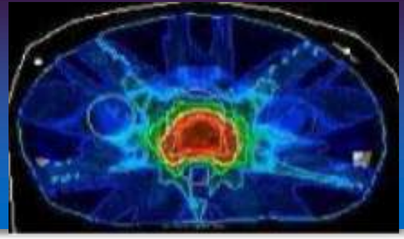


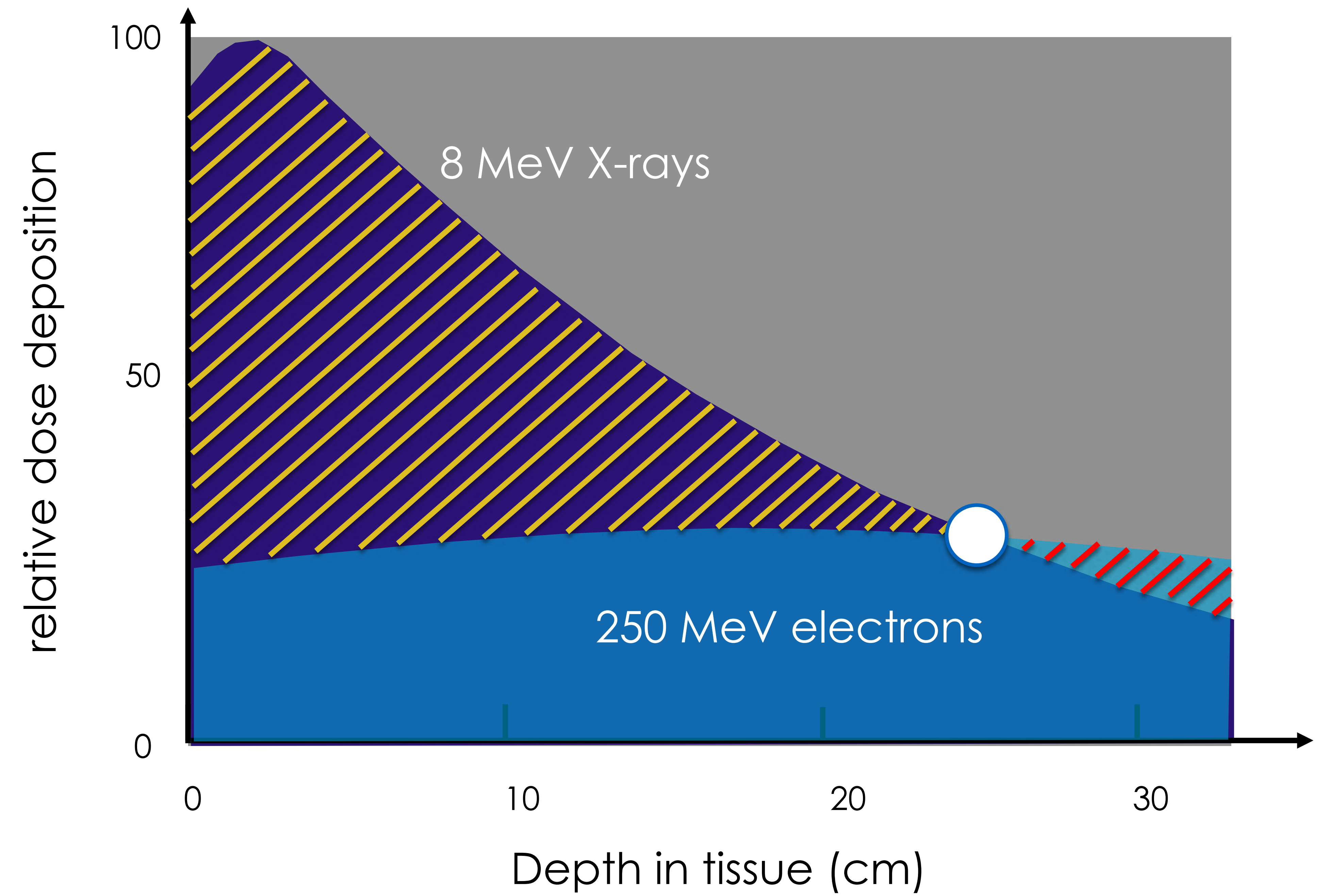
X-rays/ VHEE RT



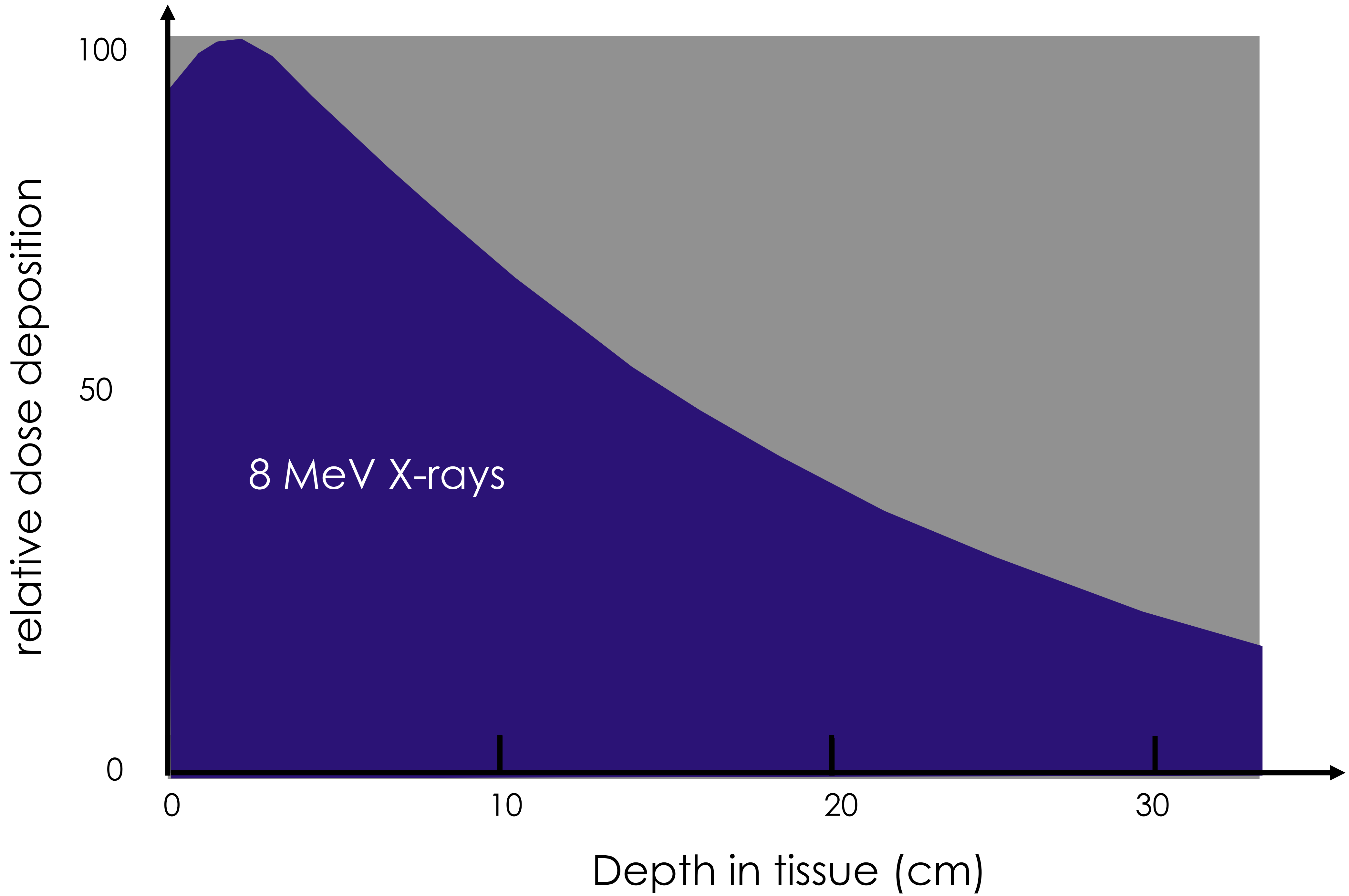


X-rays/ VHEE RT

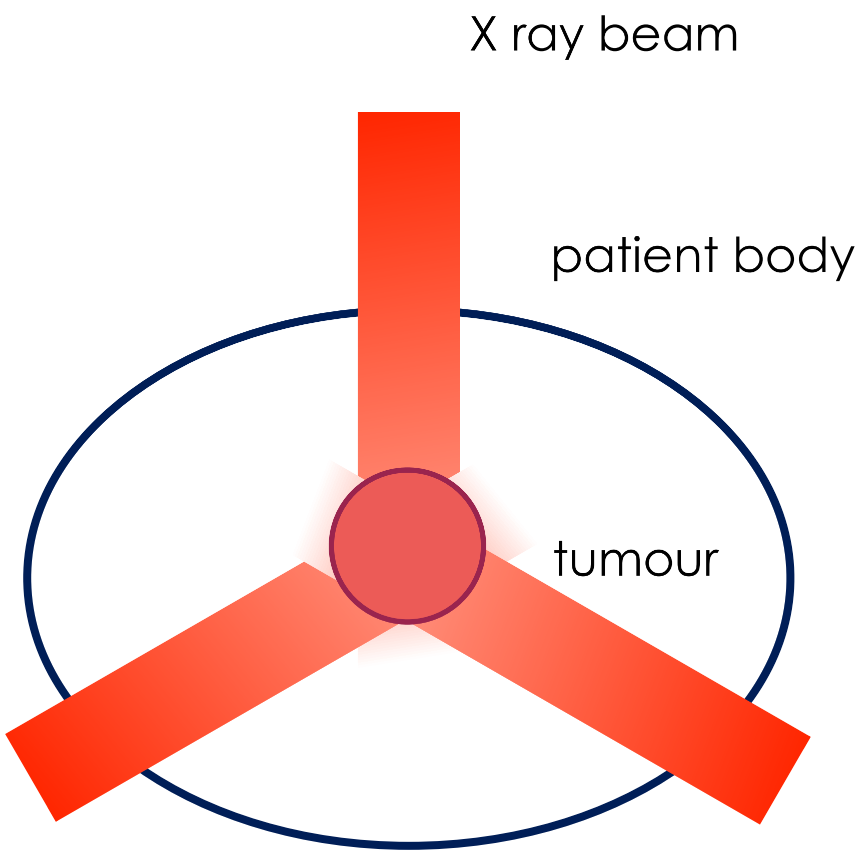


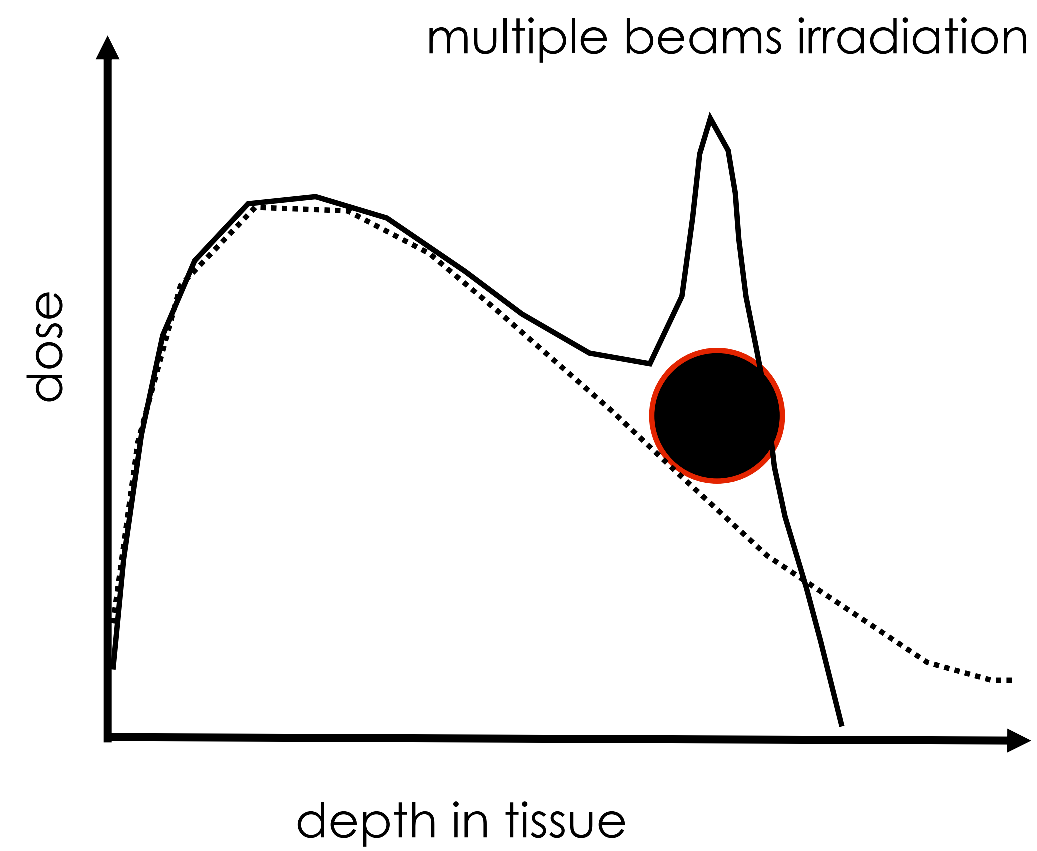


Multi-beams irradiation: a request

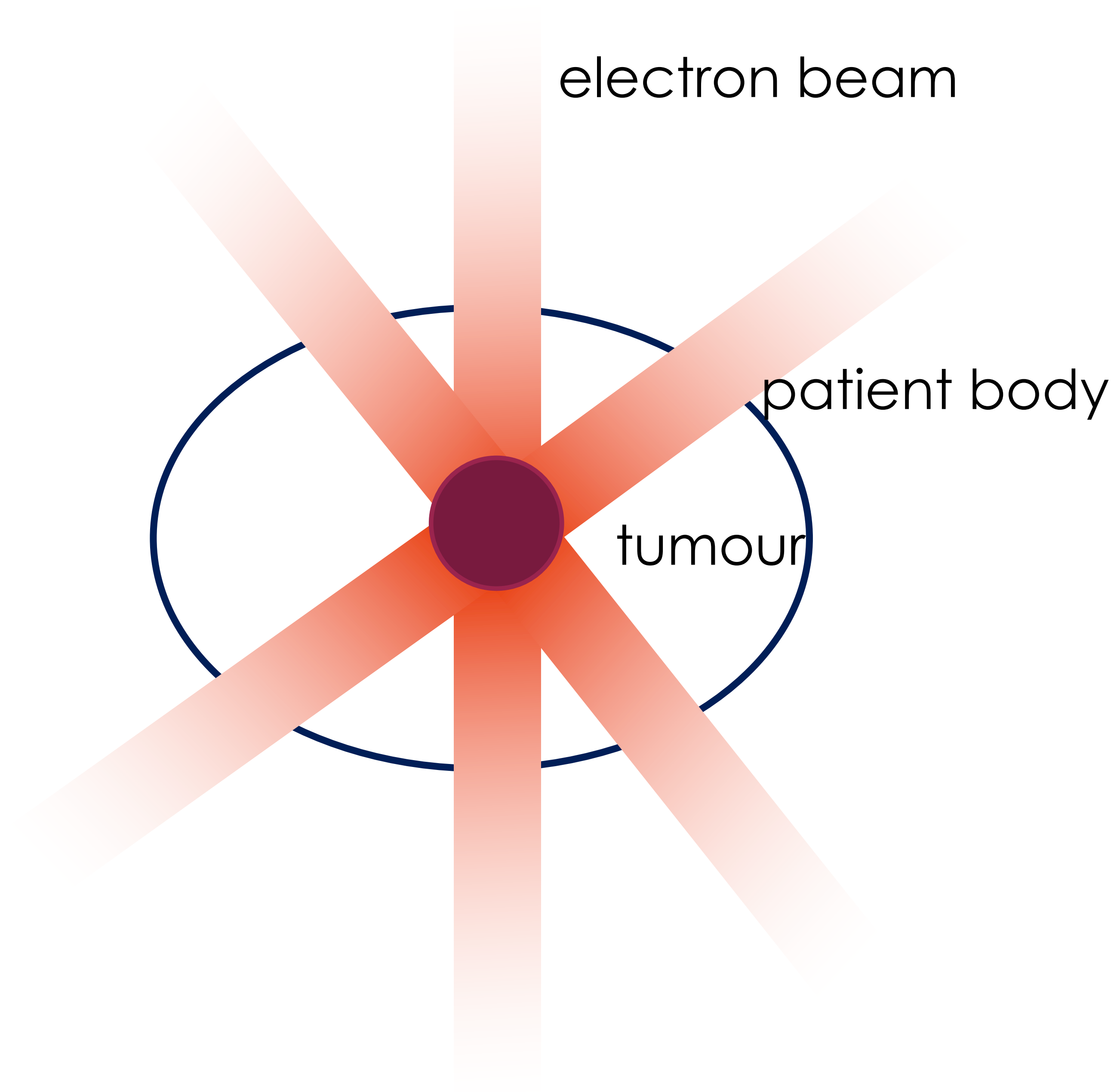


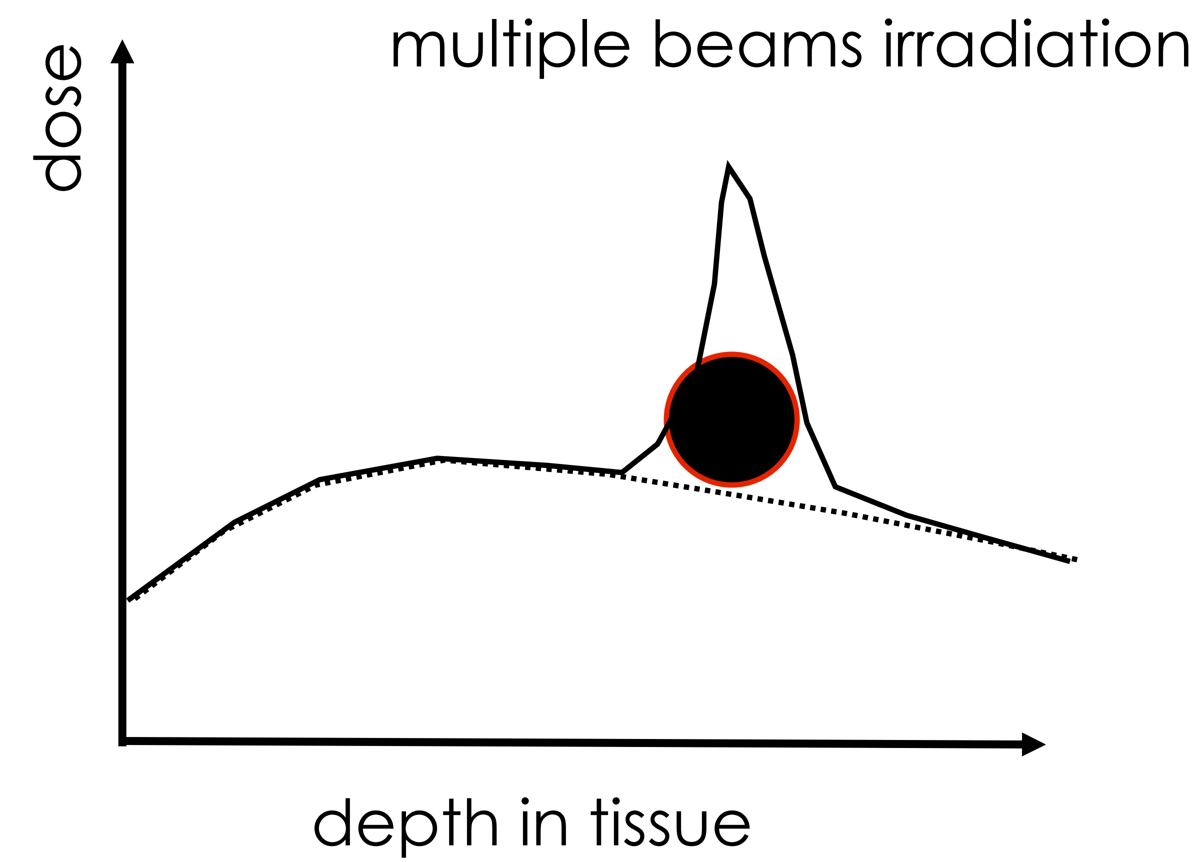
X-rays radiotherapy





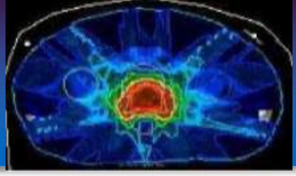
RT requires multi-fields irradiation : VHEE case



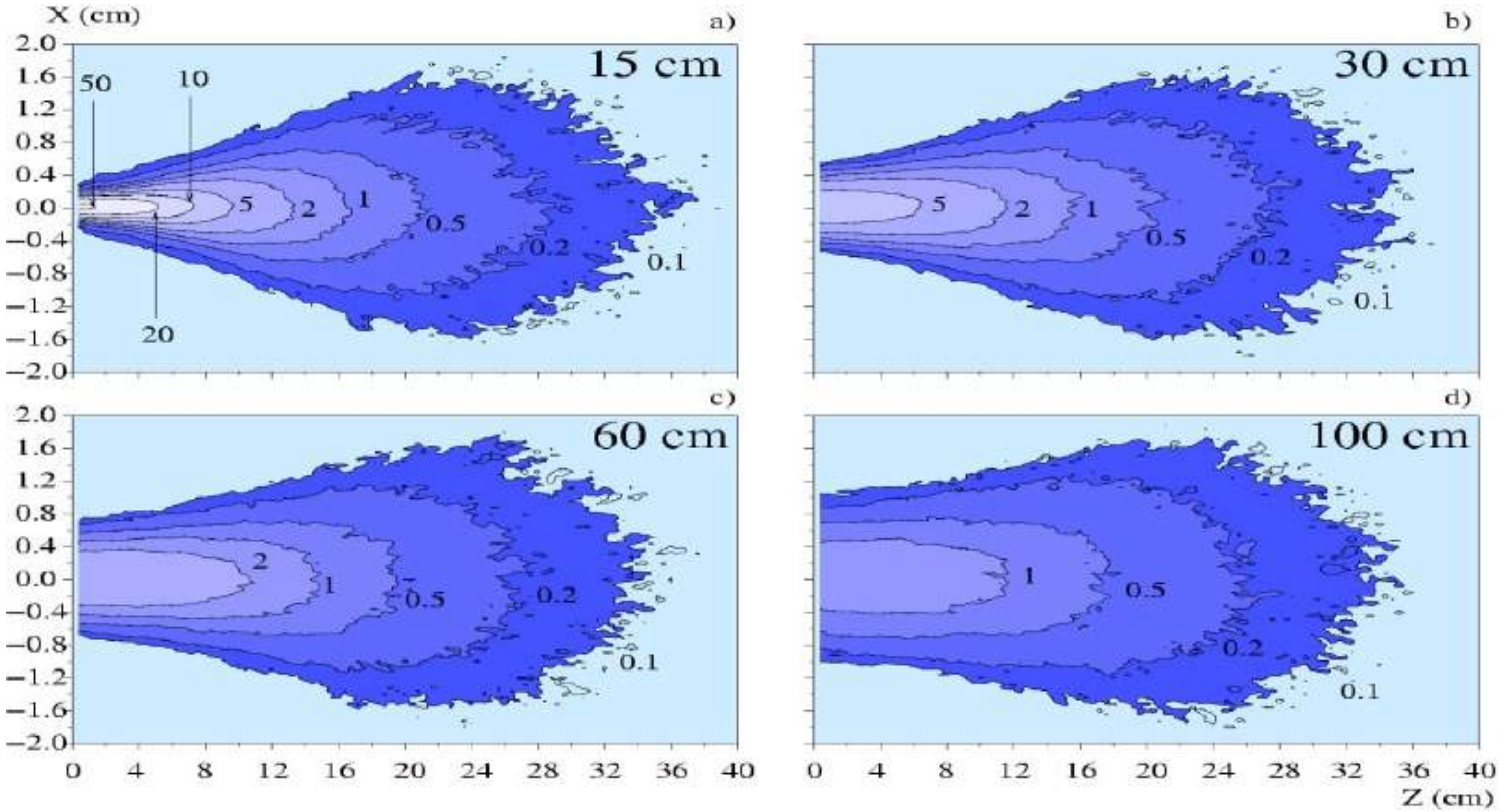


X rays machine for radiotherapy

Some examples of applications : radiotherapy



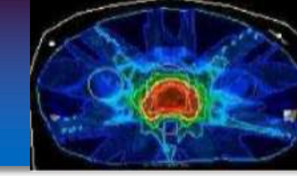
dose pencil

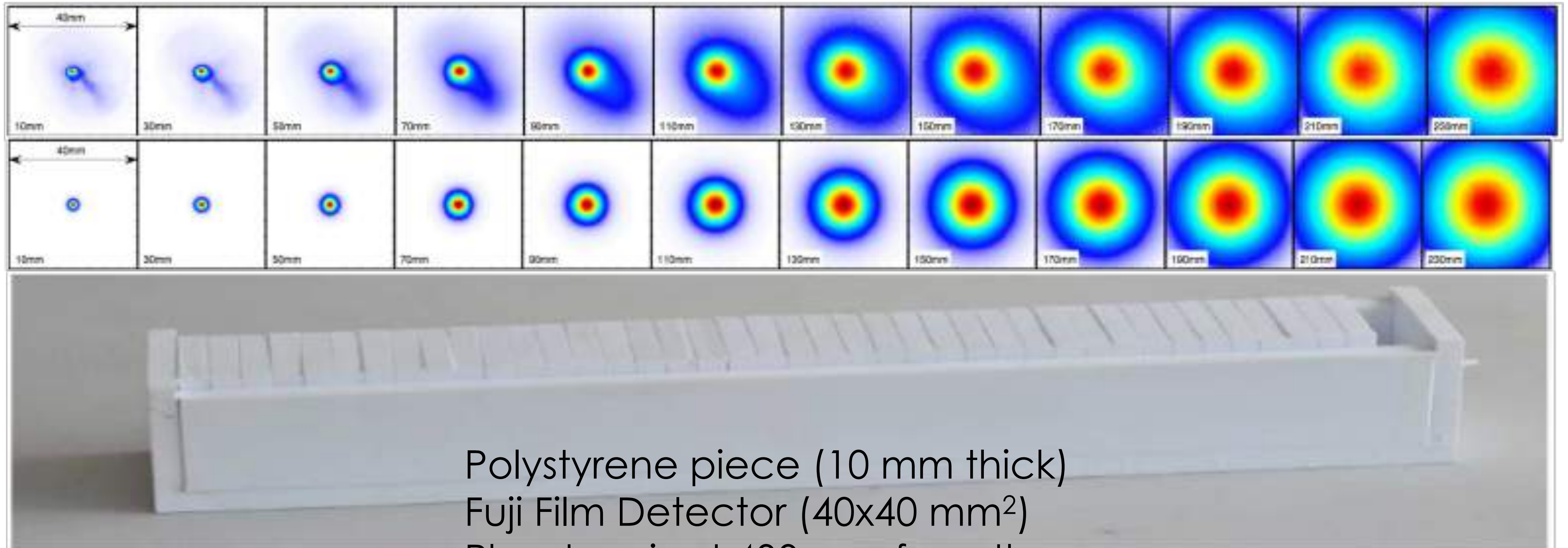


Isodose curves for different levels, 0.1, 0.2, 0.5, 1, 2, 5, 10, 20, 50 Gy/nC.
The source to surface distance is a 15 cm, b 30 cm, c 60 cm, d 100 cm

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

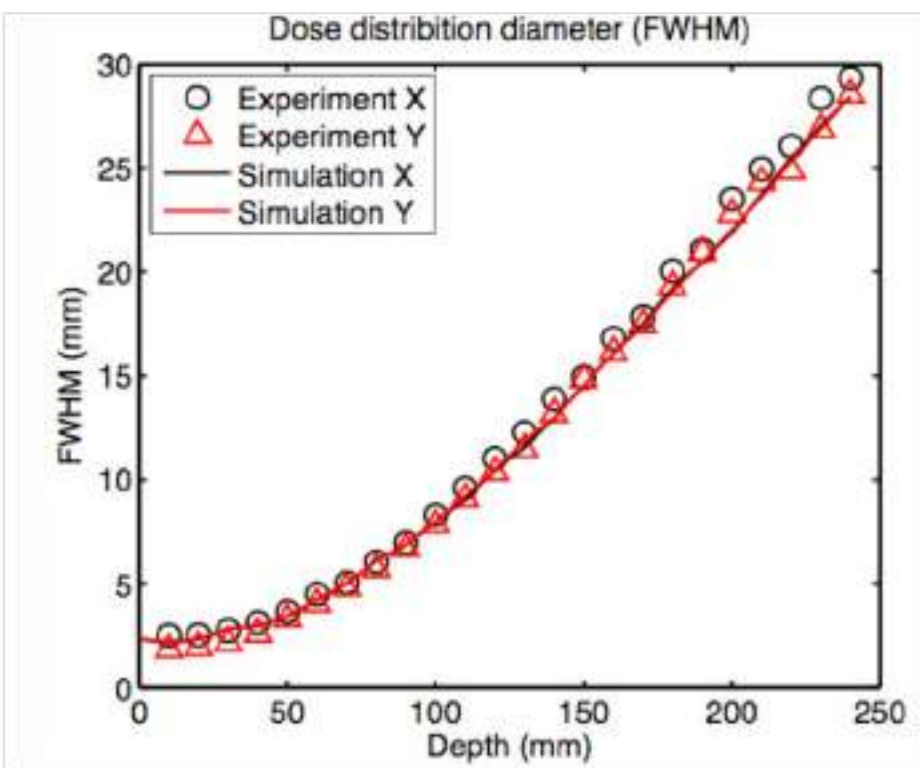
Some examples of applications : radiotherapy

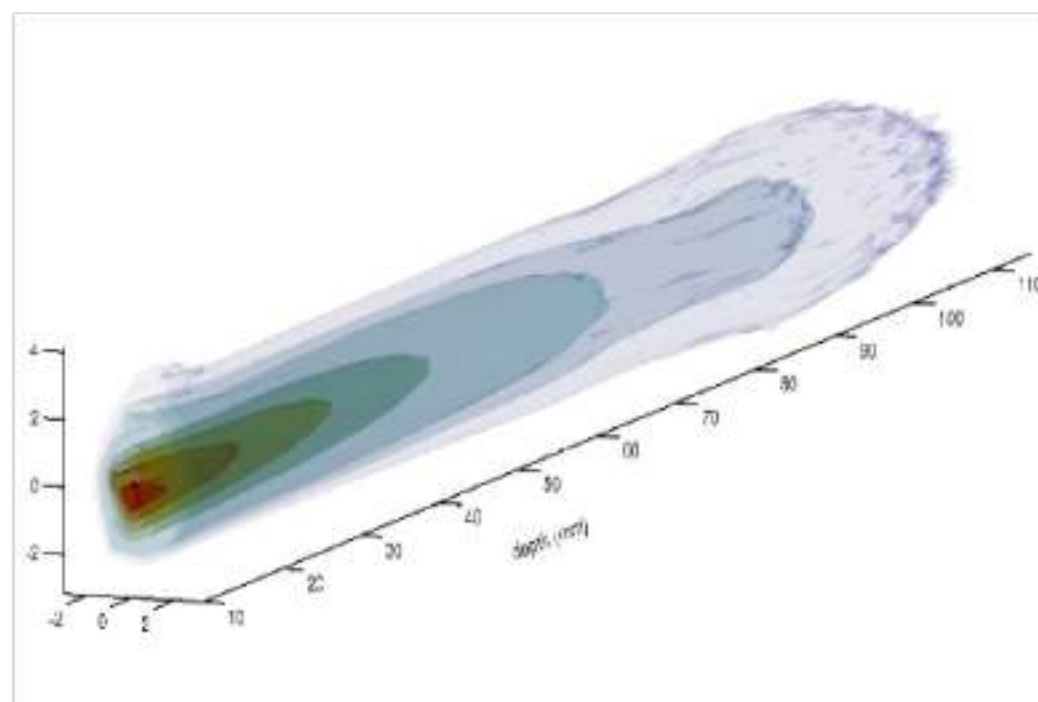




Polystyrene piece (10 mm thick)
Fuji Film Detector (40x40 mm^2)
Phantom is at 430 mm from the source

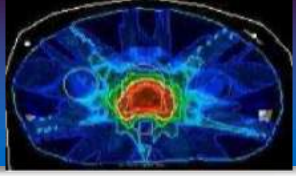
E_{pic}=120 MeV
ΔE=20 MeV
Q_{pic}=30pC
Θ=4.5mrad
D_{max}=1Gy/tir



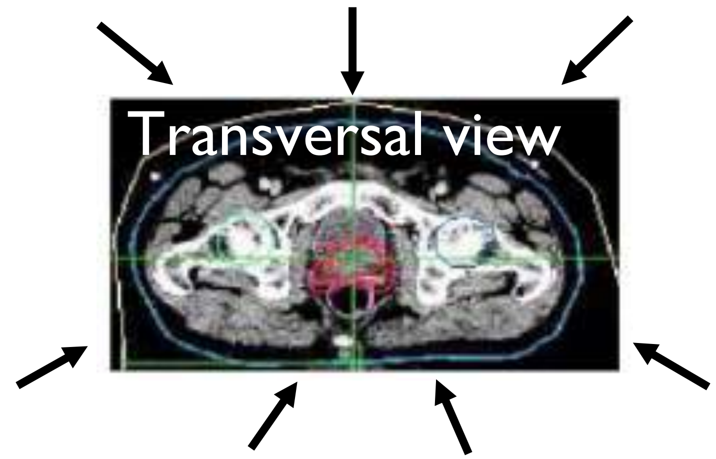


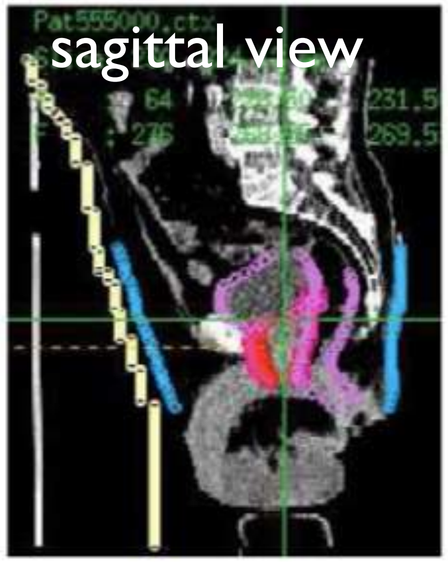
O. Lundh *et al.*, to be submitted

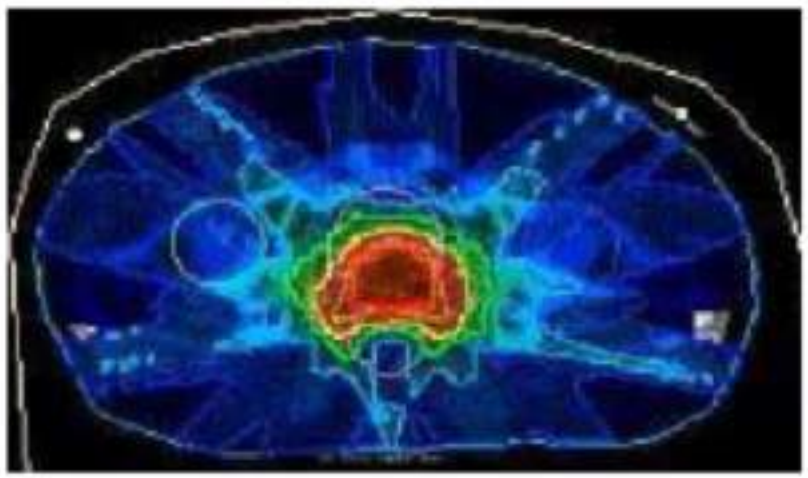
Some examples of applications : radiotherapy



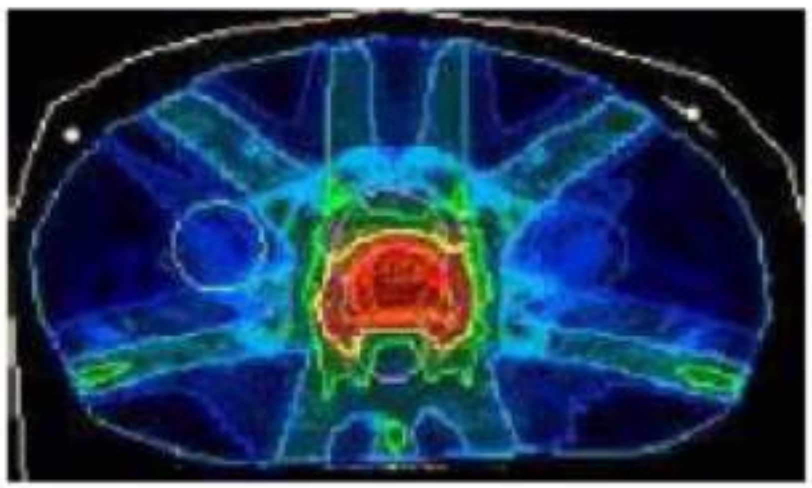
simulations of prostate cancer
with 7 irradiation beams



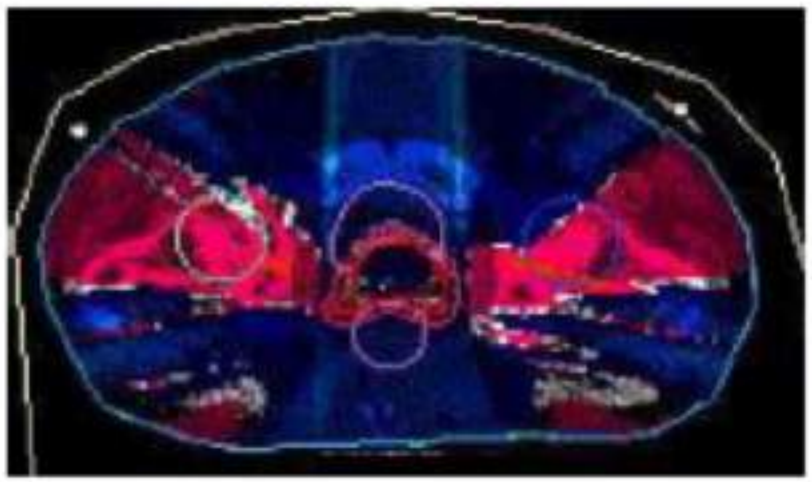




250 MeV electrons



X rays IMRT

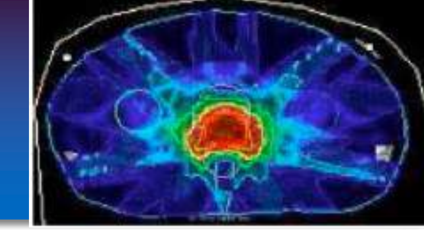


Difference

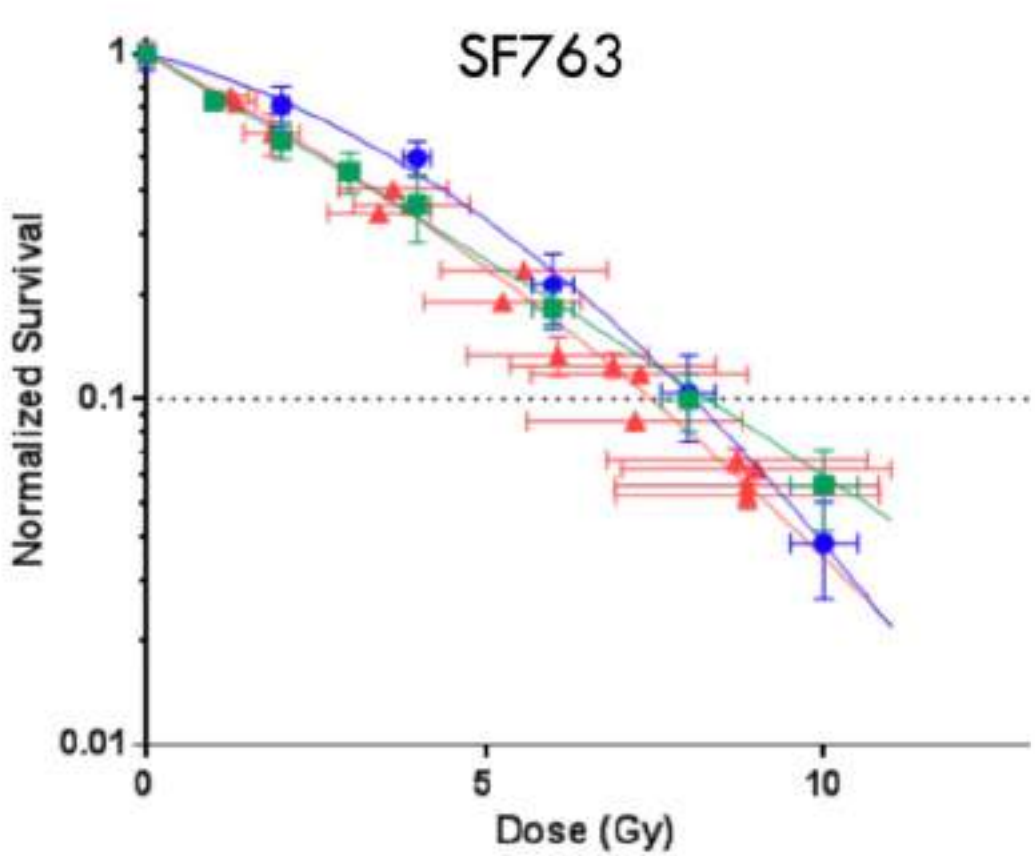
A comparison of dose deposition with 6 MeV X ray an improvement of the quality of a clinically approved prostate treatment plan. While the target coverage is the same or even slightly better for 250 MeV electrons compared to photons the dose sparing of sensitive structures is improved (up to 19%).

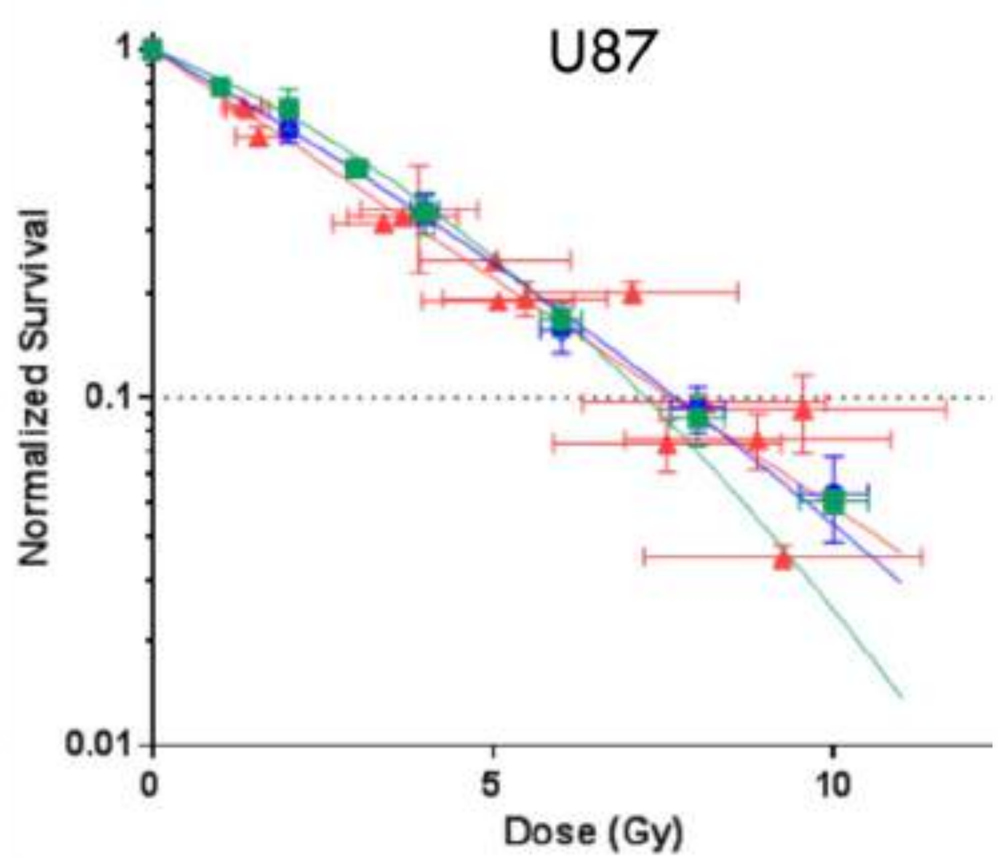
T. Fuchs *et al.* Phys. Med. Biol. **54**, 3315-3328 (2009)

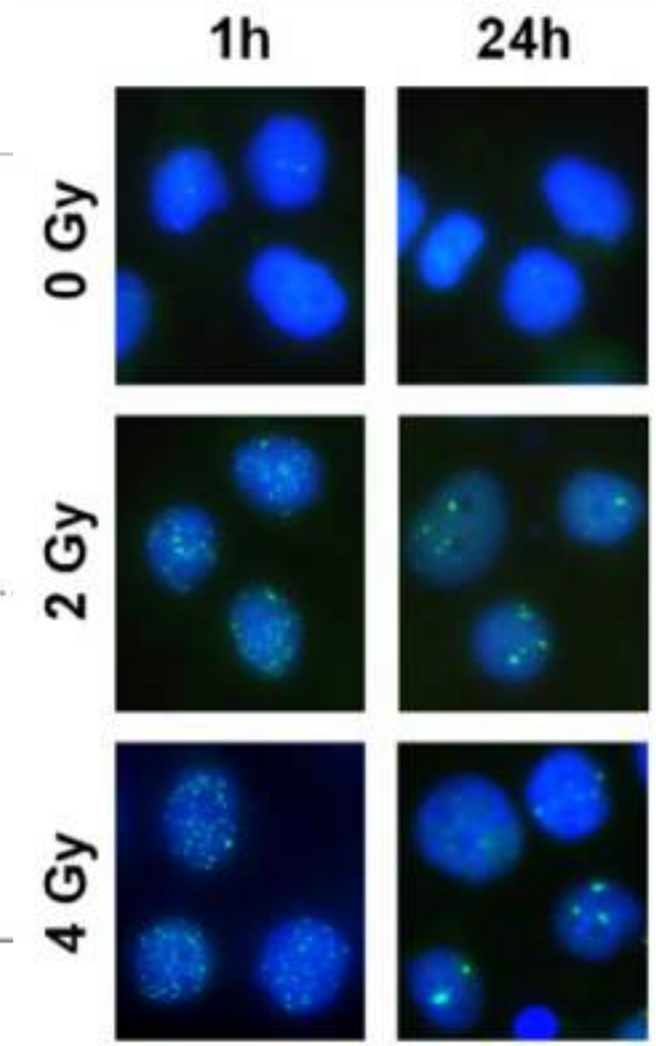
No difference in DNA damage foci irradiated by p-Laser, p-Conv, and X rays



Average dose rate : 2.1 Gy/min (Δt = 20 s



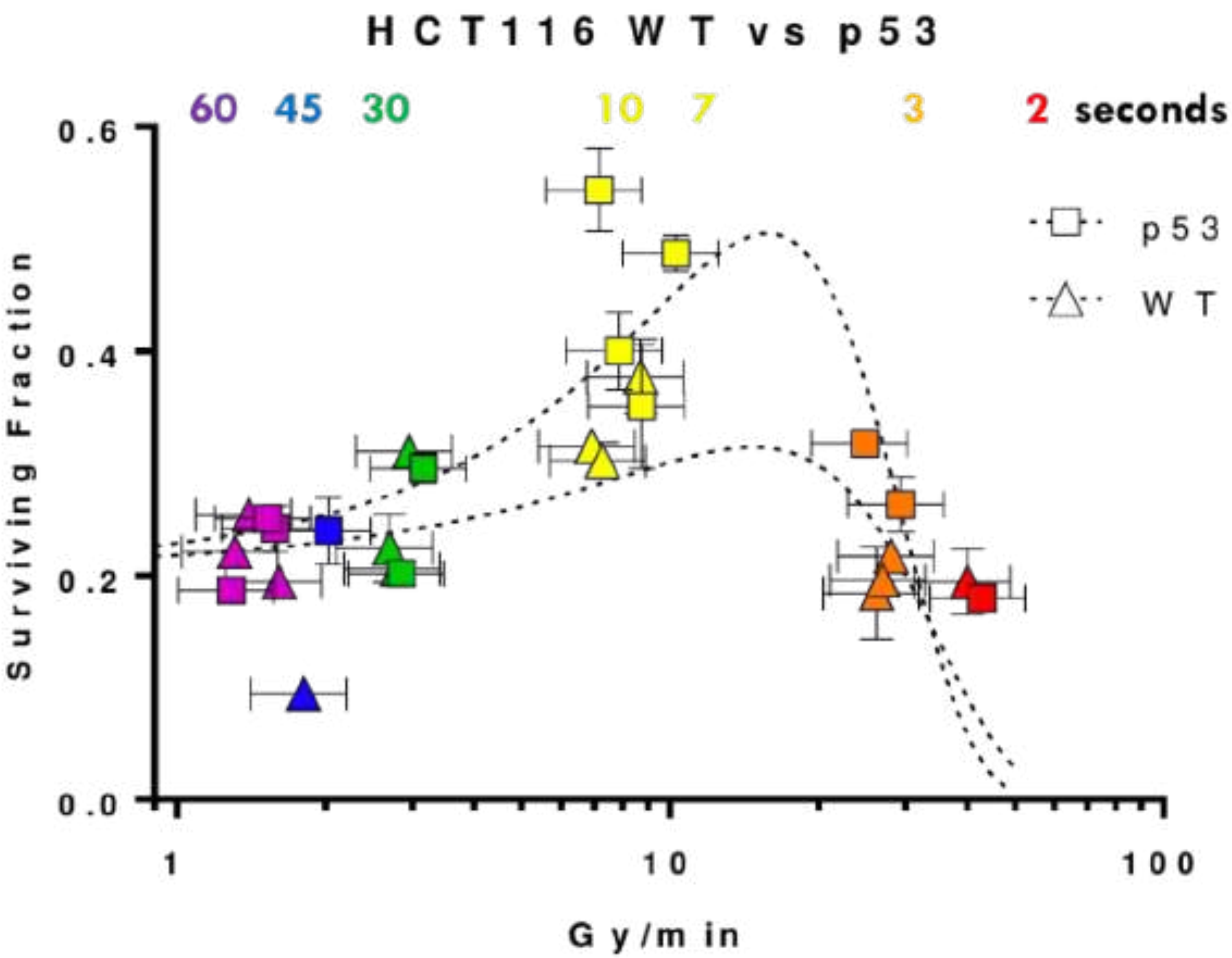




Dose responses of DNA damage foci formation and of cell survival. (A) Representative immune-fluorescent images of cells obtained 1h and 24h after exposure to the indicated doses of laser driven protons (LDP, dotted square), conventional accelerated protons (CAP, triangles) and X-rays (x cross). The negative controls (0 Gy) were sham-irradiated

Fast Fractionation effects

radiosensitive colorectal cancer cells HCT116WT and
Its radioresistant counterpart HCT116 $p53^{-/-}$p53

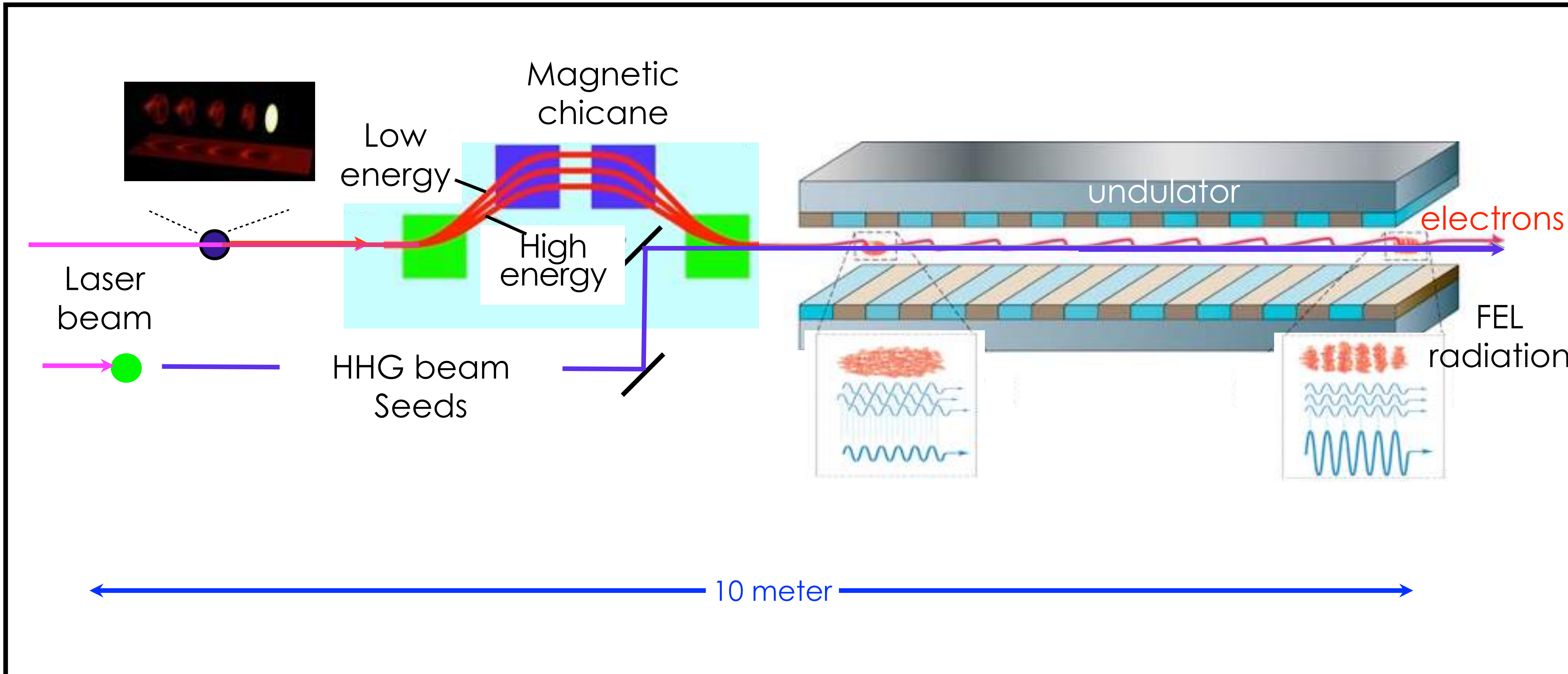


*Cell lines were exposed to a fixed number of LDP bunches with a variable delay between shots, from 60 to 2 seconds.

*Hence the total irradiation time varied from 15 to 540 seconds, which changes the overall "average" dose rate.

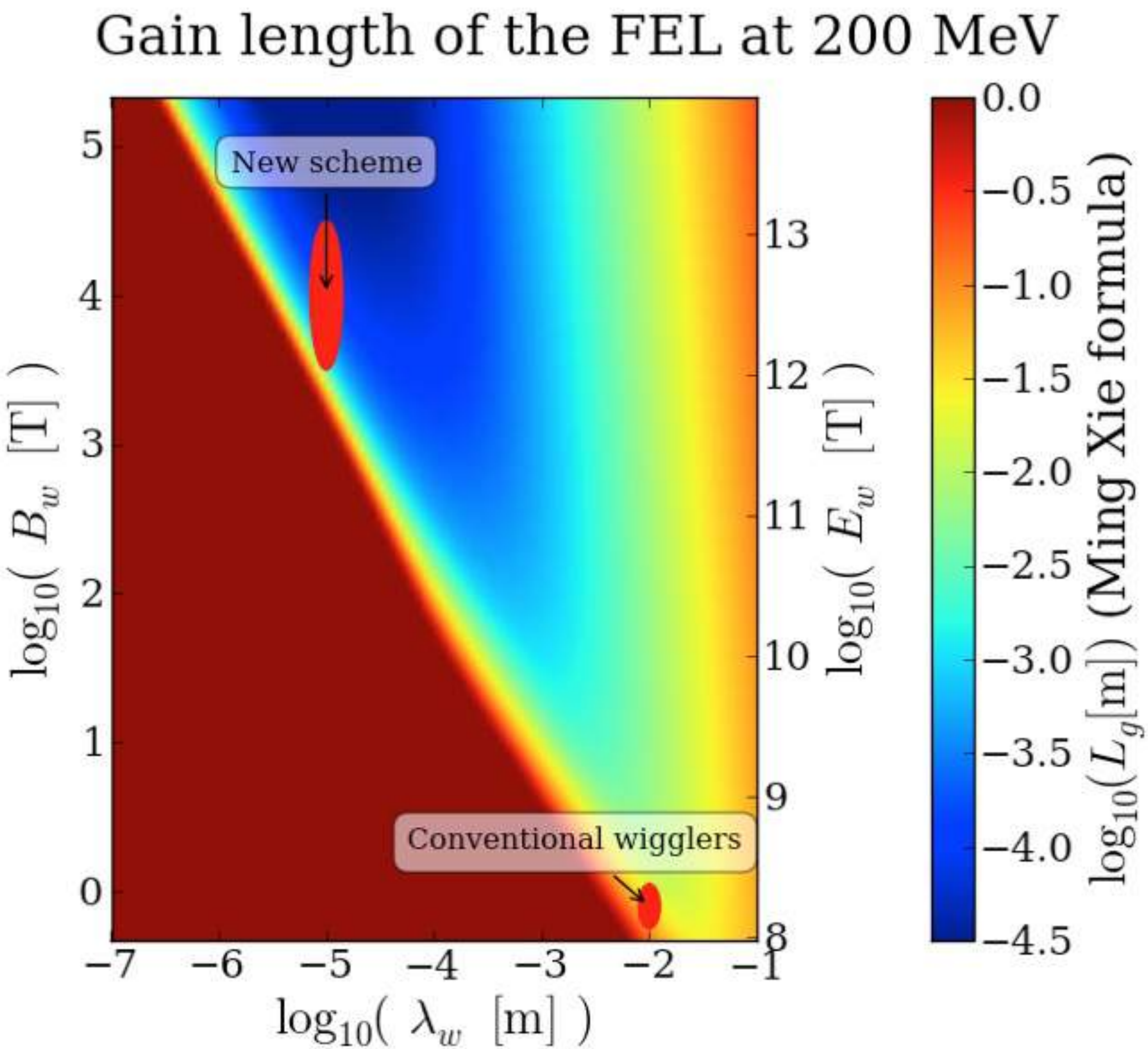
E. Bayart *et al.*, Scientific Reports, s41598 (2019)

FEL experiment on Seeding mode with LPA

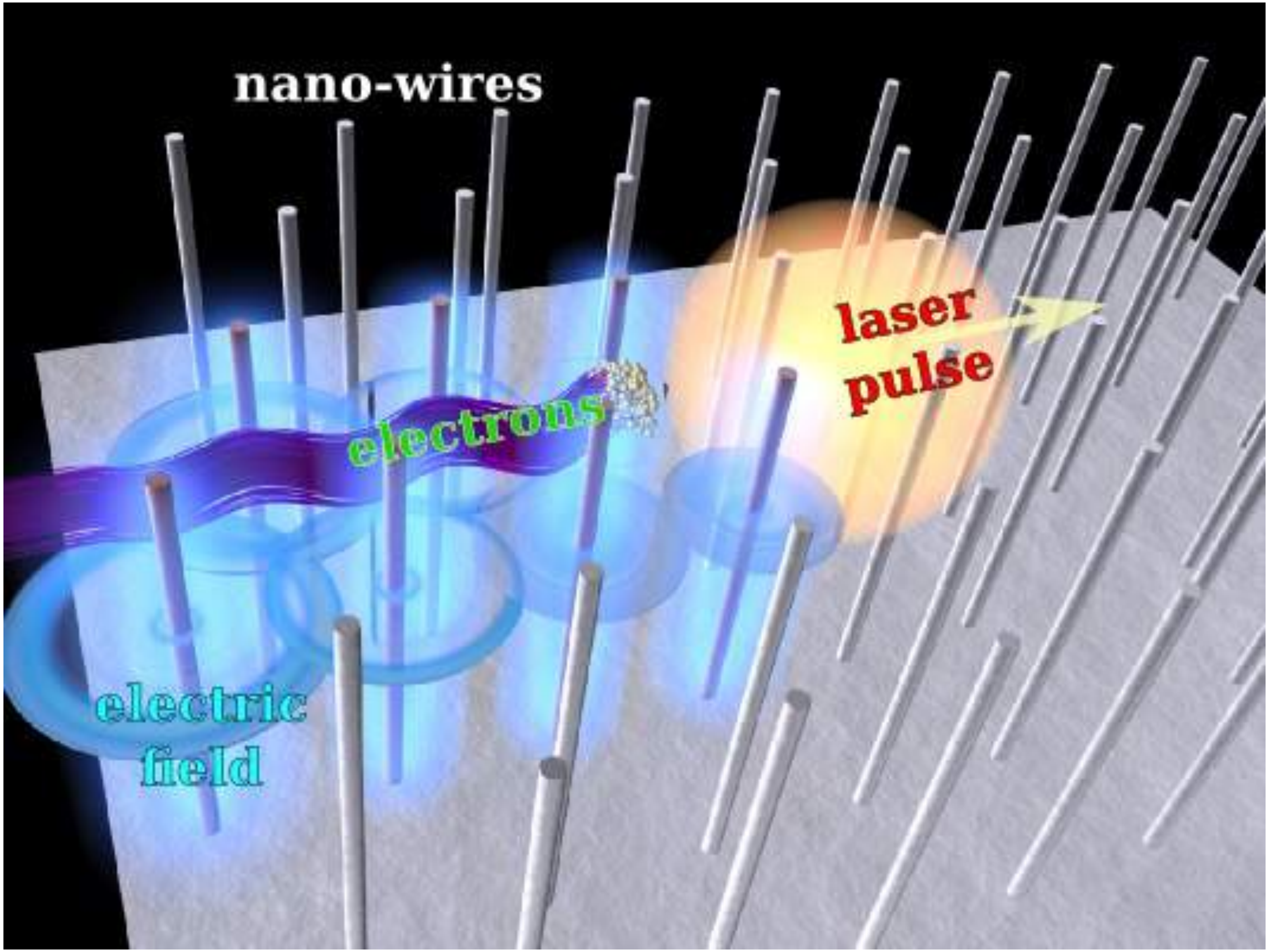


in collaboration with Marie Emmanuelle

Towards compact X-ray beams based on LPA



Concept for ultra compact X rays beam



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

Undulating with plasma fields

Varying electron energy

Energy 200 / 400 / 600 MeV

Undulator emission

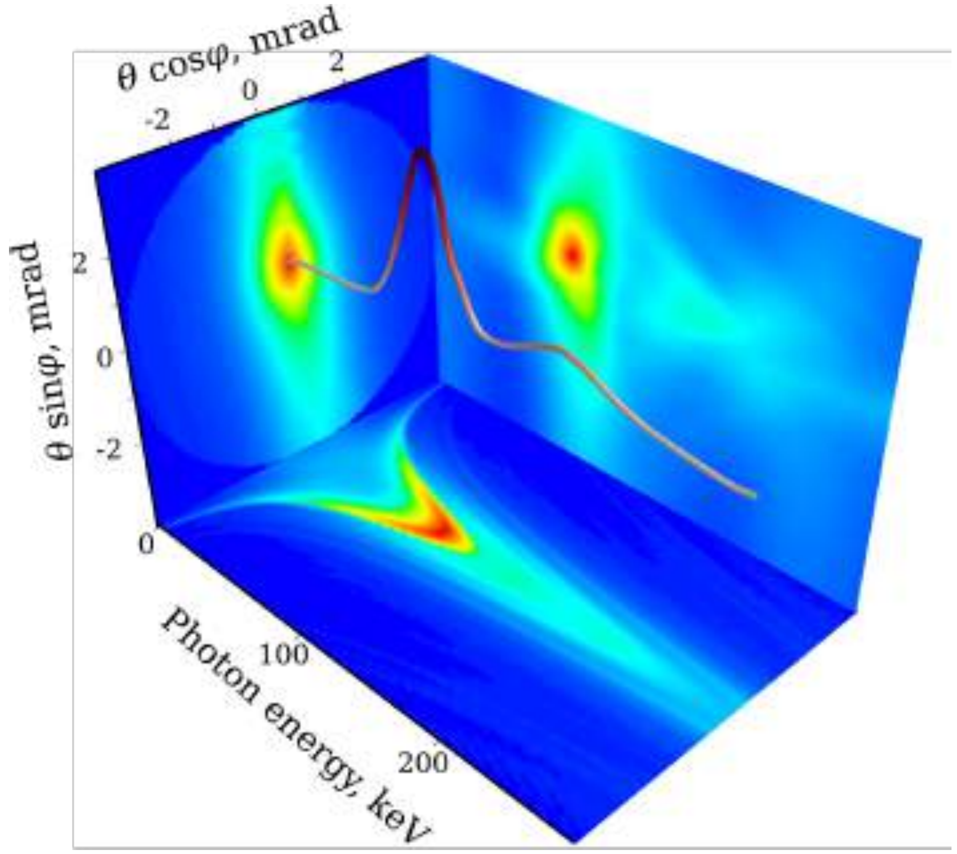
Photon energy 12 / 47 / 106 keV

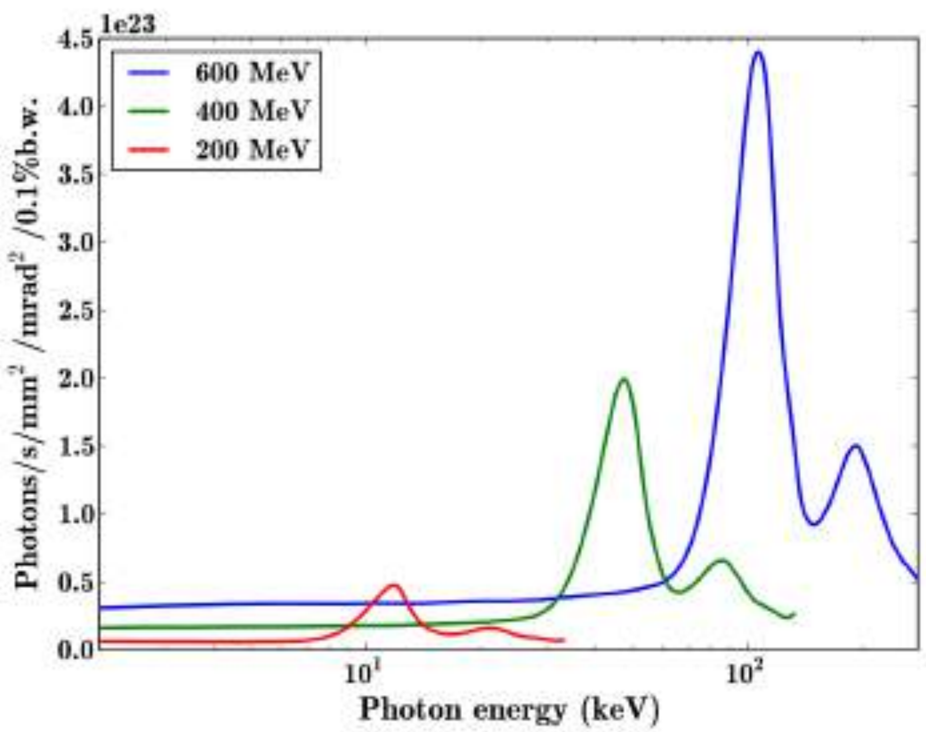
Brightness 0.5 / 2 / 4.5×10^{23}s.u.

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-Driven Plasma Linac: «Artistic view»

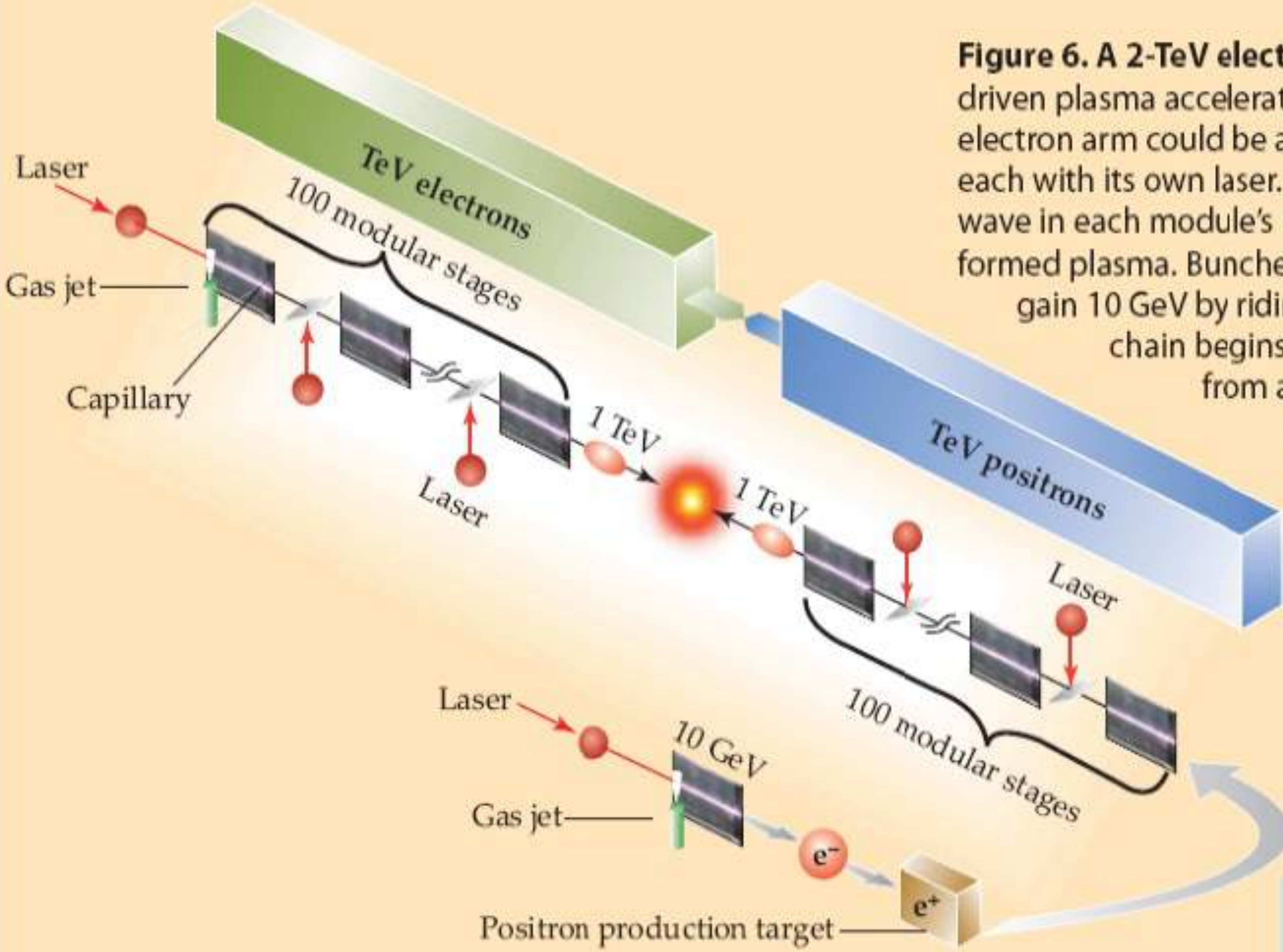
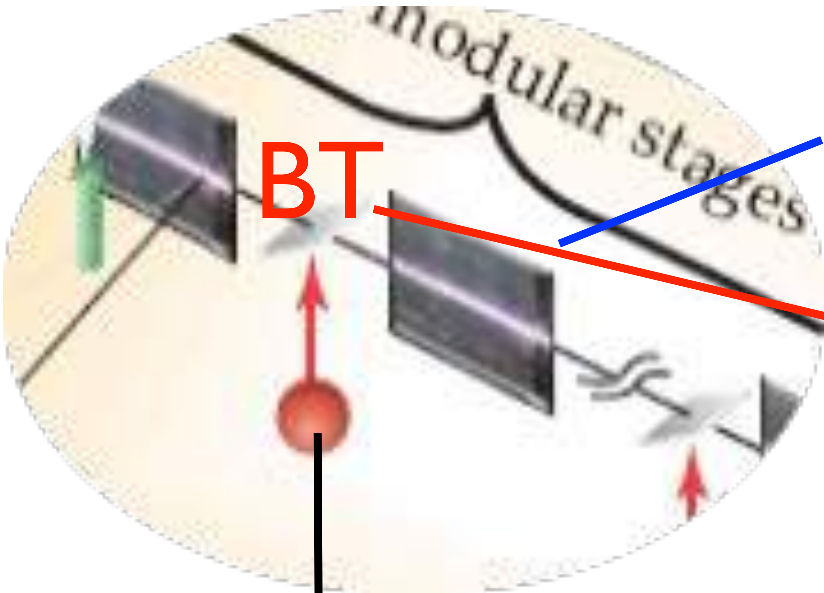


Figure 6. A 2-TeV electron–positron collider based on laser-driven plasma acceleration might be less than 1 km long. Its electron arm could be a string of 100 acceleration modules, each with its own laser. A 30-J laser pulse drives a plasma wave in each module's 1-m-long capillary channel of pre-formed plasma. Bunched electrons from the previous module gain 10 GeV by riding the wave through the channel. The chain begins with a bunch of electrons trapped from a gas jet just inside the first module's plasma channel. The collider's positron arm begins the same way, but the 10-GeV electrons emerging from its first module bombard a metal target to create positrons, which are then focused and injected into the arm's string of modules and accelerated just like the electrons.

W. Leemans, et al.,

W. Leemans et al., Phys. Today, March 2009

Concept of Laser-Driven Plasma Linac:Challenge



plasma accelerator
stage 0.1 to 1m, η = 1%

Beam transport :
1, 10 m to up to few km in the last stages
η = ? %

laser :10x50 m + focal of 5-10 m, η = few %

overall wall-plug efficiency:10^{-3},10^{-4}, i.e. for a 1 MW e, e^+ beam, required power of 1-10 GW

100 of kHz-PW Laser reliability, plasma discharge, reliability, etc..

V. Malka Phys. of Plasma 19, 055501 (2012)

Concept of Laser-Driven Plasma Linac:Challenge

1 PW laser at high rep rate (>100Hz): today in the best 1 Hz

Plasma and vacuum chambers

Transport between stages

Thermal effects on the guiding structure wall

External guiding/self-guiding

Collimation and beam filtering

Accelerating plasma structure: linear (<1GV/m) or non-linear (>few GV/m to 100s GV/m)

High efficiency laser driver : today in the best 1%

Laser Plasma Accelerators : Outline

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

Conclusions

Accelerators point of view :

Good beam quality & Monoenergetic dE/E down to 1 % √

Beam is very stable √

Energy is tunable: up to 400 MeV √

Charge is tunable: 1 to tens of pC √

Energy spread is tunable: 1 to 10 % √

Ultra short e-bunch : 1,5 fs rms √

Low divergence : 2 mrad √

Low emittance[1-3] : < π.mm.mrad √

With PW class laser : peak energy at 4.5 GeV √

[1]S. Fritzler *et al.*, Phys. Rev. Lett. **92**, 165006 (2004), [2]C. M. S. Sears *et al.*, PRSTAB **13**, 092803 (2010), [3]E. Brunetti *et al.*, Phys. Rev. Lett. **105**, 215007 (2010)

Perspectives

Results extremely important for :

Designing future accelerators

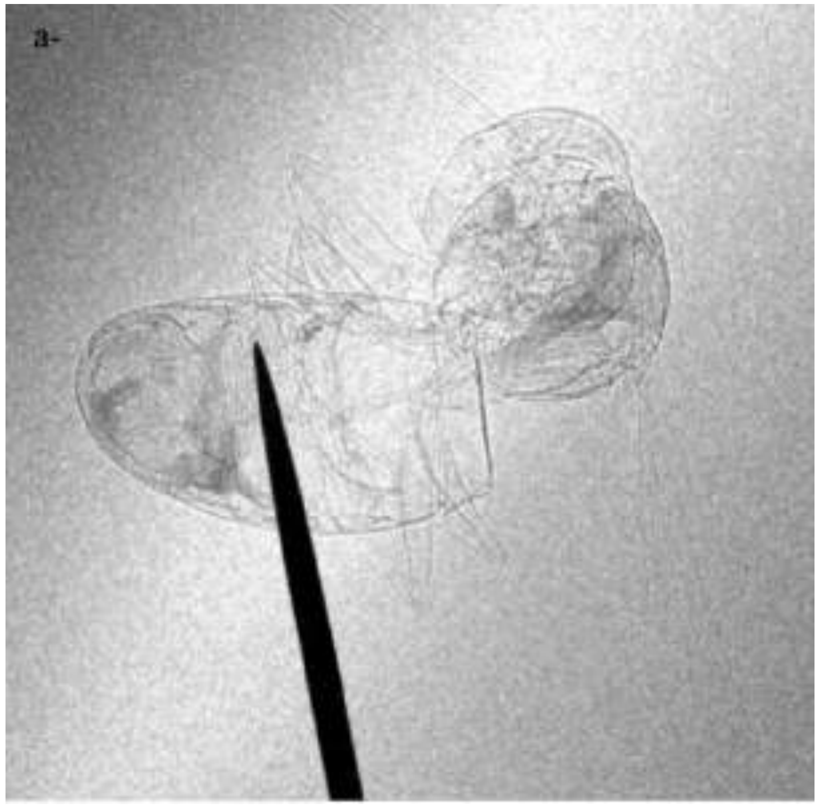
Compact X ray source (Thomson, Compton, Betatron, or FEL)

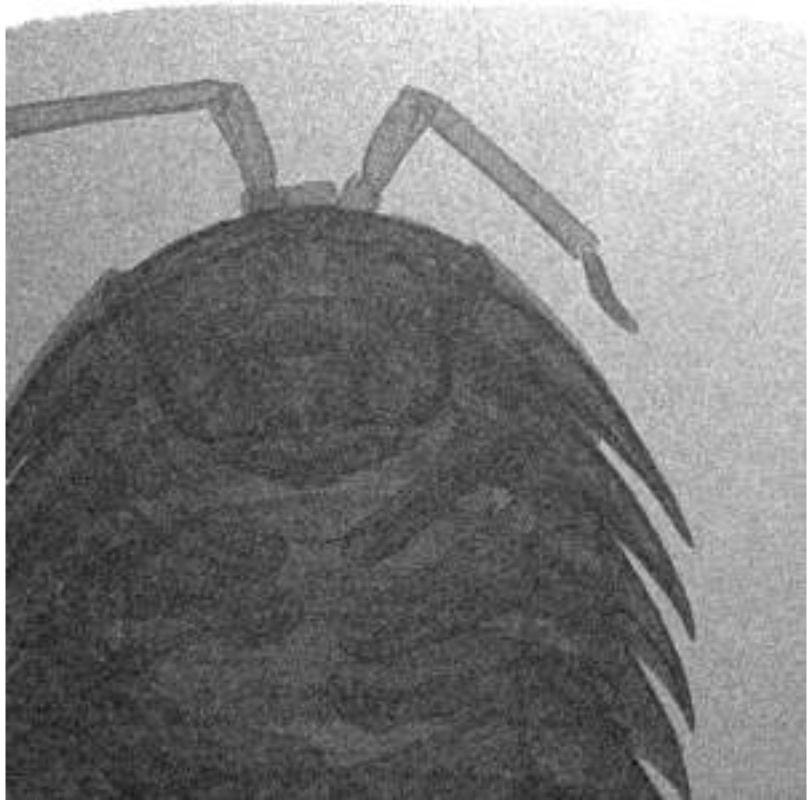
Applications (chemistry, radiotherapy, medicine, material science, ultrafast phenomena studies, etc...)

First X rays betatron contrast images

S. Fourmaux *et al.*, Opt. Lett. **36**, 13 (2011)

S. Kneip *et al.*, APL **99**, 093701 (2011)





Courtesy of K. Krushelnick

V. Malka *et al.*, Nature Physics **4** (2008), E. Esarey et al. , Rev. Mod. Phys. **81**, 1229 (2009)

Perspectives 2 for LPA

Short term perspective (< 10 years):

Relevant applications in medicine, radiobiology, material science

Compact FEL with moderate average power (10 Hz system)

Compact X ray source (Thomson, Compton, Betatron, or FEL)

Long term possible applications (>40-50 years):

High energy physics that will depend on the laser technology evolution, on laser to electron transfer efficiency, on progress of multistage design, acceleration of positron, etc...)

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.

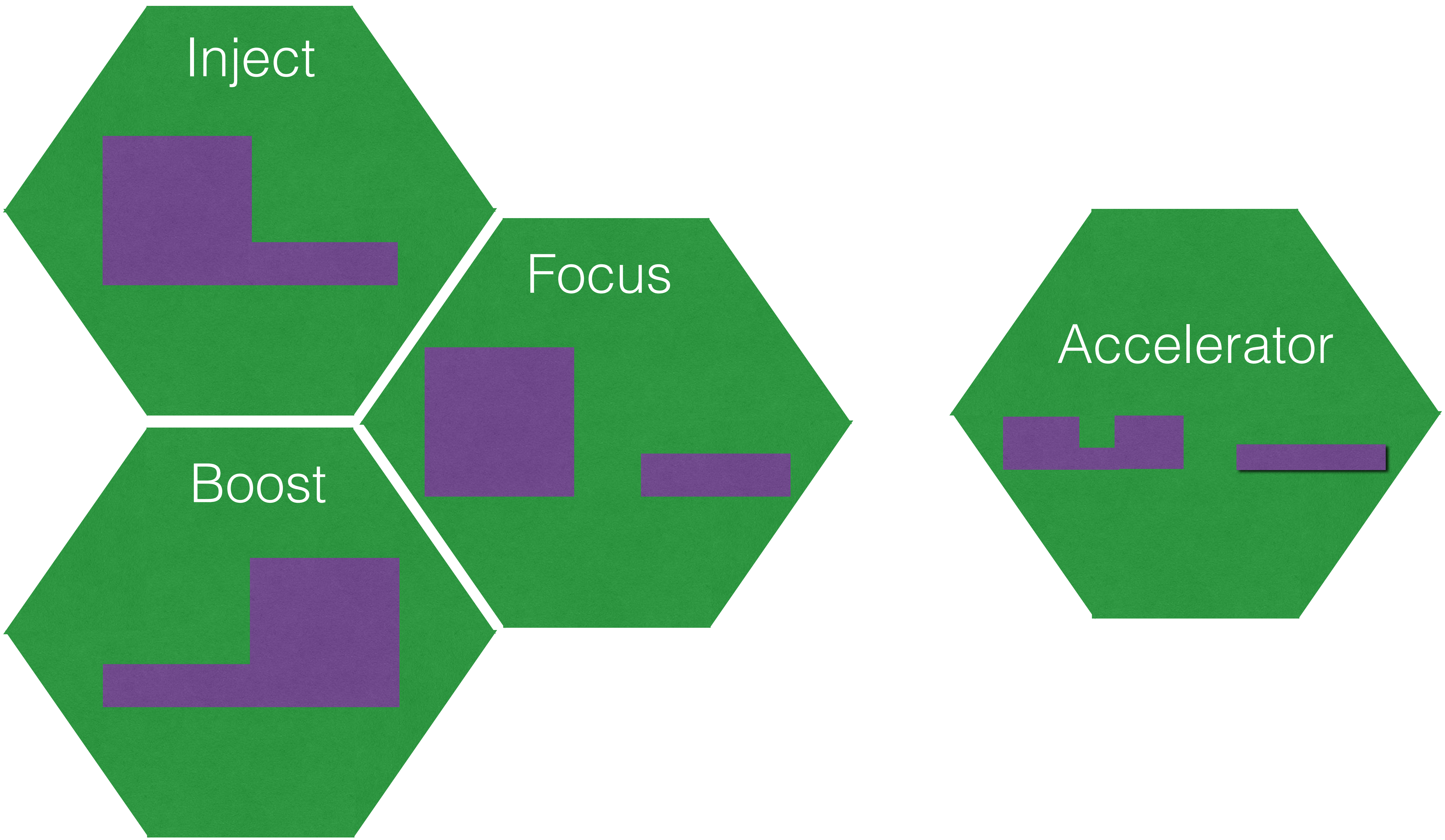
As a consequence, Laser Plasma Accelerators have made significant progresses delivering stable, reliable high quality and high current e-beams.

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

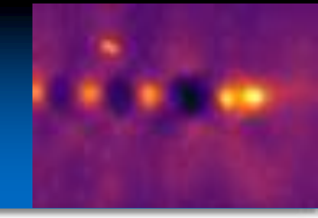
Compact FEL based on LWFA is one very important challenge that has been identified by the community.

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)

Simple plasma devices produced with a single laser pulse

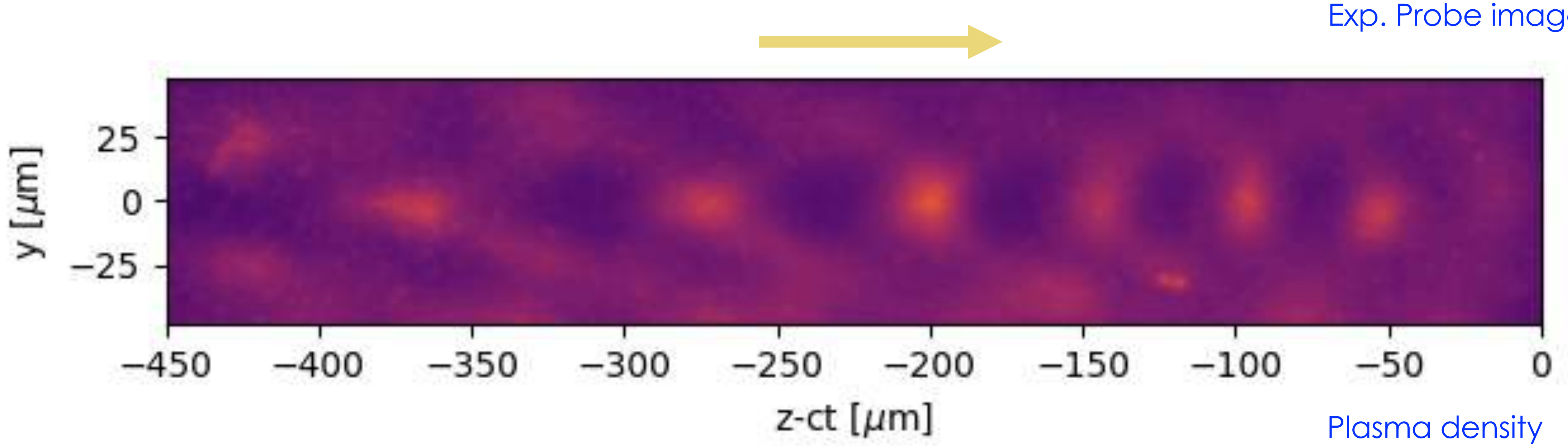


Visualization of the wakefield dynamics

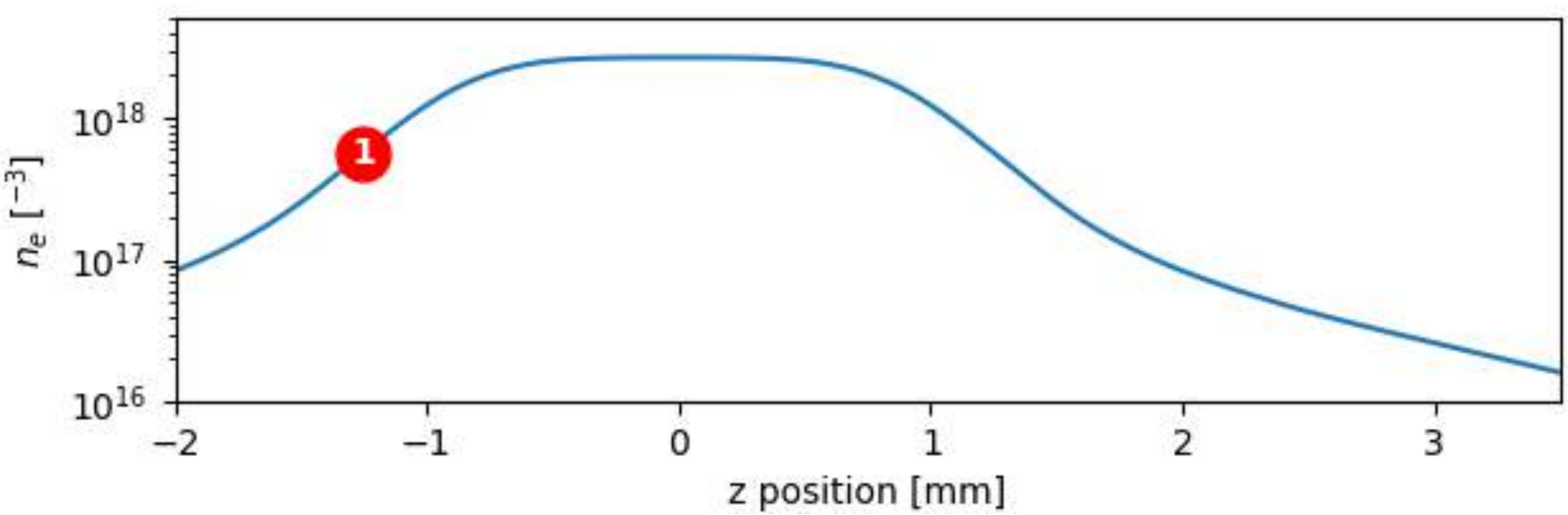


Jet 2: He (1% N_2), plasma density $2.8\text{x}10^{18}$ cm^{-3}
Laser B: on-target energy ~ 1J, linearly polarized (horizontal)

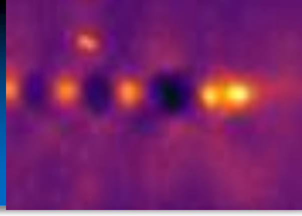
Exp. Probe image

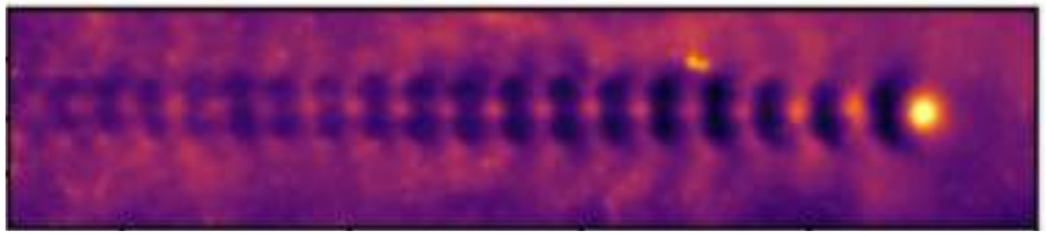


Plasma density

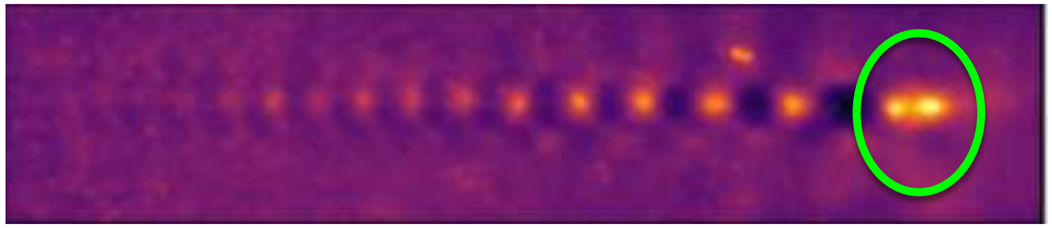


Transition from the laser to the plasma wakefield

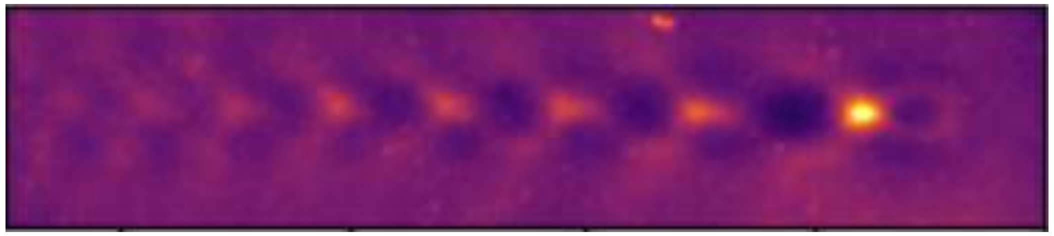




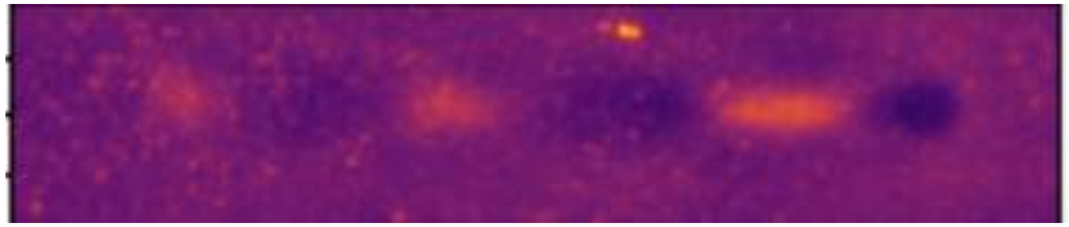
Pure LWF



Electron injection in LWF

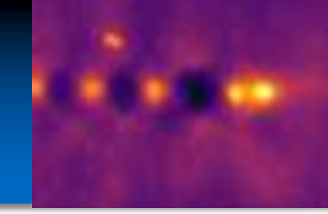


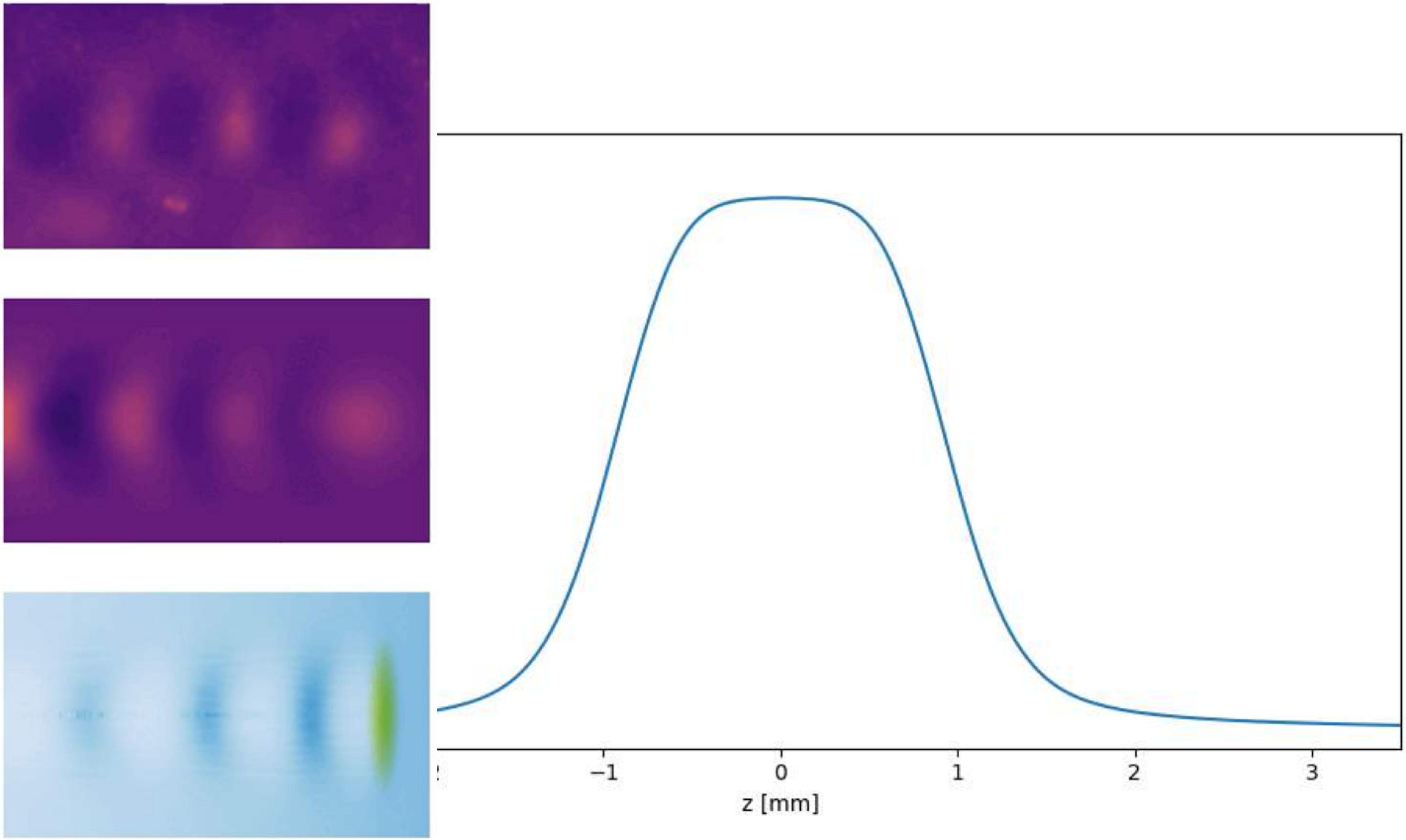
Mixed PWF and LWF



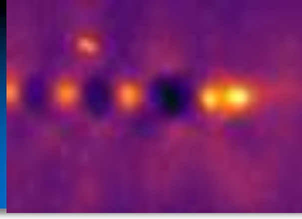
Pure PWF

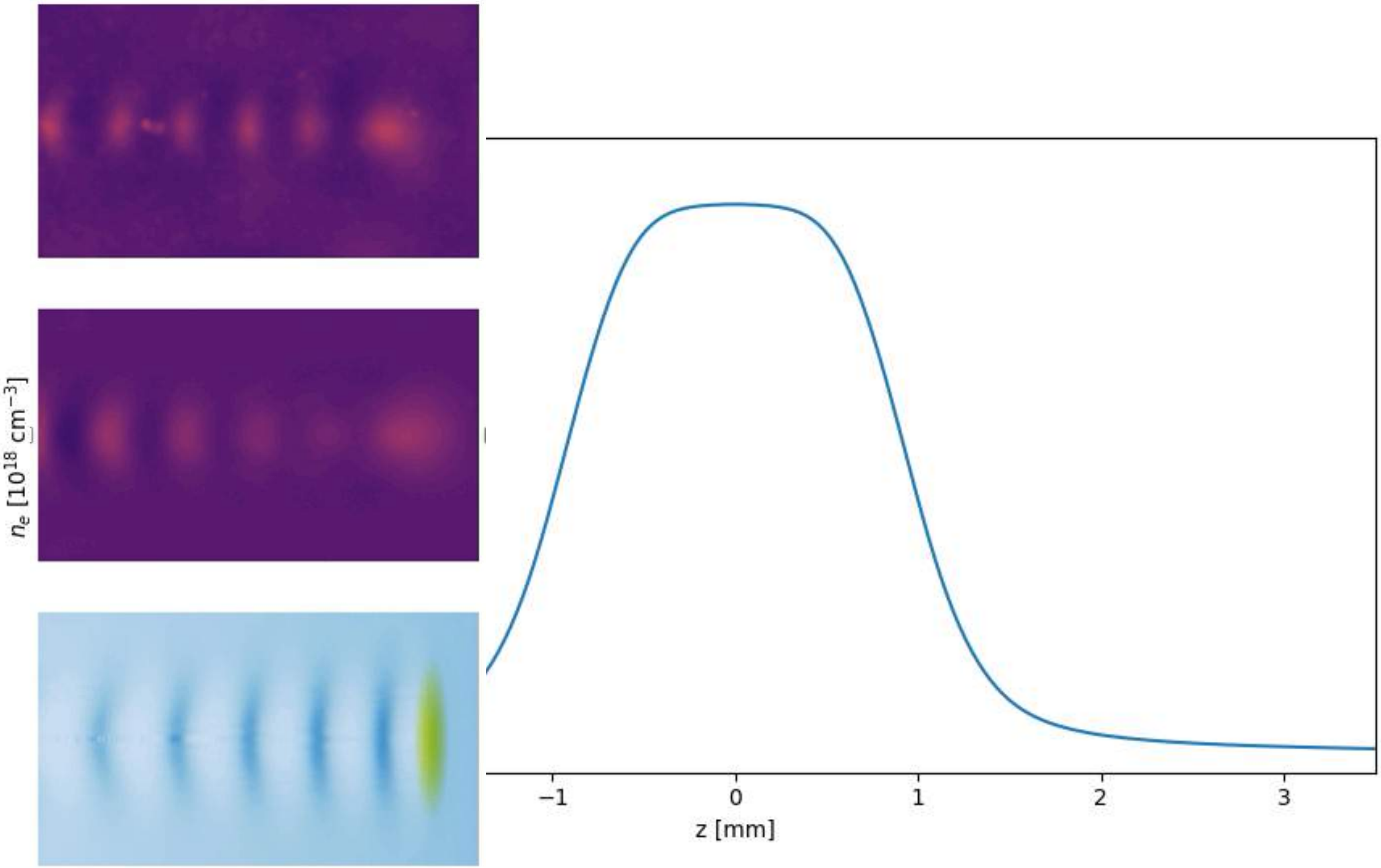
Transition from the laser to the plasma wakefield





Transition from the laser to the plasma wakefield





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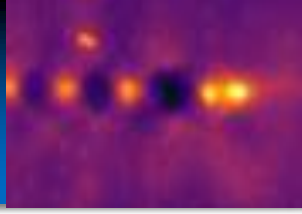

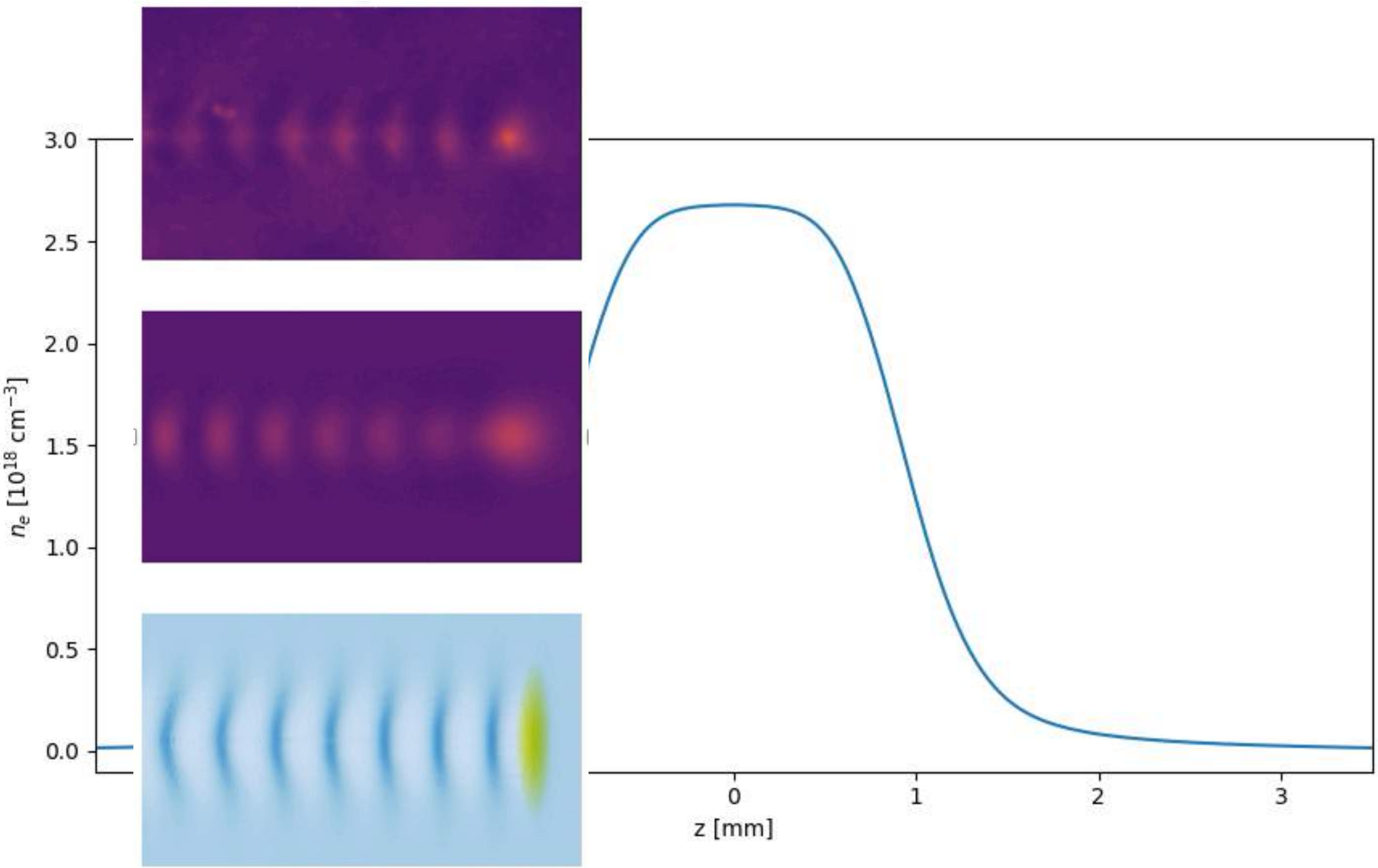

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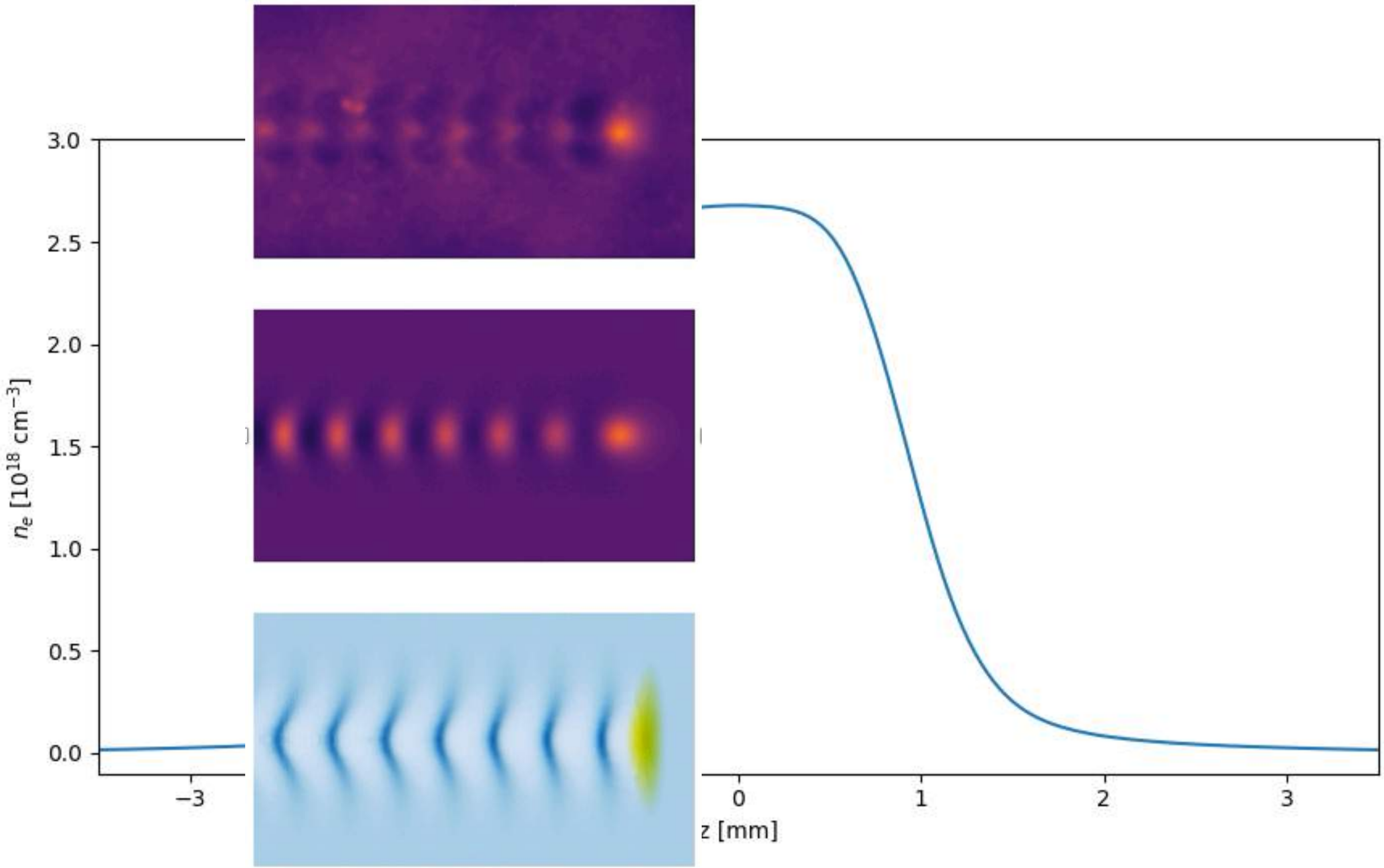

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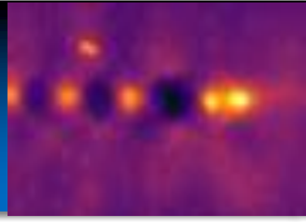

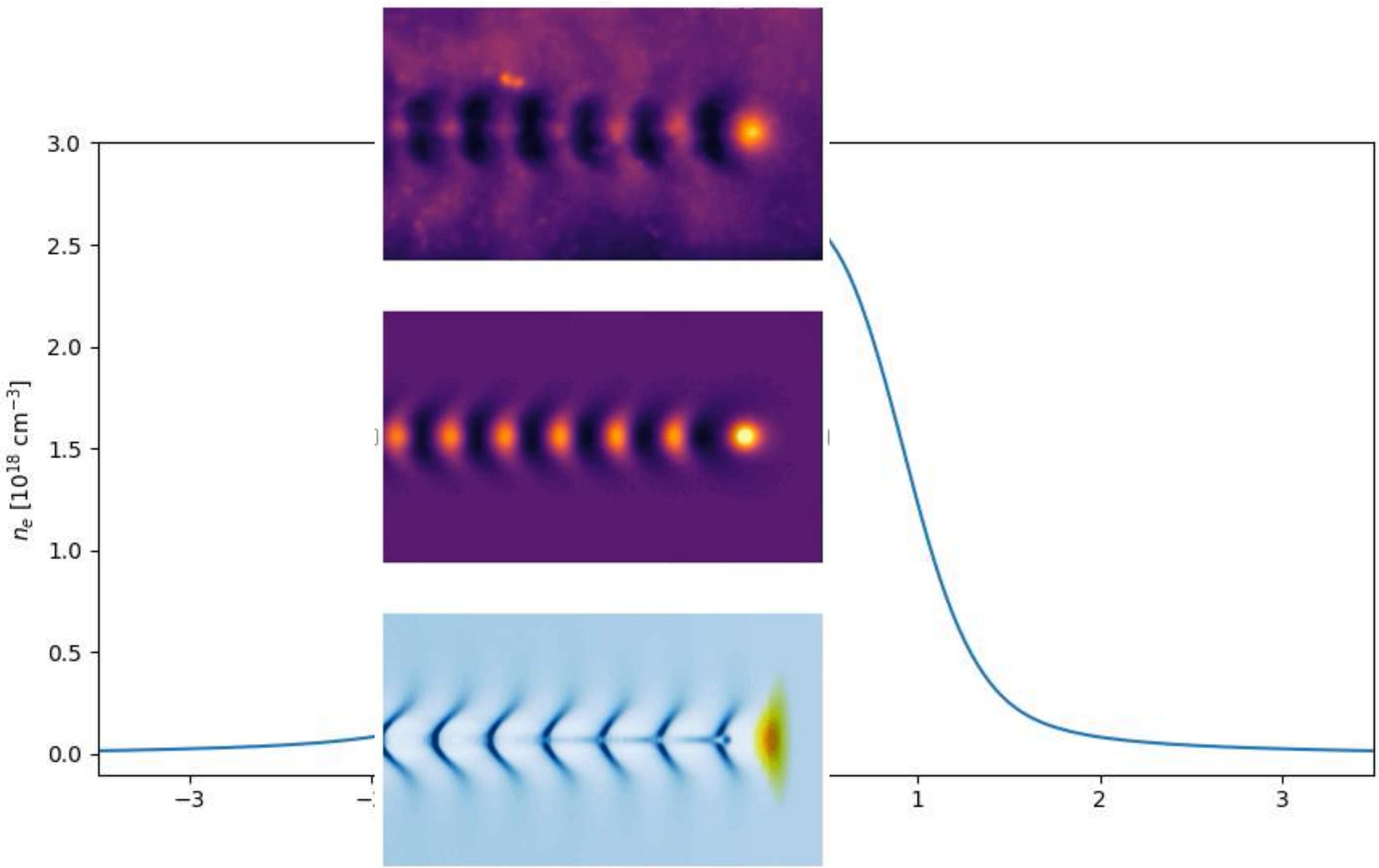

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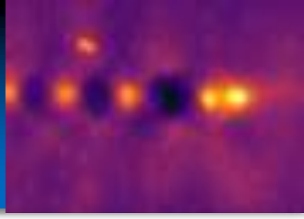

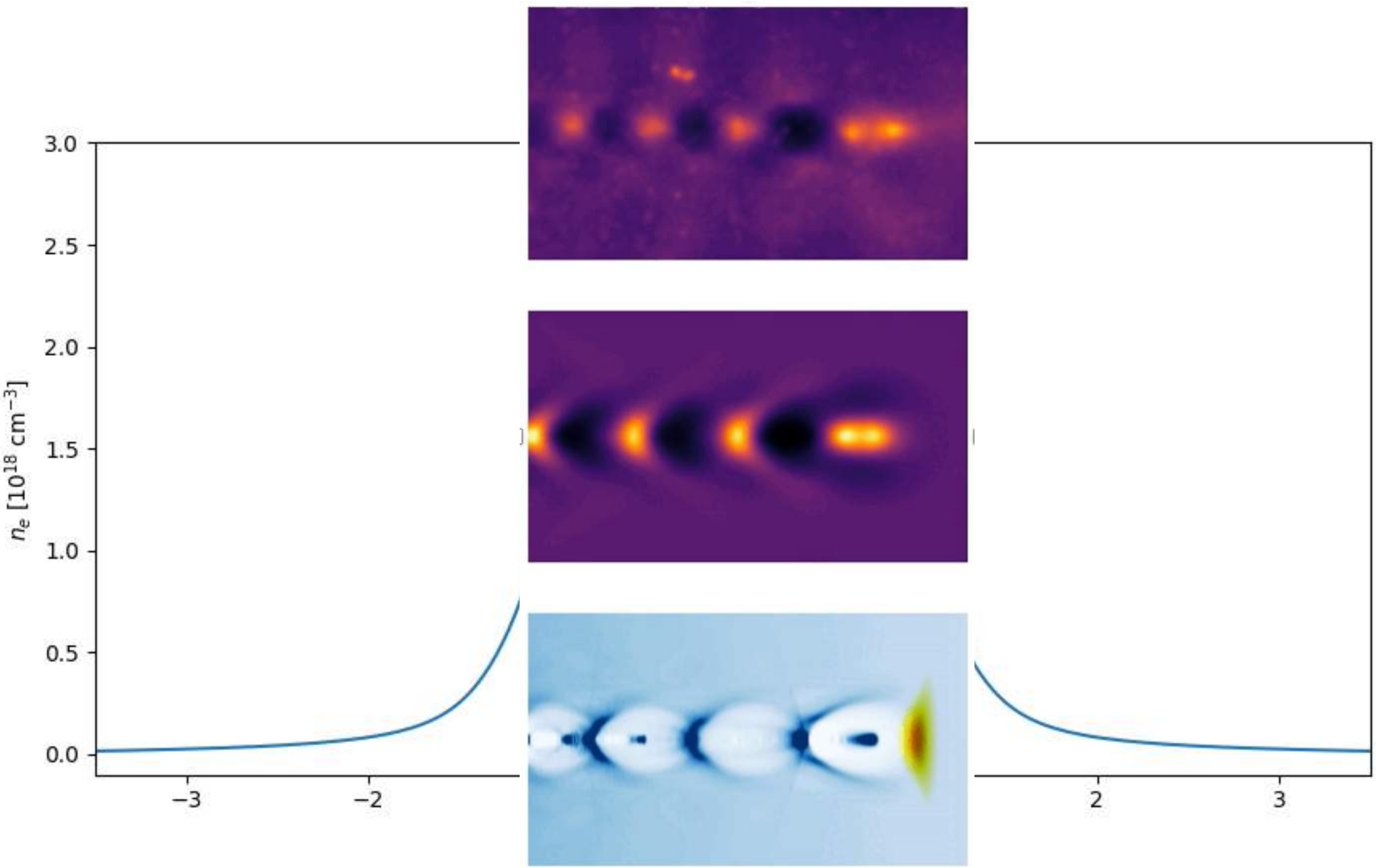

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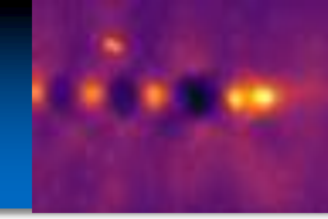

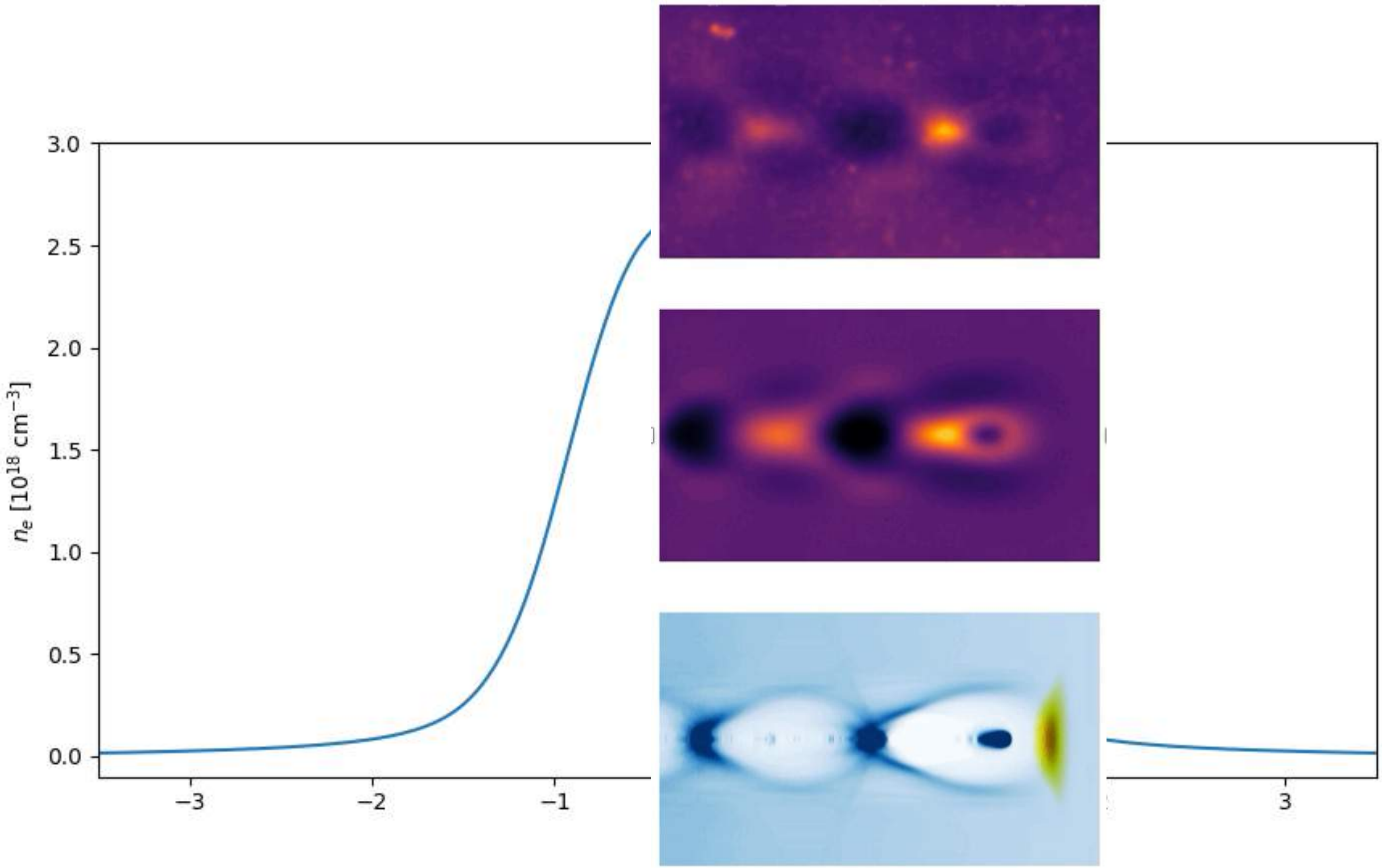

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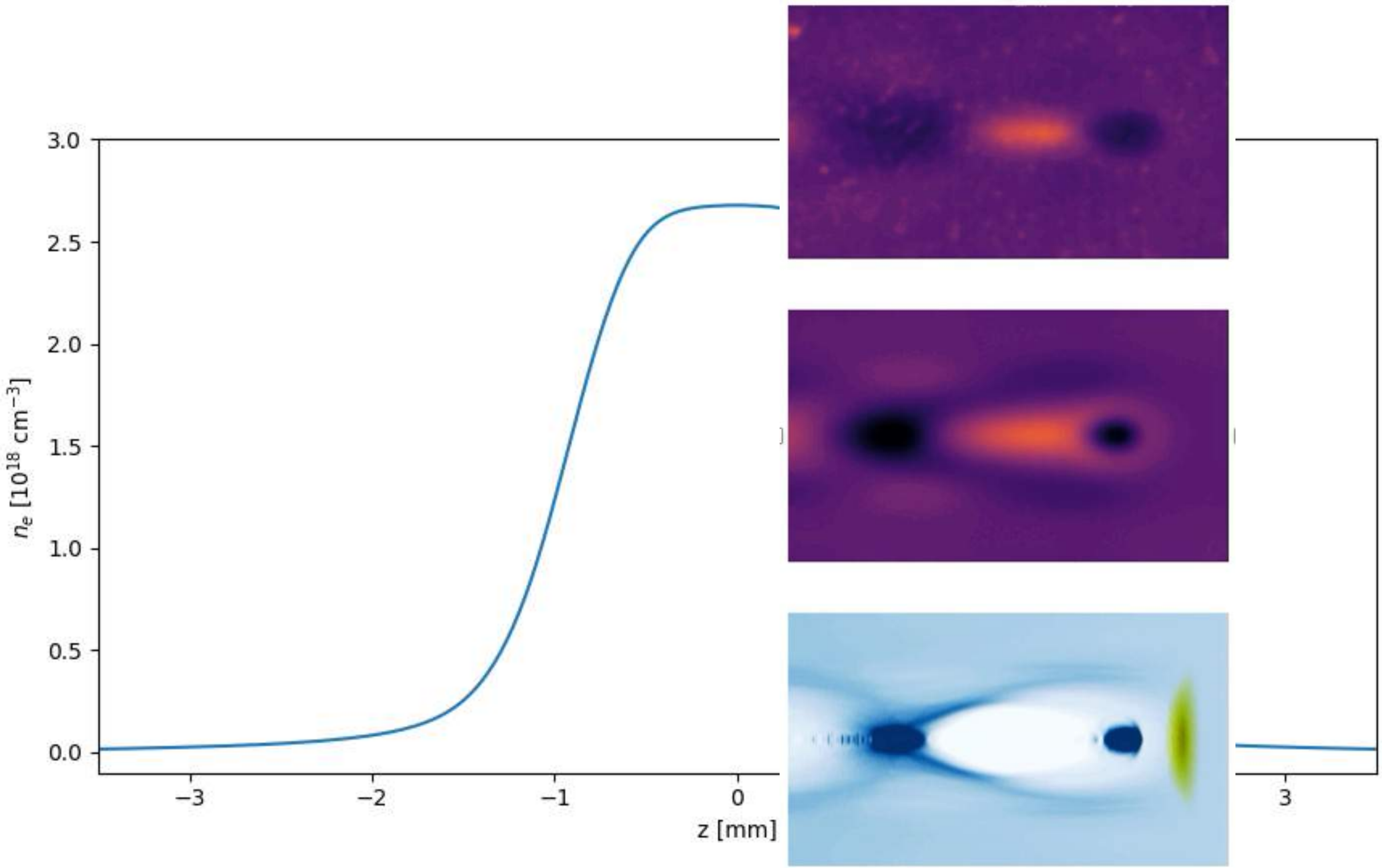

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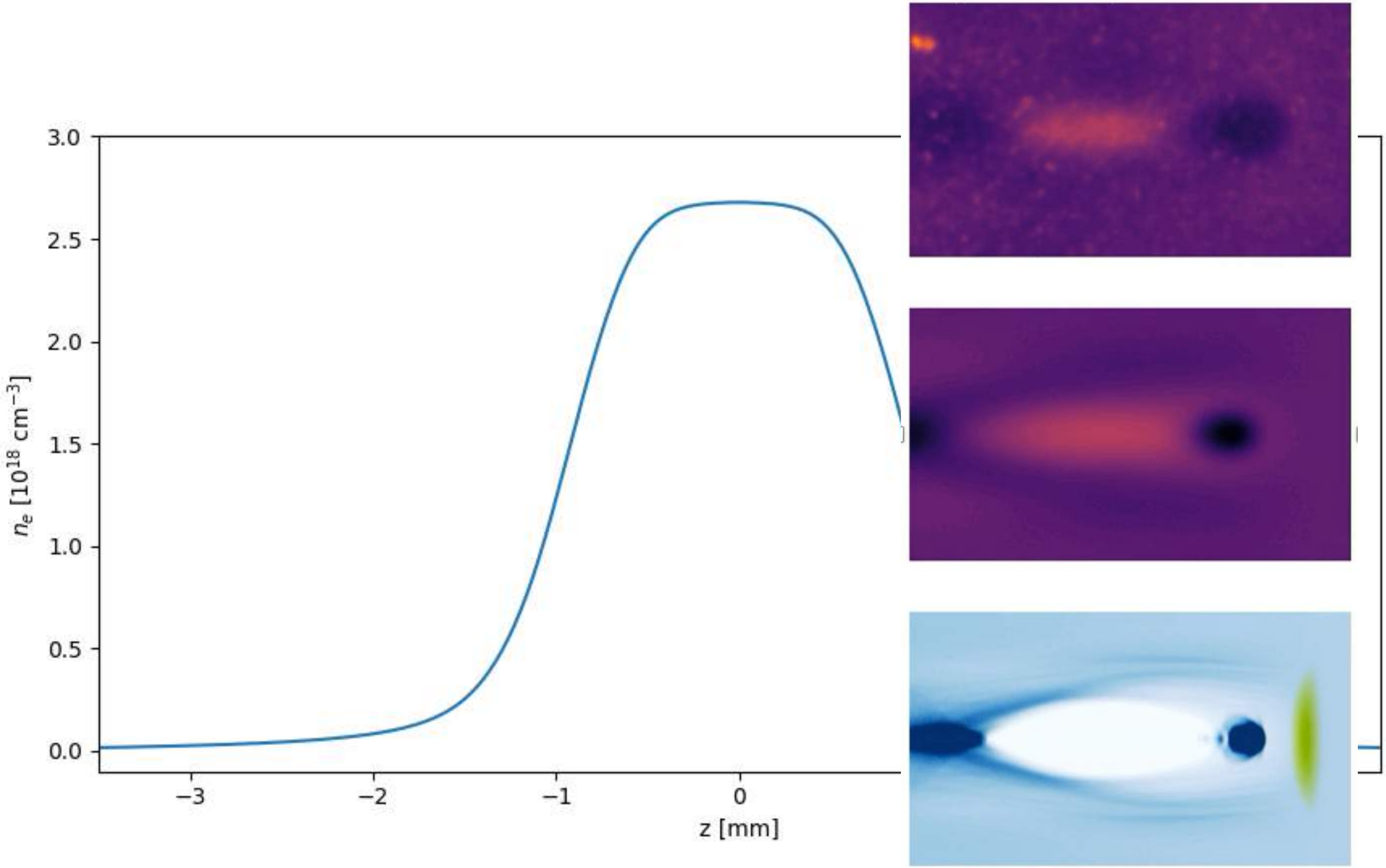

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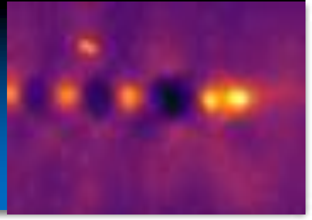

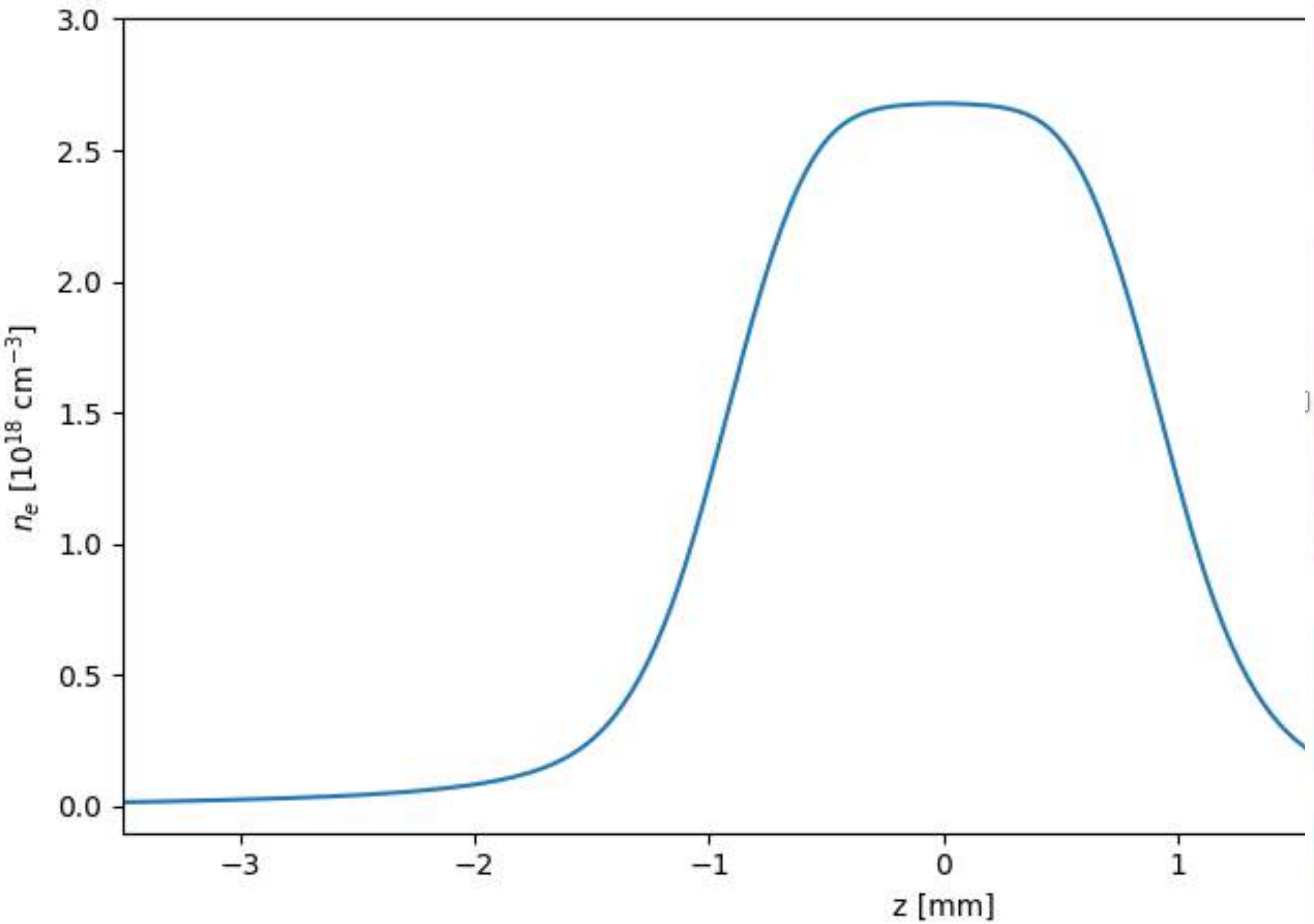

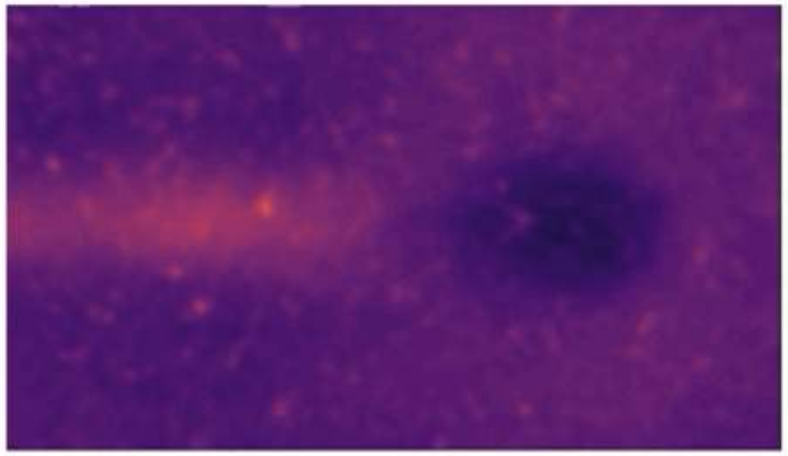

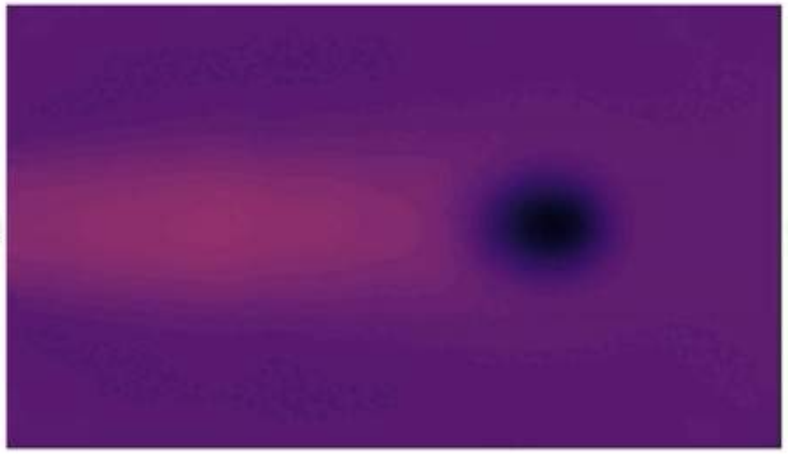

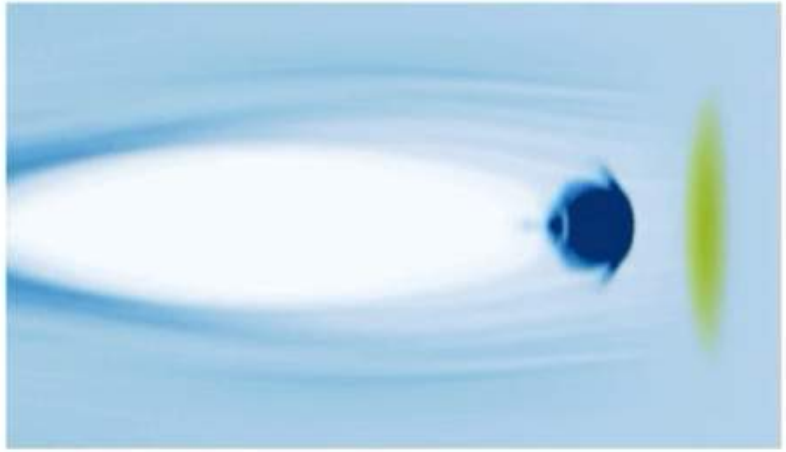

A journey in the lab…

Acknowledgements

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[3]Lund Laser Center, Lund University, Lund, Sweden

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