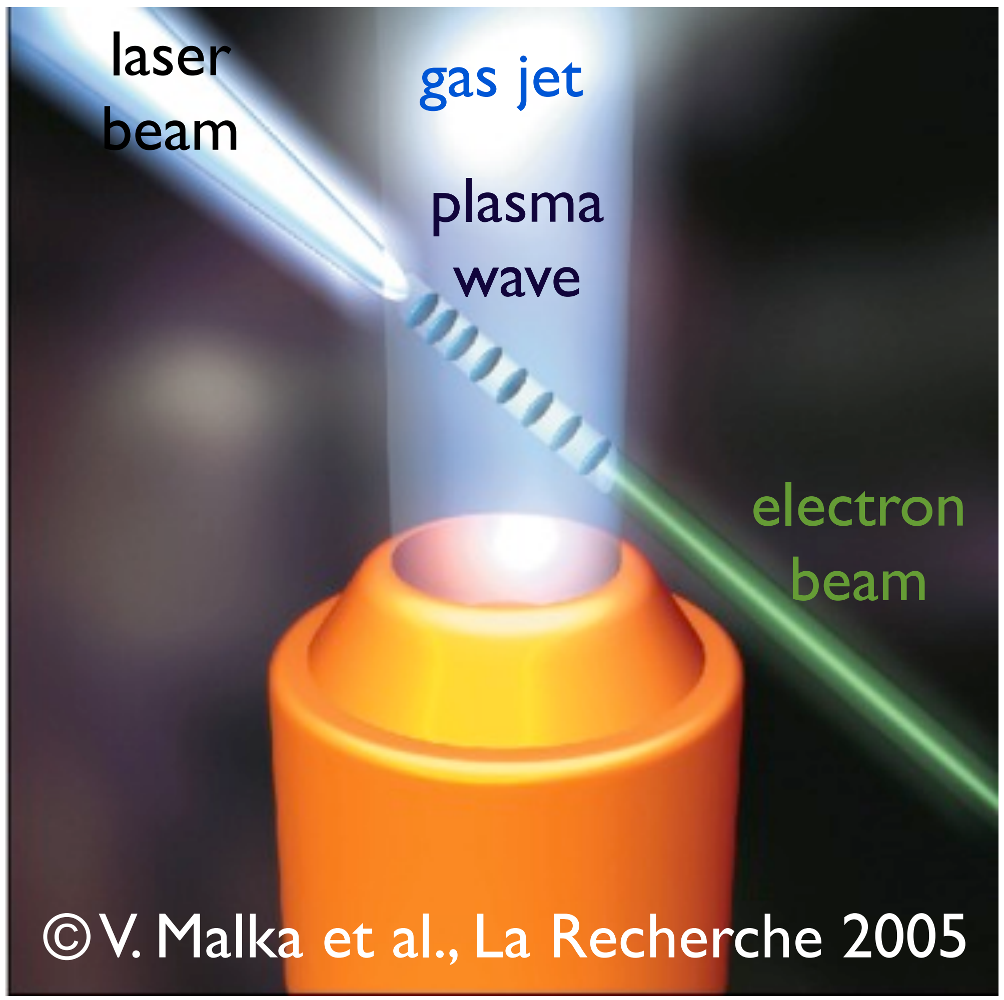
laboratoire d'optique appliquée

Recent Results on Laser Plasma Accelerators



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loa erc

FILIMITh, MPQ, Garching, Germany, September 19-21 (2012)

ÉCOLE POLYTECHNIQUE ParisTech cnrs ENSTA ParisTech

Outline

- Betatron X source as a powerful diagnostic
- Compton scattering X ray beam
- fs-kHz beam for electron diffraction
- Conclusion and perspectives

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- Compton scattering X ray beam
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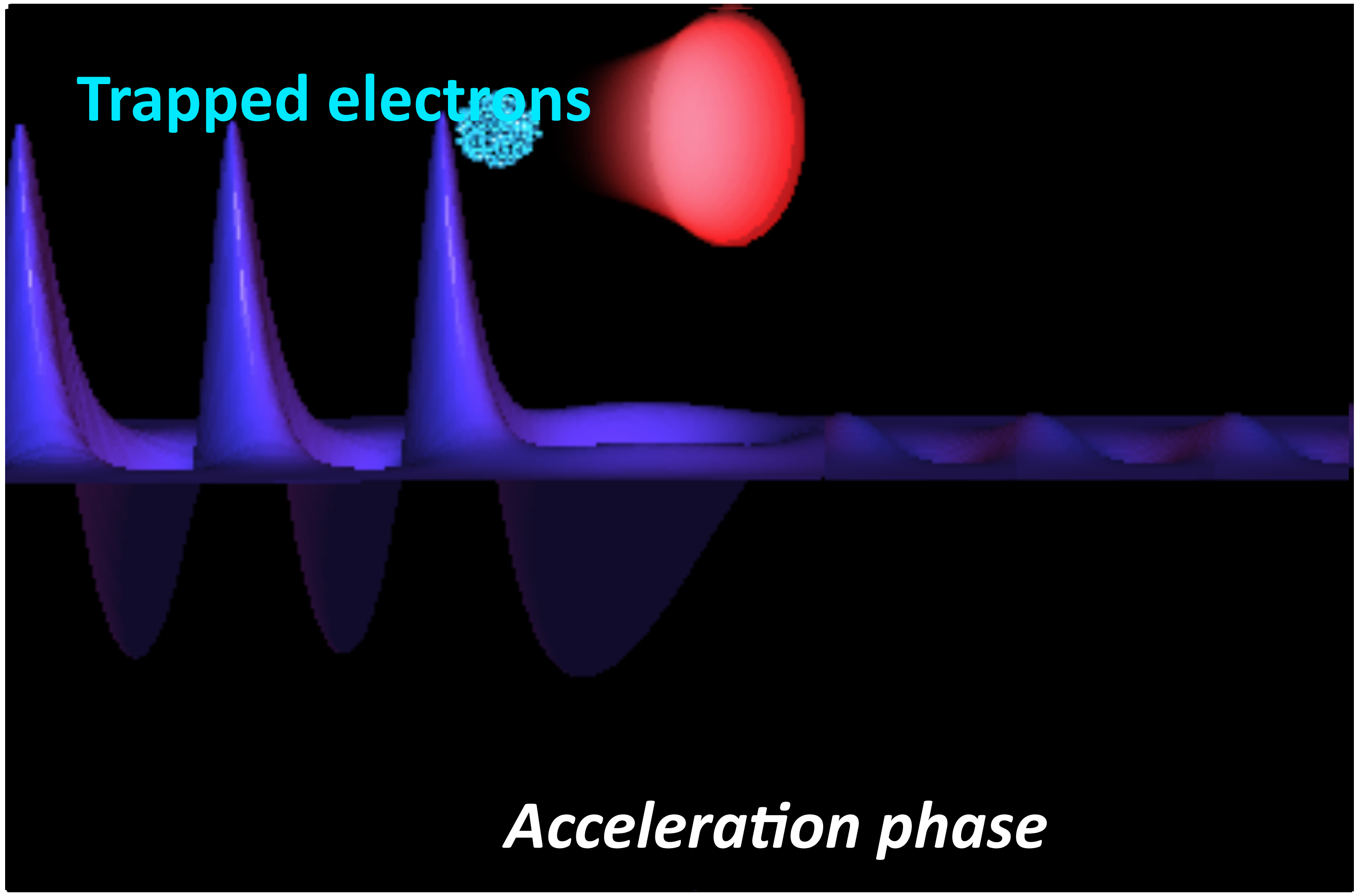
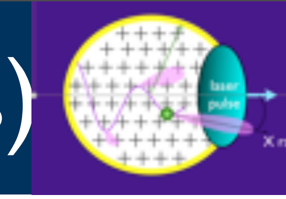
In the relativistic regime, electrons oscillate at a speed close to the speed of light : $$a_0 = \frac{eA}{m_e c}$$



- The Laplace force is non negligible and electron dynamic is non linear.
- The ponderomotive force $-\vec{\nabla} a_0^2$ excites the plasma wave.
- This excitation is efficient if : $\tau \sim \pi \omega_p^{-1}$
- The excited plasma wave amplitude is large and has a non linear behavior if : $a_0 \gtrsim 1.$

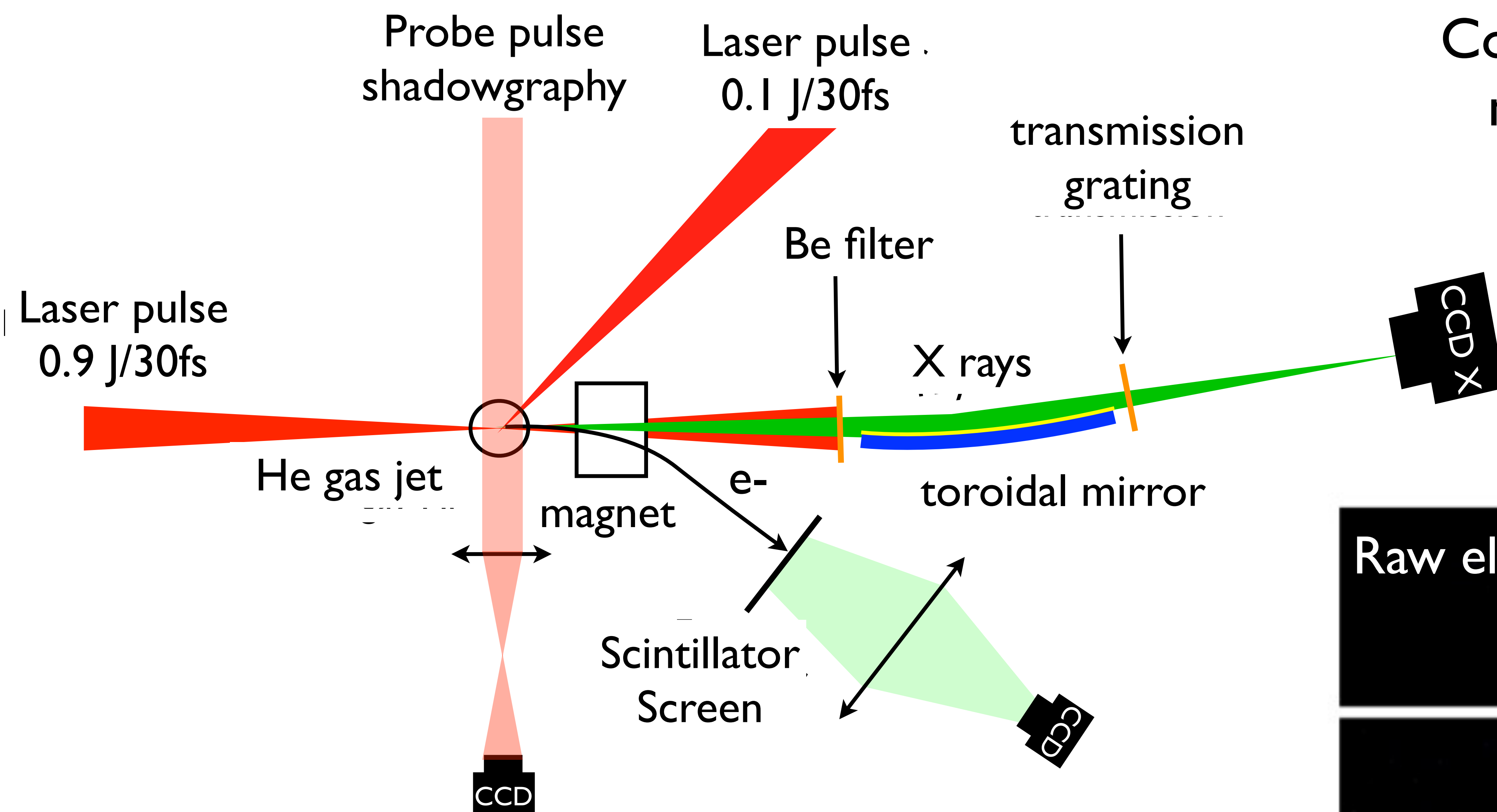
J. Faure *et al.*, Nature **444**, 737 (2006)

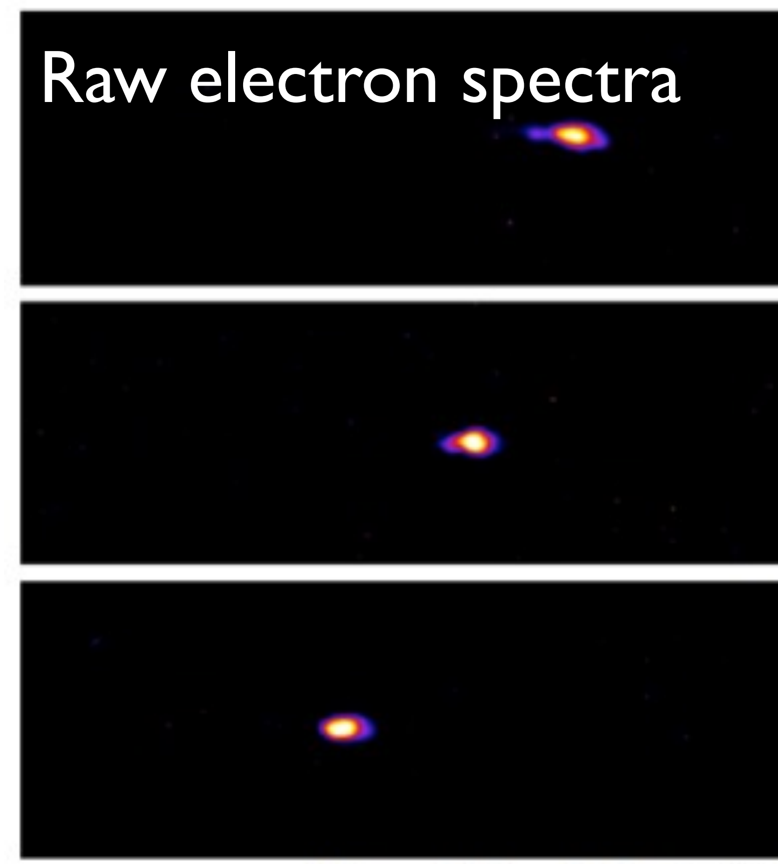
Electron and X ray correlation (LOA experiments)



Collision angle : 135°

$n_e = 8\times10^{18}\ cm^{-3}$

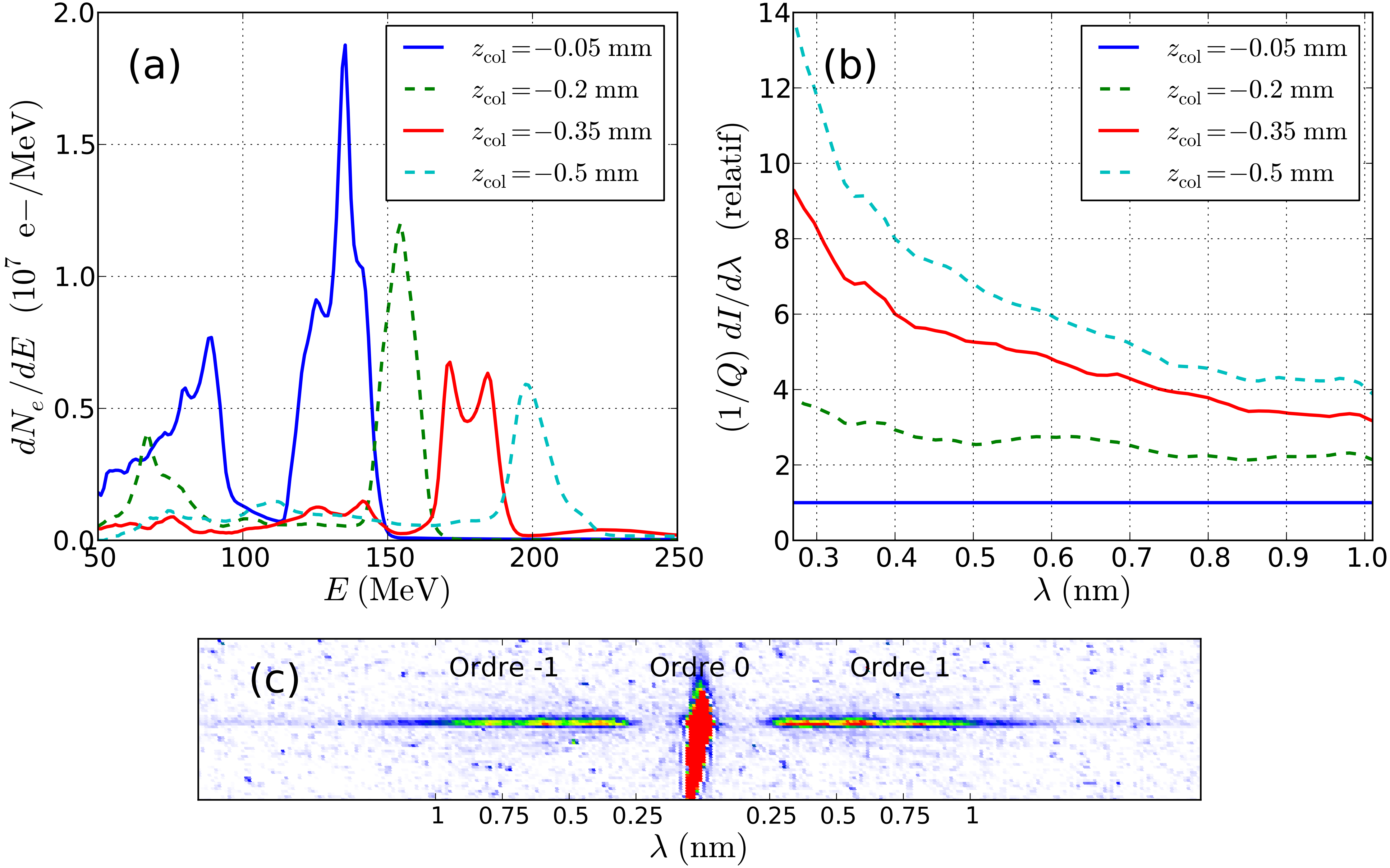




Optical injection: more stable and higher e-beam quality

E-beam energy is controlled by changing the delay line

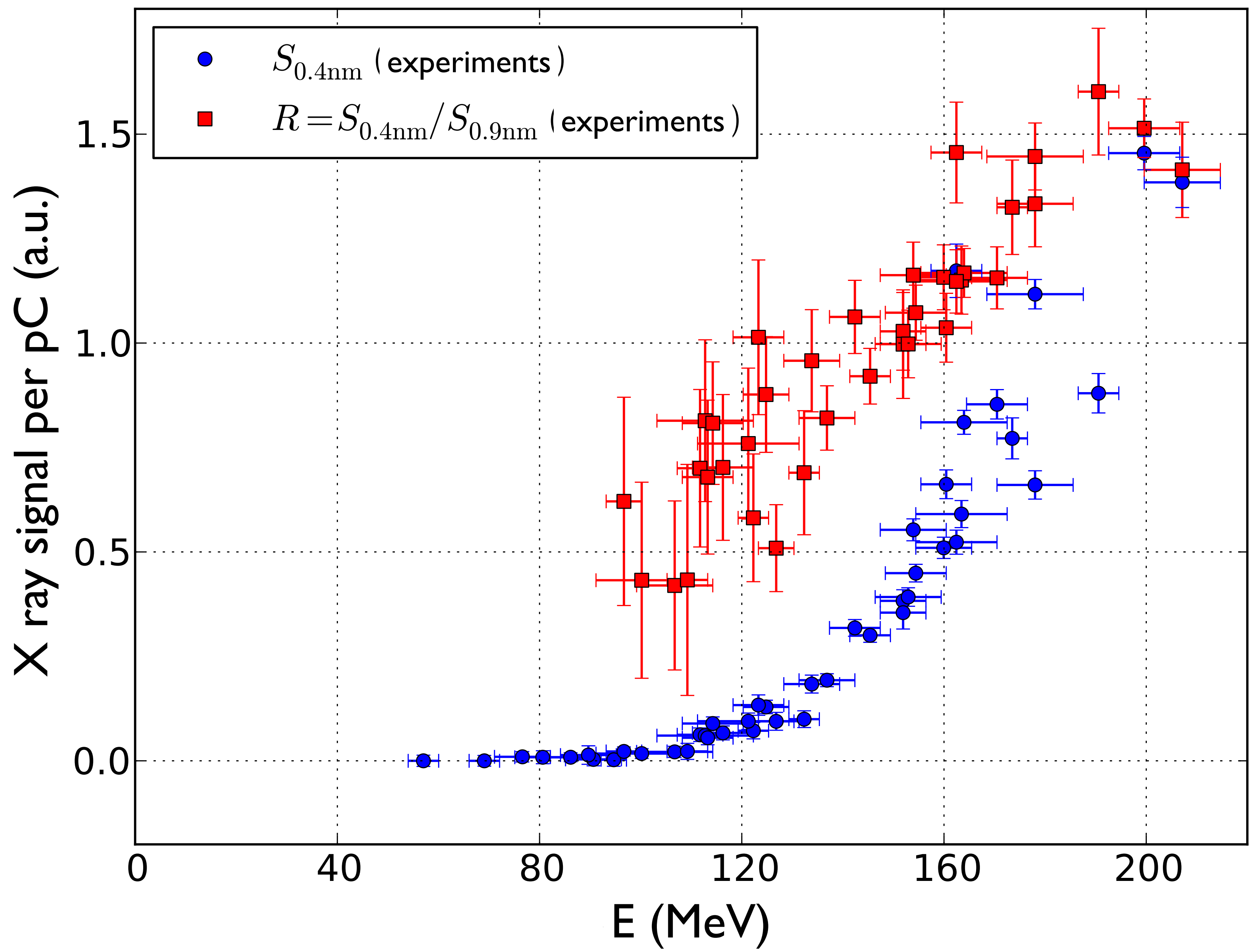
Electron and X ray correlation (LOA experiments)



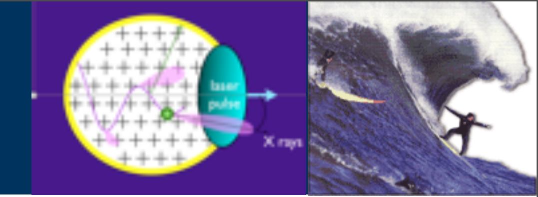
Thanks to the colliding laser pulses scheme, clear correlations between electron beam energy and betatron X ray distribution are observed

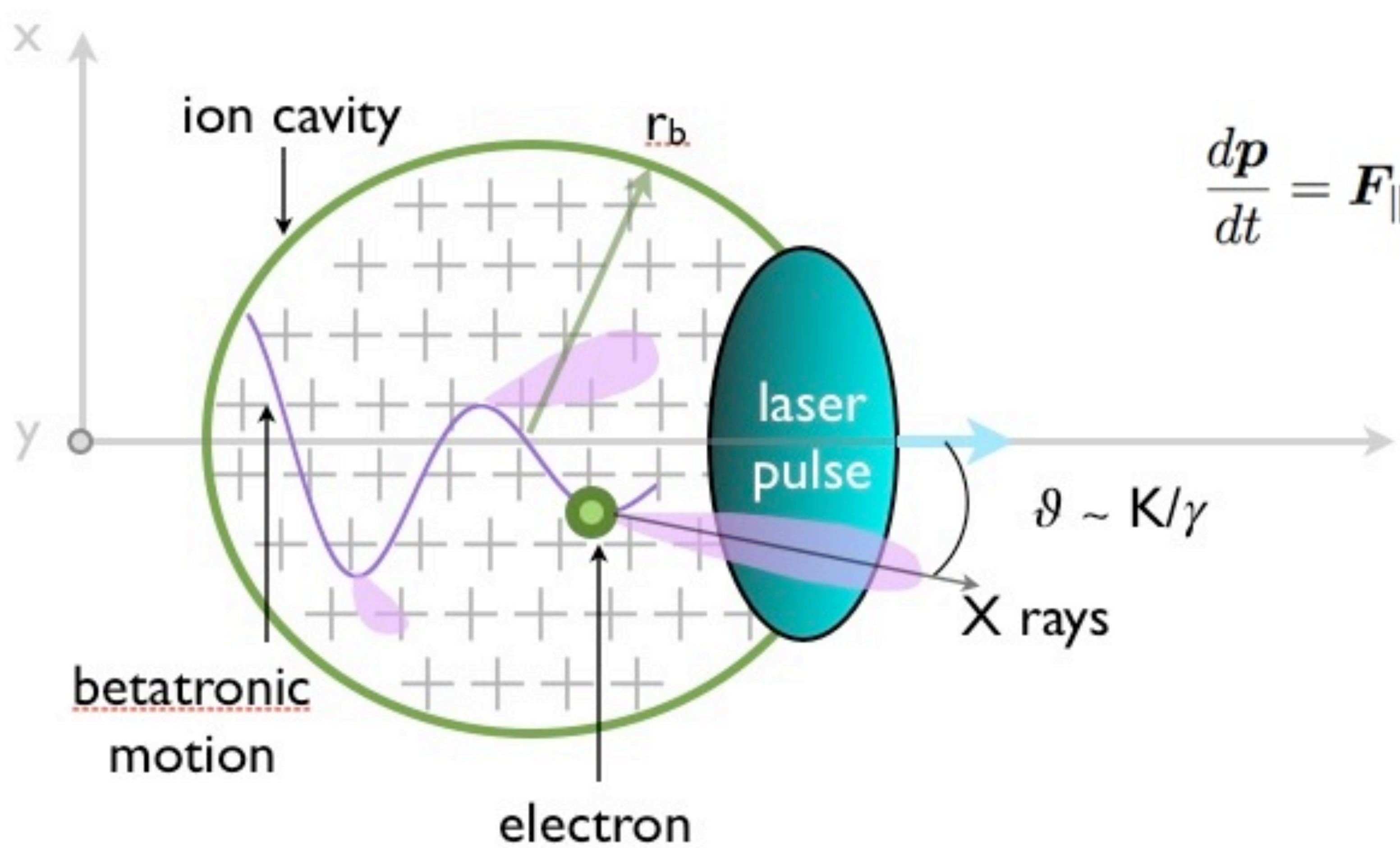
Electron and X ray correlation : results

X ray signal evolution (per pC) at 0.4 nm, $S_{0.4nm}$, and ratio $R=S_{0.4nm}/S_{0.9nm}$, as a function of the e-beam energy



Electron and X ray correlation : model





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

From the experimental data : $\mathbf{F}_{\parallel} \simeq 100\ \mathrm{GeV.m}^{-1}$

Transverse force scales as : $\mathbf{F}_{\perp} = -\alpha\frac{m\omega_p^2}{2}r\vec{e}_r$

Maxwell-Boltzmann transverse distribution : $f(x, p_x, y, p_y) = f_0 \exp(-\frac{\mathcal{H}_{\perp}}{k_B T_{\perp}})$

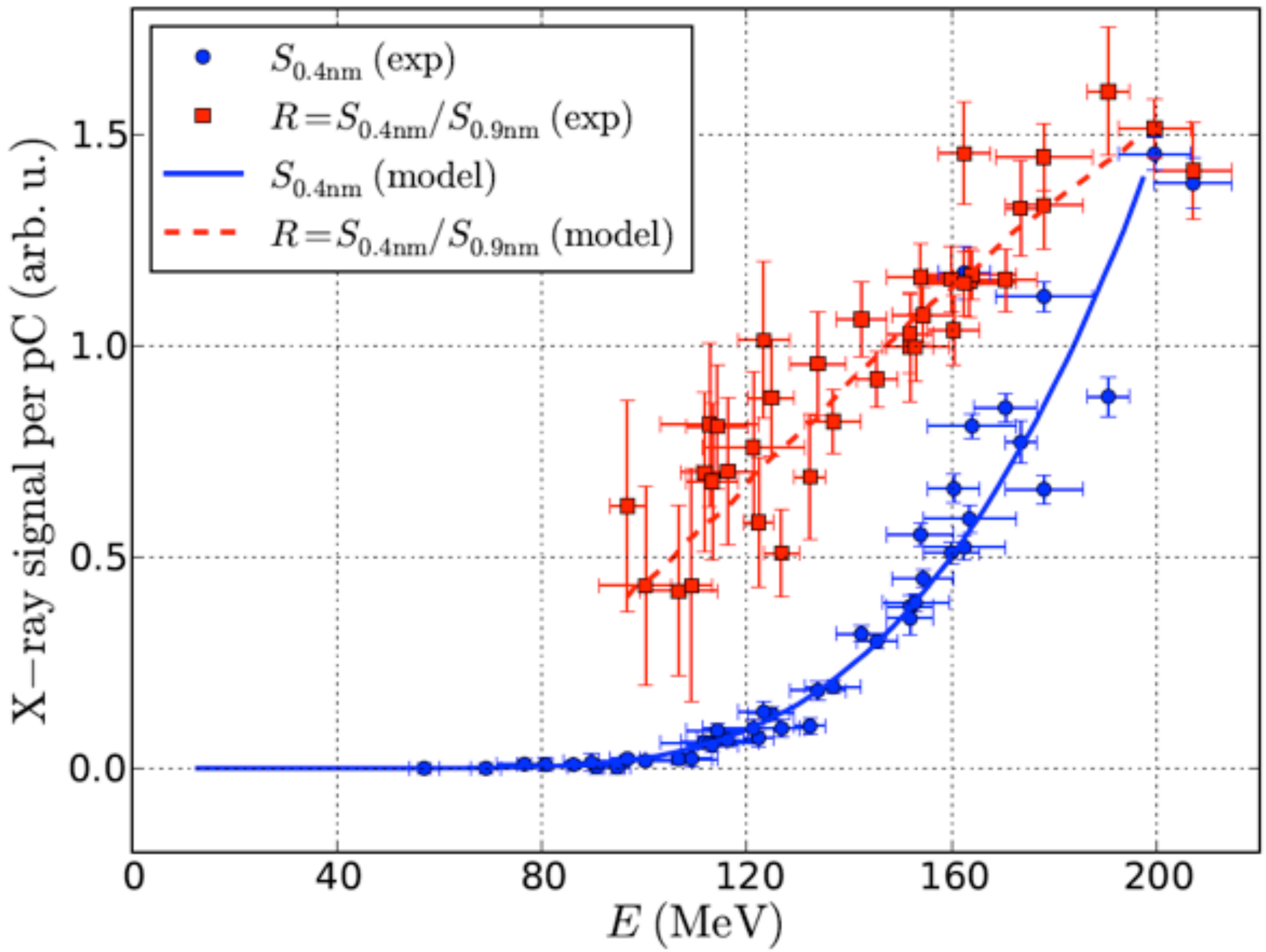
with $\mathcal{H}_{\perp} = \frac{p^2}{2\gamma m} + \frac{1}{4}\alpha m\omega_p^2 r^2$

Electron and X ray correlation : comparison

The best agreement is obtained for :

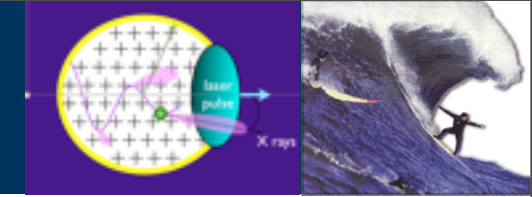
$$\alpha = 1 \text{ and } \sigma = \sqrt{2k_B T_\perp / (\alpha m \omega_p^2)} = 0.23\ \mu\text{m at } E = 200\ \text{MeV}$$

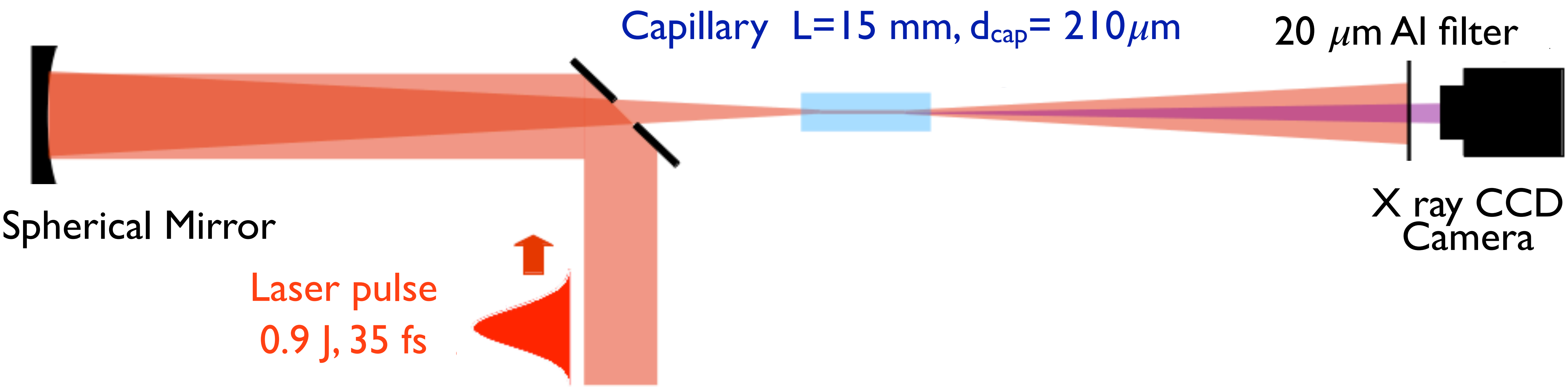
$$(\text{ or } \alpha\sigma = 0.23\ \mu\text{m})$$



S. Corde *et al.*, Phys. Rev. Lett. **107**, 225003 (2011)

Diagnostic of laser-plasma interaction : set-up

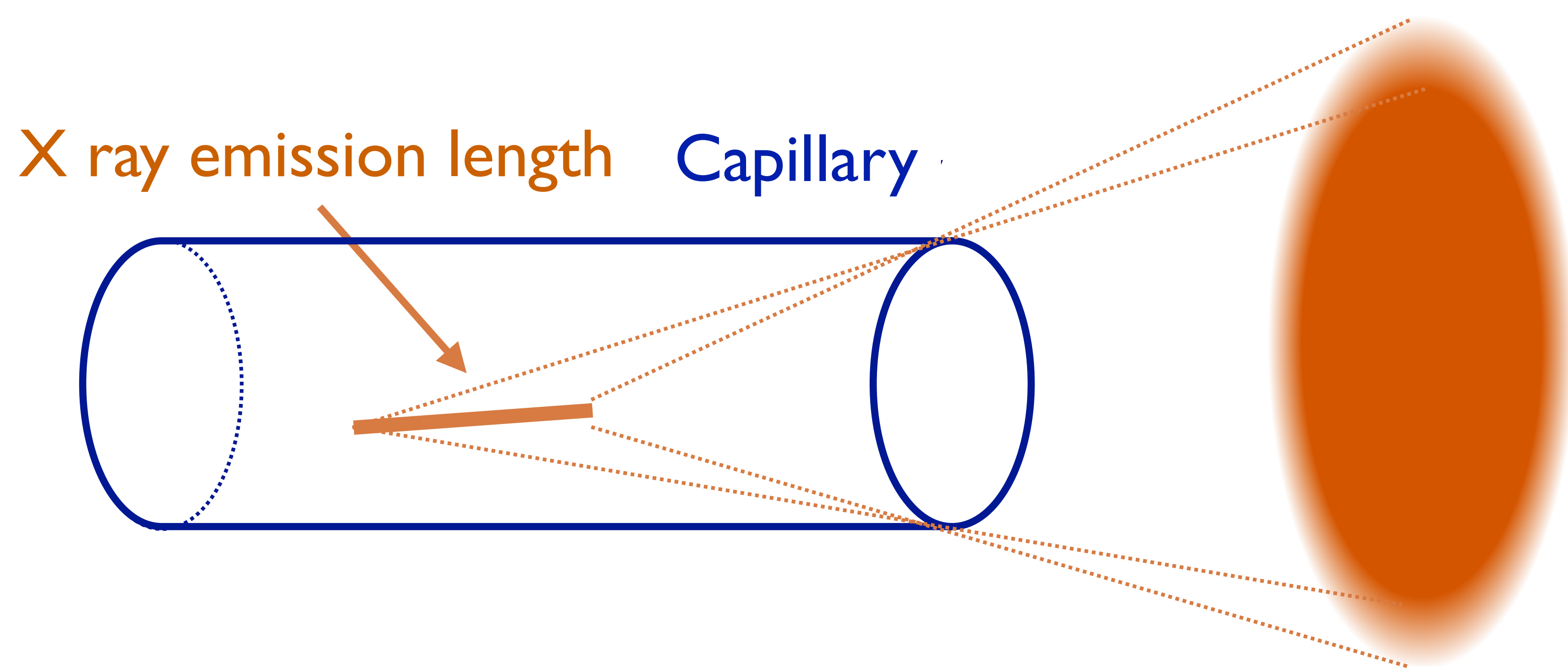




The X ray betatron beam diameter at the capillary output is wider than the capillary diameter

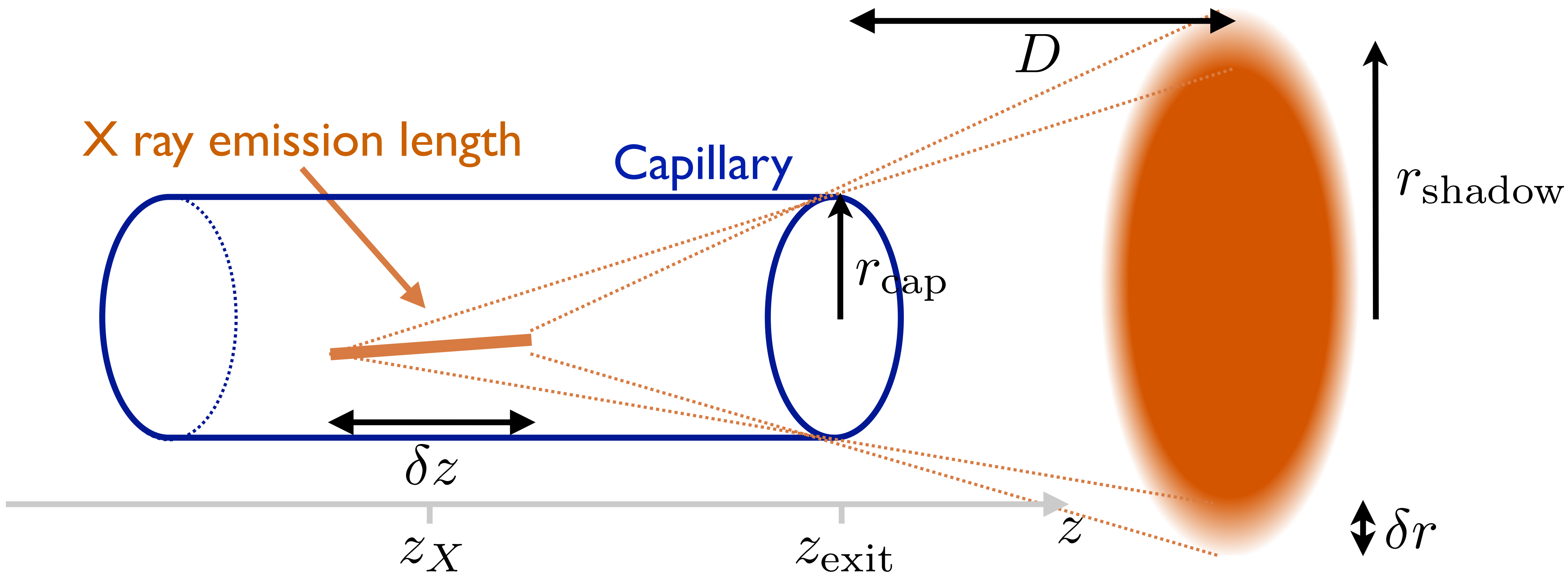
↓

the shadow of the capillary is then observed



S. Corde *et al.*, Phys. Rev. Lett. **107**, 215004 (2011)

Diagnostic of laser-plasma interaction : principle



$$\text{for } r_{\rm cap} \ll r_{\rm shadow}, \quad z_X \simeq z_{\rm exit} - r_{\rm cap} D / r_{\rm shadow}$$

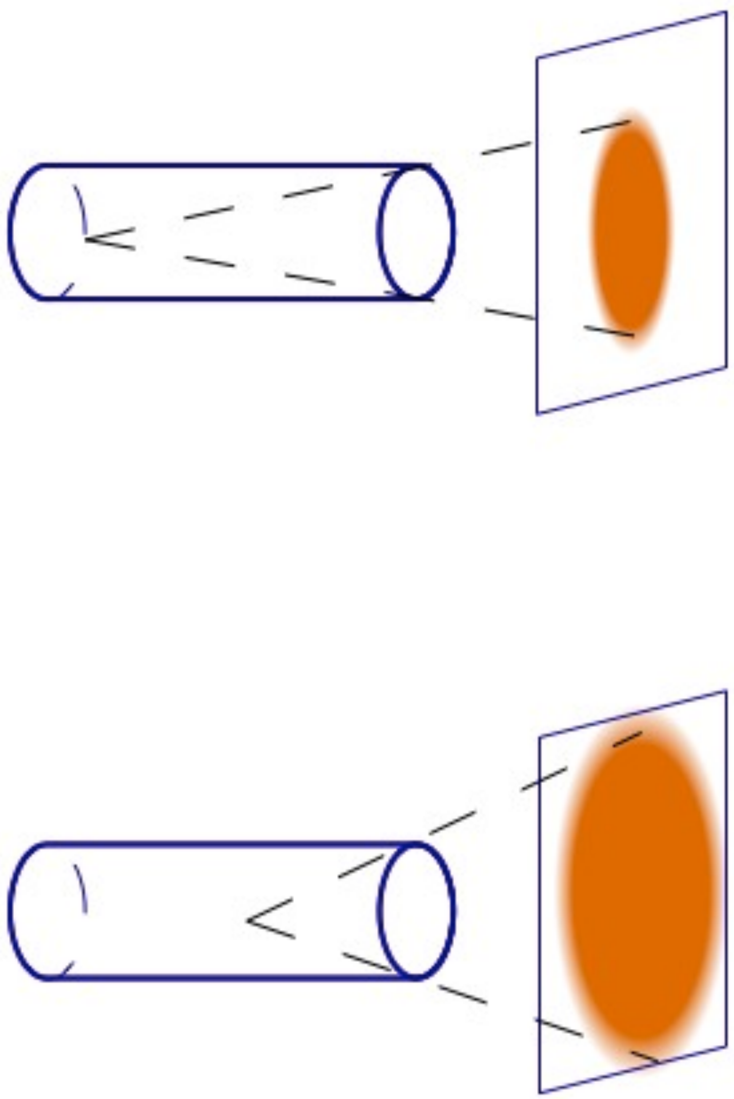
$$\text{for } \delta z / (z_{\rm exit} - z_X) \ll 1, \quad \delta z \approx \delta r (z_{\rm exit} - z_X)^2 / r_{\rm cap} D$$

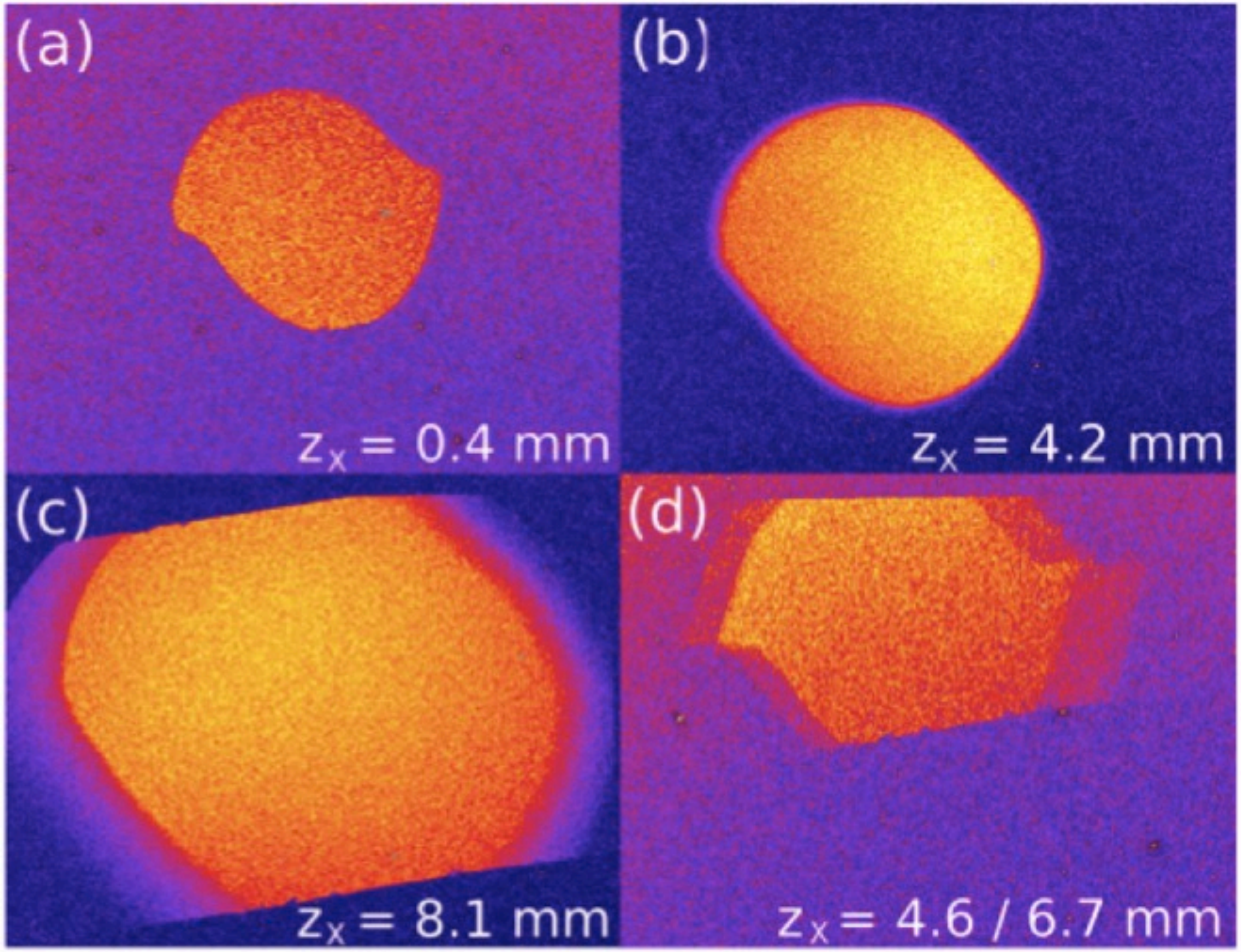
$$S(r) = \int_{z(r)}^{z_{\rm exit}} \frac{dI(z')}{dz'} dz' \longrightarrow \frac{dI(z)}{dz} = -\frac{\partial S[r(z)]}{\partial r} \frac{r(z)^2}{r_{\rm cap} D}$$

$$\text{with} \quad r(z) = r_{\rm cap} D / (z_{\rm exit} - z)$$

S. Corde *et al.*, Phys. Rev. Lett. **107**, 215004 (2011)

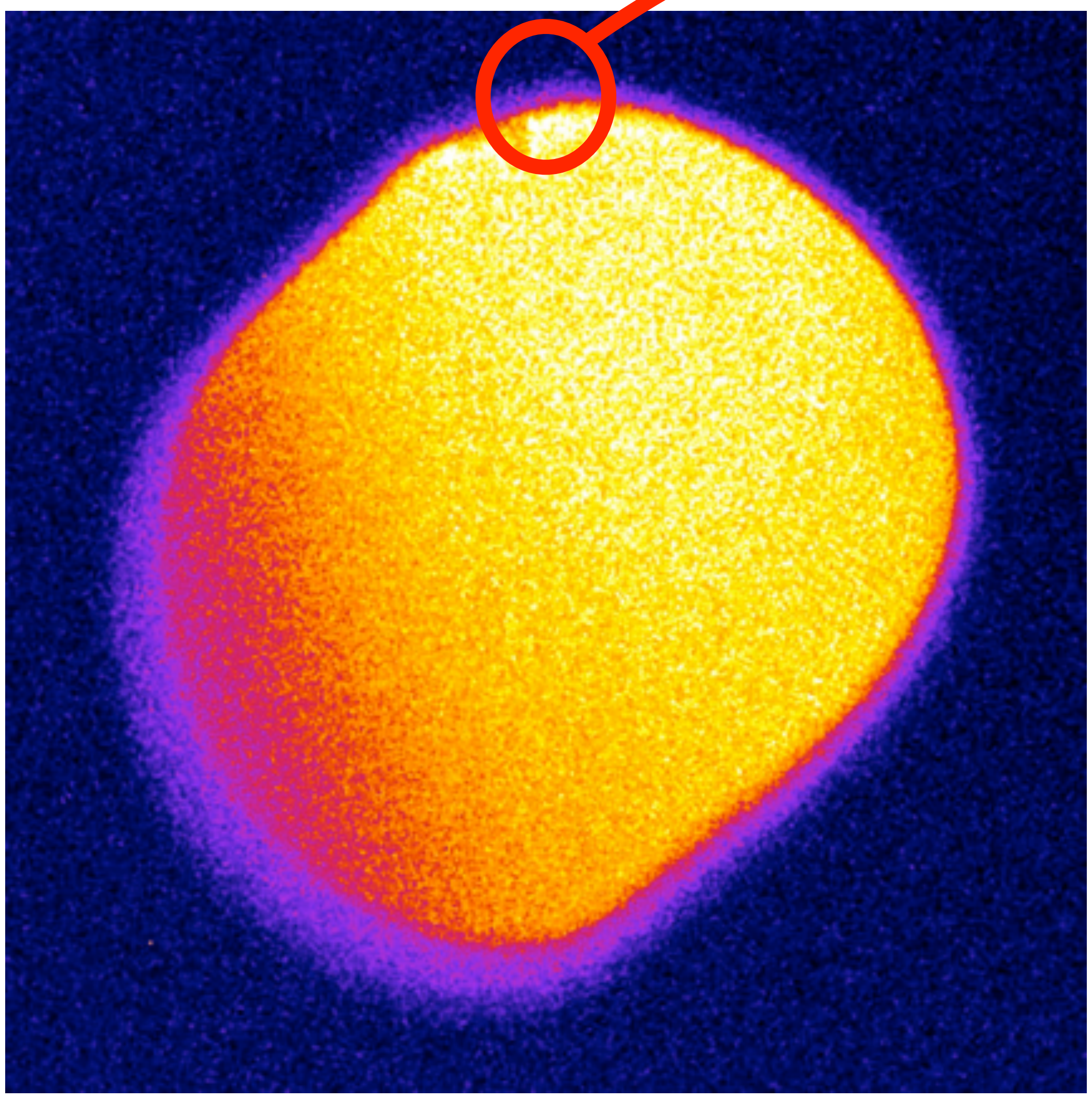
Diagnostic of laser-plasma interaction:results

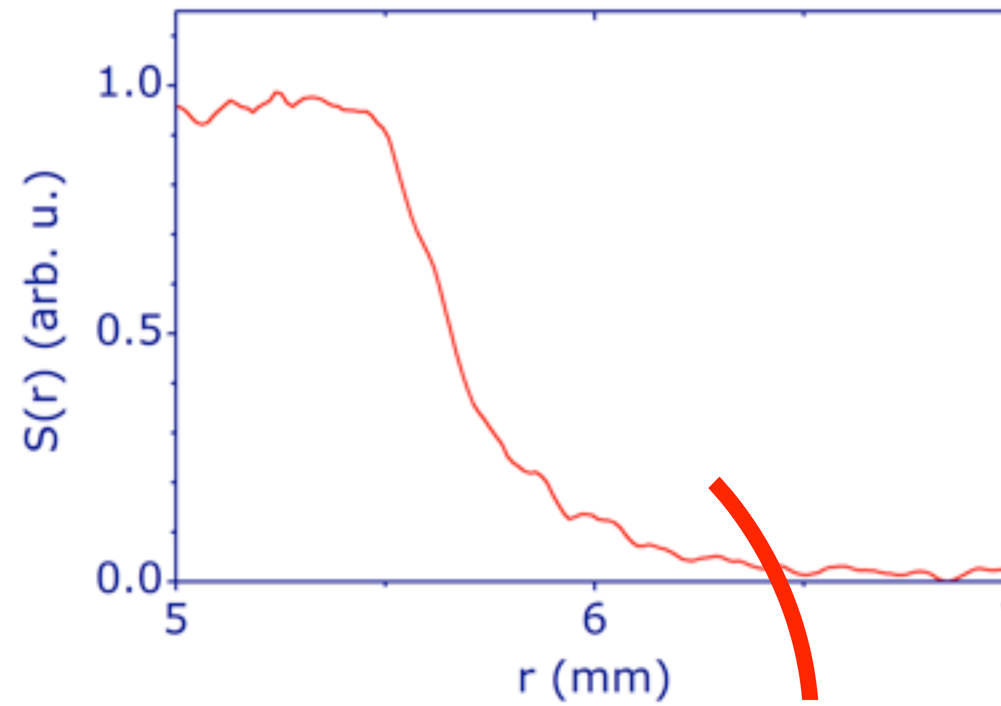




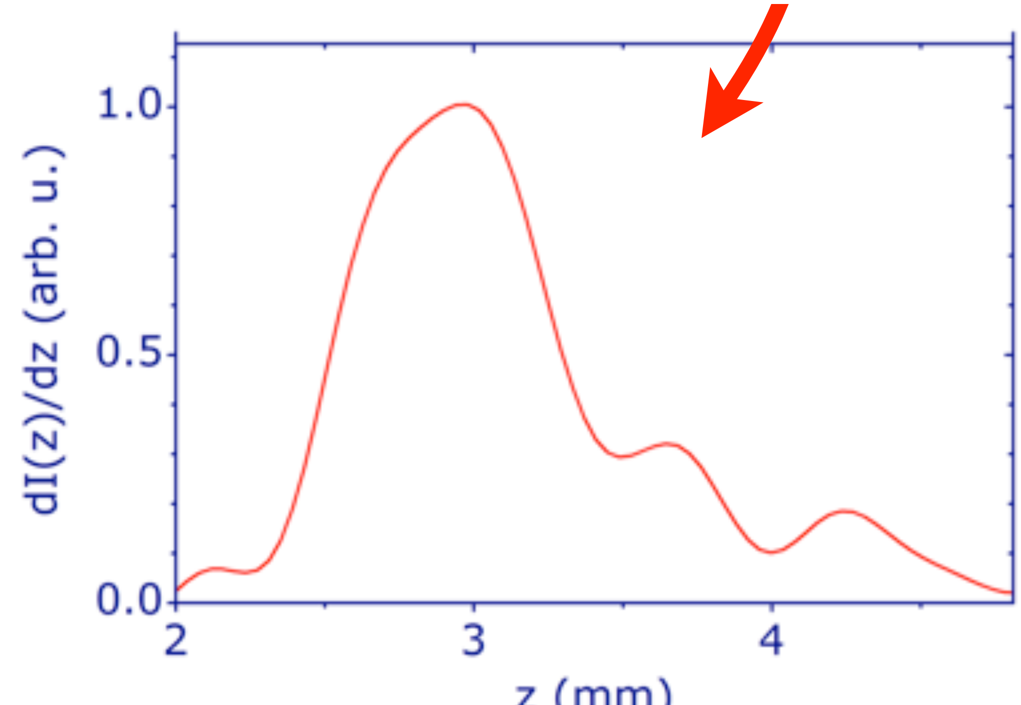
Diagnostic of laser-plasma interaction: method

Raw betatron image

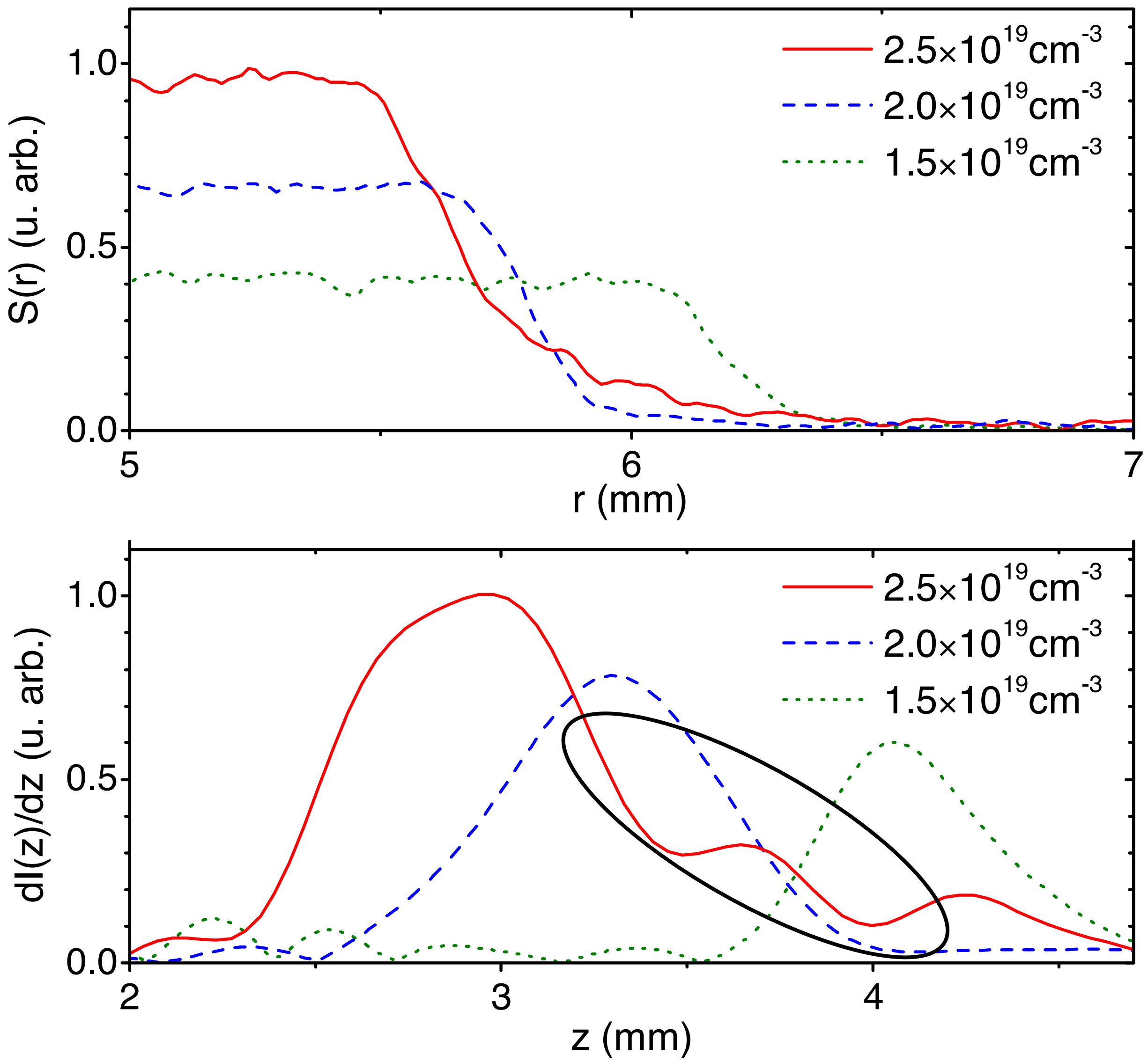


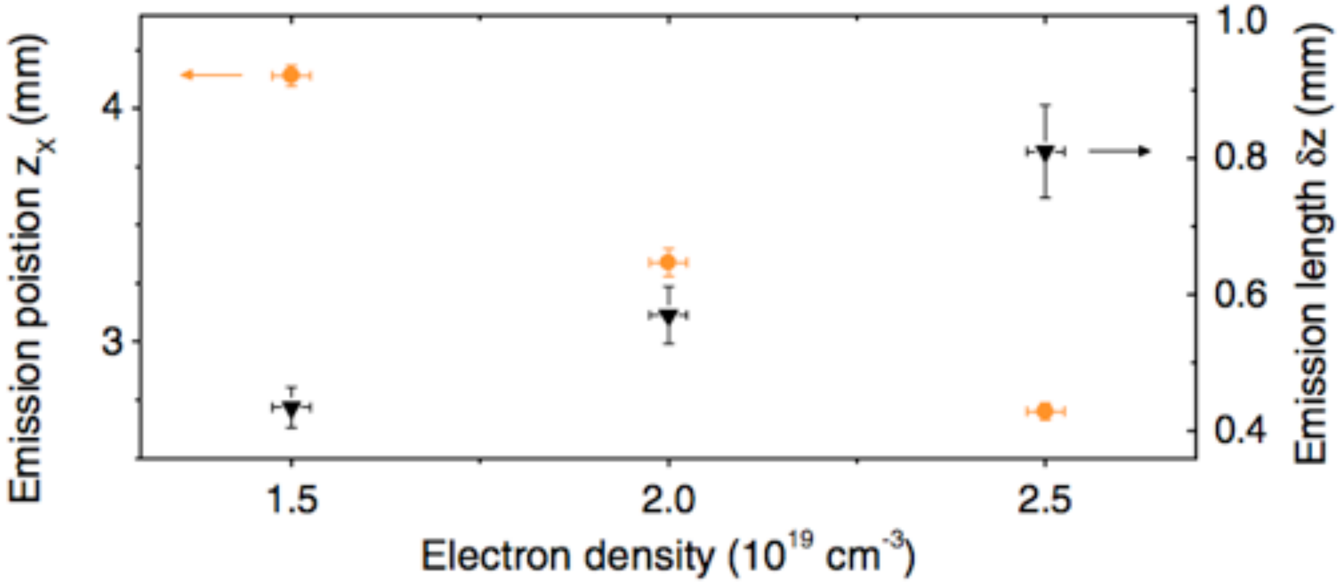


$$\frac{dI(z)}{dz} = -\frac{\partial S[r(z)]}{\partial r}\frac{r(z)^2}{r_{\mathrm{cap}}D}$$



Diagnostic of laser-plasma interaction: results





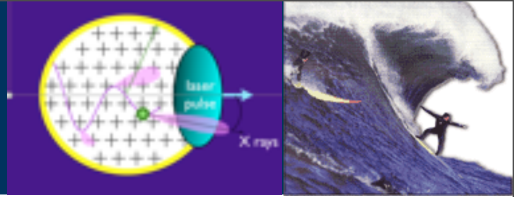
- Self focusing dynamics

⟶ Early injection at higher density

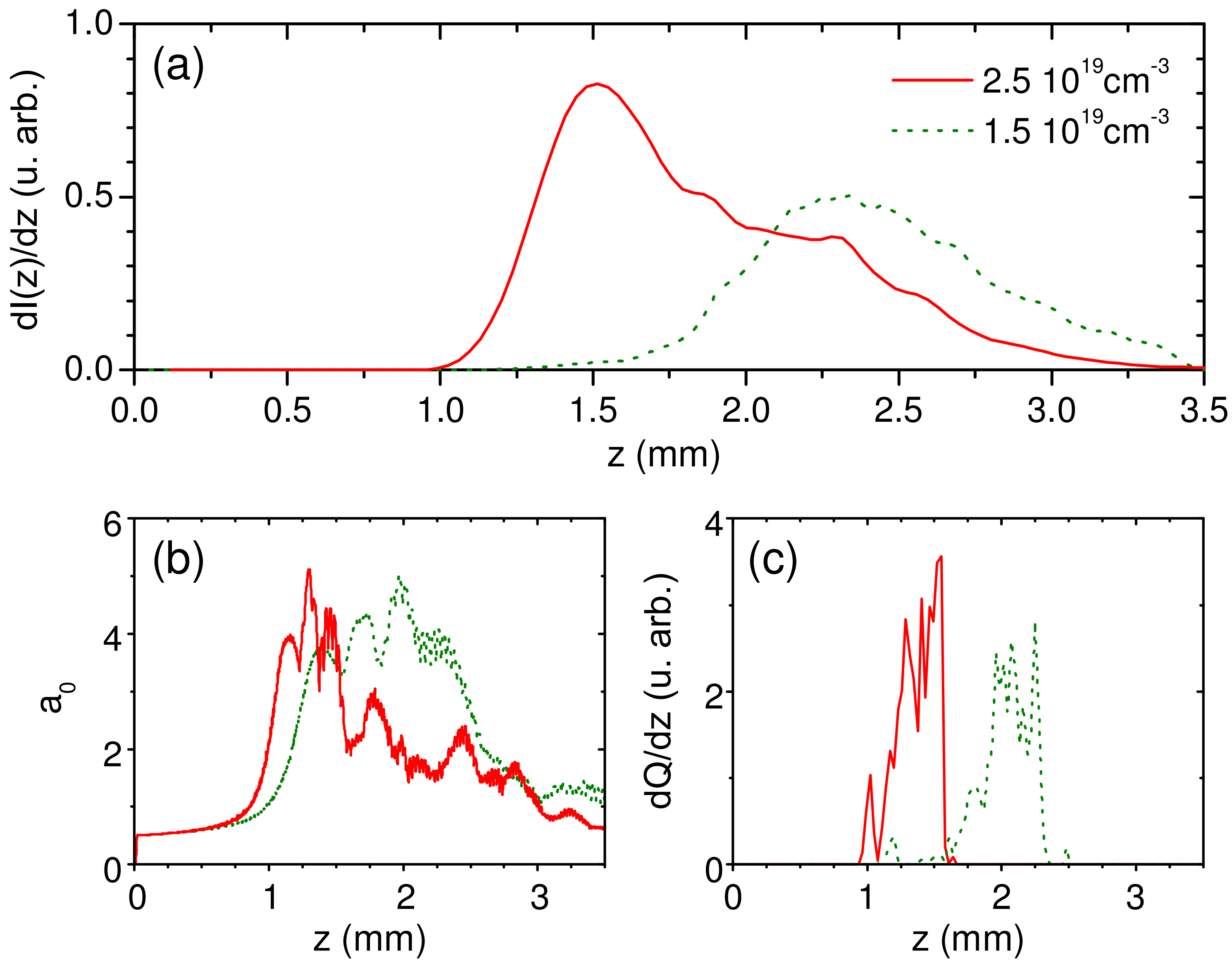
- What is the reason of the late X ray emission ?

S. Corde *et al.*, Phys. Rev. Lett. **107**, 215004 (2011)

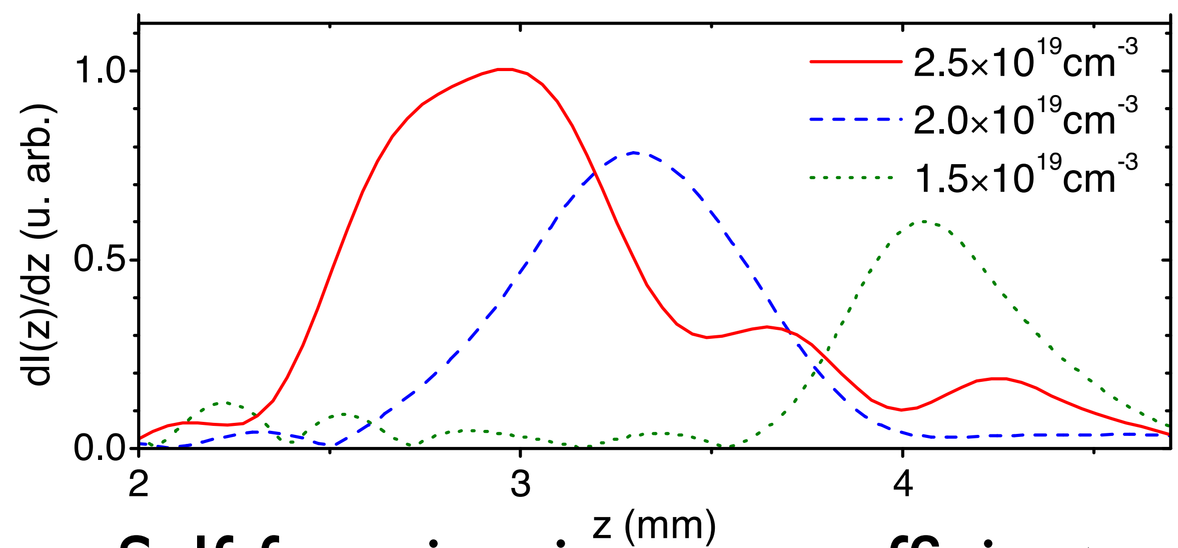
Diagnostic of laser-plasma interaction : PIC/exp



Particle-In-Cell simulations :



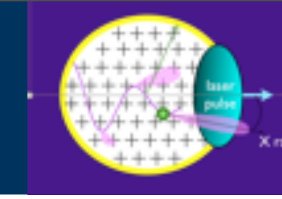
Experimental results :



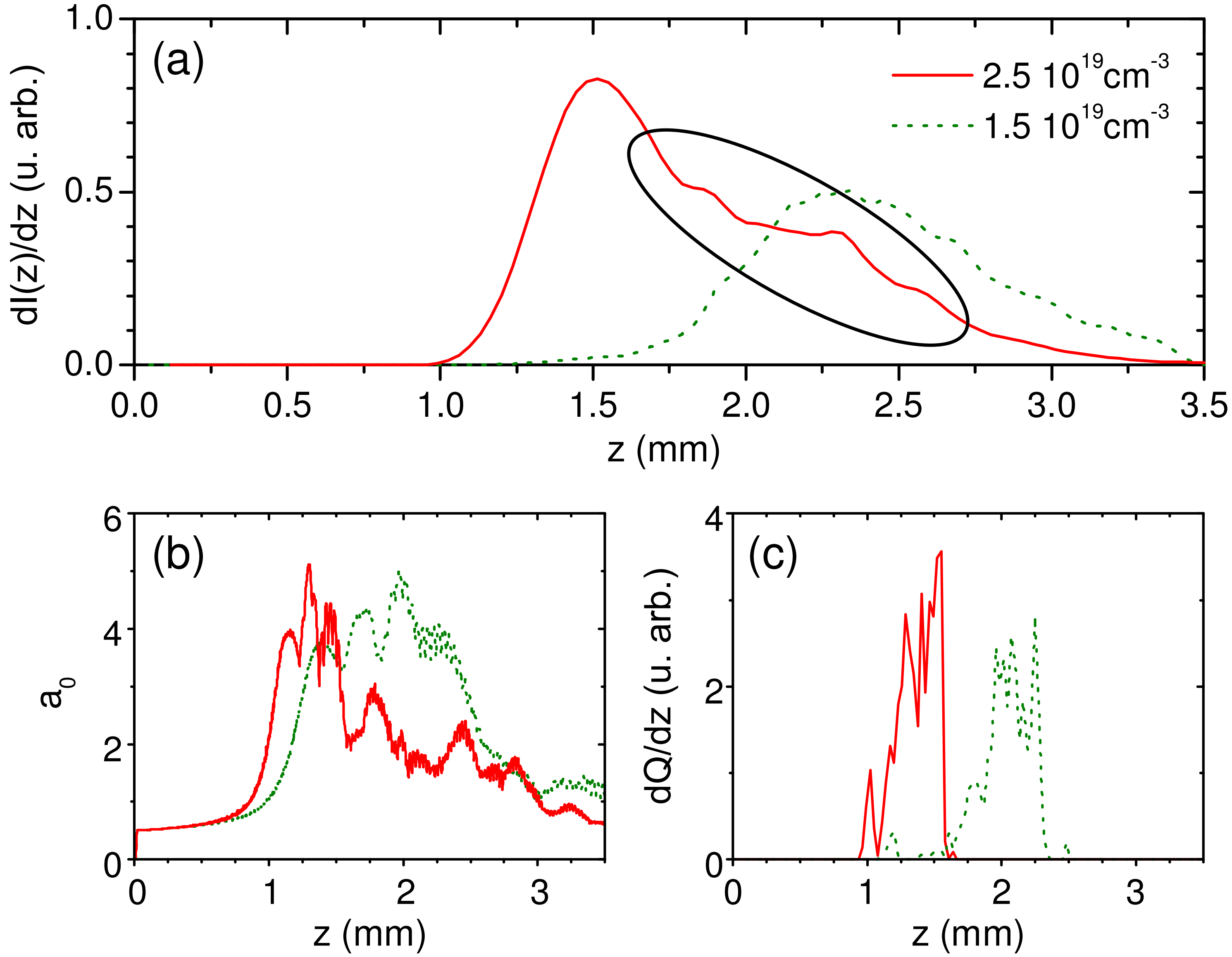
- Self-focusing is more efficient at higher densities.
- Electron injection occurs earlier at higher densities.
- The rising part of the X ray signal is related to the injection length.

S. Corde *et al.*, Phys. Rev. Lett.107, 215004 (2011)

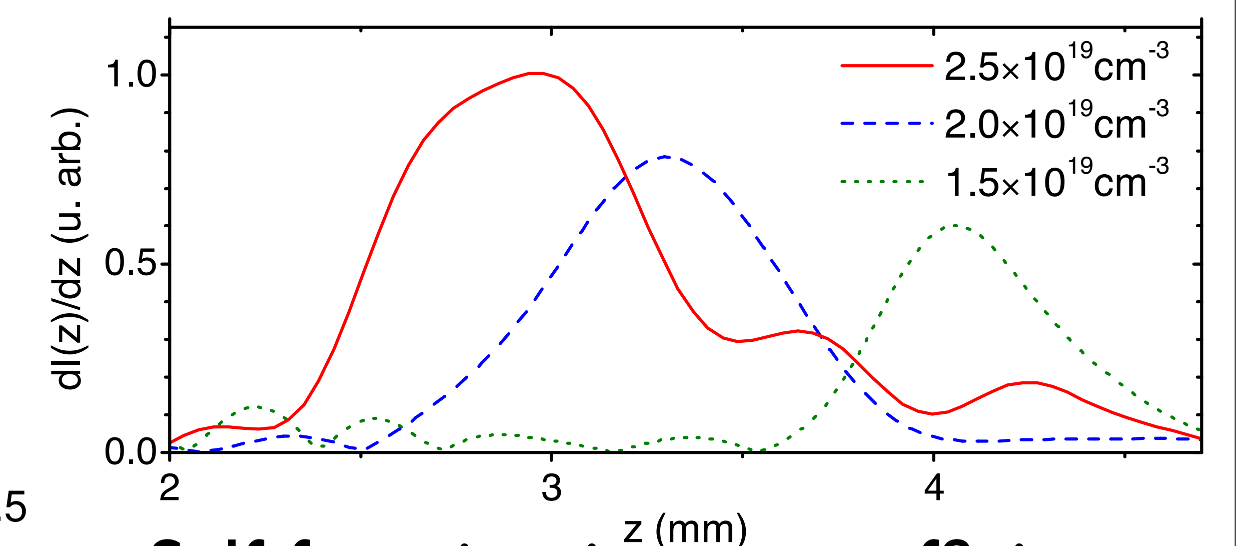
Diagnostic of laser-plasma interaction : results



Particle-In-Cell simulations :



Experimental results :

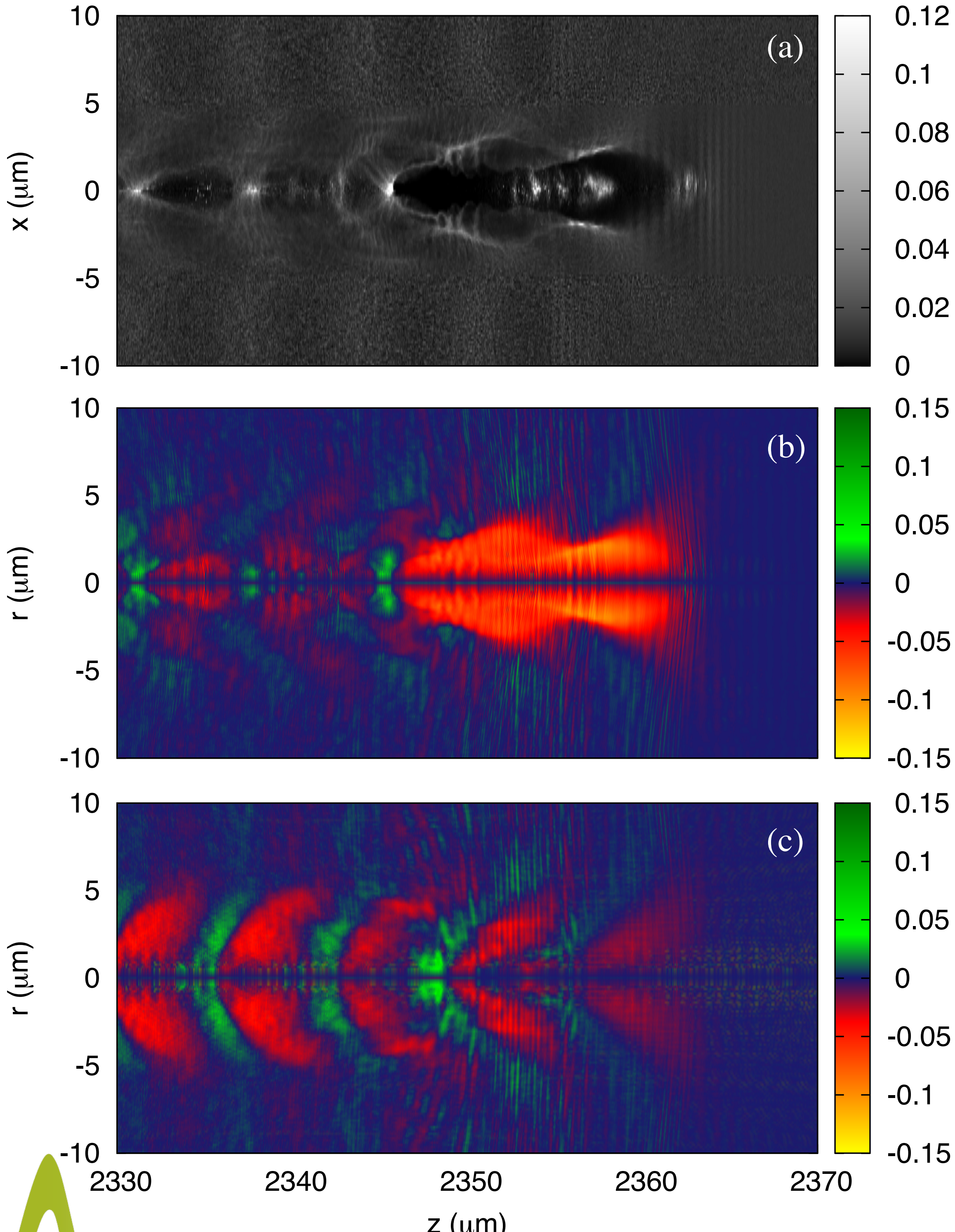


- Self-focusing is more efficient at higher densities.
- Electron injection occurs earlier at higher densities.
- The rising part of the X ray signal is related to the injection length.

- What is the reason of the late X ray emission ?

E-beam driven electron plasma wave

Simulation pour $n_e = 2.5\times10^{19}$ cm^{-3}, at z = 2.35 mm



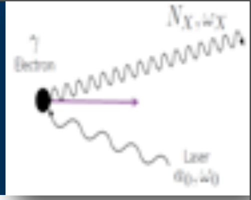
Electron density

Force transverse:

$$F_\perp \simeq -e(E_r - cB_\theta)$$

Transverse force without the e-beam effect : the laser pulse is extract from the simulation and re-injected in an homogenous plasma

Outline



- Betatron X source as a powerful diagnostic
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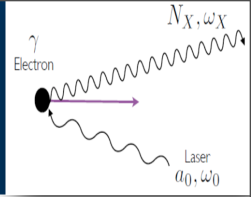
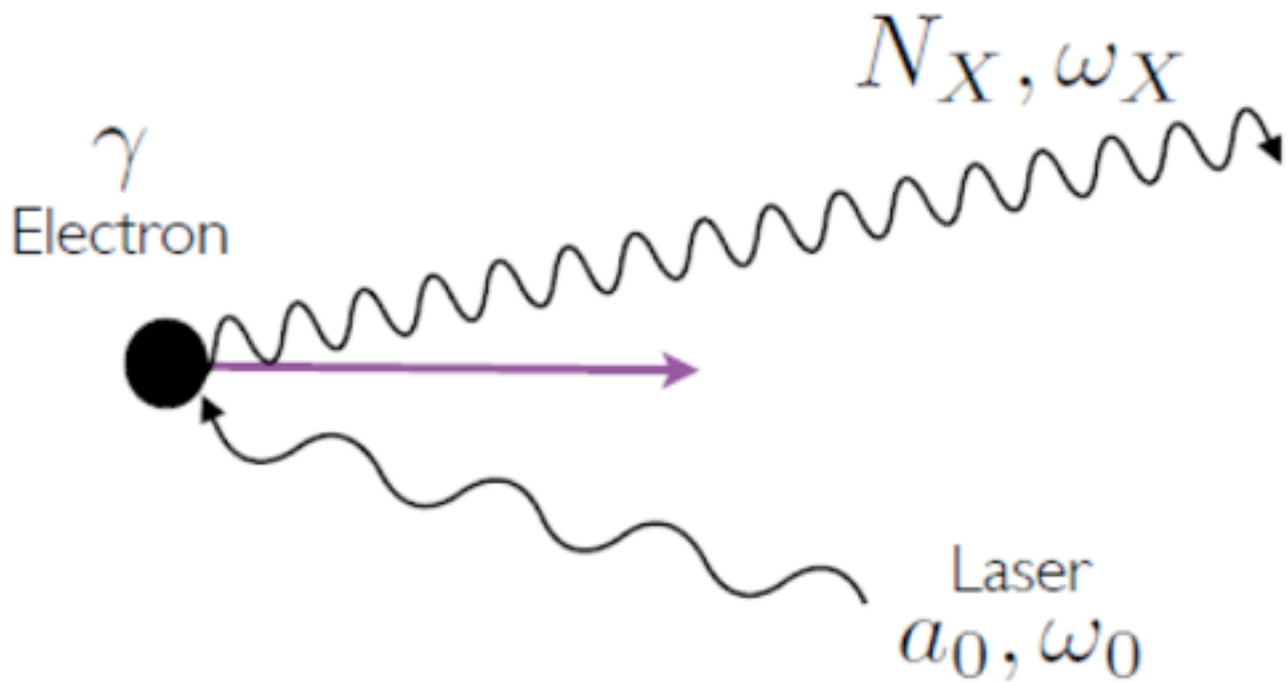
- Conclusion and perspectives

Inverse Compton Scattering





Doppler upshift : high energy photons with modest electrons energy : $\omega_x = 4\gamma^2\omega_0$

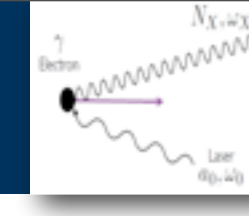
For example : 20 MeV electrons can produce 10 keV photons
200 MeV electrons can produce 1 MeV photons

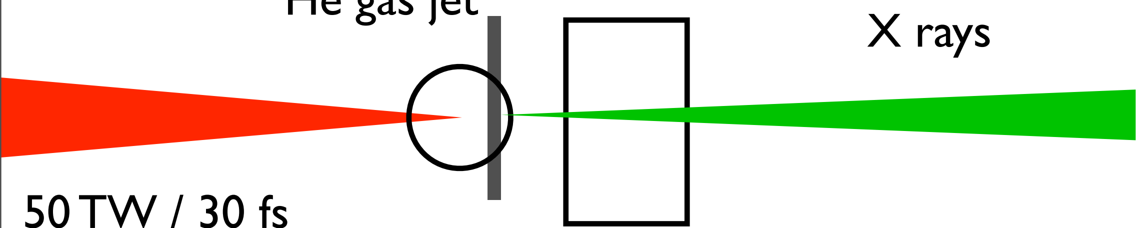
The number of photons depends on the electron charge N_e and a_0^2 : $N_x \propto a_0^2 \times N_e$

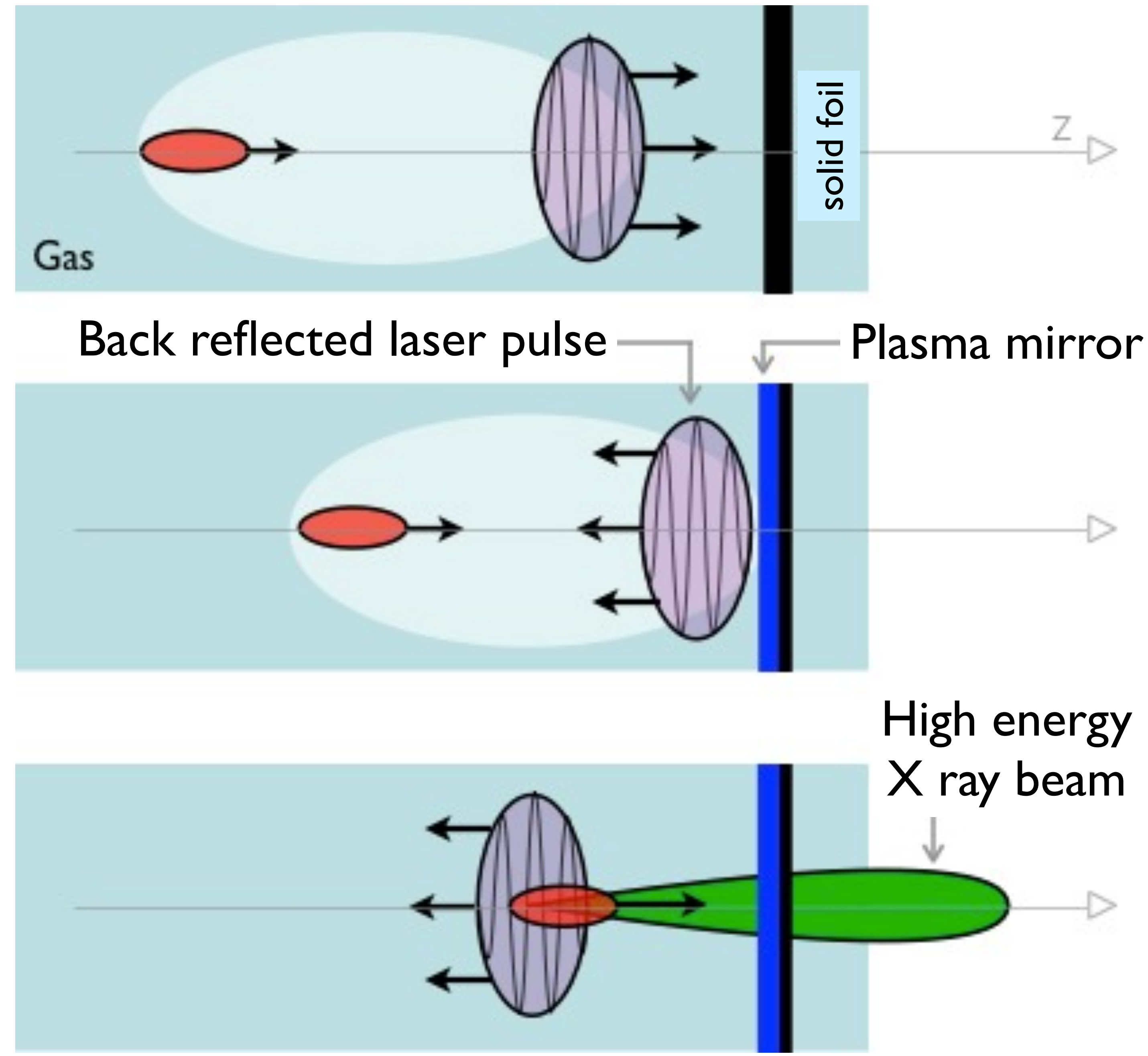
Duration (fs), source size (µm) = electron bunch length and electron beam size

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

Inverse Compton Scattering : New scheme







A single laser pulse

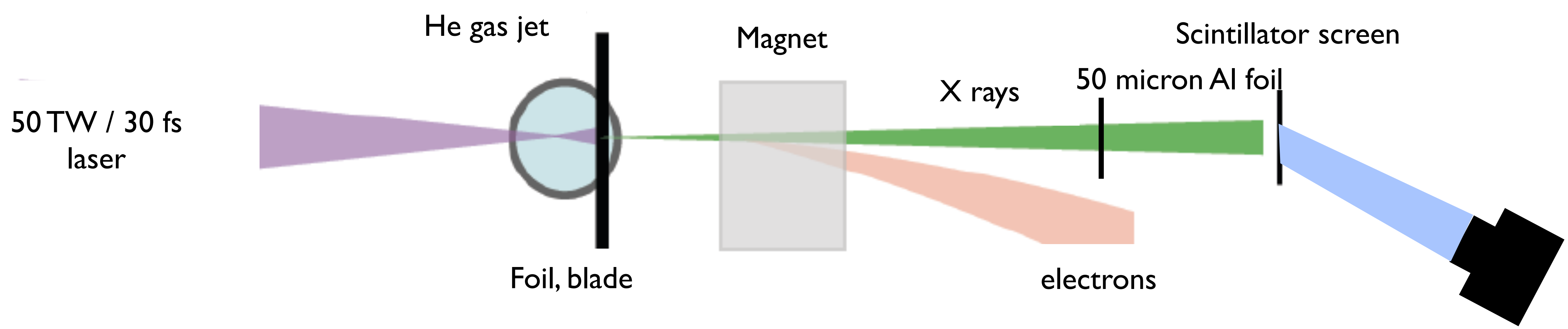
A plasma mirror reflects the laser beam

The back reflected laser collides with the accelerated electrons

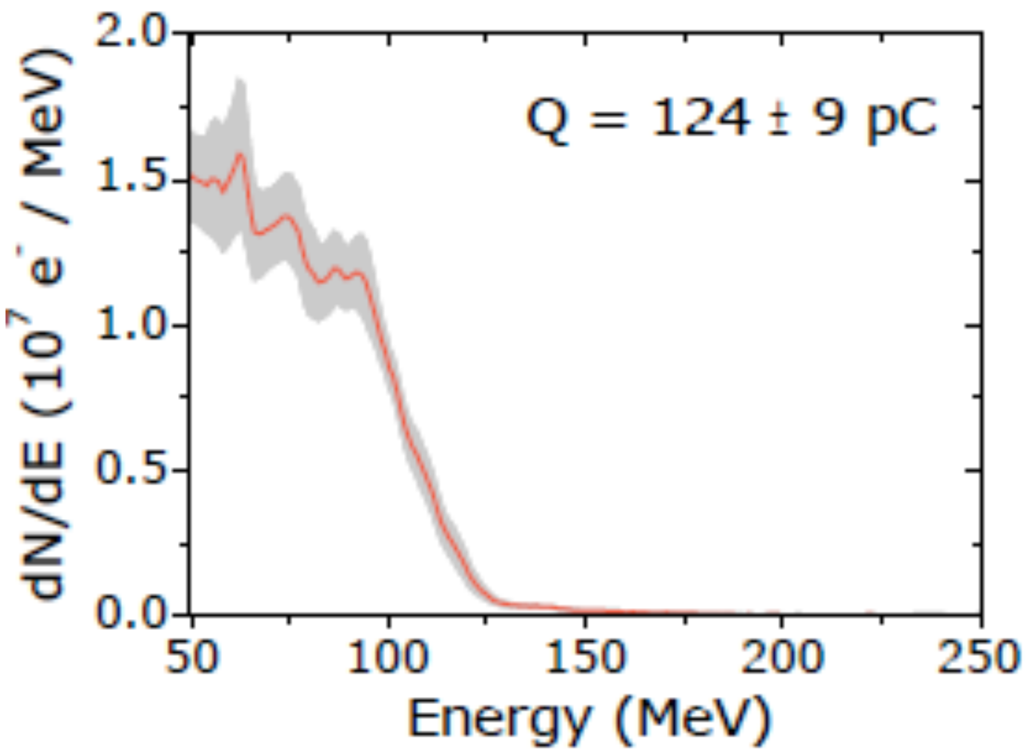
No alignement : the laser and the electron beams naturally overlap

Save the laser energy !

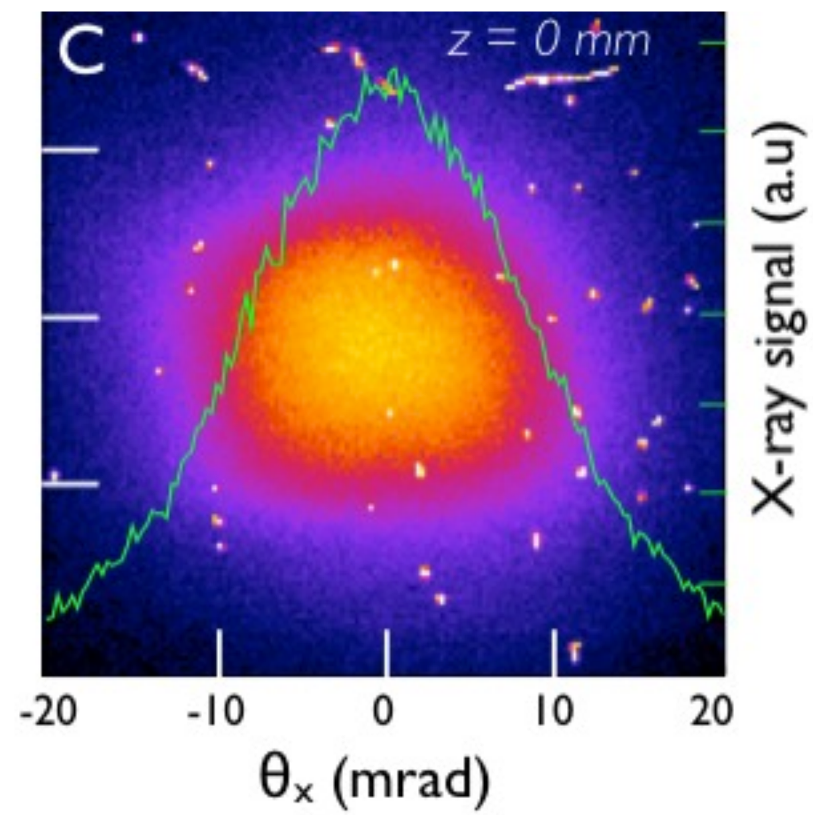
Inverse Compton Scattering : Experimental set-up



Electron spectra



X ray beam profile



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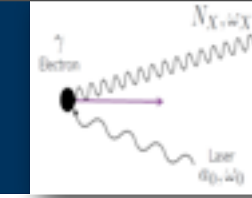
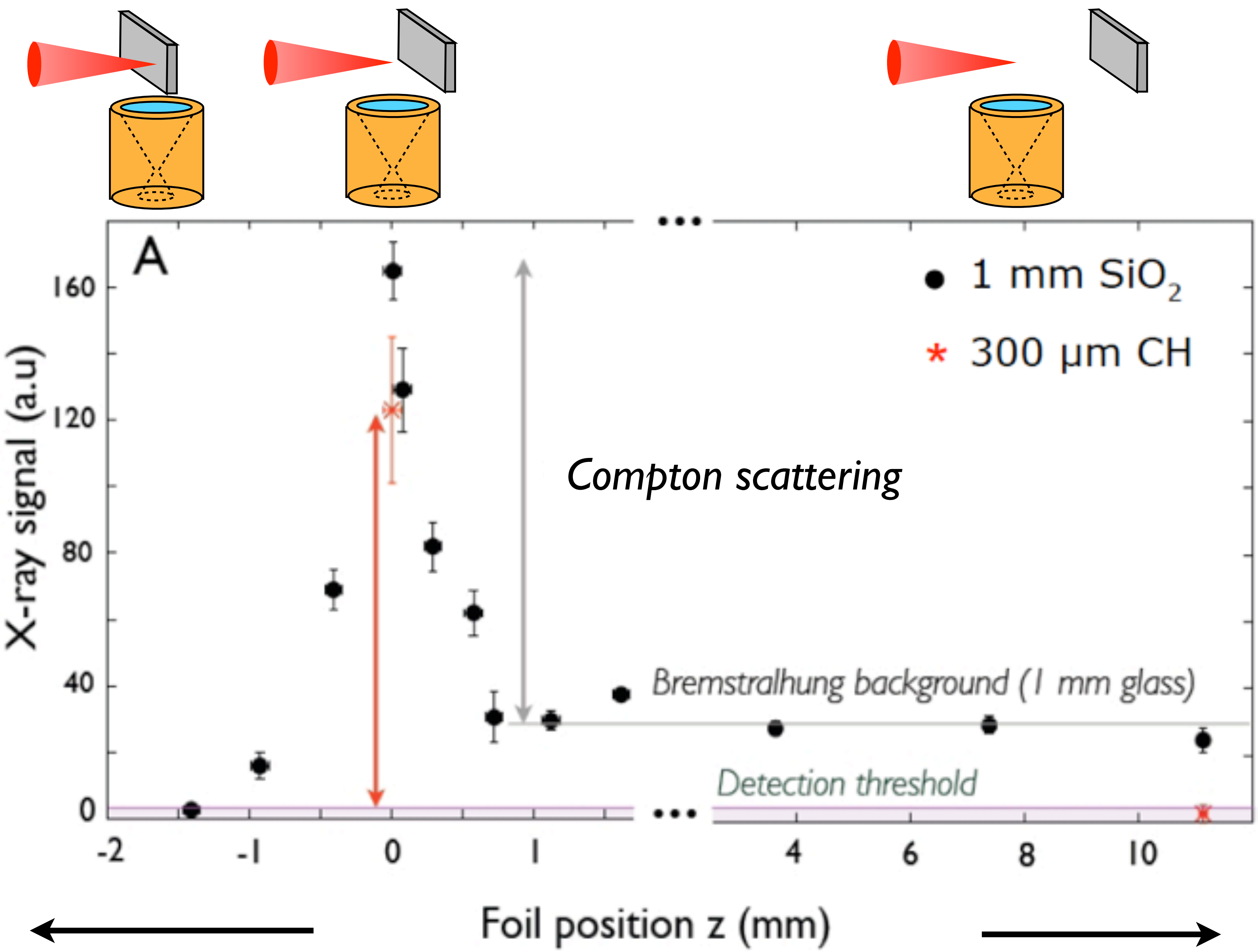
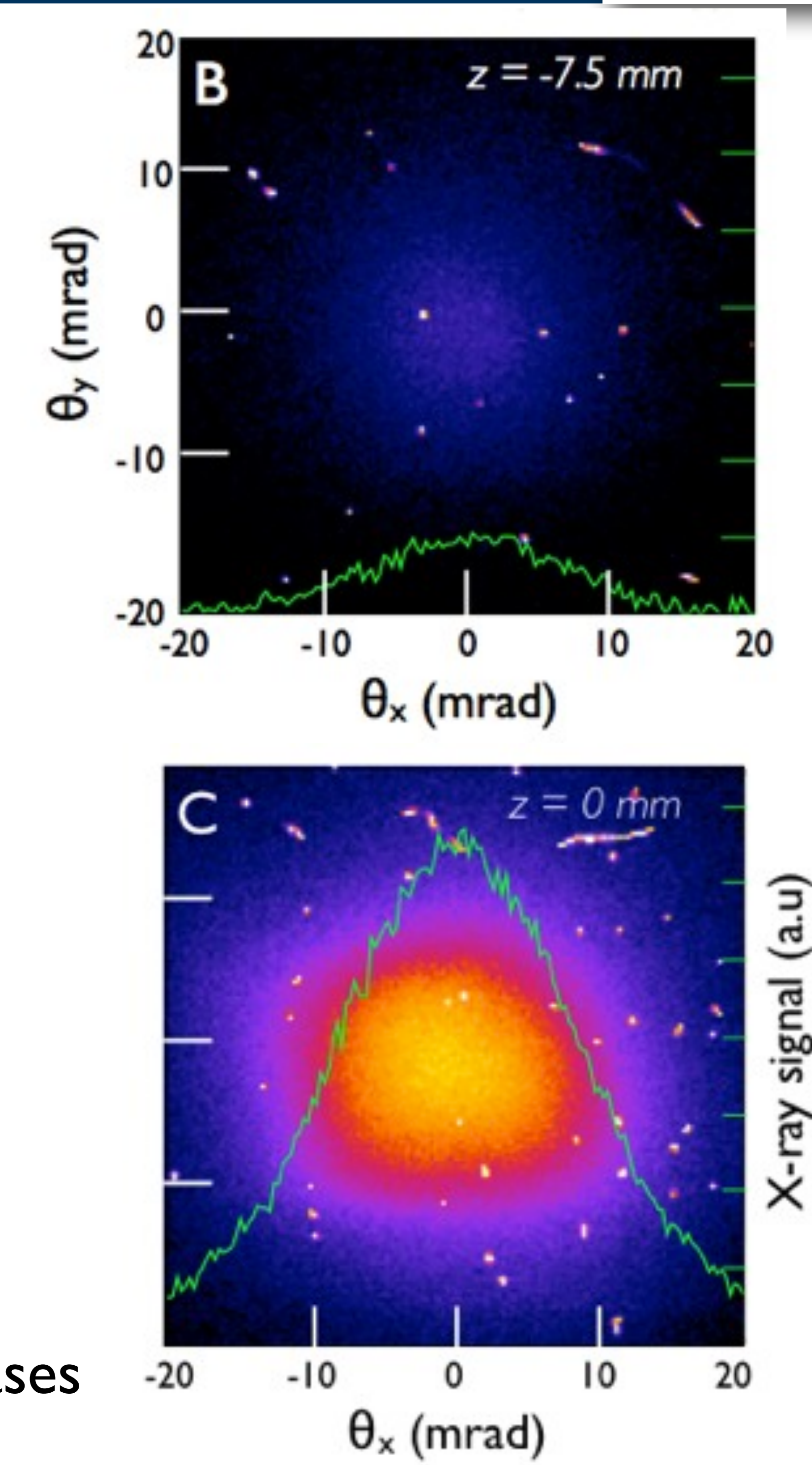
Inverse Compton Scattering : Experimental results





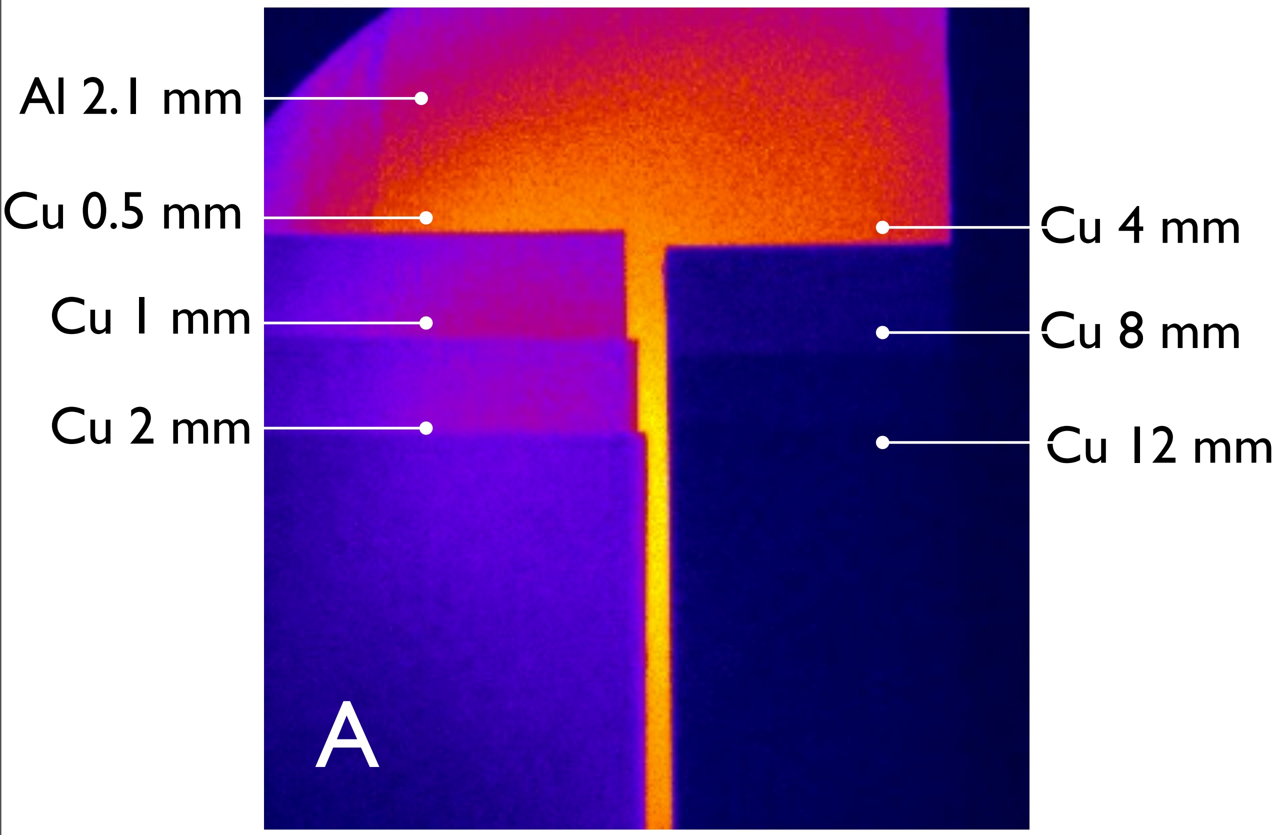


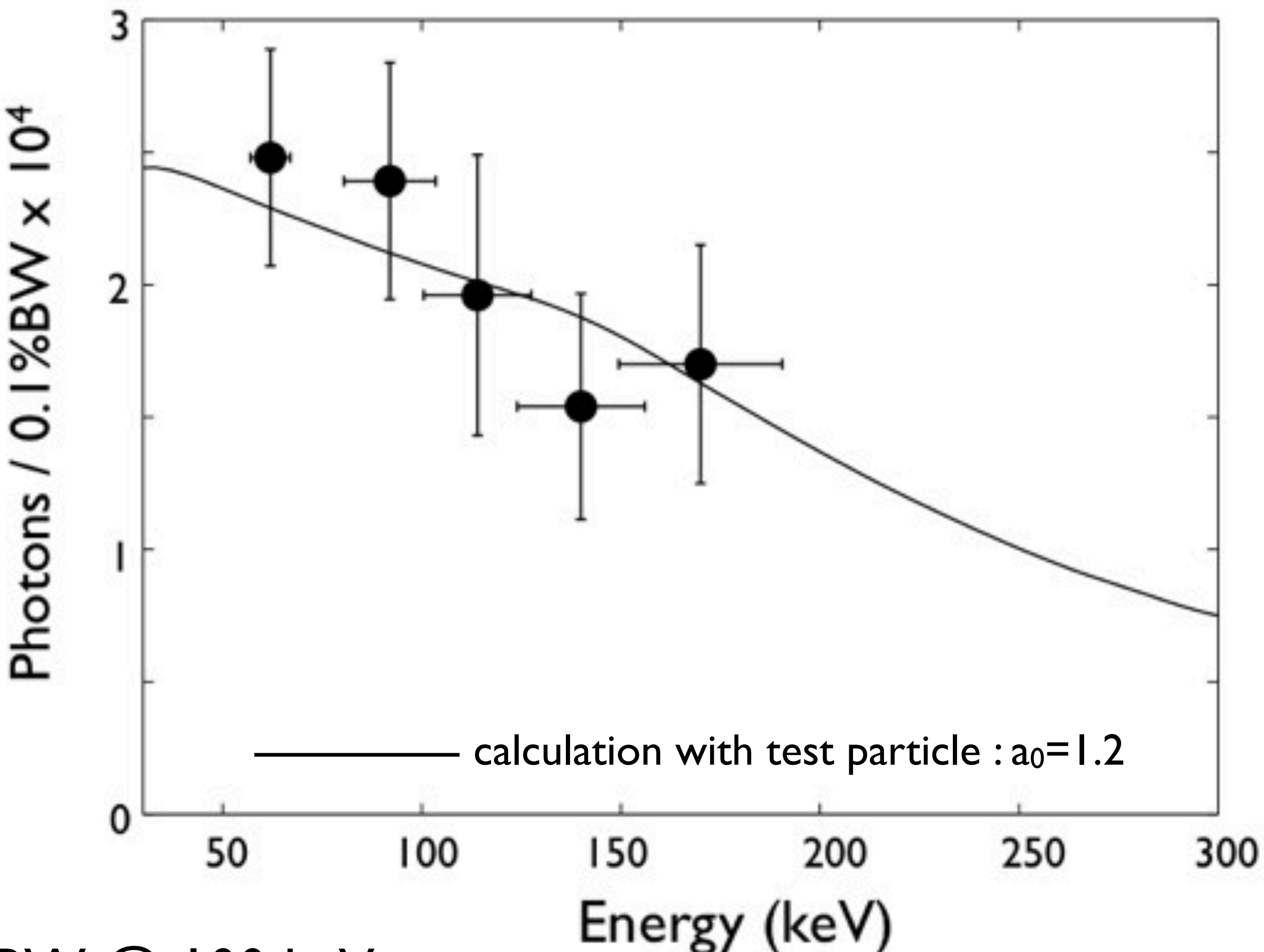
← electron energy decreases

laser intensity decreases →

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

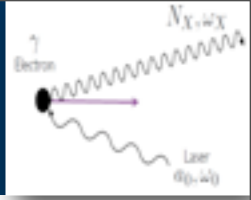
Inverse Compton Scattering : Compton Spectra





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

K. Ta Phuoc *et al.*, Nature Photonics **6** (2012)



Outline

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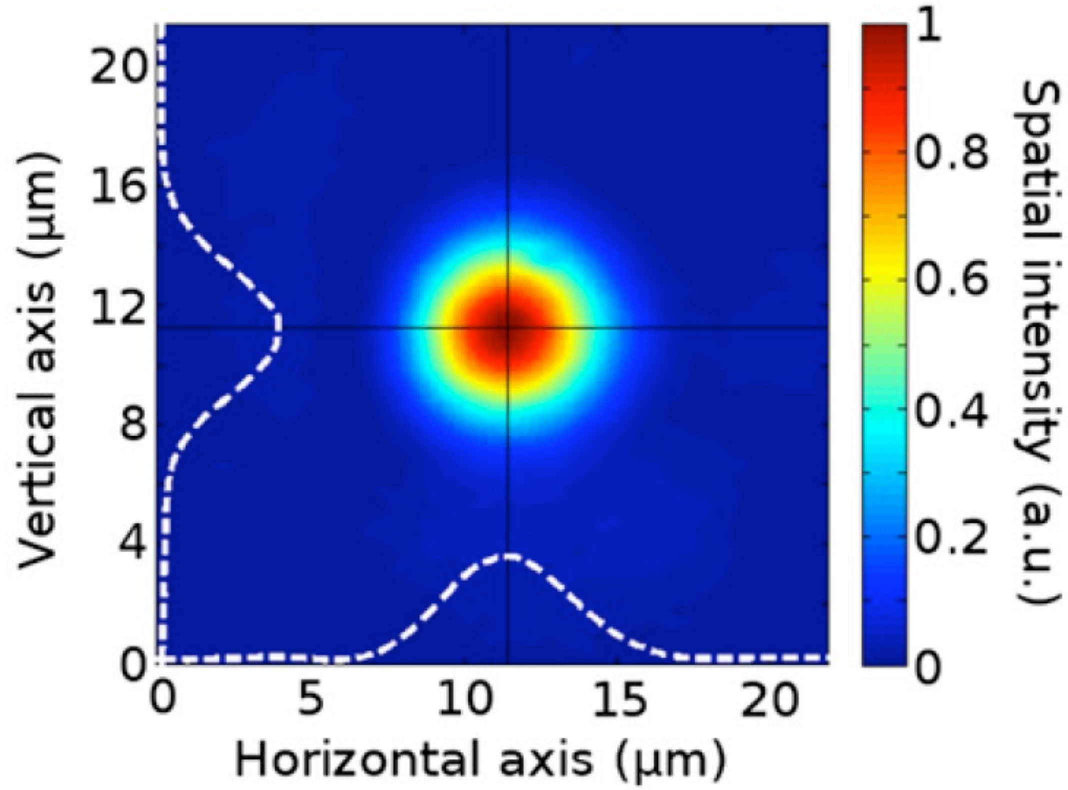
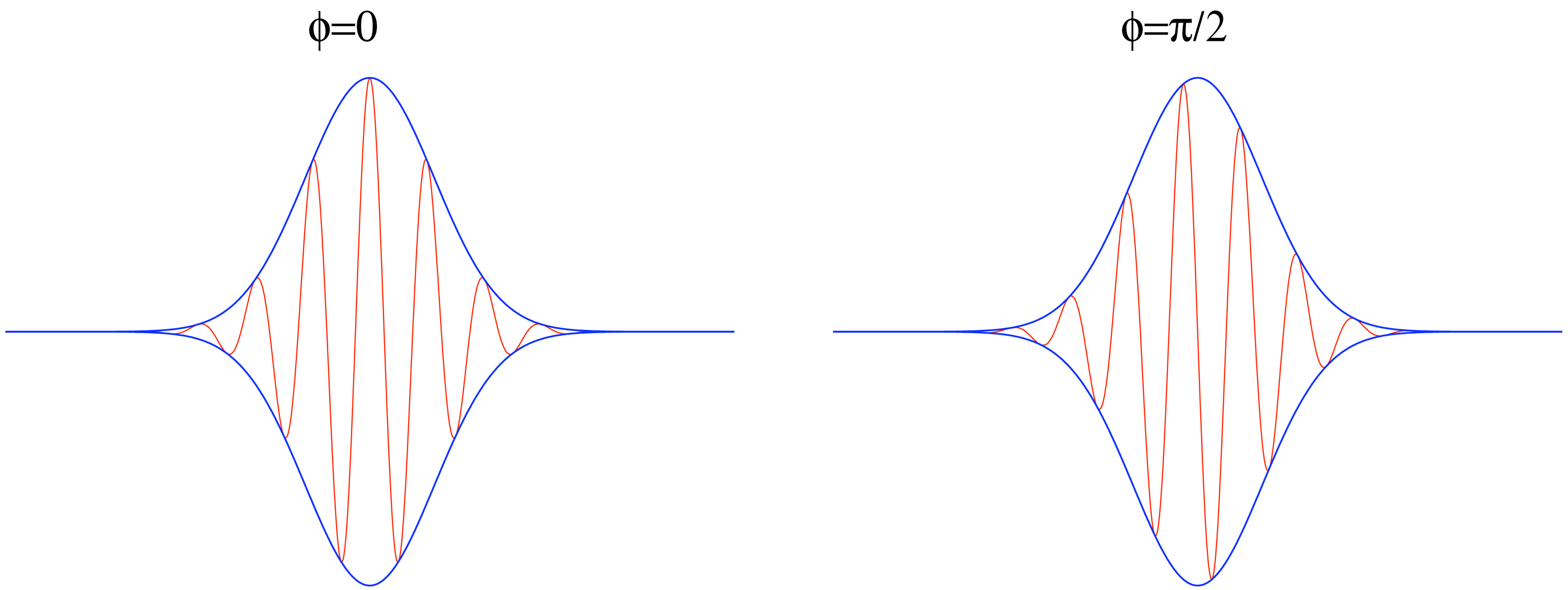
Phase stabilized laser

Duration 5 fs
kHz frequency rate
Phase-locked pulses
Very high quality and stability
1-2 mJ of laser energy



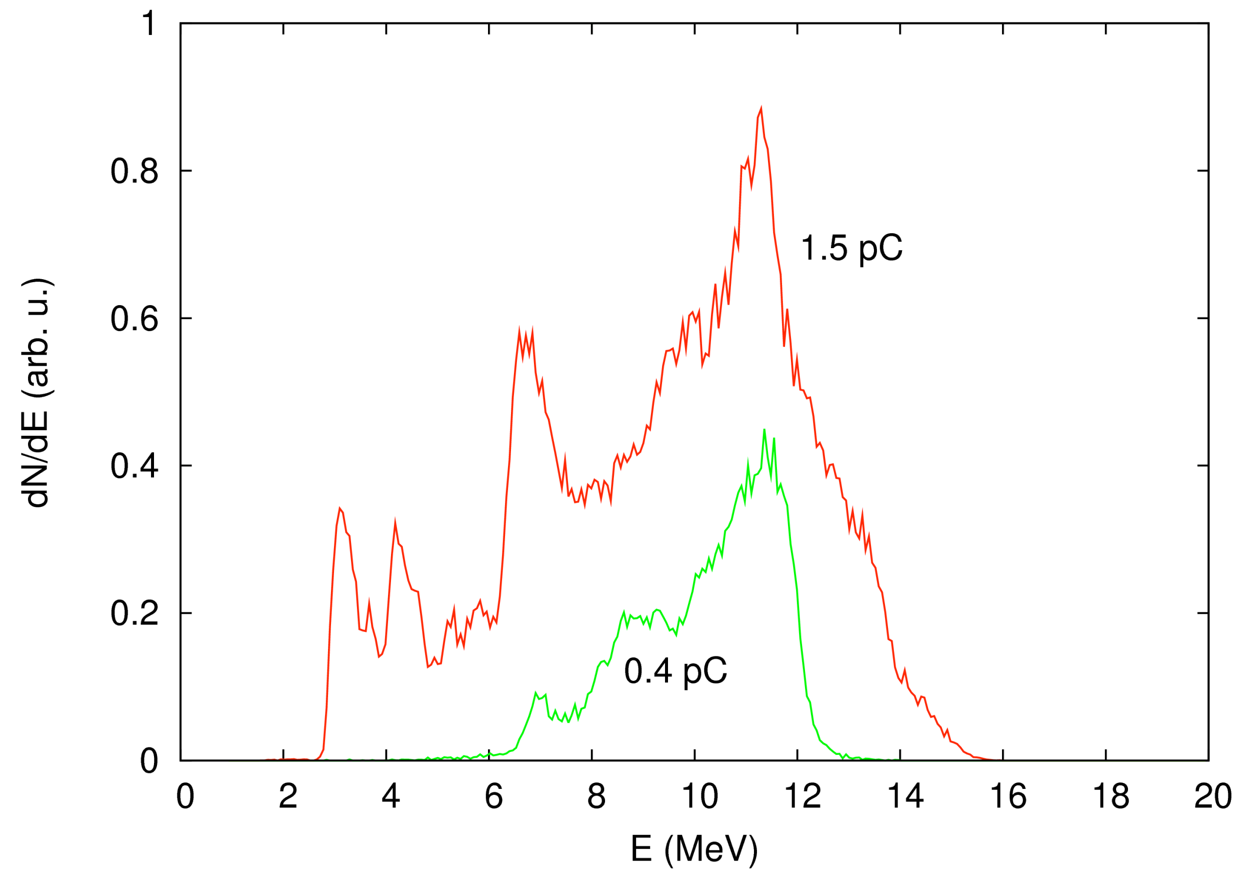
A method to fix the carrier-envelope phase is implemented



First studies : modest beam qualities

Electrons beams up to ~ 20 MeV and few pC can be produced

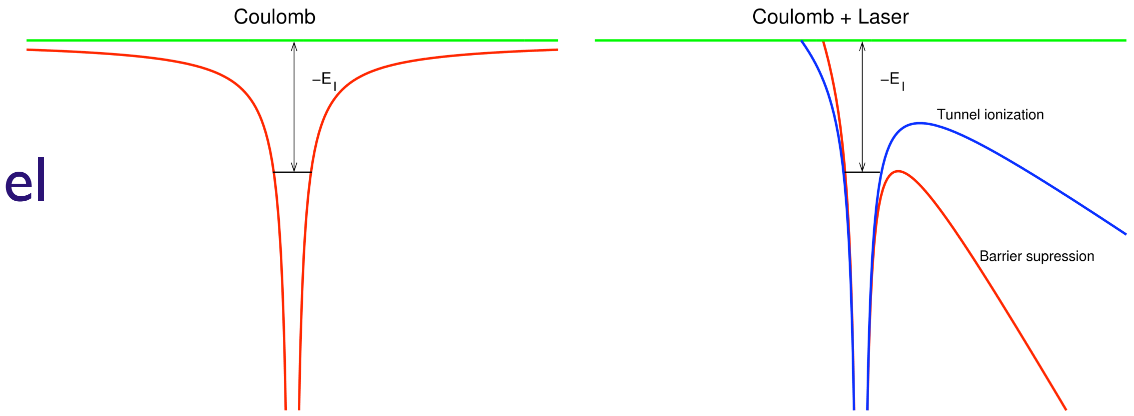
focal spot 2.5 µm FWHM, 1.6 & 1.8 mJ, He gas, 6 % n_c



⇒ We will see how to get better quality beams using tunnel ionization injection and spatial filtering

Nitrogen gas : injection is well localized

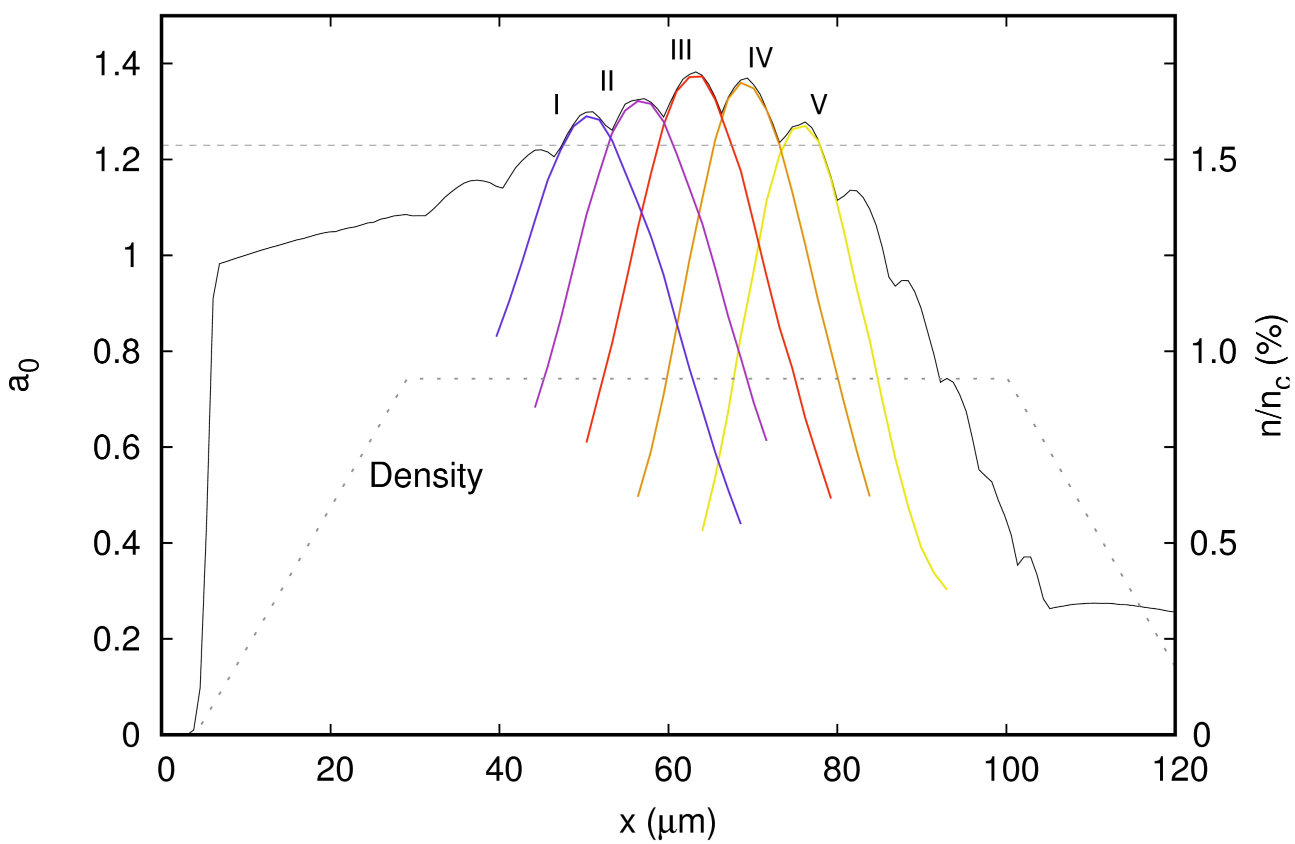
Tunnel ionization takes place close to laser field maximum, twice by optical cycle
In the code, tunnel ionization is described by the ADK model



ionized far from envelope peak ⇒ not trapped
L-shell

N^+	N^{1+}	N^{2+}	N^{3+}	N^{4+}	N^{5+}
14.5eV	29.5eV	47.7eV	77.2eV	97.8eV	551eV

Maximum laser intensity used just large enough to ionize N^{5+} ⇒ Localized injection

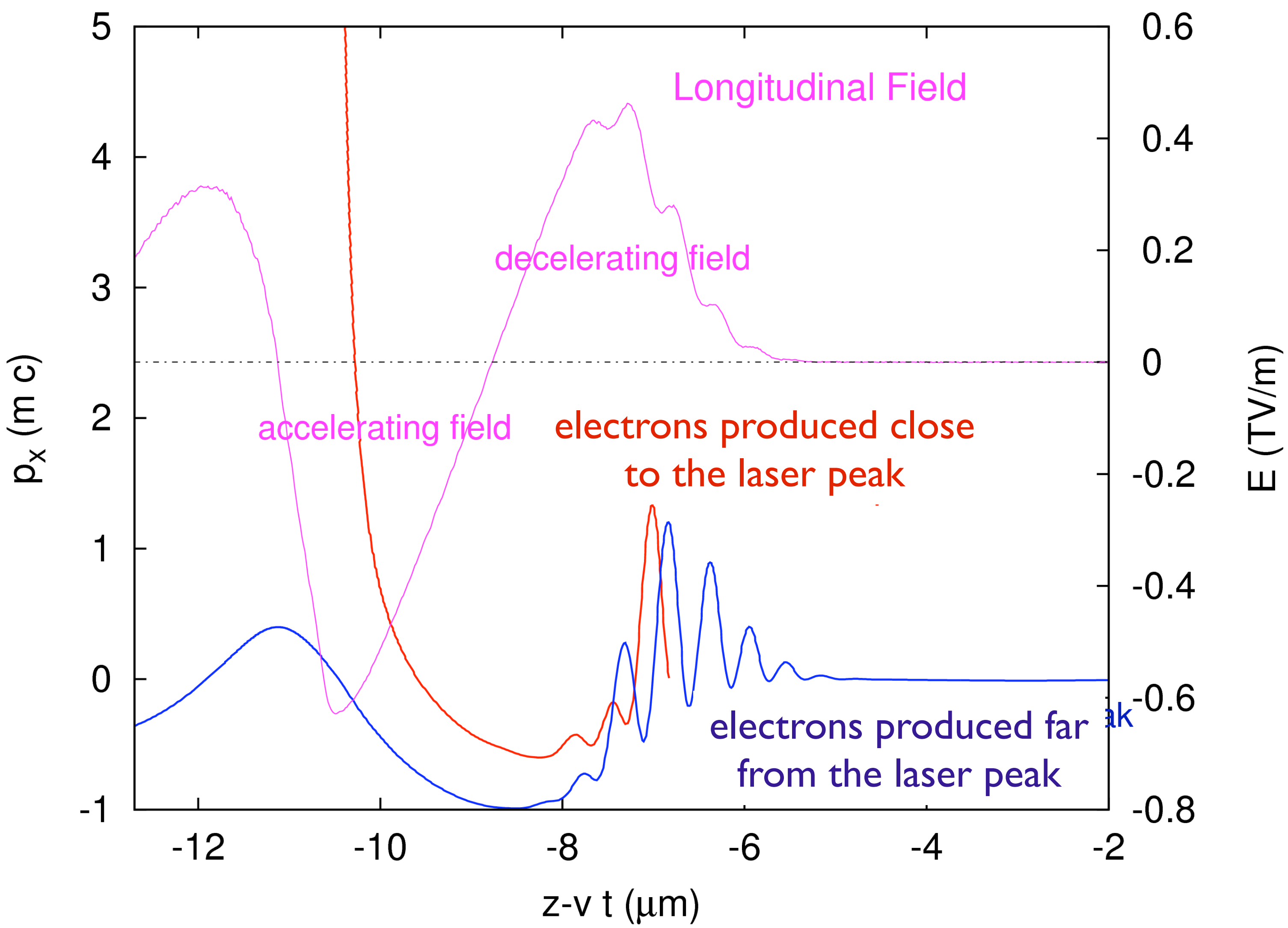


I, II, III, IV,V correspond to each half cycle of the laser electric field for which trapping is possible

Electrons coming from ionization of N^{5+} are trapped

Ionization injection is well localized

Simulation Parameters: $n_0 = 0.06 n_c = 10^{20}$ cm^{-3} (once N is stripped of first 5 electrons)
N_0 gas jet length 130 μm, Laser: 5 fs, 4 mJ, $a_0 = 1.1$, $P = 0.8$ TW (above P_c for self-focusing)

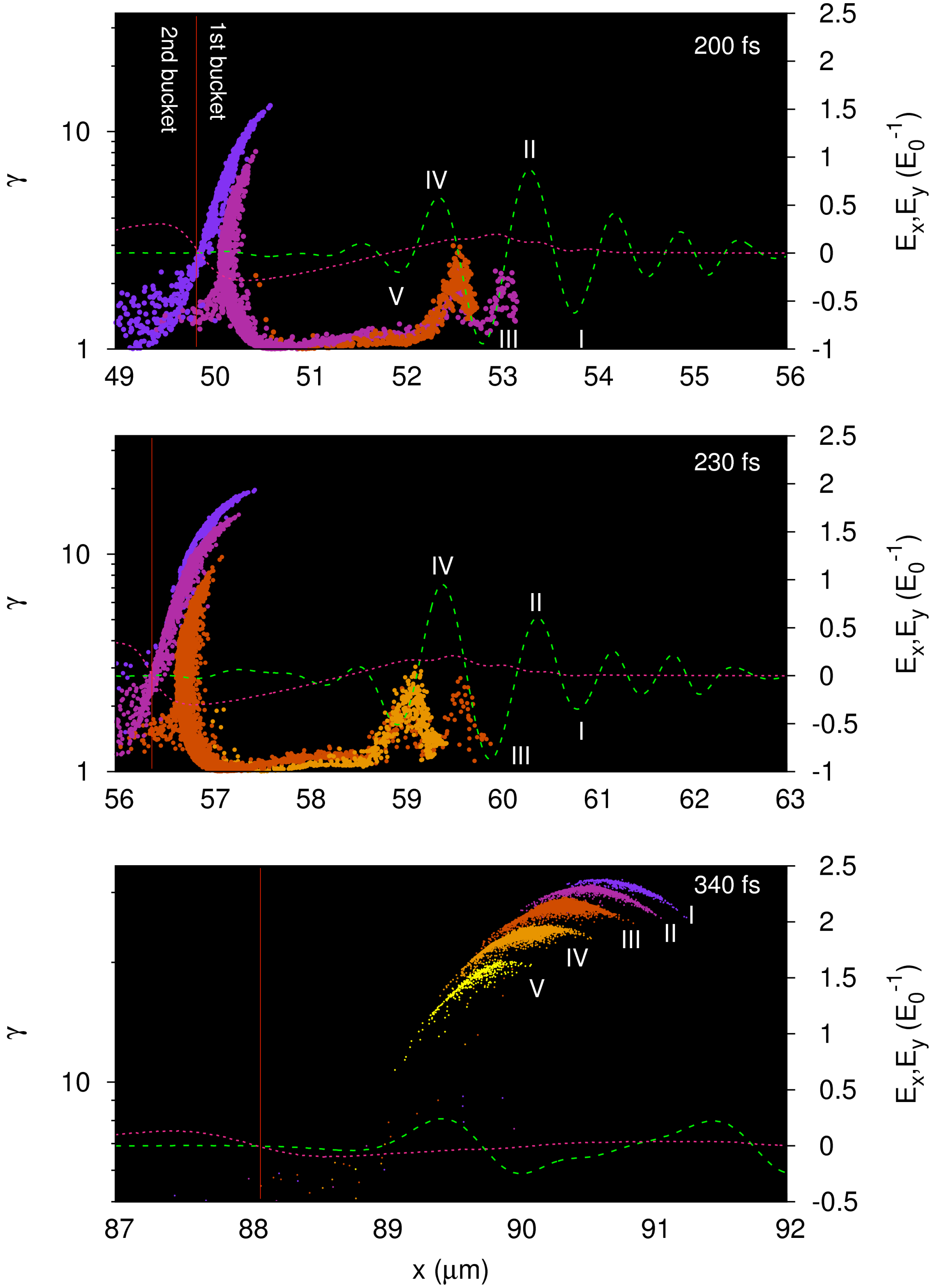


Using pure N_2 as target gas produces strong ionization defocusing, that balances relativistic self-focusing

Electrons coming from ionization of N^{5+} are trapped

Only electrons produced close to laser envelope peak can be trapped

Evolution in phase space



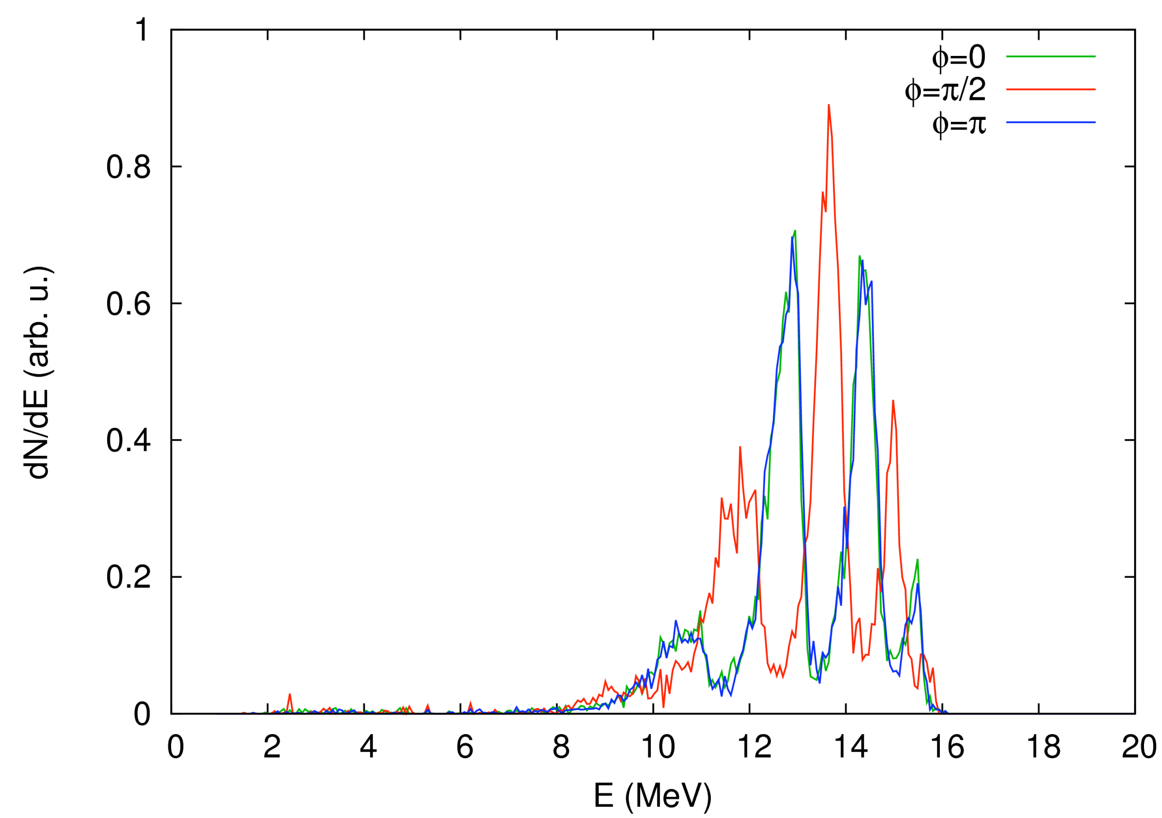
Electrons coming from a semi-cycle are packed in bunches

Phase-rotation occurs at different energies

Each peak corresponds → a semi-cycle

Peaks can be smoothly shifted by changing φ

Same spectra for φ = 0 and φ = π

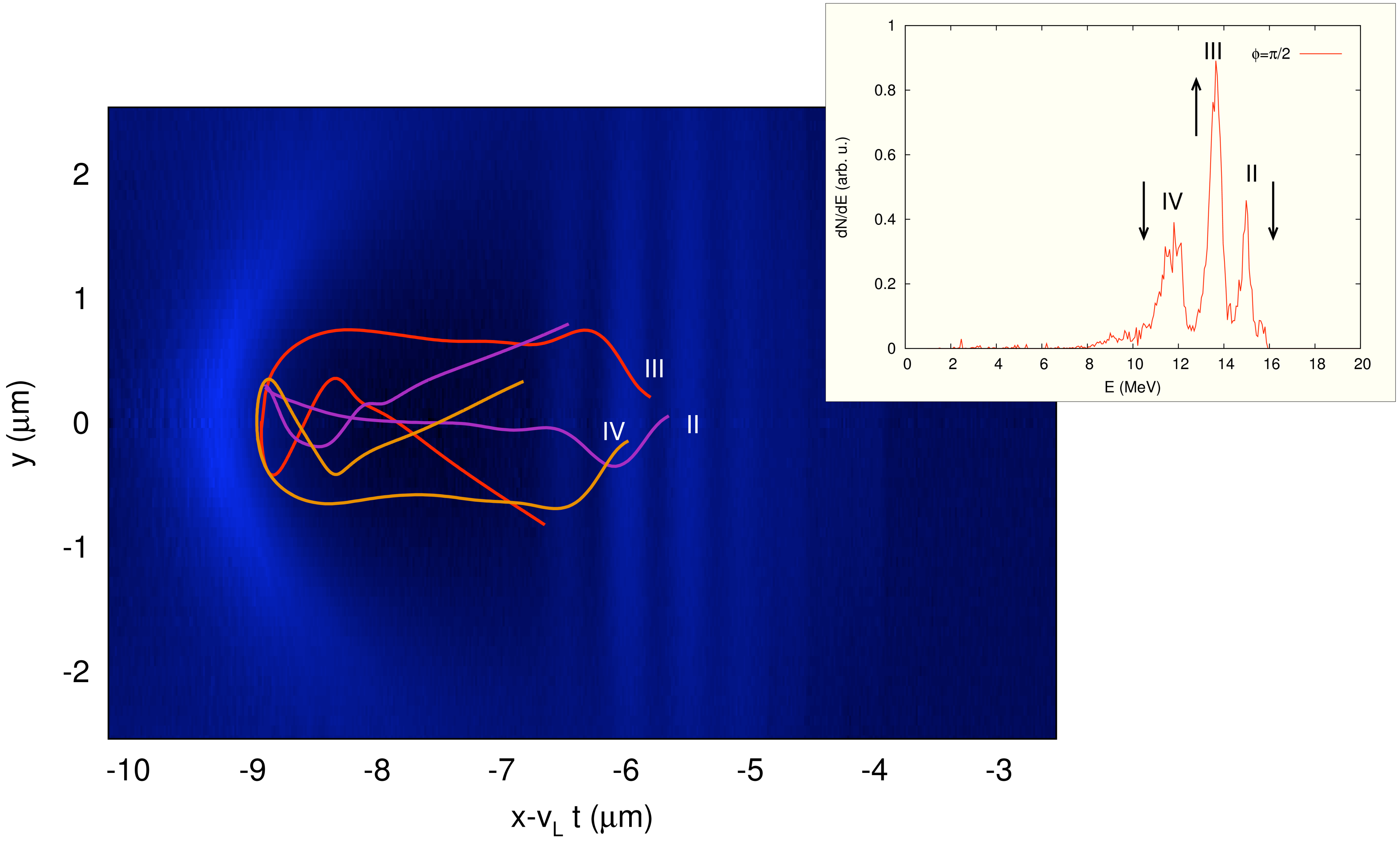


Ionization introduces asymmetry

Electrons receive an extra kick in ±y

=> Correlation between initial velocity direction and semi-cycle

=> Even after a betatron oscillation the correlation remains



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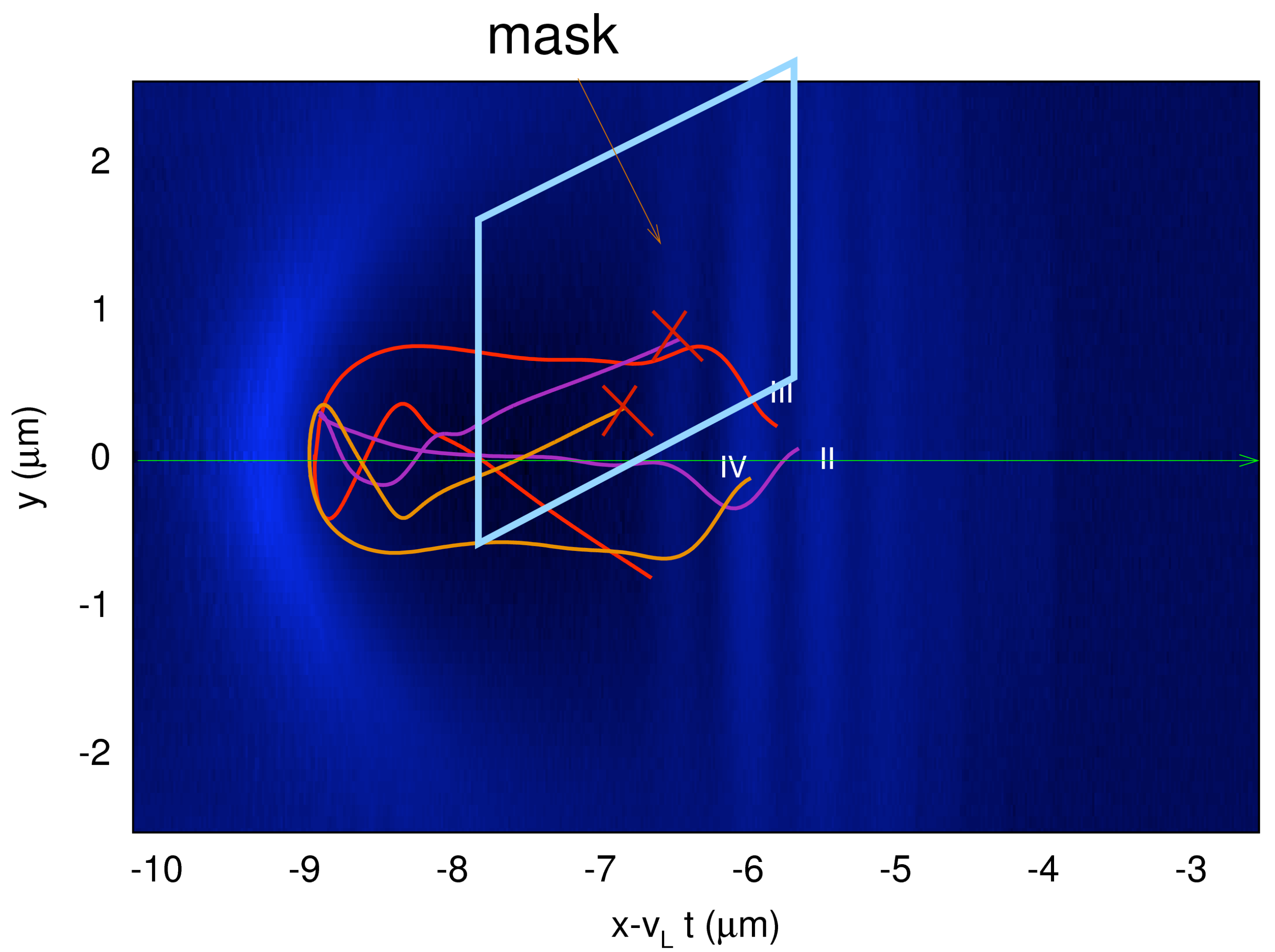
Improving beam quality by spatial filtering

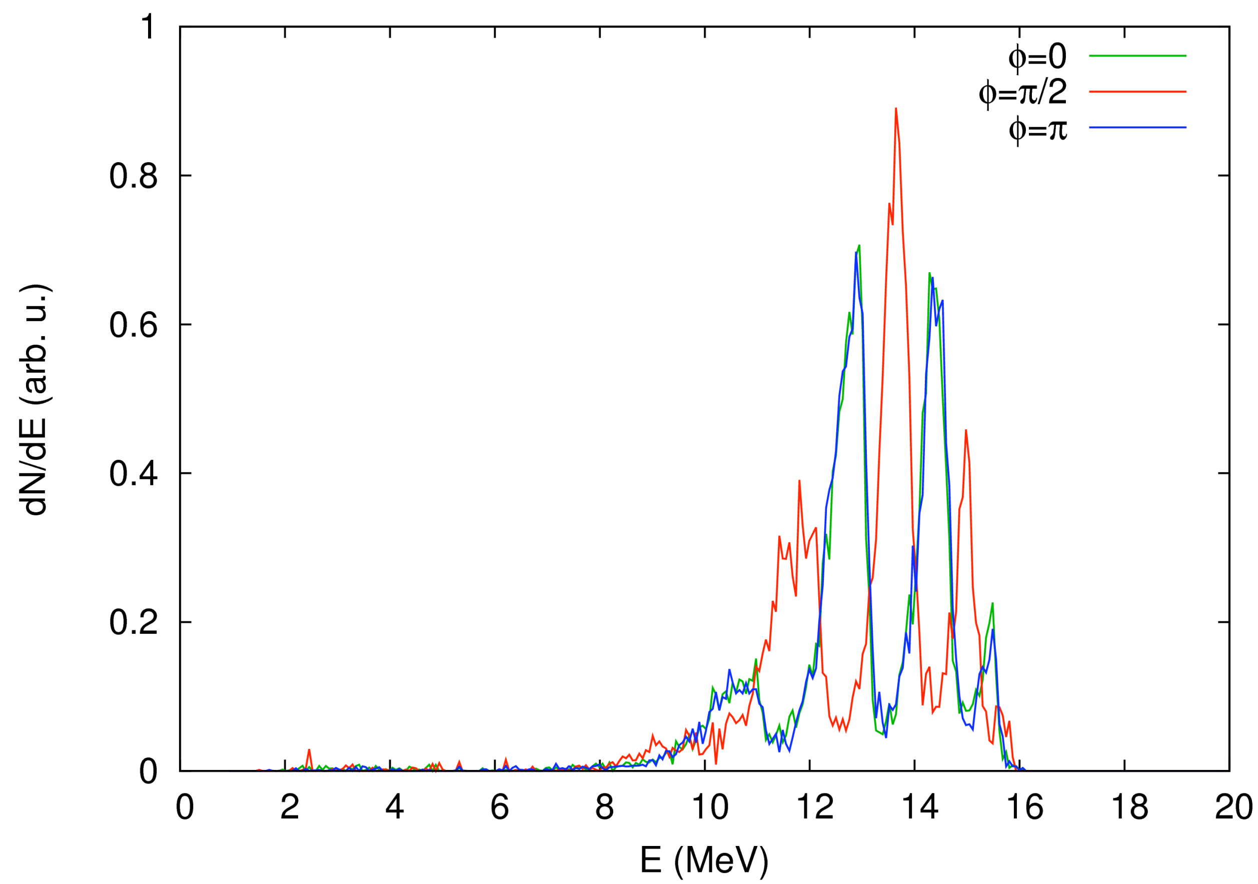
Foil perpendicular to laser propagation axis

Electrons with $v_y > 0$ are blocked

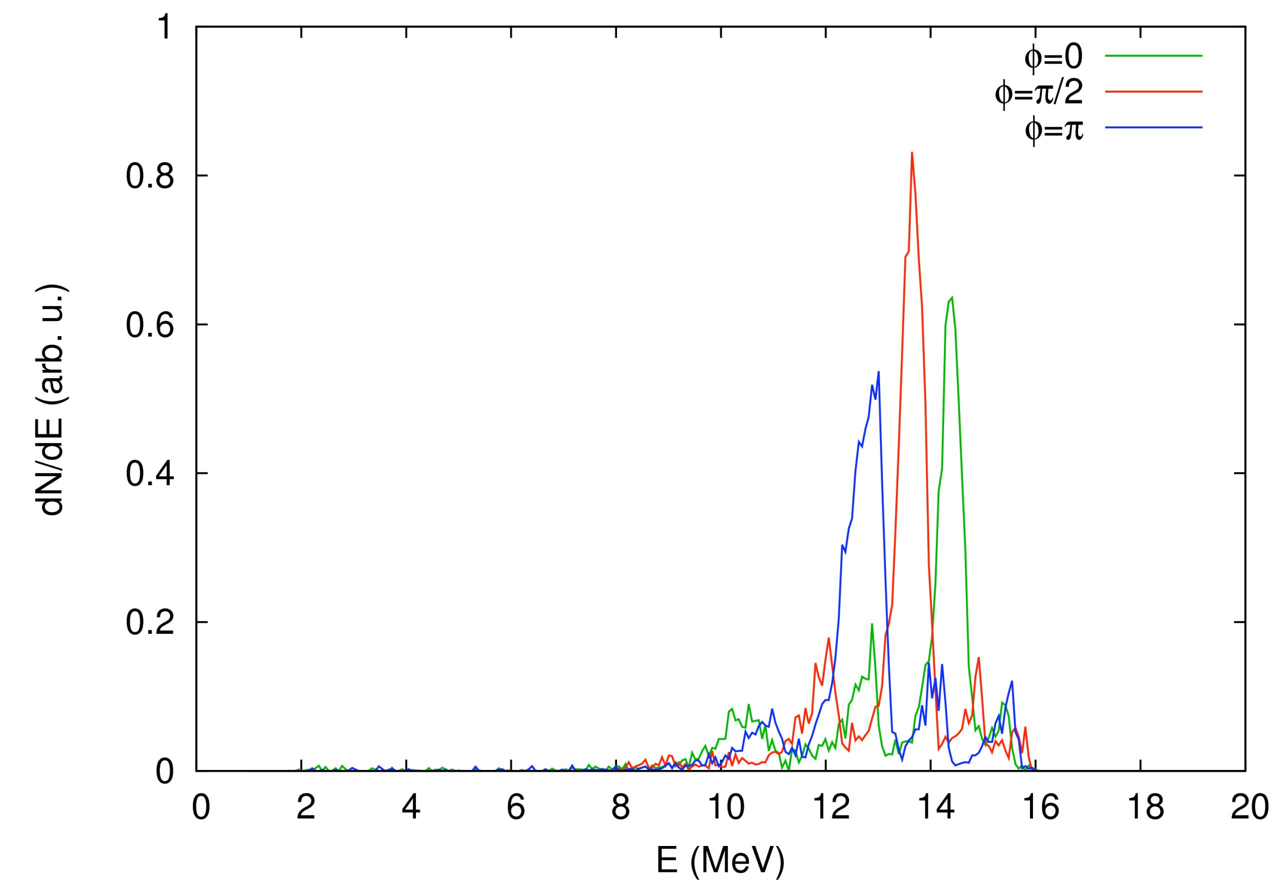


Filtered spectra

Without filter



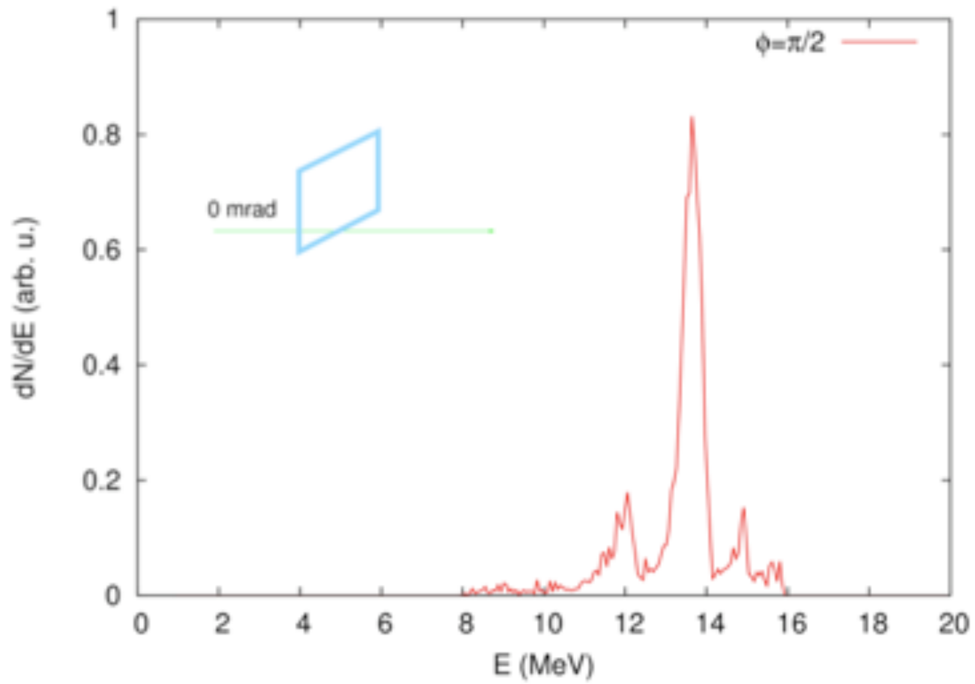
With filter



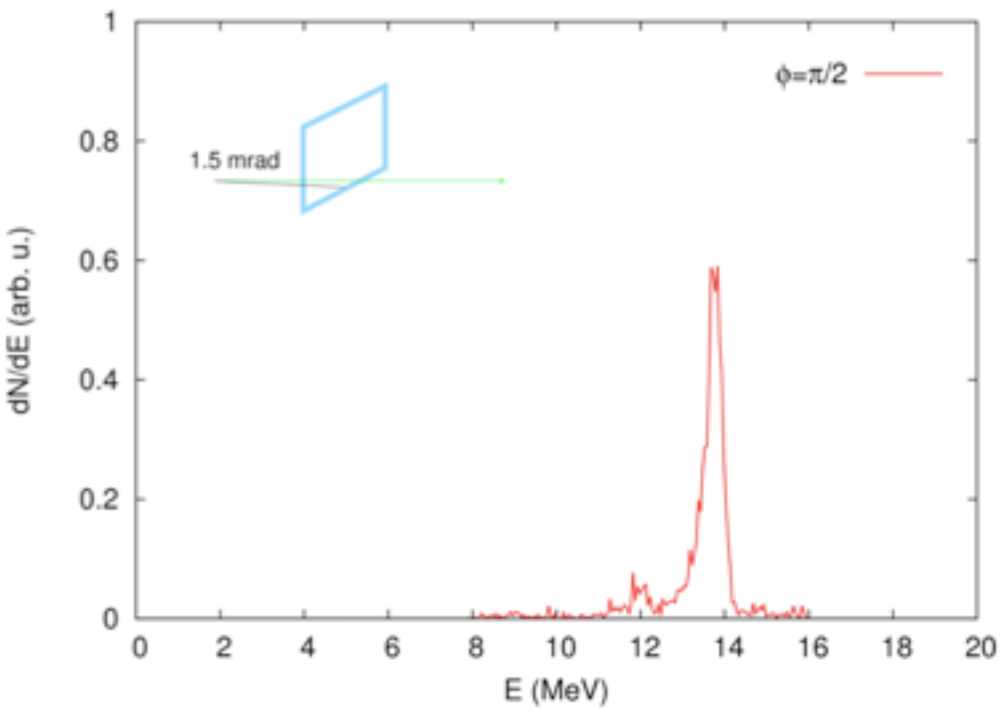
Best spectrum for $\varphi = \pi/2$

Spectra for $\varphi = 0$ and $\varphi = \pi$ become very different

High quality kHz z-beam



Charge: 83 fC
ΔE : 3 % FWHM, 9 % RMS
Divergence: 10(y)x11(z) mrad
RMS Duration: 0.6 fs

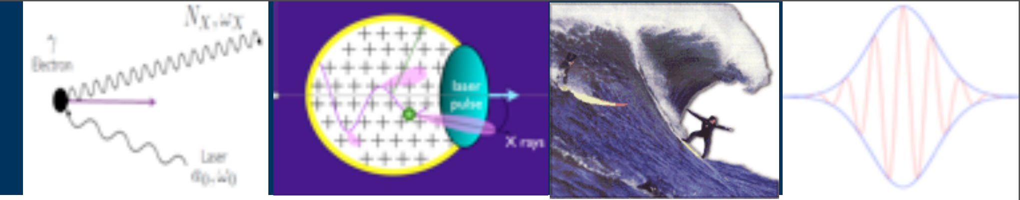


Charge: 43 fC
ΔE : 2.7 % FWHM, 6 % RMS
Divergence: 8(y)x11(z) mrad
RMS Duration: 0.6 fs

Simulations shown the feasibility of producing high quality relativistic electron beams with few-mJ few-cycle laser
Electrons bunches would be produced at kHz rates
Control of laser carrier-envelope phase allows to improve beam quality

A. Lifschitz and V. Malka, NJP **4**, 053045 (2012)

Conclusions



High quality and stable e-beam & Monoenergetic dE/E down to 1 %, kA, μm emittance, energy tunable up to 400 MeV, charge tunable 1 to tens pC, Ultra short e-bunch : 1,5 fs rms

Betatron is a powerful diagnostic

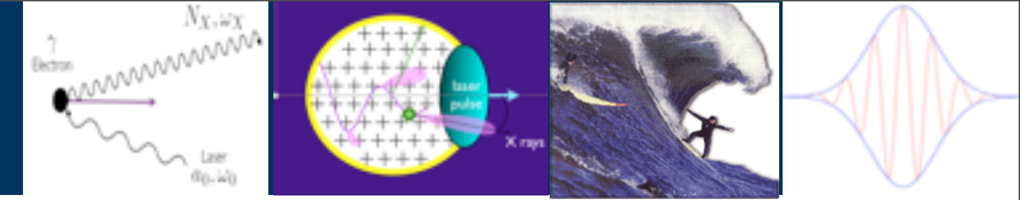
High brightness Compton source

High quality e-beam of interest for fs electron diffraction

and many pertinent applications

S. Corde *et al.*, Accepted to Rev. Modern Physics

Perspectives



Results extremely important for :

Designing future accelerators

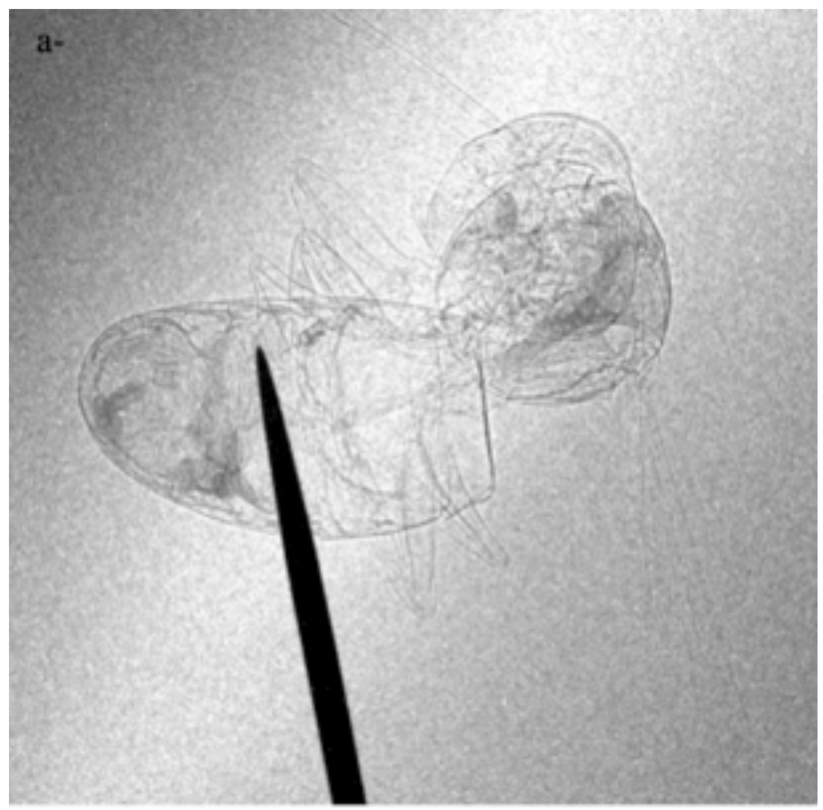
Compact X ray source (Thomson, Compton, Betatron, or FEL)

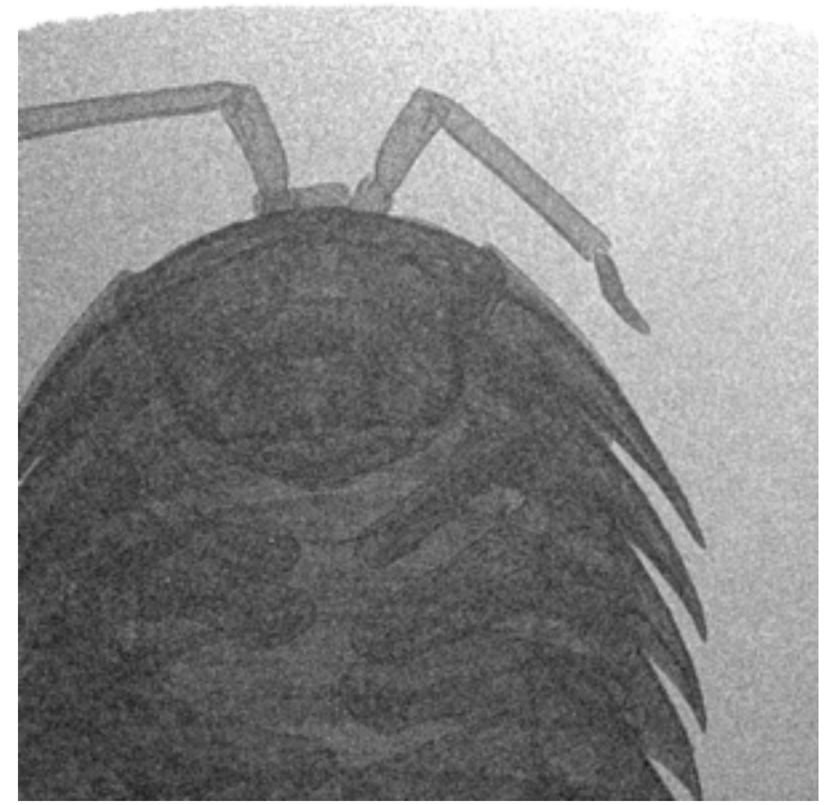
Applications (chemistry, radiotherapy, medicine, material science, ultrafast phenomena studies, etc...)

First X rays betatron contrast images

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

S. Kneip *et al.*, Appl. Phys. Lett. **99**, 093701 (2011)

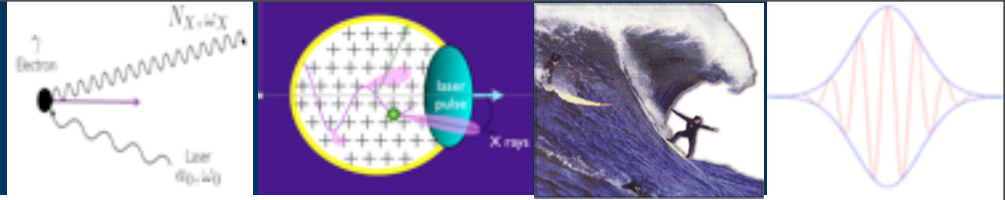




Courtesy of K. Krushelnick

V. Malka *et al.*, Nature Physics **4** (2008)

Acknowledgements



A. Ben Ismail, S. Corde, J. Faure, S. Fritzler, Y. Glinec, A. Lifshitz, J. Lim, O. Lundh, C. Rechatin, Kim Ta Phuoc, A. Rousse, S. Sebban, and C. Thaury from LOA

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